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Wave Optics of Deep Atmospheric Turbulence: From Underlying Physics Towards Predictive Modeling, Mitigation, and Exploitation

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1 Introduction

1.1 Background

There has been a growing demand in the Department of Defense (DoD) in developing optical systems capable of operating over long distances (path lengths up to and over 100 km) in the atmosphere. These systems may be a part of land-, airborne- or space-based weapon, sensing and surveillance platforms operating at different altitudes ranging from the ground and atmospheric boundary layer to the upper troposphere, stratosphere, and even space. To optimally design, build, and evaluate the performance of these new systems requires fundamental scientific knowledge of atmospheric effects along paths that may cross several extended regions with distinctive refractive index spatial structures and temporal dynamics, as well as deep understanding of impact of the extended-range atmospheric phenomena on optical wave characteristics.

1.2 Knowledge Gaps Addressed

Prior to this MURI project, analyses of optical wave propagation in the atmosphere were performed in the framework of classical “fully developed” Kolmogorov optical turbulence theory describing the atmosphere as statistically homogeneous and isotropic random fields of refractive index fluctuations and thus neglecting the impact of various large-scale meteorological factors including terrain, hydro-thermodynamic processes, gravity and solar radiation induced buoyancy and friction forces that lead to formation of distinct, nearly horizontally aligned atmospheric turbulent and refractive layers. All these global-scale factors can severely impact optical wave propagation over long distances.

The existing fundamental scientific understanding and knowledge necessary to enable accurate prediction of the impact of atmospheric effects on laser beam propagation and image formation over long distances was either insufficient or even absent. This was clearly indicated by strong mismatches between theoretical predictions and measurement results obtained in several long-range laser beam propagation experiments.

This insufficient level of scientific understanding of optical wave propagation over extended-length distances could be partially explained by the absence of atmospheric sensing techniques for operation over long-range propagation paths that provide sufficiently accurate information on the complex (4D) spatio-temporal structures of refractive index and absorption/scattering fields. The lack of such information prevented development and verification of models that account for the complexity of atmospheric processes along various long-range paths.

Another missing segment of fundamental knowledge was related to the lack of mathematical models and numerical simulation techniques that can accurately describe optical wave propagation over extended ranges in volume atmosphere with presence of turbulent and refractive layers. The commonly used wave-optics and ray tracing techniques accounted for the impact of either atmospheric turbulence or refractivity, but could not be applied when optical wave propagation occurs along the path with complicated layered structures of the refractive index field, containing inversed temperature, stratified and unstable (turbulent) layers. This lack of generalized models describing laser beam propagation and image formation in the layered atmosphere that includes both refractivity and turbulence effects prevented deep understanding and accurate predictive numerical simulation of such phenomena as optical ducting and guiding, mirage image formation, super-focusing and super-resolution effects

1.3 Research Objectives

The major objective of the program was to develop a rigorous scientific theoretical and mathematical basis for understanding of atmospheric optics effects over extended-range propagation distances and in deep turbulence. The program objectives also included development of new approaches and optical system architectures for atmospheric effects sensing, mitigation and exploitation.

An overarching goal was to facilitate the development of long-range optical systems where there is a need for understanding and performance assessment of optical wave propagation and image formation along extended distances in atmosphere.

1.4 Scientific Approach

The research was focused on elaborating a foundation for the physics of atmospheric optics effects in deep turbulence by building bridges between meteorology, computational fluid dynamics, and statistical wave optics.

Along this general theoretical approach, the research team developed a theoretical framework and the corresponding mathematical and numerical simulation tools that allow computation of 3D refractive index Reynolds-averaged fields, also referred to as optical refractivity, and atmospheric turbulence structure parameter C_n^2 along optical wave propagation paths using computational fluid dynamics. The obtained refractive index and C_n^2 fields were used for analysis of optical wave and image formation. This analysis was performed through high-resolution nested simulations by merging refractive and wave-optics propagation models.

For atmospheric refractivity and turbulence sensing over long-range propagation paths the team used several approaches including: (a) weather radar data processing, (b) analysis of image motion and degradation, (c) sensing of polychromatic (multi-wavelength) laser beacon characteristics, and (d) the target-in-the-loop atmospheric sensing based on optical reciprocity. The scientific approach included theoretical analyses, numerical simulations, and atmospheric experiments and data collection, in part using the atmospheric sensing suite that was developed under both this MURI and the AFRL STTR Phase II “Complex field atmospheric sensing suite for deep turbulence research” (contract Number: FA9451-14-C-0015; Gov. TPOC: Dr. Rao Gudimetla, AFRL/DE).

For mitigation of atmospheric effects several new approaches were investigated, including engineering of unconventional optical fields (e.g., optical fields with controllable space-varying coherence or dynamically changing phase and polarization patterns) that have reduced sensitivity to atmospheric distortions, and adaptive turbulence effects mitigation with coherent fiber-array techniques.

The team also studied several approaches for exploitation of deep turbulence effects for directed energy, atmospheric imaging and laser communications. The most promising is the developed approach for turbulence effects exploitation based on utilization of optical invariants such as the interference and speckle metrics that remains constant along the wave propagation path.

1.5 Research Strategy

The MURI team's general approach included the following major research efforts:

- Building bridges between meteorology, computational fluid dynamics and statistical wave-optics.
- Development of extended-range atmospheric optics sensors, mathematical wave propagation models and predictive computer simulation tools.
- Development of atmospheric optics effects mitigation techniques via engineering of non-conventional optical waves and systems
- Development of a scientific foundation for atmospheric optics effects exploitation.

An important aspect of the research strategy was its focus on the development of theoretical models, computer simulation capabilities, sensing and data analysis tools that were used in the extended-range comprehensive atmospheric optics sensing (ERCAOS) experimental campaign, which took place in April 2019. The experiments included laser beam projection over 149 km between two Hawaiian Islands with a specifically developed laser beacon and a comprehensive set of sensors for evaluation of beam characteristics. It led to the discovery of a previously undescribed phenomena – laser "beam mirages". The obtained experimental data provided unique information for evaluation of the mathematical models, numerical simulation and sensing techniques developed under this MURI project.

2 Accomplishments

2.1 Significant Results and Key Outcomes

2.1.1 Building Bridges between Meteorology, Computational Fluid Dynamics and Statistical Wave-optics

2.1.1.1 Computational meteorology based modeling

The key scientific objective of the MURI team in this research direction was to investigate how the framework of modern computational atmospheric fluid dynamics, also referred to as computational meteorology, can be applied for analysis of the 3D refractive index field in the

Earth's atmospheric boundary layer and low stratosphere for selected geographical areas of interest and time period.

Computation of the 3D refractive index field along am extended (on the order of 100 km or more) optical wave propagation path encounters two major problems. First, although the computational fluid dynamics methods can be in principle used for refractive index field analysis with up to sub-centimeter spatial resolution, even with currently available supercomputing resources it takes many hours computation even with significantly low (~ 0.5 km – 1.0 km) spatial resolution. Thus, the realistically achievable spatial resolution in the refractive index 3D field is not sufficient for analyses of optical wave propagation, which often require accounting for millimeter-scale refractive index features.

In the approach developed by the team, the refractive index is considered as a sum of two major components: one is associated with atmospheric refractivity and the second with optical turbulence. The refractivity component describes slowly evolving (in comparison to the time-scale of turbulence) large-scale refractive field variations caused by synoptic-scale and mesoscale atmospheric processes. This refractivity field can be defined by ensemble averaging (Reynolds averaging) performed over relatively small-scale random and rapidly changing turbulence-induced refractive index inhomogeneities (eddies). The characteristic spatial scales of these refractive index eddies are associated with turbulence inner and outer scales (ranging from a few mm to tens of meters), and their life-time associated with a characteristic turbulent "frozen time" (on the order of a few msec). The computational meteorology approach can be used for computation of the turbulence-averaged atmospheric refractivity that describes far-reaching changes in the refractive index which occur at spatial scales from a few to hundreds of kilometers and over a timeframe from several minutes to several hours.

For better understanding of the spatio-temporal variability and characteristic structures of atmospheric refractivity, the team performed extensive mesoscale analysis of refractivity fields for different geographical locations including Hawaiian Islands, Canary Islands, US East Coast, and for different meteorological conditions. These mesoscale simulations clearly demonstrated a great variability and spatial complexity of the atmospheric refractivity, including the presence of various coherent structures, inverse gradients, wave ducting, and stratified layers.

The findings from these simulations challenge the approach currently used in optics for accounting atmospheric refractivity using "formula-based" general models such as the standard US76 refractivity model. From this view point the proposed approach of atmospheric refractivity predictive modeling using computational fluid dynamic and weather forecasting techniques represents a major paradigm shift for the computational atmospheric optics.

The second challenge the team encountered is related to the adequate representation of the stochastic refractive index component that is associated with atmospheric turbulence. The problem is that computational meteorology even with highest realistically possible numerical simulation grid resolution cannot capture refractive index random perturbations on turbulence scales (from millimeters to tens of meters). At the same time, it is possible with mesoscale modeling to identify areas where air flows are unstable and even compute the refractive index structure parameter, Cn2.

This suggests that using computational fluid dynamics one can both simulate the atmospheric refractivity field and also quantify the corresponding field of the refractive index structure parameter Cn2. This allows to simply add the turbulent component to the refractivity field using the conventional statistical atmospheric optics approach based on computer generation of a set of thin turbulent layers (phase screens) that are distributed along the optical wave propagation path. These turbulent phase screens are generated using the refractive index structure parameter values obtained from the mesoscale modelling.

The approach developed by the MURI team represents a major shift from the conventional representation of atmospheric effects in optics and allows fusion of refractive (ray-tracing based) and diffractive (wave-optics) methods.

By developing this new concept the team devoted a significant effort on the key problem of quantification of the refractive index structure parameter Cn2 in the framework of computational meteorology. Given the complexity of this fundamental problem, the team explored several research avenues:

(i) Higher-order turbulence closure-based approach;

(ii) Regression approach using an artificial neural network;

(iii) Gradient Richardson number-based approach utilizing an extensive direct and large-eddy simulation dataset; and

(iv) Scaling-based approach.

The strengths and weaknesses of all these competing approaches were identified using observational data from various field campaigns such as the Hawaii 2002 thermosonde field campaign by AFRL. All these approaches were also combined with a coupled mesoscale model-ray tracing technique. With the exception of the higher-order turbulence closure-based approach, all other C_n^2 prediction approaches are original and have been developed under the MURI grant.

In addition, the team performed idealized large-eddy simulations (LES) and coupled mesoscale-large-eddy simulations for several atmospheric flows. The simulated datasets enabled to complete the development and advancement of the novel atmospheric optics modelling approaches that merges computational fluid dynamics and weather forecasting simulation techniques with refractive and statistical atmospheric optics and allows for the first time accurate prediction of optical waves and image characteristics over long-range propagation paths.

2.1.1.2 Software packages for prediction of atmospheric conditions

The MURI team actively contributed to the development of physics-based modeling package, PITBUL, for tracking airborne targets for HEL applications, including atmospheric and sensor effects and active illumination as well as to the development of the LEEDR package, which defines the atmospheric boundary layer with a worldwide, probabilistic surface climatology based on season and time of day. Under the MURI effort, for instance, the capability of the LEEDR package for characterization of meteorological parameters and radiative transfer effects of the atmospheric boundary layer using surface observations or climatological values of temperature, pressure, and humidity was evaluated.

It was demonstrated that well-mixed atmospheric boundary layers produce elevated aerosol extinction layers that are critical to cloud formation, energy propagation, and may produce elevated turbulence layers. The combining of meteorological observations, surface-based particle counts, and a validated atmospheric radiative transfer code was demonstrated to yield multispectral quantifications of aerosol optical depth, transmission, and vertical extinction regardless of clouds, weather or sun position. In order to improve the quality of the prediction of atmospheric characteristics, large atmospheric volumes, the Weather Cubes, were defined with numerical weather prediction data and coupled to a radiative transfer code to define extinction and propagation characteristics at any wavelength of interest for visualization and analysis.

2.1.2 Extended-range Atmospheric Optics Effects Sensing Techniques

The effort was focused on development of basic principles and techniques for atmospheric refractivity and turbulence sensing over extended-range distances. Characterization of turbulence and refractivity over long distances encounters several key challenges:

- Existing electro-optics sensors such as optical scintillometers – the most commonly used sensors for measurements of the atmospheric turbulence structure parameter C_n^2 – have limited operational ranges that typically do not exceed a few kilometers (~ 10 km). Besides, these sensors are designed for operation at fixed-point settings, and cannot perform measurements in dynamically changing conditions or a moving/flying sensing platform or target.
- Over long distances, atmospheric dynamics is influenced by a variety of factors including large-scale terrain elements, local weather conditions, slow variation of temperature causing optical refraction, etc. All these factors cannot be quantified by the existing electro-optics sensors developed under the assumption that optical wave propagation in the atmosphere is only influenced by fully developed statistically isotropic and homogeneous turbulence described in the framework of Kolmogorov turbulence theory.

The dependence of optical wave characteristics on a diverse set of atmospheric phenomena represents one of the most serious challenges for atmospheric sensing techniques. To address this problem the MURI team considered several new approaches for atmospheric sensing over long-range distances.

2.1.2.1 Mesoscale estimations of C_n^2 profiles based on satellite and weather radar measurements

The idea is based on utilization of information that is available from the continuously operating weather satellites and radar systems for atmospheric turbulence sensing over mesoscale size areas. The team also considered the possibility for sensing of the refractive structure parameter C_n^2 based on a combined analysis of data obtained from weather radars and satellites, and numerical weather prediction simulations. It was shown that the temperature field data from satellite measurements can be used to derive vertical index of refraction structure parameter profiles, while numerical weather prediction data can be used to enhance the accuracy of the satellite-derived C_n^2 values. The ultimate goal was to facilitate estimations of structure parameters of temperature, C_T^2, refractive index, C_n^2, and wind velocity, C_v^2 over large volumes and to obtain cloud location and aerosol extinction fields. The numerical weather forecasting results were compared to the corresponding atmospheric characteristics obtained using ground-based LIDAR measurements. This research enhanced the capabilities for atmospheric optical characteristics estimation over mesoscale size regions of interest, which include long-range laser beam propagation or optical imaging paths.

2.1.2.2 Line-of-site, in-situ measurements of atmospheric turbulence and laser beam characteristics

The MURI team developed a new target-in-the-loop atmospheric sensing (TILAS) concept for in-situ remote sensing of laser beam and turbulence characteristics along the target line of sight, including scintillation index and refractive index structure parameter. The TILAS concept is based on the integral invariant (interference metric) derived by the team, which couples the complex amplitudes of counter-propagating optical fields in the refractive and turbulent atmosphere. It was shown that the interference metric can be measured using a single-mode fiber based laser transceiver system. These measurements allow remote evaluation of intensity scintillations of the laser beam that is scattered off a small size retro-reflector at the other-end of a laser beam propagation path, as well as retrieval of the path integrated refractive index structure parameter from these measurements. The TILAS concept may be also used to examine the validity of the Kolmogorov turbulence theory as well as to develop physics-based models of the atmosphere.

Together with the development of the TILAS concept and its evaluation through wave-optics numerical simulations, the underlying reciprocity principle of counter-propagating waves was demonstrated experimentally using the atmospheric test range at UD. The team then developed the TILAS sensor using existing components, which included a single-mode fiber based laser beam transceiver that was equipped with a fiber circulator for separation of the outgoing and target-returned received waves, and photo-detector connected to the receiver path. The system was integrated into the UD atmospheric testbed and a retro-reflector was used as target on the other end of the 7 km propagation path. The retro-reflector was set up in such way that measurements of the fluctuations of the incident laser power were possible simultaneously with the measurements of the received laser power fluctuations at the TILAS transceiver. This allowed for experimental demonstration of the concept underlying the TILAS approach. The setup was then used for direct atmospheric measurements of laser beam intensity scintillation characteristics and the corresponding refractive index structure parameter C_n^2 over the 7 km propagation path to validate the approach through a comparison with data obtained with a commercial scintillometer installed at the UD testbed, where measurement results from both sensors correlated well.

The developed TILAS sensor has a considerable advantage over scintillometers, which need powered transmitters/receivers at both ends of the propagation path. In contrast, the TILAS approach requires only a powered transceiver on one end of the propagation path, while a passive device suffices at the other end (for instance a retro-reflector, but a glint of an object or a rough scattering surface may work as well).

Furthermore, numerical analyses demonstrated the application of the approach for identification of localized atmospheric turbulence layers using laser light backscattered off a moving target. It was shown that for this case the autocorrelation function of the laser power received by the TILAS system strongly depends on the turbulence distribution and is weakly sensitive to the turbulence strength, while the variance of the received power equally depends on these parameters, enabling a novel technique for turbulence profiling. Numerical simulations demonstrated the accurate recognition of the location along the propagation path and strength of a turbulence layer. The estimation errors were furthermore reduced by developing and implementing an iterative algorithm for the processing of the data from the laser power signal received by the TILAS system.

2.1.2.3 Polychromatic atmospheric turbulence and refractivity sensing

Additional opportunities for characterization of the atmosphere are opening with the polychromatic atmospheric sensing technique developed by the MURI team. Using a polychromatic laser beacon that operates with different wavelengths ($\lambda_1 = 0.53$ μm, $\lambda_2 = 1.06$ μm, and $\lambda_3 = 1.55$ μm), one can simultaneously measure the scintillation indexes corresponding to each wavelength. This information may be utilized for estimation of the refraction structure parameter distribution along the propagation path, $C_n^2(z)$. Besides the retrieval of the $C_n^2(z)$ profile, the polychromatic sensing technique can be used to measure the strength of optical refraction along the target line of sight. The polychromatic atmospheric sensing system was implemented using the photonic crystal fiber based laser beacon system that was developed under an AFRL/AFOSR ERASS STTR project and this MURI program.

The MURI team showed through numerical simulations that the impact of optical refraction can be characterized via measurement of shifts in laser beam centroids that occur at different wavelengths. The proposed polychromatic atmospheric sensing technique allows thus simultaneous sensing of both turbulence and optical refraction characteristics. The experimental validation of the polychromatic atmospheric sensing system was performed by the MURI team at UD's 7-km test range. It was then integrated into the sensing suite for the ERCAOS experimental campaign and used for extensive measurements at the 149 km propagation path between the Mauna Loa Observatory on Hawaii (Big Island) and the site of the Haleakala Observatories on Maui.

2.1.2.4 Atmospheric refractivity and turbulence sensing with time-lapse imagery

Refractive effects of the atmosphere can range from something as subtle as an apparent shift in target position to something as spectacular as mirages and the green flash. Although the physics behind these phenomena are well known, their characteristics such as strength, frequency of occurrence, and correlation to meteorological data are lacking. These characteristics can be of value to different tactical mission planning.

In order to examine the potential of predicting the refractive behavior of the atmosphere at a particular location from meteorological measurements and modeling, the MURI team pioneered a low-cost time-lapse imaging system consisting of a commercial camera with a zoom lens for the purpose of sensing the guiding and optical ray bending phenomena caused by atmospheric refraction.

A significant advantage of the time-lapse imaging system is that long duration monitoring of image dynamics (weeks or months) is possible with the camera operated in a time-lapse mode. Experiments have been performed with this type of system over a 12.8 km path in Dayton, OH and a 15.3 km path in Las Cruces, NM. Due to changes in the refractive index gradient during the course of a day, a corresponding slow vertical drift in the images was observed. An estimate of the gradient variations during the daytime was obtained from this image motion. The path averaged refractive index gradient variations derived from the time-lapse imagery were compared with those derived from a coupled mesoscale model, ray tracing and brightness function imaging frameworks developed by the team. The daytime gradient variations from the imaging experiment were in good agreement with those predicted from the mesoscale-ray tracing and brightness function models. These first results are a good indication for the possibility to predict refractive index gradient variations from both numerical weather models and time-lapse imaging.

After the initial experimental evaluation of the time-lapse imaging approach, the team extended processing codes to detect geometrical distortions of the target image rather than just the apparent target shift. These distortions can be interpreted in terms of refraction and an inversion of this data allows for an improved estimation of temperature profiles. Longer term measurement campaigns were performed, e.g., over a 15.3-km path in Las Cruces, NM. Here, the recorded imagery clearly demonstrated the presence of a strong refractivity layer. The comparison of simulations with different refractivity layer models with the experimental data showed best agreement when the strong refractivity layer was described by the Webster duct model.

The time-lapse imagery showed two distinguished components of image motion: the slow vertical motion due to changes in refractive index gradient and a faster, random motion, which can be attributed to turbulence-induced wavefront tilts. Since statistics of wavefront tilts depends on the turbulence strength, the random image motion sensing can be used for estimating the path averaged refractive index structure constant, C_n^2. Since this technique is phase based, it may be applied to strong turbulence paths where traditional irradiance based methods fail to work due to saturation effects.

The team also used the time-lapse imagery to estimate turbulence strength and turbulence profiles along the propagation path. Features of different sizes and separations were identified in the time-lapse images and their individual and differential motion was studied. The C_n^2 estimation technique uses a set of weighting functions that depend on the size of the imaging aperture and the patch size in the image whose motion is being tracked. Weighting functions for different patch sizes and separations can be linearly combined to form any desired weighting function, such as that of Fried's coherence diameter r_0 or that of a scintillometer. The time-lapse measurements can thus mimic the measurements by a scintillometer or other instruments. The technique was applied to synthetic and experimentally obtained imagery recorded, for instance, over test ranges at WPAFB and UD with success. The path-averaged estimates of C_n^2 from the experimental data agreed very well with scintillometer measurements over a horizontal path. A scheme to use the time-lapse measurements to profile turbulence along the path was also investigated and showed promising results for certain system parameters and propagation path ranges, but limitations exist due to stronger errors for C_n^2 estimates on one side of the propagation path. An experimental setup for turbulence characterization with differential image motion utilizing a set of distributed LED beacons and two cameras was developed by the AFIT team members and used for atmospheric characterization during the ERCAOS experimental campaign.

2.1.2.5 Development of general use atmospheric data collection and sharing capabilities

During the MURI effort, the team has significantly extended capabilities of the unique atmospheric propagation testbed at UD. This testbed includes a 7 km long path between a lab installation on the roof of the VA Medical Center (VAMC) in downtown Dayton and the Intelligent Optics Laboratory (IOL) located on the 5th floor of the UD Fitz Hall building. The testbed contains various laser beacon sources, imaging targets, meteorological sensors and laser beam and image characterization sensors. The laser beams are launched through the installation window, and after propagation enter optical receiver systems at the IOL through a special window. Alignment and power control of the beacon beams is performed remotely from the IOL using a microwave link. The installation at the VAMC also has several targets used for evaluation of the atmospheric optics system operating in target-in-the-loop propagation scenario. Available capabilities include sensors for continuous measurements of wind speed and direction, temperature, humidity, atmospheric pressure, C_n^2, Fried parameter, Rytov number, and scintillation index.

The atmospheric sensing suite and software developed by the MURI team offer unique capabilities for long-term (24/7) monitoring of major atmospheric characteristics important for understanding of laser beam propagation and image formation in deep turbulence conditions. The testbed was used by the MURI team and other researchers for evaluation of different atmospheric sensing techniques, and mathematical and numerical models, including a set of measurements performed jointly with researchers from DoD labs, academia and the NATO SET-226 study group. Further development of the testbed included installation of a polychromatic beacon, set up and evaluation of complex field sensors, and the installation of a time-lapse imaging sensor. In addition, the team developed software to share data measured that the testbed through the internet.

Besides atmospheric optical turbulence measurements at the UD testbed, the team also conducted the ERCAOS experimental campaign described below and a multi-month field campaign near the North Carolina coast to understand the effects of various coastal phenomena on optical turbulence. The obtained datasets helped for parameterization development and model validation.

2.1.3 The Extended-range Comprehensive Atmospheric Optics Sensing (ERCAOS) Experimental Campaign

A major objective for the MURI effort was to prepare for and conduct a comprehensive propagation/sensing field experiment between Mauna Loa on the Big Island of Hawaii and the Haleakala Observatories site on Maui. These experiments were performed under the two-year MURI extension period that began in January 2019. The campaign enabled:

a. Validation of the MURI-developed theoretical, mathematical and predictive numerical simulation framework for understanding of atmospheric optics effects over extended-range (>100 km) propagation distances and in presence of deep turbulence and strong refractive effects;
b. Validation of theoretical findings, hypotheses, and evaluate accuracy of predictive numerical simulation methods developed by the MURI team for forecasting atmospheric optical effects

(refractivity and turbulence) and their impact on laser beam and image propagation over extended (>100 km) distances;

c. Evaluation of the performance of advanced atmospheric sensing systems that have been developed for long-range applications under the MURI project and a related STTR Phase II contract; and
d. Collection of a large set of experimental data on long-range atmospheric dynamics and their effects on laser beam and image characteristics.

An overarching goal of the experimental campaign was to facilitate the ongoing development of long-range military optical weapons, communications, and surveillance platforms including HEL directed energy, ground-to-space and space-to-ground laser communications, airborne imaging, and deep-space surveillance.

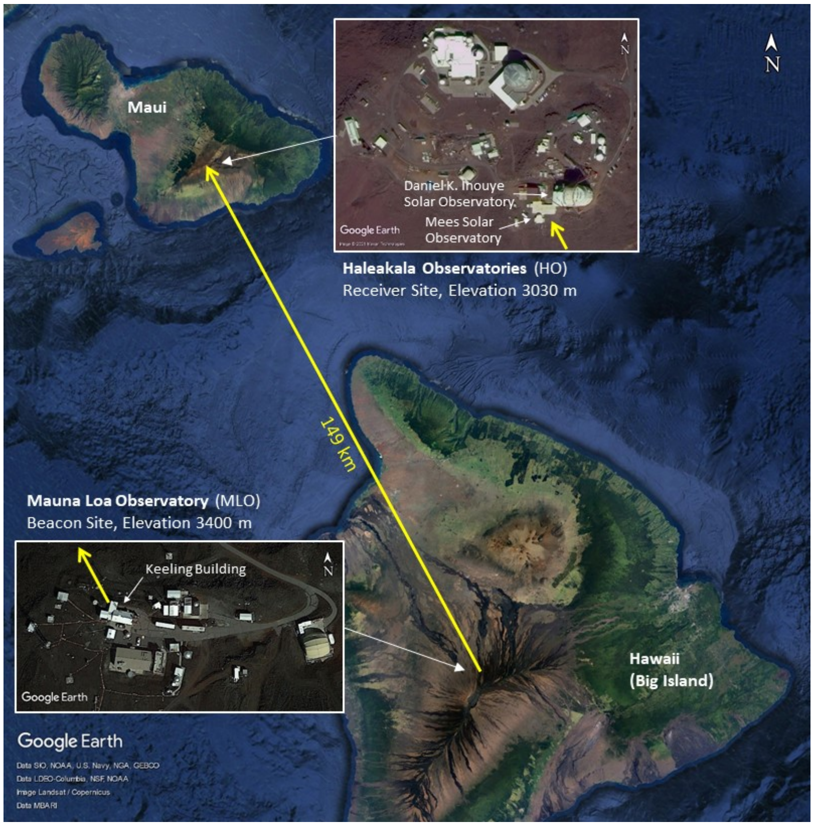

Figure 1. Aerial view of the propagation path between the beacon site at the Mauna Loa Observatory on the Big Island of Hawaii and the receiver site at the Haleakala Observatories on the island of Maui.

The experimental setting included a 149 km propagation path between the polychromatic laser beacon in a building of NOAA's Mauna Loa Observatory on the Big Island of Hawaii and receiver instrumentation located inside an instrumentation trailer located at the Haleakala Observatories (which include the AMOS facilities and telescopes operated by the University of Hawaii) near the Haleakala summit on Maui. The experimental setting not only offered the rich dynamics of the unique Mauna Loa to Haleakala path, but also potential synergies with data from nearby NEXRAD weather radar, the Keck Observatory, and NOAA aerosol measurements. The presence of NOAA's Mauna Loa Observatory on one end of the propagation path and the AMOS/University of Hawaii facilities on the other end enabled the logistical support regarding electrical power and communication resources (phone and internet), sheltering of equipment, and support by AMOS personnel so that experiments over an extended period became possible.

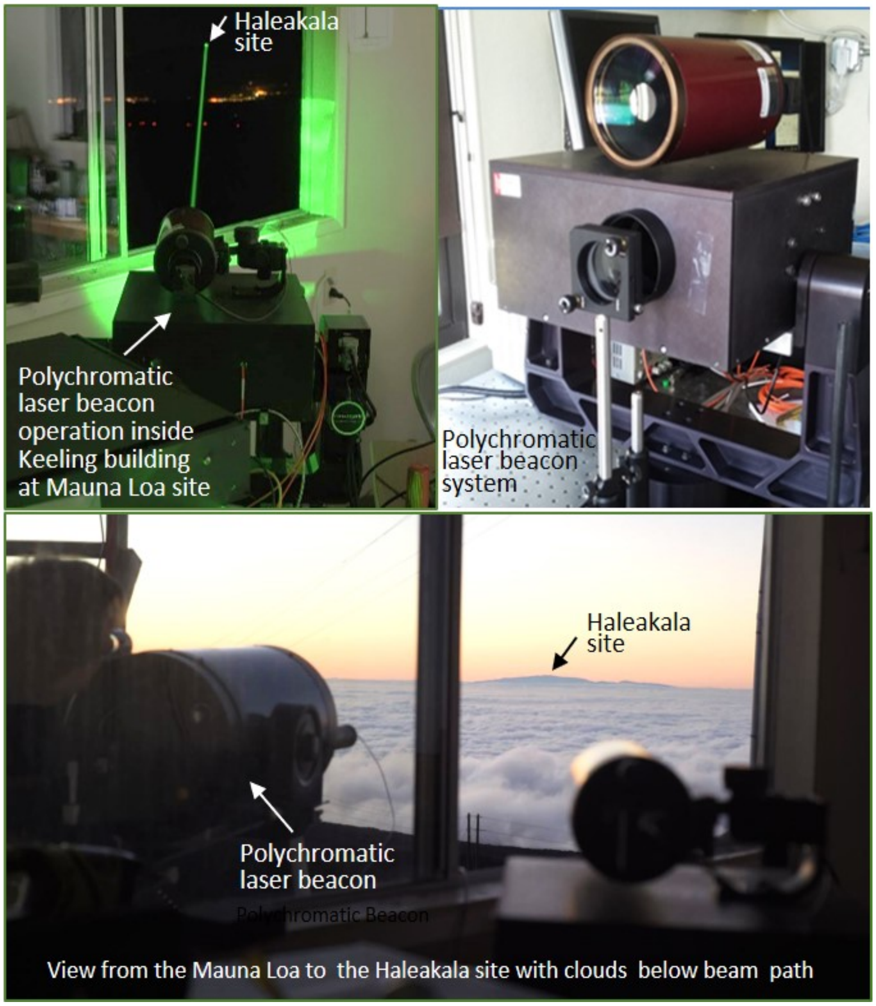

Figure 2, ERCAOS experimental setting at the Mauna Loa site

The extended range comprehensive atmospheric optics sensing (ERCAOS) experimental campaign was performed from March 29, 2019 through April 19, 2019 by scientist and engineers from UD, AFIT, and II-VI Optonicus (through a related STTR project) with support from AFRL, Boeing, the University of Hawaii, and NOAA. Data collection for optical propagation over the 149 km propagation distance between beacons located at about 3400 m elevation at the Mauna Loa Observatory and receivers located at about 3030 m elevation in front of the solar observatories at the Haleakala Observatories site (Figure 1) was performed under clear weather conditions during several hours after sunset on April 3 through 6, April 9, April 14 and April 15. The details of the experimental systems at both sites are shown in Figure 2 and Figure 3.

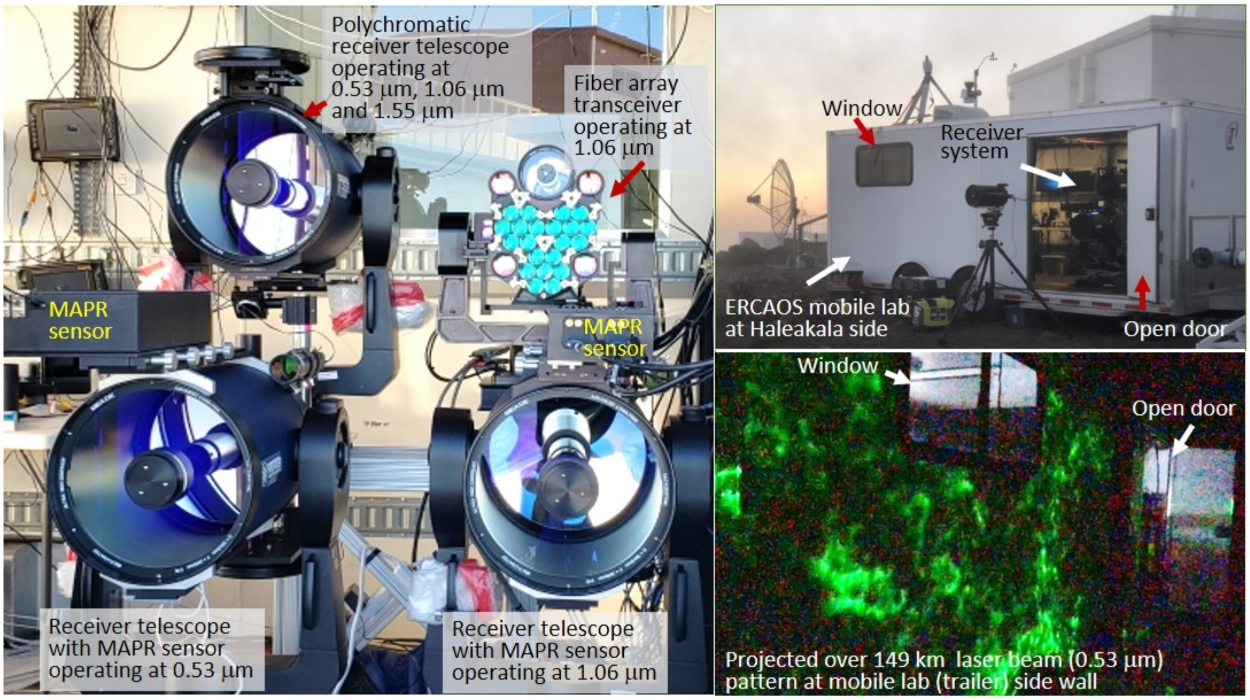

Figure 3. ERCAOS experimental setting at the Haleakala site: receiver system inside the mobile lab (left), view of the mobile lab at Haleakala site during experiments (top, right), and a characteristic image of laser beam seen at the mobile lab side wall (bottom right).

The team utilized the unique polychromatic laser beacon system based on photonic crystal fiber (Figure 2), and the optical receiver system specifically developed for these experiments under AFOSR Phase II STTR and Navy Phase II SBIR contracts as well as this MURI project by Optonicus LLC (now part of II-VI Aerospace and Defense) and UD (Figure 3). The measurements included simultaneous recording of pupil and focal plane short-exposure intensity distributions at laser wavelengths of 532 nm and 1064 nm using two Schmidt-Cassegrain receiver telescopes with 30 cm aperture that were equipped with multi-aperture phase reconstruction (MAPR) sensors [Figure 3(left)]. An additional 30 cm-aperture telescope (power-in-the-bucket polychromatic receiver) was used for recording of received power simultaneously for laser beams wavelengths of 532 nm, 1064 nm, and 1550 nm. The polychromatic beacon (Figure 3) also provided capabilities for 1-D and 2-D scanning of all three beams which allowed measurements of: (a) turbulence-induced beam widening (laser beam footprint sizes) for all three wavelengths, (b) displacements of beam centroids caused by refractivity, (c) power-in-the-bucket (PIB) signal fluctuations at different offset distances from the center of the beam footprint. An example of intensity scintillation pattern at the ERCAOS mobile lab side is shown in Figure 3(bottom right).

Recording of these laser beam characteristics were accompanied by simultaneous measurements of local meteorological data with weather stations and the atmospheric turbulence refractive index structure parameter (C_n^2) with scintillometers locally positioned at each site (approx. 800 feet local path length length).

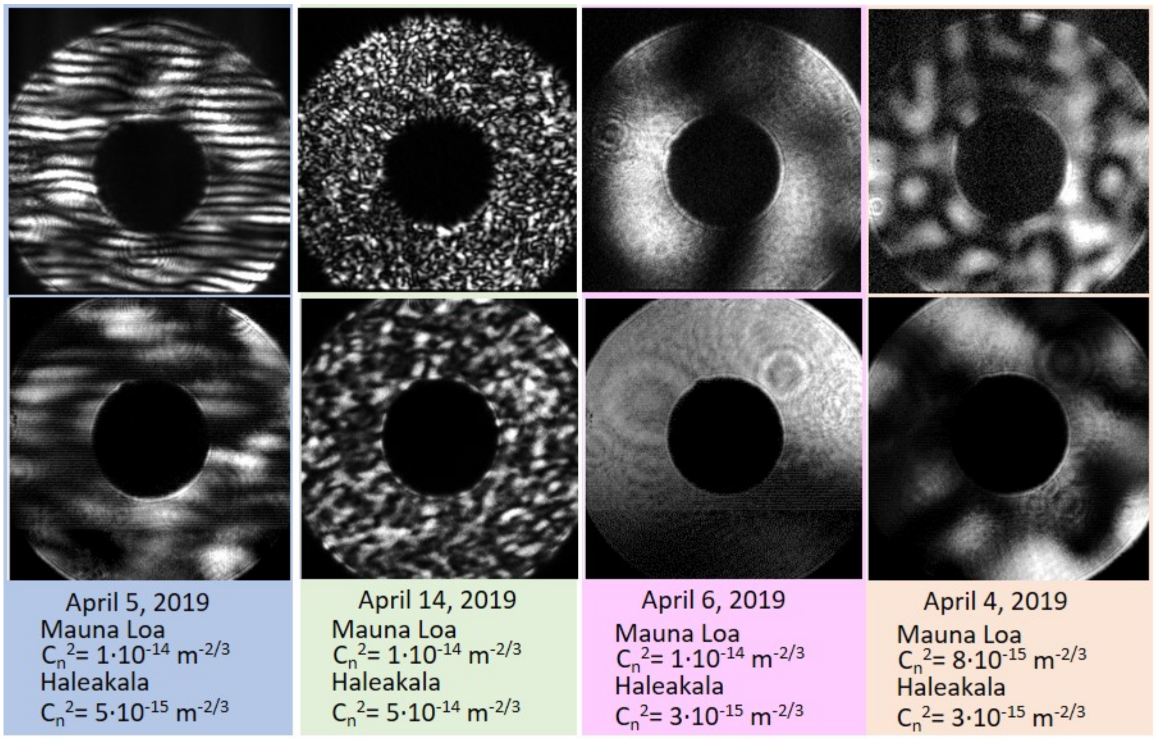

Figure 4. Characteristic pupil-plane short-exposure laser beam intensity patterns observed during the ERCAOS experiments. The intensity distributions received by the 30 cm Cassegrain telescopes resulted from propagation of 532 nm (top row) and 1064 nm laser beams (bottom row) transmitted by the polychromatic beacon located at the Mauna Loa site.

Significant discoveries include the following:

a) Discovery of coherent laser beam “mirages” [Figure 4(left row)] – a fringe-type pupil-plane laser beam intensity pattern never observed before and two well-defined focal spots at the receiver telescope. The hypothesis is that the transmitted laser beam was subdivided at a strong stratified refractive layer into two sub-beams that propagated along slightly different optical paths and enter the receiver telescope at different angles, thus producing interference fringes at the receiver pupil and two well-defined spots at the telescope focal plane. At long-range HEL DE system engagement scenarios, the coherent laser beam mirage effect could potentially negatively impact the ability to focus HEL beam into a single hit spot. These pattern were repeatedly observed over several hours with varying characteristics such as distance between fringes. More research is needed for better understanding of this new phenomenon.

b) Discovery of giant enhancement of turbulence strength and its impact on laser beam characteristics in the vicinity of clouds. Receiver pupil-plane intensity patterns in Figure 4 (second row) demonstrate the giant enhancement of scintillations in the conditions of laser beam propagation at relatively short distances from clouds (setting shown in the bottom photo in Figure 2). Note nearly identical size intensity speckles in Figure 4 (second row photos). The observed "cloud-enhanced" turbulence effect should be considered in HEL DE missions planning and should be further investigated.

c) Discovery of high variability of atmospheric refractivity and strong coupling of refractivity and turbulence-induced effects on laser beam propagation characteristics. Both, the observed vertical elongation of laser beam footprint, its size and centroid displacement magnitude were continuously changing during experiments within a characteristic time scale of a few minutes. These changes occurred even when both local meteorological and scintillometer data did not show any significant change (compare pupil-plane intensity patterns in Figure 4 that were obtained at quite similar local C_n^2 values). This suggests that the refractivity (US76) and turbulence models (Hufnagel-Valley HV 5/7, Maui 3, HV night, etc.) that are currently used for predictive efficiency evaluation of HEL DE systems cannot be applied for long-range engagements and should be revised.

d) First observation and quantitative measurements of the horizontal and vertical anisotropy of laser beam widening over long range atmospheric propagation in presence of both turbulence and refractivity. These measurements were performed via one- and two-dimensional scanning of the transmitted polychromatic beam with simultaneous measurements of the PIB signal by the polychromatic receiver. The vertical profiles of the beam footprint at different wavelengths in Figure 5(left) obtained via 1-D beam scanning illustrate both the refractivity-induced beam centroid shift and the turbulence-induced beam widening at different wavelengths. The corresponding images obtained with 2-D beam scanning in Figure 5(right) show the ellipticity of the beam footprints (i.e., the stronger beam spread in vertical direction). The performed measurements provided information on the variability of laser beam characteristics over long propagation paths – the information that was previously not available. The recorded data have been a valuable source for evaluation and for further development of the theoretical framework for better understanding large-scale atmospheric effects and their impact on laser beam and image characteristics. The unique data set provides also the opportunity for evaluation of numerical weather prediction models.

e) First qualitative measurements of laser beam intensity scintillations and frequency of giant spikes appearance. Laser beam scanning capabilities allowed repositioning position of the polychromatic beam footprint in respect to the polychromatic receiver and measuring PIB fluctuations at different sections of the beam footprint.

f) First simultaneous recording of both meteorological and C_n^2 data at both ends of the long-range path in conjunction with laser beam propagation experiments. This data can be utilized for numerical weather prediction simulations of turbulence and refractivity effects followed by numerical analysis of polychromatic laser beam propagation to compare the measured and simulated results. This side-by-side comparison can provide a basis for development of modeling and simulation tools in support of long-range laser weapon and optical surveillance platforms to the DoD.

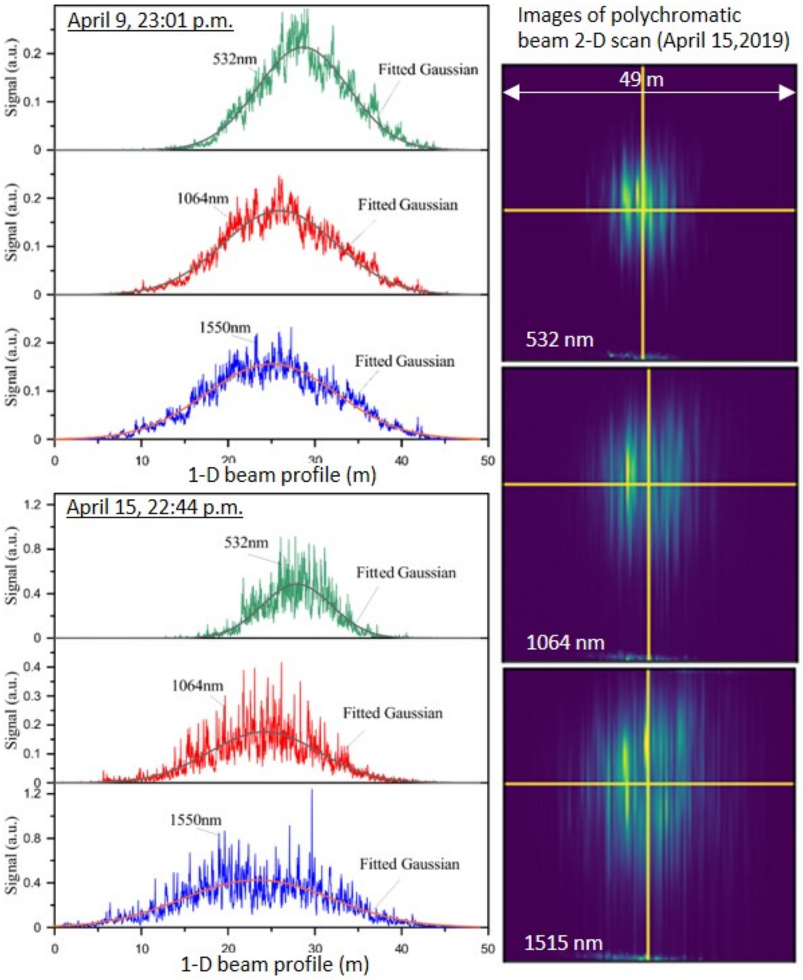

Figure 5. Characteristic beam profiles obtained using polychromatic beam vertical (left) and two-dimensional (right) scanning for different wavelengths.

Figure 6 shows two examples for the spatio-temporal distribution of turbulence strengths, as described by the refractive index structure constant, C_n^2, obtained through mesoscale simulation of atmospheric conditions using the techniques developed under this MURI effort. The graphs show the color-coded predicted C_n^2 values in a vertical plane that contains the ERCAOS 149 km propagation path for the same time (22:18 local time) at two different days of the campaign. The beam path is indicated by lines near the top of each panel. The lines are curved, because the beam height above sea level changes along the propagation path due to the curvature of the Earth's surface. As can be seen from Figure 6, the C_n^2 values along the beam path are in general lower on April 5 (top panel) than on April 9 (bottom panel). The simulation results therefore corroborate the much stronger turbulence impact on the projected beams observed on April 9, 2019 in comparison to the impact measured on April 5, 2019.

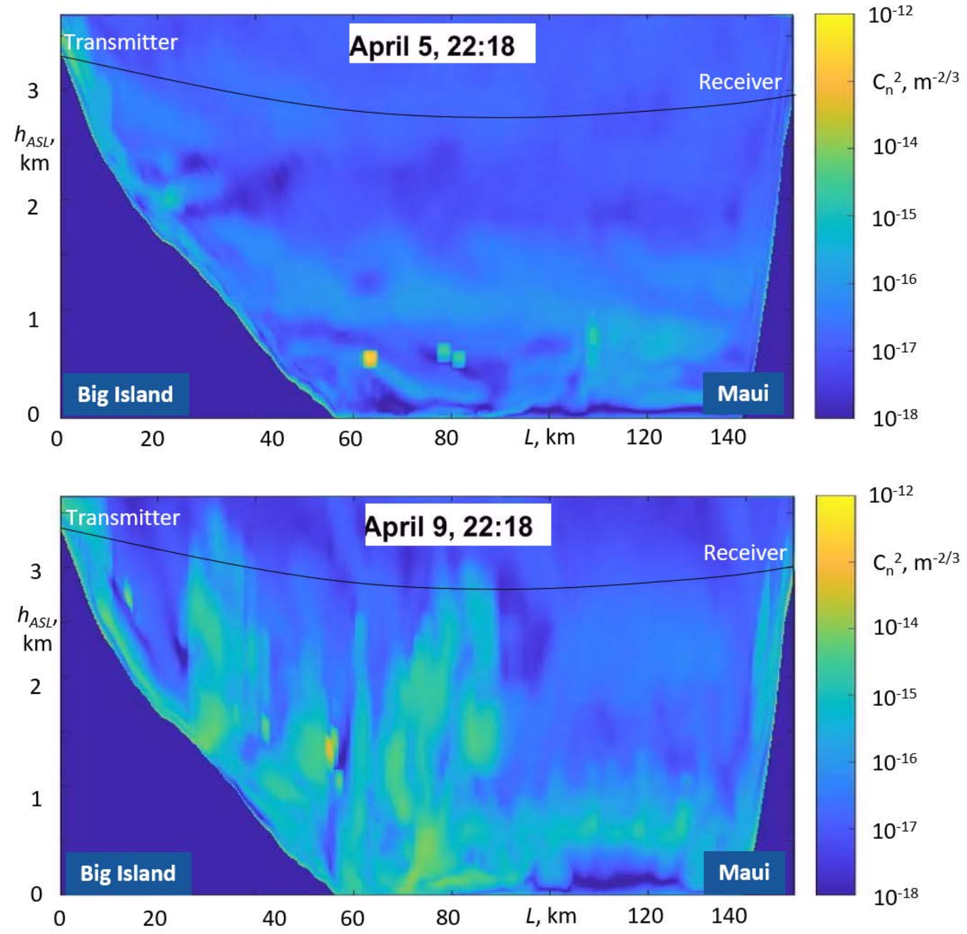

Figure 6. Refractive index structure constant (C_n^2) distributions along the ERCAOS propagation path between a transmitter at Hawaii (Big Island) and receivers at Maui obtained from WRF simulations for April 5 and 9, 2019 (top and bottom panels, respectively. The line near the top indicates the optical propagation path, which is shown curved because its height above sea level varies, mainly due to the Earth's curvature. The simulations confirm the much stronger turbulence observed on April 9 in comparison to conditions on April 5.

Figure 7 depicts the spatio-temporal distribution of the vertical gradient of refractivity (dn/dh) for the same times and dates as the turbulence strengths shown in Figure 6. They were obtained through the same mesoscale simulation of atmospheric conditions. The modeling results indicate that the vertical gradient of refractivity was generally stronger on April 9 in comparison to April 5. However, the conditions on April 5 apparently favored horizontal refractivity layers, which made the occurrence of laser beam mirages more likely – a result that sustains the experimental observations.

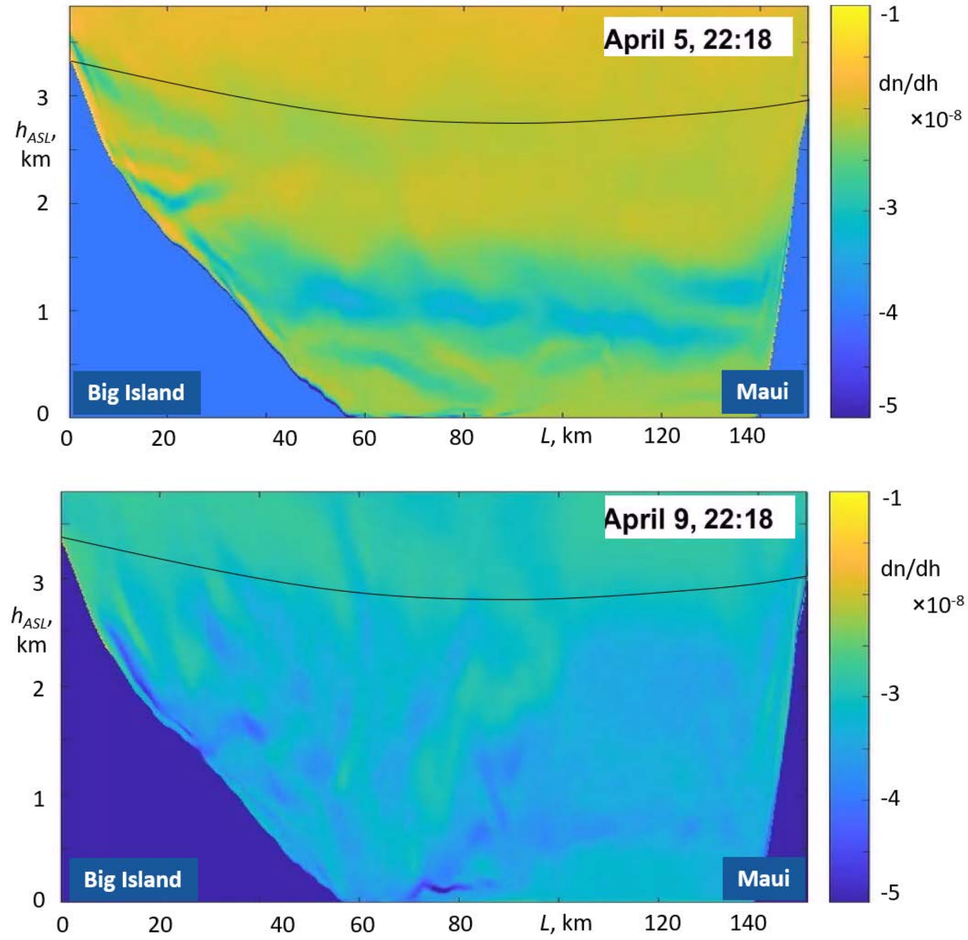

Figure 7. Distributions of the vertical gradient of refractivity (dn/dh) in the vertical plane containing the ERCAOS propagation for April 5 and 9, 2019 (top and bottom panels, respectively. The simulations indicate that the general refractivity gradient may have been generally stronger on April 9, but horizontal refractivity layers were more prominent on April 5.

2.1.4 New Atmospheric Wave Propagation Models and Computer Simulation Tools

2.1.4.1 Modeling of wave propagation in non-Kolmogorov and anisotropic turbulence

The MURI team modeled light propagation through coherent atmospheric structures created by a temperature inversion in the manner of a pseudo-guided wave. By processing large data bases of vertical temperature profiles measured with weather balloons, it was discovered that temperature inversions that can support this type of propagation are quite common and geographically widespread. Because the character of the wind in the vicinity of the inversions must be such that the vertical component of the wind is essentially zero, the team conjectured that the turbulent mixing in the vicinity of inversions could be non-Kolmogorov by virtue of being anisotropic, and very likely having a non -11/3 power law for the power spectral density. To model this effect the team developed a technique of simulating non-Kolomogorov turbulence by generating phase screens with different non-Kolmogorov power spectra.

Using both theoretical analyses and laboratory simulations, the MURI group analyzed optical wave propagation in non-Kolmogorov and anisotropic turbulence. It was shown that a deviation from Kolmogorov’s assumptions and a strong anisotropy of the turbulence power spectrum can significantly impact laser beam characteristics. The team has also performed a predictive analysis of optical communication systems operating in anisotropic and non-Kolmogorov turbulence and found that such link characteristics as scintillation index, probability of fade, and bit-error-rate are reduced as the degree of turbulence anisotropy is increased.

Besides numerical simulations the team members conducted a set of laboratory experiments in which various non-Kolmogorov and/or anisotropic regimes of turbulence have been simulated using phase-only spatial light modulators. The simulation results are in a good agreement with theory.

2.1.4.2 Coupling of mesoscale atmospheric refractivity modeling with ray-tracing simulations

For realistic predictive modeling of optical refraction effects over long-range propagation distances, the MURI team used mesoscale computations of the atmospheric refractive index field and ray tracing to simulate propagation of optical rays through strongly stratified refractive layers. In these numerical simulations, a range of effects were observed, such as optical rays guiding inside and scattering off refractive layers, focusing and defocusing of bundles of rays, temporal variation in ray trajectories and their strong dependence on initial conditions (light source elevation and angular orientation). With the aid of the imaging data collected in the field, the MURI team performed validation of the developed theoretical framework. Specifically, the vertical drift in the time-lapse imagery of a distant object was well captured in the ray-tracing simulations. To the best of our knowledge, no other similar model-based framework that couples mesoscale refractivity modeling with ray-tracing computations was described in the literature prior to the MURI effort.

The developed technique enabled to characterize and understand the effects of various coherent meteorological phenomena on optical wave propagation. For example, the team found that the von Kármán vortices are capable of diverting optical ray trajectories by tens of meters at a range of approximately 50 km. Anomalous ray trajectories were also found during the nighttime hours in a coastal region due to the presence of low-level jets. Based on observations and anecdotal evidences, the existence of anomalous ray trajectories was known in the literature. However, the newly developed modeling framework can simulate and forecast such atmospheric phenomena in a reliable manner.

The path the team chose for the initial studies was from Isle Royale National Park, in Lake Superior, to the northwestern edge of the Keweenaw Peninsula, in Upper Michigan, due to circumstantial, but credible reports that, while these two geographic structures are well over the horizon from each other, they are occasionally mutually visible. The team was able to merge meteorological predictions with detailed optical modeling to verify that these circumstantial claims are predicted by modeling.

2.1.4.3 Development of a theoretical framework for analysis of the joint impact of atmospheric turbulence and refractivity on laser beam propagation

In the Fresnel approximation of the diffraction theory, also known as wave-optics approximation, which was exclusively used in atmospheric optics prior to this MURI effort, propagation of a monochromatic (or quasi-monochromatic) optical wave is described in terms of the evolution of the optical field complex amplitude along a straight line direction. On the other hand over long distances, atmospheric refractivity may result in significant deviations of the optical wave propagation trajectory from a straight line, thus posing a significant problem for direct accounting of refractive effects in the framework of the wave-optics approximation.

The refractive effects were described in the past using the geometrical optics approximation by representing laser beam as a bundle of rays connecting the transmitter and receiver planes. The bundle of ray trajectories is described by ray equations that do not account for diffraction effects. For this reason the ray equations cannot be used for evaluation of laser beam characteristics that are strongly effected by turbulence, including short- and long-exposure beam width, centroid wander, scintillations, etc. Since the turbulence characteristics vary along the laser beam trajectory (e.g., they depend on trajectory elevation), atmospheric refractivity may also result in significant changes in turbulence-dependent laser beam parameters (beam spread, scintillations, etc.). The turbulence-induced random variation in the refractive index gradient may also impact the laser beam propagation trajectory. This implies that in long-range laser beam propagation scenarios both atmospheric refractivity and turbulence effects can be strongly coupled and should be considered jointly.

The MURI team addressed this important problem by developing a theoretical framework and the corresponding mathematical models and numerical techniques (generalized split operator), which allow analysis of long-range laser beam propagation in the presence of both atmospheric turbulence and refractivity layered structures. The physics-based model includes new coupled wave-optics and modified ray-tracing equations. It was shown that numerical integration of this system of equations can be performed using a generalized split-operator technique also developed by the team.

Using these techniques the team performed extensive numerical simulation of Gaussian laser beam propagation over long distances in a turbulent atmosphere in the presence of inverse temperature layers. The obtained results show a strong potential impact of refractive gradient layers on the laser beam characteristics, including a break of symmetry in the long-exposure laser beam intensity distribution and beam wander. It should be noted that such asymmetries were in the past often misinterpreted as presence of anisotropic turbulence. The research under this MURI project demonstrated that this is not necessarily the case.

2.1.4.4 Theoretical framework for analysis of image formation in presence of atmospheric turbulence and refractive gradient layers

Optical mirages – well known and frequently observed atmospheric optics phenomena – are commonly explained in the framework of geometrical optics as optical rays bending occurring due to propagation through an atmospheric layer with strong refractive index gradient. This simplified explanation is quite limited since it doesn’t take into account such factors important for image formation as diffraction on the imaging system's aperture and presence of atmospheric turbulence along the propagation path from an observed object to an imaging system aperture. These factors, neglected in the currently used geometrical optics approach, may significantly impact image formation. Correspondingly, the conventional approach doesn't provide adequate tools for predictive numerical simulations of mirage images as well as for analysis of the more general problem of image formation in atmospheric conditions that are characterized by the presence of both strong refractivity and turbulence.

The MURI team has addressed this challenging problem by generalizing the brightness function technique recently developed by the MURI PI and his collaborators. The proposed approach has allowed the first predictive simulations of turbulence- and refractivity-degraded images, including mirage images. The developed technique has been applied for analysis of the experimental data obtained with time-lapse imaging sensor as well as for simulation of the mirage imagery data provided by Dr. Steve Hammel (SPAWAR Systems Center).

Due to implementation of both the generalized brightness function technique and GPU-based computational algorithms, the team was able to achieve a hundred- to a thousand-fold computation acceleration in analysis of incoherent and anisoplanatic imaging systems in volume turbulent and refractivity fields. This new imaging technique was transitioned to AFRL/RV (POC Dr. Dan LeMaster).

2.1.5 Mitigation of Atmospheric Optics Effects: Creating a Foundation for Intelligent Engineering of Optical Waves and Systems

Research in this area was focused on: (a) non-conventional atmospheric mitigation techniques based on generation of new type of laser beams with controllable spatial coherence properties which are more robust in respect to atmospheric turbulence-induced aberrations; (b) development of speckle mitigation techniques for active imaging and beam projection (directed energy) systems; (c) development of new wavefront sensor types, which can operate in strong scintillation conditions typical for propagation in deep turbulence, for advanced adaptive optics systems.

2.1.5.1 Generation of exotic laser beams with fiber-array based laser beam transmitter systems

The team proposed a new approach for engineering a variety of unconventional (exotic) laser beams with complex spatio-temporal characteristics using coherent (coherently combinable) fiber-array laser transmitter systems. These laser beams, referred to here as exotic beams, include beams with periodic, quasi-periodic, and stochastic spatio-temporal phase modulation. Using numerical simulations, the MURI team showed that exotic laser beams can be generated in fiber-array transmitters using feedback control systems of different architectures based on a network of beam-tail interference sensors and fiber-integrated phase shifters. Due to extremely short (nanosecond time scale) response time of these phase shifting elements, the proposed technique permits generation of laser beams with controllable spatial coherence which can be used for mitigation of speckle effects in various applications including directed energy, laser communications, active imaging, and wavefront sensing.

The research team simulated and studied the performance of multi-beam systems such as the University of Dayton adaptive fiber-collimator array when operating with randomization of piston phases of the transmitted multiple beams. It was shown that controllable phase randomization can result in scintillation reduction in all turbulence cases. Analysis with a performance metric indicates that partial coherence is helpful for medium to strong turbulence. However, if the fluctuation regime is weak, the fully coherent beam can still yield the best performance.

The team for the first time experimentally demonstrated a laser illuminator system with controllable spatial coherence using randomization of piston phases in the coherent fiber-array beam director. In these experiments they used the coherent fiber-array system with 21 sub-apertures and electronic phase controller developed under the DARPA Excalibur program. It provided randomization of piston phases with 80 MHz bandwidth. The fiber-array was used to illuminate an extended target over 7 km propagation path. The experiments successfully demonstrated a significant decrease of atmospheric turbulence induced scintillations and image quality improvement. These results clearly demonstrated advantages of the new fiber-array systems for active imaging and may lead to a paradigm shift in active imaging technology.

2.1.5.2 Computational approaches for generating electromagnetic Gaussian Schell-model sources

Another approach to turbulence effects mitigation is related to generation of electromagnetic Gaussian-Schell model (EGSM) laser sources. The team developed two different methodologies for generating EGSM laser sources. One approach uses a sequence of random phase screens at the source plane and the other uses a sequence of random complex transmittance screens. The relationships between the screen parameters and the desired electromagnetic Gaussian-Schell model source parameters have been derived. The approaches have been verified by comparing numerical simulation results with theory. This work enables one to design an electromagnetic Gaussian-Schell model source with pre-defined characteristics for wave optics simulations or laboratory experiments. The same ideas can be used in the field to generate EGSM beams for laser communications and other laser systems applications where mitigation of turbulence induced scintillation is of utmost importance.

2.1.5.3 Laser beams with pre-defined far-field mean irradiance patterns

The team used a partially-coherent Schell-model source and phase-only control for generation of pre-defined far-field intensity distribution for optimal illumination of remotely located target and increase of signal-to-noise ratio (SNR) in active imaging. It was found in both simulation and proof-of-concept experiments that the phase-only control method can produce a variety of mean far-field irradiance patterns and can be used to improve SNR.

2.1.5.4 Development of speckle mitigation techniques for active imaging and beam projection

The research was focused on the analysis of laser beam projection in deep turbulence onto an extended (resolved) target with randomly rough surface. Coherent beam scattering off the target's rough surface leads to strong speckle modulation at transceiver plane, which represents a long-standing challenge for adaptive optics (known from the late 70's as the speckle problem in adaptive optics). The team addressed this problem by utilizing the recently developed speckle-metricoptimization adaptive optics technique. This research enabled the first successful demonstration of target-in-the-loop adaptive laser beam projection onto an extended target with randomly rough surface. The team also extensively analyzed, both experimentally and through numerical simulations, the impact of turbulence on the statistics of speckle field. The team showed an excellent match between the experimental and numerical simulation results for speckle field propagation over 7 km distance in deep turbulence. Besides adaptive optics, this research is important for understanding of speckle-noise effects in various active imaging systems.

2.1.5.5 Scintillation resistant wavefront sensing techniques for advanced adaptive optics systems

Operational principles of wavefront sensors used in conventional adaptive optics (AO) systems, such as Shack-Hartmann wavefront sensors, curvature sensors or lateral shearing interferometers, are based on the assumption of weak scintillations. These sensors do not perform well in the conditions of optical wave propagation over near-horizontal or slant atmospheric paths, which are commonly characterized by moderate to strong intensity scintillations. This drawback significantly limits utilization of these wavefront sensing and AO techniques for a number of rapidly growing atmospheric optics applications.

Under the MURI effort, the team introduced and analyzed the performance of the multi-aperture phase reconstruction techniques specifically developed for simultaneous high-resolution sensing of the optical field wavefront phase and intensity distributions under conditions of strong intensity scintillations. In general terms, the proposed wavefront sensing technique integrates both zonal (aperture division) and modal (phase retrieval over the entire aperture) approaches, combining an array of Zernike type wavefront sensors. The first results were quite promising – the team showed that the multi-aperture Zernike wavefront sensor can operate in strong intensity scintillation regime (Rytov number exceeding 1.5). A major focus of the subsequent work was the development of efficient phase reconstruction algorithms and finding the optimal phase mask in order to provide rapid convergence. A performance analysis of the resulting multi-aperture phase contrast (MAPCO) sensing concept demonstrated the capability to reach phase retrieval or complex field sensing for a resolution of 256×256 pixels with processing times in the order of a millisecond or even faster.

2.1.6 Development of a Scientific Foundation for Atmospheric Optics Effects Exploitation

2.1.6.1 Exploitation of the strong correlation between counter propagating waves in deep turbulence

The team discovered, first in numerical simulations and then through experimental validation, a new effect related to counter-propagating waves in atmospheric turbulence: there is an ideal correlation (theoretically 100%) between the power signals received on both ends of bidirectional optical links with monostatic transceivers based on single-mode fiber collimators.

One of the most obvious applications of this effect is related with mitigation of atmospheric turbulence-induced signal fading in bidirectional laser communication links. Although the existing turbulence mitigation techniques can provide some performance improvements of optical free-space communication systems, they nevertheless require either installation of additional quite complicated, bulky and expensive opto-electronic hardware, as in the case of adaptive optics and diversity based techniques, or setting up an additional link (optical or RF) for real-time channel-state information transmission, as in the case of adaptive data-rate, and adaptive modulation and coding methods.

The discovered strong correlation between received power signals in bidirectional optical links of different architectures opens attractive opportunities for combination of optical and electronic (signal processing) tools for efficient mitigation of atmospheric turbulence effects. Indeed, with nearly 100% correlation of received power-signals that can be achieved in optical links based on single-mode fiber collimator transceivers, the data can be transmitted and received only during time intervals (fading-free time windows) when the received signal level exceeds a predefined threshold and can be buffered during fade times intervals (fading time windows). In the case of ideal correlation between received signals, these fading-free time windows occur at both ends of communication link synchronously. This allows opening and closing the optical communication channel simultaneously for both laser communication transceivers without the need for sending channel-state (link availability) information back and forth between both transceivers.

This turbulence-induced “cooperation” between remotely located laser communication transceivers can also be used to enhance communication link security without data encryption key distribution through the communication link. Different characteristics of simultaneously measured randomly varying power-signals can be used to generate and/or change the encryption key at both ends of the communication link. For example, by setting a certain threshold value for the received power-signals and having identical devices that can generate a new encryption key at both ends of communication link each time when the received power-signals exceed this threshold, one can use the ideal correlation between independently measured received power-signals to synchronously change the data encryption key at the same random set of times at both transceivers. Due to the rapid decay in the correlation coefficient with a lateral shift of the receiver aperture any attempt to use an optical receiver to intercept the data encryption key will fail even if the used threshold power level is known, since decorrelation of signals results in a different set of key change times. This turbulence-enhanced (physics based) communication link security provides an attractive alternative to technically complicated quantum communication techniques.

2.1.6.2 New atmospheric wave propagation phenomena: giant intensity spikes in deep turbulence

During numerical wave-optics simulation of laser beam propagation in deep turbulence conditions the team observed for the first time irregular appearance of giant intensity spikes with amplitudes exceeding the diffraction-limited intensity value by a factor of ten or even more. The spikes in the form of narrow spots emerge after propagation of a collimated Gaussian beam over an approximately 5-km path in homogeneous volume (deep) turbulence with $C_n^2 = 10^{-14}\ \mathrm{m}^{-2/3}$. The formation of spikes is observed only in deep turbulence conditions, when the distributed turbulence along the propagation path is strong enough to occasionally generate focusing lenses with relatively short focal distance, which focus the laser beam into a small spot (smaller than the diffraction-limited beam). The spikes can propagate with relatively small changes in their profile over several kilometers distance.

Besides the interesting new physics, the occurrence of giant spikes may offer new opportunities to deliver laser radiation of high irradiance to a remote target through deep turbulence where conventional approaches currently considered for maximizing the irradiance at a target, such as adaptive optics wavefront control techniques, do not work or are very limited in their efficiencies.

The discovery of giant spikes may also challenge the currently used laser eye safety regulations and standards that should be reconsidered by accounting for giant spikes. Another aspect of this phenomenon is related to the potential need for reevaluation of the laser damage threshold for military electro-optics systems. The giant spikes also strongly impact the intensity scintillation index value and their presence can explain a strong mismatch between theoretical prediction of the scintillation index and its values obtained in wave-optics simulations and in experimental measurements.

2.1.7 Atmospheric Optics Sensors Integration and Networking for Predictive Modeling, Artificial Intelligence and Exploitation

This section describes the work on atmospheric optics sensors integration and networking as well as the research on artificial intelligence-based analysis of sensing information that were performed under the two-year extension of the MURI project beginning from January 2019.

2.1.7.1 Development of a theoretical, numerical simulation, and experimental basis for atmospheric optics sensors integration and networking

This research supported the ERCAOS sensing hardware integration and atmospheric evaluation. Using the available atmospheric sensors, the team integrated two sensing clusters. These clusters were interconnected via Internet, RF to provide real-time data and imagery transfer between the sensing clusters.

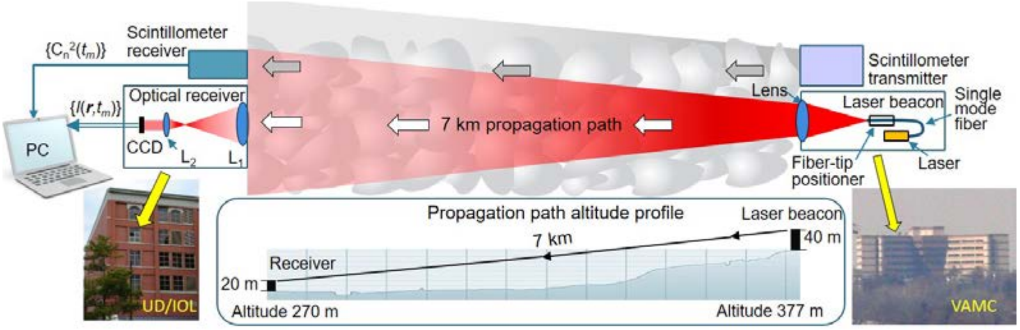

Figure 8. Notional schematic of the experimental setting used for collection of short-exposure laser beam intensity scintillation images and the corresponding values of the refractive index structure parameter C_n^2 (ATM datasets) under different atmospheric turbulence conditions. The insert shows the propagation path altitude profile.

The developed integrated sensing clusters were validated in comprehensive laser beam propagation and imaging experimental trials over the 7 km path at the UD testbed and over the 149 km propagation path between atmospheric optics sensing clusters located near the AFRL AMOS facilities on the Haleakala summit (Maui, HI) and at the NOAA Observatory at the Mauna Loa summit (Big Island, HI) as described in Section 2.1.3.

During these field trials, the sensing clusters were utilized to address the following research objectives:

(a) Validation (or contest) of the theoretical, mathematical, and predictive numerical simulation frameworks developed under the MURI program for understanding of atmospheric optics effects over tactical and extended-range propagation distances and in presence of deep turbulence and strong refractive effects;

(b) Evaluation of predictive numerical simulation methods developed by the MURI team for forecasting of atmospheric optical effects (refractivity and turbulence) and analysis of their impact on laser beam and image propagation;

(c) Performance evaluation of advanced atmospheric sensing systems that have been developed under the MURI grant and STTR contracts;

(d) Collection and processing of a large set of experimental data on atmospheric variability and its impact on laser beam and image characteristics;

(e) Performance evaluation of coherent beam combining and active imaging with partially coherent illumination generated by fiber array-based laser illuminator.

Short-term forecasting of the atmospheric conditions along the propagation path was performed using the processed sensing data and weather research forecasting (WRF) simulations.

2.1.7.2 Development of new approaches for artificial intelligence-based analysis of sensing information

A new paradigm for machine learning-inspired atmospheric turbulence sensing was developed and applied to predict the atmospheric turbulence refractive index structure parameter using deep neural network (DNN)-based processing of short-exposure laser beam intensity scintillation patterns obtained with both: experimental measurement trials conducted over a 7 km propagation path and imitation of these trials using wave-optics numerical simulations as illustrated in Figure 8. The developed DNN model was optimized and evaluated in a set of machine learning experiments. The results obtained demonstrate both good accuracy and high temporal resolution in sensing. The machine learning approach was also employed to challenge the validity of several eminent atmospheric turbulence theoretical models and to evaluate them against the experimentally measured data. In the machine learning experiments the MURI team utilized datasets comprised of a large number (up to 1.2×10^5) of data instances consisting of C_n^2 values and laser beam intensity scintillation images either computed (SIM datasets) or measured during the experimental trials (ATM datasets). A description of the developed DNN architecture (referred to as the Cn^2Net model), major performance characteristics and testing results were outlined in the recently published paper “Atmospheric turbulence study with deep machine learning of intensity scintillation patterns” by A. M. Vorontsov et al.

The possibility for DNNs to be the core element of a new C_n^2 sensor type was evaluated in the machine learning experiments. In these experiments the ATM datasets were subdivided on two non-overlapping segments (subsets), each containing data representing the full range of C_n^2 values observed in the experimental trials. One data sub-set was used for the Cn^2Net training while the second was applied for evaluation of the DNN efficiency in prediction of the true (measured) C_n^2 values based on scintillation images that had never been utilized (never “seen”) during the DNN training. The obtained results demonstrated a high accuracy in C_n^2 value predictions within the entire range of C_n^2 measurements as illustrated in Figure 9.

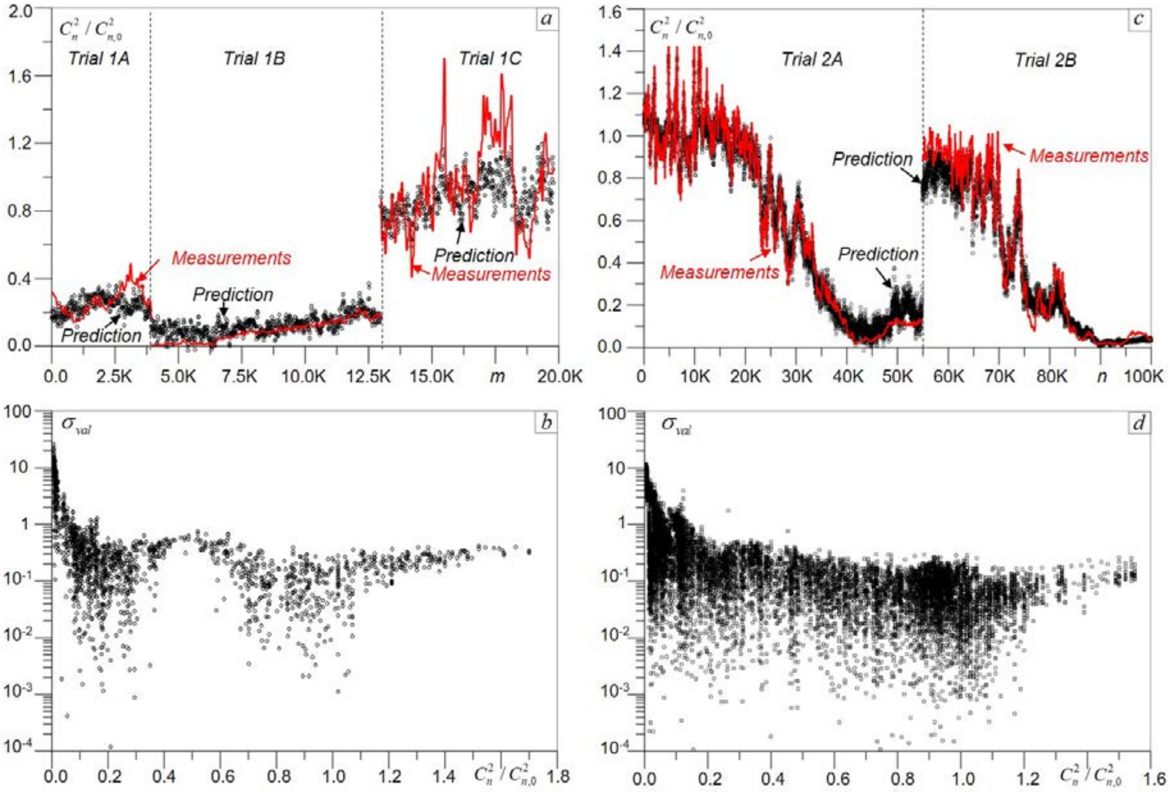

Figure 9. Results of the C_n^2 prediction with deep machine learning performed for ATM#1-V (a, b) and ATM#2-V (c, d) datasets using preliminary trained Cn^2Net models (N_{model} =20). The plots (a) and (c) compare measured (solid lines) and predicted (dots) C_n^2 values dependent on the frame stamp number *m* in the corresponding datasets. The scatter plots in (b) and (d) characterize the standard deviation of prediction error for the entire range of C_n^2 values in the corresponding ATM datasets ($c_n^2 = C_n^2 / C_{n,0}^2$ and $C_{n,0}^2 = 1\cdot 10^{-14}\ \mathrm{m}^{-2/3}$).

This suggests that an optical sensing system with DNN-based signal processing that is side-by-side trained with a “trusted” scintillometer could further be independently used as a C_n^2 sensor

(DNN-based scintillometer). It was shown that the Cn^2Net- scintillometer provides capabilities for significantly higher temporal resolution in C_n^2 sensing.

In other machine learning experiments, the MURI team investigated the possibility for the Cn^2Net to challenge the validity of several eminent theoretical atmospheric turbulence models and evaluated them against experimentally measured data. The Cn^2Net was trained using SIM datasets corresponding to spatially homogeneous turbulence described by the Kolmogorov power spectrum model. The SIM-trained DNN was used to predict the true (i.e., measured with a scintillometer) C_n^2 values via processing of the scintillation images obtained during atmospheric sensing trials (images from the ATM dataset).

The Cn^2Net model was also applied for cross-evaluation of various atmospheric turbulence models. In the computer simulation experiments the MURI team utilized SIM datasets corresponding to the classical Kolmogorov turbulence model and its most known modifications (Von Karman and Andrews models). These models were evaluated in several “cross-dataset” modeling and simulation experiments in which a DNN trained at one SIM dataset was challenged to predict the true C_n^2 values based on scintillation images computed for a different turbulence spectrum model. The results obtained demonstrated high C_n^2 prediction accuracy and its relatively weak dependence on the examined turbulence models and their major parameters (turbulence inner l_0 and outer L_0 scales), unless these parameters were artificially altered beyond a range reasonable from a physics viewpoint. This suggests that intensity scintillation patterns corresponding to the examined turbulence spectrum models have nearly identical (undistinguished by the DNN) spatial structures.

At the same time, DNN processing of scintillation images obtained using a recently developed turbulence model with noticeable deviation from the Kolmogorov two-thirds power law (non-Kolmogorov turbulence) resulted in large C_n^2 prediction errors. Similarly, large errors were observed when the DNN trained using non-Kolmogorov turbulence models was contested by the experimental sensing data.

2.2 Dissemination of Results

Results of this MURI program were published in 136 papers in peer-reviewed scientific journals, plus four papers currently under review or in preparation. In addition, the MURI team published 111 papers in archived conference proceedings. Oral presentation were given in over fifty scientific conferences, AFOSR review meetings and other government briefings (see lists in Sections 2.2.1 and 2.2.2 below).

2.2.1 MURI Team Participation in Scientific Conferences

Papers resulting from research performed under this MURI project were presented in the following scientific conferences:

- SPIE Optical Systems Design, 2012, Barcelona, Spain, 26-29 November 2012
- 2012 Annual Directed Energy Symposium, Albuquerque, NM, 26-30 November 2012
- SPIE LASE, 2013, San Francisco, CA, United States, 2-7 February 2013
- 2013 IEEE Aerospace Conference, Big Sky, MT, March 2-9, 2013
- SPIE Defense, Security, and Sensing, 2013, Baltimore, MD, United States, 29 April - 3 May 2013
- OSA Imaging and Applied Optics Congress 2013, Arlington, VA, 23-27 June 2013
- SPIE Optical Engineering + Applications, 2013, San Diego, CA, 25-29 August 2013
- 2013 Directed Energy Systems Symposium, Monterey, CA, 26 - 29 August 2013
- 2014 IEEE Aerospace Conference, Big Sky, MT, USA, 1-8 March 2014
- OSA Imaging and Applied Optics 2014, Seattle, WA, 13–17 July 2014
- SPIE Optical Engineering + Applications 2014, San Diego, CA, 17-21 August 2014
- 2014 Directed Energy Systems Symposium, Monterey, CA, 25-28 August 2014
- OSA Frontiers in Optics 2014, Tucson, AZ, 19-23 October 2014, Environmental Sensing Invited Special Talk: "AFOSR Program on Imaging and Beam Control through Deep Turbulence" by Dr. M. Roggemann (MTU)
- 2015 IEEE Aerospace Conference, Big Sky, MT, USA, March 7-14, 2015
- SPIE Defense + Security, 2015, Baltimore, MD, 20-24 April 2015
- OSA Imaging and Applied Optics 2015, Arlington, VA, 7-11 June 2015
- SPIE Optical Engineering + Applications, 2015, San Diego, CA, 9-13 August 2015
- SPIE Defense + Security, 2016, Baltimore, MD, 17-21 April 2016
- OSA Propagation Through and Characterization of Atmospheric and Oceanic Phenomena 2016, Washington, DC, 27–29 June 2016
- SPIE Optical Engineering + Applications, 2016, San Diego, CA, 28 August - 1 September 2016
- SPIE Remote Sensing, 2016, Edinburgh, United Kingdom, 26-29 September 2016
- 2017 IEEE Aerospace Conference, Big Sky, MT, March 4-11, 2017
- SPIE Defense + Security, 2017, Anaheim, CA, 9-13 April 2017
- OSA Imaging and Applied Optics 2017, San Francisco, CA, 26–29 June 2017
- SPIE Optical Engineering + Applications, 2017, San Diego, CA, 6-10 August 2017
- SPIE Defense + Security, 2018, Orlando, FL, 15-19 April 2018
- OSA Imaging and Applied Optics 2018, Orlando, FL, 25–28 June 2018
- 2019 Annual Directed Energy Science & Technology Symposium, Destin, FL, 8-12 April 2019
- OSA Imaging and Applied Optics 2019, Munich, Germany 24-27 June 2019
- OSA Imaging and Applied Optics Congress, Washington DC, 22-26 June 2020
- OSA Optical Sensors and Sensing Congress, Washington DC, 22-26 June 2020

- OSA Imaging and Applied Optics Congress, Virtual Event, 19-23 July 2021
- SPIE Optics and Photonics 2021, San Diego, CA and Virtual Event, 1-5 August 2021

2.2.2 Government Reviews and Briefings

Research performed under this MURI project was reviewed by and briefed to government officials in a number of meetings, including the following:

- MURI Kickoff Meeting, Dayton, Ohio, 4-5 October 2012
- MURI overview presentation at ARL/Adelphi, June, 2013
- MURI review with AFOSR, Dayton, OH, June 26-27, 2013
- Atmospheric characterization workshop, MIT/LL, Lexington, MA, September 2013
- MURI overview presentation at AFRL/DE, SOR, Albuquerque, NM, October 2013
- MURI team workshop, Miami, FL, November 2013
- MURI overview presentation at AFRL/AMOS, Kihei, HI, February 2014
- Navy atmospheric sensing workshop, San Diego, CA, February 2014
- MURI overview presentation for NATO SET-165 study group at ONERA, Paris, France, May 2014
- MURI review with AFOSR, Dayton, OH, July 23, 2014
- Technical presentation for Dr. Lemaster (AFRL/RV), WPAFB, Dayton, OH, August 14, 2014
- Technical presentation for Dr. Eismann (AFRL/RV), WPAFB, Dayton, OH, September 11, 2014
- MURI overview presentation for George Duchak (AFRL/Rome), Dayton, OH, October 29, 2014
- MURI overview for Dr. Matson (AFOSR), Dayton, OH, October 30, 2014
- NATO SET-165 study group meeting, Dayton, OH, November 2014
- AFOSR program review meeting, Albuquerque, NM, November 17, 2014
- Technical presentation at NSF (Dr. Abed), Arlington, VA, November 25, 2014
- MURI overview presentation at AFRL/AMOS, Kihei, HI, December 17, 2014
- Technical presentation for John Malowicki (AFRL/Rome), Dayton, OH, January 29, 2015
- MURI team technical exchange meeting, Miami, FL, March 16-17, 2015
- MURI overview presentation for NATO SET-226 study group, Paris, France, April 16-18, 2015
- MURI review with AFOSR, Arlington, VA, June 11, 2015
- MURI technical exchange meeting, Dayton, OH, April 29, 2016
- MURI review with AFOSR, Arlington, VA, June 29, 2016
- MURI review with AFOSR, Arlington, VA, October 23, 2017

- AFOSR remote sensing portfolio review, Albuquerque, NM, September 4-6, 2018
- MURI review with AFOSR, Dayton, OH, November 1, 2018

2.2.3 Government Participants

The list of government participants in MURI review meetings and briefings includes:

- Lawrence Barnes (AFRL/RYNMB)
- Elizabeth Beecher (AFRL/RYMW)
- Patrick Carrick (AFOSR)
- George Duchak (AFRL/RI)
- Tom Defelice (ARL/CISD)
- Matt Dierking (AFRL/RYM)
- Michael Eismann (AFRL/RY)
- Thomas Farrell (AFRL/RDSA)
- Venkata S. Rao Gudimetla (AFRL/DE)
- Steve Hammel (SPAWAR Systems)
- Byron Knight (NRO)
- Daniel LeMaster (AFRL/RYMT)
- Arun Majumdar (NAWCWD)
- Peter Marasco (AFRL/RYMT)
- Dan Marker (AFRL/RD)
- Chuck Matson (AFOSR)
- Nicholas Miller (AFRL/RY)
- Kent Miller (AFOSR)
- Saba Mudaliar (AFRL/RY)
- Julie Moses (AFOSR)
- Arje Nachman (AFOSR)
- David Newton (NSWC Dahlgren)
- Kathy Ragsdale (AFOSR)
- Darryl Sanchez (AFRL/RDSS)
- Bryce Schumm (AFRL/RY)
- Don Seeley (HEL-JTO)
- David Tofsted (ARL/CISD)
- Mark Williams (NRO)
- Stacie Williams (AFOSR)

3 Impacts

3.1 Development of the Principal Disciplines of the Project

The following results obtained by the team can be regarded as breakthroughs or new discoveries:

- Developed a physics-based framework and the corresponding mathematical models (system of equations) and numerical techniques (generalized split operator) for analysis of long-range laser beam propagation in presence of both atmospheric turbulence and refractivity layered structures.
- Theoretical prediction of atmospheric refractivity-induced spatial anisotropy of laser beam characteristics in presence of volume turbulence and strong refractive index gradient layers. The predicted spatial anisotropy in laser beam centroid wander and widening has been confirmed in numerical simulations.

- A new approach and numerical simulation framework for analysis of image formation in presence of atmospheric turbulence and refractive gradient layers. This approach has allowed first predictive simulations of the turbulence-degraded mirage images.
- Through numerical wave-optics simulations discovery of deep turbulence-induced irregular giant intensity spikes in laser beam intensity distributions. The giant spikes' physics-based origin, probability of appearance, and their impact on scintillation index are analyzed.
- Discovery in numerical simulation and further experimental validation of the possibility of an ideal (theoretically 100%) power-signal correlation in optical links with monostatic transceivers based on single-mode fiber collimators. Promising applications include signal fading mitigation and turbulence-enhanced security in optical communication links.
- A new target-in-the-loop (TIL) atmospheric sensing concept for in-situ remote measurements of key turbulence characteristics along the target line of sight.
- A new (brightness function based) approach and computational algorithms for predictive numerical performance analysis of incoherent and anisoplanatic imaging systems in volume turbulence, which provides a 100 to 1000-fold computation acceleration.
- First successful experimental demonstration of multiple (21) beams phasing and deep turbulence effects adaptive mitigation with a coherent fiber-array system over a 7 km propagation path.
- A novel concept of a scintillation resistant wavefront sensor (multi-aperture Zernike filter) for deep turbulence characterization under strong scintillations.
- A new approach for engineering a variety of unconventional (exotic) laser beams with complex spatio-temporal characteristics using, for instance, coherent fiber-array laser transmitter systems.
- Discovery of laser beam mirages in long-range laser beam projection over an 149 km atmospheric propagation path.
- First measurements of atmospheric refractivity effects on polychromatic laser beam propagation over 149 km, demonstrating the wide variability of refractivity and the, at times, considerable difference to predictions using standard atmospheric models (such as US1976).
- Experimental evidence of strong turbulence enhancement for atmospheric laser propagation paths near clouds.
- A novel technique based on a deep neural network (DNN) model was developed for fast prediction of C_n^2 values from pupil-plane scintillation pattern. The approach was validated with both computer-generated scintillation pattern and measurements at UD's test range.

3.2 Impact on Teaching and Educational Experiences

Working together, the MURI team developed a unique interdisciplinary course “Introduction to Atmospheric Optics” that covers the educational topics most relevant for this MURI. The course elaborates on a foundation for the physics of atmospheric optics effects by building bridges between meteorology, computational fluid dynamics, and statistical wave optics. It provides solid theoretical knowledge of optical wave propagation in the atmosphere, and practical computational tools for realistic characterization assessment and prediction of laser beam projection and imaging in the atmosphere. The course includes the following major topics that were taught by the MURI PI and co-PIs:

- Fundamentals of atmospheric physics, global and macro-optical effects
- Atmospheric optical turbulence and its impact on imaging systems
- Atmospheric optical systems modeling and performance analysis
- Laser beams propagation in atmosphere
- Mitigation and exploitation of atmospheric effects

The course has been offered by the University of Dayton since the spring semester 2014 and is offered for distant learning. The lectures were also video-logged for a distant learning course offered by AFIT. In addition to this 3-credit hour course, the MURI team, offered a week-long short course in summer 2015 (1 credit hour). Besides these university-based educational efforts, Dr. Italo Toselli, a MURI team member from UM, presented a short course “Introduction to laser beam propagation through atmospheric turbulence with applications” at the SPIE Annual Meeting, San Diego, CA, August 2015.

Besides development and teaching of special courses, more than twenty graduate students (Ph.D. and Master level) and six post-doctoral researchers have been supported through the MURI effort and have been actively involved in the research. Collaboration among graduate students and post-doctoral researchers working under the MURI grant was facilitated through a number of visits.

4 Changes

The three-year Base period for the MURI project was originally awarded for the period September 15, 2012 through September 14, 2015. Due to funding issues on the government side, an intermediate no-cost extension was awarded that extended the Base period through January 14, 2016. Exercising the two-year Option extended the project's period of performance through January 14, 2018. A no-cost extension of one year was approved in September 2017 and extended the period of performance through January 14, 2019. Additional funding for the University of Dayton in response to a supplemental proposal was awarded in September 2018 with a two-extension of the period of performance through January 14, 2021. During this extension, the long-range (149 km) laser beam propagation experiments (ERCAOS campaign) was prepared, which included the development of the sensor network used in the trials. The campaign took place in April 2019 and the corresponding data processing, including fluid dynamic simulations of atmospheric conditions on the days of the experiments, was performed subsequently. During the extension period, the target-in-the-loop atmospheric sensing concepts was expanded to identify turbulence layers with a moving target. An additional six-month no-cost extension was granted in December 2020, shifting the end of the period of performance to July 14, 2021.

5 List of Archived Publications by the MURI Team

5.1 Publications in Peer-reviewed Scientific Journals

1. N. R. Van Zandt, S. J. Cusumano, R. J. Bartell, S. Basu, J. E. McCrae, and S. T. Fiorino, "Comparison of coherent and incoherent laser beam combination for tactical engagements," *Optical Engineering* **51**(10), 104301 (OCT 2012). doi: 10.1117/1.OE.51.10.104301
2. Zhangrong Mei, Zhisong Tong, and Olga Korotkova, "Electromagnetic non-uniformly correlated beams in turbulent atmosphere," *Optics Express* **20**(24), 26458 (NOV 2012). doi: 10.1364/OE.20.026458
3. Zhangrong Mei and Olga Korotkova, "Random light scattering by collections of ellipsoids," *Optics Express* **20**(28), 29296 (DEC 2012). doi: 10.1364/OE.20.029296
4. Zhangrong Mei and Olga Korotkova, "Random sources generating ring-shaped beams," *Optics Letters* **38**(2), 91 (JAN 2013). doi: 10.1364/OL.38.000091
5. Jean Minet, Mikhail A Vorontsov, Ernst Polnau, and Daniel Dolfi, "Enhanced correlation of received power-signal fluctuations in bidirectional optical links," *Journal of Optics* **15**(2), 022401 (FEB 2013). doi: 10.1088/2040-8978/15/2/022401
6. Zhangrong Mei, Olga Korotkova, and Elena Shchepakina, "Electromagnetic multi-Gaussian Schell-model beams," *Journal of Optics* **15**(2), 025705 (FEB 2013). doi: 10.1088/2040-8978/15/2/025705
7. Zhangrong Mei and Olga Korotkova, "Gradient-index waveguide lens systems for polarization modulation of random electromagnetic beams," *Applied Physics B* **110**(4), 491 (MAR 2013). doi: 10.1007/s00340-012-5284-2
8. Elena Shchepakina and Olga Korotkova, "Canard explosion in chemical and optical systems," *Discrete and Continuous Dynamical Systems B* **18**(2), 495 (MAR 2013). doi: 10.3934/dcdsb.2013.18.495
9. Santasri Basu, Milo W. Hyde IV, Salvatore J. Cusumano, Michael A. Marciniak, and Steven T. Fiorino, "Examining the validity of using a Gaussian Schell-model source to model the scattering of a fully coherent Gaussian beam from a rough impedance surface," *Optical Engineering* **52**(3), 038001 (MAR 2013). doi: 10.1117/1.OE.52.3.038001
10. Milo W. Hyde, Santasri Basu, Mark F. Spencer, Salvatore J. Cusumano, and Steven T. Fiorino, "Physical optics solution for the scattering of a partially-coherent wave from a statistically rough material surface," Opt. Express **21**, 6807-6825 (MAR 2013). doi: 10.1364/OE.21.006807
11. M. A. Vorontsov, V. V. Dudorov, M. O. Zyryanova, V. V. Kolosov, and G. A. Filimonov, "Bit error rate in free-space optical communication systems with a partially coherent transmitting beam," *Atmospheric and Oceanic Optics* **26**(3), 185 (MAY 2013). doi: 10.1134/S1024856013030159

12. Noah R. Van Zandt, Steven T. Fiorino, and Kevin J. Keefer, "Enhanced, fast-running scaling law model of thermal blooming and turbulence effects on high energy laser propagation," Opt. Express **21**(12), 14789 (JUN 2013). doi: 10.1364/OE.21.014789
13. Zhangrong Mei, Elena Shchepakina, and Olga Korotkova, "Propagation of cosine-Gaussian-correlated Schell-model beams in atmospheric turbulence," *Optics Express* **21**(15), 17512 (JUL 2013). doi: 10.1364/OE.21.017512
14. Olga Korotkova and Elena Shchepakina, "Tuning the spectral composition of random beams propagating in free space and in a turbulent atmosphere," *Journal of Optics* **15**(7), 075714 (JUL 2013). doi: 10.1088/2040-8978/15/7/075714
15. Zhangrong Mei and Olga Korotkova, "Cosine-Gaussian Schell-model sources," *Optics Letters* **38**(14), 2578 (JUL 2013). doi: 10.1364/OL.38.002578
16. Elena Shchepakina and Olga Korotkova, "Spectral Gaussian Schell-model beams," *Optics Letters* **38**(13), 2233 (JUL 2013). doi: 10.1364/OL.38.002233
17. Matthew J. Krizo, Salvatore J. Cusumano, Steven T. Fiorino, Ryan Heap, Victor Velten, Joshua Brown, Richard J. Bartell, "Design, development, and in-flight testing of a pointer/tracker for in-flight experiments to measure aero-optical effects over a scaled turret," *Optical Engineering* **52**(7), 071415 (JUL 2013). doi: 10.1117/1.OE.52.7.071415
18. Xifeng Xiao and David Voelz, "Analysis and simulation of a fiber bundle method for creating a partially spatially coherent beam," Applied Optics **52**(23), 5794 (AUG 2013). doi: 10.1364/AO.52.005794
19. Glen E. Archer, Jeremy P. Bos, and Michael C. Roggemann, "Reconstruction of long horizontal-path images under anisoplanatic conditions using multiframe blind deconvolution," *Optical Engineering* **52** (8), 083108 (AUG 2013); doi: 10.1117/1.OE.52.8.083108
20. Svetlana L Lachinova and Mikhail A Vorontsov, "Exotic laser beam engineering with coherent fiber-array systems," *Journal of Optics* **15**(10), 105501 (SEP 2013). doi: 10.1088/2040-8978/15/10/105501
21. Zhangrong Mei and Olga Korotkova, "Electromagnetic cosine-Gaussian Schell-model beams in free space and atmospheric turbulence," *Optics Express* **21**(22), 27246 (NOV 2013). doi: 10.1364/OE.21.027246
22. Halil T. Eyyuboğlu, David Voelz, and Xifeng Xiao, "Scintillation analysis of truncated Bessel beams via numerical turbulence propagation simulation," *Applied Optics* **52**(33), 8032 (NOV 2013). doi: 10.1364/AO.52.008032
23. Charles Nelson, Svetlana Avramov-Zamurovic, Olga Korotkova, Reza Malek-Madani, Raymond Sova, and Frederic Davidson, "Probability density functions of power-in-bucket and power-in-fiber for an infrared laser beam propagating in the maritime environment," *Applied Optics* **52**(31), 7449 (NOV 2013). doi: 10.1364/AO.52.007449
24. Lee R. Burchett and Steven T. Fiorino, "Wavelength correction of refractivity variation measurements," *Optics Express* **21**(26), 31990 (DEC 2013). doi: 10.1364/OE.21.031990

25. Mikhail A. Vorontsov, "Speckle effects in target-in-the-loop laser beam projection systems," *Advanced Optical Technologies* **2**(5-6), 369 (DEC 2013). doi: 10.1515/aot-2013-0054

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27. Olga Korotkova, "Random sources for rectangular far fields," *Optics Letters* **39**(1), 64 (JAN 2014). doi: 10.1364/OL.39.000064

28. Steven T. Fiorino, Robb M. Randall, Michelle F. Via, Jarred L. Burley, “Validation of a UV-to-RF high-spectral-resolution atmospheric boundary layer characterization tool” *Journal of Applied Meteorology and Climatology* **53**(1), 136 (JAN 2014). doi: 10.1175/JAMC-D-13-036.1

29. Yahong Chen, Fei Wang, Lin Liu, Chengliang Zhao, Yangjian Cai, and Olga Korotkova, "Generation and propagation of a partially coherent vector beam with special correlation functions," *Physical Review A* **89**(1), 013801 (JAN 2014). doi: 10.1103/PhysRevA.89.013801

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41. S. Avramov-Zamurovic, C. Nelson, R. Malek-Madani, O. Korotkova, "Polarization-induced reduction in scintillation of optical beams propagating in simulated turbulent atmospheric channels," *Waves in Random and Complex Media* **24**(4), 452 (OCT 2014). doi: 10.1080/17455030.2014.944242
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44. Santasri Basu, Milo W. Hyde IV, Xifeng Xiao, David G. Voelz, and Olga Korotkova, "Computational approaches for generating electromagnetic Gaussian Schell-model sources," *Optics Express* **22**(26), 31691 (DEC 2014). doi: 10.1364/OE.22.031691
45. Min Yao, Italo Toselli, and Olga Korotkova, "Propagation of electromagnetic stochastic beams in anisotropic turbulence," *Optics Express* **22**(26), 31608 (DEC 2014). doi: 10.1364/OE.22.031608
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