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M.Sc. Thesis

Measuring optical turbulence with the PARSAX radar



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The undersigned hereby certify that they have read and recommend to the Faculty of Electrical Engineering, Mathematics and Computer Science for acceptance a thesis entitled “**Measuring optical turbulence with the PARSAX radar**” by **B.Sc. A.K. (Anna) Verhoek** in partial fulfillment of the requirements for the degree of **Master of Science**.

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Abstract

The use of lasers for satellite communication has recently become a growing field. However, a major challenge in their use is the distortion caused by the atmosphere. The distortion that this study focuses on is optical turbulence. The strength of optical turbulence is related to fluctuations in the refractive index of air and is generally described by C_n^2 . There is a growing body of literature that aims to measure this C_n^2 . One of the methods uses radar, and works by receiving backscattered echoes from turbulent eddies under clear-sky conditions, also known as Bragg scattering. This thesis investigates whether this method, that has so far only been applied to pulsed Doppler weather radars, can also be used with an S-band Frequency-Modulated Continuous-Wave (FMCW) radar.

In this work numerical radar data were used to filter out noise and isolate Bragg scattering. When only clear-sky days in June were included, the results from the 12 selected days showed an average correlation of 0.48 when compared with scintillometer validation data. This is higher than the correlation coefficient of 0.34 found using the pulse-Doppler radar method. However the results also showed a large systematic error, which was found to be related to calibration issues of the used radar. Because this error remained relatively stable over time, a correction factor could potentially be applied to compensate for it. Overall, the results indicate that it is possible to measure optical turbulence using vertical reflectivity measurements from a FMCW radar, although further research and improvements are needed before the method can be used operationally.

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Statement on the use of AI

During the preparation of this work, I made use of AI tools such as ChatGPT and Claude to improve readability and work more efficiently. The AI tools were used to translate words and phrases to English, rewrite sentences to a more academic style, and check for spelling and grammar mistakes. In addition, they were used to generate layout code for graphs in MATLAB, improve a self-drawn image (Figures 3.1 and 4.6), automate repetitive table entries such as dates, and transcribe formulas from paper to $\text{\LaTeX}$. In all these cases, the results were checked and I, as the author, take full responsibility and accountability for the content of this work.

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Introduction

In 1960 the first working laser was demonstrated and since then, the technology has developed substantially [1]. Nowadays, it is used in multiple fields such as communication, remote sensing, weaponry, imaging, medical diagnostics and surgery, entertainment, space exploration, and many more [2]. This thesis focuses on the use of lasers in the field of communication, in particular laser satellite communication. The use of laser for this application has recently become a growing field because of the advantages compared to radio frequency (RF) communication. RF is facing growing challenges as demand for data transfer continues to rise in our data-driven world. With the RF spectrum being limited and becoming increasingly saturated, it may not be able to keep up with this growth. Laser communication could be part of the solution, providing higher data rates, greater security due to its low probability of interception, and lower power consumption [3]. Recent achievements in this field include NASA's successful laser link during the Artemis II mission in April 2026. During line of sight, it was possible to transmit high-definition video from the Orion spacecraft to Earth [4]. In the Netherlands, the first successful space to ground link took place in January 2025 by TNO and its partners, using a CubeSat-compatible laser terminal and the ground station in The Hague [5].

However, these achievements by NASA and TNO are only possible under certain weather conditions, since the state of the atmosphere plays a major role in how a laser beam propagates. As the beam interacts with atmospheric constituents, several forms of distortion can occur. The focus of this thesis is on one particular type of distortion: optical turbulence. The amount of optical turbulence is linked to fluctuations in the refractive index of air, and is generally described by C_n^2 . More detailed information can be found in the physical background (Chapter 2). Research has been conducted to measure and predict C_n^2 using various methods. In the literature review (Chapter 3), these existing methods are grouped and compared based on both qualitative and quantitative factors. The following methods are examined: Weather Research and Forecasting (WRF), starlight methods (in particular CO-SLIDAR), Light Detection and Ranging (LIDAR), scintillometers, balloon-borne instruments, sonic anemometers, and Radio Detection and Ranging (RADAR). From this literature review, one of the most important findings is a method that uses radar. This method works by receiving a backscattered echo from turbulent eddies during clear-sky conditions, also known as Bragg scattering. So far, this method has only been applied to a pulse-Doppler weather radar, and it has not yet been investigated whether other S-band radars, such as the PARSAX FMCW radar, are capable of measuring C_n^2 using a similar approach. This led to the following research question, which is addressed in this study: Is it possible to measure optical turbulence C_n^2 using reflectivity measured in the vertical direction by the S-band PARSAX radar?

First in Chapter 4, a feasibility study is performed using images of the radar data. The goal of the feasibility study is to find a first indication that signals due to Bragg scattering can be detected with a S-band radar and whether they could be relevant for retrieving C_n^2 . Another objective is to identify which unwanted signals are present in the radar return and how they could be separated from the Bragg scattering signals. In addition, the study investigates to what extent the measurements are performed within the inertial subrange. In the main research, the unwanted signals identified in the feasibility study are removed using numerical data processing. Several filters are applied, each specifically designed for a particular type of unwanted signal. After filtering, the reflectivity Z is translated into a value for C_n^2 and compared with scintillometer data for validation. Chapter 5 presents the complete methodology of the main research. The results are presented in Chapter 6, followed by the discussion in Chapter 7 and finally the conclusions and recommendations are given in Chapter 8.

Physical background

This chapter presents the relevant physical background. It begins with the role of the atmosphere in laser communication. The different atmospheric losses are introduced, and it is clarified in which conditions optical turbulence is a relevant loss and when it can be neglected. Furthermore, a more physical description of optical turbulence, including the Kolmogorov theory, inner and outer scales, and power spectrum is given. Finally, the effects on the laser link of optical turbulence and possible mitigation techniques are discussed.

2.1 Atmospheric effects on laser communication

The state of the atmosphere plays a major role in how a laser beam propagates. As the beam interacts with atmospheric constituents, several forms of distortion can occur. The most important ones for communication purposes are absorption, scattering, and optical turbulence. In this thesis, the focus is on the last. It is only relevant to study this loss if it has a relatively large effect compared to the other losses. Therefore, an overview is given of which loss is dominant under different weather conditions [2].

2.1.1 Absorption, scattering, and optical turbulence

Absorption

One of the losses due to the atmosphere is absorption. When a photon interacts with a gaseous molecule of the atmosphere, the energy of the photon is converted into the molecule's kinetic energy, thereby heating up the atmosphere. The extent of the interaction between the laser light and the atmosphere depends on the relative size of the wavelength and the atmospheric particles [6]. In this comparison the wavelength refers to the wavelength outside of the particle. In general, absorption is strongest when this outside wavelength is comparable to the size of the particles [7].

Scattering

A second loss that a laser beam can experience is scattering. This happens when the laser light interacts with the atmosphere and the light is forced to deviate from its initial trajectory. The light will propagate in different directions, and therefore usually less light will reach the receiver.

There are two main types of scattering that occur due to particles in the atmosphere: Rayleigh scattering and Mie scattering. Rayleigh scattering takes place when a

particle is much smaller than the outside wavelength of the laser and Mie scattering takes place when the particles and the outside wavelength are comparable in size [2].

Optical turbulence

The third effect that distorts the propagation of light in the atmosphere is optical turbulence. The amount of optical turbulence is linked to fluctuations in the index of refraction of the air. These fluctuations are primarily driven by thermal (heating) and mechanical (wind) processes in the atmosphere [6]. Because of this the amount of turbulence varies with, for example, location, altitude, and time of the day. For example, when the sun heats the surface of the earth the resulting convection causes large temperature variations and the optical turbulence usually becomes stronger. In contrast, in a stable windless atmosphere, the turbulence is typically much lower.

2.1.2 Kolmogorov turbulence theory

Structure function

C_n^2 indicates the strength of the turbulence, but it is not sufficient to fully describe optical turbulence. This is because turbulence effects also depend on spatial separation. To include this behaviour the structure function is used. Structure functions are closely related to covariance (and correlation) functions, as both describe variability between two points in a field. Structure functions are generally used in this field because covariance functions assume that the underlying process is stationary, which is often not the case for atmospheric parameters such as C_n^2 [6][8].

The refractive-index structure function $D_n(R)$ works by averaging the squared difference in refractive index n between two points separated by a distance R and is defined as

$$D_n(R) = \langle [n(0) - n(R)]^2 \rangle [2]. \quad (2.1)$$

Kolmogorov theory

The widely used Kolmogorov theory describes the relation between the refractive-index structure function $D_n(R)$ and the spatial separation R and is given by

$$D_n(R) = \langle [n(0) - n(R)]^2 \rangle = C_n^2 R^{2/3}, \quad l_0 \ll R \ll L_0. \quad (2.2)$$

It states that the structure function follows a $R^{2/3}$ relation and includes C_n^2 as the scalar measure of how turbulent the atmospheric flow is. In the 1940s, Kolmogorov introduced the foundation of this idea, and since then, a lot of investigation has built upon this [2].

Inner and outer scale

The $l_0 \ll R \ll L_0$ is known as the inertial (sub)range. The L_0 is the outer scale of turbulence and the l_0 is the inner scale of turbulence. An important limitation of the

Kolmogorov theory is that it is only valid in this inertial subrange. Determining the precise value of this inner and outer scale is challenging. As a result, the techniques used to identify the inertial subrange vary, and no unified approach exists[2].

Within the inertial subrange eddies are assumed to be statistically homogeneous, isotropic, and independent of large scale structures. Statistical homogeneity implies that the mean value of the field is constant and that correlations between random fluctuations depend only on the separation vector between two points, and not on their absolute location. That it is also statistically isotropic means that this correlation depends only on the magnitude of the separation vector[9].

Energy cascade theory

The energy cascade theory states that within the inertial subrange, large-scale unstable air masses break down into smaller eddies, with no loss of energy throughout the cascade. This cascade is visualized in Figure 2.3. At scale size larger than L_0 energy is injected into this cascade from atmospheric motion. At the other end of the cascade, at scale sizes smaller than l_0 , viscous effects become dominant and most of the energy is dissipated as heat. Therefore, this range below l_0 is known as the dissipation range. Most important is that above L_0 and below l_0 the Kolmogorov scaling does not apply any more [6].

Power spectrum

The power spectrum that follows from Kolmogorov's theory represents the distribution of energy over different scale sizes. To obtain this power spectrum, a conversion from the structure function to the (spatial) frequency domain needs to be made. This is a standard used Fourier conversion and can be applied to obtain either a one- or three-dimensional power spectrum. Following the 2/3 power law of the structure function, a corresponding one-dimensional power spectrum of refractive-index fluctuations is described by

$$E(\kappa) = C \varepsilon^{2/3} \kappa^{-5/3}, \quad 1/L_0 \ll \kappa \ll 1/l_0. \quad (2.3)$$

Here, C is a universal constant that has been experimentally found to have a value of approximately 1.5 [10]. Furthermore, ε is the turbulent kinetic energy dissipation rate with units of $\text{m}^2 \text{s}^{-3}$, and κ is the spatial wavenumber with units of m^{-1} , which characterizes the corresponding scale size. The most important element of this expression is the $-5/3$ power law of κ , as it represents the distribution over the scale sizes [6].

2.1.3 Dominant loss for laser wavelength

Absorption, scattering, and optical turbulence all contribute to loss on a laser link. These processes are not constant but they vary with wavelength, atmospheric conditions, and the time of the day. It is therefore important to identify which effects are dominant under given circumstances and which are small enough to be neglected, to understand turbulence in different scenarios.

Attenuation

The first two phenomena, absorption and scattering, will lead to attenuation, and can be described by Beer's law. This equation is a way to get a value for the transmittance τ of the atmosphere at wavelength λ . This is a unitless value and describes the fraction of light that passes through the medium. It is given by

$$\tau = \exp[-\alpha(\lambda) L], \quad (2.4)$$

[2]

where $\alpha(\lambda)$ represents the extinction coefficient, L the path length and the product $\alpha(\lambda) L$ the optical depth. As discussed in the section above, this $\alpha(\lambda)$ is highly dependent on wavelength.

Wavelength of the laser

To discuss the dominant losses, a constant wavelength is chosen. In general, typical laser wavelengths for free space optics are 850 and 1550 nm[6]. This is based on the losses that they experience but also on other factors such as eye safety and the availability and costs of related hardware. In severe fog and rainy conditions 850 and 1550 nm experience nearly identical attenuation effects[11]. In more moderate haze conditions, the 1550 nm wavelength performs better compared to 850 nm wavelength [12]. Because of this, the typical wavelength is 1550 nm in the field of laser and therefore this wavelength will be used to determine which losses are most dominant[13].

Attenuation at 1550 nm

If a wavelength of 1550 nm is considered, to what degree does it experience absorption and scattering in the atmosphere? Regarding absorption, the wavelength of 1550 nm lies within one of the atmospheric transmission windows, meaning that absorption by atmospheric constituents at this wavelength is minimal. Rayleigh scattering is not relevant for wavelengths above 1000 nm, so this effect can be neglected [14]. Mie scattering is also relatively small in clear sky conditions. However, this is not the case in the presence of hydrometeors such as fog, haze, rain, or snow. Under such conditions, the loss increases mainly due to Mie scattering and often becomes the dominant attenuation mechanism [7, 15].

2.1.4 Effect of different atmospheric conditions

Mie scattering in clear air, haze and fog

As discussed in the previous section, the amount of attenuation is highly dependent on the weather conditions [7]. A good representation of this dependency is given in Figure

2.1, where different weather categories are defined based on the atmospheric visibility range V . This range is the distance that a beam travels through the atmosphere until its intensity drops to 2% of its original value [16]. A relation that links this range to the amount of attenuation is given by

$$\sigma = \frac{3.91}{V} \left(\frac{\lambda}{550 \text{ nm}} \right)^{-q}, \quad (2.5)$$

where σ is the atmospheric attenuation coefficient, V is the visibility in kilometres, λ is the wavelength in nanometres, and q is the size-distribution parameter of the scattering particles. This latter is defined as

$$q(V) = \begin{cases} 1.6, & V > 50 \text{ km}, \\ 1.3, & 6 < V < 50 \text{ km}, \\ 0.585 V^{1/3}, & V < 6 \text{ km}, \end{cases}$$

based on the widely used model by Kim [16].

Table 2.1 and Figure 2.1 present the attenuation values under three weather conditions: clear air, haze, and fog. In the situation of clear air, the attenuation is relatively low [6]. As the weather worsens (haze), attenuation due to Mie scattering increases and the loss will be larger [15]. The worst weather for a laser beam is fog. In this case, attenuation is usually the dominant loss mechanism. This problem is so big that it even slowed the commercial deployment of near-ground laser communication [2].

Table 2.1: Attenuation and Visibility of clear air, Haze, and fog at 1550 nm

Atmospheric Condition	Visibility (km)	Attenuation (dB/km)
Clear air	10–50	0.4416 – 0.0647
Haze	1–10	10.12 – 0.4416
Fog	0–1	1698 – 10.12

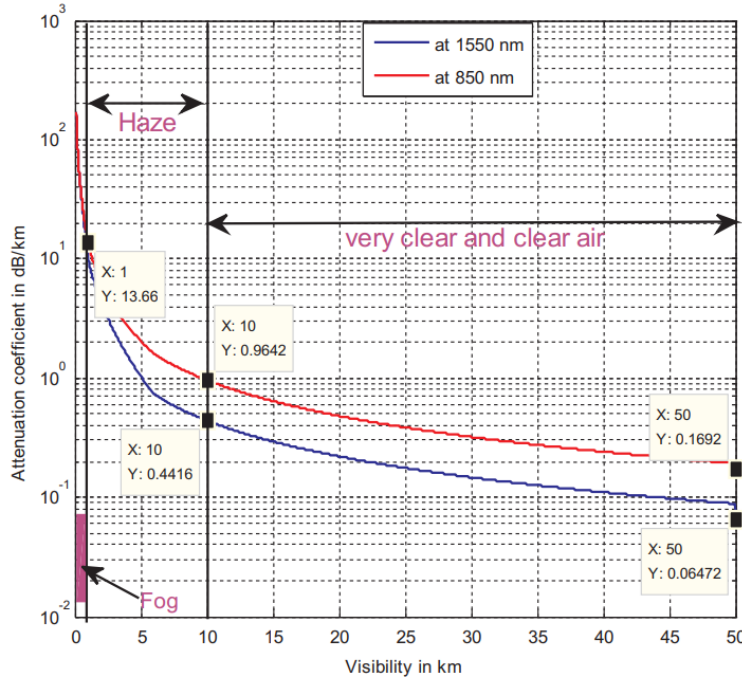


Figure 2.1: Attenuation coefficient in dB/km under different weather conditions [7]

Presence of atmospheric constituents and clouds

One note to this classification is that it is a simplification of the real atmospheric situation. In practice, there are rain, snow, hail, aerosols, and the presence of clouds. The term fog is sometimes used to refer to clouds, but this is an oversimplification. There is a large variety of clouds, with different heights and types, and they affect the signal differently. For example, water clouds attenuate the signal more than ice clouds [17], and for stratocumulus clouds affect the signal more than stratus or cumulus clouds [18]. Therefore, in real life conditions, a critical interpretation of the actual atmospheric state is required.

Relation to optical turbulence

In the previous section the focus was on losses other than the main topic of this thesis. The idea behind this is to have a reference whether turbulence is or is not negligible compared to attenuation losses. Ideally, it would be useful to predict how strong optical turbulence will be under different weather conditions, but this is not yet clearly described in the literature. However, one interesting result that is found is that attenuation and turbulence strength show an inverse correlation [19]. When attenuation due to Mie scattering decreases (clear-air conditions), the chance of experiencing stronger optical turbulence increases and vice versa. This underlines the importance of measuring optical turbulence mainly under clear-sky conditions. It also suggests that studying turbulence in non-clear sky conditions is less meaningful, since turbulence will not be the dominant loss mechanism in those cases.

2.2 Optical turbulence

In this section, the classification, spatial and temporal dependence of C_n^2 are discussed, followed by the effects of optical turbulence on the laser link and possible mitigation techniques.

2.2.1 Refractive index structure parameter C_n^2

Fluctuations in the refractive index are generally described by C_n^2 . Stronger turbulence generally leads to larger optical intensity fluctuations, commonly referred to as strong irradiance conditions. Conversely, weak atmospheric turbulence typically results in weaker irradiance fluctuations. It is considered the most critical parameter to characterize the effects of optical turbulence along the propagation path[2].

Classification of C_n^2

The higher the C_n^2 , the more turbulent the atmosphere. It is common to link a certain range of C_n^2 values to a specific turbulence level. However, this is not uniform in the literature. Different ranges are used, corresponding to different turbulence strengths. For example, Shah associates weak, moderate, and strong turbulence with representative C_n^2 values of approximately 1×10^{-17} , 6×10^{-14} , and $2 \times 10^{-13} \text{ m}^{-2/3}$, respectively [20]. Andrews and Phillips define weak turbulence as $C_n^2 \leq 10^{-17} \text{ m}^{-2/3}$ and strong turbulence as $C_n^2 \geq 10^{-13} \text{ m}^{-2/3}$ [6]. Furthermore, a more recent book by Andrews and Beason states that high values of C_n^2 (on the order of $10^{-12} \text{ m}^{-2/3}$) indicate a turbulent atmosphere, whereas low values (on the order of $10^{-16} \text{ m}^{-2/3}$) indicate weak turbulence [2]. Although the exact boundaries vary in the literature, the classifications are generally in the same order of magnitude, with weak turbulence occurring around 10^{-17} – 10^{-16} and strong turbulence above approximately $10^{-13} \text{ m}^{-2/3}$.

Spatial dependence of C_n^2

The refractive-index structure parameter C_n^2 varies in space due to atmospheric dynamics. This variability is large, however, some basic behaviour can still be identified. Along a horizontal propagation path over homogeneous terrain, C_n^2 is usually assumed to be constant [2]. For the vertical dependence, this assumption does not hold. Consequently, many models have been developed to describe the vertical profile of C_n^2 , each based on different assumptions and applicable to specific conditions [6].

One of the most widely used models is the empirical Hufnagel-Valley (H-V) model. This model is based on standard atmospheric profiles and assumes land-based, mid-latitude conditions. The vertical profile of this model is defined as

$$C_n^2(h) = 0.00594 \left(\frac{v}{27} \right)^2 \left(\frac{h}{10^5} \right)^{10} \exp\left(-\frac{h}{1000}\right) + 2.7 \times 10^{-16} \exp\left(-\frac{h}{1500}\right) + A \exp\left(-\frac{h}{100}\right), \quad (2.6)$$

where h is the altitude in meters, v is the wind speed at an altitude of 5 km in m/s, and A is the ground-level turbulence strength in $\text{m}^{-2/3}$. The most commonly used

variant is the H-V 5/7 model, which assumes $A = 1.7 \times 10^{-14} \text{ m}^{-2/3}$ and $v = 21 \text{ m/s}$ [2].

Temporal dependence of C_n^2

The refractive-index structure parameter C_n^2 also varies in time due to atmospheric dynamics. C_n^2 often shows a daily cycle. An example of measurements that show this typical cycle is presented in Fig. 2.2. During the day, when the sun heats the surface, the layer of air near the ground warms and rises. This rising air creates vertical mixing air in the atmosphere, which results in higher values of C_n^2 . During the night, this heating does not happen and usually less vertical movement takes place. This leads to lower C_n^2 values [2].

It should be noted that this typical daily cycle is not followed every day, as it depends strongly on factors such as wind, solar heating, and the length of the day. Because these factors change with the seasons, seasonal differences in C_n^2 can also be observed [21, 22]. For example, measurements over the South China Sea show that optical turbulence is strongest in summer, moderate in winter and autumn, and weakest in spring. It should be noted that these seasonal patterns may differ in other regions.

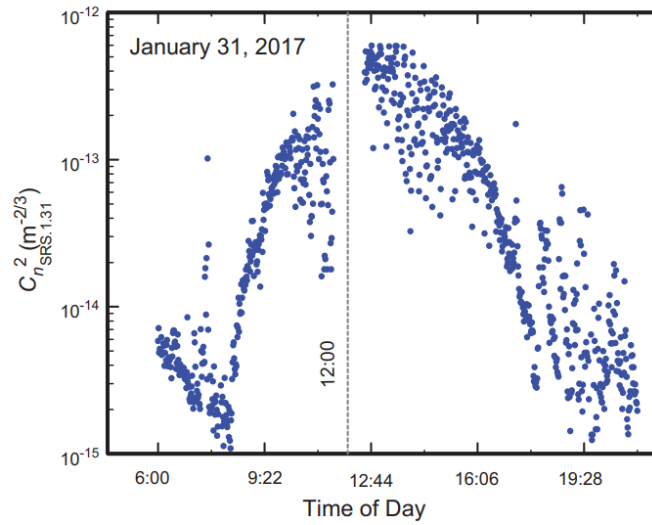


Figure 2.2: One-minute averaged measurements obtained with a scintillometer over 150 m distance at a height of 1.5 at meter Kennedy Space Center, Florida[2]

Three-dimensional power spectrum

Building on the one-dimensional power spectrum described in Equation 2.3, the related three-dimensional power spectrum $\Phi_n(\kappa)$ is described by [2]

$$\Phi_n(\kappa) = 0.033C_n^2\kappa^{-11/3}, \quad 1/L_0 \ll \kappa \ll 1/l_0. \quad (2.7)$$

This expression has a slightly different form than the one-dimensional variant because of the difference in dimensionality. In this three-dimensional power spectrum, the most important element is again the power law of κ , which is $-11/3$ in this case. For both expressions, the inertial range, in which the power spectrum is valid, is written in terms of κ using the relation $\kappa = 2\pi/R$. The energy cascade, inertial range, and the (three-dimensional) $-11/3$ power law are visualized in Figure 2.3.

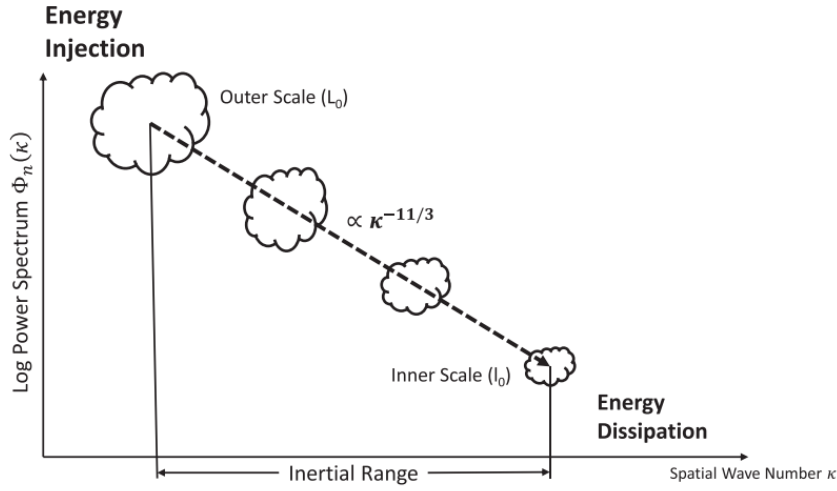


Figure 2.3: Kolmogorov theory: Cascade theory of the power spectrum [2]

2.3 Effects of optical turbulence on the laser link

2.3.1 beam wander, beam spread, scintillation, and AoA fluctuations

The main optical turbulence effects on a laser link are beam wander, beam spread, scintillation, and angle-of-arrival (AoA) fluctuations. The cause of these effects can be separated according to their dependence on the scale size of the turbulent eddies. Eddies that are large compared to the beam mainly cause refractive effects: the beam is bent and the wavefront phase is distorted, resulting in beam wander and angle-of-arrival fluctuations. Eddies that are smaller than the beam mainly cause diffractive effects and affect the beam through beam spreading and scintillation [2]. This is visualised in Figure 2.4

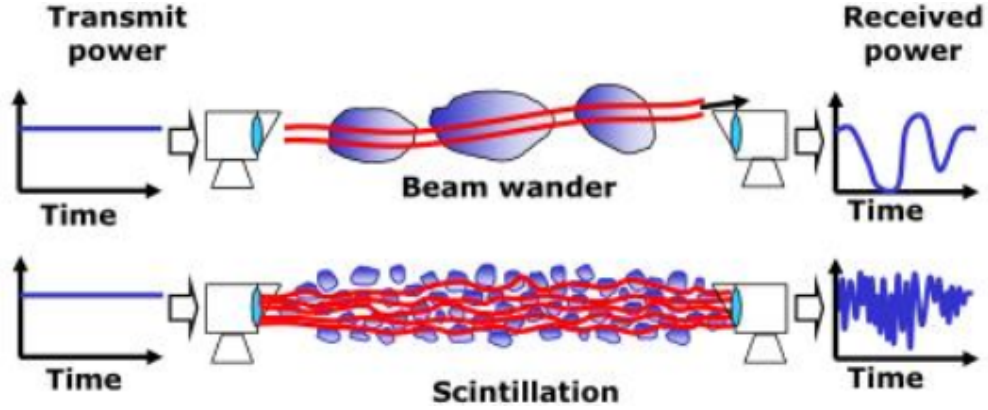


Figure 2.4: Illustration of beam wander due to relative big eddies and scintillation due to relative small eddies [23]

The four effects can also be classified based on where along the propagation path they mainly originate. Scintillation is caused by turbulence distributed along the entire propagation path. Beam spread and beam wander are most strongly influenced by turbulence near the transmitter, since distortions introduced at the start of the link have more distance to develop during propagation. Angle-of-arrival fluctuations are mainly influenced by turbulence close to the receiver. This is important to consider when using either a downlink or an uplink for satellite laser communication [2].

2.3.2 Laser satellite link budget

For laser satellite communication, turbulence over the whole vertical path is of interest. Therefore the Fried parameter r_0 is often used, which includes the path integral of $C_n^2(h)$ from Equation 2.6. With among others this parameter, the turbulence-related losses can be computed, for which more information can be found in [24]. The computed losses in dB are included in the laser link budget, to describe the effect on the performance of laser communication. The link budget can be made much more extensive including all of the effects, but for simplicity this simple form is given in Equation 2.8, where P_R is the received power, P_T is the transmitted power, G are the gains and L the losses [25]. The losses due to the atmosphere will be included in this last term.

$$P_R = P_T + G - L \quad (2.8)$$

2.3.3 Mitigation techniques

Furthermore, diversity techniques can be applied. Temporal, spatial, or wavelength diversity can all improve link performance [20, 26]. Another approach is the use of coding techniques, such as forward error correction and interleaving. Finally, aperture averaging can be used, which involves increasing the receiver aperture size [27]. All techniques have advantages and disadvantages in terms of performance, cost, size, and complexity. Several of them can also be used simultaneously. For some techniques, such

as spatial diversity, an understanding and prediction of optical turbulence is relevant. This, together with the fact that optical turbulence effect can never be fully corrected supports the relevance of studying methods to measure C_n^2 .

2.4 Conclusion

Altogether, the three main ways in which the atmosphere contributes to losses in the laser link are absorption, scattering, and optical turbulence. To what extent each effect plays a role varies with wavelength, atmospheric conditions, and time of day. During non-clear-sky conditions, absorption and scattering dominate the loss, and therefore studying optical turbulence is less meaningful in those cases. Optical turbulence is characterized by C_n^2 and is both time- and height-dependent. The Kolmogorov theory used in this study is only valid in the inertial subrange, and therefore it should be checked whether this is the case. Mitigation techniques exist to minimize the effect of optical turbulence, but they can never be fully corrected. All of this supports the relevance of studying methods to measure C_n^2 during clear-sky days.

Literature review on methods to obtain optical turbulence C_n^2

3

There exist many different ways to obtain C_n^2 . In this literature review, these different measurement methods for C_n^2 are compared based on the following comparison factors: spatial and temporal resolution, range, availability, costs, accuracy, (dis)advantages, assumptions and limitations. Since it is not possible to discuss every method, only the most relevant and most commonly used techniques are discussed. The following methods are examined: Weather Research and Forecasting (WRF), starlight methods (In particular CO-SLIDAR), Light Detection and Ranging (LIDAR), scintillometers, balloon-borne instruments, sonic anemometers, and Radio Detection and Ranging (RADAR). The methods are categorized into the following groups: numerical mesoscale models method, optical methods, in situ methods, and radar methods. For some methods, a representative method is selected to allow comparison. Furthermore, for some methods, not all factors are discussed. This is because certain factors are not applicable, not available, or not relevant. Finally, all of this is presented in a summary table. The goal of this review is to identify a research gap in the measurement of C_n^2 , that could provide new insights into the field. An extra condition applied to these is that the system should be available at TU Delft. A subgoal of this review is to identify which existing systems can be used for validation purposes.

3.1 Numerical mesoscale model method

3.1.1 Weather Research and Forecasting model

One of the methods that is currently used to obtain C_n^2 is through numerical mesoscale models. This modelling concept was introduced in the optics field in 1995 [28], and since then it has been studied worldwide, leading to the further development of optical turbulence modelling [29–32]. In the list of methods, this is an odd one, since it is the only method that does not directly measure C_n^2 . Although several mesoscale models exist, the Weather Research and Forecasting (WRF) model is considered here as a representative example.

In the WRF model, the smallest horizontal grid size is typically 1 km x 1 km [33]. The vertical resolution is determined by the number of layers and the thickness of each layer. It is common to use 30 to 60 vertical layers and to space them in a non-uniform way. The thickness of a vertical layer should be less than 100 m to capture clear-air turbulence [34]. Therefore, obtaining C_n^2 at high resolution typically requires the use of high-performance computing resources, making this method expensive.

For the time resolution, there are two ways to define this: the model time step and the time interval over which C_n^2 is output. The time step of the model can be varied, but a common guideline is time step (s) $\lesssim 6 \times dx$, where dx is the grid size in km [35]. The

C_n^2 output interval can also be adjusted, but is often set to 10 minutes [33, 36, 37].

Within these spatio-temporal settings, the accuracy that can be achieved depends, among other factors, on the quality of the input data used by WRF. WRF is driven by data such as ERA5, which is based on measurements from weather stations, ships, aircraft, satellites, and other sources around the world. Since these observations are not evenly distributed worldwide, the accuracy of the input data, and therefore of the WRF simulations, is also not uniform everywhere [38].

WRF uses different physics schemes during its simulations. These schemes are parameterizations and are based on assumptions and simplified representations of physical processes. These assumptions should be taken into account when interpreting the results.

An advantage of WRF is that it makes it possible to estimate C_n^2 at locations where local observations are not available, and that it provides a wide range of atmospheric variables describing the atmospheric state. A disadvantage of WRF is that it does not provide a direct way to obtain C_n^2 [33], that it has a high computational cost and that it has a relatively steep learning curve.

3.2 Optical methods

3.2.1 Starlight methods used in astronomy

In the field of astronomy, there are several methods to obtain the C_n^2 profile. One such method is Slope Detection and Ranging (SLODAR), which uses a double-star source and measures the cross-covariance of the slopes of the optical phase aberrations [39]. Another method is Scintillation Detection and Ranging (SLIDAR), which also uses starlight and analyzes scintillation patterns. A coupled method combining these two approaches is CO-SLIDAR [40]. Multi-Aperture Scintillation Sensor (MASS) is another starlight-based method, which measures the scintillation of a bright star through four apertures of different diameters. However, this method only provides the strength of the turbulence in specific altitude layers [41].

As a representative starlight-based method, CO-SLIDAR is considered. CO-SLIDAR combines the principles of SLODAR and SLIDAR and therefore generally provides performance that is comparable to, or better than, these individual methods. Since MASS does not provide a continuous C_n^2 profile, it is less suitable for comparison.

The vertical resolution of CO-SLIDAR is 600 m, and it can measure C_n^2 up to 17 km. The timescale at which C_n^2 is obtained is one minute. The accuracy of CO-SLIDAR is quantified using the root mean square error (RMSE) and is reported to be on the order of 10^{-16} to $10^{-18} \text{ m}^{-2/3}$ in numerical simulations when compared to a known reference profile [40].

However, major limitations for the wider application of these methods are that they can only operate under clear-sky nighttime conditions, require specialized and relatively expensive hardware, and depend on the availability and successful acquisition of a suitable star (in some cases a double star).

3.2.2 LIDAR

Light detection and ranging (LIDAR) is used to measure atmospheric turbulence [42–44]. This method is widely used to measure wind velocity and atmospheric turbulence profiles, for example in applications related to air traffic safety [45]. The use of LIDAR for measuring optical turbulence, remains limited. Two relevant methods have been identified in the literature and these are discussed.

LIDAR combined with microwave radiometer method

First of all, a doppler wind LIDAR can be combined with a microwave radiometer, where the LIDAR measures atmospheric wind velocities and the radiometer provides temperature and humidity profiles. By combining these measurements, the refractive-index structure parameter C_n^2 can be derived.

The vertical resolution is between 30 and 150 meter, depending on the altitude, and the results show a range up to a distance of 5 km. The temporal resolution is around 2 to 3 minutes. The accuracy of this method is obtained by comparing it to scintillometer measurements. The results showed a correlation coefficient of 0.81, a mean error of $8.18 \times 10^{-16} \text{ m}^{-2/3}$, and an RMSE of $1.27 \times 10^{-15} \text{ m}^{-2/3}$ [46].

An advantage of this system is that it can be used during both daytime and nighttime conditions. However, a limitation of the algorithm that retrieves C_n^2 is that it is not suitable when stratification is unstable, which is often the case during daytime. The method assumes Kolmogorov turbulence with a 2/3 power-law scaling, and it is further assumed that the contribution of humidity to refractive-index fluctuations can be neglected. Finally, the costs of this system can be considered as moderate [46].

LIDAR intensity fluctuations method

Another LIDAR-based approach to obtaining C_n^2 is based on analyzing intensity fluctuations in a returned LIDAR signal. These fluctuations, which arise from Mie-scattered light reflected from aerosols, can be used to obtain C_n^2 .

This method has a vertical spatial resolution of 37.5 meters, and can measure up to a distance of 2000 meters. It has a 10 Hz laser repetition rate and obtains C_n^2 over 10,000 pulses, so every 17 minutes. The results show consistent trend with the Hufnagel–Valley (HV) model, however no numerical accuracy is reported. The system used for this method is said to be small in size, easy to move and simple to use. However the system seems to be built for this specific research and not widely available. Limitations of the method are that it is strongly dependent on aerosol backscattering. When there are too little or too much aerosols, this method does not work properly. Another

limitation, is that it only showed result during the night. Furthermore, it assumes Kolmogorov turbulence and neglects humidity effects. Finally, an advantage that holds for all LIDAR methods, is that it measures optical turbulence in the optical part of the spectrum, so no or just a minor scale mismatch is present [47].

3.2.3 Scintillometer

It is one of the earliest methods used to measure optical turbulence [2, 48]. A scintillometer transmits a beam of light through the atmosphere, and a detector measures the resulting irradiance fluctuations. These fluctuations are recorded over a certain time period to determine the variance of the natural logarithm of the intensity $\sigma_{\ln I}^2$. Assuming Kolmogorov, this variance is then used to obtain time-averaged values of the refractive-index structure constant C_n^2 by using

$$C_n^2 = 1.12 \sigma_{\ln I}^2 D^{7/3} L^{-3}, \quad (3.1)$$

where D is the effective aperture diameter of the receiver in meters and L is the distance between transmitter and receiver in meters. Typical large-aperture scintillometers (LAS) include the Kipp & Zonen LAS MkII and the Scintec boundary-layer scintillometers (BLS900 and BLS2000) [49, 50]. The Scintec BLS instrument can measure over a path length up to 12 km. The LAS MkII up to 20 km, but has a default distance that is much shorter (890 m), because of saturation effects at longer distances. [49, 50]. The temporal resolution is of around minutes (10 min default), but can be adjusted to seconds or hours [50]. The costs and availability of a scintillometer can be considered as moderate.

An advantage of this method is that it provides a direct measurement of optical turbulence. Its main limitations are that only a path-averaged value of C_n^2 can be obtained and only on the location of the set up. A disadvantage is that the measurement requires a clear line of sight between the transmitter and receiver. On the other hand, the scintillometer has the advantage that it can measure 24 hours a day.

An important point to note is that the technical specifications of the LAS state that it can measure turbulence strengths in the range 10^{-17} to $10^{-11}, \text{m}^{-2/3}$, which fall in the strong turbulence range (see section 2.3) [50]. At the same time, the instrument assumes a log-normal distribution of irradiance fluctuations, which is only valid under weak turbulence conditions [2]. Due to this and saturation effects over higher path lengths, this method is less accurate under strong turbulence conditions and over long distances. Nevertheless, it is generally regarded as an accurate technique and is often used as a reference for validating other methods.

3.3 In-situ methods

3.3.1 Balloon borne instrument

Another method to obtain C_n^2 is to attach a measurement system to a balloon. One way is by using data from radiosondes. These are launched worldwide on a daily basis to measure relatively simple meteorological data [51]. A more accurate, but less widely available, way is to use more specific balloon-borne measurements, such as microthermal sensors. They are able to measure small and rapid temperature fluctuations, instead of only basic meteorological data. They have been used to measure optical turbulence for over 40 years and are often used as ground truth to validate other measurement methods [52–54].

These microthermal measurement balloons can achieve a vertical resolution of about 5 m and reach up to 30 km above ground level. The temporal resolution of the measurements is said to be poor [55]. Usually, these balloons only measure the temperature component of optical turbulence and thereby neglect the humidity component. The method assumes Kolmogorov theory. Each profile requires a new balloon, because of this, costs are quite high in terms of effort. The financial costs are hard to find and difficult to compare with other methods.

3.3.2 Sonic anemometer

A sonic anemometer is another instrument that can be used to measure optical turbulence. This instrument uses sound wave travel time between two transducers to gather temperature and wind data. It can also gather directional information by using multiple pairs of transducers arranged in a simple geometry. It measures samples at frequencies of 10 to 60 Hz and multiple samples are used to obtain C_n^2 , leading to a temporal resolution of C_n^2 of 10 to 30 minutes. It is ideal for quite accurate in situ continuous measurement however, it is limited by its location. The assumptions that are made using this method is that they assume Kolmogorov turbulence, and the humidity component is neglected. Advantages of a sonic anemometer is that it is easy to purchase, relative low in costs, and robust [56–58].

3.4 Radar methods

The final method discussed to measure optical turbulence is Radio Detection and Ranging, better known as radar. It works by receiving a backscattered echo from turbulent eddies during clear-sky conditions, also known as Bragg scattering. From the backscatter echo intensity η_b , it is possible to derive C_n^2 using the relation from Ottersten [59]:

$$\eta_b = \frac{0.38}{\lambda^{1/3}} C_n^2 \quad (3.2)$$

where λ is the radar wavelength. The radar is primarily sensitive to refractive-index irregularities at the $\lambda/2$ scale, so the type of radar determines the scale that is observed. Research has been carried out using radars from VHF to X-band, and across

this entire frequency range this relation has been applied [60–62].

The formula linking radar backscatter to C_n^2 has some assumptions that will be discussed. First of all it assumes Kolmogorov turbulence, meaning that the $\lambda/2$ scattering scale must lie within the inertial subrange, and that the turbulence is homogeneous and isotropic [63]. Furthermore, it assumes that all clear-air echoes result from Bragg scattering. In practice, the signal often also includes contributions from other troposcattering mechanisms which means that the classical relation is not always valid [64]. Finally, the $\lambda/2$ scale of X-band, and in some cases S-band, does not always fall within the inertial subrange.

3.4.1 VHF and X-band radar

This section discusses VHF and X-band radars, and why these are not the best options. VHF measures larger turbulent scales (on the order of meters) due to its long wavelength. Following the turbulence power spectrum (see Figure 2.3), there is more energy in these larger scales, so the echo signal is expected to be stronger, which is an advantage. However, these measurement systems are typically large phased-array antennas, and the spatial resolution is poorer.

At the other end of the radar spectrum, X-band and higher-frequency radars measure much smaller turbulent scales due to their shorter wavelengths, and can therefore achieve higher spatial resolution. However, following the turbulence power spectrum, there is less energy at these smaller scales, so the Bragg echo signal is expected to be weaker. Moreover, X-band (and higher frequencies) echoes are far more sensitive to backscattering from cloud droplets and insects, which makes it more difficult to isolate the pure Bragg signal [62].

These drawbacks of VHF and X-band (and higher) do not make them useless, but they do make them less ideal for measuring optical turbulence.

3.4.2 S-band radar

S-band lies between VHF and X-band and measures turbulent scales of several centimeters. Compared to VHF, S-band observes smaller turbulent scales, so the clear-air backscatter is weaker but the resolution is higher. Compared to X-band, S-band is much less sensitive to backscatter from cloud droplets and biological targets, making it more suitable for measuring mainly Bragg scattering under the right atmospheric conditions. In the following section, a specific method that uses these advantages of S-band to measure optical turbulence is discussed [65].

S-band Doppler weather radar method using NEXRAD

The representative method for S-band to obtain C_n^2 is from Fiorino and works by receiving Bragg-scattered echoes from a Doppler weather radar. The weather radar used in this method is the Next Generation Weather Radar System (NEXRAD WSR-88D), which is deployed across the United States. NEXRAD performs a full 360-degree

azimuthal scan in 5 to 10 minutes, during which it samples a large atmospheric volume on the order of 10^{15} m^3 [65]. Within such a scan, the radar bin sizes are not uniform but vary from bin to bin, with a minimum range spacing of about 250 m [65, 66]. An advantage of this method is that it uses operational weather radars, which are widely available and involve no additional cost since they are already in place. Results showed that this method can capture the overall trend of C_n^2 , which is validated using scintillometer data [61].

However, this method also has several disadvantages. First of all, the radar measures a three-dimensional volume, a conversion to a path-integrated value is required to be able to evaluate the turbulence along an optical link. This conversion is possible, but determining exactly which radar bins intersect the path is complex due to the varying bin geometry [67]. Second, when scanning at low elevation angles, ground clutter reduces the accuracy [61]. Third, the method is only available under clear-air conditions [65]. Fourth, there is a wavelength mismatch between radar and optical systems. However a correction for this problem exists [65]. Fifth, the radar measurements can be influenced by large outer-scale eddies. Again for this problem there exists a solution, which corrects reflectivity contributions from refractive-index gradients outside the inertial subrange [61, 65].

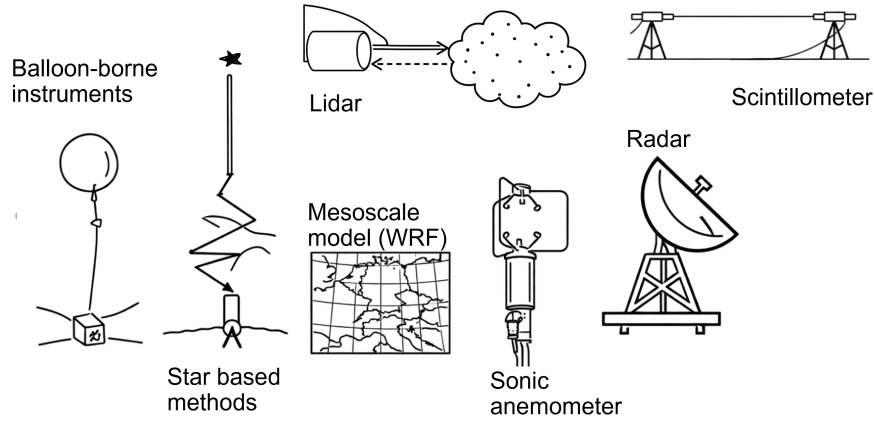


Figure 3.1: Illustrative overview of the methods to obtain C_n^2 discussed in this literature review

3.5 Conclusion

There is a variety of methods to obtain C_n^2 , of which the following are compared in this review: mesoscale models, starlight methods, LIDAR, scintillometers, balloon-borne instruments, sonic anemometer, and radar. An overview of the quantitative comparison factors is given in Table 3.1, and the more qualitative aspects are summarised in Table 3.2. From these tables, it becomes clear that no method performs ideally in every aspect. Some methods are expensive, others suffer from limited spatial or temporal resolution, and some are restricted in terms of availability or operating conditions.

Because of this, there is no “perfect” method; instead, they together form a pool of techniques, each suitable for different applications, and in some cases complementary to one another. This also highlights the value of developing new approaches, as they can contribute to and expand this pool.

The goal of this review is to identify a method of measuring C_n^2 that has not been previously investigated. From this literature review, the method used by Fiorino is especially relevant [65]. His work, in which an S-band radar is used to measure C_n^2 presents an opportunity to expand the pool of existing techniques. Fiorino’s work has so far only been applied to a pulse-Doppler weather radar, and it has not yet been investigated whether other S-band radars are capable of measuring C_n^2 using a similar approach. In addition to the relevance of continuously exploring new measurement techniques, this approach is particularly promising because it can measure a large atmospheric volume in the vertical direction. Moreover, it does not require additional costs when integrated into existing S-band radar systems, such as weather radars or military radars. Another advantage compared to the other instruments is that it could be used at a ship to measure optical turbulence above sea. Altogether, these advantages of using radar support the added value of addressing the literature gap in this study, which concerns the feasibility of using an S-band PARSAX radar to obtain C_n^2 . This leads to the following research question: Is it possible to measure optical turbulence C_n^2 using reflectivity measured in the vertical direction by the S-band PARSAX radar?

Finally, a sub-goal of this review was to identify which methods are suitable for validation. The results show that balloon-borne instruments and scintillometers are generally well suited for validation purposes. Other methods are not specifically intended for validation, but can still provide valuable information for comparison.

Table 3.1: Comparison table of methods to obtain C_n^2 with quantitative factors, with colours indicating good (green), moderate (orange), and poor (red) performance.

Method	Spatial resolution	Temporal resolution	Range	Availability	Cost
Mesoscale models (WRF)	1 x 1 km	≈ 10 min	∞	Open source	HPC
Starlight-based (CO-SLIDAR)	600 m	≈ 1 min	17 km	Limited	Financial
LiDAR (wind + MWR)	30–150 m	2–3 min	5 km	Research	Financial
LiDAR (Mie scintillation)	37.5 m	17 min	2 km	Research	Financial
Scintillometer	Path avg	≈ 10 min	20 km	Commercial	Financial
Balloon-borne instruments	5 m	Poor	30 km	Single use	Effort
Sonic anemometer	Point	10 - 30 min	Poor	Commercial	Low
Radar (NEXRAD)	> 250 m	5 - 10 min	10 ¹⁵ m ³	US only	Financial

Table 3.2: Comparison table of methods to obtain C_n^2 with a summary of the qualitative comparison factors.

Method	Accuracy, (dis)advantages, assumptions and limitations
Mesoscale models (WRF)	The accuracy depends on input data, such as ERA5. Assumptions are made in the physics schemes. A disadvantage is that C_n^2 is not measured directly, while an advantage is that the method can be applied worldwide.
Starlight-based methods (CO-SLIDAR)	The main limitation of this system is its low availability, caused by the requirement for suitable stars, the need for expensive and specialized hardware, and the fact that it only works during nighttime.
LiDAR (wind + MWR)	Shows a correlation of 0.81 when compared to scintillometer measurements. Operates mainly under nighttime conditions, and an advantage is the little to no scale mismatch with the laser wavelength.
LiDAR (Mie scintillation)	This system is small in size but not widely available. Limitations include dependence on aerosol concentration and that it only works during the night. An advantage is that it has little to no scale mismatch with the laser wavelength.
Scintillometer	Scintillometers provide direct, path-averaged measurements of C_n^2 at a single height during both day and nighttime. A limitation is that they require a clear line of sight. The accuracy is generally good, but degrades under strong turbulence and over long paths.
Balloon-borne instruments	These instruments can obtain spatially accurate C_n^2 profiles and are often used as ground truth. Its main limitation is that it is single-use.
Sonic anemometer	This method is ideal for accurate in situ continuous measurements, but it is limited by its location. Advantages are that it is easy to purchase, relatively low in cost, and robust.
Radar	This method has a wide range and is capable of capturing the overall trend. However, it does come with several disadvantages, such as ground clutter, wavelength mismatch and the fact that it can only be used under clear-sky conditions.

Feasibility study

The purpose of the feasibility study is to verify that Bragg scattering can be used to retrieve C_n^2 . A second goal is to find out which unwanted signals are present and what their characteristics are. The third goal is to verify to what extent the measurements are performed within the inertial subrange. The first part of this chapter presents the feasibility study methodology. The second part presents the observations, including limitations and support for the main research.

4.1 Radar image data and methodology

4.1.1 Radar image data

The PARSAX radar data are available in several forms. One of them is images, which are saved for multiple years. This is the type of radar data that will be used for the feasibility study. Approximately every two minutes an image is saved in which the reflectivity is shown up to 7500 meter with time on the x-axis and height on the y-axis. The reflectivity is available in both co-polarised and cross-polarised channels. The most relevant for this study is the co-polarised reflectivity (Z_{HH}). Here, HH stands for horizontal transmission and horizontal reception, meaning that the radar transmits a horizontally polarised signal and receives the reflected signal in the same horizontal polarisation.

4.1.2 Relation reflectivity Z and C_n^2

The method in this thesis to obtain C_n^2 with an S-band radar is based on the work of Fiorino [61], which is discussed in Chapter 2. It uses the intensity of the received Bragg-scattered echoes to compute C_n^2 . Bragg scattering occurs when the atmospheric refractive-index fluctuations have a characteristic scale of approximately half the radar wavelength. In that case, the scattered waves add constructively, producing an echo that is strong enough to be detected by the radar. The PARSAX radar has a wavelength of approximately 9 cm and is therefore sensitive to structures with a size of around 4.5 cm. This is visualised in Figure 4.1, where d represents the structure size (4.5 cm) and λ the radar wavelength. For the feasibility study, the focus is on the relationship between reflectivity (dBZ) and C_n^2 , including a term that accounts for wavelength dependency. The complete relationship is discussed in the main research.

$$C_n^2(h, t) \propto 10^{\left(\frac{\text{dBZ}(h, t)}{10}\right)} \cdot \lambda^{-11/3}$$

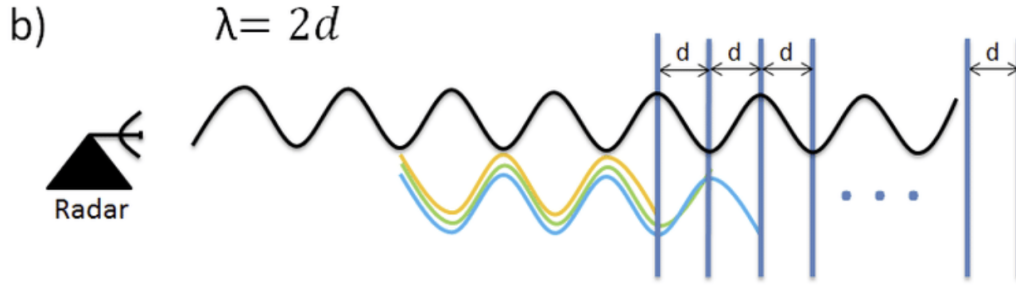


Figure 4.1: Simplified visualisation of Bragg scattering, where atmospheric structures with a scale of $\lambda/2$ cause backscattered waves that add constructively [68]

Select clear-sky days

The goal is to find Bragg scattering and not precipitation. Therefore, the first step is to select clear sky days. Ten days will be selected. The selection of these days is done using hourly observations from the weather institute KNMI. The measurement location closest to Delft is Rotterdam Airport. A dataset containing hourly cloud cover, expressed on a scale from 0 to 8 is used, in which 0 is no cloud cover, and 8 is maximum cloud cover. Five days with the least cloud cover in winter and five days with the least cloud cover in summer are selected. To double-check the amount of cloud cover, photos taken from the EWI building are combined into a film covering the entire day. These films show mostly blue skies, with short periods of clouds on some days.

Cluster the images

The radar images will be clustered to observe different types of radar reflectivity and their daily behaviour. In this way, it may be possible to identify groups of images that are characteristic of Bragg scattering. One day contains approximately 624 images, so the total number of images for all ten days is approximately 6240. Clustering them manually would be very time-consuming and potentially biased. A more efficient and reproducible approach is to use a clustering algorithm. This is done using the torchvision and scikit-learn libraries in Python and consists of the following steps:

1. Load all HH reflectivity images of the ten selected clear-sky days.
2. Crop the images using the following fractions:
 - The top 45% is excluded
 - The bottom 6.5% is excluded
 - 10% is excluded on both sides

This is done so that only the relevant data (up to 4 km out of 7.5 km in height) is included and so that the colorbar and axes are removed.

3. A pretrained Convolutional Neural Network (CNN) model, ResNet18, is used. Such a CNN is trained on more than one million images and can extract important features from images. The model is used to convert each radar image into a feature vector containing 512 features.
4. Next, Principal Component Analysis (PCA) is applied which reduces the 512 features to 50 variables. These 50 new variables are formed as a linear combination of the original variables which capture the maximum variance in the dataset.
5. Each image has a location in a 50-dimensional space. The further images are from each other, the more they differ, and vice versa. Clustering of all images is performed using Euclidean distance in this higher-dimensional space. The number of clusters can be varied until it provides the best description of the radar data. Finally, images within the same cluster are relatively close to each other and therefore look relatively similar.
6. Each image in a cluster is stored in a separate folder.
7. Create a histogram per cluster to determine the times of the day the images occur.

4.1.3 Characterising noise in radar image data

The second part of the feasibility study is the characterisation of disturbances and noise. This will be done with the help of subject matter experts that work at the radar department at the TU Delft. This approach is used because they are experienced in the by-eye inspection and characterisation of features present in the images. For detection, FlightRadar¹ will be used to be able to confirm the presence of an airplane.

4.1.4 Validation of inertial subrange assumption

For the reliability of an S-band radar measurement, it is important to verify to what extent the measurements are performed within the inertial subrange. The PARSAX radar operates at a frequency of 3.315 GHz, which corresponds to a wavelength of approximately 9 cm. The structure size that can be observed is on the order of half the wavelength, so in this case approximately 4.5 cm. To determine if this lies within the inertial subrange, this last part of the feasibility study investigates the boundaries of the inertial subrange.

Inner scale

The inner scale defines the lower limit of the inertial subrange. Near the ground it is typically of the order of a few millimeters (2–10 mm) and can increase to several centimeters with altitude. A generally accepted vertical profile of the inner scale is, however, not yet available [2]. Measurements that are considered representative of

¹<https://www.flightradar24.com>

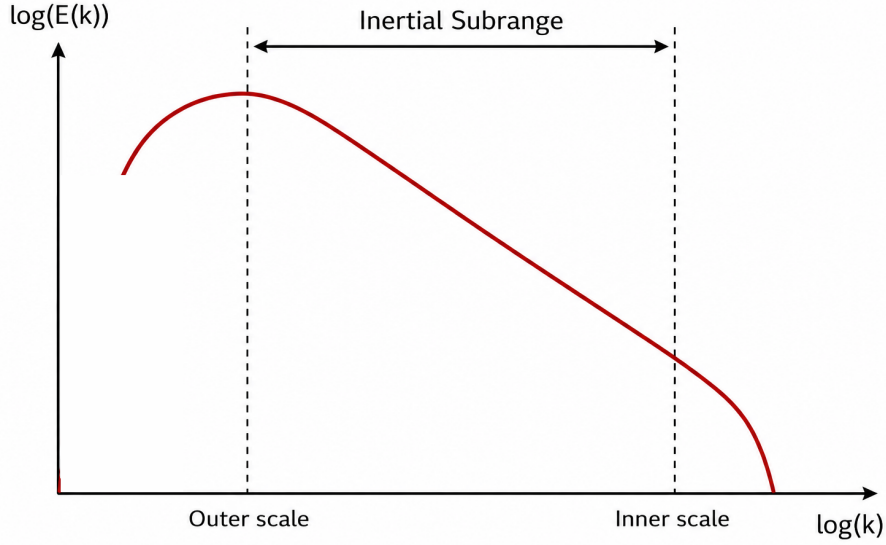


Figure 4.2: Visualisation of the outer and inner scale of the inertial subrange

near-ground atmospheric conditions confirm this scale size [69]. A paper that provides numerical values for the height dependence states that the inner scale has a value of about 1 cm at 5 km altitude and about 7 cm at 20 km altitude [70]. From this it can be concluded that in the lower atmosphere the PARSAX scale size is larger than the inner scale, but that caution is required at higher altitudes, where the scale that PARSAX observes may approach the inner scale boundary.

Outer scale

The second limit that is considered is the outer scale L_0 . It is not a constant value, and it should be interpreted in order of magnitude [71]. The value varies based on location and atmospheric conditions. Atmospheric stability and wind conditions can influence the size of turbulent eddies and therefore the outer scale. Vertical motion is suppressed by stratification and gravity, while wind shear can deform eddies. As a result, there is no universal value for the outer scale. Although these factors influence the outer scale, height-dependent profiles provide a reasonable indication of the order of magnitude in which the outer scale typically lies. Three examples of height-dependent profiles are presented to estimate the order of magnitude of the outer scale.

The simplest guideline that is often used is that the outer scale is proportional to height, with $L_0 \approx 0.4h$ [2]. In addition, more detailed profile models exist in which the outer scale is treated differently in the atmospheric boundary layer and in the free atmosphere. For the boundary layer, an empirically determined profile is used that is specifically valid for altitudes below 1000 m, with a vertical resolution of 25 m. This profile is based on radiosonde and thermosonde measurements conducted at several

astronomical sites and represents an average value. The empirically derived profile is valid up to a height of 1000 m and is given by

$$L_0(z) = 3.21 z^{-0.11},$$

where z is the altitude in meters [70]. For the free atmosphere, the Coulman fit provides a simple model for the outer scale as a function of height,

$$L_0(z) = \frac{4}{1 + \left(\frac{z-8500}{2500}\right)^2},$$

where z is the altitude in meters. This model is valid for the range 2000 to 17000 meters. It is not universal, as it is an older fit based on SCIDAR and radiosonde observations from only two locations, namely France (the Observatoire de Haute-Provence) and Texas (McDonald Observatory). The shape of this profile shows a clear peak around an altitude of approximately 9000 meter. However, it has been shown that both the shape and the order of magnitude of this height profile are comparable to later profiles measured at other mid-latitude locations. Since the PARSAX radar is also located at mid-latitudes, this model is considered suitable for providing insight into the order of magnitude of the outer scale [72]. In Figure 4.3, the detailed outer-scale profiles are presented. Whether the S-band radar falls within this inertial subrange is discussed in the next section.

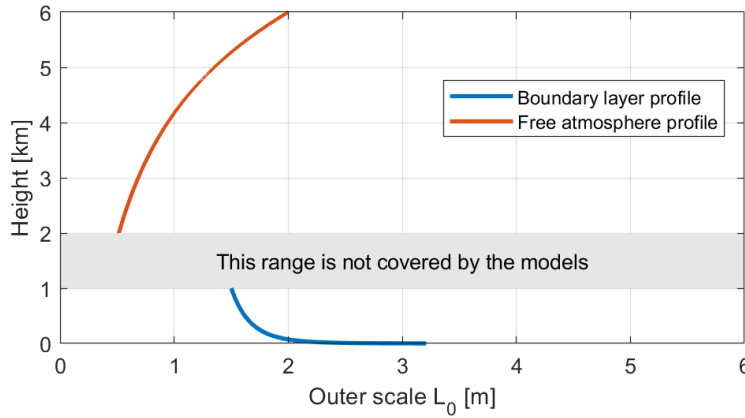
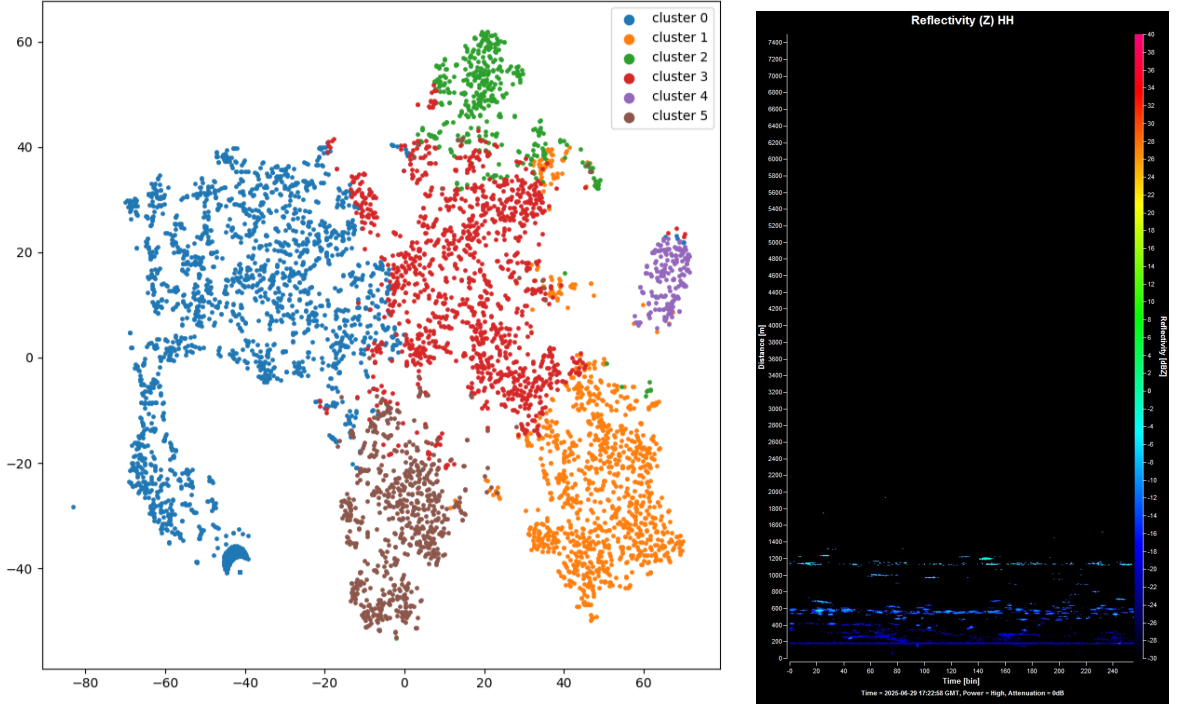


Figure 4.3: The profile of the empirically determined boundary-layer profile up to 1000 meters, then a region that both models do not describe, and above 2000 meters the Coulman free-atmosphere profile.

4.2 Observations

4.2.1 Observations of feasibility study

First of all, the observations of the clustered clear sky days radar image data will be discussed. The clustering model revealed several groups of images.



(a) High-dimensional clustering of radar image data visualised in a two-dimensional space

(b) An example of an image from cluster 1, with time on the x-axis (2 minutes) and range on the y-axis (7500 meters)

Figure 4.4: Clustering a total of approximately 6240 images out of 5 summer and 5 winter day images, and an example of a image that appeared in cluster 1

One of the clusters (cluster 1) contained approximately 1,000 images that look similar to Figure 4.4b. The images show reflections during a clear sky day, which suggests the presence of Bragg scattering. However, they can also include other types of reflection, such as the deterministic lines at 200 m, 600 m, and 1200 m. Most of the images in this cluster originate from the three summer days among the ten clear-sky days. These images show a clear daily cycle when plotted as a histogram. This daily cycle is comparable to the typical daily cycle of C_n^2 from literature (Figure 2.2) In Figure 4.5, the histogram is visualised. This similarity in daily behaviour suggests that the images in this cluster may be related to variations in C_n^2 . These first observations indicates that using the PARSAX radar data for estimating C_n^2 may be promising.

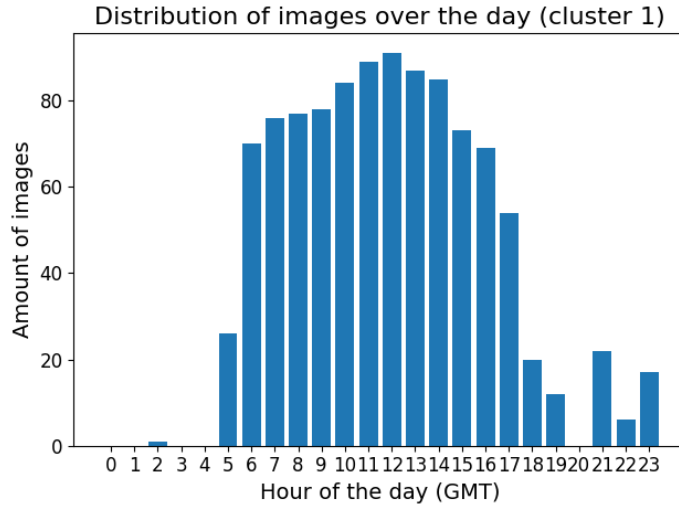


Figure 4.5: Feasibility study observation show a daily cycle of images in cluster 1 similar to the daily cycle of optical turbulence

The second goal of the feasibility study is to characterise noise and disturbance in radar image data. The following type of noise are characterised: rain, clouds, interference, noise floor that is not correctly compensated, birds and planes. The results from this is visualized in appendix A. The other clusters show images that are either fully black or contain these types of noise.

The third goal of the feasibility study is to verify to what extent the measurements are performed within the inertial subrange. All three height profiles indicate an outer scale on the order of meters or larger. An exception occurs at very low altitudes (on the order of centimeters above the ground), but since a radar system is never located directly at ground level, this can be neglected. This implies that the observable scale of 4.5 cm lies well within the inertial subrange. This is also concluded by Chilson, when he measures Bragg scattering with an S-band radar [73].

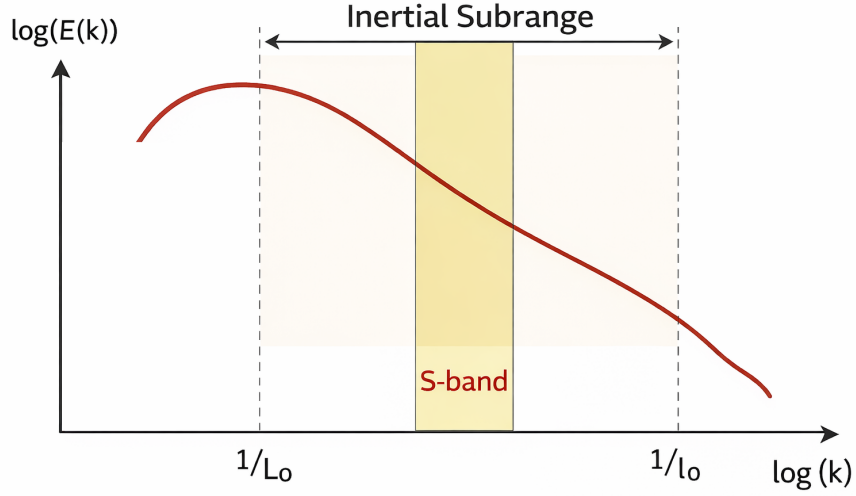


Figure 4.6: S-band lies within the inertial subrange

4.3 Conclusion

This feasibility study analysed radar image data from five clear-sky days, both in winter and in summer. One cluster, which showed reflections during clear sky days and similarities in daily behaviour with optical turbulence, suggests that the images in this cluster may be related to variations in C_n^2 . However, noise was observed in the radar data, making clear that signal processing is needed to filter these contributions out in order to isolate the reflectivity Z caused by Bragg scattering. Furthermore, this feasibility study confirmed that the measurements are performed within the inertial subrange. Altogether, these findings provide sufficient support that further research is valuable, in which numerical data is used so that noise can be filtered. Therefore, this will be carried out in the main part of the research.

Radar system and method

This chapter introduces the radar system used in this study and the applied method. First, the radar and its specifications are described. Next, the filtering steps for different kinds of noise, as characterised in the feasibility study, are discussed. The filtered data is then translated into a value for C_n^2 . Finally, the method for evaluating C_n^2 in relation to the validation data is presented.

5.1 Radar System

This section covers the main system used in this thesis: the PARSAX radar. The type of data, waveform, and the differences compared to the NEXRAD radar will be discussed. The latter is of particular relevance, as the method used is based on an approach developed for the NEXRAD radar[61]. The impact of these differences is examined to determine to what extent this processing method used can be applied to the PARSAX radar.

5.1.1 PARSAX radar specifications

PARSAX radar

The Polarimetric Agile Radar in S- and X-band (PARSAX) is the instrument used in this thesis. It is located in Delft, The Netherlands on top of the 92 m high building of the Faculty of Electrical Engineering, Mathematics and Computer Science (EWI). It is a programmable radar developed by the Microwave Sensing, Signals and Systems (MS3) group. As the name suggests, it is a polarimetric radar. It can simultaneously transmit two orthogonal signals via two orthogonal polarization channels. Moreover, it is a Doppler–polarimetric radar, meaning that in addition to dual polarization, Doppler information is combined, which improves the characterization of targets and is beneficial for target identification[74]. The radar can operate in S-band and X-band, however for this thesis, it is used in S-band configuration. This is the frequency band that the radar has operated in during the past few years, so more data is available. In addition, the X-band is more sensitive to backscatter from cloud droplets, which is considered as noise.

Available PARSAX radar data

The PARSAX data made available for this thesis comes in different forms: raw data, numerical data, and images. These differ in data volume, accuracy, and availability, see Table 5.1. Understanding the backscattered reflections is done in the feasibility study

using the images, because this makes it possible to analyse more days due to the lower data volume. Filtering and obtaining a value for the path-averaged radar reflectivity is done using numerical (netCDF) data because this is more accurate.

Data	Data volume	Accuracy	Availability
Raw data	very high	High	Not stored
numerical	Medium	Medium	Available
images	Low	Low	Available

Table 5.1: Overview of PARSAX data

FMCW radar

The PARSAX radar is a Frequency-Modulated Continuous-Wave (FMCW) Radar. It works by transmitting a continuous wave modulated in frequency by a repetitive linear frequency sweep. The frequency over which it does a sweep is B_{sweep} , and the time that it takes to do transmit this whole sweep is the sweep time T_s . The transmitted radar signal is reflected by the target and is received by the radar antenna. The time that it takes to propagate to the target and back (Δt), results in a frequency beat difference f_b , with this the range can be calculated using

$$R = \frac{c T_s f_b}{2 B_{\text{sweep}}}.$$

where R is the target range, c is the speed of light, T_s is the sweep time and f_b is the beat frequency. A moving target causes a Doppler shift, which results in a phase change over time. This can be extracted by observing the phase shifts over multiple pulses. In the case of the PARSAX radar, the sweep time is usually set to 1 ms and typically 512 sweeps are used to extract the Doppler information. Consequently, Doppler information is obtained every 512 ms. This process is called slow-time Doppler processing [74].

PARSAX waveform

A FMCW radar can use different type of waveforms. For this study the most important is the standard waveform used by PARSAX, which is the Linear Frequency Modulated (LFM) waveform. If the frequency change has a positive slope, it is known as an up-chirp which is visualised in Figure 5.1. A negative slope is also possible, then it is called a down-chirp. The PARSAX uses the up-chirp for the horizontally polarised channel and the down-chirp for the vertically polarised channel. These two are used simultaneously, which is possible due to the waveform orthogonality [75].

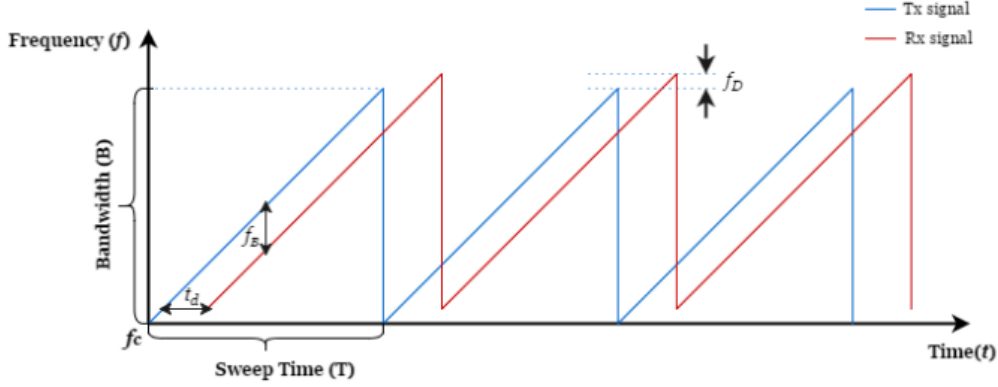


Figure 5.1: This graph shows the waveform of a Linear Frequency Modulated (LFM) signal, with time on the x-axis and frequency on the y-axis. The red line represents the transmitted signal, while the blue line represents the received signal. The delay between the two signals corresponds to the range of the target that caused the echo[76].

Near field to far field transition

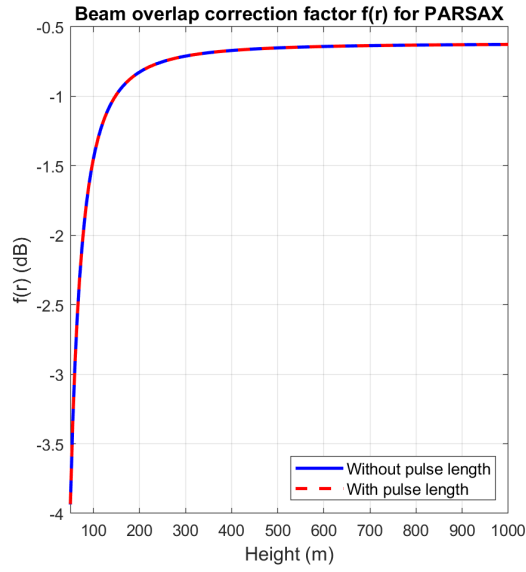
The total electromagnetic field of an antenna can be divided into a near-field and a far-field region. The radar equation, which is used in the computation of the radar reflectivity Z , is only valid in the far field. The boundary between these regions can be approximated by

$$d_2 = \frac{2a^2}{\lambda},$$

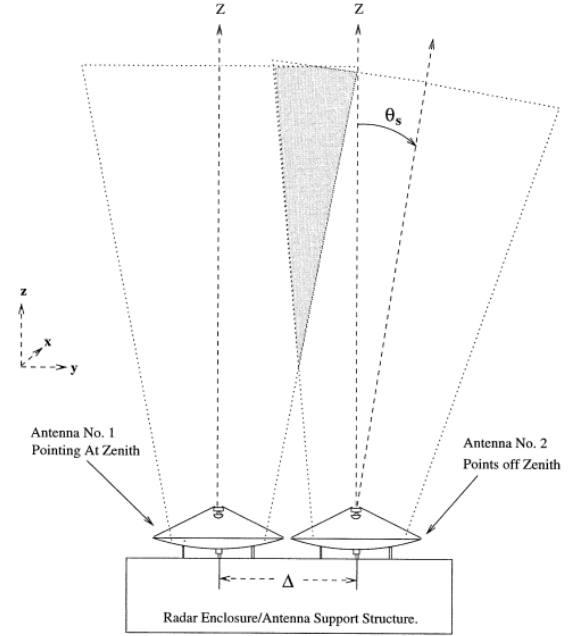
where a is the largest linear dimension of the antenna in meters and λ is the wavelength in meters [77]. For PARSAX, the largest dimension is the diameter of the transmitter, which is 4.28 m. The wavelength of PARSAX is $\lambda = 0.09$ m. Therefore, the theoretical near-field boundary is approximately 405 m. It is important to note that this boundary is only an approximate indication of the transition between the near-field and far-field regions rather than a precise cut-off [78]. Due to this, the data measured below the boundary is not directly useless.

Parallax error

For a radar, such as the PARSAX, where the transmitter and receiver are physically separated, the beams do not fully overlap, which results in a parallax error. To account for this, a range-dependent correction can be applied, which mainly affects the reflectivity close to the antenna [79]. The correction factor $f(r)$ as a function of the height can be seen in Figure 5.2. This correction assumes perfect alignment and an antenna separation of $D = 3.2$ m.



(a) Beam overlap correction factor $f(r)$ as a function of height, assuming an antenna separation of $D = 3.2$ m and perfect alignment. Results are shown both with and without the pulse length simplification.



(b) Visualisation of transmitter and receiver beam that have beams that do not overlap up to a certain height [79]

Figure 5.2: Parallax error

5.1.2 Comparison of PARSAX and NEXRAD radar

Figure 5.3 shows the two radar systems, and the table presents a comparison between the NEXRAD and PARSAX radar systems. The most important differences are radar type, power, and scanning mode. The impact of these differences will be discussed.



(a) PARSAX radar.



(b) NEXRAD radar.

Figure 5.3: Picture of the PARSAX and NEXRAD radar

Table 5.2: Comparison of NEXRAD WSR-88D and PARSAX radars.

Parameter	NEXRAD WSR-88D [80]	PARSAX [74]
Frequency band	S-band	S-band
Radar type	Pulse-Doppler	FMCW
Antenna diameter	$D_t = D_r = 8.5$ m	$D_t = 4.28$ m, $D_r = 2.12$ m
Beamwidth	1°	$T = 1.8^\circ$, $R = 4.6^\circ$
Peak power	750 kW	400 W (100 W per channel)
Average power	1.56 kW	400 W (100 W per channel)
Bandwidth	0.795 MHz	2–50 MHz
Pulsewidth	$1.57 \mu\text{s}$ and $4.57 \mu\text{s}$	0.655 ms–10.48 ms
Range resolution	250 m [65]	75–3 m
Elevation angle	-1° to $+60^\circ$ ($\lesssim 20^\circ$ operational)	No fixed limit
Scanning (default)	Continuous azimuthal rotation	Vertical (static)

Note: The NEXRAD system was upgraded between 2010 and 2013 to include dual-polarisation capability.

The data used by Fiorino were obtained prior to this upgrade [81].

First of all, regarding radar type, NEXRAD is a pulsed Doppler (PD) radar, while PARSAX is a frequency-modulated continuous-wave (FMCW) radar. Both systems can measure the range and velocity of a target. The PD radar transmits short bursts at a single frequency, while FMCW radar transmits and receives continuously at the same time and uses a frequency sweep. Due to this sweep, the FMCW radar has a larger bandwidth. Since a larger bandwidth can achieve a higher resolution, FMCW radar is better suited for high-resolution applications [82]. On the other hand, FMCW radar transmits continuously and therefore operates at a lower transmit power compared to PD radar. As a result, it is generally less suitable for applications at long ranges [82].

Besides this, another important difference is the default scanning mode. The NEXRAD radar has a continuous azimuthal rotation, with an elevation angle between 1 and 60 degrees. PARSAX has the possibility to rotate, but usually operates in a vertical static mode [74]. This has the advantage of providing continuous data in one vertical volume instead of non-continuous rotational data. Furthermore, it is almost unaffected by ground clutter, which is one of the main limitations when using the NEXRAD radar. One of the conclusions of Fiorino et al. (2011) is that a higher elevation angles improves the results. This improvement is possible when using the PARSAX radar [61].

The impact of the difference in radar type is expected to not be a problem. Multiple papers support that an S-band FMCW radar, measuring in the vertical direction, can still observe Bragg scattering [83–85]. All three papers use a FMCW S-band radar and relate this Bragg scattering to the refractive index structure function parameter, C_n^2 . By doing this, all three refer to equation (Eq. 5.3), which is also used by Fiorino et al. [59].

5.2 Radar Data Model

Received power to reflectivity Z

In the PARSAX numerical data, the primary products obtained for every radar bin are reflectivity Z , mean Doppler velocity V , and Doppler spectrum width W . Each of these consists of four signal values due to the four polarization channels. For example, for reflectivity: Z_{HH} , Z_{HV} , Z_{VH} , and Z_{VV} , where Z_{HV} represents horizontal transmission and vertical reception [74].

The reflectivity Z is only valid in the far field, and is computed as follows:

$$Z(r) = \frac{P_{r,\text{atm}}(r)}{P_t} \cdot \frac{512 \ln 2 \lambda^2}{\pi^3 G_t G_r G_{\text{rec}} \theta_t \theta_r |K|^2} \cdot \frac{2\Delta f}{c} \cdot L_{\text{atm}}^2 r^2 10^{18}$$

Here, G_t and G_r are the gains of the transmitting and receiving antennas, with values of 40 dB and 32.75 dB, respectively. θ_t and θ_r are the half-power beamwidths of the transmitting and receiving antennas, with values of 1.8° and 4.6° , respectively. Δf is the frequency excursion (50 MHz), and λ is the central wavelength (0.09 m). L_{atm} is the one-way atmospheric attenuation, which is set to 1. P_t is the transmit power (100 W per channel), and G_{rec} is the gain of the receiver chain, which is assumed to be equal to 1. The factor 10^{18} is included to express the reflectivity in units of $\frac{\text{mm}^6}{\text{m}^3}$. The term $2 \ln 2$ originates from the Probert-Jones correction, which accounts for the fact that the antenna does not have identical gain in all directions. This correction assumes a Gaussian antenna pattern. The factor 512 corresponds to the number of sweeps used to obtain one reflectivity value. The parameter $|K|^2$ is the dielectric factor of the scatterer, which is set to 0.93, corresponding to water. This value is not used because water is necessarily the scattering particle, but as a reference. This leads to the concept of equivalent reflectivity. In this convention, a cloud at 273 K containing one million droplets of $100 \mu\text{m}$ per cubic meter corresponds to a reflectivity of 0 dBZ, which explains the unusual unit $\frac{\text{mm}^6}{\text{m}^3}$. This formula can be simplified by introducing a calibration constant C , which contains all fixed radar parameters:

$$Z(r) = C \cdot \frac{P_r}{P_t} \cdot r^2$$

Corrections for reflectivity Z

Next, a calibration is applied by comparing the theoretical noise reflectivity with the measured noise. The calibration factor is range dependent:

$$Z_{\text{off}}(r) = \frac{Z_{\text{noise}}(r)}{P_{\text{noise}}(r)}$$

For PARSAX, specific time slots (between four and eight times a day) are used to estimate the noise. This represents the noise floor, which is subtracted from the measured power. The result is then multiplied by Z_{off} to obtain the final reflectivity:

$$Z(r) = Z_{\text{off}}(r) (P_r(r) - P_{\text{noise}}(r))$$

When measuring reflectivity over distance, the radar resolution volume increases with range. To account for this, a correction is applied, which is included in the formulation of $Z(r)$.

$$V = \frac{\pi}{4} r^2 \theta_t \theta_r \frac{c}{2B}$$

Another effect is that when measuring reflectivity over distance, the signal strength decreases with range due to geometric spreading. To account for this, a correction of r^4 is applied. At the same time, the resolution volume as discussed above gives a factor of $1/r^2$. Because the range r appears in both effects, the final formulation of $Z(r)$ contains a factor of r^2 . Due to these corrections, the reflectivity Z is, as much as possible, corrected for noise, bin size, and distance.

5.2.1 Numerical radar data variables

Besides the reflectivity Z , there are two more radar data variables for each bin: mean Doppler V and doppler spectrum width W . This is obtained from the Doppler power spectrum of which an example can be seen in Figure 5.4[74].

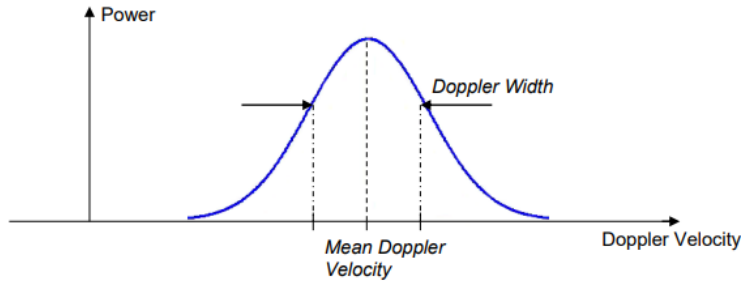


Figure 5.4: Example of a Doppler power spectrum with Doppler velocity on the x-axis and power on the y-axis[74].

For each range cell, a Doppler Fast Fourier Transformation (FFT) is performed, resulting in the Doppler power spectrum. This spectrum represents the amount of power at each Doppler frequency. Unlike what is shown in Figure 5.4, this spectrum is discrete and consists of L bins (typically $L = 512$). Each Doppler bin has a value for the power m_i at that bin, and a corresponding velocity v_i , which is the Doppler velocity associated with that frequency.

Using these values, the full spectrum can be reduced to three moments, which reduces the amount of data required for storage. The 0th moment represents the reflectivity Z .

The 1st moment m_1 of the Doppler power spectrum is the mean doppler velocity V and can be computed using:

$$m_1 = \langle v \rangle = \frac{\sum_{i=1}^L m_i v_i}{\sum_{i=1}^L m_i} = \frac{\sum_{i=1}^L m_i v_i}{m_0} = V$$

The 2nd moment m_2 of the Doppler power spectrum is the Doppler spectral width W and can be computed using:

$$m_2 = \sqrt{\frac{\sum_{i=1}^L m_i (v_i - \langle v \rangle)^2}{m_0}} = W$$

These variables are valuable, but they reduce a spectrum to only three values. This means that information is lost, making the use of these velocity variables less reliable.

Static clutter filter

The PARSAX uses the velocity value for each bin to filter out static clutter. In Figure 5.5, a gap between -0.3 and +0.3 can be seen for the horizontal as well as the vertical polarised signals. This gap is too specific to be caused by something other than a filter. However, there is still an unexpected peak at $v = 0$ m/s. When including all of the bins (including the non valid bins), this peak is even higher. This suggests that invalid reflectivity bins are given a zero velocity value, or possibly the other way around. The remaining valid bins associated with this zero velocity are not located at specific ranges, times, or reflectivity values. Instead, they appear randomly in groups of bins distributed throughout the data. The cause of this will not be investigated in depth, but the effect it can have should be taken into account.

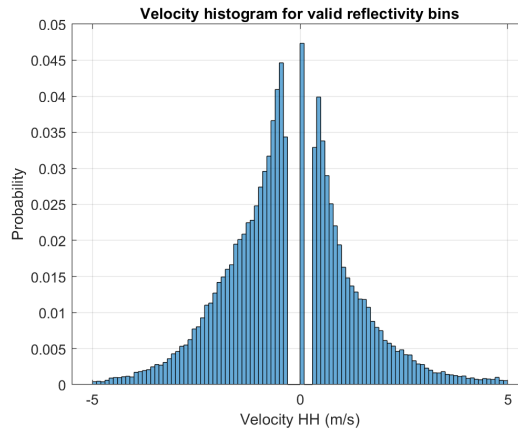


Figure 5.5: Histogram of velocity HH for one day, which shows a gap between -0.3 and 0.3 m/s due to a static clutter filter

5.2.2 Additional derived variables

The differential reflectivity is computed using [74]:

$$Z_{DR}(r) = 10 \log \left(\frac{Z_{HH}(r)}{Z_{VV}(r)} \right)$$

This parameter can only be computed when both horizontal reflectivity (HH) and vertical reflectivity (VV) are available. Since it uses horizontally and vertically polarized radar signals, it can only be obtained when using a dual-polarised radar. The differential reflectivity (ZDR) is defined as the ratio of horizontal to vertical reflectivity, expressed in logarithmic units (dB). For isotropic scatterers, the reflectivity in both polarizations is expected to be similar, resulting in ZDR values close to 0 dB. In contrast, for non-isotropic scatterers such as raindrops, ZDR values are typically greater than 0 dB due to their oblate shape. For rain, ZDR values are generally larger than 1 dB and can reach up to approximately 5 dB for larger drops [86].

5.3 Noise characteristics and filtering method

5.3.1 Type of filters and testing days

In this section, the following three types of noise and the methods used to filter them out are discussed: calibration errors and interference lines, anisotropic objects, and high intensity spots. In the feasibility study, days were selected based on KNMI data, choosing days with the lowest amount of cloud cover. Out of the ten selected days, three summer days and one winter day contained valid numerical data and were used to develop the filter.

5.3.2 Calibration errors and interference lines

Calibration errors and interference lines are types of noise found in the data that need to be filtered out when observing Bragg scattering. The PARSAX radar is never accurately calibrated in amplitude, because the ratio of amplitudes and phase differences between the two polarimetric channels was of interest, not the amplitude itself. Within this inaccurate amplitude calibration, a calibration error can appear due to a wrong value for the noise floor, which gives every range bin a systematic error for a short period. This is easy to recognize upon first inspection of the data. In this study, this is handled by inspecting the data and only using days on which this calibration error does not appear. The second type, interference lines, appear every day, so for this a filter needs to be applied to the data. The interference lines are characterised by a high intensity over just a single column. To develop the filter, one single test day is used. For this day, all interference lines were detected by observing the data manually. The filter is then compared with these identified points to evaluate its performance. The characteristic that interference lines show high intensity over the full column, from the first to the last range bin, is used to construct the filter. First, the sum of all bins within a column was computed. However, this turned out to be dominated by high values over a short range within a column. Therefore, a percentile-based approach was used to better isolate the interference lines. The 50th percentile (median) did not detect all interference lines, while the 75th percentile resulted in false alarms. For this reason, the final filter uses the 60th percentile. This value detected all interference lines and did not produce false alarms when evaluated for the test day.

5.3.3 Anisotropic objects

Insects are also a source of noise that need to be filtered out when observing Bragg scattering. A first thought would be that insects do not fly that high, but some insects do. Some insects migrate over large distances and can reach heights of several kilometres [87]. The approach to filter them out, which is also used by Chilson, is based on the differential reflectivity (ZDR) [73]. Insects are anisotropic objects, meaning that their measured reflectivity depends on the direction of observation. If the reflection is measured in both the horizontal and vertical directions, an anisotropic object will produce different values. This results in a higher ZDR value. In contrast, an isotropic signal (such as Bragg scattering) yields similar reflectivity in both directions, leading to a ZDR value close to 0 dB. A simple filtering method, as used by Chilson, compares the ZDR with a predefined range. If the differential reflectivity ZDR falls outside this range, the corresponding data is filtered out [73].

$$-2 < \text{ZDR} < 2$$

There were also other options for filtering considered. Another approach, used by Richardson, is to use a statistical filter based on ZDR [81]. In this method, multiple bins are used to create a histogram of ZDR. Insects and clutter tend to have wider histograms compared to Bragg scattering. For this method to work, a minimum of 10,000 range gates is required. Since the PARSAX data contains quite some invalid values, it is difficult to ensure that these conditions are, which makes this option less suitable for this study.

To check the performance of this filter, the number of bins that are filtered out relative to the valid horizontal Z_{HH} and vertical Z_{VV} reflectivity data is evaluated. It is expected that this filter removes more bins during a summer day than during a winter day, due to the presence of insects in summer. The filtering percentages are shown in the table below. A difference between summer and winter days can indeed be seen, as expected. However, since insects are not expected to appear in winter, this also indicates that bins are filtered out that are not insects, meaning the filter does not perform perfectly.

Type of day	Date	Percentage filtered out by anisotropic filter (%)
Summer day	2024-06-24	48%
Summer day	2024-06-25	50%
Winter day	2024-10-01	28%
Winter day	2024-09-01	30%

Table 5.3: Percentage of data filtered out by the anisotropic filter when the ZDR range is -2 to 2.

Besides this method to check the filter, it is also considered to use velocity information to check the performance of the filter. The mean Doppler velocity V and Doppler spectrum width W of filtered and non-filtered data are also evaluated. It was expected that, since insects have their own velocity, the velocity and spectrum width

of the anisotropic bins would show differences. However, this is not observed in the data that is evaluated. A possible explanation is that the three moments contain too little information. In a Doppler spectrum, insects could create a separate peak. When converting the spectrum to three parameters, not everything is captured, and relevant differences may no longer be visible.

5.3.4 High intensity spots such as birds and planes

There are also larger objects, such as birds, helicopters, planes, and drones, flying through the air that cause reflections which should be filtered out. The characteristics of such reflections are that they do not occur often and that the intensity of the reflected energy is relatively high. As a result, they appear as bright spots. This characteristics can be used for filtering. A simple approach is to filter out regions where a reflection higher than a certain threshold is detected. However, this approach does not capture the lower intensity parts of the target, which are typically found in the outer region of the spot. Even better would be to compare the intensity relative to the surrounding background intensity using a set of neighbouring cells, and when this detects a spot, filter out the area surrounding it to make sure that none of the spots intensity passes the filter.

A spot contains relatively high values over a short range. Therefore, for each column, the n_{top} highest values are selected and the average of these values is then taken. This computation is done in dBZ, which is physically not correct because averaging decibel values directly is not valid. The dBZ values should first be converted to linear reflectivity values, averaged, and then transformed back to dBZ. However, if linear values were used, a few very high values would influence the average much more. Using a dBZ average helps to prevent this effect.

$$P_n = \frac{1}{n_{\text{top}}} \sum_{m=1}^{n_{\text{top}}} x_{(m)}$$

Where x_m the value of the bins within a column in dBZ and n_{top} the number of highest values. This P_n is collected for every time step and will be used for detection, using a dynamic threshold.

Dynamic threshold

For detection the concept of constant false alarm rate (CFAR) will be used. This means that instead of using a constant threshold, a dynamic threshold will be applied. For every tested column, the neighbouring columns will act as reference cells. Based on these neighbouring columns $n_{\text{reference}}$, the local background level is estimated and a threshold is determined. In this way, the threshold adapts to variations in the background signal. To get a valid reference, a minimum amount of bins n_{valid} is added as a condition to be able to be sure that the reference is correct. Another problem is that a peak with high intensity can span multiple columns instead of just one. This means that the

columns directly next to the test column may still contain part of the target signal and are therefore not suitable as reference. To deal with this, guard columns are used. These are the columns around the test column that are excluded when estimating the background reference level. This method is visualised in Figure 5.6.

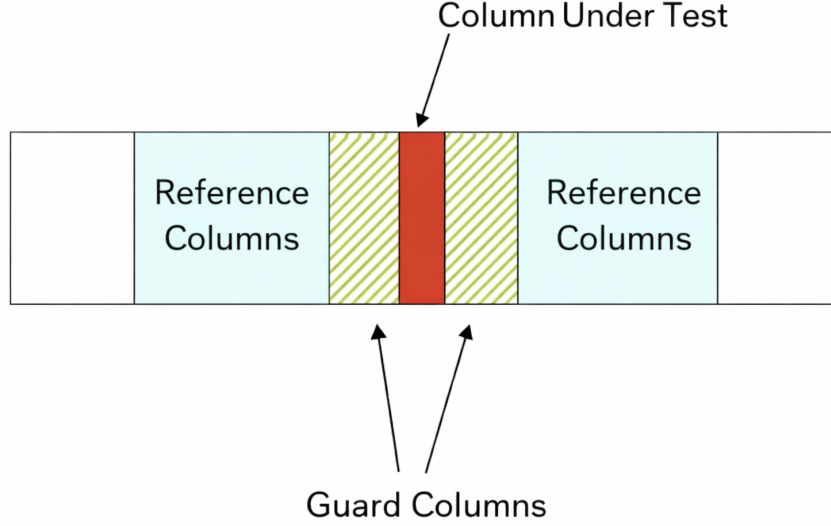


Figure 5.6: Dynamic threshold applied on columns used for filtering larger objects, such as birds, helicopters, planes, and drones.

Normally, with CFAR, the threshold is based on a predefined false alarm rate. However, due to the non-physical mean dBZ values, this approach cannot be used. Therefore the following approach will be used

$$\text{Threshold} = R + R_{\text{offset}}.$$

Where the reference R is the average value of $n_{\text{reference}}$ columns, and R_{offset} is the offset used to tune how strict the threshold is. Note that the threshold, and R , change for every column, since they are computed by sliding over all columns. The value of R_{offset} remains constant. When the column under test exceeds this dynamic threshold, it is labelled as a spot. This column, together with a certain number of neighbouring columns, n_{removed} , is then removed on both sides.

To determine the values of all variables in this filter, the spot detected in Appendix A, Figure A.3b, is used. This leads to the following values: $n_{\text{top}} = 10$, $n_{\text{valid}} = 20$ (combined from both sides), and $n_{\text{removed}} = 10$. The remaining variables are determined during the implementation and testing of the filter, resulting in the following values: $n_{\text{reference}} = 600$ per side and $n_{\text{guard}} = 30$ per side. The threshold offset is 7 dB.

5.4 C_n^2 Retrieval

5.4.1 Signal after filtering: Bragg scattering

All above-mentioned filters are combined and applied to the reflectivity. By doing this, the bins are aligned, so that each bin in a filter corresponds to the same bin in the reflectivity. It is assumed that the reflectivity that remains is mainly Bragg scattering. However, while developing the filters, it becomes clear that creating a perfect filter is complex. Therefore, it has to be taken into account that some intensity from noise may still pass through the filter. Nevertheless, for this study, Bragg scattering is assumed to dominate the filtered reflectivity Z . For every bin with available data (not NaN values), a C_n^2 value is calculated. In addition, to identify the effect of each filter, the percentage of data filtered out per filter is specified. The percentage is defined as the number of data bins that are removed relative to the valid bins in the reflectivity Z_{HH} .

5.4.2 Computation of C_n^2

The following equation to obtain C_n^2 is implemented:

$$C_n^2 = 2.63 \pi^5 \lambda^{-11/3} |K_w|^2 \frac{10^{(\frac{\text{dBZ}}{10})}}{(1000)^6} \quad (5.1)$$

where λ is the radar wavelength, K_w ($|K_w|^2 = 0.93$) the complex index of refraction for water, and dBZ the reflectivity of a radar bin. Equation 5.1 combines the following two equations [8].

$$Z_e = \frac{\lambda^4 \eta}{\pi^5 |K_w|^2} \quad (5.2)$$

$$\eta = 0.38 C_n^2 \lambda^{-1/3} \quad (5.3)$$

Equation 5.2 gives the relation between the volume reflectivity η and the equivalent radar reflectivity Z_e . This quantity Z_e represents the reflectivity, whether it originates from Rayleigh, Mie, or Bragg scattering, (in $\text{mm}^6 \text{m}^{-3}$) that would produce the same radar return as a cloud at 273 K containing one million droplets of 100 μm per cubic meter ($1 \text{mm}^6 \text{m}^{-3}$).

Equation 5.3 relates the refractive index structure parameter C_n^2 that we want to obtain, with the volume reflectivity η and λ the radar wavelength. This is used to relate Bragg scattering to C_n^2 [61, 83–85]. By substituting the first equation into the second equation, and adding a correction term $(1000)^6$ to convert from mm to m, the final equation 5.1 is obtained. With this, a value for C_n^2 can be calculated for each bin.

Path average value of C_n^2

With a calculated C_n^2 for every bin, the vertical path-averaged value of C_n^2 can be computed [65].

$$C_n^2 = \frac{1}{N} \sum_i C_{n,i}^2 \quad (5.4)$$

In this equation, $C_{n,i}^2$ is the C_n^2 value of the i -th bin and N is the total number of bins. The path over which the averaged value ranges from Z_{min} to Z_{max} and all values that are NaN are not included. Since every bin has a range of three meters, this results in $N \approx \frac{Z_{max}-Z_{min}}{3}$.

Minimum height Z_{min}

The correlation between radar retrieved C_n^2 and validation data becomes higher when selecting a specific height range instead of using the full range. Ideally, a full 2D optimisation of both the minimum and maximum range boundaries would be performed, but this would require too much computation time. Therefore, a stepwise approach is used where Z_{min} is varied while keeping Z_{max} fixed.

The lower boundary height was first tested in steps of 75 m (100, 175, 250, 325, 400, and 475 m). Around the region with the highest average correlation, additional points were added with half of the initial step size (37.5 m), resulting in the points at 213 and 288 m. A final step with one quarter of the initial step size (18.75 m) was then added around the highest correlation value, resulting in the points at 231 and 270 m. Further refinement was not performed due to computation time limitations.

Maximum height Z_{max}

The maximum height Z_{max} is based on the validation data. Since the results are compared with scintillometer measurements at ground level, it is not valid to include turbulence measurements at larger heights. This is because, above a certain height, a decoupling occurs between the turbulence near the surface (measured by the scintillometer) and the turbulence at higher altitudes. A general model that can be used to estimate this decoupling height is the H-V model [2]. In Figure 5.7, the ground-level turbulence strength (the C_n^2 value represented by the parameter A in the H-V model) is varied according to the classification of weak and strong turbulence [6]. From this, it can be seen that the ground-level turbulence mainly influences the C_n^2 profile up to approximately 1000 m. Based on this, it is reasonable to limit the PARSAX data to heights below 1000 m when comparing it with scintillometer measurements at ground level. It should be noted that this is based on a model, which simplifies reality. In practice, the height, which is the boundary layer height, at which this decoupling occurs depends on atmospheric conditions. Therefore, a check is performed for this Z_{max} . The check consists of changing Z_{max} while keeping all other settings fixed, and then evaluating whether the correlation increases or decreases. The values that will be tested are 800 m, 900 m, 1100 m, and 1200 m.

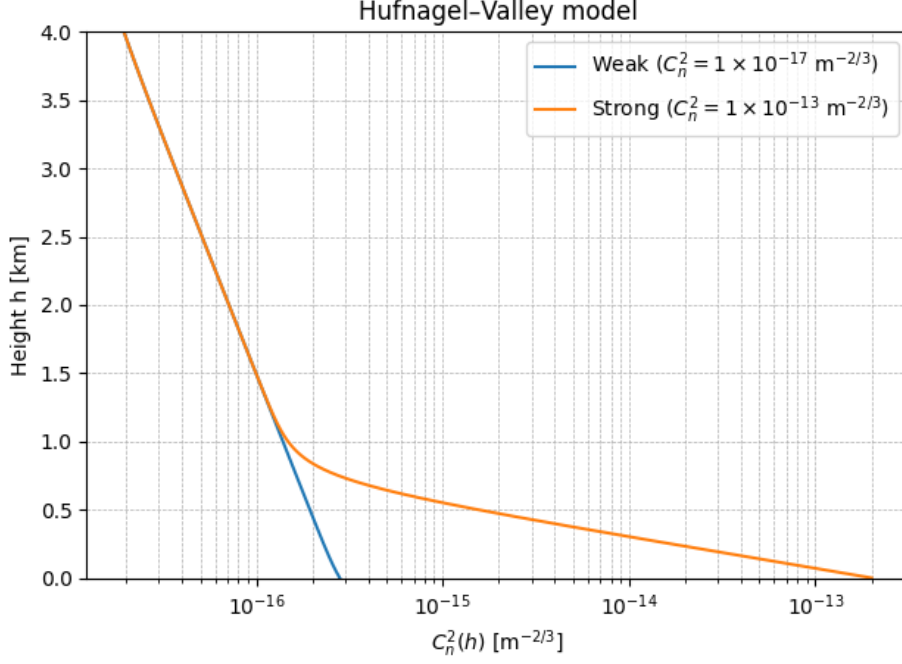


Figure 5.7: H-V model at weak and strong C_n^2 measurements at ground level

Time alignment

The PARSAX data contains path-averaged values of C_n^2 up to Z_{max} , for every time step of 512 ms. However, the validation data contains C_n^2 values for every 10 minutes. To align these two, the PARSAX data is converted to 10-minute interval data. The intervals that align with the PARSAX data are selected. Then, for each interval, all path average values of the PARSAX data that fall within this interval are included to compute the time-averaged value for that 10-minute interval.

Variance of C_n^2 within one data block

The data is now reduced from separate bins to data blocks. A data block represents a path average up to Z_{max} , combined with a time average over 10 minutes. When considering all C_n^2 values within such a data block, it is important to take the variance of these values into account. This provides information about the accuracy of the averaged value for that block. The variance is computed in the following steps and is translated into an error bar for the final C_n^2 value.

First, for every height within a data block, the variance is computed. The variance is computed over time, since there is a natural variation over height that should not affect the variance related to the data itself. NaN values within the data are ignored and the default normalization with $N - 1$ is used:

$$\sigma_h^2 = \frac{1}{N-1} \sum_{i=1}^N |A_i - \mu|^2$$

Here, N is the number of valid bins at a given height, A_i is the value of bin i , and μ is the average of the bins at that height. Repeating this for all heights results in a vector of variances σ_h^2 . [88]. Next, for every height, the square root is taken to obtain the standard deviation:

$$\sigma_h = \sqrt{\sigma_h^2}$$

While doing this, one condition is applied. The number of valid bins must satisfy $N \geq N_{\min}$. This ensures that a sufficient number of data points is available to compute a reliable variance. The higher $N_{\min}$, the more accurate each computed spread is. However, a higher $N_{\min}$ excludes more heights, since higher altitudes have fewer valid bins. This leads to a value of $N_{\min}$ set to 10, as this is approximately the average number of bins at the $Z_{\max}$ altitude (1000 m), which is the maximum height. This value is based on one representative day, 25 June 2024. Figure 5.8 shows the daily average for this day (2024-06-25). Note that in the computation, the average over the whole day is not used. This Figure 5.8 is only included to provide more insight into the behaviour of the spread as a function of height. One insight from this figure, when compared with Equation 5.1, is that in general both the standard deviation and the number of valid bins are higher when C_n^2 has a higher value in the vertical profile. For computation the data for every 10 min block is used, which can be seen in Figure 5.9. Finally, the standard deviations are averaged over all heights. This gives the average standard deviation over the full data block, which is used as the error bar.

$$\sigma_{10\min} = \frac{1}{M} \sum_{h=1}^M \sigma_h$$

Where M is the number of range bins (heights) within the data block.

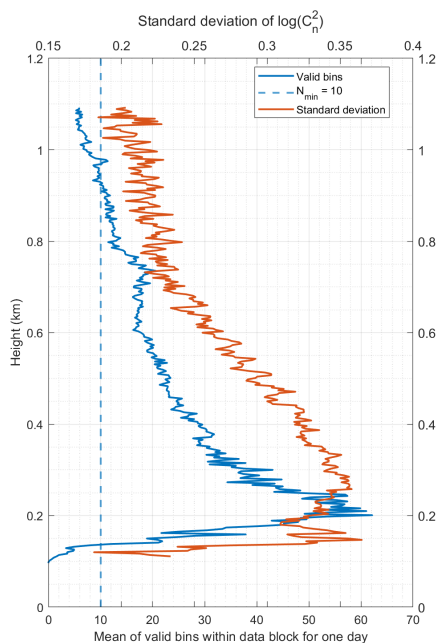


Figure 5.8: At the 25th of June 2024, the averaged valid bins and standard deviation with a vertical line for N_{min}

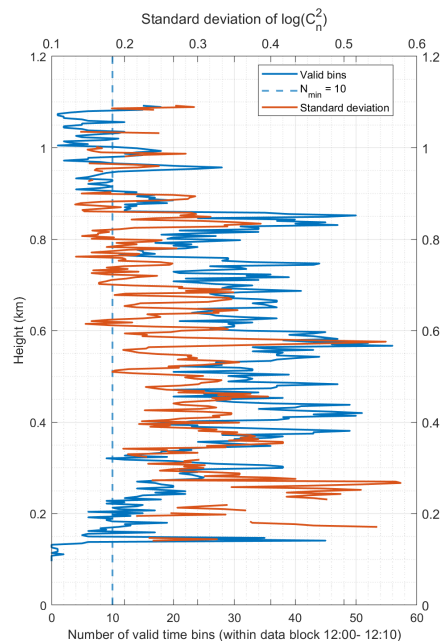


Figure 5.9: At the 25th of June 2024, one 10 minute valid bins and standard deviation with a vertical line for N_{min}

5.4.3 Wavelength correction

The amount of optical turbulence determines to what extent the propagation of light is distorted. The PARSAX radar operates at a wavelength on the order of centimetres, whereas optical wavelengths are on the order of micrometres, which creates a mismatch between the radar and optical wavelengths. As a result, C_n^2 measured at radar wavelengths is not equal to optical C_n^2 . A correction must therefore be applied to obtain a value for optical C_n^2 . This correction is described in [89], where the conversion from radar wavelengths to optical wavelengths is discussed. The results show (Figure 5.10) that applying this correction improves the correlation with scintillometer measured C_n^2 .

Assumptions for wavelength correction

The wavelength correction used in this work includes some assumptions. First of all, it assumes that differences in C_n^2 are caused by temperature, pressure and water vapor. For radar, water is the only species whose effect is accounted for individually, because its effect is significant enough. Furthermore, it is assumed that locally advected air undergoes adiabatic expansion or compression, meaning that there is no heat transfer with its surroundings. It also assumes that water vapor is dependent on the average e_v , modified only by temperature and pressure fluctuations. It is also assumed that there are no other gases than dry air and water vapor, so no aerosols or dust are taken into account. In addition, it assumes that there are no strong absorption lines at the

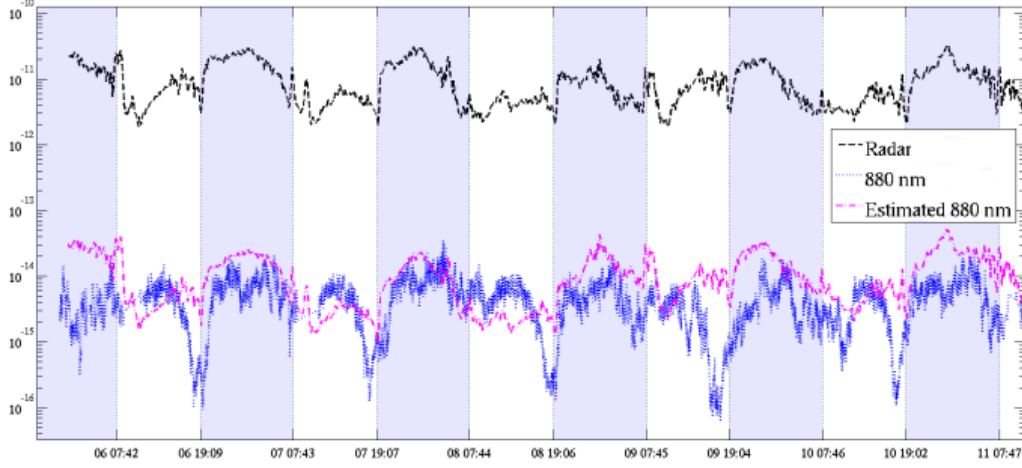


Figure 5.10: C_n^2 measured with radar wavelength (black), C_n^2 with wavelength correction (blue) and measured C_n^2 with scintillometer [89]

optical wavelength of interest. This correction is defined for a wavelength of 880 nm [89]. For this study, the wavelength of interest is 1550 nm, see Section 2.1.2 for more information. Since both optical wavelengths lie within a transmission band (see Figure 5.11), it is assumed that the correction can also be applied to 1550 nm.

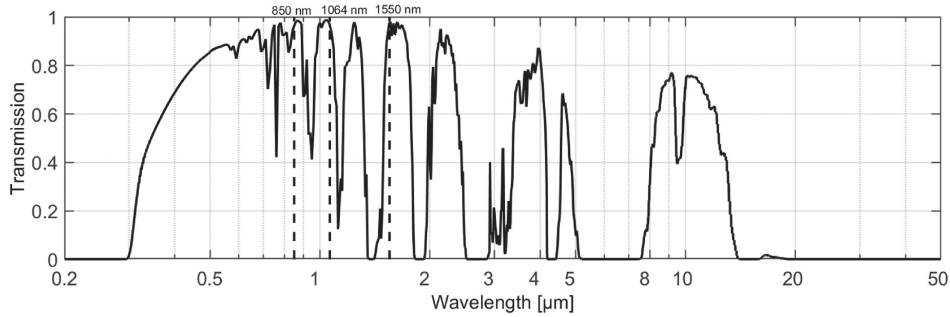


Figure 5.11: Transmission of Earth's atmosphere from sea level to space in zenith as a function of wavelength [90]

Weather data input for wavelength correction

The input needed for this wavelength correction is temperature, pressure and humidity. For this, data from the Miratlas weather station at the Aerospace Engineering building is used. A resolution of 10 minutes is selected, to align it with the time resolution of the other datasets. These measurements include some values that are physically not realistic. Therefore, the data is filtered to prevent non-physical values of temperature, pressure or humidity from influencing the results. The following ranges are applied for filtering:

Besides this, another check is applied. Sometimes the temperature, pressure or hu-

Table 5.4: Filtering ranges for weather data

Parameter	Valid range	Unit
Pressure	980 – 1050	hPa
Temperature	-25 – 45	°C
Humidity	0 – 100	%

midity remains constant for an unrealistically long time. This may indicate that the data is not valid during those periods. To detect this, a warning is given when values remain constant. For temperature and humidity this is when more than seven consecutive values (1 hour and 10 minutes) are equal, and for pressure when more than 70 (11 hours and 40 minutes) consecutive values are equal. The data for temperature and humidity have a resolution of 0.1 °C and 0.1 %, respectively, and pressure is recorded in hectopascals. Due to this coarser resolution, pressure can realistically remain constant for a longer period, which is why its threshold is higher. When this occurs, a warning is given, but the values are not removed automatically. For the final analysed days, all days for which weather data was available passed this check.

Computation of correction factor

The wavelength correction includes a number of computation steps. For all of the equations, the details can be found in the work of Burchett and Fiorino or Ciddor [89, 91]. The wavelength correction for an arbitrarily chosen day is visualised in Figure 5.12. The figure shows that the correction factor depends on the atmospheric conditions. The gaps in the data are caused by the filtering of unrealistic values, based on the ranges given in Table 5.4. The reference dashed line in the plot represents the correction factor when standard pressure, humidity and temperature are used, instead of locally measured data from the weather station. For the days that this atmospheric data is not available (see Table 5.6), the standard wavelength correction value of 0.00127 instead of the weather dependant correction value is used.

The wavelength correction used in this study is of the same order as the correction found in the literature [89]. When using temperature, humidity, and pressure values at 1000 m height, the wavelength correction changes by less than approximately 5%. For this a temperature decrease of 6.5, a pressure decrease from 1013 to 899, and a humidity increase from 40% to 90% are used. This shows that atmospheric conditions have only a limited influence on the correction. The dominant factor is the wavelength dependence of refractivity.

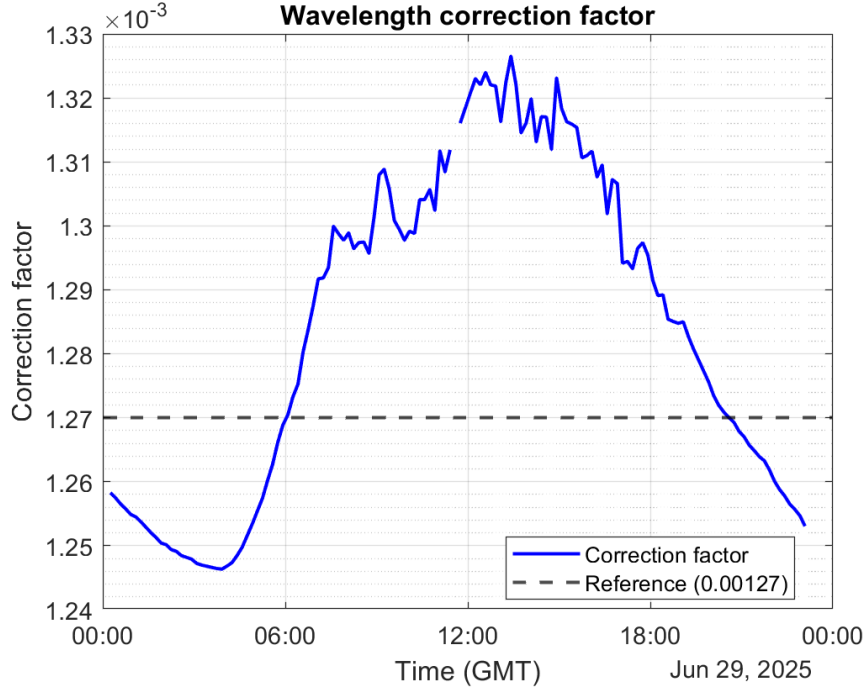


Figure 5.12: Wavelength correction for one day using locally measured atmospheric data (blue line) or standard values (black dashed line).

5.5 Validation Method

5.5.1 Scintillometer for validation

The literature review provided an overview of existing methods for validation that were available in this thesis is presented in Table 5.5. This table includes only the available validation methods, excluding potentially better but unavailable options such as balloon-borne instruments. The conclusion is that the preferred option is to use scintillometer data, with mesoscale model WRF data as a second option. Scintillometer data are available close to the radar location, and a scintillometer was also used as validation method for other radar-based methods [61].

Method	Suitable?	Limitation
Scintillometer	yes	Measures horizontally
WRF	medium	1 km resolution
Starlight-based method	medium	Only at night
Anemometer	medium	Only point measurement

Table 5.5: Overview of available methods and their main limitations

5.5.2 Assessment of quality of scintillometer data

Scintillometer

General information about how a scintillometer works can be found in Section 3.2.3. The scintillometer used in this thesis is the Kipp & Zonen LAS MkII [50], located at the TU Delft campus. During the first part of the measurement period, the scintillometer was located at the EWI building, and during the second part at the Aerospace Engineering (AE) building (see Figure 5.13). The same system is used in both cases, only the location changes. The available data spans from 2019 until the present time, and includes measurements from both locations.

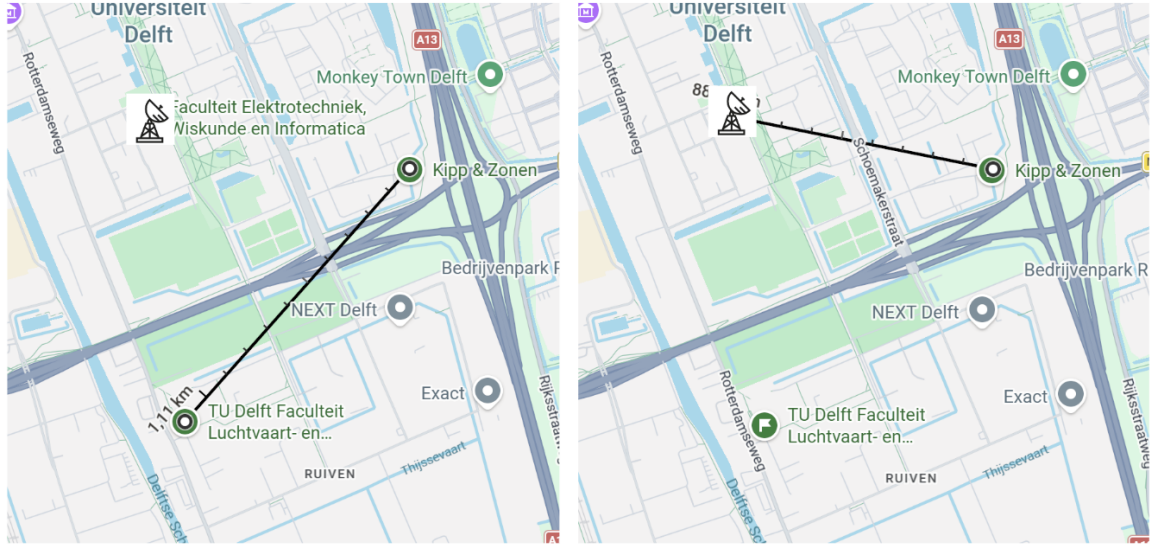


Figure 5.13: Location of the two scintillometer setups: The available data for each set up ranges from april 2023 - present (left) and October 2019–August 2020 (right). The antenna icon is the location of the PARSAX radar.

First observation of scintillometer data

The scintillometer computes a value of C_n^2 for every 10-minute interval. To focus on the trend of the data rather than day-to-day variability, monthly averaged daily cycles are computed and plotted. In these averaged cycles, the typical C_n^2 daily cycle is sometimes visible. Figure 5.14 shows the monthly averaged daily cycle of C_n^2 for one month in random month in winter and in summer. A first finding is that both locations show a similar daily cycle in all months. This supports the reliability of the measurements. Furthermore for summer, a daily cycle in which the C_n^2 values rise during the day is observed, which is in line with what is expected from the literature [2]. In winter, this cycle is usually not present. This is also expected due to less surface heating and more rain, haze and fog in the air, which suppresses optical turbulence.

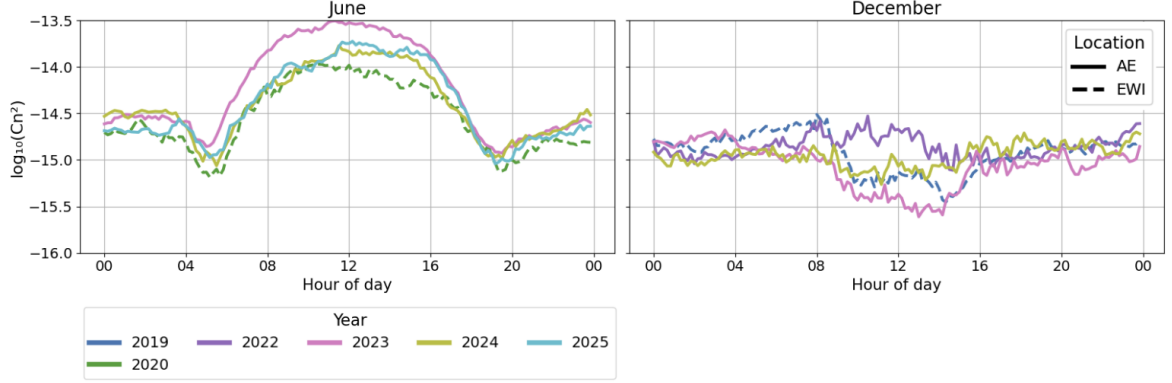


Figure 5.14: Scintillometer monthly averages of the daily cycle of C_n^2 of multiple years and both locations.

Other findings when analysing this data are that some days are missing. Sometimes single days, sometimes entire weeks. Another finding is that in some months, when the scintillometer was located at EWI, unexplained peaks occurred in the evening. This turned out to be caused by the sun shining directly into the receiver of the scintillometer. Furthermore, the setup consists of two scintillometers placed next to each other: LAS1 and LAS2. Both give results, but LAS1 should not be used, since the clock in LAS 120001 can slowly drift over time, as there is no GPS synchronisation. LAS2 does have the correct time and is given in GMT. Altogether, LAS2 will be used and attention is needed for the missing days and the peaks caused by direct sunlight.

5.5.3 Statistical metrics for validation

For comparison with the validation data, a statistical method is needed. The following statistics are applied: the correlation coefficient (R_{xy}), the mean error (ME), and the root mean square error (RMSE). This is based on a similar study that also used scintillometer data for validation [46]. The statistical analysis is performed after alignment in time. It is computed over the 10-minute data points for which both the validation data and the radar data contain a valid value. First, the correlation coefficient is computed.

$$R_{xy} = \frac{\sum_{i=1}^N (X_i - \bar{X})(Y_i - \bar{Y})}{\sqrt{\sum_{i=1}^N (X_i - \bar{X})^2 \sum_{i=1}^N (Y_i - \bar{Y})^2}} \quad (5.5)$$

Here, X_i is the logarithmic value of the scintillometer measurements ($X_i = \log(C_{n,\text{LAS},i}^2)$), and Y_i is the logarithmic value of the radar-derived measurements ($Y_i = \log(C_{n,\text{radar},i}^2)$). The averages $\bar{X}$ and $\bar{Y}$ are computed over all valid data points within the selected day after time alignment. A value of $R_{xy} = 1$ indicates a perfect correlation between the two datasets. The second statistic is the mean error (ME), which provides information about the systematic bias between the two datasets.

$$e_i = Y_i - X_i \quad (5.6)$$

$$ME = \frac{1}{N} \sum_{i=1}^N e_i \quad (5.7)$$

In which e_i represents the difference between X_i and Y_i expressed in log-space and N is the number of data points for which both X_i and Y_i have a valid value after time alignment. Finally, the root mean square error (RMSE) is used to analyse the typical difference between the two datasets [92].

$$RMSE = \sqrt{\frac{1}{N} \sum_{i=1}^N e_i^2} \quad (5.8)$$

5.6 Selection and relevant information of selected days

5.6.1 Selection of days

This section presents the method used for the selection of days included in the final analysis. In addition, the concentration of particles in the air on the selected days and a visual inspection of cloud cover during these days are discussed. This are important because it could cause additional backscattering, which adds noise to the reflectivity signal. First, KNMI data from 1 November 2022 until 1 October 2025 were collected. This period was selected based on the availability of scintillometer data. The KNMI dataset contains daily cloud cover values expressed in eighths (oktas), and the measurement station closest to Delft, namely Rotterdam, is used. For both the summer and winter months, the 20 days with the lowest cloud cover were identified and listed. For each of these days, it was checked whether both PARSAX and scintillometer data were available and complete. For the PARSAX data, a minimum of 97.5% of the total daily dataset size was required for a day to be classified as complete. For the scintillometer data, a threshold of 96.5% was used. Days that did not satisfy these conditions were considered incomplete or invalid and are highlighted in red in Table 5.6. Besides this, videos and weather information of the selected days are collected. Although these are not strict selection criteria, they are considered useful additional information. The videos are used for visual inspection and are discussed later in this section, and the weather information is used for the weather-dependent wavelength correction. In total, seven winter days and twelve summer days were selected for the final analysis. An overview of these selected days is given in Table 5.6.

5.6.2 Visual inspection of selected days

For these final selected days, photos taken vertically upward from the EWI building were combined into videos. This was done to visually inspect the cloud conditions during these days at the measurement location and to double-check the amount of cloud cover. The observations for these days can be found in Table 5.6.2, in which three categories are used: level 1 corresponds to no clouds, level 2 to less than one hour of cloud cover, and level 3 to days with more than one hour of cloud cover. Note that although the days were selected as clear-sky days, these observations show that this was not always fully the case in practice. Furthermore, birds, insects, planes, and even drones were observed during some of the days. However, these observations are not relevant enough to track in detail and are therefore not included in the table.

Date	Cloud cover
2023-06-09	2
2023-06-10	1
2023-06-14	1
2023-06-15	3

Date	Cloud cover
2023-06-16	2
2023-06-25	1
2024-06-23	3
2024-06-24	2

Date	Cloud cover
2024-06-25	3
2024-06-26	2
2025-06-29	2
2025-06-30	2

Table 5.6: Overview of selected winter and summer days including cloud cover from 0-3 and data availability

Date	Cloud Cover	Scintillometer	PARSAX	Video	Weather
Winter days					
2023-02-14	0	No data found	-	Yes	No
2024-01-09	0	Complete	Yes	Yes	Yes
2024-01-10	0	Complete	Not complete	Yes	No
2025-02-01	0	Complete	Yes	No	No
2022-12-12	1	Complete	No	No	No
2022-12-16	1	Complete	No	No	No
2023-02-07	1	No data found	-	Yes	No
2022-12-15	2	Complete	No	Yes	No
2023-01-17	2	No data found	Yes	Yes	No
2023-02-27	2	No data found	Yes	Yes	No
2024-01-18	2	Complete	Yes	Yes	Yes
2024-01-19	2	Complete	Yes	Yes	Yes
2025-02-17	2	Complete	No	Yes	No
2022-12-14	3	Complete	Yes	No	No
2023-02-13	3	No data found	-	Yes	No
2023-02-26	3	No data found	-	Yes	No
2024-01-26	3	Complete	Yes	Yes	No
2025-01-10	3	Complete	Not complete	Yes	No
2025-01-11	3	Complete	No	Yes	No
2025-02-02	3	Complete	Yes	Yes	No
Summer days					
2023-06-03	0	Complete	Not complete	Yes	No
2023-06-04	0	Complete	No	Yes	No
2023-06-05	0	Not complete	Not complete	Yes	No
2023-06-09	0	Complete	Yes	Yes	No
2023-06-10	0	Complete	Yes	Yes	No
2023-06-13	0	Complete	Not complete	Yes	No
2023-06-14	0	Complete	Yes	Yes	No
2023-06-24	0	Complete	No	Yes	No
2024-06-24	0	Complete	Yes	Yes	Yes
2024-06-25	0	Complete	Yes	Yes	Yes
2024-06-26	0	Complete	Yes	Yes	Yes
2024-08-11	0	Complete	No	Yes	No
2025-06-29	0	Complete	Yes	Yes	Yes
2025-06-30	0	Complete	Yes	Yes	Yes
2025-08-10	0	No data found	-	Yes	No
2023-06-08	1	Complete	Not complete	Yes	No
2023-06-15	1	Complete	Yes	Yes	No
2023-06-16	1	Complete	Yes	Yes	No
2023-06-25	1	Complete	Yes	Yes	No
2024-06-23	1	Complete	Yes	Yes	Yes

5.6.3 PM_{10} values during selected days

A high concentration of particles could influence the results, because this could cause additional backscattering, which adds noise to the reflectivity signal. Therefore, the particle concentration on the analysed days is evaluated. This is done by analysing the PM_{10} values. The data used for this analysis are publicly available and originate from an air quality monitoring station [93]. This station is located in Delft and uses a Nova SDS011 sensor to measure the concentration of PM_{10} particles in the air. PM_{10} refers to all airborne particles smaller than 10 micrometres. The particles originate from traffic, agriculture, industry, and natural sources such as sea salt. The PM_{10} values of the selected days are plotted in Figure 5.15. Saharan dust events, which occurs only occasionally, can also be identified by elevated PM_{10} concentrations [94]. In addition, for reference, a day with Saharan dust in the Netherlands is also included and shown in orange.

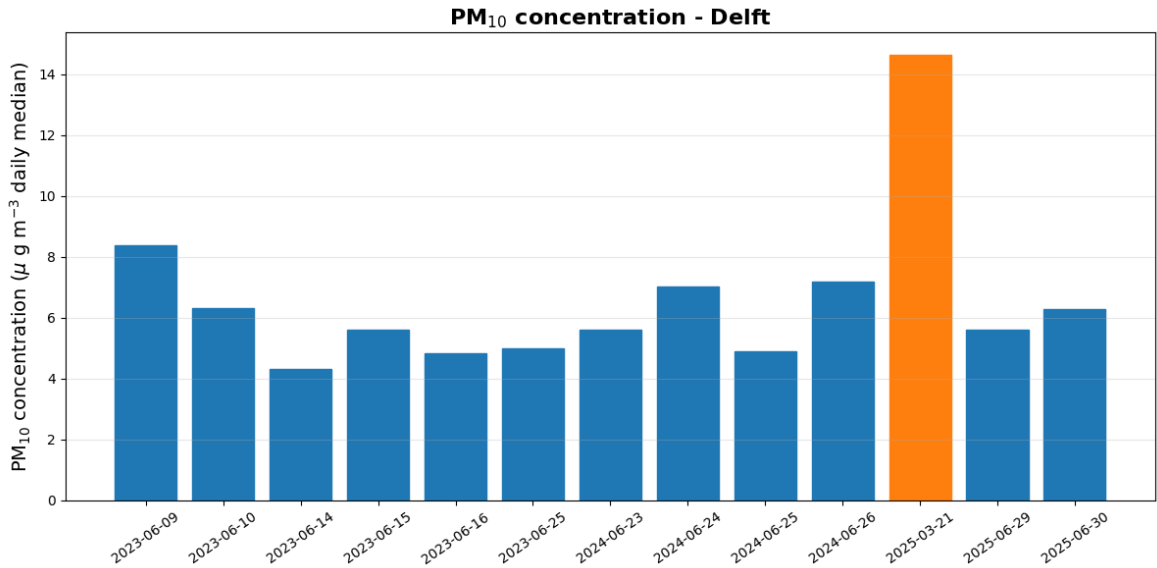


Figure 5.15: PM_{10} concentration in Delft during selected days including a Saharan dust event in Delft in orange for reference

5.7 Conclusion

The numerical data measured by the PARSAX radar is used to study whether Bragg scattering, measured as reflectivity Z , can be used to obtain optical turbulence C_n^2 . First, filters are developed to remove unwanted signals such as interference, objects, and insects. The remaining signal is then translated into a value for C_n^2 , including a correction for the wavelength mismatch between the radar and optical wavelengths. A stepwise approach is used to determine the optimal range boundaries $Z_{\min}$ and $Z_{\max}$. For validation, scintillometer data is used, but before applying it, the data is first analysed to assess its reliability. Finally, the selection of days for the final analysis is discussed. The results of these days are presented in the next chapter.

Results

In this chapter, the relevant results are presented. First, a comparison between winter and summer days is discussed. Next, the filters both separate and combined and the effect they have on the reflectivity are presented. After that, the final PARSAX results are compared with the scintillometer data. For some results, one day is visualised, while the others can be found in the appendix.

6.1 Differences between summer and winter days

Seven winter days were analysed. However, compared to the summer cases, the winter analysis was considered less reliable. Four of the winter days contained a very low number of valid bins, approximately two orders of magnitude lower than the other datasets. In addition, three of the winter days showed unrealistic high percentages for the interference filter, ranging from 58% to 86%. The cloud cover during the winter cases was also generally higher, even though days with the lowest possible cloud cover were selected. Furthermore, the measured optical turbulence during winter conditions was generally weaker. Altogether, the winter days show a mean correlation of 0.0254 and a median correlation of 0.0270. Therefore, the remainder of the analysis focuses on the summer days.

6.2 Percentage of valid bins

A first result is that the used data contains many invalid bins in the reflectivity data. For the analysed summer days, the percentage of valid bins before filtering range from 4.66% to 14.38%. This percentage is calculated using the final values of Z_{min} and Z_{max} throughout the day.

Date	Valid bins (%)	Date	Valid bins (%)
9 June 2023	13.66	23 June 2024	4.66
10 June 2023	13.77	24 June 2024	5.24
14 June 2023	9.10	25 June 2024	5.51
15 June 2023	14.71	26 June 2024	7.68
16 June 2023	14.00	29 June 2025	5.19
25 June 2023	14.38	30 June 2025	9.21

Table 6.1: Percentage of valid bins for each selected summer day before filtering.

6.3 Results of each of the individual filters

This section presents the filtering results. First of all, the results of the reflectivity before and after the combined filter. An example day can be seen in Figure 6.1. The other eleven days can be seen in Appendix B. The summer days show a clear daily cycle in reflectivity, where the amount of reflected signal increases during the day and decreases again towards the end of the day. Another notable observation is that for 8 out of the 12 summer days, increased reflectivity can be observed below approximately 400 m.

Second, the results of the analysis for the different filters. One example day, can be seen in Figure 6.2. The other eleven days can be seen in Appendix C. The range of removed percentages is given together with a description of the behaviour of each filter. There is an order in the amount of bins removed by the different filters, which will be discussed from low to high. Starting with the interference filter, which removes 0.09% – 0.59% of the bins and therefore has the lowest percentage of removed bins. This filter mainly consists of thin vertical lines and is therefore not clearly visible in the figures without zooming in. Secondly, the spots filter removes 4.73% – 16.93% of the bins and removes bins throughout the whole day without showing a clear daily behaviour. Third, the VV invalid filter removes 8.87% – 34.56% of the bins. The spread during the day follows a similar behaviour as the valid bins in the HH reflectivity plots. Fourth, the anisotropic-object filter removes 33.32% – 50.63% of the bins and also follows the daily cycle, but in addition shows increased activity below approximately 400 m. This corresponds to the region where increased reflectivity was observed for 8 out of the 12 summer days. Finally, the combined filters remove 54.36% – 73.80% of the bins. A complete overview of all of the percentages per filter per day is presented in Table 6.2.

Table 6.2: Percentage of data removed by each filter (described in section 5.3) relative to the number of valid bins.

Date	Interference	Spots	VV invalid	Anisotropic objects	Combined
9 June 2023	0.20%	5.56%	18.87%	42.02%	63.27%
10 June 2023	0.09%	4.73%	14.51%	41.68%	58.30%
14 June 2023	0.37%	8.31%	9.16%	50.33%	63.13%
15 June 2023	0.22%	6.27%	8.87%	42.71%	54.36%
16 June 2023	0.19%	5.52%	10.52%	42.48%	55.41%
25 June 2023	0.23%	9.81%	10.56%	42.06%	57.34%
23 June 2024	0.30%	15.89%	34.56%	33.32%	72.97%
24 June 2024	0.19%	13.37%	29.56%	34.51%	68.87%
25 June 2024	0.22%	16.93%	31.37%	35.79%	72.85%
26 June 2024	0.18%	7.86%	31.90%	36.39%	71.16%
29 June 2025	0.59%	12.76%	19.48%	50.63%	73.80%
30 June 2025	0.32%	10.93%	17.61%	43.77%	65.24%
Mean	0.26%	9.83%	19.75%	41.31%	64.73%

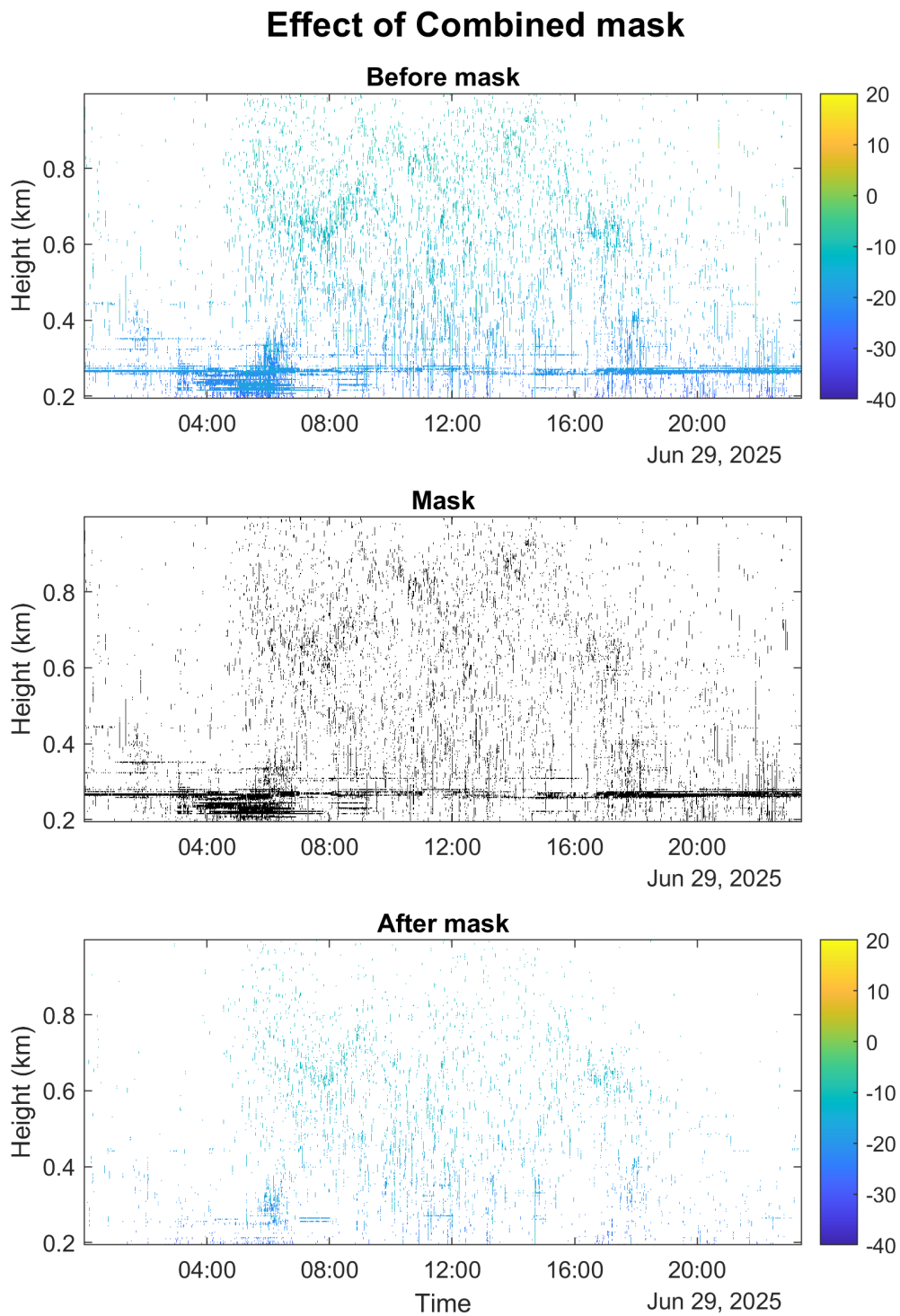


Figure 6.1: Example day (2025-06-29) showing Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter.

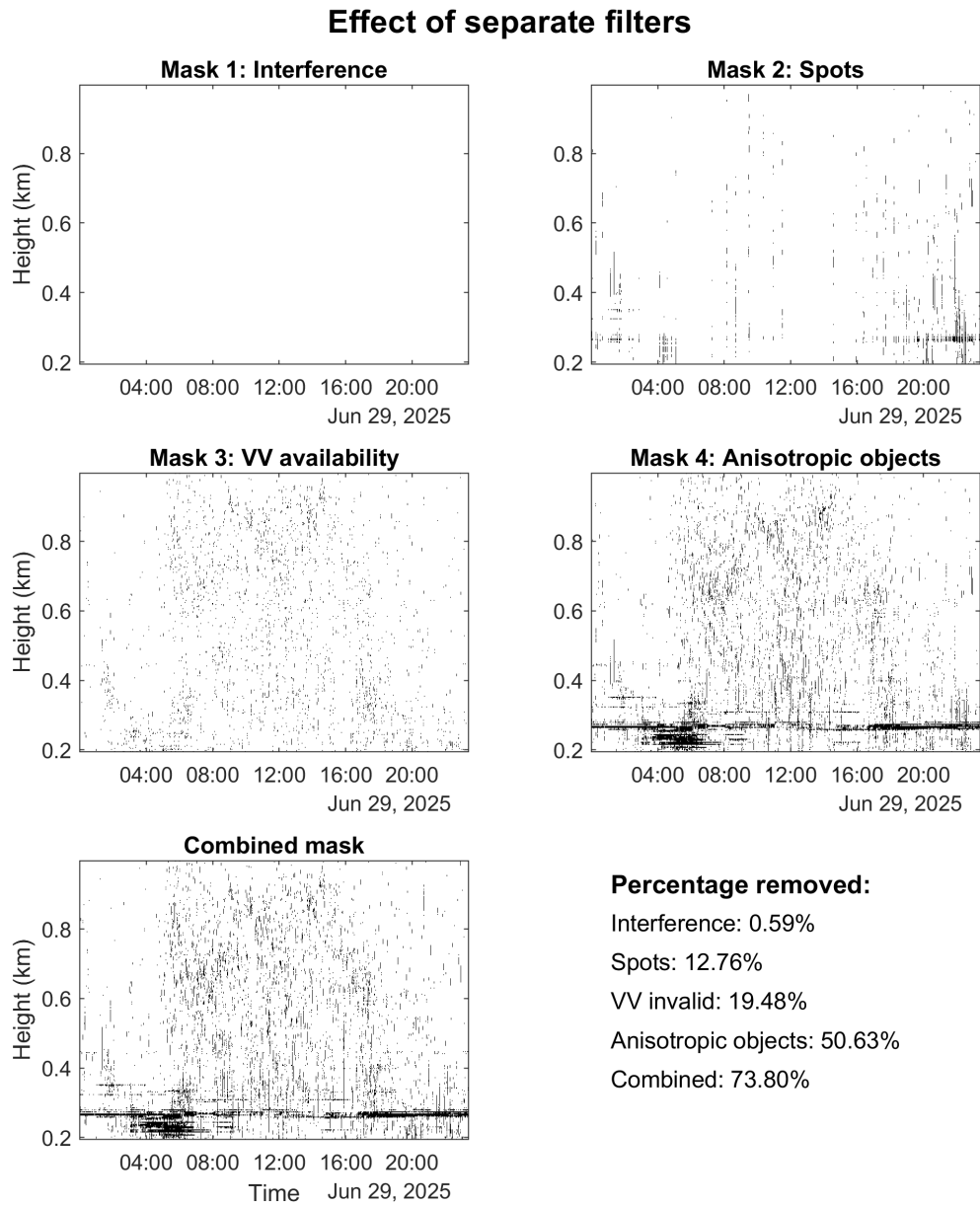


Figure 6.2: Example day (2025-06-29) showing the effect of the individual filters, including the percentage of bins removed relative to the total number of valid bins.

6.4 Final boundaries $Z_{\min}$ and $Z_{\max}$

The results show that when $Z_{\max}$ is kept fixed at 1000 m, a range starting from 231 m gives the highest correlation (see Figure 6.3). When keeping $Z_{\min}$ constant and tuning $Z_{\max}$, a $Z_{\max}$ of 1000 m gives the highest correlation (see Figure 6.4). Furthermore, the results show that changing $Z_{\min}$ has a larger impact on the correlation than changing $Z_{\max}$.

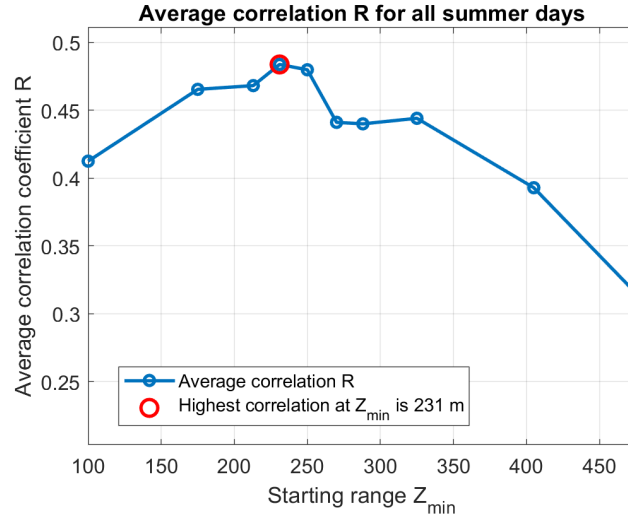


Figure 6.3: Average correlation R for varying $Z_{\min}$, while keeping $Z_{\max}$ fixed at 1000 m.

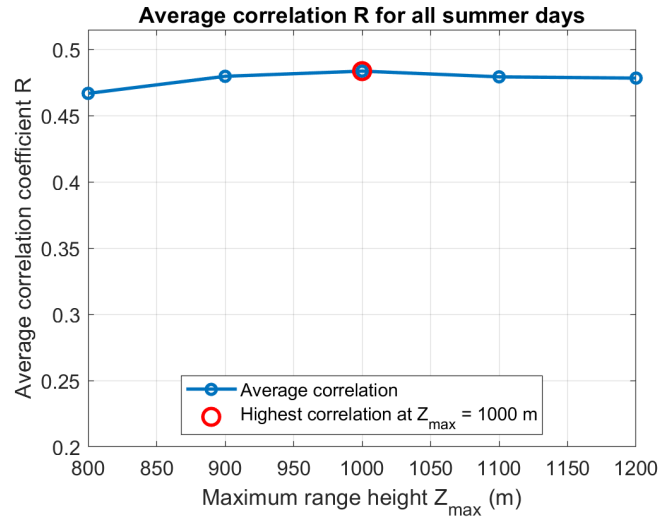


Figure 6.4: Average correlation R for varying $Z_{\max}$, while keeping $Z_{\min}$ fixed at 231 m.

6.5 Final comparison between PARSAX-derived C_n^2 and the validation data

One example day of the final comparison between PARSAX-derived C_n^2 and the validation scintillometer data is presented in Figure 6.5. Similar graphs for the other days can be found in Appendix D. For each day, the correlation, mean error, and root mean square error were computed. The complete results for all analysed summer days are presented in Table 6.3. The correlation R for all days lies between 0.33 and 0.69, except for one outlier of 0.05 on 23 June 2024. Including this outlier, the mean correlation is 0.48 and the median correlation is 0.49. The mean error mainly lies in the range from -1.46 to -1.75, with both a mean and median of -1.58. The root mean square error lies in the range from 1.52 to 1.80, with a mean of 1.65 and a median of 1.64.

Besides these general results, five additional observations can be made. First, if the days with weather-dependent wavelength correction and standard wavelength correction are compared as two groups, while excluding the outlier, no significant difference is observed between them. Second, June 24th, 25th, and 26th show dips during sunrise and sunset, while the other days do not show this behaviour. These three days overlap with the four days that do not show additional noise below 400 m. The fourth day in this group is the identified outlier. Third, the outlier day has the lowest number of valid bins before filtering and the second-highest percentage of filtered bins. This is mainly caused by a high number of bins removed by the spots filter and the highest percentage removed by the VV invalid filter. Fourth, the PARSAX data varies less in magnitude during the day, while the scintillometer shows larger variations throughout the day. Fifth, the spread (error bars) of the PARSAX data remains relatively stable for all analysed days.

Date	Correlation R	Mean Error	Root mean square error
9 June 2023	0.55	-1.53	1.63
10 June 2023	0.33	-1.52	1.58
14 June 2023	0.60	-1.68	1.74
24 June 2024	0.45	-1.61	1.66
25 June 2024	0.47	-1.46	1.52
26 June 2024	0.47	-1.56	1.61
29 June 2025	0.62	-1.50	1.62
30 June 2025	0.60	-1.55	1.63
15 June 2023	0.69	-1.62	1.67
16 June 2023	0.51	-1.75	1.80
25 June 2023	0.46	-1.59	1.65
23 June 2024	0.05	-1.59	1.69
Mean	0.48	-1.58	1.65
Median	0.49	-1.58	1.64

Table 6.3: Overview of correlation, mean error, and RMSE values for the final analysed summer days.

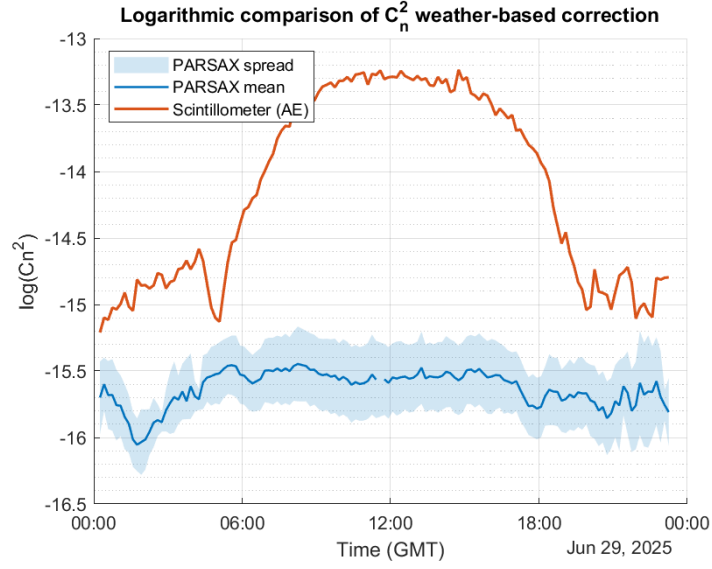


Figure 6.5: Example day (2025-06-29) showing the final comparison between PARSAX-derived C_n^2 and the validation scintillometer data using 10-minute averaged data points, for which a weather based wavelength correction in applied.

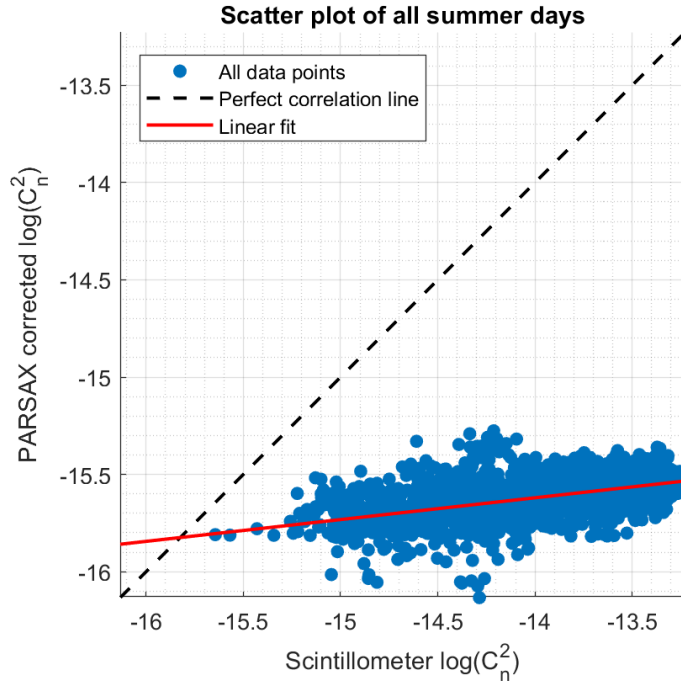


Figure 6.6: Scatter plot of all summer days showing the correlation between PARSAX-derived C_n^2 and scintillometer validation data, with the PARSAX values on the y-axis and the scintillometer values on the x-axis. The outlier day (23 June 2024) and the systematic offset are excluded.

Discussion

7.1 Differences between summer and winter days

The reduced performance during the winter cases is likely related to several factors. During winter conditions, optical turbulence is generally weaker due to reduced solar heating and weaker convective activity. As a result, the Bragg-scattered signal becomes weaker and more difficult to distinguish from interference and noise. In addition, the generally higher cloud cover during the winter days may have introduced additional unwanted contributions to the radar signal. The very low number of valid bins for several winter datasets further reduced the robustness of the retrieved C_n^2 values and the resulting correlations. Together, these factors can explain why the winter results are less consistent and less meaningful compared to the summer cases. Therefore, the summer datasets are considered more suitable for this first study in finding a relation between the radar reflectivity and optical turbulence.

7.2 Percentage of valid bins

The difference in percentages of valid bins shows no clear relation with cloud cover or PM_{10} particle concentration. However, a clear difference is observed when comparing the groups with and without additional noise below 400 m. The days with additional noise show a higher average percentage of valid bins of 11.75%, compared to an average of 5.77% for the days without this noise. This makes sense, since the additional noise still contains reflectivity, regardless of whether it is actual signal or unwanted noise.

7.3 Performance of the individual filters

The relatively low percentage of removed bins by the interference filter is likely caused by a combination of two factors. First, the filter appears to be accurate, since mainly the interference lines are removed and only a limited amount of surrounding bins is affected. Second, interference, primarily caused by nearby radar systems, is only occasionally present, so the filter is not expected to remove a large amount of bins. Although this filter has the lowest removed percentage, it remains relevant because the intensity of the affected bins is relatively high.

The spots filter does not show a clear daily cycle, which is in line with expectations, since birds, planes, and other temporary objects can appear at random times throughout the day. The filter removes a relatively high amount of bins compared to the number of objects that appear during a day. This is a trade-off in the sense that fewer noise objects remain in the filtered data, with the downside of higher bin removal percentages. In addition, once an object is detected, the whole vertical region together

with additional side columns is filtered out, which further increases the number of removed bins.

The VV valid filter is applied because Z_{DR} cannot be computed when the VV value is invalid. Therefore, these bins are removed to prevent invalid VV measurements from contributing to the calculated Z_{DR} percentage. As a result, the percentages removed by this filter are mainly related to data availability and are therefore less relevant for further analysis.

While developing the anisotropic objects filter, a check was performed which resulted in the values shown in Table 5.3 in Chapter 4.3. The higher percentage of filtered bins during summer compared to winter is in line with the fact that insects occur more frequently during summer conditions, suggesting that the filter indeed responds to insects. However, since insects are not expected to appear in winter, this also indicates that bins are filtered out that are not insects, meaning the filter does not perform perfectly.

The relatively high percentage of bins removed by the combined filters shows that a large part of the radar data is affected by unwanted signals. Since the amount of valid bins before filtering is already limited, the amount of remaining data after filtering becomes very low. This affects the robustness of the retrieved C_n^2 values and may cause lower correlations. Besides this, it is also important to note that the filters do not perform perfectly. Because of this, part of the non-Bragg scattering reflectivity will still pass through the filtering process.

Related to this, is the increased reflectivity below approximately 400 meters which is likely not caused by Bragg scattering, but by additional noise. The observed behaviour appears non-physical, since the structures show abrupt changes and straight horizontal bands, which is not expected for realistic atmospheric behaviour. The most reasonable explanation is that this behaviour is related to temporary processing errors or radar settings within the PARSAX system. This is further supported by the fact that the behaviour does not appear for 4 out of the 12 days, suggesting that it is caused by temporal error rather than a continuous atmospheric effect. Since this noise is only partly removed by the filtering process, it still affects the reliability of the filtered reflectivity and therefore also effects the final obtained C_n^2 values.

7.4 Choice of $Z_{\min}$ and $Z_{\max}$

The reason that a $Z_{\min}$ of 231 m gives the best correlation can be explained by the fact that data below this level is influenced by near-field effects and is therefore not fully reliable. This 231 m boundary value is lower than the 405 m near-field boundary found in literature. However, as already mentioned, this theoretical value is only an estimation and not a precise cut-off value, so it is not surprising that this difference appears.

$Z_{\max}$ has a value of 1000 meters. Ideally, computing an accurate value for the Fried

parameter r_0 would require a vertical path integral up to infinity, rather than up to Z_{max} . However, this is not possible due to the maximum range up to which reflections are received by the radar. This is the reason why further computation to a Fried parameter r_0 and losses for the link budget is not performed. Furthermore, the effect of changing Z_{max} is relatively small, which is likely related to the low number of valid bins available in this higher region.

7.5 Final comparison between PARSAX-derived C_n^2 and scintillometer validation data

7.5.1 General results of final comparison

First the general results regarding the correlation, mean error and root mean square error are discussed. The mean correlation coefficient R of 0.48 is higher than the correlation found by Fiorino using a pulsed Doppler radar, which was 0.34 [89]. The strong statistical relation between PARSAX and scintillometer data can be observed in the scatter plot in Figure 6.6. This suggests that for this selection of days the PARSAX radar performs better in terms of correlation with the scintillometer measurements.

The PARSAX-obtained values show a mean error (ME) of -1.58 compared to the scintillometer measurements. The RMSE is only slightly larger than the absolute ME, which suggests that a large part of the error is caused by a systematic bias rather than by strong random fluctuations. Compared to the RMSE of 0.60 found in the study using a pulse Doppler radar [89], this indicates a relatively large systematic error. Note that C_n^2 is plotted on a logarithmic scale. Therefore, a systematic error of approximately 2 corresponds to a factor 100 difference in linear scale. However, since the systematic error remains relatively stable, it may be possible to apply a correction factor for this offset. This systematic error can likely be explained by an old and not accurate calibration of the PARSAX radar. This was discovered by analysing newer radar data, which showed significantly higher reflectivity Z values. For 29 June 2025, the mean reflectivity of the new dataset was approximately 51 dB higher than that of the old dataset. Such a large difference between the two datasets indicates that they are not in agreement and therefore cannot both be considered fully reliable. If this difference is constant cannot be confirmed, as only one day of the new dataset is analysed. Al together, this mean error shows that a better radar data processing pipeline needs to be developed.

7.5.2 Additional results of final comparison

In addition to these general results, the five additional observations are discussed. First, the weather-dependent wavelength correction does not perform significantly better than the standard wavelength correction. This can be explained by the relatively small difference in magnitude between the two correction methods compared to the much larger variations observed in the C_n^2 values themselves. Second, The overlap between the days with no additional noise below 400 m and the days showing dips

during sunrise and sunset suggests that removing this additional noise reveals a more realistic atmospheric behaviour, since dips during sunrise and sunset are expected for optical turbulence. Third, the outlier value of 0.05 on 23 June 2024 could partly be explained by the low number of valid bins available after filtering. However, the large effect on R suggests either the presence of another contributing factor or a high sensitivity of R to the number of available bins. The latter could be mitigated by introducing a threshold for the minimum number of valid bins required after filtering before including a day in the analysis. Fourth, the reason for the smaller variation in C_n^2 amplitude in the PARSAX radar data is still unclear. A possible explanation is the contribution of non-Bragg scattering reflectivity. Although days with the lowest amount of clouds were selected, some clouds are still present. In addition, no specific precipitation filter is included in this method to remove this unwanted contribution. Besides this, the filters for other noise sources are also not perfect, which further contributes to non-Bragg scattering in the final filtered reflectivity. As a result, the total reflectivity is likely a combination of Bragg scattering and non-Bragg scattering, while the ratio between both is difficult to assess. It could be that the non-Bragg scattering contribution flattens the amplitude variation of the radar-obtained C_n^2 . Fifth, the relatively stable spread of the PARSAX-obtained C_n^2 values indicates that there is not much change in the variability of the data over time, both within a day and between different days.

7.6 Other limitations and their impact

7.6.1 Validation data

A first limitation is that the radar measures vertically, while the scintillometer measures a horizontal value of C_n^2 . Comparing these measurements using extrapolation introduces additional uncertainty. This uncertainty is minimised by using a maximum height based on the boundary layer height (BLH). This is the height at which decoupling occurs, meaning that extrapolation can be justified up to this height. In addition, the PARSAX radar is located at the EWI building, while the scintillometer was located on a building approximately one kilometre away during the final analysed days. This should be taken into account when the data are used together. Whether such a separation can be neglected depends on the flow properties, which in this case mainly relate to terrain surface heterogeneities. The terrain at TU Delft is complex but relatively similar across this area. The scintillometer provides measurements averaged over a path length of approximately 1 km. Therefore, the separation distance is of the same order as the resolution of the scintillometer data. For now, it is assumed that the separation is acceptable. If needed, a WRF simulation could be used to further support the comparison. Finally, the scintillometer should not be considered absolute ground truth, and it does not include an uncertainty estimate or error bars. It would therefore be beneficial to include an estimate of the accuracy or uncertainty of the scintillometer data.

7.6.2 Processing and filtering

For a radar such as PARSAX, where the transmitter and receiver are physically separated, the transmit and receive beams do not fully overlap, which results in a parallax error. The correction factor is much larger below the final minimum range of 231 m than above it. This could help explain why a Z_{min} of 231 m led to the highest correlation. This effect is not corrected for in this study because it is relatively small above the boundary Z_{min} as can be seen in Figure 5.2. Furthermore, the sidelobe effect is not included because of the vertical pointing direction. However, it cannot be excluded that it still affects the results. Some precipitation may still remain within the Bragg scattering signal, since a filter specifically for precipitation was not included because only clear-sky days were used. However, it turned out that not all days were completely cloud free. This could explain part of the increase in reflectivity observed in the higher layers.

Reliability of data

The numerical data of the PARSAX radar used in this study are not fully reliable. This was discovered when analysing a newer type of data with updated processing. The first discovery was the unreliable calibration, which likely explains the systematic error found in the results of this study. A second discovery when comparing with the newer data is that the velocity gap between -0.3 m/s and $+0.3$ m/s is caused by a setting in the old processing. This setting cannot be changed and creates missing data, which also affects the results of this thesis.

Doppler information for turbulence retrieval

As optical turbulence is related to atmospheric motion, it is intuitive to also consider including velocity information. However, the method on which this study is based only uses reflectivity Z . Besides that, when looking into the Doppler information of the PARSAX radar, it became clear that data storage limitations reduce the full Doppler spectrum to only three moments, causing loss of information. In addition, the processing that causes the velocity gap described above could not be inspected or adjusted. These factors led to the choice of not including Doppler information in this study. However, since this reflectivity-based approach has problems with filtering, a velocity-based approach to estimate C_n^2 from the Doppler spectrum through the reconstruction of eddies, which does not require accurate amplitude calibration of the radar, should also be considered.

Selection of days

More measurement days are needed to make stronger conclusions about seasonal behaviour. In addition, only days in June were selected for the summer dataset after applying the lowest cloud cover selection. Therefore, the results are more representative for June conditions than for overall summer behaviour.

Selection of range

Splitting the radar data into multiple height layers could provide C_n^2 profile information instead of a single range-averaged value. However, due to the parallax error and near-field effects, range-dependent values are considered not reliable enough. These effects should be better understood before multi-layer analysis can give meaningful results. Therefore, this study uses a single vertical region to obtain C_n^2 values.

8.1 Conclusion

The research question which was investigated in this thesis was : Is it possible to measure optical turbulence C_n^2 using reflectivity measured in the vertical direction by the S-band PARSAX radar?

First, the feasibility study verified that the measurements are performed within the inertial subrange and identified the types of unwanted signals present in the radar data. These observations formed the basis for a dedicated data search procedure and signal processing pipeline, which were developed in the main research.

The signal processing pipeline included digital filtering of these unwanted signals and an estimation procedure for C_n^2 . The results show that interference and objects such as aircraft, birds, drones, and insects can largely be removed using these filters. Although some non-Bragg scattering signals still remain after filtering, and therefore influence the final reflectivity, the results show that the filtering performed well enough. The filtered data was translated into C_n^2 values using a similar approach to a method that has so far only been applied to a pulse-Doppler radar.

The c_n^2 data, which were retrieved by the developed processing pipeline, were compared with the scintillometer data. The pipeline verification showed that, for the selected days in June, a mean correlation coefficient of 0.48 was obtained. This is significantly higher than the correlation coefficient of 0.34 that was found using the pulse-Doppler radar method. However, the PARSAX-derived C_n^2 values showed a much higher, although relatively stable, root mean square error compared to the pulse-Doppler radar method. This large systematic error was found to be related to calibration issues of the PARSAX radar. Since the error appears to be relatively stable, it could potentially be corrected for.

Looking further into the radar input data revealed additional issues. A static clutter filter removes part of the data during preprocessing, and temporal non-physical noise was observed during 8 of the 12 selected days. These issues affect the quality of the radar data and therefore the reliability of the results. In addition, beam overlap, side-lobe effects, and the spatial mismatch between the PARSAX radar and scintillometer validation data should be considered when interpreting the results.

Despite these important limitations, the results indicate that it is possible to measure optical turbulence using vertical reflectivity measurements from the PARSAX radar. At this stage, the method is not yet ready for operational use, but further re-

search and improvements could overcome the current limitations. When this happens, the advantages of large measurement volumes, vertical profile measurements, and the possibility of deployment on moving platforms such as ships could make radar-based optical turbulence measurements a valuable addition to the field.

8.2 Recommendations

The study should be repeated using new PARSAX radar data that is properly calibrated and does not contain a static clutter filter during preprocessing. Since both issues were found to affect the radar data. A further study could also include the effect of transmitter and receiver beam overlap, sidelobes, and potentially the effect of wind during the testing days. These effects were not investigated in this study but could influence the final results. Although the filtering methods were able to remove many unwanted signals, some non-Bragg scattering contributions remained in the final dataset. Future research could focus on improving the filtering methods to further isolate the Bragg scattering signal, for example by developing a filter specifically for precipitation.

Future studies should include days other than those in June in order to investigate seasonal effects. Since only summer days in June were analysed in this research, it is not possible to determine how the method performs during other seasons. Changing location could also be interesting. Measurements in different climates, or in non-urban environments within the same climate, could provide additional insights, since optical turbulence is strongly influenced by local environmental conditions.

This study used a horizontal scintillometer for validation. Future studies could also include other validation methods, such as WRF or multiple scintillometers at different heights. In addition, it would be better to place the scintillometer closer to the radar in order to reduce the spatial mismatch between the radar and validation data.

More broadly, future research could investigate whether velocity measurements contain relevant information about optical turbulence. Although this would require a different method, it could provide valuable additional insights. To do this properly, the raw PARSAX data should be used, since this contains the full Doppler spectrum instead of only the first three moments. Also a more broader recommendation is to investigate how other types of (FMCW) S-band radars perform in measuring C_n^2 from reflectivity. This would help determine whether the results found in this study are specific to PARSAX or can also be obtained with other radar systems. If the accuracy of obtaining C_n^2 improves, future research could investigate whether profile information can be obtained by dividing the vertical range into multiple layers. This could provide additional insight into the vertical profile of optical turbulence.

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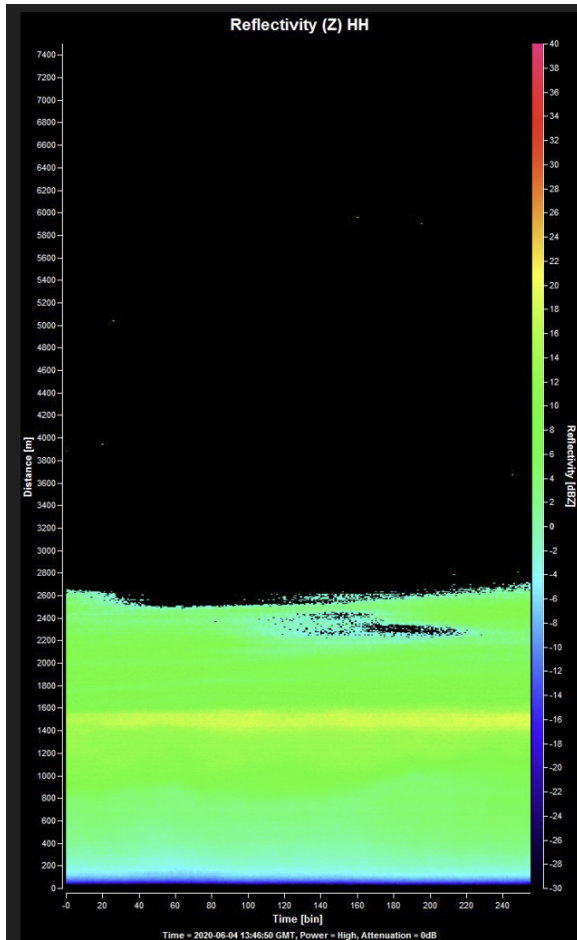
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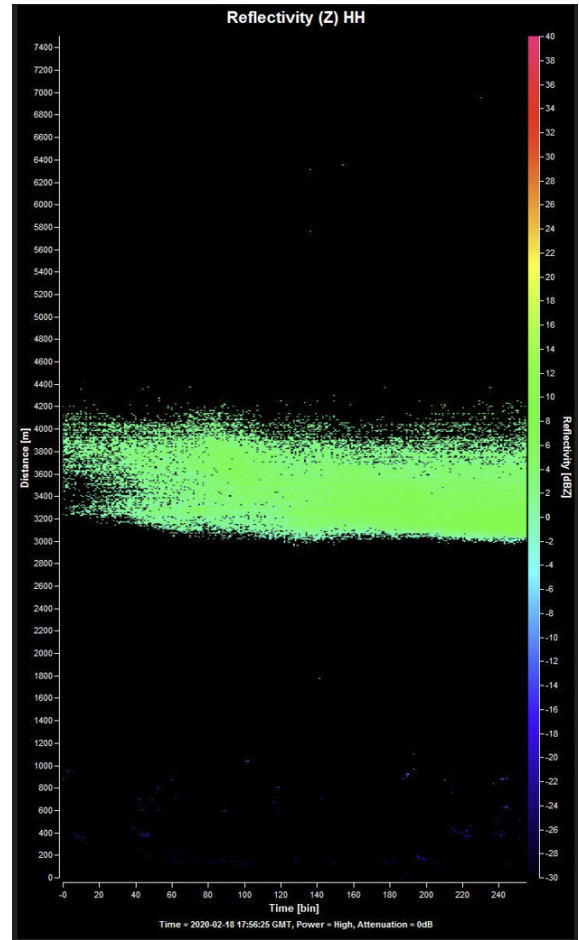
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Examples of reflectivity HH under different conditions

A

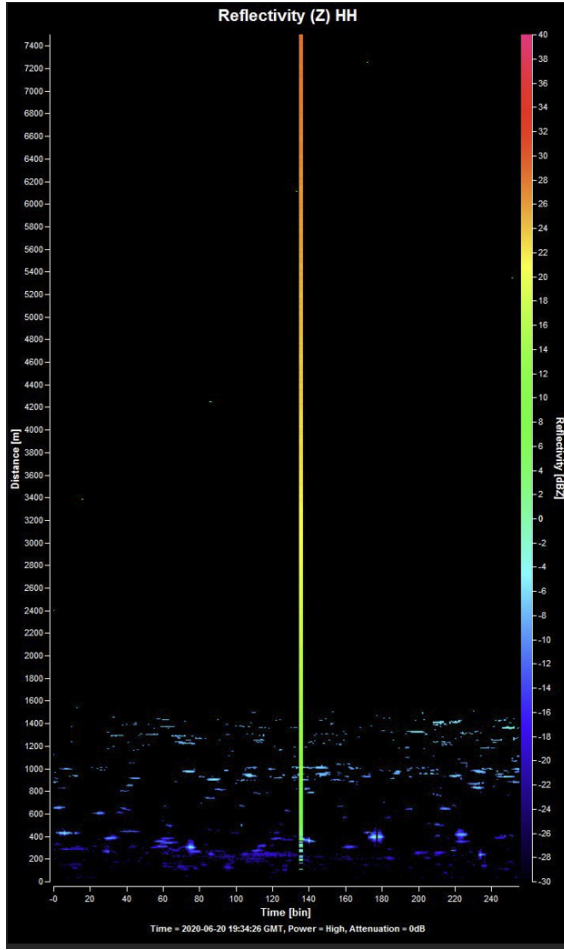


(a) Rain

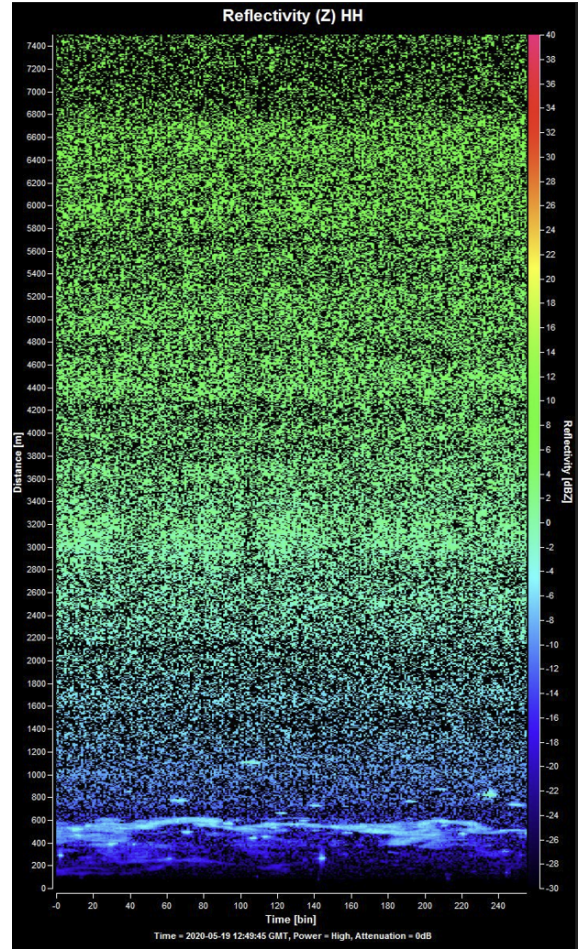


(b) Middle-level cloud

Figure A.1: Quick-looks of the timelines (1 bin = 0.512 sec) of the HH effective reflectivity profiles in cases of a stratiform rain and a middle-level cloud.

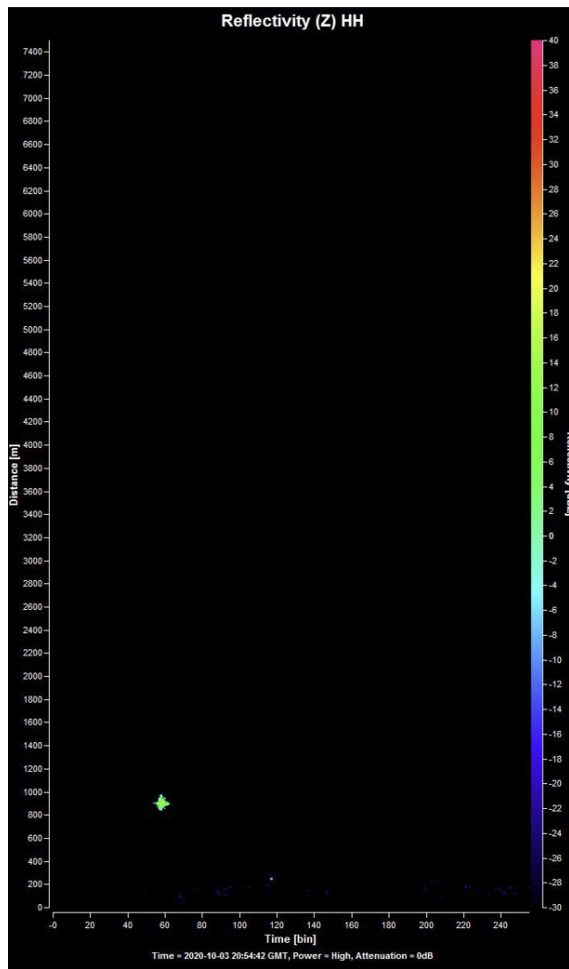


(a) Interference

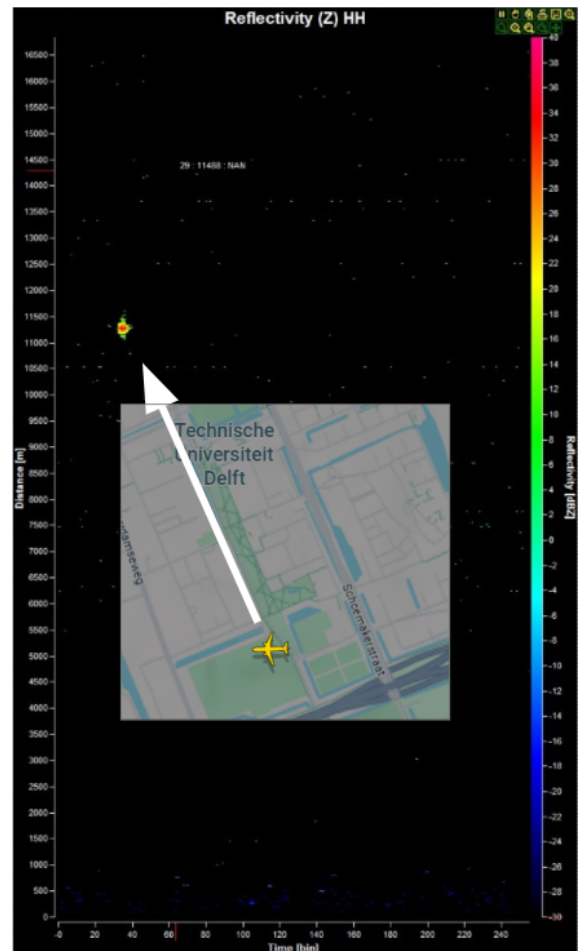


(b) Noise floor that is not correctly compensated

Figure A.2: Quick-looks of the timelines (1 bin = 0.512 sec) of the HH effective reflectivity with processing errors



(a) Birds



(b) Plane (Flightradar: 8:45 at 10050 m)

Figure A.3: Quick-looks of the timelines (1 bin = 0.512 sec) of the HH effective reflectivity profiles with reflection from a bird and an aircraft

Combined filter results

B

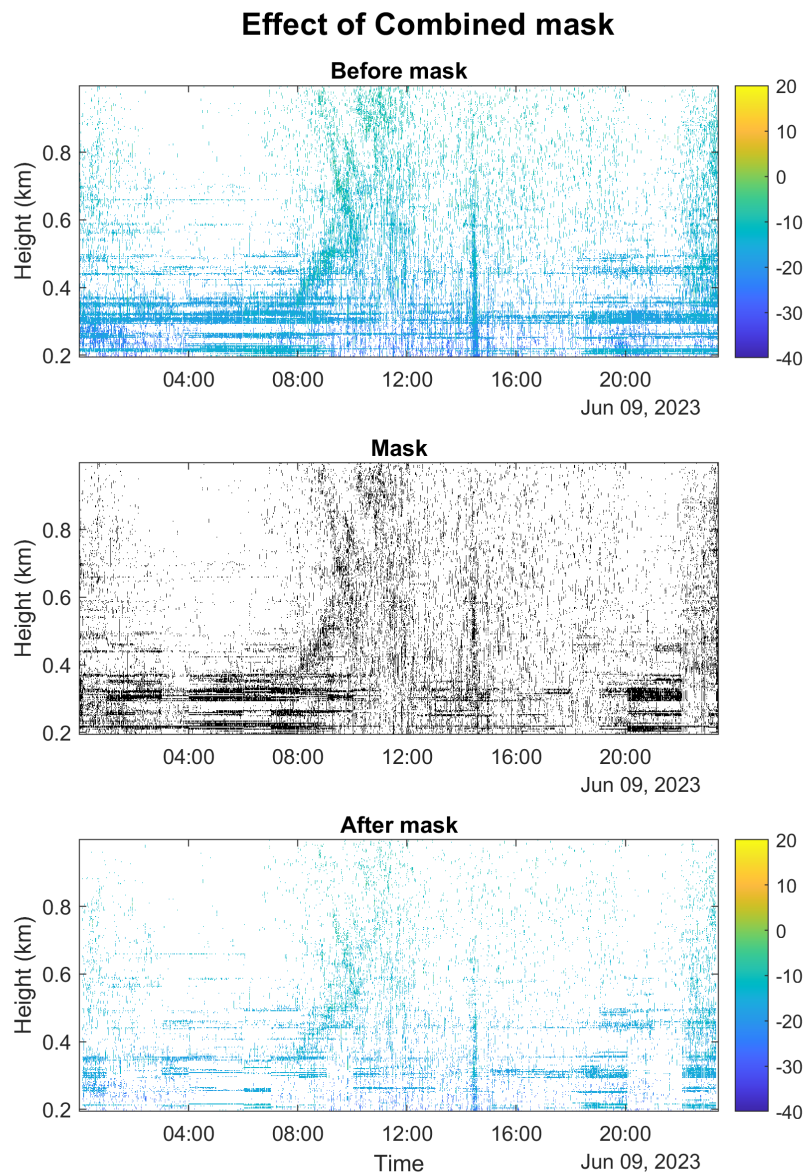


Figure B.1: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2023-06-09.

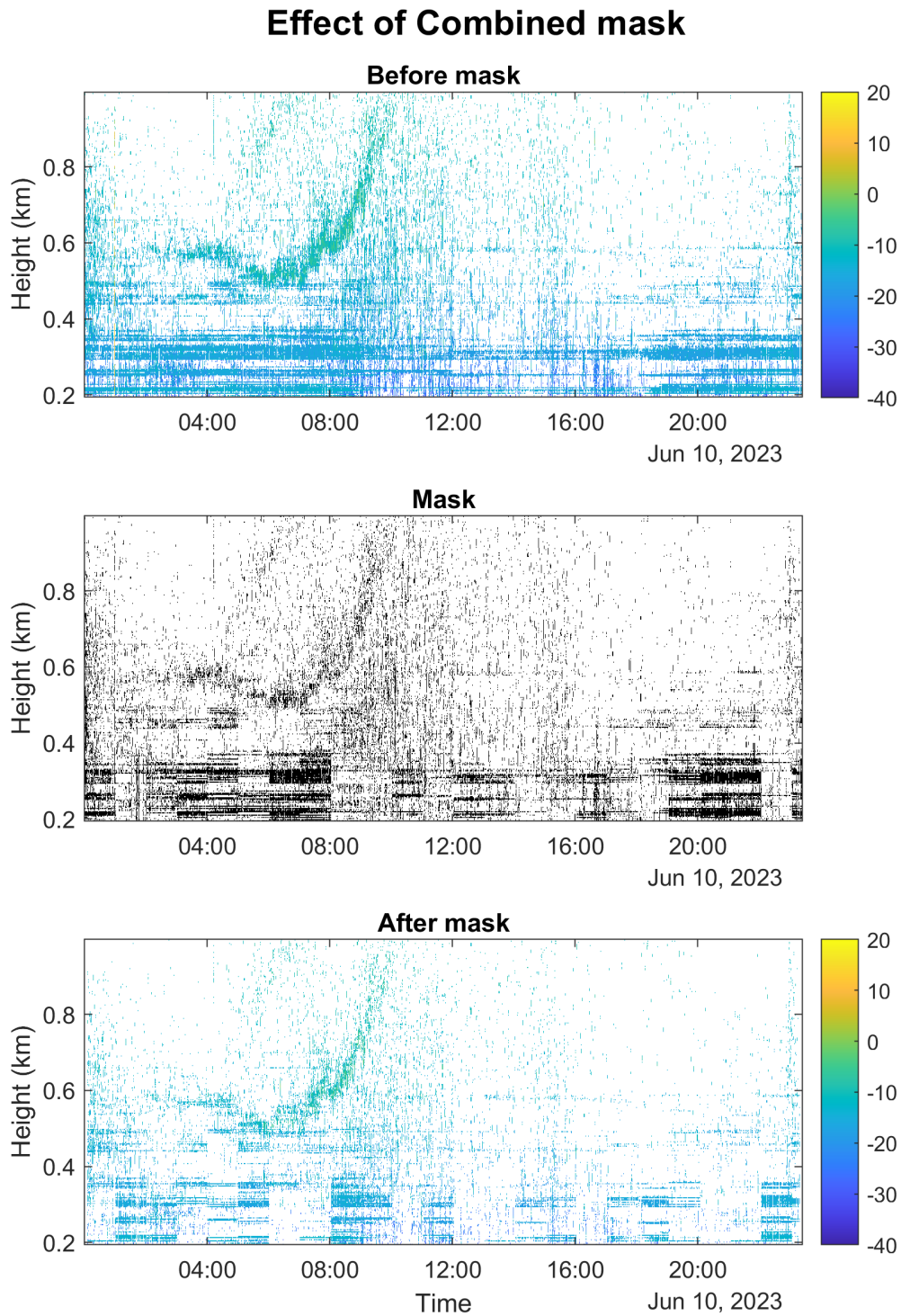


Figure B.2: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2023-06-10.

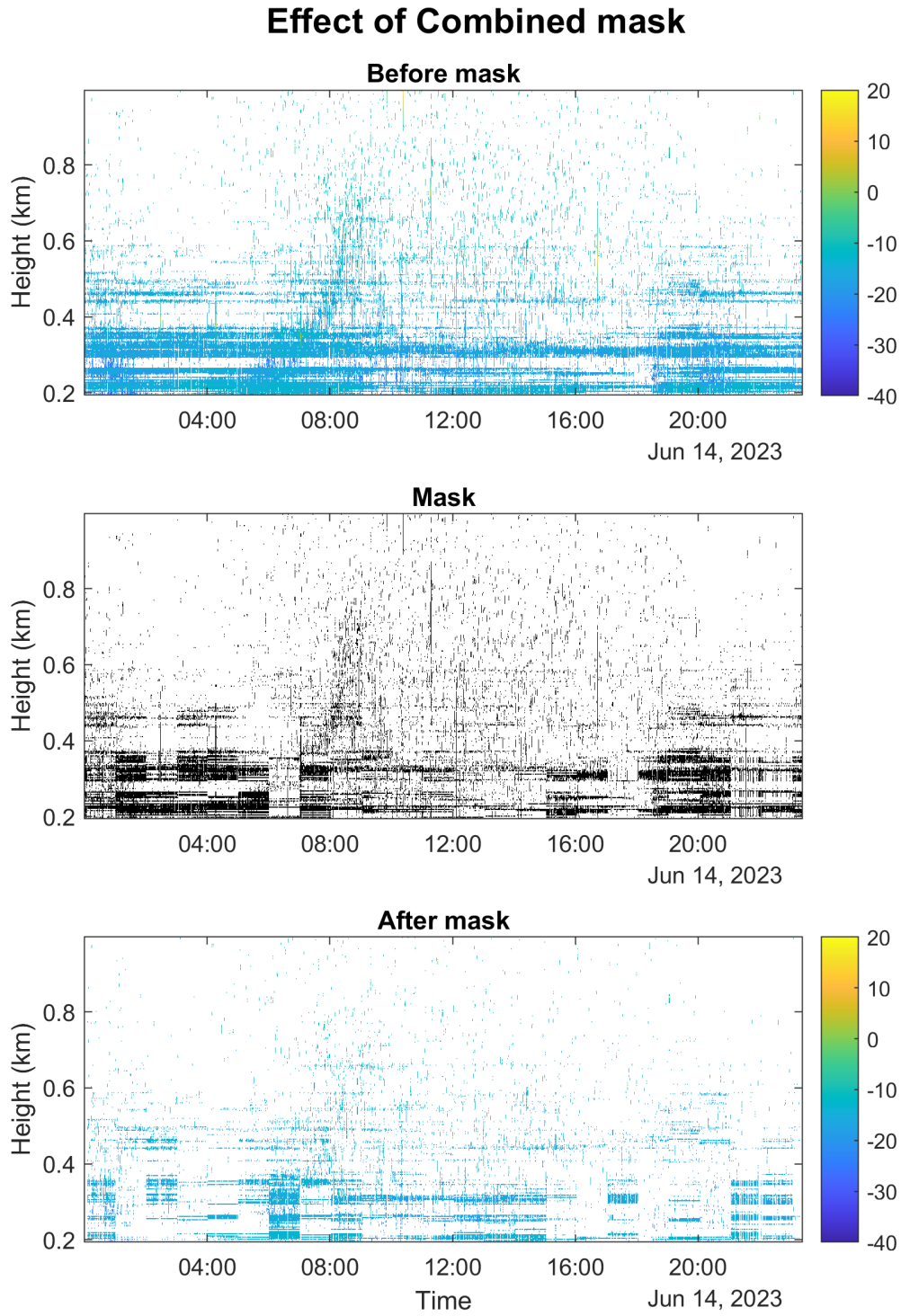


Figure B.3: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2023-06-14.

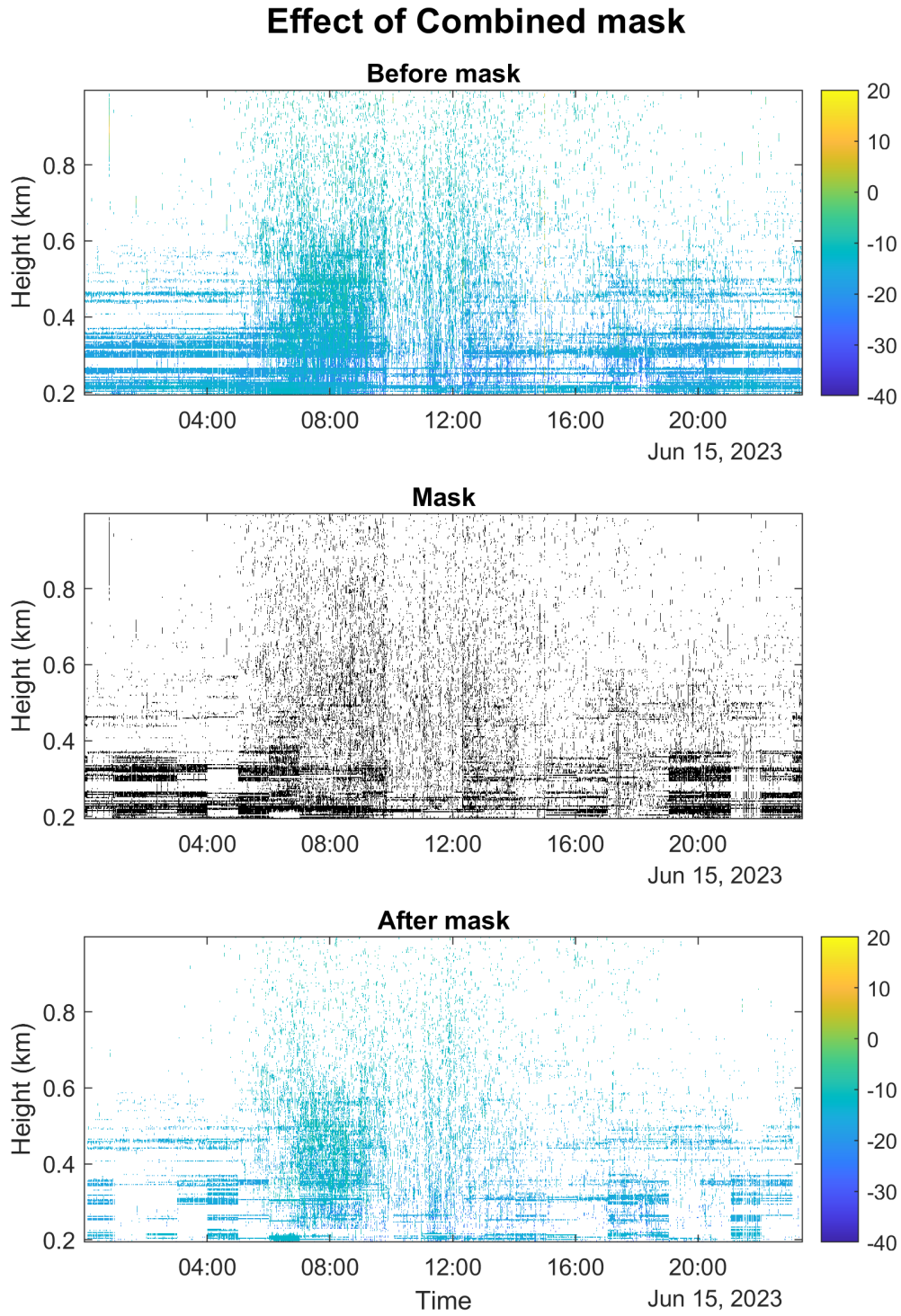


Figure B.4: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2023-06-15.

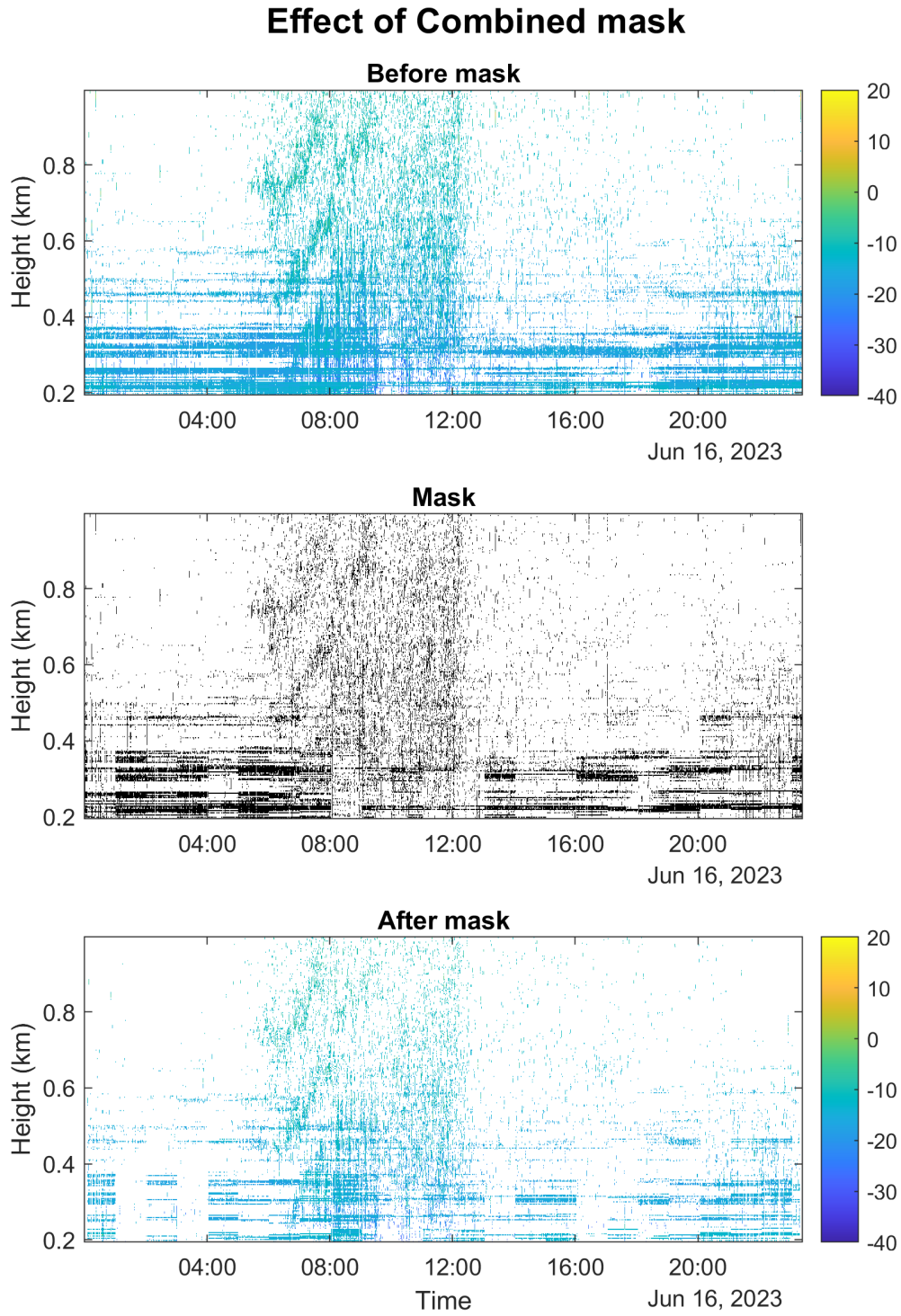


Figure B.5: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2023-06-16.

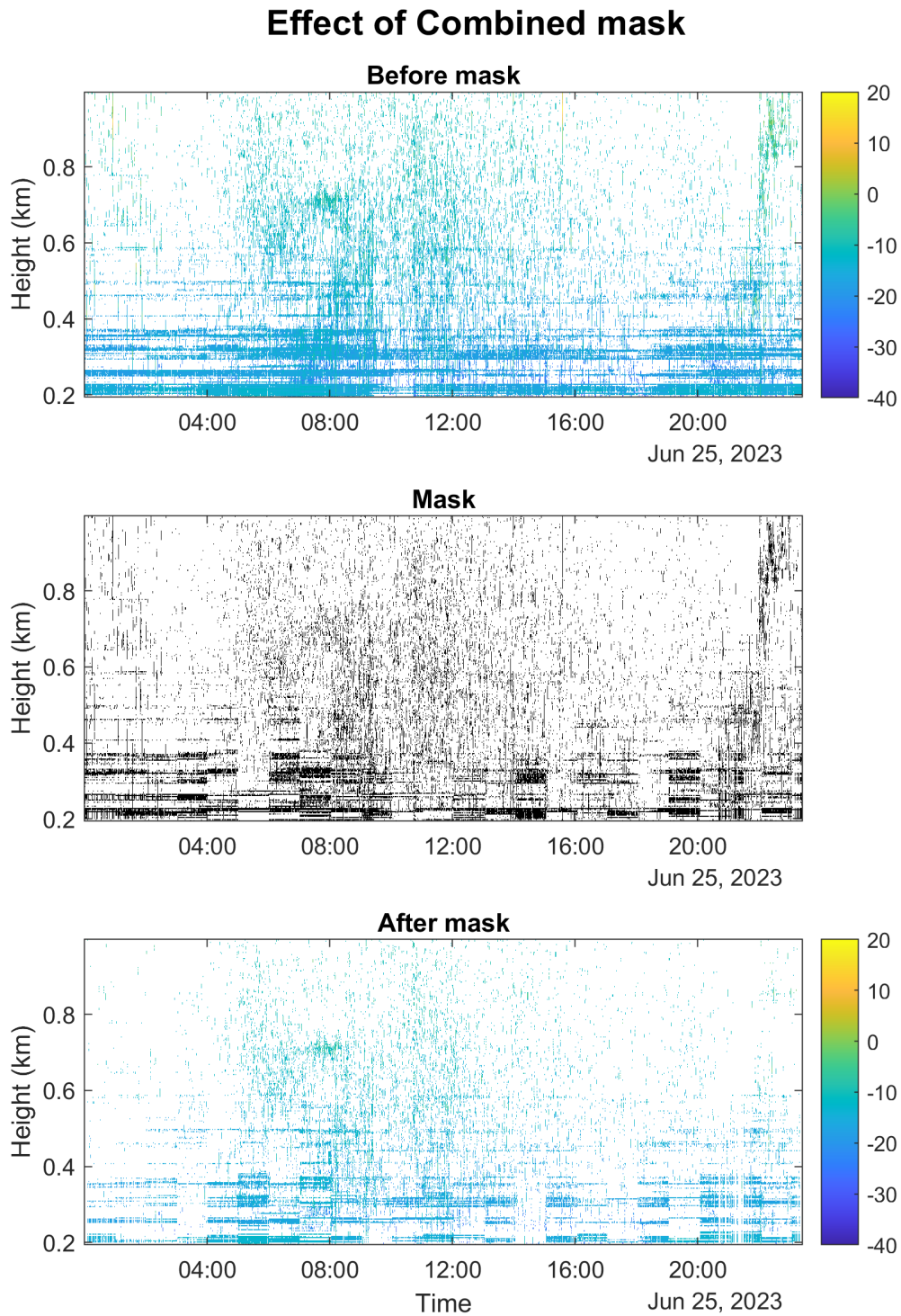


Figure B.6: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2023-06-25.

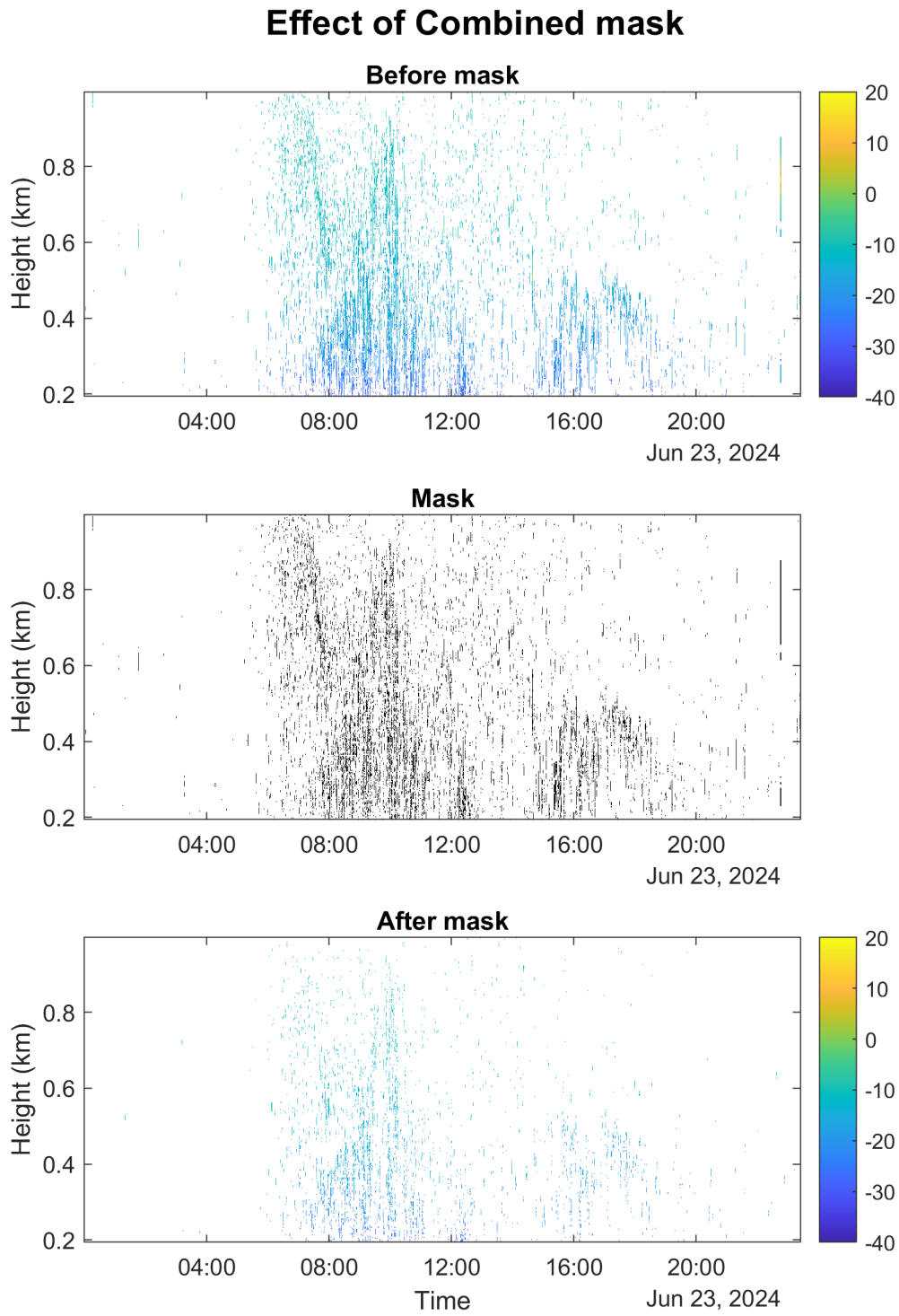


Figure B.7: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2024-06-23.

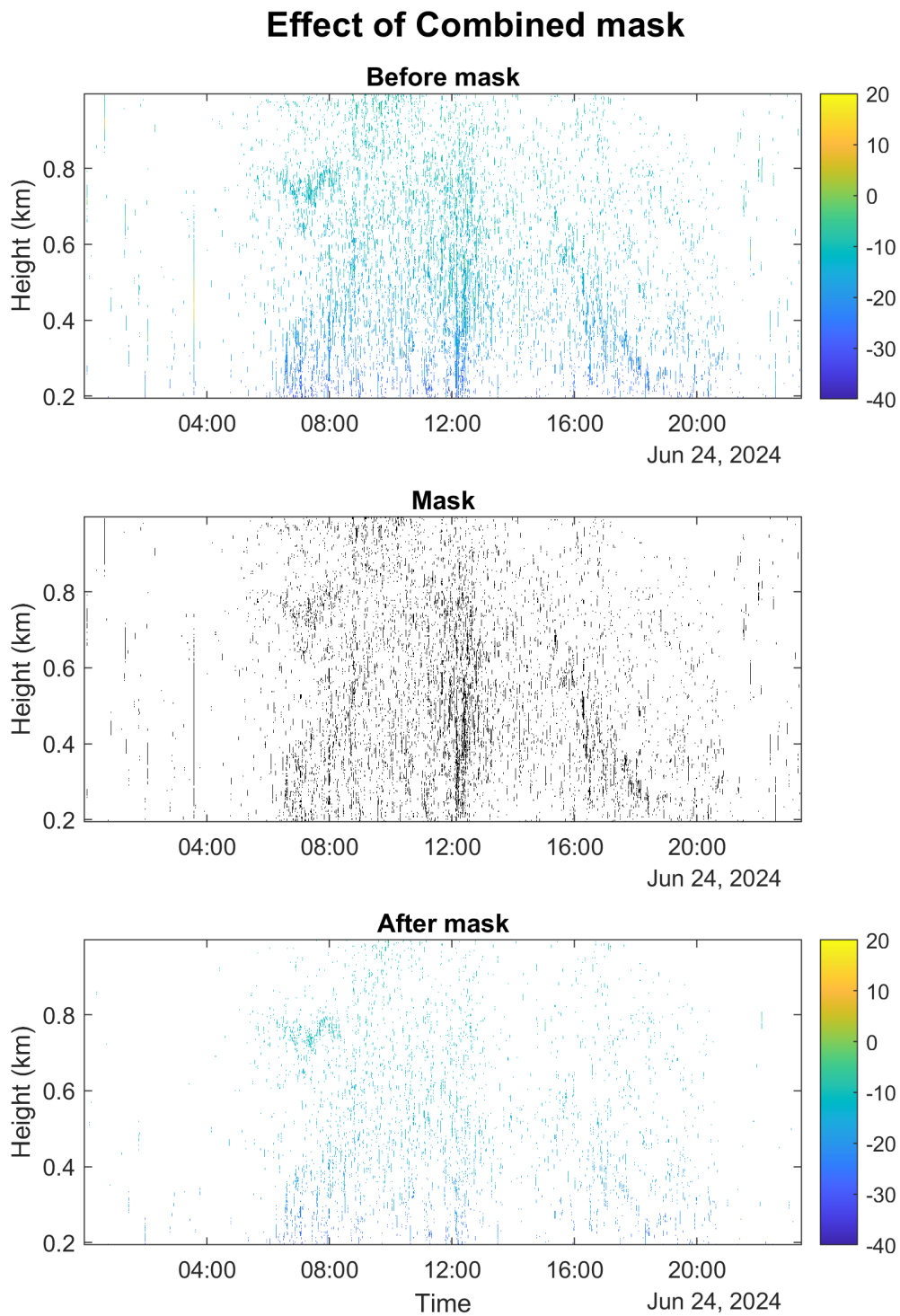


Figure B.8: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2024-06-24.

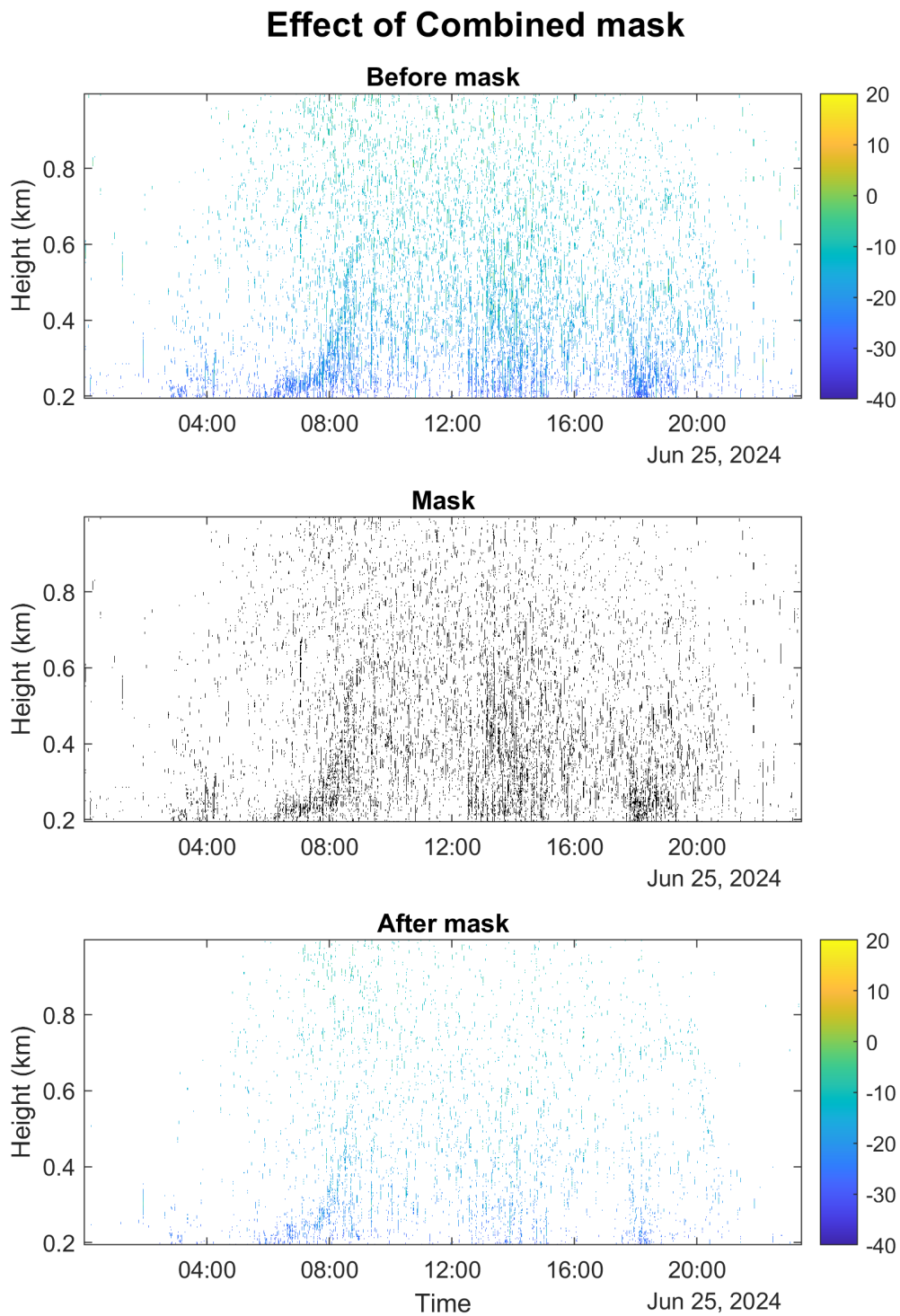


Figure B.9: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2024-06-25.

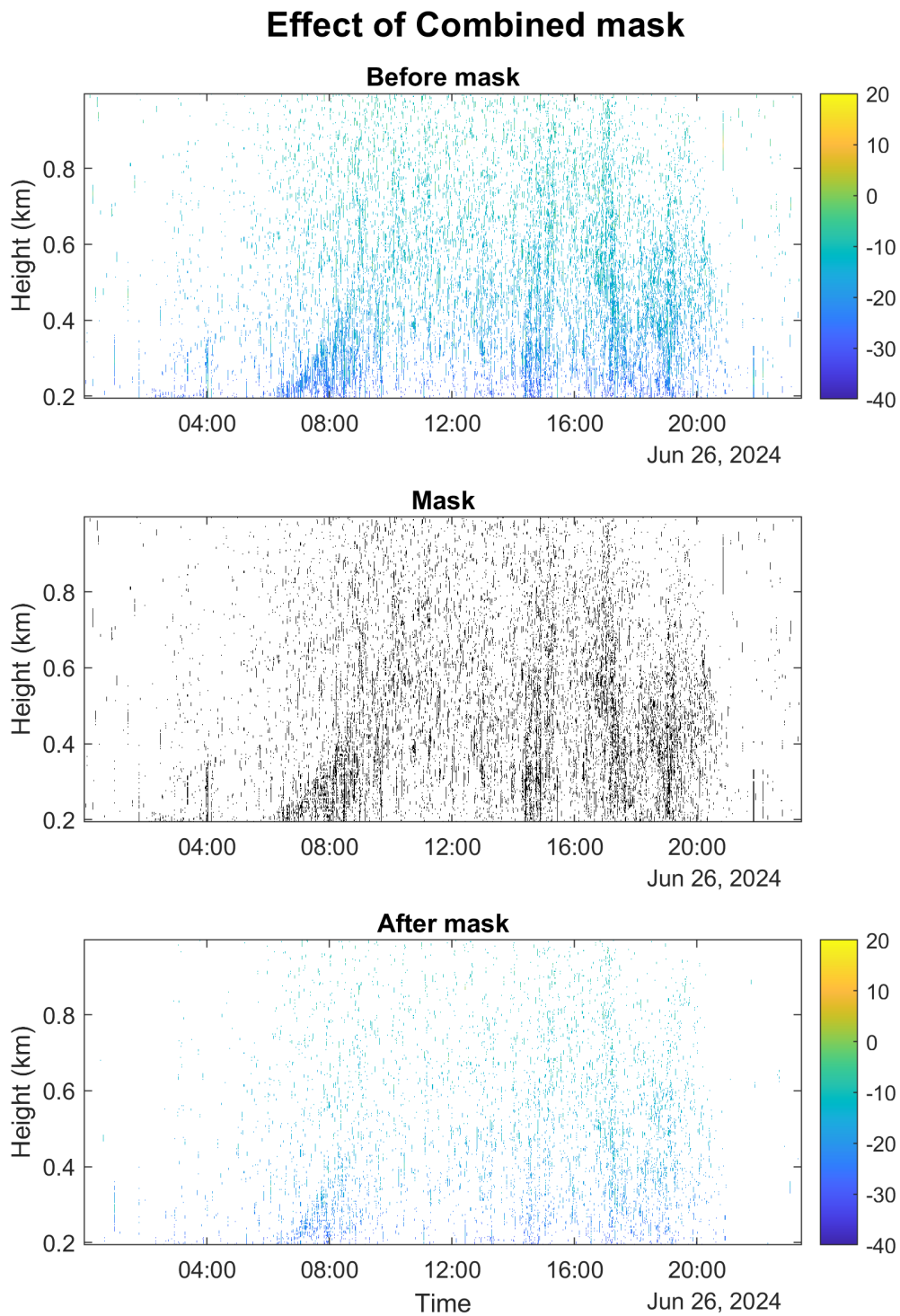


Figure B.10: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2024-06-26.

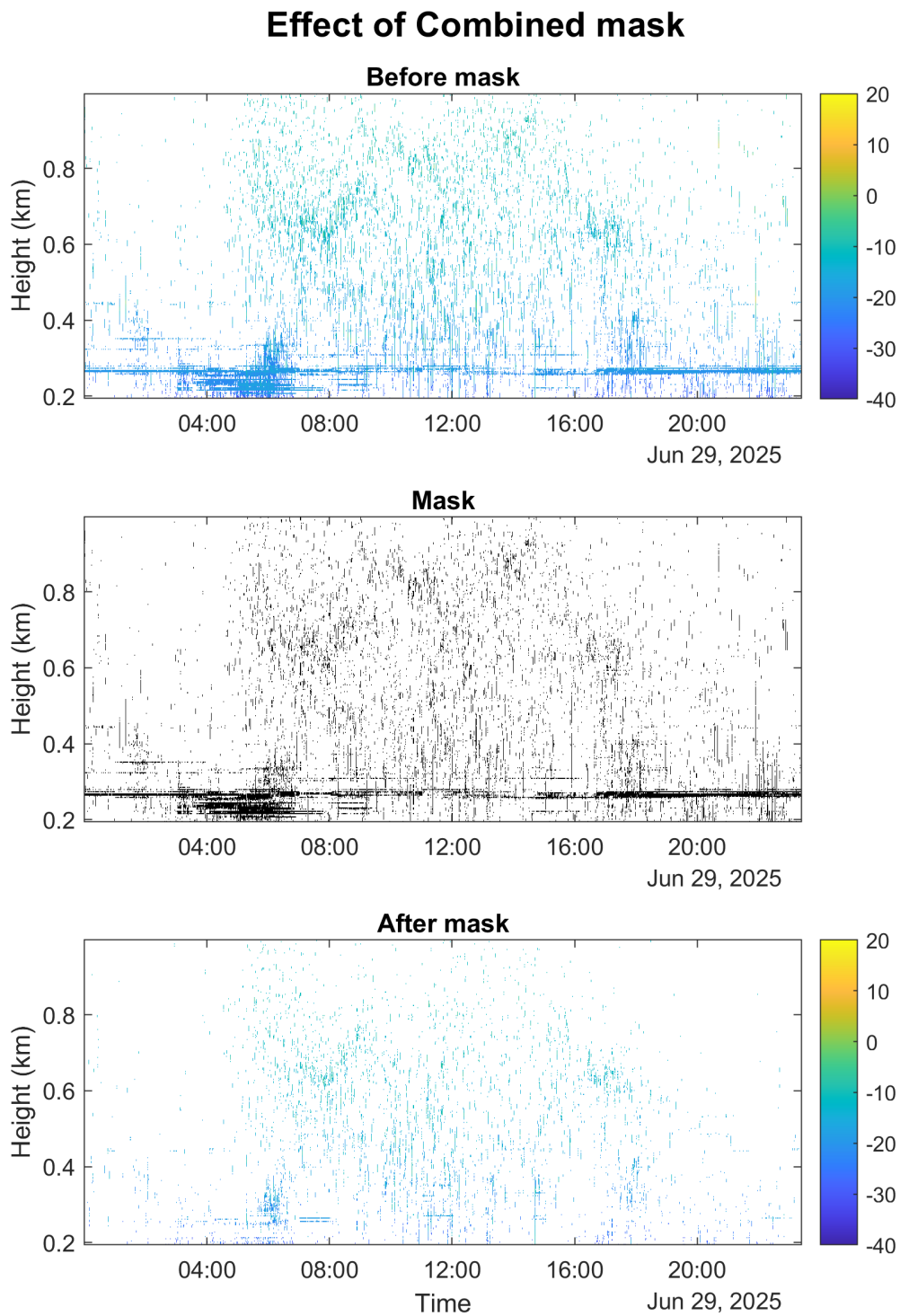


Figure B.11: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2025-06-29.

Effect of Combined mask

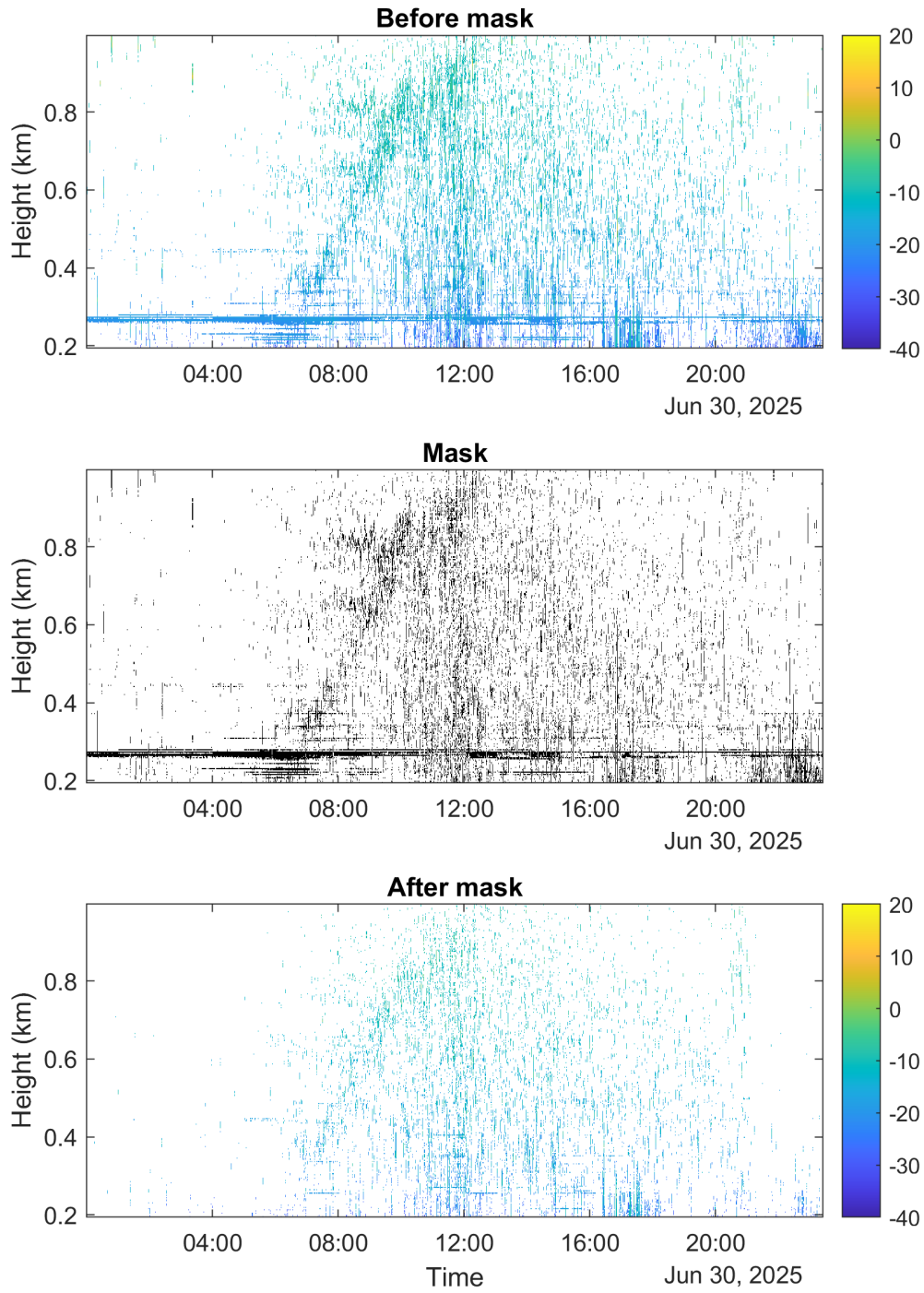


Figure B.12: Reflectivity HH before filtering, the combined filter mask, and Reflectivity HH after applying the combined filter for 2025-06-30.

Effect of separate filters

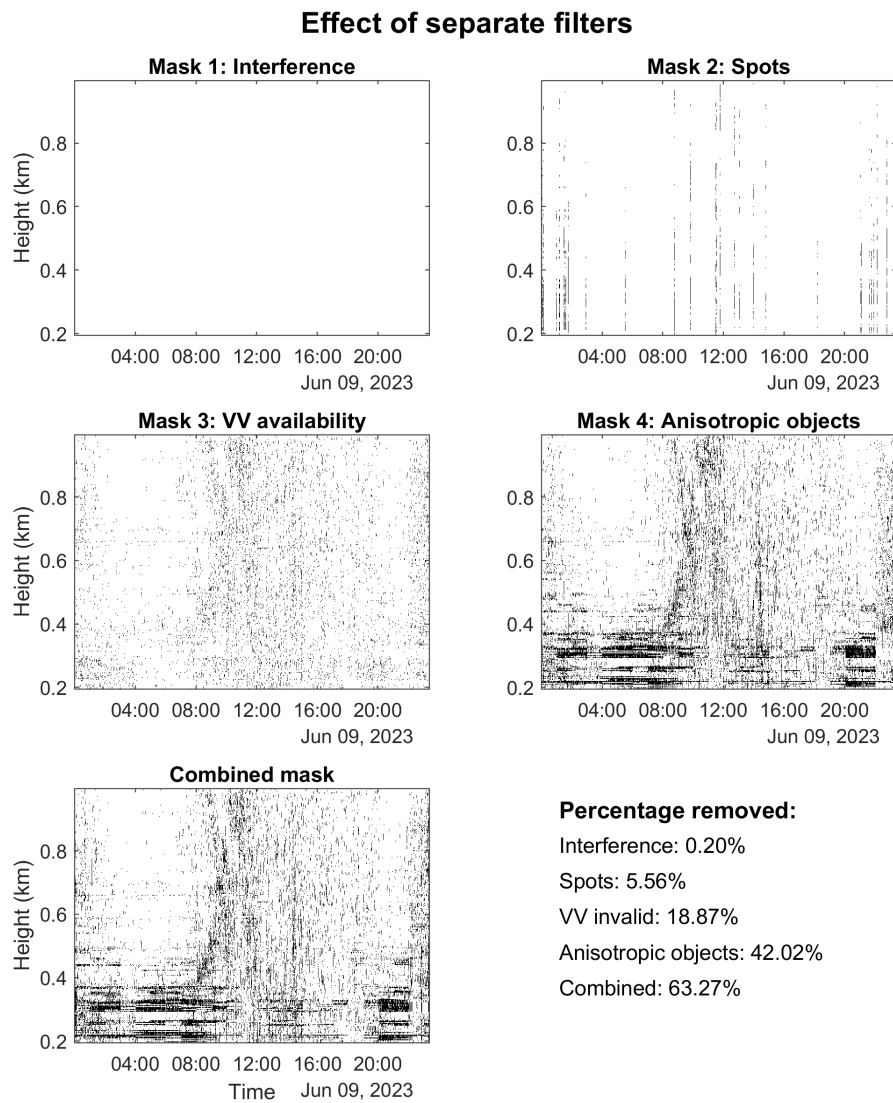


Figure C.1: Effect of the individual filters for 2023-06-09, including the percentage of bins removed relative to the total number of valid bins.

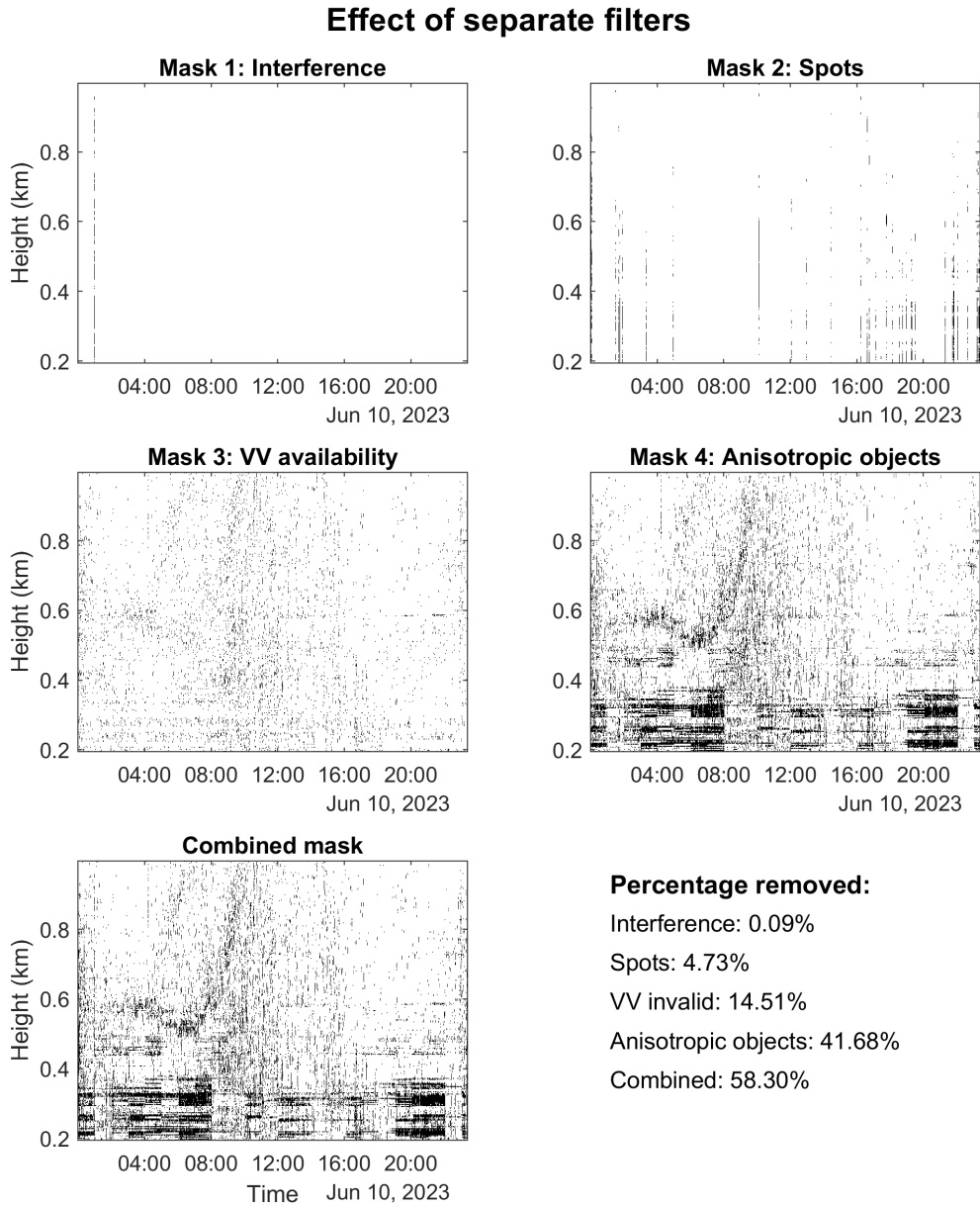


Figure C.2: Effect of the individual filters for 2023-06-10, including the percentage of bins removed relative to the total number of valid bins.

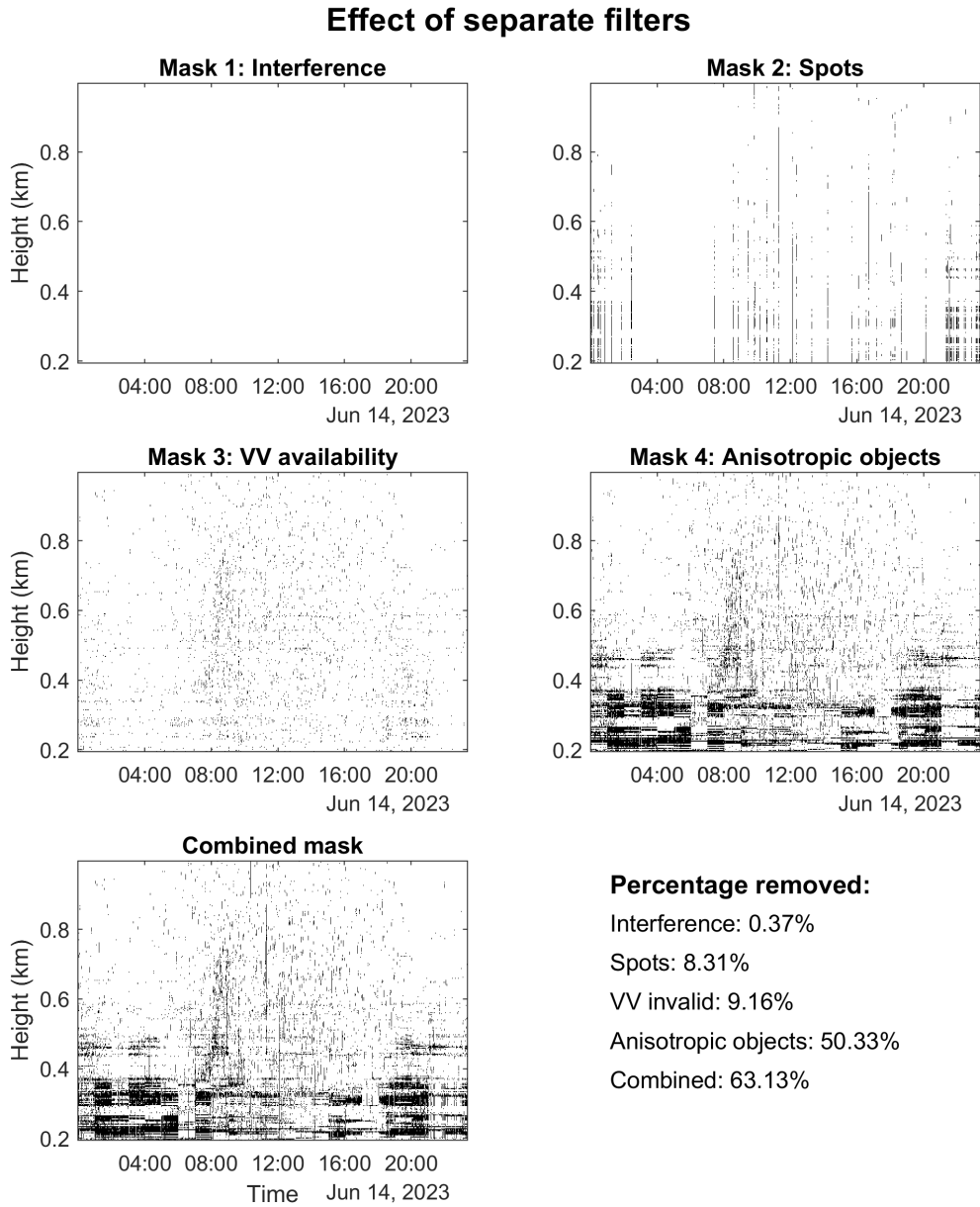


Figure C.3: Effect of the individual filters for 2023-06-14, including the percentage of bins removed relative to the total number of valid bins.

Effect of separate filters

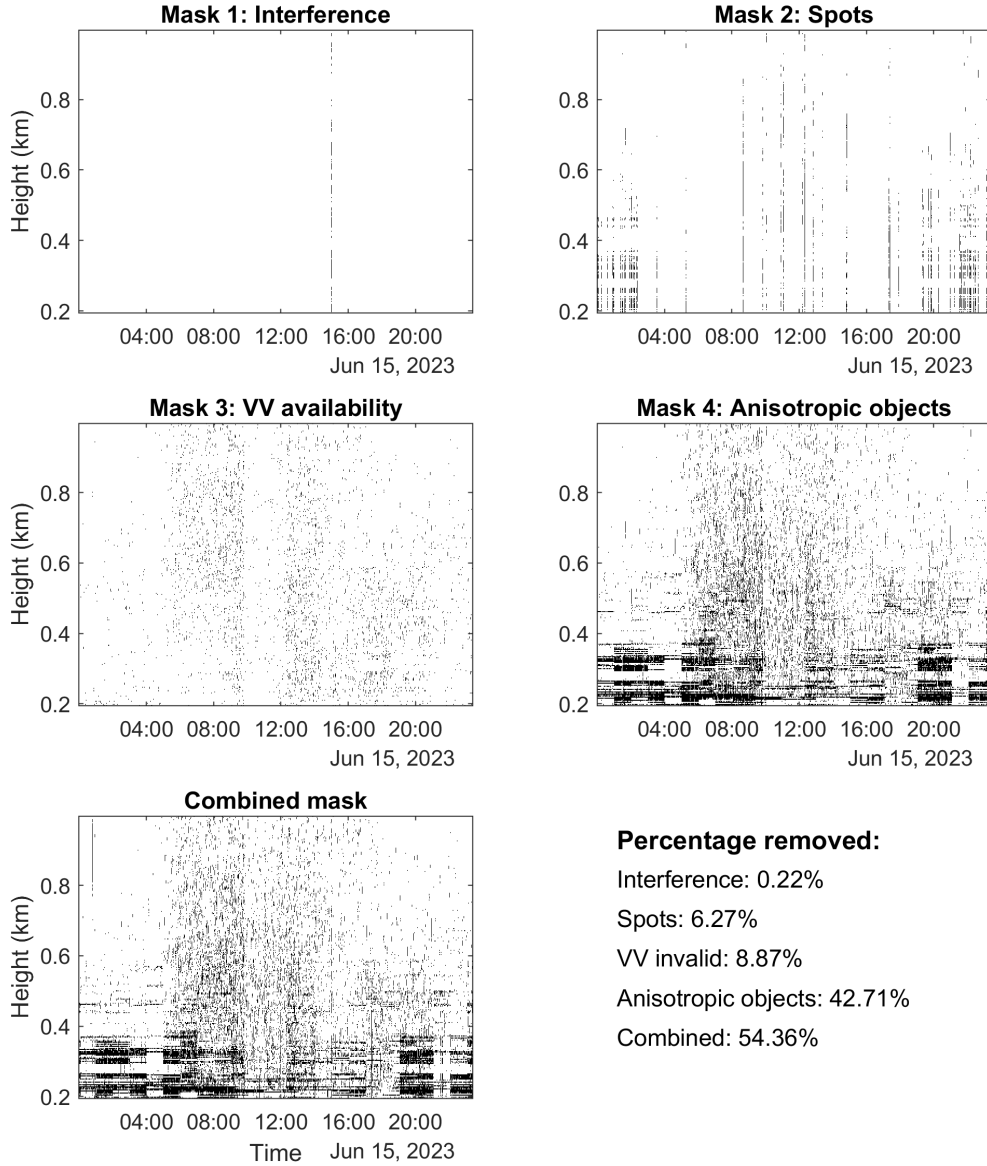


Figure C.4: Effect of the individual filters for 2023-06-15, including the percentage of bins removed relative to the total number of valid bins.

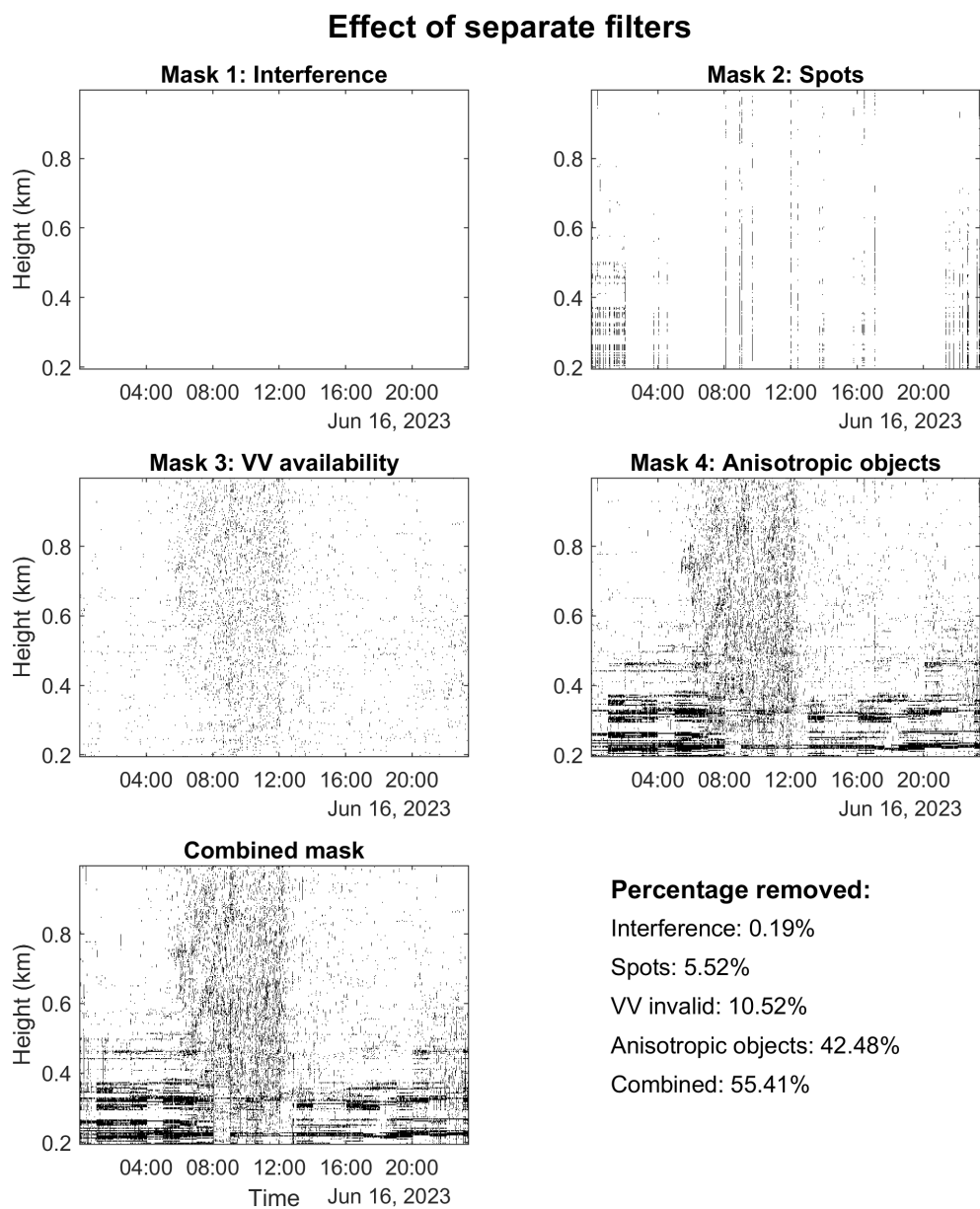


Figure C.5: Effect of the individual filters for 2023-06-16, including the percentage of bins removed relative to the total number of valid bins.

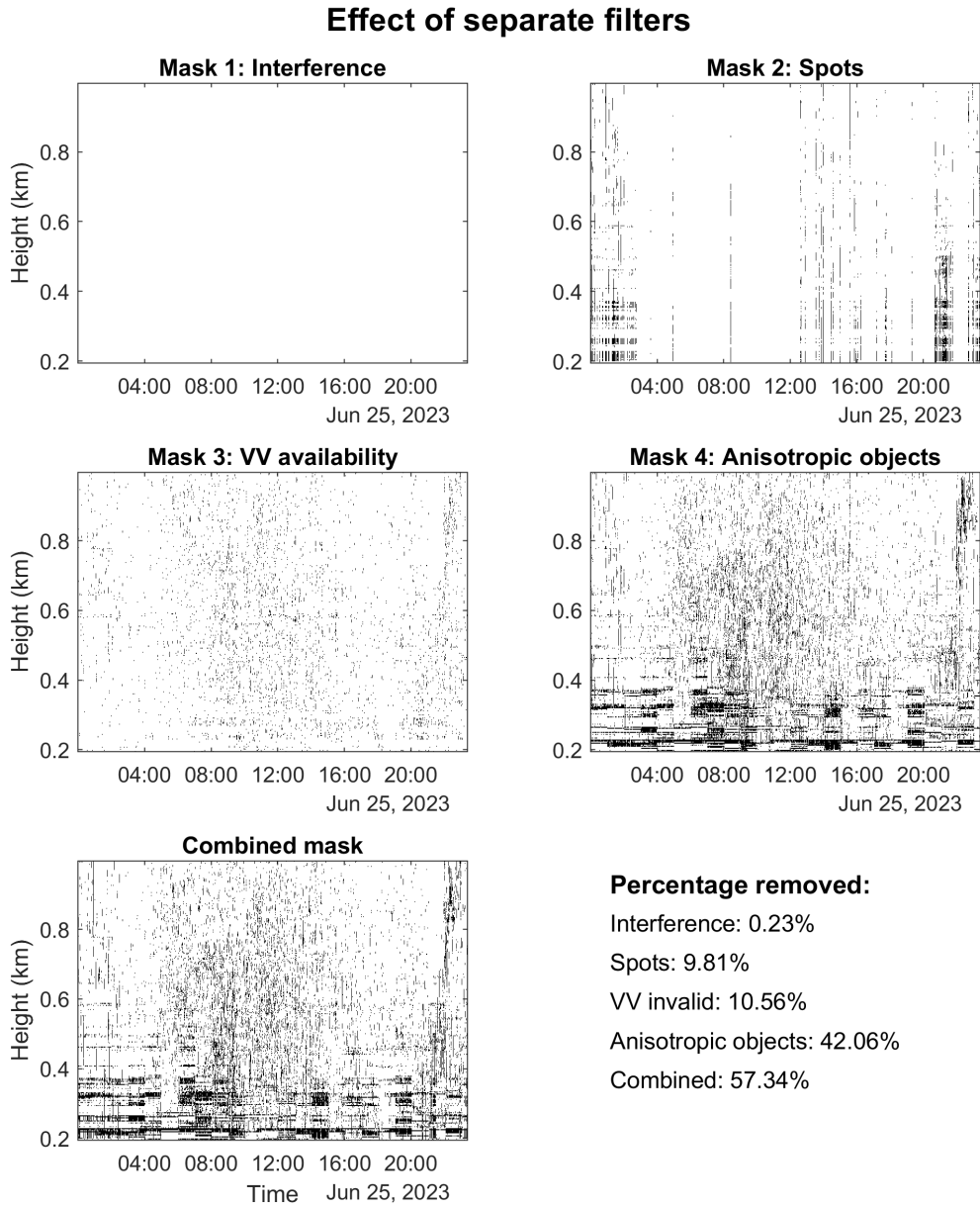


Figure C.6: Effect of the individual filters for 2023-06-25, including the percentage of bins removed relative to the total number of valid bins.

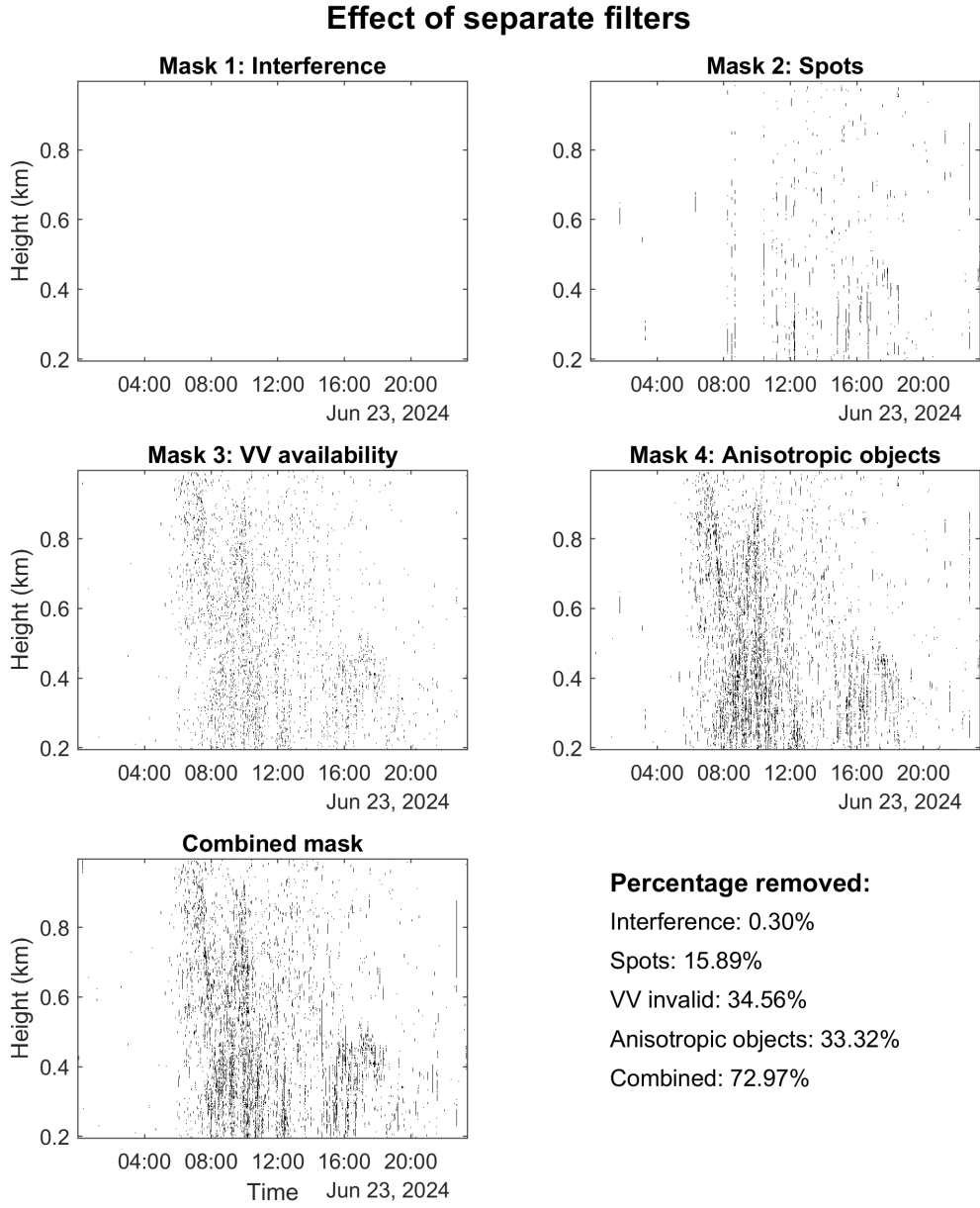


Figure C.7: Effect of the individual filters for 2024-06-23, including the percentage of bins removed relative to the total number of valid bins.

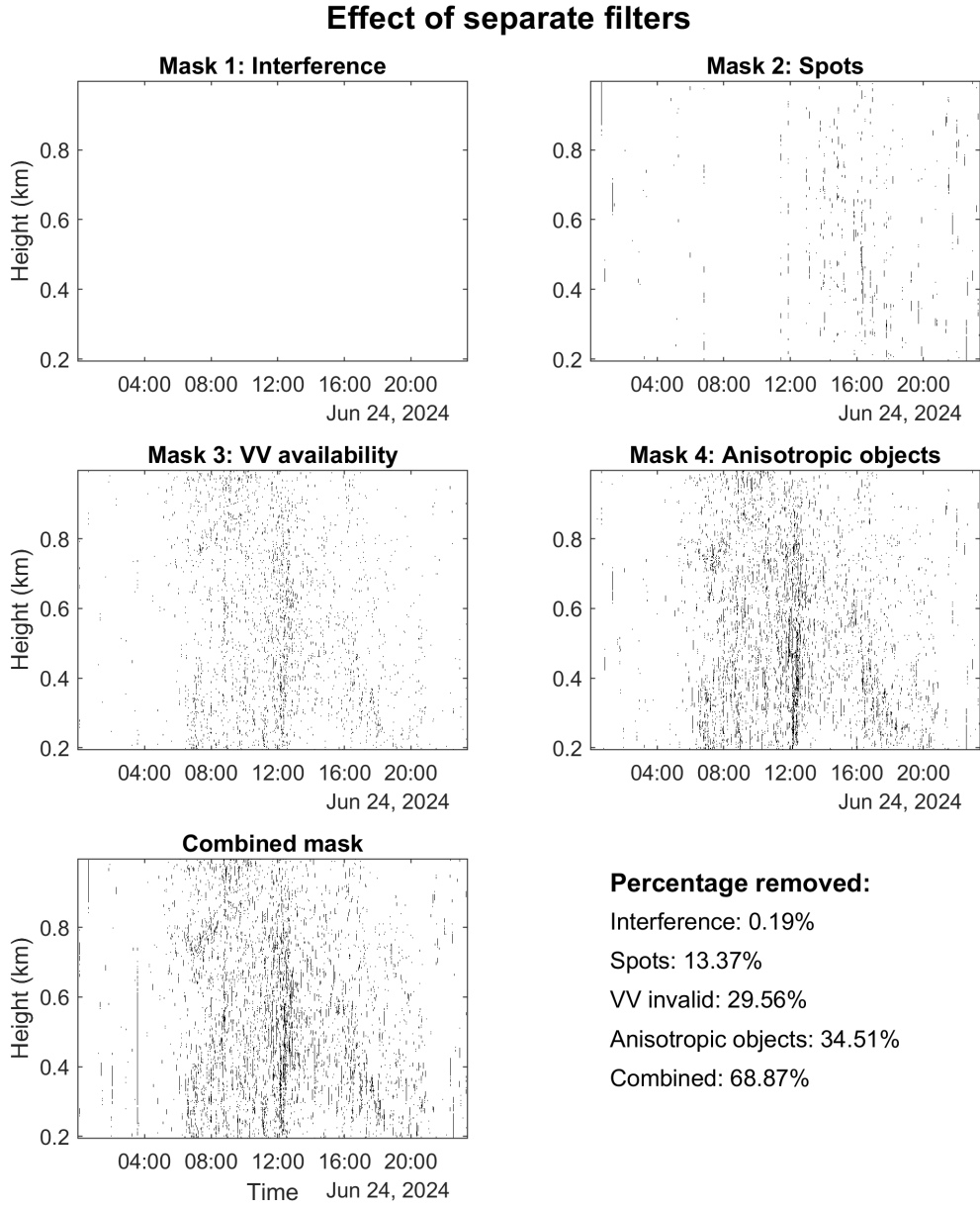


Figure C.8: Effect of the individual filters for 2024-06-24, including the percentage of bins removed relative to the total number of valid bins.

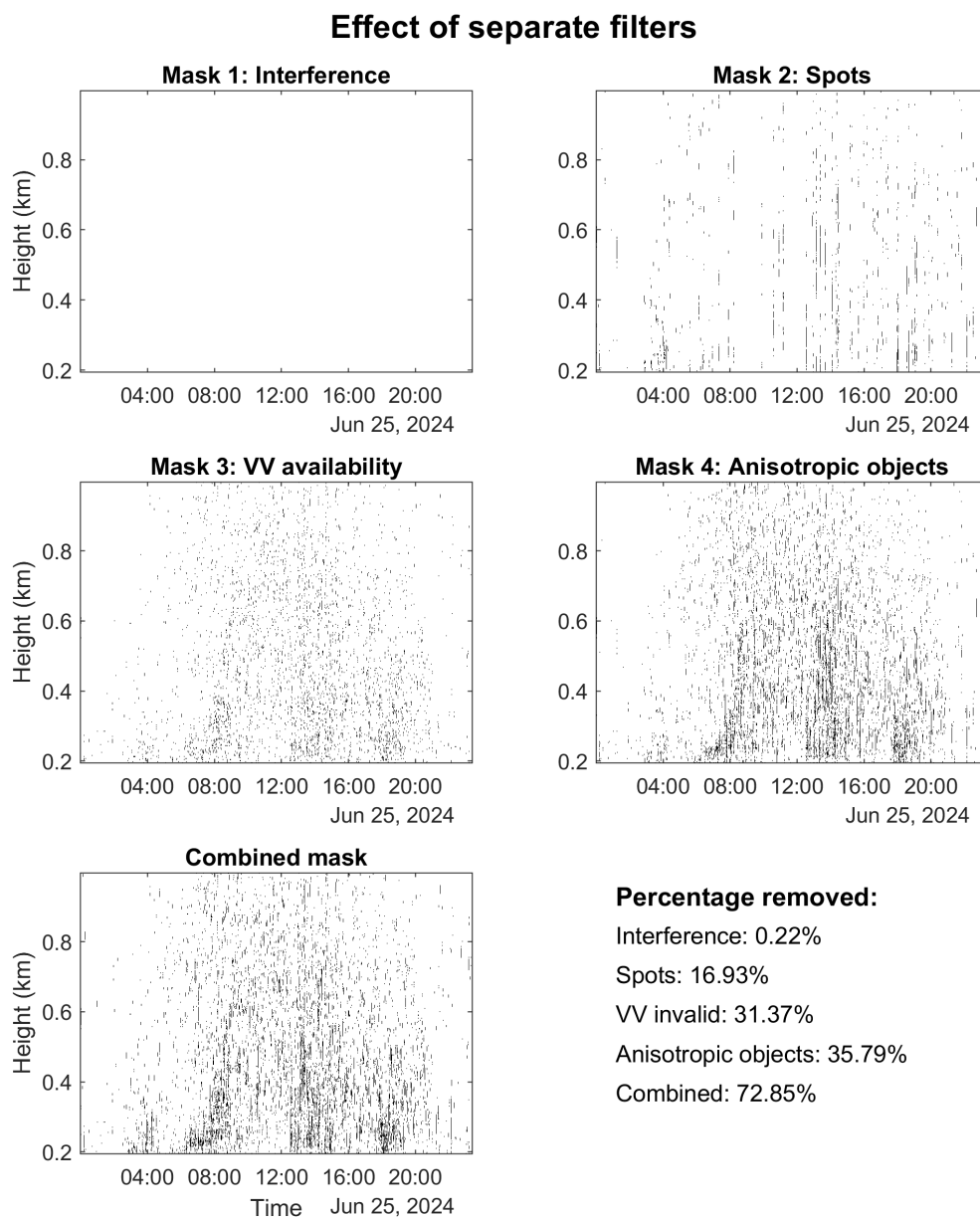


Figure C.9: Effect of the individual filters for 2024-06-25, including the percentage of bins removed relative to the total number of valid bins.

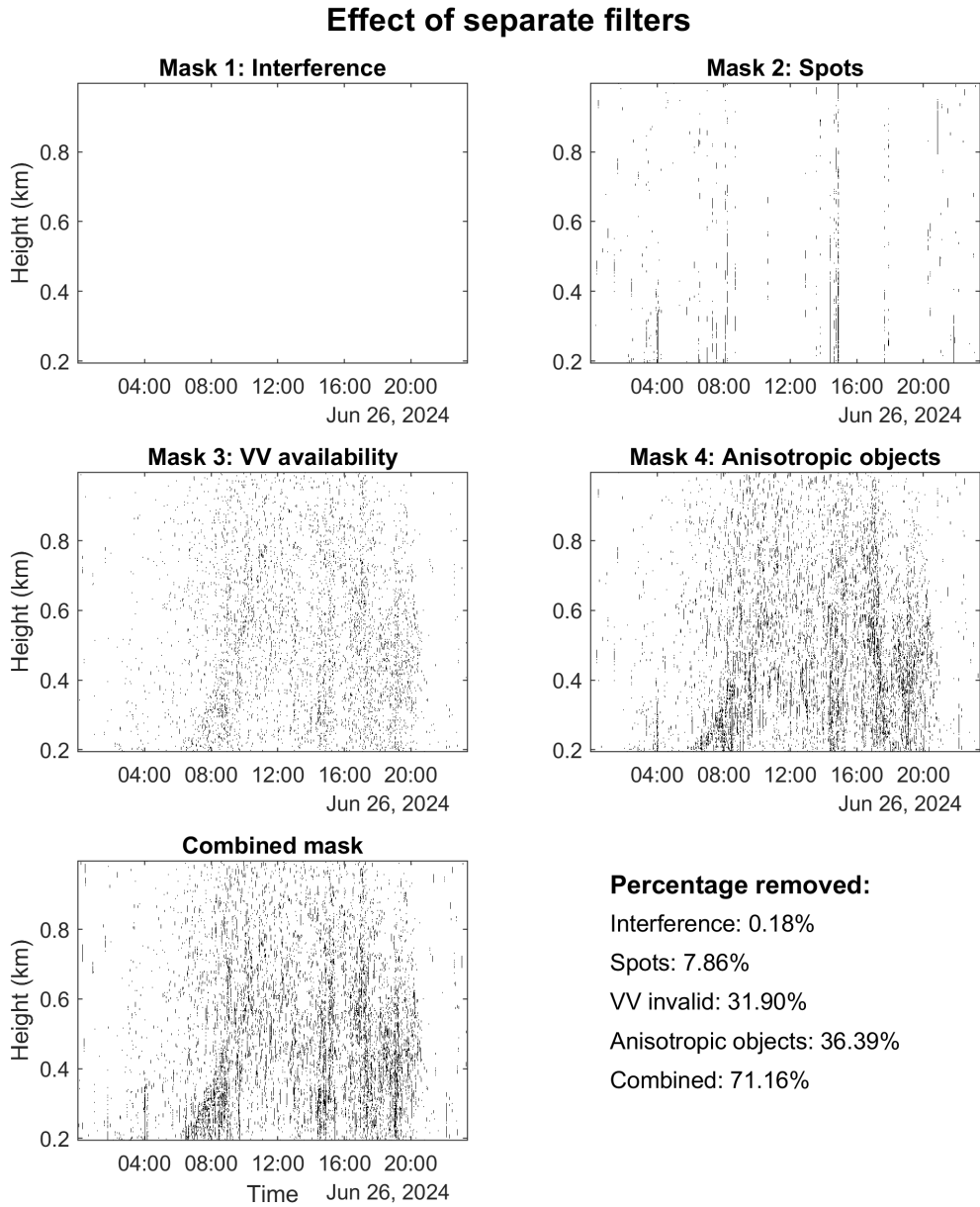


Figure C.10: Effect of the individual filters for 2024-06-26, including the percentage of bins removed relative to the total number of valid bins.

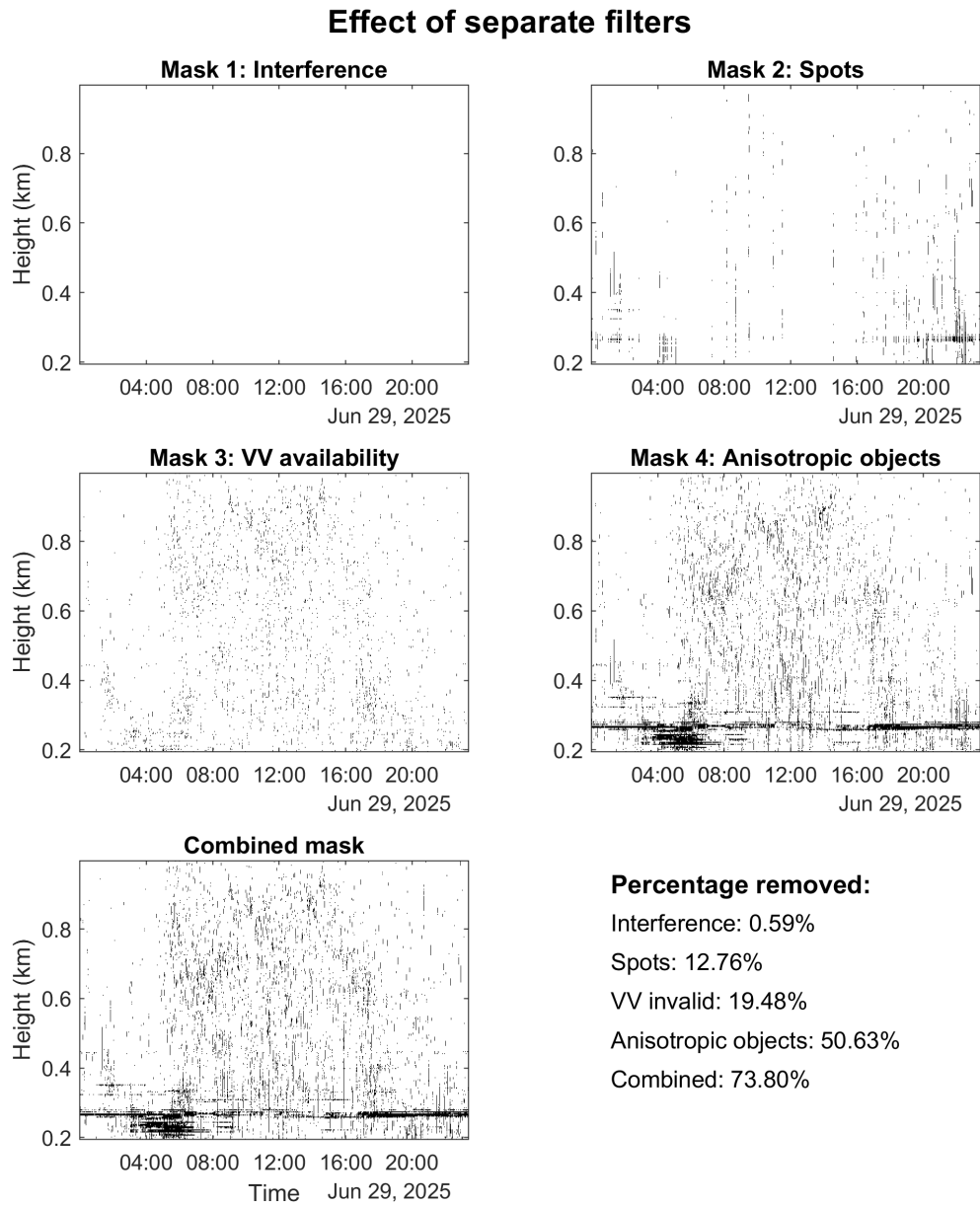


Figure C.11: Effect of the individual filters for 2025-06-29, including the percentage of bins removed relative to the total number of valid bins.

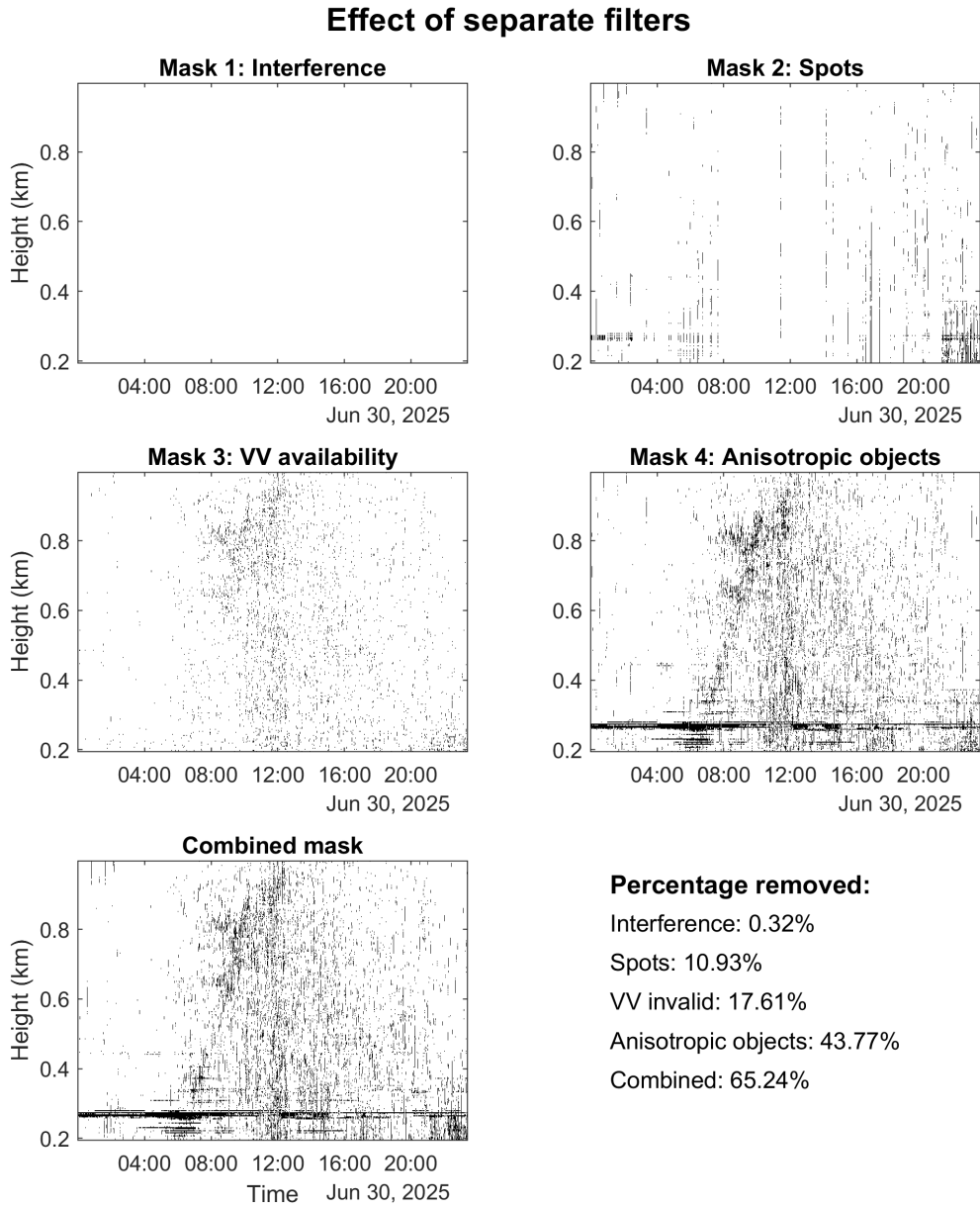
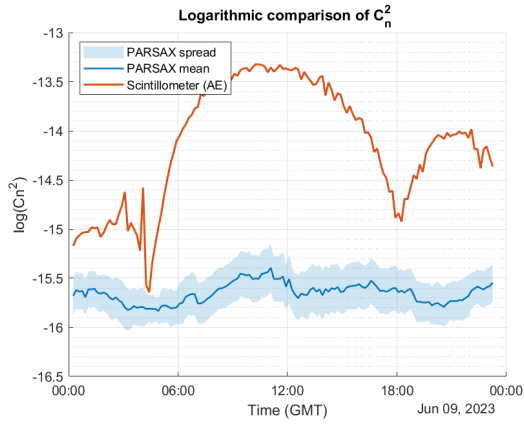


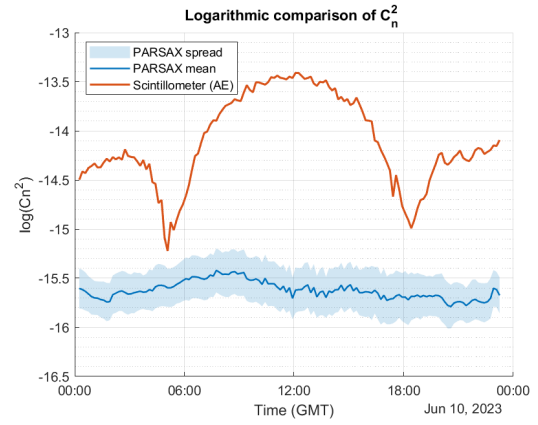
Figure C.12: Effect of the individual filters for 2025-06-30, including the percentage of bins removed relative to the total number of valid bins.

Comparison between PARSAX and scintillometer C_n^2

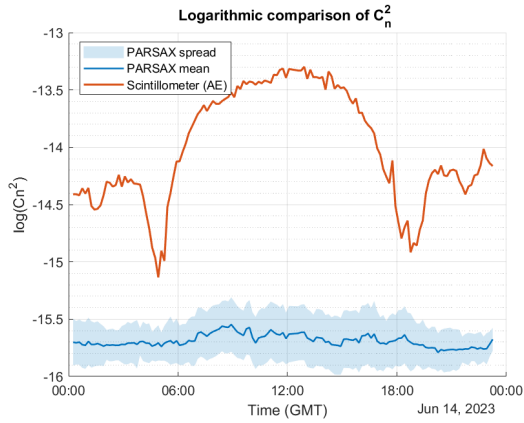
D



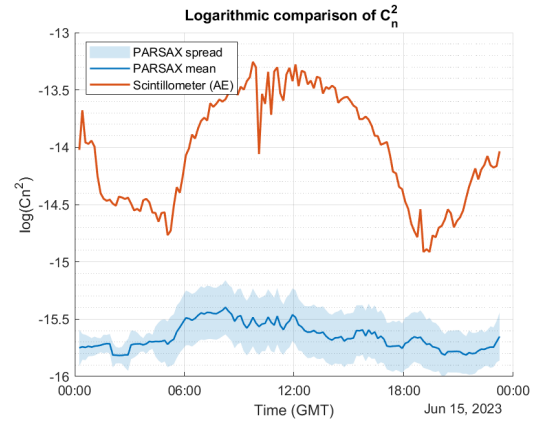
(a) 2023-06-09



(b) 2023-06-10

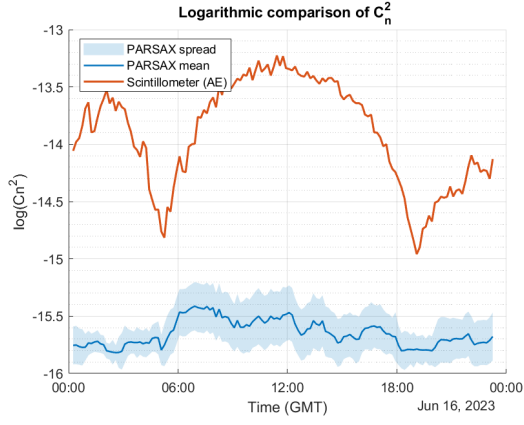


(c) 2023-06-14

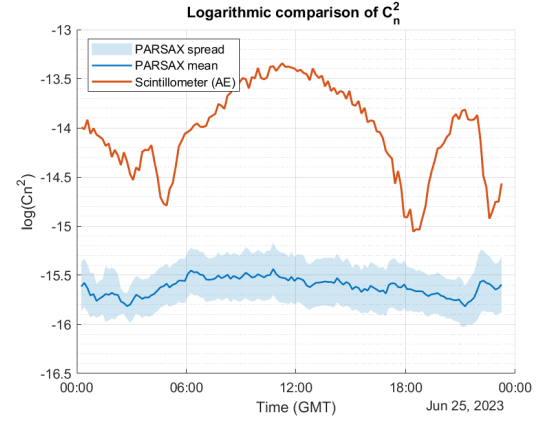


(d) 2023-06-15

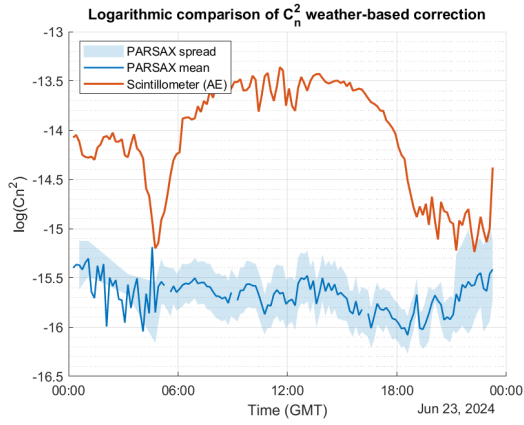
Figure D.1: Comparison between PARSAX-derived C_n^2 values and scintillometer validation data for four of the twelve selected days.



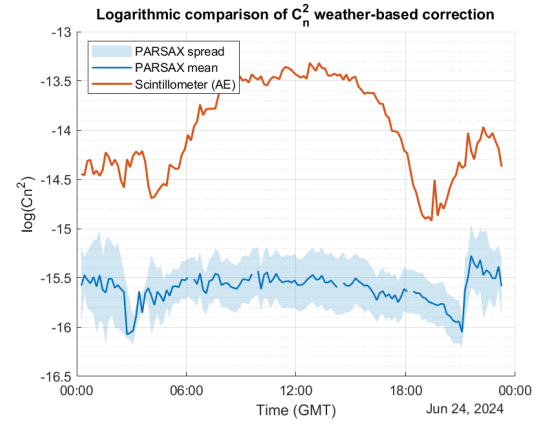
(a) 2023-06-16



(b) 2023-06-25

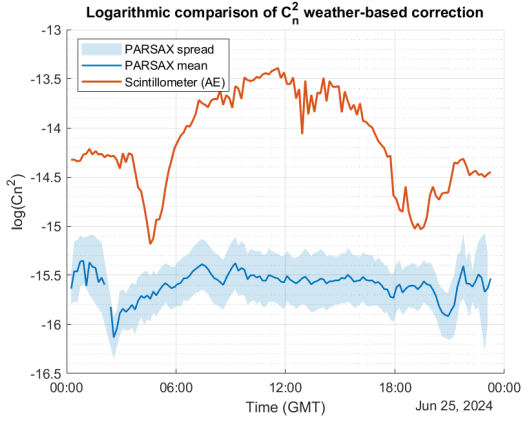


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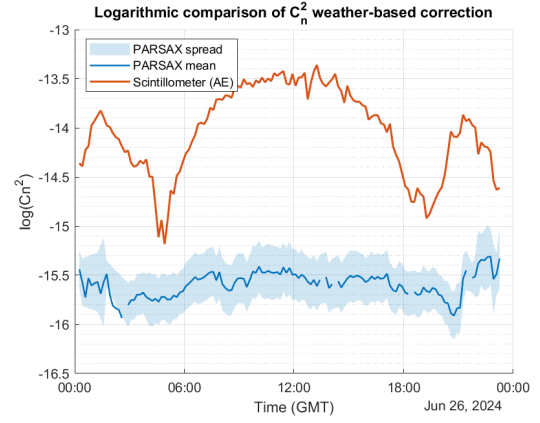


(d) 2024-06-24

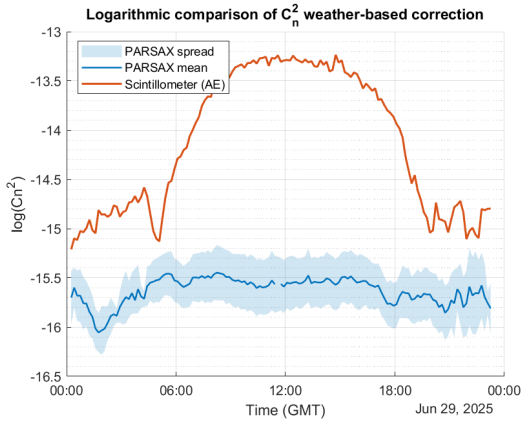
Figure D.2: Comparison between PARSAX-derived C_n^2 values and scintillometer validation data for four of the twelve selected days.



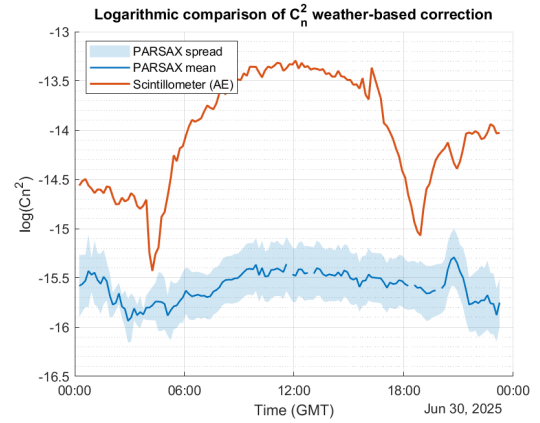
(a) 2024-06-25



(b) 2024-06-26



(c) 2025-06-29



(d) 2025-06-30

Figure D.3: Comparison between PARSAX-derived C_n^2 values and scintillometer validation data for four of the twelve selected days.