

Comparing Vertical Turbulence Profile Reconstructions with STORM and SHIMM in Delft

Marguerite Arvis^a, Perrine Lognoné^b, Florian Quatresooz^{c,d}, Alex Frost^e, Jérôme Loicq^a, and Rudolf Saathof^a

^aSpace Engineering Department, TU Delft, Kluyverweg 1, 2629HS Delft, Netherlands

^bPhysics Department, Durham University, Durham, UK

^cDOTA, ONERA, Université Paris Saclay, 92320 Châtillon, France

^dICTEAM, Université Catholique de Louvain, 1348 Louvain-la-Neuve, Belgium

^eInternational Centre for Radio Astronomy Research, The University of Western Australia, Perth, Western Australia, Australia

ABSTRACT

Monitoring optical turbulence profiles (OTPs) over optical ground stations is a necessary step in preparing a site for laser satellite communication operations. In this specific context, it is also of particular interest to monitor OTPs along the line-of-sight of LEO satellite links for improved uplink wavefront correction. While numerous methods and instruments exist for reconstructing vertical turbulence profiles in general, it is of interest to understand the strengths, weaknesses, and optimal use cases of each. The performance of these different techniques can be compared in terms of reconstruction accuracy and overall practicality of hardware and software implementations. In this comparative study, we evaluate the performance of two measurement methods: Speckle-based Turbulence Observation and Reconstruction via Machine learning (STORM), developed at the TU Delft, and the Shack-Hartmann Image Motion Monitor (SHIMM), developed at Durham University. The SHIMM, which has already been validated on sky, can reconstruct a 4-layer OTP using input from time-series of wavefront slopes and intensities on a fixed line-of-sight. STORM, on the other hand, was designed to reconstruct 8-layer OTPs along the line-of-sight of LEO links using single-shot pupil plane speckle images. However, the latter method remains to be validated, adding a strong motivation for a joint experiment between TU Delft and Durham University. To provide a reference baseline, both methods are also evaluated against validated high resolution profiles from WRF simulations developed at the UCLouvain. This article presents the first experimental results of a STORM-SHIMM vertical turbulence profiling campaign conducted at the TU Delft in August 2026. This measurement campaign brought together all three of these methods to validate STORM, provide some first vertical turbulence profile measurements from the TU Delft Aerospace Observatory, and to experimentally compare the strengths and weaknesses of each method.

Keywords: Atmospheric turbulence, optical turbulence profiles, STORM, SHIMM

1. INTRODUCTION

Albeit a promising technology for higher data rates, low-cost space terminals and more secure links, laser satellite communications are weighed down by the effects of beam propagation through clouds, aerosols and atmospheric turbulence.^{1,2} Turbulence is of particular concern on laser satellite communications (laser satcom) links as it causes beam wander and scintillation.³ In turn, this leads to irregular irradiance and occasionally loss of signal, which can both dramatically reduce the overall availability of the link and increase the total bit error rate.⁴

Thanks to well-known mitigation techniques for wavefront correction, turbulence effects can be compensated on the the satellite downlink.⁵ Implementing such techniques requires expensive optical components; thus, a site characterization of turbulence is required to design systems optimized to the amplitude of the necessary corrections.^{6,7}

To address the need for turbulence characterization at optical ground stations, low-cost and portable turbulence profilers have been developed and deployed, such as the Shack-Hartmann Image Motion Monitor (SHIMM)

instrument.⁸⁻¹⁰ As an alternative or complement to dedicated monitoring instruments, turbulence profiles can also be estimated from numerical weather prediction (NWP) simulations, using the Weather Research and Forecasting (WRF) model for example.¹¹

While turbulence effects can be relatively well compensated on downlink optical communications, though, the problem is far less straightforward on the uplink. Firstly, due to geometric considerations, turbulent effects near the ground will have stronger implications at satellite altitude. Secondly, due to the point-ahead angle (PAA), the uplink path will easily fall outside the downlink path’s region of coherent turbulence defined by the isoplanatic angle. This means that the wavefront corrections applied to the downlink are inadequate for the needs of uplink correction. Proposed solutions involve estimating an adequate uplink correction from the downlink correction using the PAA and information from the turbulence profile.¹² Such methods would require computing turbulence profiles on the downlink path, as recently demonstrated for geostationary optical links.¹³ However, the PAA varies significantly more on low-Earth orbit (LEO) links, calling for high-speed line-of-sight turbulence profiling. In view of this need, STORM¹⁴ was designed to enable single shot line-of-sight turbulence profiling by using machine learning (ML) based estimations of turbulence profiles. As of the writing of this paper, however, this instrument has not yet been validated on-sky or compared to another profiler.

In light of the above, a turbulence profiling measurement campaign was conducted in Delft to compare the different profiling methods which could play a role in implementing turbulence compensation for laser satellite communication links, namely, STORM, SHIMM and WRF simulations. As part of the main agenda, this comparison between STORM and the more verified methods (SHIMM and WRF simulations) will also serve as a first on-sky validation of the STORM instrument, as well as a benchmark for improving the actual STORM ML model.

In this paper we describe the said measurement campaign and present some first results. The first section will introduce the methods being used and provide a short overview of their inherent specificities. This will be followed by a more detailed description of the measurement campaign itself. Finally, the first results and figures will be presented and briefly discussed before concluding.

2. TURBULENCE PROFILING METHODS

The prime objective of this study is to compare the performance and accuracy of different turbulence profiling methods in an urban environment. In particular, we seek to experimentally compare three methods: STORM, SHIMM and WRF simulations. This section presents the different methods that were used in the data, their instrument form, and a quick overview of how they compare on paper.

2.1 STORM instrument

Speckle-based Turbulence Observation and Reconstruction via Machine learning, otherwise referred to as STORM,¹⁴ is a method designed for obtaining line-of-sight turbulence profiles for laser satellite communications. Based on the concept of single star SCIDAR^{15,16} and leveraging Taylor’s frozen turbulence assumption, this method aims to reconstruct a reduced layer turbulence profile using the spatial information on a single pupil plane image of an extra-atmospheric source rather than the temporal variations of a series of such images. At the expense of vertical resolution, this method currently provides 8-layer vertical turbulence profiles using single speckle images. In simulations, this method yielded an estimated accuracy of 90% on the Fried parameter, isoplanatic angle and scintillation index. Its unique single shot advantage makes STORM turbulence profiling a valuable candidate for real-time correction implementations on optical terminals for LEO satellite laser links. However, at the time of writing, the method has not been previously evaluated on-sky against profiles estimated by other validated instruments.

In essence, the STORM instrument consists of a collimating lens, a filter and an imaging device, as shown in Fig. 1a. The telescope focal point is adjusted to coincide with the collimating lens and the detector is placed slightly beyond the pupil by a distance Δz . This latter positioning equates to propagating the beam “below ground” by a conjugate on-sky distance Δh (Eq. 1), and is a technique borrowed from generalized SCIDAR,¹⁷ which allows the beam to propagate an extra distance without turbulence effects.

$$\Delta h = (F_{telescope}/f_{lens})^2 \Delta z \quad (1)$$

Parameter	STORM estimator	STORM instrument
Telescope diameter (mm)	405	405
Wavelength (nm)	550	550 $\pm$ 20
Speckle dimensions (pixels)	105x105	256x256
G-SCIDAR distance (m)	300	1400

Table 1: Comparison between the STORM instrument and STORM ML model parameters.

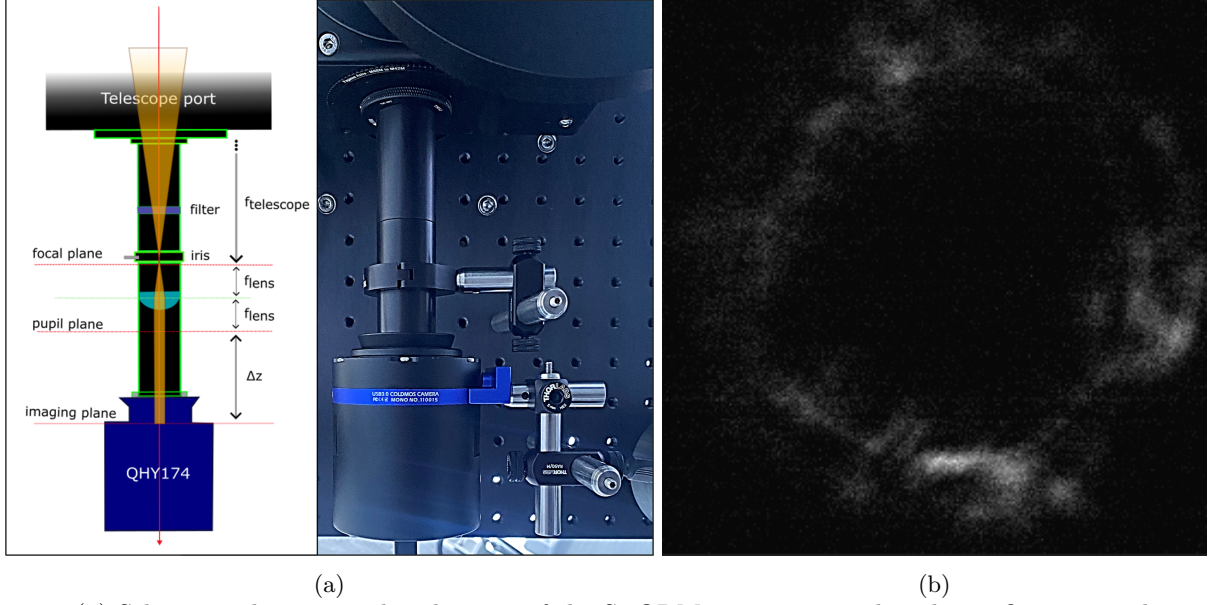


Figure 1: (a) Schematic drawing and real image of the STORM instrument. Though not figuring in the image, the real instrument also consists of the iris and a filter. (b) Sample image of STORM while imaging Arcturus at 2.5ms with low gain (23:15:50 04-04-2028).

This extra propagation allows lower layer speckle features to develop to a characteristic size d , as per the Fresnel distance:

$$d = \sqrt{\lambda L} \quad (2)$$

with λ the wavelength and L the propagation distance from the disturbance. The diffraction rings visible on STORM samples are a residual effect of this implementation choice. A short-exposure image is then collected by the detector and processed by the STORM estimator (non-real-time in this experiment).

As described in References 14,18, the STORM estimator is a neural network trained on simulation generated speckle images, which returns an 8-layer integrated profile along the slant-path (non-adjusted to zenith). In the intended operational use, site and instrument parameters are used to generate the neural network's training dataset, such that a STORM estimator is adapted to a given instrument and telescope pair. However, in the current version of the results, the STORM estimator is not optimized for measurement instrument, which has obvious consequences on the processing and results, as presented in Section 4. Some of the important parameters of the telescope/instrument pair compared to those of the STORM estimator are listed in Table 1.

2.2 SHIMM instrument

The Shack-Hartmann Image Motion Monitor is a 4-layer turbulence profiler developed at Durham University.⁹ The method consists in collecting short time series (30s) of slope and intensity measurements from a Shack Hartman Wavefront Sensor (SHWFS). By exploiting the covariances of slopes and intensities of pairs of SHWFS subapertures separated by varying distances, a turbulence profile can be reconstructed

Thanks to a collaboration with the University of Western Australia, the SHIMM instrument was redesigned to be optimized for telescope and camera interoperability. This modified design can be seen in Fig.2. Due to coatings on the multi-lens array (MLA) and collimating lens, the SHIMM is designed to collect data in 1550nm.

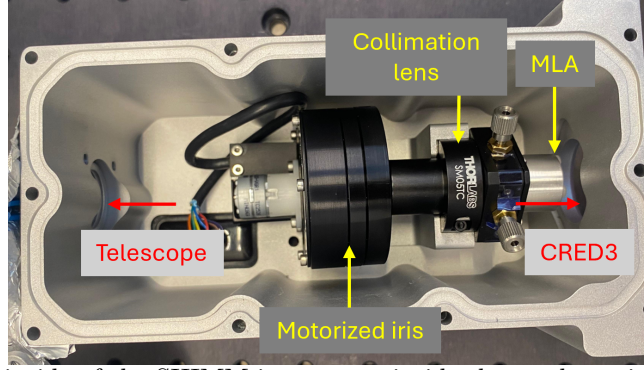


Figure 2: Picture of the inside of the SHIMM instrument inside the newly optimized and adapted casing.

2.3 WRF simulations

To obtain realistic C_n^2 profiles that can be used to simulate the performance of the STORM and SHIMM instruments, NWP simulations were conducted for the TU Delft optical ground station location (51.9897841°N, 4.3754318°E). We used the WRF model, that provides estimates of zenith C_n^2 profiles over 100 vertical levels using the turbulent kinetic energy (TKE)-based C_n^2 parameterization described in Reference 11. This model has previously been validated with optical turbulence measurements in Belgium¹⁹ and its performance at Delft is further assessed through comparison with C_n^2 profiles measured by the STORM and SHIMM instruments in this work.

2.4 C-DIMM instrument

For reference purposes, Fried parameter measurements from the site’s compact Differential Image Motion Monitor²⁰ (C-DIMM) are also utilized in the results presented in this paper. Although the C-DIMM is only able to measure integrated turbulence parameters, it serves as a relatively trusted benchmark value. In fact, it can be expected to find a C-DIMM on most optical ground station sites, so it is a useful reference.

Visible in Fig.3, this instrument consists of a fixed binocular pointed at Polaris.²¹ By measuring the variance of the distance between the two image centroids, an estimation of the Fried parameter can be derived. As with the other meteorological parameters from the site instruments, this processing is conducted by Miratlas, through whom the authors are able to collect the data.

Nonetheless, exchanges with the manufacturers in previous studies have led to the acknowledgment that the raw Fried values should be adjusted by +30%.¹⁹ The C-DIMM values presented in this study are all adjusted accordingly.

2.5 Method trade-offs

From the above, it is clear that each method has its own set of strengths and weaknesses. While the C-DIMM is the general reference point for the measured Fried parameter, it is limited to estimating integrated parameters. Albeit a telling metric for designing ground station adaptive optics systems, the Fried parameter provides no insight about the vertical distribution of turbulence. Since high altitude turbulence has a strong impact for laser satellite communications, this does not make it a candidate for in-the-loop applications.

WRF simulations, on the other hand, provide a very high resolution vertical turbulence profile and do not require hardware installations. As such, this type of modeling is an excellent solution for site analysis and post-processing of turbulence impacted data. Moreover, because of its non-hardware dependency, WRF simulations are a great tool for cross-comparisons with other vertical profilers. This method is however limited to off-line measurements as it requires a heavy simulation process.

Returning to the hardware methods, SHIMM provides a 4-layer turbulence profile in the line-of-sight, which is a significant advantage for laser satcom applications. In addition, multiple validations of these metrics ensure their fidelity, and it has been shown that 4 layers could be a sufficient resolution for uplink pre-compensation

applications.²² In its current form, however, this method requires a lengthy timeseries of slopes and intensities in order to obtain a high-confidence fit. Where this may not be a problem for geostationary applications, for LEO applications it may well be.

Designed specifically for real-time line-of-sight profiling, STORM offers an 8-layer solution adapted to LEO laser link needs. However, this method requires a pupil plane image with a sufficient signal-to-noise ratio, meaning that such an instrument would not benefit from the standard sophisticated optical terminal components (such as a WFS) and that optical power would need to be sacrificed for the application. In addition, as the STORM estimate uses fewer data points, the on-sky accuracy of this method needs to be verified against other profilers.

3. MEASUREMENT CAMPAIGN

To put to test these “on-paper” comparisons, it was decided to bring together all afore-mentioned instruments and methods in Delft, The Netherlands, during the first week of August 2026, and to conduct a comparative turbulence profiling measurement campaign.

3.1 Campaign objectives

The aim of this campaign is to collect a large dataset of vertical turbulence profiles over Delft using STORM, SHIMM and WRF simulations. Relevant for laser satcom applications as well as astronomy, the objectives of these measurements are threefold:

1. STORM method validation

The first goal of this cross-method campaign is to evaluate the accuracy of the STORM vertical turbulence profiling method. Although designed for laser communications, it is also appropriate to validate the underlying method using starlight. The validation lies in the fact that these results are compared to the quasi-simultaneous results of a validated method, the SHIMM, measured on the same targets.

2. First Delft vertical turbulence characterization

The secondary purpose of this study is to get a first assessment of local vertical turbulence profiles over Delft. Due to the particular location of this site in an urban area and near a coastal environment, it is of interest to understand the specificities of local turbulence profiles. This can serve for better design of optical ground station hardware, as well as provide a benchmark for comparisons to other monitored locations. Compiled, this information could reveal useful insights for general turbulence modeling, both for astronomy and laser satellite communications. To maximize the diversity of profiles, the idea is to collect many profiles at different times of day and night, in different conditions. Although some data was collected for this objective during the initial campaign week, the full results will be published at a later time in order to acquire a larger variety of seasonal data.

3. Comparative performance study

Finally, it is of interest to compare the measurement methods’ (STORM and SHIMM) performance to the more stable WRF simulation profiles. In regions where WRF profiles have remaining uncertainties – namely sunset and sunrise – the measurements of STORM and the SHIMM can also serve to validate or improve the modeling. This final objective can provide a more complete overview of each candidate method’s strengths and weaknesses for laser satellite communication applications.

3.2 Experimental Setup

The experimental setup was enabled by the TU Delft Aerospace Observatory.²³ Situated on the rooftop of the TU Delft Aerospace Engineering faculty, this laboratory pertains of an observatory and a weather monitoring station (Fig. 3). The observatory is a Baader Planetarium dome housing a 40cm Ritchey-Chrétien telescope with a breadboard designed to host multiple instruments. The different breadboard instruments are connected to the telescope via the Instrument Multi-Port (IMP), which uses a small mirror switch to redirect the light to different instrument ports. The telescope, dome, instruments and IMP are all controlled by a sophisticated Observatory



Figure 3: The TU Delft Aerospace Observatory: the Baader Dome housing a 16" Ritchey-Chrétien telescope and turbulence monitoring instruments, including the C-DIMM on the lower right side.



Figure 4: Mounting of the different instruments on the telescope breadboard. The primary mirror is directly behind the breadboard and the IMP redirects the light towards either Port 2 or Port 3. Each instrument is connected to a power and data hub which is directly linked to the observatory computer.

Management System (OMS or host PC). The weather station, also called MISO, contains multiple instruments including a C-DIMM, a sonic anemometer, all-sky image cloud monitors and the usual set of meteorological instruments).

For the experimental setup of this campaign, the breadboard of the observatory was equipped with the STORM instrument on Port 2 and the expressly modified and telescope-fitted SHIMM box on Port 3. As the instruments were attached to different ports, the starlight measurements using the respective instruments were only quasi-simultaneous, as there was a need to switch the IMP and readjust the focus between each measurement.

3.3 Measurements

Over the course of the week of August 3rd to August 7th, a total of over 300 measurements were collected for both STORM and SHIMM. Due to a lack of automation, all measurements needed to be initiated manually, making it unrealistic to collect data at all opportunities offered by the untypically clear Dutch skies. Nonetheless, combined measurements were acquired over 3 nights (including 2 sunsets), 2 sunrises, and multiple times over various portions of the afternoon.

The main target stars, Arcturus and Vega, are conveniently bright and stayed quite visible throughout the week, though other stars were also measured throughout a session in order to observe the effects of variations in elevation. Despite the difference in measuring wavelength between the 2 instruments, the target stars were equally visible in both cases, with a slightly lower SNR at 550nm during the daytime. In order to make plate scale adjustments on the SHIMM processing, a binary star (Mizar) was also imaged over the course of the second night.

For each SHIMM measurement, a pair of 30s acquisitions were made at around 1 to 2ms exposure time and 400fps. For each STORM measurements, a pair of 10s captures were made at one lower ($\sim 1ms$) and one higher ($\sim 2ms$) exposure time and a limited frame rate of around 50Hz.

The results presented in the next section are limited to the measurements on the night of August 4th to August 5th. Further results will be presented in future works after additional data analysis.

4. RESULTS

In this section, the results of the profile reconstructions and integrated parameters for STORM, SHIMM and WRF are compared, as well as a short discussion.

4.1 Profile estimation

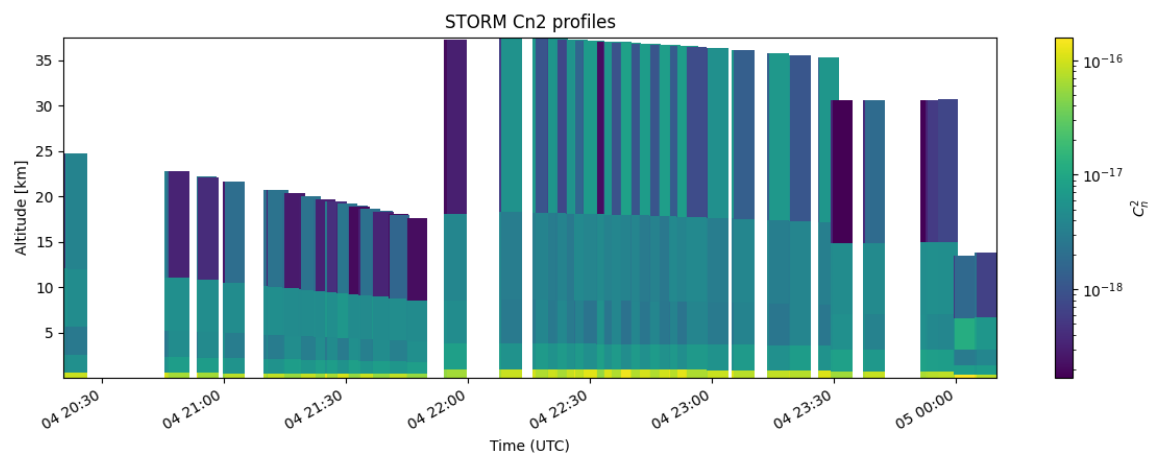
To begin with, the turbulence profiles were reconstructed along the slant path for STORM and SHIMM. These profiles were then adjusted to zenith via a factor $\cos(\zeta)$ on the propagation distance. In the case of STORM, due to the misalignment between GScidar distance of the ML model and that of the actual instrument, the ground level was readjusted to 1.1km. As a result, the first three of the 8 layers were cropped, leaving only a 5-layer model. The time series of the C_n^2 profiles computed for each method over the course of the night are shown in figures 5a-5c.

While there are obvious differences in the results, the trend of a very strong ground layer and weak turbulence on the higher atmospheric layers is apparent in all reconstructions. Interestingly, STORM and SHIMM estimate a lower ground layer below $10^{-14} m^{2/3}$, whereas WRF simulations estimate it two order of magnitudes stronger. This can be attributed to the higher resolution of WRF and the fact that the strong layer only seems to reach a couple hundred meters. Since the first STORM layer is 1km and that of SHIMM is 4km, their C_n^2 value is averaged down by the weaker turbulence past a few hundreds of meters. For the higher layers, however, WRF estimates generally lower turbulence than the other two methods. This can be seen more clearly on the median C_n^2 profiles in Fig.6.

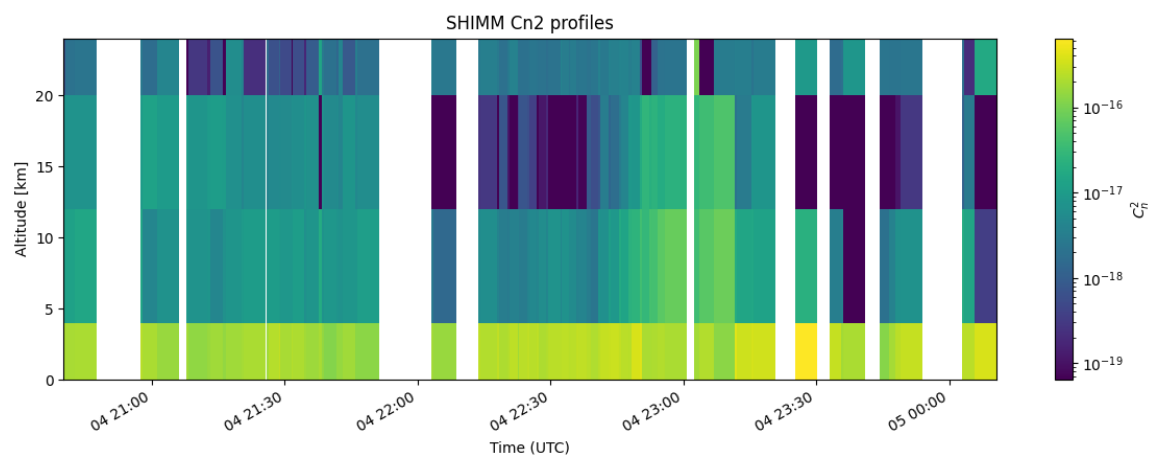
It should be noted that due to the difference in base wavelength between the STORM and SHIMM instruments, a baseline difference of around 3% is to be expected between their vertical profiles.

4.2 Turbulence parameters

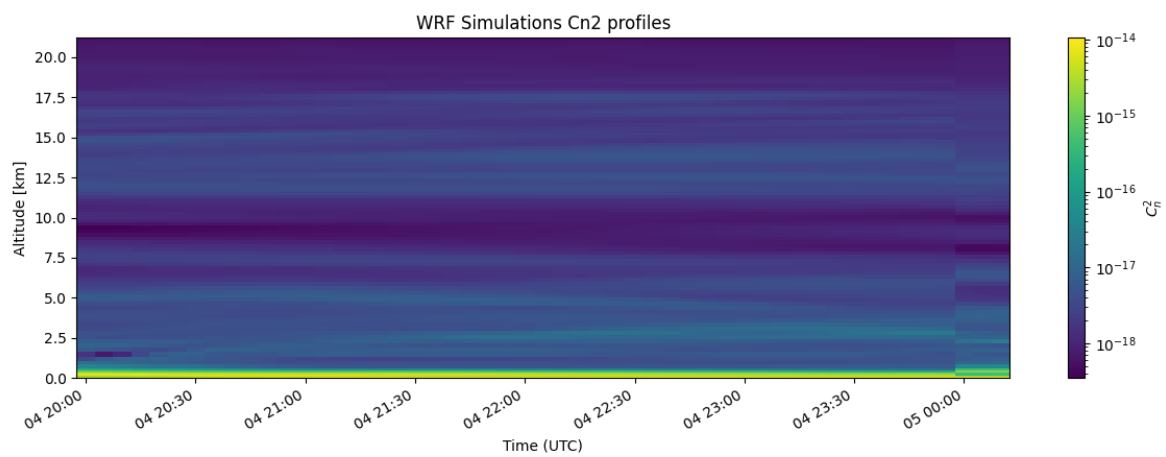
In order to compare these reconstructions with single integrated values, the Fried parameter r_0 [m], isoplanatic angle θ_0 [rad], and scintillation index σ_I^2 (or Rytov variance due to weak turbulence assumptions), were computed from all vertical profiles using the following equations:



(a)



(b)



(c)

Figure 5: Time series of the C_n^2 values computed for each method. All profiles are normalized to zenith

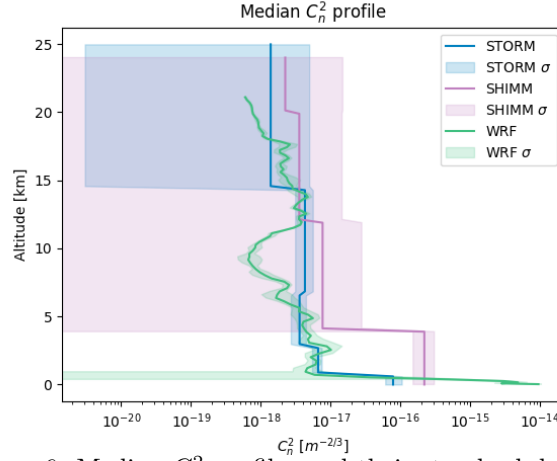


Figure 6: Median C_n^2 profiles and their standard deviations

$$r_0 = \left(0.423 \left(\frac{2\pi}{\lambda} \right)^2 \sec(\zeta) \int_0^\infty C_n^2(h) dh \right)^{-3/5}, \quad (3)$$

$$\theta_0 = \left(2.913 \left(\frac{2\pi}{\lambda} \right)^2 \sec^{8/3}(\zeta) \int_0^\infty C_n^2(h) h^{5/3} dh \right)^{-3/5}, \quad (4)$$

$$\sigma_I^2 = 2.25 \left(\frac{2\pi}{\lambda} \right)^{7/6} \sec^{11/6}(\zeta) \int_0^\infty C_n^2(h) h^{5/6} dh. \quad (5)$$

where λ is the wavelength, ζ the zenith angle (0° corresponding to zenith), and h the altitude above ground. For a proper comparison, all values are normalized to the zenith and converted to the approximate value at 550nm for the SHIMM using a factor $(\lambda_{550}/\lambda_{1550})^\gamma$ with $\gamma = 6/5$ for the Fried parameter and isoplanatic index, and $\gamma = -7/6$ for the scintillation index.

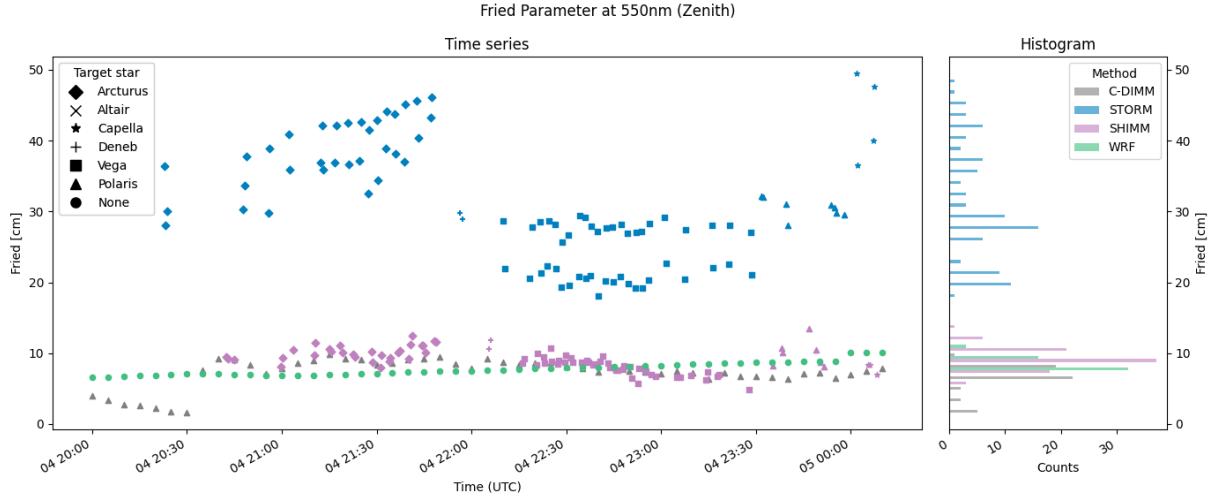
As can be seen in Fig.7, the SHIMM and C-DIMM values nicely follow the same trends, with a median separation of 1.2 cm. Similar results were also observed in Reference 24. WRF simulations, on the other hand, are on average closer to the C-DIMM values, even though the short term variations are less coinciding.

As for STORM, the results in Fried parameter are visibly overestimated. This can assumedly be attributed directly to an underestimation of the strong lower layer. That being said, another noticeable feature is the appearance of two series in the data, which correspond to the different exposure times for a pair of measurements. The series of shorter Fried parameters correspond to the estimations from higher exposures. The cause of this artifact is could be an insufficient SNR at lower exposure times. This would lead the STORM model to miss all features, especially finer low altitude features which are be mistaken for noise. This is also the cause for the “zebra-like” artifact on the STORM C_n^2 profiles from the previous section

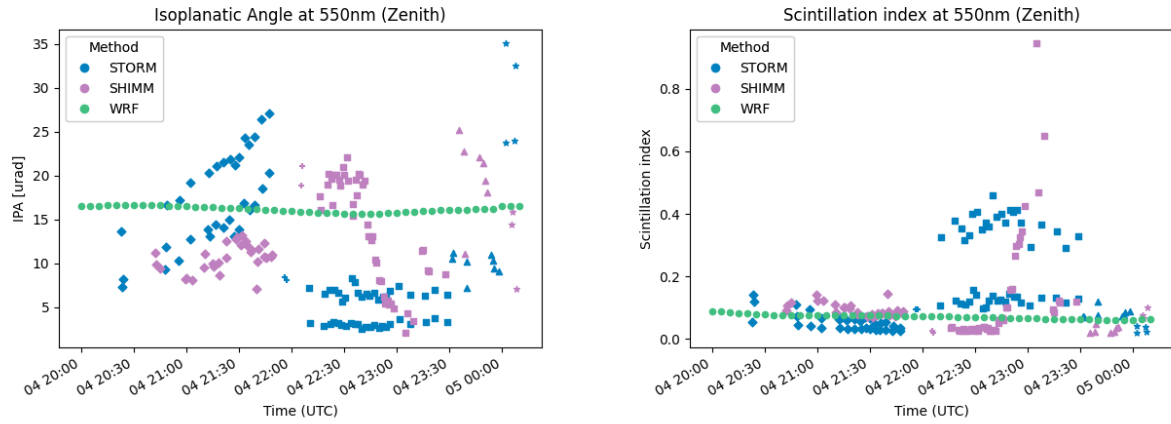
In terms of isoplanatic angle and scintillation index, the results of both STORM and SHIMM vary around the stable WRF line, without any obvious mutual trends. On STORM, there appears to be a residue from zenith normalization on the Arcturus samples, which is also manifest on the Fried parameter computations. The SHIMM results on the scintillation index also reveal an unexpected peak around 23:00, which is not associated with meteorological changes visible in the WRF simulation. However, low SNR frames were acquired around that time and may explain this observation.

4.3 Discussion points

All combined, these vertical profile and integrated parameter results underline specific features for each method. It clearly appears from the parameter series that WRF is a statistically accurate method, but that it struggles to



(a)



(b)

(c)

Figure 7: Time series and histogram of the (a) Fried parameters, (b) isoplanatic angles, and (c) scintillation index, as computed for STORM, SHIMM and WRF, converted to 550nm and normalized to zenith. The C-DIMM values are added as a reference for the ground truth for the Fried parameter and isoplanatic angle

closely follow the short variation trends. In fact this is something that is known and will be addressed in future iterations by reworking the higher altitude layers with layer boosting and LES improvements.²⁴

SHIMM on the other hand, is excellent for the short term estimation of the Fried parameter, though the results on the isoplanatic angle and scintillation index are less conclusive. In addition, the SHIMM generally estimates stronger higher altitude layers than both counterparts. Arguably, though, these small differences could also be due to some slight instrument misalignment and poor SNR on certain measurements.

Finally, the STORM results obtained with this model are not very conclusive. While the graphs show a complete underestimation of the strong lower layer, which results in a wildly overestimated Fried parameter, it also appears that the higher layers are well estimated. However, due to the lack of overall variations in the profiles, as well as the dubious processing that needed to be performed to align the STORM ML model predictions with the actual instrument configuration, it is more accurate to say that the results are inconclusive. The only certain features are the notable effect of exposure time and star elevation angle, which point to the need to tune the training data for future models.

5. CONCLUSION

In conclusion, a week-long turbulence profiling measurement campaign was conducted at the TU Delft Aerospace Observatory on the week of August 3rd to August 7th, 2026. The purpose of this campaign was to compare three different methods of turbulence monitoring for laser satellite communication applications: STORM, SHIMM and WRF simulations. This campaign was also the first experimental comparison of the STORM instrument against another turbulence profiler. As a result, these results were primarily aimed at validating this method on-sky. As of the first results, though, the conclusions for STORM are relatively amorphous due to a mismatch between the current STORM ML model and the on-sky STORM instrument, as well as a lack of proper variation in the observed turbulence profiles. Nonetheless, these serve as a benchmark for improving the model, since some interesting features linked to exposure time and elevation were reported. Second and third in line, the results of this campaign helped confirm observations made during previous campaigns with SHIMM and WRF, and provided a first vertical profile over the Delft urban area. In light of this, the STORM-SHIMM campaign in Delft was an overall successful collaboration, of which this report is only the first fruits.

REFERENCES

- [1] Kaushal, H. and Kaddoum, G., “Optical communication in space: Challenges and mitigation techniques,” **19**(1), 57–96.
- [2] Saathof, R., den Breeje, R., Klop, W., Kuiper, S., Doelman, N., Pettazzi, F., Vosteen, A., Truyens, N., Crowcombe, W., Human, J., Ferrario, I., Calvo, R. M., Poliak, J., Barrios, R., Giggenbach, D., Fuchs, C., and Scalise, S., “Optical technologies for terabit/s-throughput feeder link,” in *[2017 IEEE International Conference on Space Optical Systems and Applications (ICSOS)]*, 123–129.
- [3] Andrews, L. C. and Phillips, R. L., *[Laser Beam Propagation through Random Media]*, SPIE.
- [4] Stotts, L. B. and Andrews, L. C., “Communication performance in the focusing and saturation regimes inherent to the turbulent channel: a tutorial,” **63**(12), 120801.
- [5] Hardy, J. W., Lefebvre, J. E., and Koliopoulos, C. L., “Real-time atmospheric compensation,” **67**(3), 360.
- [6] Glindemann, A., “Relevant parameters for tip-tilt systems on large telescopes,” **109**(736), 682.
- [7] Hardy, J. W., *[Adaptive Optics for Astronomical Telescopes]*, Oxford University Press.
- [8] Perera, S., Wilson, R. W., Butterley, T., Osborn, J., Farley, O. J. D., and Laidlaw, D. J., “SHIMM: a versatile seeing monitor for astronomy,” *Monthly Notices of the Royal Astronomical Society* **520**, 5475–5486 (Apr. 2023).
- [9] Griffiths, R., “Continuous 24-hour Shack-Hartmann optical turbulence profiling on a small telescope,” *Durham e-Theses* (15845).
- [10] Beesley, L. F., Griffiths, R., Hartley, K., Farley, O. J. D., Quatresooz, F., Rodríguez-Gómez, A., Comerón, A., Townson, M., Alaluf, D., and Osborn, J., “Demonstration of 24-hour continuous optical turbulence monitoring in a city,” *Opt. Express* **33**, 10140–10149 (Mar 2025).

- [11] Quatresooz, F., Griffiths, R., Bardou, L., Wilson, R., Osborn, J., Vanhoenacker-Janvier, D., and Oestges, C., “Continuous daytime and nighttime forecast of atmospheric optical turbulence from numerical weather prediction models,” *Optics Express* **31**(21), 33850–33872 (2023).
- [12] Lognoné, P., Conan, J.-M., Rekaya, G., and Védrenne, N., “Phase estimation at the point-ahead angle for AO pre-compensated ground to GEO satellite telecoms,” **31**(3), 3441–3458.
- [13] Quatresooz, F., Robert, K., Petit, C., Bonnefois, A., Henrion, J., Kermarrec, G., Alaluf, D., and Védrenne, N., “Line-of-sight optical turbulence and wind profile monitoring during free-space optical communication links,” *Optics Express* **34**(8), 15074–15099 (2026).
- [14] Arvis, M., Ciarella, S., Loicq, J., and Saathof, R., “Single shot line-of-sight atmospheric turbulence profiling for laser satellite communications with STORM,” *Applied Optics, Vol. 64, Issue 32, pp. 9586-9597* (Nov. 2025).
- [15] Potanin, S. A., Kopylov, E. A., Shikhovtsev, A. Y., Kornilov, M. V., Savvin, A. D., Sulbaev, A. A., and Sachkov, M. E., “Methods for reconstructing the high-altitude profiles of optical turbulence from the observations of single bright stars,”
- [16] Coburn, D., Garnier, D., and Dainty, J. C., “A single star SCIDAR system for profiling atmospheric turbulence,” in [*Optics in Atmospheric Propagation and Adaptive Systems VIII*], **5981**, 105–114, SPIE.
- [17] Avila, R., Vernin, J., and Masciadri, E., “Whole atmospheric-turbulence profiling with generalized scidar,” **36**(30), 7898–7905.
- [18] Ciarella, S., Orozco, L., Azizi, V., Arvis, M., and Saathof, R., “Speckle cn2 profiler: Improving satellite communications with machine learning,” **10**(114), 9127.
- [19] Quatresooz, F., Prezerowitz, J., and Oestges, C., “Availability estimation for free-space optical communications in belgium,” *Appl. Opt.* **65** (Jul 2026).
- [20] Tokovinin, A., “From differential image motion to seeing,” **114**(800), 1156.
- [21] Jabet, F., “C-DIMM: an autonomous, outdoor and fixed seeing monitor for astronomy, atmospheric studies and free space optical communications,” in [*Environmental Effects on Light Propagation and Adaptive Systems IV*], **11860**, 6–10, SPIE.
- [22] Lognoné, P., Farley, O., Griffiths, R., Conan, J.-M., and Osborn, J., “Atmospheric c n 2 profile requirements for GEO-feeder uplink AO optimisation,” in [*Optica Imaging Congress 2024 (3D, AOMS, COSI, ISA, pcAOP) (2024), paper PTh4E.6*], Optica Publishing Group.
- [23] Saathof, R., Søndergaard, M., Root, B., Arvis, M., Shajahan, R., Spaander, J., and Loicq, J., “Experimental research in laser satellite communications to earth in an urban environment,” in [*International Conference on Space Optics (ICSO2026)*], (2026).
- [24] Quatresooz, F., Lognoné, P., Vincent-Randonnier, A., Lucas, Y., Lecarme, G., Henrion, J., Petit, C., Montmerle-Bonnefois, A., Hartley, K., Osborn, J., Kermarrec, G., Alaluf, D., and Védrenne, N., “Multi-source optical turbulence characterization for free-space optical communications,” in [*International Conference on Space Optics (ICSO2026)*], (2026).