Comparison of vertical profile turbulence structure measurements at John Bryan Observatory

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Abstract: Many ground-based space object imaging systems are impacted by atmospheric turbulence. Atmospheric turbulence distorts the incoming optical wavefront leading to object blur, often resulting in an unrecognizable target. Advancements in detecting these disturbances and assessing the profiled turbulence strength and its changes have led to mitigation techniques that are able to overcome the atmospheric turbulence induced impacts on these ground-based imaging systems. The goal of our research is to better understand the techniques available for measuring the profiled strength of optical turbulence for a ground-to-space imaging scenario.

This paper describes three methods for measuring and assessing the profiled strength of atmospheric turbulence that were used in a joint data collection campaign at the John Bryan Observatory site located in Yellow Springs, Ohio. Method one involved the use of a dynamically ranged Rayleigh beacon system. Method two utilized a commercial system called DELTA-Sky that is based off delayed tilt anisoplanatism variance statistics derived from object features in the scene. Method three employed numerical weather prediction (NWP) data generated from radiosonde, aircraft, and satellite measurements used in a turbulence strength estimation model derived from Tatarski's relations for estimating C_T^2. These three methods are cross-compared in their ability to accurately assess the profiled strength of atmospheric turbulence and correlations are examined. We discuss the strengths and weaknesses of each technique.

Keywords: Turbulence, Rayleigh Beacons, Wavefront Sensing, Refractive Index Structure Parameter, Fried Parameter, Remote Sensing and Sensors, Atmospherics, Imaging through Turbulence

1. Introduction

Many ground-based space object imaging systems are impacted by atmospheric turbulence. Atmospheric turbulence distorts the incoming optical wavefront leading to object blur, often resulting in an unrecognizable target. Advancements in detecting these disturbances and assessing the profiled turbulence strength and its changes have led to mitigation techniques that are able to overcome the atmospheric turbulence induced impacts on these ground-based imaging systems. The goal of our research is to better understand the techniques available for measuring the profiled strength of optical turbulence for a ground-to-space imaging scenario.

This paper describes three methods for measuring and assessing the profiled strength of atmospheric turbulence that were used in a joint data collection campaign at the John Bryan Observatory site located in Yellow Springs, Ohio. Method one involved the use of a dynamically ranged Rayleigh beacon system. Method two utilized a commercial system called DELTA-Sky that is based off delayed tilt anisoplanatism variance statistics derived from object features in the scene. Method three employed numeric weather data gathered from satellite measurements used in a turbulence strength estimation model derived from Tatarskii's relations for estimating C_T^2. These three methods are cross-compared in their ability to accurately assess the profiled strength of atmospheric turbulence and correlations are examined. We discuss the strengths and weaknesses of each technique.

2. Turbulence Strength Estimate Methodology

2.1 TARDIS System Description and Processing Methodology

Method one data collections are captured by a system designated as TARDIS, which stands for Turbulence and Aerosol Research Dynamic Interrogation System. The TARDIS is an optical sensing system that is based on quickly changing the range between the collecting sensor and a Rayleigh beacon during a near-static period of relatively unchanging turbulence-induced wavefront perturbations. A depiction of the collecting scenario is shown in Figure 1, where the cartoon "beacons" are the air molecule and aerosol particle backscatter images captured at different distances from the collecting aperture based on laser pulsing and fast camera shutter speeds. The TARDIS is comprised of three main sub-systems: a beam projection system (BPS), a collecting telescope, and a sensor system. Specific details of the TARDIS have been reported in prior publications. [1-6]

Obtaining measurement based estimates of the turbulence strength profile from the TARDIS is based around concatenating segmented refractive index structure parameter, $C_{n_{seg}}^2$, values traced to specific layers of the atmosphere. These $C_{n_{seg}}^2$ values are developed from Fried parameter segments, r_{0_i}, which are deduced from measurements on the Shack-Hartmann wavefront sensor as

$$C_{n_{seg}}^2 = \frac{{r_{0_i}}^{-5/3}}{0.423k^2\Delta z_i} \tag{1}$$

where $r_{0_i} = r_{0_{j+1}} - r_{0_j}$ with $j+1$ and j representing two measurements of r_0 from neighboring beacon ranges, Δz_i is the thickness of the turbulence volume, and k is the wavenumber. A single value of the Fried parameter is estimated from the variance of the phase measurement present on the sensing system's collecting aperture as

$$r_0 = \frac{0.134D}{(\sigma^2)^{3/5}} \tag{2}$$

where this r_0 is a representative metric of the turbulence strength within the volume of a single beacon measurement, D is the aperture diameter, and σ^2 is the variance of the estimated phase across the aperture that is built from the zonal tilt tiles on a Shack-Hartmann wavefront sensor.[1] First, proof of concept data collections using the TARDIS were established in 2021.[6]

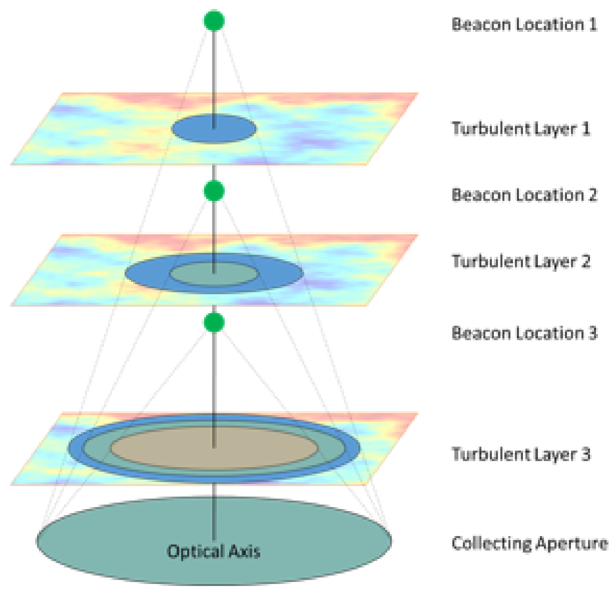

Fig. 1. Notional dynamic beacon collection scenario displaying a three beacon collecting scenario where the beacon is placed a different ranges along the sensing system's optical axis.

When taking these subsequent measurements of r_0 to build up a turbulence strength profile it is important to consider focal anisoplanatism influences as error sources could manifest into the localized turbulence strength estimates. Full details on focal anisoplanatism influences on dynamically ranged Rayleigh beacon measurements have been presented previously.[2]

2.2 DELTA-Sky System Description and Processing Methodology

The Delayed Tilt Anisoplanatism (DELTA) technique involves tracking features on a target through a time-series of rapidly captured images. Anisoplanatic tilt is estimated from the differential jitter, or difference in angular shifts, of feature pairs in the images. These measurements are used to deduce the C_n^2 profile over the viewing path. The technique, first known as the Difference of Differential Tilt Variance (DDTV), has been demonstrated successfully with the DELTA system over horizontal and non-horizontal slant paths.[7, 8]

The DELTA-Sky system employs the DDTV technique on images captured from highly featured regions of the moon. DELTA-Sky was adapted for ground-to-space measurements and a system is located at the John Bryan State Park Observatory in Yellow Springs, Ohio. The DELTA-Sky system is shown in Figure 2.

The differential jitter between feature pairs generate a unique turbulence moment relatable to the turbulence strength profile, with smaller separations corresponding to C_n^2 values further along the path from the imaging aperture. The angular field of view of the imaging system and the corresponding finite angular separation of high-contrast features on the moon's surface limits the sensitivity at range of the DELTA-Sky system.

Fig. 2: DELTA-Sky lunar telescope.

2.3 Turbulence Strength Estimates from Numerical Weather Prediction (NWP) Data

Optical C_n^2 can be inferred from the temperature structure function, C_T^2, using expressions derived by Tatarskii.[9] C_T^2 is calculated from parameterized weather data vs. altitude. Input parameters used include temperature, pressure, wind and their respective vertical gradients. This methodology has been previously compared against measured turbulence values obtained via optical methods between mountain peaks in Hawaii and has shown adequate agreement.[10, 11] For the analysis presented in this paper, this methodology is implemented using the Laser Environmental Effects Definition and Reference (LEEDR) toolset. This tool was developed by the Air Force Institute of Technology Center for Directed Energy. LEEDR is a first principles atmospheric propagation and characterization code that is packaged into an easy to user graphical user interface. Through this interface specific weather parameter data vs. altitude is gathered from National Oceanic and Atmospheric Administration (NOAA) publically available resources. This data is used in LEEDR with the prescribed geometry matching the data collection scenario, and Tatarskii based calculations are carried out to estimate C_n^2.

3. Data Collected

A joint data collect event occurred on 22 June 2022 with the TARDIS and DELTA-Sky turbulence strength profiling systems at the John Bryan Observatory site in Yellow Springs, OH. The TARDIS collected three main datasets during the joint data collect, each with a different range depth configuration, 450m, 300m, and 200m. This was done to ensure at least one of the data collects produced high quality Shack-Hartman wavefront sensor image data. It was discovered through prior collection campaigns with TARDIS that the range depth setting was not only a function of range to beacon from the collecting aperture, but also dependent on the atmospheric conditions of the specific collection event. The 300m range depth data collect was deemed to produce the best Shack-Hartmann wavefront sensor images balancing signal-to-noise ratio and a tightly focused spot for all beacon ranges. This is the data used for presentation in this paper. The setup configuration for TARDIS for this data collect is described in Table 1. An image of the beam in operation on 22 June 2022 is shown in Figure 3.

The DELTA-Sky system operated for the duration of the night on 22 June 2022, however, only the overlapping time segment with TARDIS is used for presentation in this paper. DELTA-Sky collected lunar imagery while tracking a specific region on the moon, like that shown in Figure 3. The DELTA-Sky system is comprised of a 12 inch LX200 Meade telescope outfitted with a FLIR GS3-U3-23S6M-C USB camera. Lunar imagery data was captured at a rate of 100 Hz. Using high contrast features from diverse angular separations in the image stacks, DELTA-Sky's processing software calculates turbulence statistics based on differential jitter in these feature targets. These statistics are applied to the path weighting functions to estimate the turbulence strength profile along the viewing path.

Table 1. TARDIS configuration parameters.

Parameter	Value
Azimuth	105 degrees (from North clockwise)
Elevation	35 degrees
Ranges	800 m, 1000 m, 1200 m, 1400 m, 1600 m, 1800 m, 2000 m, 10,000 m (dark reference frame)
Range Depth	300 m
Pulse Frequency	200 Hz
Frames Collected	79,075
Wavelength	527 nm
Start Time	3:52 AM EDT

Fig. 3. (left) TARDIS operation showing beam projection (P.C. Steven Zuraski), and (right) region of the moon used for the DELTA-Sky system.

4. Discussion

Results from the joint data collect of TARDIS and DELTA-Sky are shown in Figure 4. TARDIS data is shown as an average and standard deviation with distribution histogram plots on the right in Figure 4. This is done for ease in comparison to the DELTA-Sky methodology which captures a turbulence strength profile as a time average measurement based estimate. It should be noted that the TARDIS system captured a profile of the turbulence strength every 40 ms by directly measuring the perturbed wavefront from beacons at varied ranges within that timescale, with a unique change in beacon location every 5 ms. During these timescales turbulence can be considered unchanging, and an instantaneous estimate of the profiled turbulence strength is captured. DELTA-Sky, on the other hand, was setup to produce a turbulence profile estimate every minute. This estimate was based on approximately 300 frames of captured lunar imagery taken at 100 Hz. The results from the DELTA-Sky collects are shown by the dotted black line in figure 4. Lastly, a LEEDR produced turbulence strength profile, dashed blue line, is shown and used for comparison in Figure 4. The methodology used in LEEDR was based off of satellite based weather parameter measurements. Data was used from the closest grid point to John Bryan Observatory, which was less than 0.25 km away, and from the nearest time to the joint collection of TARDIS and DELTA-Sky. The data used was offset in time by approximately 1 hour and ten minutes. Over one hour, turbulence strength profiles could experience large changes, so presented LEEDR results should be only viewed with this in mind.

Looking at Figure 4, some obvious trends are present. First, TARDIS estimated overall turbulence strength that was weaker than the other two methodologies, on average. However, the range from the average value to the maximum value is large, indicating that over the collected time window the turbulence strength was changing greatly. This is an important observation, and a benefit of the TARDIS system which provides a continues update to the turbulence strength profile as it evolves through time. Possible reasons for TARDIS to underestimate the strength of atmospheric turbulence could stem from inaccuracies in spot centroiding in the Shack-Hartmann wavefront sensor images. This usually happens when there is low signal to noise ratio (SNR) in an image or there is defocus in a spot. Low SNR and defocus lead to estimated tilts that exhibit smaller deviations from center, hence weaker turbulence strength estimates. For this data collect it is believed that this is not the case. Multiple range depths were used throughout the night and the optimum SNR range depth case of 300 m was used for analysis in this paper. Looking at the histogram plots, it should be noted that 459 m altitude beacon had a distribution of was different in shape than the rest. When looking at the corresponding Shack-Hartmann wavefront images from the 459 m altitude slot, the spots in these images were slightly defocused. It is plausible that the lowest altitude data point from the TARDIS system is slightly under predicting turbulence strength.

Second key observation is that the DELTA-Sky turbulence profile estimate deviates greatly from the TARDIS measurements at the lowest altitudes. DELTA-Sky's technique is most sensitive near the aperture where the weighting functions used are strongest.[8] A Hufnagel-Valley 5/7 profile was used as the initialization state for the DELTA-Sky methodology, which could bias profile shapes to appear stronger at lower altitude in proximity of the assumed boundary layer. In reality this strong turbulence region may or may not be present at the designated location used in the Hufnagel-Valley 5/7 initialization state. So, although the DELTA-Sky measurements have the greatest influence at low altitude designations, it is plausible that not enough energy was attributed to the lower altitude weighting functions; meaning that the angular jitter statistics matched what could be expected from turbulent paths matching the average strength of a Hufnagel-Valley 5/7 profile. Also, it is important to note that DELTA-Sky only captures imagery over 3 seconds and if there is strong instantaneous turbulence within that three second window, it could bias the averaged DELTA-Sky estimate collected towards stronger turbulence values. It is important to keep these notions in mind when analyzing DELTA-Sky measurements. With that said, most of the DELTA-Sky estimated values fell within the range of TARDIS produced turbulence strength values, albeit all towards the stronger turbulence strength values. This could indicate that DELTA-Sky did match some of the near instantaneous TARDIS values over the data collection window.

Another key observation is how the LEEDR produced profile compares to both TARDIS and DELTA-Sky profiles. The LEEDR produced turbulence strength estimates, blue dashed line in Figure 4, fall entirely within the range of TARDIS values. Since LEEDR bases its estimate off the Tatarski relationships to estimate C_T^2 and C_n^2 from weather parameters vs. altitude data[9] that is sparse in both time and spatial context as compared to TARDIS or DELTA-Sky data, the agreement shown by the overlap is a very positive trend. This indicates that these sorts of measurements fall within the range of some near instantaneous measurements, although biased towards a stronger turbulence strength estimate. In addition, the convergence at the lowest altitudes shows promise of the LEEDR produced technique. Although this should be cross-validated with a larger set of measurements across many nights of collection in diverse weather conditions such that a more robust conclusion could be drawn.

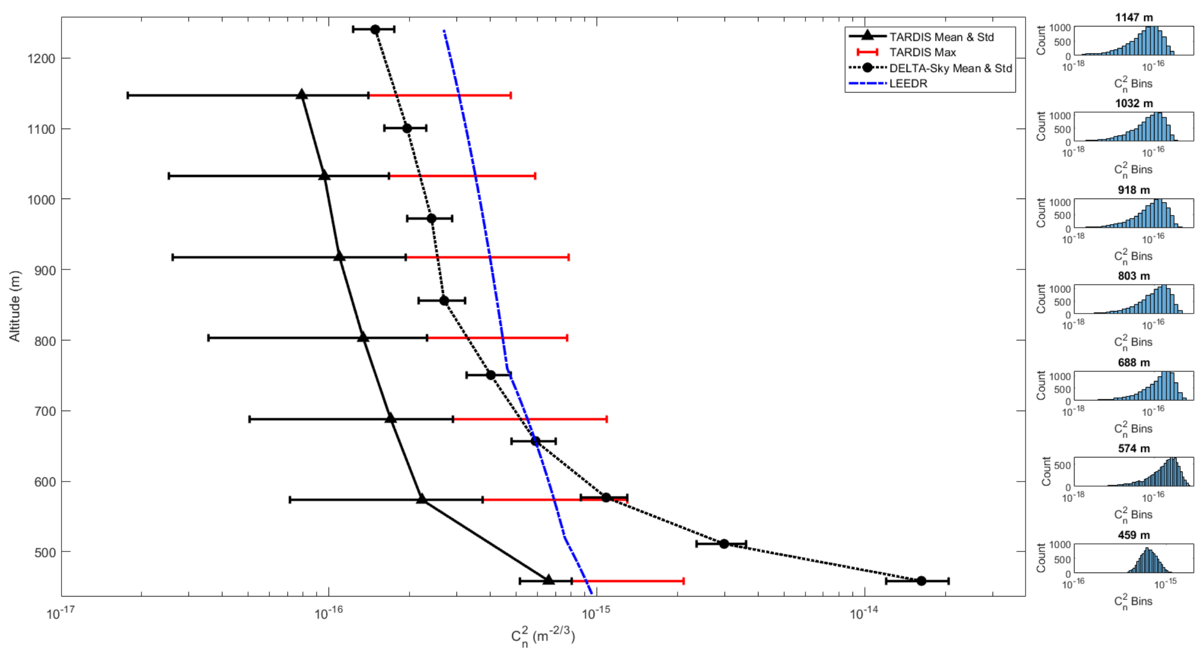

Fig. 4. (left) Comparison of resultant turbulence strength profiles: TARDIS in solid black with triangle data points, DELTA-Sky in dotted black with circular data points, and LEEDR produced profile in dashed blue. (right) histogram plots of turbulence strength for the TARDIS collected data for each beacon range.

5. Impact

This body of research provides a comparison of multiple established techniques to measure or estimate the turbulence strength profile. The TARDIS system provides a direct measurement of the perturbed wavefront, which is fundamentally different than alternative methodologies[12-15]. Utilizing a direct measurement of the wavefront embeds knowledge of how light is effected by turbulent eddies in the atmosphere. Additionally, this method for C_n^2 estimation is not susceptible to the same type of errors as other non-direct C_n^2 estimation techniques. For these reasons, the TARDIS system is viewed as a truthing system for this research and adds confidence to other measurement methodologies presented. Furthermore, since this technology utilizes direct measurements of the wavefront, it is conceivable that this could be linked to an adaptive optics system used for image correction. In particular, very large next generation telescopes[16] have difficulty providing adequate full field adaptive correction for the atmosphere based on total path integrated volume measurements. This is why these programs are exploring the uses of multiple beacons from varied ranges, and turbulence profile estimation techniques. Lastly, this technology is well suited to be coupled with a long range projection system. Similar to a passive imaging system, a beam projection system could benefit from knowledge of the profiled turbulence strength.[17]

The DELTA-Sky methodology has the distinctive advantage on a system level of being entirely passive and produces estimates of C_n^2 for distances near the collecting aperture where the techniques measurement sensitivity is highest. Being passive and working off standard high frame rate imagery DELTA-Sky is a technique that could easily be employed at any observatory site and can provide a reasonable assessment of the turbulent environment that the site experiences.

Lastly, Estimating C_T^2 and consequently inferring C_n^2 from numeric weather data opens up the possibility of predicting the profiled strength of atmospheric turbulence. This could be extremely beneficial for a number of applications and observation planning activities optimized around favorable turbulence conditions. Weather parameter prediction methodologies are well established and available globally, making this methodology very appealing. However, the precision of this method has not been robustly tested against a truthing system such that a "standard" accepted means for estimating turbulence strength profiles could be gleaned from this methodology. Furthering the comparison between TARDIS, DELTA-Sky, and LEEDR produced turbulence strength estimation methodologies could lead to more robust widely accepted and easily employed methodologies for estimating turbulence strength at observatories and globally. This work presented is part of a larger body of research to inform, assess, and provide potential updates to the methodologies of estimating turbulence strength profiles.

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