Statistical analysis of measurements of atmospheric turbulence in different climates

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\textbf{ABSTRACT}

Atmospheric turbulence may have a strong impact on the imaging quality of long range warning sensors and other electro-optical systems. Major effects are beam broadening, intensity fluctuations (or scintillation) and angle-of-arrival fluctuations. The structure constant of refractive index fluctuations, $C_n^2$, is the parameter most commonly used to describe the strength of atmospheric turbulence.

FGAN-FOM measured $C_n^2$ values in two different climates, moderate climate in mid-Europe, Germany and arid climate in Israel. The measurements in arid climate were carried out in co-operation with the EORD (Electro-Optics Research & Development Foundation Ltd.), TECHNION, Haifa, Israel. The measurements were performed with identical laser scintillometers along a horizontal optical path of about 100 m, above grassland in mid-Europe, and above stony ground without vegetation in Israel. The data were collected continuously for a time period of at least one year at a time resolution of 5 minutes.

For both climates examples of the diurnal cycle of $C_n^2$ are given. Since $C_n^2$ usually changes as a function of time-of-day and of season its influence on electro-optical systems can only be expressed in a statistical way. Therefore the cumulative frequencies of occurrence of $C_n^2$ were calculated for a time period of one month for both climates. These results were used to calculate the corresponding turbulence modulation transfer function (MTF) and point spread function (PSF) for a typical IR sensor with a Cadmium Mercury Telluride detector (CMT) and a UV sensor.

\textbf{Keywords:} atmospheric turbulence, structure constant of index of refraction $C_n^2$, turbulence modulation transfer function MTF, and point spread function PSF.

\section{INTRODUCTION}

One of the most important effects of atmospheric turbulence on electro-optical systems is the induced degradation of system resolving power. The modulation transfer function MTF is commonly used to describe the resolving power of a sensor as a function of the spatial frequency. The turbulence MTF characterizes the impact of optical turbulence to the overall spatial resolution of a sensor. Prediction of turbulence MTF is important for cost-effective design and sensor selection and gives a quantitative measure for expected sensor performance reduction.

$C_n^2$ is used to characterize turbulence MTF. Good image quality requires $C_n^2$ values to be as small as possible. As an example for highest respectively lowest atmospheric turbulence strength the $C_n^2$ values measured during a time period of an arbitrary selected summer respectively winter month were analyzed for two different climates, moderate climate in mid-Europe and arid climate in Negev, Israel. Calculations of turbulence MTF were carried out for a typical UV sensor in the solar blind region and a typical IR sensor in the spectral region of 4 $\mu$m. The selected $C_n^2$ values correspond to a cumulative frequency of occurrence of 60 \% and 90 \% in arid climate and in mid-Europe. Additionally the corresponding point spread functions PSF, which indicate the spatial power distribution of a point source in the detector plane, were calculated.

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2. THEORY

2.1 Atmospheric Turbulence
The turbulent atmosphere is a random medium with respect to variations of its physical properties in space and time. Generally turbulence is completely random, but there is a range from few millimeter (the inner scale of turbulence $l_0$) to a few meter (the outer scale $L_0$) in which turbulence is considered to be isotropic and homogeneous. The inner scale $l_0$ is the small-scale size at which wind viscosity becomes dominant and energy is dissipated into heat. The outer scale $L_0$ represents the distance at which correlation goes to zero. Representative values of $L_0$ are from tens to a few hundred meters. In strong turbulence $l_0$ decreases.

The structure constant of refractive index fluctuations, $C_n^2$, is the parameter most commonly used to describe the strength of atmospheric turbulence. $C_n^2$ is governed by the fluctuation of the refractive index of air. For optical frequencies the refractive index of air, $n$, is given by Clifford:

$$n = 1 + 77.6 \left( 1 + 7.52 \times 10^{-3} \lambda^{-2} \right) \frac{P}{T} \times 10^{-6},$$

(1)

where $\lambda$ is the wavelength in micrometer, $p$ is atmospheric pressure in hPa, and $T$ is the temperature in Kelvin. In the visible and in the IR fluctuations of $n$ are mainly caused by temperature fluctuations.

The fluctuations of the refractive index of air can be generally characterized by a refractive index structure function $D_n(r)$, given by Tatarski:

$$D_n(r) = \left\langle [n(r_1) - n(r_2)]^2 \right\rangle$$

(2)

where $n(r_1)$ and $n(r_2)$ are the refraction indices at two points $r_1$ and $r_2$ separated by distance $r$, and $\langle \rangle$ denotes ensemble averaging. Similarly, the fluctuations of the temperature can be generally characterized by a temperature function, $D_T(r)$:

$$D_T(r) = \left\langle [T(r_1) - T(r_2)]^2 \right\rangle$$

(3)

where $T(r_1)$ and $T(r_2)$ are the temperatures at two points $r_1$ and $r_2$ separated by distance $r$.

The structure functions are described by the Kolmogorov-Obukhov two-thirds law:

$$D_n(r) = C_n^2 \cdot r^{2/3} \quad \text{for} \quad l_0 < r < L_0$$

(4)

$$D_T(r) = C_T^2 \cdot r^{2/3} \quad \text{for} \quad l_0 < r < L_0$$

(5)

where $C_n^2$ is the structure constant of refractive index fluctuations and $C_T^2$ is the structure constant of temperature fluctuations.

$C_n^2$ decreases with increasing height above ground. There are several formulae describing the height profile of $C_n^2$.

- For heights $h < 9$ m the height profile for $C_n^2$ can be simply approximated by the formula:

$$C_n^2 \sim h^{-4/3} \quad \text{during day}$$

$$C_n^2 \sim h^{-2/3} \quad \text{during night}$$

2.2 Turbulence Modulation Transfer Function MTF and Point Spread Function PSF
The MTF yields a quantitative estimate for degradation of a target resolution of an electro-optical system. The contribution of atmospheric turbulence to the time dependent MTF of an imaging system is given by Azoulay to be:

$$MTF_{\text{tur}} (\xi, \tau) = \exp \left[ - \frac{\lambda \xi}{\rho_p(\tau)} \right]^{1/3}$$

(6)

with spatial frequency $\xi$ and wavelength $\lambda$ were the time dependent effective coherence length $\rho_p(\tau)$ is given by

$$\rho_p(\tau) = \rho_p \left[ 1 + 0.37 \left( \frac{\rho_p}{D_0 + V \cdot \tau} \right)^{1/3} \right]$$

(7)
with the effective aperture diameter $D(\tau) = D_0 + v_c \tau$, were $v_c$ is the crosswind velocity and $\tau$ the exposure time. The effective aperture diameter $D(\tau)$ varies between the aperture diameter $D$ of the electro-optical system for very short integration time and infinity for extremely long exposure time.

For a uniform path were $C_n^2$ is constant the transverse coherence length $\rho_p$ is given by:

$$\rho_p = \left[ 21.614 \cdot C_n^2 \frac{L}{\lambda^2} \right]^{1/5}$$

(8)

with propagation distance $L$.

The point spread function PSF indicates the spatial irradiance distribution of a point source in the detector plane. Assuming no phase shift the point spread function PSF can be calculated by applying the inverse Fourier transformation to the MTF:

$$PSF(x,y) = F^{-1}[MTF(\xi)]$$

(9)

If the MTF is fitted to a Gauss function, then the standard deviation of the PSF, $\sigma_{PSF}$, can be calculated by the formula:

$$MTF_{Fs} = \exp\left(-2\pi^2 \sigma_{PSF}^2 r^2 \right)$$

(10)

The standard deviation of the PSF, $\sigma_{PSF}$, can be used to describe the degradation of the spatial resolution of the sensor due to atmospheric turbulence. The energy within such a deviation of radius $\sigma_{PSF}$ is 68 % of the total one.

3. EXPERIMENT

Measurements of $C_n^2$ values were performed with two identical laser scintillometers in moderate climate, mid-Europe, Germany, and in arid climate, Israel. The systems were SLS-20 laser scintillometers manufactured by Scintec GmbH, Germany. The laser scintillometer uses the independently measured scintillation of two displaced but parallel laser beams to derive $C_n^2$ and $l_0$. The source is a 1 mW laser diode with a wavelength of 670 nm and divergence of approximately 5 mrad. The dynamic range for $C_n^2$ measurements covers values from $1 \cdot 10^{-16}$ up to $3 \cdot 10^{-12}$ m$^{-2/3}$.

The scintillometers provided $C_n^2$ values integrated over the optical path length of 100 m. In mid-Europe $C_n^2$ values were measured at a height of 1.25 m over grassland m (weighted toward the centre of the path). For technical reason in arid climate $C_n^2$ measurements were carried out at a height of 2.2 m above ground without vegetation (only stones and sandy soil). To compare the results of both measurements the $C_n^2$ values measured at a height of 2.2 were scaled to 1.25 m.

All data were collected continuously for a period of at least one year at a time resolution of 5 minutes. The data were stored in daily files with 288 data sets. The utilization of the laser scintillometer is limited by atmospheric attenuation. For the case of dense fog and precipitation like rain and snow fall the laser beam may not be detected and in the output file the corresponding $C_n^2$ value is set equal zero. Each $C_n^2$ value is averaged over 100 measurements during the time interval of 5 minutes. $C_n^2$ values equal to zero or averaged over less than 20 measurements had to be suppressed for the evaluation.

4. ANALYSIS OF $C_n^2$ MEASUREMENTS IN ARID CLIMATE AND IN MID-EUROPE

Temperature and humidity fluctuations are known to be the primary mechanism affecting the index of refraction and thus the atmospheric turbulence. For wavelengths in the visible and IR temperature fluctuations are dominant.

In day-time the solar radiation warms up the ground and the air. The temperature gradient between ground and atmosphere results in a turbulent vertical air stream. Higher ground temperature usually leads to larger temperature gradient and hence to stronger turbulence. Temperature gradient is generally greatest at midday when the ground is warmer than the overlying air, thus increasing $C_n^2$. High relative humidity is usually related to small temperature and small humidity gradients and hence to weaker turbulence. Surface roughness increases temperature gradient and thus $C_n^2$. Wind causes air mixing and therefore decreases the inhomogeneity of temperature and humidity and hence
decreases $C_n^2$. Increasing wind also enhances the dissipation of ground heating, which causes decreasing temperature gradient and $C_n^2$. When air temperature is closest to ground temperature, mainly at sunrise, $C_n^2$ shows minimum value.

During night there is no heating of the ground and the air, the temperature gradient is smaller and hence the vertical heat flux decreases. The strength of atmospheric turbulence depends on the net radiation which is sensitive to cloudiness. In the case of laminar temperature flux (horizontal flux) the $C_n^2$ values are very low. If the temperature of the ground is lower than the air wind causes vertical temperature flux which results in turbulent flux and shortly lasting strong turbulence. This results in a strong oscillation of $C_n^2$ values, this effect is called intermittence. Higher wind velocity increases this effect. Intermittence can mainly be observed during winter night and over snow covered ground.

The strength of turbulence was classified in the following way:

<table>
<thead>
<tr>
<th>Turbulence Type</th>
<th>$C_n^2$ Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>very weak turbulence</td>
<td>$C_n^2 &lt; 6 \cdot 10^{-16}$ m$^{-2/3}$</td>
</tr>
<tr>
<td>weak turbulence</td>
<td>$6 \cdot 10^{-16}$ m$^{-2/3} &lt; C_n^2 &lt; 6 \cdot 10^{-15}$ m$^{-2/3}$</td>
</tr>
<tr>
<td>medium turbulence</td>
<td>$6 \cdot 10^{-15}$ m$^{-2/3} &lt; C_n^2 &lt; 6 \cdot 10^{-14}$ m$^{-2/3}$</td>
</tr>
<tr>
<td>strong turbulence</td>
<td>$6 \cdot 10^{-14}$ m$^{-2/3} &lt; C_n^2 &lt; 6 \cdot 10^{-13}$ m$^{-2/3}$</td>
</tr>
<tr>
<td>very strong turbulence</td>
<td>$6 \cdot 10^{-13}$ m$^{-2/3} &lt; C_n^2$</td>
</tr>
</tbody>
</table>

As an example for strongest respectively weakest atmospheric turbulence conditions the $C_n^2$ values measured during an arbitrary summer respectively winter month will be analyzed in the following.

### 4.1 Diurnal cycle of $C_n^2$ in arid climate

In arid climate the weather conditions were constant. During summer season there was no overcast sky and the ground was totally dry, but during winter season there was overcast sky and in the case of rain, which is rarely possible, the ground could be significantly different.

Examples for the diurnal cycle of $C_n^2$ values measured during different seasons for a time period of one month in arid climate are plotted in Figure 1.

**Fig. 1:** Diurnal cycle of $C_n^2$ values measured in arid climate for a time period of one month during different seasons. Left graph: summer August 1999, right graph: winter January 2000.

During summer season, here August 1999 (left graph), all days show the same diurnal cycle of $C_n^2$ due to constant conditions, only cloudless sky. Around noon (local time = UTC +2 hours) the atmospheric turbulence was strongest, it rose up to values of about $2 \cdot 10^{-12}$ m$^{-2/3}$. In the early morning around sunrise when the temperature stratification of the atmosphere was stable the daily variation indicates a distinguished minimum of $C_n^2$ with values of about $2 \cdot 10^{-15}$ m$^{-2/3}$.

During winter season, here January 2000, the lower solar irradiance leads to lower ground temperature and the maximum of $C_n^2$ is reduced to values $\leq 1 \cdot 10^{-12}$ m$^{-2/3}$. The diurnal cycles indicate a significant variability of the $C_n^2$. 

values due to changing cloudiness. At day-time overcast sky reduces the temperature gradient and hence the $C_n^2$ values. The characteristic diurnal pattern can still be recognized.

4.2 Diurnal cycle of $C_n^2$ in moderate climate

In mid-Europe the weather situation can significantly change during a short time period. It should be mentioned that for the turbulence measurements in mid-Europe the number of $C_n^2$ values available for evaluation was always smaller than the theoretical number of measurements (288 measurements per day multiplied by the number of complete data files per month). Only 70 % - 90 % of the theoretical amount of a monthly data set could be evaluated.

Examples for the diurnal cycle of $C_n^2$ values measured during different seasons for a time period of one month in moderate climate, mid-Europe are plotted in Figure 2. Due to the weather variability in mid-Europe the $C_n^2$ values show large variance. Nevertheless the characteristic pattern of the daily variation is perceptible during summer (left graph). Winter season (right graph) is quite different from winter season in arid climate. Air temperature is significantly lower, causing a very small temperature gradient and hence weak turbulence even during sunny days. Intermittence is likely which results in oscillating $C_n^2$ values, hence singular large $C_n^2$ values up to $2 \cdot 10^{-12}$ m$^{-2/3}$, corresponding to very strong turbulence, could appear. There is no longer the characteristic diurnal pattern identifiable. Most of the $C_n^2$ values are $< 1 \cdot 10^{-13}$ m$^{-2/3}$.

![Figure 2](image)

**Fig. 2:** Diurnal cycle of $C_n^2$ values measured in moderate climate, mid-Europe, for a time period of one month during different seasons. Left graph: summer July 1999, right graph: winter January 2000.

4.3 Cumulative frequency of occurrence of $C_n^2$ values

Since the atmospheric parameters and hence the atmospheric turbulence usually change as a function of time-of-day and of season their influence on the effectiveness of electro-optical systems can normally only be expressed in a statistical way. To provide a statistical data base for the atmospheric turbulence the cumulative frequency of occurrence was calculated for a time period of one month for both climates. The time interval of one month was arbitrary selected (from the first day up to the last day of a month). As mentioned above in mid-Europe only 70 % – 90 % of the data delivered by the laser scintillometer data could be evaluated. For this reason the calculation of the cumulative frequency of occurrence is based on smaller monthly data files than in arid climate.

It should be pointed out that in mid-Europe the cumulative frequencies of occurrence of two months in the same season can show significantly different features due to the strong variability in meteorological conditions (for example August 1999 and July 1999).

Figure 3 demonstrates examples for the cumulative frequency of occurrence on a monthly basis for $C_n^2$ values measured in arid climate and in mid-Europe during the different seasons winter, spring, summer, and fall.

In arid climate (left graph) about 24 % of the $C_n^2$ values measured during summer corresponds to very strong turbulence, whereas during spring and fall only 17 % respectively 12 % and during winter 2.5 %. In the moderate climate of mid-Europe (right graph) during the selected summer month 17 % of the evaluated $C_n^2$ values corresponds to very strong turbulence, respectively 6 % and 7 % during spring and fall, and about 0.4 % during winter. Even
during winter due to intermittence singular large $C_n^2$ values up to $2 \cdot 10^{-12}$ m$^{-2/3}$ could appear even though with a low frequency of less than 0.5 %.

![Cumulative frequency of occurrence of the $C_n^2$ values measured for a time period of one month during different seasons.](image)

**Fig. 3:** Cumulative frequency of occurrence of the $C_n^2$ values measured for a time period of one month during different seasons. Left graph: arid climate, right graph: moderate climate in mid-Europe.

### 5. CALCULATION OF TURBULENCE MTF AND PSF

Modulation transfer functions (MTF) are becoming increasingly important in the characterization of electro-optical devices. Prediction of atmospheric MTF, here turbulence MTF is important for cost-effective design, since it permits sensor selection according to turbulence MTF, which often is the weakest link in imaging systems through the atmosphere.

Calculations of turbulence MTF were carried out for two typical sensors: for a UV sensor, wavelength 275 nm, aperture diameter 50 mm, exposure time 100 ms and an optical path length of 2 km and for an IR sensor with CMT detector, wavelength 4 µm, aperture diameter 100 mm, exposure time 100 µs and an optical path length of 20 km. The $C_n^2$ values were selected to correspond to a cumulative frequency of occurrence of 60 % and 90 % in arid climate and in mid-Europe as listed in Table 1.

<table>
<thead>
<tr>
<th>Cumulative frequency of measured $C_n^2$ values</th>
<th>Arid summer</th>
<th>Arid winter</th>
<th>Mid-Europe summer</th>
<th>Mid-Europe winter</th>
</tr>
</thead>
<tbody>
<tr>
<td>90 %</td>
<td>$&lt; 1 \cdot 10^{-12}$ m$^{-2/3}$</td>
<td>$&lt; 3 \cdot 10^{-13}$ m$^{-2/3}$</td>
<td>$&lt; 7.9 \cdot 10^{-13}$ m$^{-2/3}$</td>
<td>$&lt; 8.3 \cdot 10^{-14}$ m$^{-2/3}$</td>
</tr>
<tr>
<td>60 %</td>
<td>$&lt; 2 \cdot 10^{-13}$ m$^{-2/3}$</td>
<td>$&lt; 7 \cdot 10^{-14}$ m$^{-2/3}$</td>
<td>$&lt; 1.7 \cdot 10^{-13}$ m$^{-2/3}$</td>
<td>$&lt; 2 \cdot 10^{-14}$ m$^{-2/3}$</td>
</tr>
</tbody>
</table>

**Table 1:** $C_n^2$ values corresponding to a cumulative frequency of occurrence of 90 % and 60 % for two different seasons measured in arid climate and in moderate climate in mid-Europe.

Figure 4 demonstrates the turbulence MTF calculated for the UV sensor for arid climate (left graph) and in moderate climate in mid-Europe (right graph). Figure 5 demonstrates the corresponding turbulence MTF calculated for the IR sensor. Stronger atmospheric turbulence causes a stronger degradation of the spatial resolution of a target for a given electro-optical system (less line pairs per mrad are resolved). The graphs also indicate that the arbitrary selected value of cumulative frequency of occurrence, here 60 % and 90 %, strongly influences the calculated turbulence MTFs of electro-optical systems. For example, in arid climate the $C_n^2$ value corresponding to a cumulative frequency of occurrence of 90 % in winter is larger than the value corresponding to the cumulative frequency of occurrence of 60 % in summer yielding in a smaller MTF.

For mid-Europe conditions, due to the lower $C_n^2$ values, the corresponding MTFs show a broader feature, respectively larger spatial resolution. The difference between arid and moderate climate is more evident for winter conditions.
Considering the cumulative frequency of occurrence of 60%, the broad feature of the calculated turbulence MTFs indicates a low degradation of a point target resolution of the sensor (compact dots) due to atmospheric turbulence.

**Fig. 4:** Turbulence MTF calculated for a typical UV sensor. 
Aperture diameter 50 mm, exposure time 100 msec, optical path 2 km, and cross wind 3 m/sec. 
\( C_n^2 \) values corresponding to the cumulative frequencies of occurrence of 90% and 60%. 
Left graph: arid climate, right graph: moderate climate in mid-Europe.

**Fig. 5:** Turbulence MTF calculated for a typical IR sensor (CMT detector). 
Aperture diameter 100 mm, exposure time 100 µsec, optical path 20 km, and cross wind 3 m/sec. 
\( C_n^2 \) values corresponding to the cumulative frequencies of occurrence of 90% and 60%. 
Left graph: arid climate, right graph: moderate climate in mid-Europe.

The point spread function, PSF, can be calculated from the MTF by inverse Fourier transformation applying formula (9). Figure 6 demonstrates the PSFs calculated for the UV sensor for arid climate (left graph) and moderate climate in mid-Europe (right graph). Figure 7 shows the corresponding PSFs calculated for the IR sensor. The more narrow the PSF, the less blurring occurs in the image forming process. Strong turbulence broadens significantly the PSF and decreases the maximum, causing a significant degradation of a target resolution in the focal plane of an electro-optical system.
The corresponding standard deviations of the PSFs, $\sigma_{PSF}$ (in mrad) were calculated applying formula (10). The energy within the deviation of radius $\sigma_{PSF}$ is 68% of the total one. The values of $\sigma_{PSF}$ calculated for the different turbulence conditions in different climates (winter and summer in arid climate and mid-Europe) and for different sensors (UV and IR sensor) are listed in Table 2. Regarding the cumulative frequency on a monthly basis there is only a small difference between the determined value of $\sigma_{PSF}$ in arid climate and mid-Europe during summer season. Whereas during winter the $\sigma_{PSF}$ values in mid-Europe are significantly smaller, by a factor > 2, than in arid climate.

**Fig. 6:** Turbulence PSF of a typical UV sensor calculated for measured $C_n^2$ values corresponding to the cumulative frequencies of occurrence of 90% and 60%. Left graph: arid climate and right graph: moderate climate in mid-Europe.

**Fig. 7:** Turbulence PSF of a typical IR sensor (CMT detector) calculated for measured $C_n^2$ values corresponding to the cumulative frequencies of occurrence of 90% and 60%. Left graph: arid climate and right graph: moderate climate in mid-Europe.

<table>
<thead>
<tr>
<th>Climate</th>
<th>Detector</th>
<th>PSF standard deviation $\sigma_{PSF}$ in µrad</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>summer</td>
</tr>
<tr>
<td>arid</td>
<td>UV sensor</td>
<td>168</td>
</tr>
<tr>
<td>mid-Europe</td>
<td>UV sensor</td>
<td>147</td>
</tr>
<tr>
<td>arid</td>
<td>IR sensor</td>
<td>371</td>
</tr>
<tr>
<td>mid-Europe</td>
<td>IR sensor</td>
<td>321</td>
</tr>
</tbody>
</table>
Table 2: Standard deviation $\sigma_{psf}$ of the turbulence PSFs calculated for $C_n^2$ values corresponding to different cumulative frequencies of occurrence in different climates for different sensors.
6. CONCLUSION

Measurements of $C_n^2$ were performed with identical laser scintillometers in two different climates, moderate climate in mid-Europe and arid climate in Israel. The optical path length of 100 m runs at a height of 1.25 m above grassland in mid-Europe, respectively 2.2 m above ground without vegetation in arid climate. $C_n^2$ values measured in arid climate were height scaled to 1.25 m. For both climates diurnal cycles of measured $C_n^2$ were plotted for a selected winter and summer month. The diurnal cycle of $C_n^2$ strongly depends on weather conditions. For sunny days, that means no overcast sky, it shows maximum values around midday when solar radiation is strongest and temperature gradient between air and ground is greatest and it shows minimum when air temperature is closest to ground, mainly at sunrise. In arid climate when the weather conditions during the summer season were constant, only clear sky, the diurnal runs of $C_n^2$ show such a typical feature. $C_n^2$ values varied between $2 \times 10^{-15}$ m$^{-2/3}$ around sunset and $2 \times 10^{-12}$ m$^{-2/3}$ around midday. During winter due to lower solar radiation the maximum $C_n^2$ values were reduced to about $1 \times 10^{-12}$ m$^{-2/3}$. Overcast sky could occur in arid climate, leading to smaller $C_n^2$ values during day-time, but the characteristic pattern can still be recognized. In mid-Europe the weather conditions can change significantly within a short time period. This causes a significant variability of $C_n^2$ values measured during day-time. Nevertheless the characteristic features can be recognized well during summer season in mid-Europe, but during winter they are hardly present.

The cumulative frequency of occurrence was determined on a monthly basis. It should be mentioned that in mid-Europe weather conditions like precipitation may limit the utilization of the laser scintillometer and therefore only 70% -90% of measured data could be evaluated and used for further data analysis. This may influence the graph of the particular cumulative frequency of occurrence. In arid climate about 24% of the $C_n^2$ values measured during summer indicate very strong turbulence, $C_n^2 > 6 \times 10^{-13}$ m$^{-2/3}$, whereas during winter only 2.5%. In moderate climate in mid-Europe 17% of the evaluated $C_n^2$ values measured during the selected summer month indicate very strong turbulence. Even in winter there is evidence of very strong turbulence, with a low probability of about 0.4%, these singular high $C_n^2$ values are caused by intermittence.

Calculations of turbulence MTF were carried out for a typical UV and a typical IR sensor. The $C_n^2$ values were selected to correspond to a cumulative frequency of occurrence of 60% and 90% in arid climate and in mid-Europe for an arbitrary selected month in summer and in winter season. If $C_n^2$ values have to be considered which correspond to a cumulative frequency of occurrence of 90%, the spatial resolution of the electro-optical system would be always smaller by at least a factor of two compared to the calculations which were carried out for $C_n^2$ values corresponding to a cumulative frequency of 60%.

The corresponding PSFs were calculated. Regarding the cumulative frequency on a monthly basis there is only a small difference between the spread of the PDS, $\sigma_{PSF}$, for the arbitrary selected summer months in arid climate and mid-Europe. But during winter in mid-Europe the $\sigma_{PSF}$ of electro-optical systems are significantly smaller by a factor >2 than the values in arid climate, indicating a smaller degradation of point target resolution of a sensor.

7. ACKNOWLEDGEMENT

We would like to thank our colleague Wolfgang Schuberth for providing us with his computer code for calculating the MTF and the PSF and the colleagues at EORD, Israel, for technical support in the desert.

8. REFERENCES