Atmospheric turbulence temperature on the laser wavefront properties

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Abstract. Temperature is a physical magnitude that if it is higher, the refractive index presents more important random fluctuations, which produce a greater distortion in the wavefront and thus a displacement in its centroid. To observe the effect produced by the turbulent medium strongly influenced by temperature on propagation laser beam, we experimented with two variable and controllable temperature systems designed as optical turbulence generators (OTG): a Turbulator and a Parallelepiped glass container. The experimental setup use three CMOS cameras and four temperature sensors spatially distributed to acquire synchronously information of the laser beam wavefront and turbulence temperature, respectively. The acquired information was analyzed with MATLAB® software tool, that it allows to compute the position, in terms of the evolution time, of the laser beam center of mass and their deviations produced by different turbulent conditions generated inside the two manufactured systems. The results were reflected in the statistical analysis of the centroid shifting.

Keywords. Optical Turbulence Generators, Atmospheric Turbulence, Laser Beam, Centroid Beam.

1. Introduction
The earth atmosphere is a medium whose refractive index is close to unity. This condition allows, with slight modifications to the current techniques of propagation of light in vacuum, perform propagation simulations through the atmosphere. The refractive index takes random values in space and time produced by the atmospheric variations; it causes a distortion in the propagation of light beam and its wavefront. For this reason optical systems must overcome the great challenge of reduce the turbulence effects [1].

Research is currently ahead seeking to increase the resolution in imaging and reducing errors in communication systems when the presence of turbulence at low altitudes becomes troublesome [2]. Under these conditions some difficulties have been avoided, as in imaging systems where to elude the turbulence at ground level because is much stronger than any other height, the astronomical observatories are placed on top of the mountains [1].

In the following sections, we show the turbulence characterization using a laser beam that propagates a horizontal distance at ground level (at laboratory scale) and the establishment of the temperature modification effects on the centroid of beam.

2. Systems description
2.1. Turbulator
To protect variations other than the temperature variables, a metal tube whose dimensions are illustrated in Figure 1, has inside a resistor gap of dimensions 20 cm long, 3 cm in inner diameter and 3.5 cm in outer diameter. The drilling scheme previously designed for feeding said resistor, provides the temperature control inside the system called "turbulator".
2.2. Parallelepiped glass container
The second design made was a cubic temperature controlled system as shown in Figure 2. Glass room has a hole of 0.8 [cm] diameter on both opposite sides (front and rear) through the laser beam propagates, and is coated to ensure that the light inside the device does not spread to any of the nearest CMOS cameras to reduce its thermal noise.

For wavefront data acquisition, three CMOS cameras and a microcontroller module specially developed are used (see setup in Figure 3). The cameras CMOS-1 and CMOS-2 are located near the laser mirror output with the idea in mind of estimate the laser intracavity banding effect. The third camera CMOS-3 records such effect in addition to deviations due to turbulence temperature modification along the beam propagation horizontal distance.

Over experimental setup described, acquisition algorithm captures images for each camera and each temperature value on a card expressly developed, in groups of 3000 samples synchronously at 1 Hz of sample frequency. For this reason, acquisition devices (cameras and temperature sensors) are independently connected to a different computer, their operation start from optical synchronization (when laser port is open) with timers preset in each computer where are saved samples to process offline.

2.3. Temperature distributions
It was then fundamental to know the temperature distribution within both systems, where it was measured at different spatial positions from the ends to the center (where the highest temperature is
concentrated). For this objective, it sets three sensor LM35 and its measurements are shown in Figures 4 to 9.

![Figure 4](image1.png)

Figure 4. Temperature characteristic curve at the turbulator center. Longitudinal position of sensor, 50 cm at the center of the cross section.

![Figure 5](image2.png)

Figure 5. Temperature characteristic curve close to the ends of the turbulator. Longitudinal position of sensors, 35 cm (Orange) and 65 cm (Yellow) at bottom of the cross section.

![Figure 6](image3.png)

Figure 6. Temperature characteristic curve close to the ends of the turbulator. Longitudinal position of sensors, 35 cm (Blue) and 65 cm (Green) at top of the cross section.

![Figure 7](image4.png)

Figure 7. Temperature distribution inside the turbulator according to the distance from the end. Sensors position at bottom and center of the cross section.

![Figure 8](image5.png)

Figure 8. Temperature vs Time characteristic curve in the parallelepiped glass container. Sensors position close to the laser optical path near the ends, as indicated on plot, and at the device center.

![Figure 9](image6.png)

Figure 9. Temperature distribution inside the parallelepiped glass container. Horizontal distance in cm.

Temperature values are selected like to produce significant changes in the captured wavefront at the camera CMOS-3 where the beam centroid becomes fundamental to the turbulence characterization.

3. Results

3.1. Centroid and diameter beam analysis in the laboratory environment.
Figures 10 and 11 correspond to the benchmark made in the natural laboratory environment. Remark that the centroid displacement produced by intracavity beam wander projected from the cameras CMOS-1 and CMOS-2, has similar one to the camera CMOS-3, because the atmospheric turbulence is low under normal laboratory conditions. In fact, CMOS-3 sensor captured directly images whereas that mass center on observation plane was estimated from images of CMOS-1 and CMOS-2.

The pixel values of the mass center were divided into 34 different positions in the X-axis, and 27 in the Y-axis. The spatial distribution found in each axis was similar, most of the points are found around the fixed coordinate (17,14) with 90 repetitions (close to the center of displacement) as seen in Figure 12.

On the other hand, the beam diameter was also found in order to seek temporal changes confirming that centroids both measured and estimated were consistent (see Figure 13).

### 3.2. Beam centroid and its diameter when turbulator is at Temperature of 105 °C.

Establishing a constant internal temperature of 105 °C (schematic is shown in Figure 1), the laser beam propagates through the internal hole diameter of the resistor where the temperature is higher.
Comparable results to shown in Figures 10 to 12, where the data verify the beam behavior and temperature effect were obtained and analyzed. For this experiment, the distance from the laser output mirror to the turbulator was 248 cm and to the camera CMOS-3, 397 cm. The results are shown in Figures 14 to 16, where is evident that the centroid had X and Y shifting like discussed in last section. Initially, the results were unexpected since in the current theoretical models the effect produced by turbulence depend strictly on the temperature [3]. Thus, the results of each test at 105 °C could have been given for the exposed reasons.

![Figure 14](image1.png)

**Figure 14.** X-shifting of the centroid at 105°C. Left: Measured on the far camera and, Right: Estimated from nearby cameras.

![Figure 15](image2.png)

**Figure 15.** Y-shifting of the centroid at 105°C. Left: Measured on the far camera and, Right: Estimated from nearby cameras.

![Figure 16](image3.png)

**Figure 16.** Estimated banding effect on Z3 at 105°C.

### 3.2.1. The manner in which the temperature source is placed in the medium and generating a uniform temperature gradient.

To explain a little better this phenomenon, an experimental test where the heat source is a point source placed close to the laser beam [4] (measured temperature near to the point source was 210°C) has been conducted. Results presented in figures 17 and 18 have the same results appearance that in sections 3.1 and 3.2, but this time the turbulator has been removed from the setup. In Figure 18, it is provided to observe the difference in the estimated shifting (23 pixels) compared to measured one (10 times larger). This effect is shown in 2D histogram form in Figure 19, wherein the dispersion produced by local temperature variation is evident.
While the resistor remaining surrounded by a larger metal cylinder, the propagation of the laser beam will not be greatly affected by other physical conditions; different temperature distributions can generate greater turbulence like in the case of point heat source. This turbulator configuration ensures a uniform temperature distribution within the device since the temperature gradient is smooth (no any abrupt temperature changes) from the ends of the turbulator and the center thereof, see Figure 19, thus generating less turbulence inside the device.

3.2.2. Generation of non-uniform gradients.
To observe the beam centroid behavior against no uniform gradients of temperature, experiments have been conducted in the laboratory using the second device, a parallelepiped glass container (see Figure 20). Due to its geometry and its generation temperature mode is very easy to create no uniform gradients inside and close to its walls.
3.3. Beam centroid and diameter when the parallelepiped glass container is at Temperature of 105 °C. Tests on the glass parallelepiped shown a notable transversal shifting achieved by the 2D centroid shifting (Figures 21 and 22) the difference in the estimated shifting was 19 pixels compared with the measured one that was 79 pixels. On the X-axis measured shifting was of 54 pixels and the estimated was 13 pixels. On the Y-axis measured shifting was of 79 pixels versus 16 pixels for estimated one, all tests took into account the additive effects of banding and temperature of turbulence.

![Figure 21. X-shifting of the centroid at 105°C. Left: Measured on the far camera and, Right: Estimated from nearby cameras.](image1)

![Figure 22. Y-shifting of the centroid at 105°C. Left: Measured on the far camera and, Right: Estimated from nearby cameras.](image2)

The pixel values of the mass center were divided into 140 different positions in the X-axis, and 100 for the Y-axis. The distribution was like that found for each axis, most of the points are found around points coordinate (65,51) with a maximum of 15 repetitions at some points of the 2D histogram (near the center of the shifting) as shows Figure 23. In Figure 24 is displayed consistency with the measures of beam diameter.

![Figure 23. Estimated banding effect on Z3 plane.](image3)

![Figure 24. Temporal estimated beam diameter from experimental data on the Camera CMOS-3.](image4)
Table 1. Maximum centroid shifting for all experimental tests.

| Test (T)          | Test (T)          |
|-------------------|-------------------|
|                   | Centroid Movement (pixels) |       |
|                   | Radially          | X axis | Y axis |
|                   | Measured          | Calculated | Measured | Calculated | Measured | Calculated |
| Benchmark         | 7                 | 13     | 5      | 9         | 6        | 13         |
| Turbulator        | T1                | 8      | 10     | 5         | 8        | 7          | 14         |
|                   | T2                | 14     | 7      | 6         | 6        | 13         | 7          |
|                   | T3                | 14     | 15     | 5         | 12       | 12         | 12         |
|                   | T4                | 15     | 15     | 7         | 9        | 14         | 9          |
| Parallelepiped glass container | T1            | 17     | 5      | 13        | 5        | 12         | 9          |
|                   | T2                | 49     | 10     | 40        | 8        | 43         | 11         |
|                   | T3                | 48     | 11     | 33        | 9        | 38         | 17         |
|                   | T4                | 79     | 19     | 54        | 13       | 74         | 16         |
| Point heat source | T1                | 23     | 205    |           |          |            |            |
|                   | Turbulator: propagation distance: 153 cm. | 22 | 25 | 16 | 18 | 16 | 18 |

3.4. Turbulence characterization.

3.4.1. Structure function.

In physical optics, correlation functions are widely used to describe statistically varying fields, so we might find it natural to express the fluctuations in such terms; however, since the mean value of the refractive index can vary slowly with position and time, it becomes uncertain which changes should be considered as drifts of the mean and which as fluctuations around their mean value. Kolmogorov devised a slightly different way of expressing his results which overcomes this difficulty. He defined a structure function to relate the values of a function \( f(r) \) at neighboring points \( r_1 \) and \( r_2 \), this is a function only of \( r = r_2 - r_1 \) and not of their individual values. The atmospheric turbulence is a non-stationary process because its average value varies over time. Therefore, it is necessary to use an expression for interpreting when stationary fluctuations increases. To do this the structure function is used [5].

\[
D_f(r) = \langle [f(r_1 + r) - f(r_1)]^2 \rangle
\]  

(1)

where \( \langle \ldots \rangle \) indicates a time-averaged value in a homogeneous region [6].

Although vertical profiles are commonly known and described in Labeyrie (5.2 section) [6], our model is thought in horizontal path, because empirical models had rebuilt atmosphere layers in vertical profiles. Then, to analyze fluctuations centroid structure function was performed in experimental test performed both in the parallelepiped glass container (see Figures 26 to 28) and in the turbulator on the CMOS-3 camera. Each of these graphs have temporal windows of ten seconds, that means, it has 2800 samples for each test, therefore, 280 values of local fluctuations were obtained.

Since the information obtained since analysis of the structure-function of the tests performed in glass parallelepiped, it was observed that global fluctuations increase to higher temperature levels (Figures 25-26). Global fluctuations centroid on the Y-axis are greater than the X-axis, due to the relative temperature difference which exists at different heights in the parallelepiped.
Figure 25. Structure function for component X of centroid, tests T1 to T4 performed in parallelepiped glass container.

Figure 26. Structure function for component Y of centroid, tests T1 to T4 performed in parallelepiped glass container.

Figure 27. Structure function for component X of centroid, tests T1 to T4 performed in turbulator.

Figure 28. Structure function for component Y of centroid, tests T1 to T4 performed in turbulator.
Table 2. Overall average X and Y fluctuation of centroid performed in parallelepiped glass container.

| Test   | Average of Fluctuation (X-centroid) | Average of Fluctuation (Y-centroid) |
|--------|-------------------------------------|-------------------------------------|
| T1 – [45 °C] | 2.2066e-10                        | 2.4321e-10                        |
| T2 – [60 °C] | 1.1423e-9                          | 1.3099e-9                          |
| T3 – [80 °C] | 1.9586e-9                          | 2.8736e-9                          |
| T4 – [105 °C] | 2.8566e-9                          | 3.6986e-9                          |

From the experimental information obtained since the structure function in the turbulator (see Figures 27 and 28), it remarked that global fluctuations in the first and third test increase, while for the second and fourth ones fall, these results are due probably to the way in which the generating temperature gradient has been previously exposed.

Table 3. Overall average X and Y fluctuation of centroid performed in turbulator.

| Tests   | Average of Fluctuation (X-Centroid) | Average of Fluctuation (Y-Centroid) |
|---------|-------------------------------------|-------------------------------------|
| T1 – [45 °C] | 2.2079e-10                        | 2.3591e-10                        |
| T2 – [70 °C] | 1.691e-10                         | 1.5863e-10                        |
| T3 – [105 °C] | 2.550e-10                         | 3.1142e-10                        |
| T4 – [145 °C] | 1.5611e-10                        | 1.8231e-10                        |

Table 4. Overall average X and Y fluctuation of centroid benchmark performed.

| Test   | Average of Fluctuation |
|--------|------------------------|
| X-Centroid | 1.9011e-10            |
| Y-Centroid | 2.7546e-10            |

3.4.2 INNER SCALE CALCULATION.

The inner scale of turbulence $l_0$, being the scale at which energy is dissipated by atmospheric turbulence convection, is of fundamental importance in determining surface fluxes of heat and momentum [7].

$$l_0 = 1.08L \left( \frac{\langle \alpha^2 \rangle}{\sigma_I^2} \right)^{1/2}$$

(2)

Where $\alpha$ and $\sigma_I^2$ are the arrival angle of beam and scintillation index, respectively (see equation 4 for scintillation index). We check out that $\alpha$ is very small (micro-radians order). In addition, computed inner scale are shown in Figures 29 and 30 and Table 5.

Figure 29. Inner scale fluctuations in benchmark test and from T1 to T4 tests inside the parallelepiped glass container.
Table 5. Inner scale average for benchmark test and from T1 to T4 tests inside the parallelepiped glass container.

| Tests       | Average of Inner Scale [x10^-3 m] |
|-------------|-----------------------------------|
| Benchmark   | 1.07                              |
| T1 – [45 °C]| 1.83                              |
| T2 – [60 °C]| 3.08                              |
| T3 – [80 °C]| 3.92                              |
| T4 – [105 °C]| 3.02                             |

![Graphs showing inner scale fluctuations from T1 to T4 tests inside the turbulador.](image)

Figure 30. Inner scale fluctuations from T1 to T4 tests inside the turbulador.

Table 6. Inner scale average fluctuation from T1 to T4 tests inside the turbulador.

| Tests       | Average of Inner Scale [x10^-3 m] |
|-------------|-----------------------------------|
| T1 – [45 °C]| 1.10                              |
| T2 – [70 °C]| 1.16                              |
| T3 – [105 °C]| 1.26                             |
| T4 – [145 °C]| 0.98                             |

3.4.3. $C_n^2$ calculation.

Supposing a plane wave that propagates through the homogeneous and isotropic turbulence, due to we acquire data in a small sensor, within the limits of geometrical optics approximation, that means for $L \ll L_0^2/\lambda$, where $L$ is the path length, $L_0$ the inner scale and $\lambda$ the wavelength, the mean square fluctuations of the arrival angle is given by [7]:

$$\langle \alpha^2 \rangle = \langle \beta^2 \rangle = 3.28C_n^2 L_0^{-1/3}$$  \hspace{1cm} (3)

where $\alpha$ and $\beta$ are orthogonal components of the arrival angle, respectively. Their variances can be obtained as derivatives of the phase structure function. Inner scale $l_o$ has been computed in section 3.4.2. Tables 7 - 8, and Figures 31 - 32 show these outcomes.

Table 7. $C_n^2$ average fluctuation for benchmark test and from T1 to T4 tests inside the parallelepiped glass container.

| Tests       | Average of $C_n^2$ [m^-2] |
|-------------|---------------------------|
| Benchmark   | 2.0352e-13                |
| T1 – [45 °C]| 1.1982e-12                |
| T2 – [60 °C]| 8.8053e-12                |
| T3 – [80 °C]| 2.0655e-11                |
| T4 – [105 °C]| 2.6309e-11               |
This measurement produces an estimation about intensity variance to assess if spot acquired was inside 2D sensor. Finally, we show in Figures 33-34 and Tables 9 -10 scintillation index. 

3.4.4. Scintillation index calculation.

The mean square of the normalized intensity fluctuations is known as scintillation index and is expressed by (7):

\[ \sigma_i^2 = \frac{\langle i^2 \rangle - \langle i \rangle^2}{\langle i \rangle^2} \]  

(4)

This measurement produces an estimation about intensity variance to assess if spot acquired was inside 2D sensor. Finally, we show in Figures 33-34 and Tables 9 -10 scintillation index.
Scintillation index fluctuations from T1 to T inside the parallelepiped glass container.

Table 9. Scintillation index average for benchmark test and from T1 to T4 inside the parallelepiped glass container.

| Tests      | Average of Scintillation |
|------------|--------------------------|
| Benchmark  | 1.0001e-06               |
| T1 – [45 °C] | 2.7890e-06               |
| T2 – [60 °C] | 2.3425e-06               |
| T3 – [80 °C] | 4.2129e-06               |
| T4 – [105 °C] | 7.9181e-06               |

Scintillation index fluctuations from T1 to T inside the turbulator.

Table 10. Scintillation index from T1 to T4 inside the turbulator.

| Tests      | Average of Scintillation |
|------------|--------------------------|
| T1 – [45 °C] | 1.9161e-04               |
| T2 – [70 °C] | 6.6046e-07               |
| T3 – [105 °C] | 6.5561e-07               |
| T4 – [145 °C] | 9.1303e-07               |
4. Conclusions
The centroid behavior of the laser beam in the experimental tests performed inside the turbulator had similar results to the test conducted in the atmosphere at normal conditions inside the lab; we suggest as explanation the way in which the transfer of heat from the source to the surrounding air and as the gradient of uniform temperature is produced. The inner scale had a similar performance.

The centroid transversal shifts present greater fluctuations along its two orthogonal coordinate axis, it is due to the positive gradient of temperature that exists inside the turbulator throughout its height.

The structure function shows big fluctuations when centroid transversal shifts increases at higher temperature levels, it is easy to see in the parallelepiped glass container. While in the turbulator it was observed that these fluctuations were presented with strong intensity in the first and third experimental test, while in the second and fourth decreases with respect to the above ones without one good defined behavior pattern.

We show that is possible to calculate the inner scale, $C_n^2$ and scintillation index of generated turbulence using a very simple method based in the measurement and analysis of the propagated beam wavefront.

A possible deduction from experimental results is concerning the inner scale $C_n^2$ at high temperature in turbulator prototype, in our case, fluctuations were similar to ones under the normal conditions in laboratory then, we suggest that dependences between the inner and outer scale did not allow heat convection and, its consequences were small shifts of beam centroid. Future works would yield to identify this hypothesis, we must orient tests with other devices patterns.

5. Acknowledgments
Research partially supported by Universidad Industrial de Santander with project 5707. Thanks to Colciencias for financial support to project 110256933773: “Uso de la telescopía de Fourier de tiempo promedio para caracterizar la turbulencia horizontal a baja altura”, National Call for the Bank of Projects in Science, Technology and Innovation 2012. O.J. Tíjaro Rojas acknowledges the support and sponsorship from Colciencias, by Call 647-2014: National Doctoral program.

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