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Availability of FSO Link in Cairo, Egypt, From Cairo Tower to the Great Pyramid, (11.5 km long)

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***Abstract*— The proposed terrestrial free space optic (FSO) link from Cairo tower to the great Pyramid (distance 11.5 km) with 130 m altitude and 1550 nm wavelength is evaluated with data rate 10Gb/s and transmitted power 500mw.**

In this proposed, the measured visibility gives the equivalent effects of all weather parameters and so, it is used to calculate the weather attenuation by using Mie scattering law. And the scintillation (C2n) is evaluated using a combatable model of Cairo weather. The effect of turbulence becomes very weak by using the receiver aperture greater than the maximum optical spot size due to divergence and turbulence.

During year 2016, the visibility usually greater than 2km, except it equals zero during 90 minutes only, but it becomes 1 km during 56.5 hr. Also weak atmospheric turbulence C2n < 6*10-16 m-2/3 at altitude h=130 m, the scintillation index σ2 ≤ 0.8, except three days, and the air dispersion very small around 0.47 ps km-1 nm-1.

The availability dependence not only on the SNR (BER) but also on the value of received power (Pr) to realize the minimum received power (Pr min). With visibility V ≤ 1km, or scintillation index (σ2 >1), the link becomes not available. We consider the availability occurs if the SNR ≥ 36 ≡ 15.56 db (i.e. BER ≤ 10-9 and Q-factor ≥ 6) also, Pr ≥ minimum received power (Pr min). SNR increases with the ratio of the transmitted power (Pt) to the data rate (Br).

The effects of all parameters on the performance of FSO are discussed, and the simplified design steps are achieved. The calculations of weather effect are based on the measured data of Cairo weather which published by Egyptian meteorological authority.

The required transmitted power must be related to the expected visibility. In year 2016, the availability, becomes 99.983%.

***Index Terms*— Free Space Optic (FSO), Atmospheric Turbulence, Scintillation (C2n), Scintillation Index (σ2), Availability of Link, Egyptian Meteorological Authority.**

I. INTRODUCTION

One of the main challenges in free-space optical (FSO) communications is the channel fading due to turbulence-induced scintillation and misalignment [1]

The influence of weather is an important factor during planning Free Space Optical (FSO) links [2]. Where, FSO links are affected by different meteorological impacts [3]. Effect of weather on the performance of FSO is classified into absorption (very small at some wavelengths such as 1.55 μm), scattering and turbulence (turbulence occurs due to temperature variations, winds and humidity).

Turbulence is generally defined as the changes of the path of light due to the changes of the refractive index of air (n_a) pockets [4]-[7]. Optical turbulence is one of the majority factors affecting FSO transmission [8].

The atmospheric turbulence causing both beam wander, beam spreading [4],[5], [9] and random variations in density (redistribution of intensity within the beam) [4]-[7], which cause phase shifts of the propagating optical signals [10] resulting in distortions in the wave front [5],[7], referred to as scintillation (C^2_n).

With atmospheric turbulence, there are a loss the power of FSO [4], [7], [9], [11]-[14] and increasing the link error probability especially for link distance, L > 1km [12] (due to fluctuation in intensity and phase of the received signal) [7]. Fading limits the link rate, reliability and distance [8].

Air refractive index (n_a) changes due to the random fluctuations in temperature, pressure, humidity, wind variations of the atmospheric region through which the FSO signal has to pass [5] -[7], [9]. Also, n_a dependent upon the operating wavelength [7], [9], [12], [13], [15], [16].

Typically time variations of the refractive index are slow compared to the frequency of the optical wave, therefore the wave is assumed to be monochromatic [17].

Scintillation (C^2_n) is the refractive index structure parameter [4], [5], [18], [19] and it is the turbulence strength [5], [7] and so it is the most significant parameter for FSO systems. The strength of scintillation can be measured in terms of the variance of the beam amplitude or irradiance [9] ,[12] and it is measured by scintillometer [7]. $C^2_n = T_{WP} * 10^{-16}$ ($m^{-2/3}$), where T_{WP} is the turbulence weather parameter which describe the strength of turbulence.

For weak turbulence, (T_{WP} = 1 [9], [12], [19] or T_{WP} = 0.1 [5], [14]), for medium turbulence (T_{WP} = 8 [19] or T_{WP} = 10 [5], [9], [12]) and for strong turbulence (T_{WP} = 100 [9,19] or T_{WP} =1000 [3], [22] or T_{WP} =10000 [12], [14]).

C^2_n is a function of geographical location, altitude, time of day (current hour), wavelength, and temperature [5], [14]. The value of C^2_n can be positive or negative and decreases with altitude [5]. At near ground level, C^2_n values will show a diurnal cycle, which peaks during midday hours [14], [19], reaches near-constant values at night, and has minima near sunrise and sunset [14], [19], [20]. Maximum C^2_n can't every-time be expected at midday [19].

Nevertheless, for applications involving propagation along a horizontal or quasi-horizontal path, C^2_n can be assumed to be constant, especially for near-ground links were the variance in altitude due to the Earth's curvature is negligible [19]. The effect of turbulence is defined by scintillation index.

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Scintillation index (σ^2) describes such intensity fluctuation as the normal variance of the intensity fluctuations [5]. The value of σ^2 decreases with rain fall drop ® and it increases with temperature (T) [20]. σ^2 is described as;

For weak regime ($\sigma^2 < 0.3$ [21], [22] or $\sigma^2 < 1$ [5], [17], [21], [23], [24] or $\sigma^2 < 056$ [25]), for moderate regime (focusing regime) ($0.3 < \sigma^2 < 5$ [21], [22] or $\sigma^2 \approx 1$ [5], [17], [21], [23]) and for strong regime($\sigma^2 > 5$ [21], [22] or $\sigma^2 > 1$ [5], [17], [21], [23])

The value of σ^2 is important to calculate the signal-to-noise ratio (SNR) which is used later to calculate the bit-error-rate (BER) [6], also it used to fined the FSO optical losses due to atmospheric turbulence.

In this study, a theoretical design of FSO link in Cairo city, Egypt, 11.5 km long and 130m altitude is shown in Fig.1.

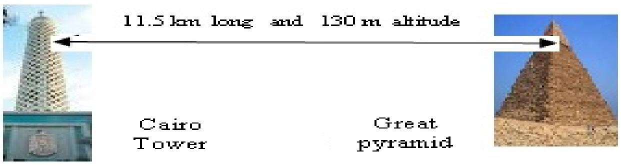


Fig. 1 Proposed link from big pyramids to Cairo tower (11.5 km long and 130 m altitude)

(Cairo city is the capital of Egypt, lies south of the delta in the Nile basin, 30°05 N, 31°17 E and its local time equals UTC +2 [27].
The 24 hr system is used, and time 14.19 means at 14 hr and 19 min)

In this study of Cairo weather, operating wavelength, λ=1550 nm (which is the best wavelength for free space optic [26]), transmission factor (τ) is taken as $\tau = 0.02$, and Kurluse model for the parameter of particles size (q).

The availability of this link is calculated, where availability of FSO is measured as the ratio of successful transmission time (with, BER $\le 10^{-9}$) to the failure transmission time (with BER $>10^{-9}$) [28].

The values of weather parameters, temperature, pressure, humidity, wind speed and visibility are determined for Cairo, Egypt from [29]

The required transmitted power must be related to the expected visibility. In year 2016, the availability, becomes 99.983%.

II. Mathematical Analysis

A. Air refractive index (n_a) and air dispersion ($D_{m\ air}$)

i- Evaluation of air refractive index (n_a): Air refractive index (n_a) depends on wavelength (λ µm), temperature (T °K), pressure (P mbar), and gas composition [7], [9], [12], [13], [15], [16]. While the contribution of humidity (RH %) to the refractive index fluctuation is very small at optical wavelengths [14]

The general formula for n_a is [7];

$$n_a = 1 + 10^{-6}\,\frac{P}{T}\left\{23.7135 + \frac{6839.43}{130 - \lambda^{-2}} + \frac{45.474}{38.9 - \lambda^{-2}}\right\} - 10^{-6}\,\frac{292.75}{T}\,\frac{RH}{100}\left(3.7345 - \frac{0.0401}{\lambda^2}\right) * \left\{\begin{array}{l} 0.0000006177\ T^4 - 0.00066299\ T^3 \\ +0.26846T^2 - 48.576\ T + 3311.8 \end{array}\right\} \quad (1)$$

The values of both T and P are decreasing with altitude [16] and their relations are simplified as;

$$T = T_{SL} - 0.0065\ h \qquad K \quad (2)$$

$$P = P_{SL}\ [1 - 0.0341625784\ h/T_{SL}] \qquad mbar \quad (3)$$

Where, h (meter) is the height, T is the temperature at altitude (h), T_{SL} is the measured temperature at sea level (T_{SL} depends on the position and the time), P is the pressure at altitude (h), P_{SL} is the measured pressure at sea level and it depends on the value of T_{SL}.

Note 1: The standard temperature value at sea level (T_S = 288.15 °K), the standard pressure value (P_S = 1013.25 mbar at T= T_S) and the temperature lapse rate ($\Delta T/dh$ = - 0.0065 °K/m).

Note 2: At T = T_S, the corresponding value of

$P \approx 1013.25 - 0.12\ h$ mbar (as defined in [16])

Note 3: The air refractive index is decreased with both, temperature, altitude and wavelength.

ii- Material (air) dispersion, $D_{m\ air}$ (ps / km nm)

In free space optic, the total dispersion is approximately equal the material dispersion, which is defined as [30],

$$D_{m\ air} = -\frac{\lambda}{c}\frac{d^2 n_a}{d\lambda^2} \quad (\text{Where, c is the light velocity} = 3 * 10^8\ m/s)$$

(4)

And from equation “1”, $D_{m\ air}$ {ps/(km. nm)} is derived with RH=0 and λ in µm as;

$$D_{m\ air} = 0.01\,\frac{\lambda}{3}\,\frac{P}{T}\left\{\frac{40316.382}{(130\,\lambda^2 - 1)^2} + \frac{54715.176}{(130\lambda^2 - 1)^3} + \frac{260.835}{(38.9\lambda^2 - 1)^2} + \frac{374.784}{(38.9\lambda^2 - 1)^3}\right\}$$

(5)

Note 4: The bit rate (data rate) is decreased with dispersion, D_{air} (i.e. strong turbulence). The data rate (B_r Gb/s) in the link is defined as [28];

$$B_r < \frac{250}{L\ \Delta\lambda_{laser}\ |D_{m\ air}|} \quad (6)$$

Where, $\Delta\lambda_{laser}$ is the line width of the laser source (nm), D_{mair} is the air dispersion (ps/km. nm) and L is the link distance.(km).

B. Turbulence

i- Evaluation of Scintillation (C^2_n $m^{-2/3}$)

$$C_n^2 = 10^{-16}\,T_{WP} \qquad m^{-2/3} \quad (7)$$

Where T_{WP} is the turbulence weather parameter which describes the strength of turbulence and it is determined as [4], [31];

$$T_{WP} = -5300 + 20\ T + 380\ W_{TH} + (-28\ RH + 0.29\ RH^2 - 0.0011\ RH^3) + (-25\ V_W + 12\ V_W^2 - 0.85\ V_W^3) \quad (8)$$

Where T is the air temperature (°K), RH is the relative humidity (%), V_W is the wind velocity (m/s) and W_{TH} is the temporal-hour weight which determined from Table A.1, corresponding to the value of C_{TH}. Where;

$$C_{TH} = 12\ (\text{current hour} - \text{sunrise hour})/(\text{sunset hour} - \text{sunrise hour}) \quad (9)$$

Current hour is the moment of calculating scintillation.

Note 5: Equation 8 is applied with conditions, altitude around 15m elevation, dynamic range for temperature is from 9 ^oC to 35 ^oC, relative humidity from 14% to 92% and wind speed from 0 to 10 m/s [4], [31]. So, equation 9 is available for the weather of Cairo, Egypt over most the days of year.

Note 6: C^2_n independent on the optical wavelength (λ), but the effect of wavelength evident in scintillation index (σ).
To indicate the effect of weather parameters, temperature, temporal hour weight, humidity and wind velocity on the scintillation, we discus each term of equation 8 as follows;:
- The value of the second term, ($Y_T = +20$ T), is ranged from 5640 to 6160 if the temperature varies from 9^oC to 35 ^0C, respectively. So, Y_T is positive value.
- The value of the third term, ($Y_{WTH} = +380\ W_{TH}$), is ranged between 19 and 380 according to current hour. So, Y_{WTH} is positive value.
- The value of the fourth term, (Y_{RH} = -28 RH + 0.29 RH^2 –0.0011 RH^3), is ranged between negative 338.18 and negative 1062 for RH varies from 14 to 92. So, Y_{RH} is negative value (Fig.2).
- The value of fifth term, ($Y_{VW} = -25\ V_W + 12\ V^2_W - 0.85\ V^3_W$), is negative even V_W less than 2.55 m/s, maximum negative value 14.19 (at V_W=1.2 m/s) and the maximum positive value 133.22 (at V_W=8.2 m/s) as shown in Fig.3. We should notice that, Y_{VW} return to negative value at V_W=11.58 m/s.

And so, the value of T_{WP} (i.e. the value of C^2_n) can be positive or negative.

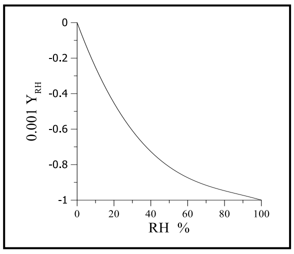


Fig.2: Value of Y_{RH}

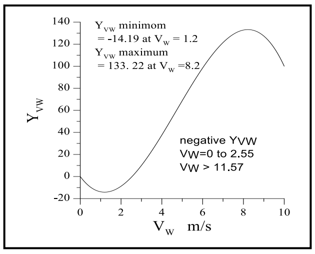


Fig.3: Value of Y_{VW}

Note 7: the value of RH is increasing while the temperature decreasing, and vice versa (RH increases in night than in day and in winter than in summer). And so, we can't study the effect of each weather parameter individually on C^2_n.

As example1, In Cairo city,10 Aug 2016, sunrise at 5.19, sunset at18.41 and midday at 12.00,
At current hour =6.00 (near sunrise), T= 298 ^oK, RH=88% and V_W =2.222 m/s

$$C_{TH} = \frac{12\ \{(6*60+0) - (5*60+19)\}}{\{(18*60+41) - (5*60+19)\}} = 0.613$$

From Table A.1, the corresponding value of W_{TH} = 0.05 and from equation 9, the value of T_{WP} = - 294 (i.e. C^2_n = -294*10^{-16} $m^{-2/3}$).
Similarly, at current hour =12.00 (midday, T=307^oK, RH=39 % and V_W=2.778 m/s) the values of T_{WP}= 432 (i.e. C^2_n = 432 *10^{-16} $m^{-2/3}$) and at current hour 18.00 (near sunset, T=309^oK, RH=29 % and V_W=4.167 m/s) the values of T_{WP} = 366 (i.e. C^2_n = 366 *10^{-16} $m^{-2/3}$)

As expected in [14] and from as example 1, the value of C^2_n at midday greater than that at sunrise and at sunset. And so, for availability, we evaluated the values of C^2_n at midday.

ii- Effect of altitude on C^2_n: The value of C^2_n decreases with altitude (h meter) as [14];

$$C^2_n = C^2_0\ (0.4\ h)^{-4/3} \qquad (\text{where, } 2.5\ \text{m} < \text{h} < 1000\ \text{m}) \tag{10}$$

So, C^2_n (at h=130) = 0.005153 C^2_n (at h=0)

therefore, the values of Twp in example 1 at altitude h=130m become, 1.515 , 2.23 and 1.886 respectively.

The value of C^2_n depends on the kind of ground [19]

iii- Scintillation index (σ); Scintillation index with weak turbulence regime (i.e. σ ≤ 1) for plain wave given by [6], [12], [17], [21] with λ (μm) and L (link distance, km);

$$\sigma^2_{weak} = 0.0033198\ T_{WP}\ \lambda^{-7/6}\ L^{11/6} \tag{11}$$

The maximum value of distance (L_{max}) increases with λ while it decreases with T_{WP} (turbulence).
Thus to keep the value of σ^2_{weak} < 1, With λ=1.55 μm, the value of L_{max} must be ;

$$L_{max} < 29.733/T_{WP}^{6/11} \tag{12}$$

Another definition of σ^2 (with plain wave) is [12]

$$\sigma^2 = \min(\sigma^2_{weak}\ , 0.5\ ) \tag{13}$$

iv- Effect of turbulence on the spot size (spreading and centroid deviation)

Beam spreading: Field distribution of Gaussian fundamental mode (TEM_{00} mode) is defined as [9]

$$\psi(r, L) = \psi_0\ \frac{D_0}{D_{eff}}\ e^{\frac{-4r^2}{D^2_{eff}}} \tag{14}$$

Where; r is the transverse distance, L is the long distance, D_o is the spot size diameter at transmitter (generally transmitter aperture diameter $D_t = D_o$), and D_{eff} is the spot size diameter at long distance (z =L) due to both diffraction and turbulence,

Note 8: the spot size radius is the transverse distance at which the field amplitude is decreased by a factor e^{-1} compared to its value on the axis.
Beam formatting optics either converging or diverging or collimated (collimated is the common used [12]). For collimated optical wave, the divergence is typically small, and the full wave divergence angle (θ mrad) is defined as [9], [12], [21], [32]

$$\theta(\text{mrad}) = 0.1\ \frac{\lambda}{\pi D_t} \qquad (\text{With } D_t \text{ in cm and } \lambda \text{ in } \mu\text{m}) \tag{15}$$

The diameter of the beam spot size (D_L) at distance (L) from the transmitter increases as a beam diffraction [32];

$$D_L\ (\text{cm}) = D_t + 100\ L\theta = D_t + 10\ L\lambda/\pi D_t \qquad (\text{where L in km}, \lambda \text{ in } \mu\text{m and } D_t \text{ in cm}) \tag{16}$$

Also the diameter of the beam spot size increases (spreading) due to turbulence (D_{eff}) as [5], [25], [33], [34];

$$D^2_{eff}\ (\text{cm}^2) = D^2_L \{1 + 3.4906\ \sigma^2_{weak}\ (L\lambda/D^2_L)^{5/6}\} \qquad (\text{where L in km}, \lambda \text{ in } \mu\text{m and } D_L \text{ in cm})$$

(17)

The maximum effective diameter occurs at σ^2_{weak} =1, so;

$$D_{eff}\ (\text{cm}) = D_L\ \{1 + 3.4906\ (L\lambda/D^2_L)^{5/6}\}^{0.5} \qquad (\text{where L in km}, \lambda \text{ in } \mu\text{m and } D_L \text{ in cm}) \tag{18}$$

Beam centroid deviation: The deviation of the beam centroid (deviation distance, r_{dev}, and deviation angle, γ_{dev}) from the optical axis with L (km) and D_t (cm) are [33], [34];

$$r_{dev}\,(mm) = 0.0011541\; T_{WP}^{1/2}\; L^{1/2}\; D_t^{-1/6} \quad \text{(where L in km and } D_t \text{ in cm)} \tag{19}$$

And the deviation angle;

$$\gamma_{dev}\,(rad) = \arctan\left(\frac{\gamma_{dev}}{L}\right) \approx \frac{\gamma_{dev}}{L} = 1.1541 * 10^{-6}\, T_{WP}^{1/2}\; L^{1/2}\; D_t^{-1/6} \quad \text{(where L in km and } D_t \text{ in cm)} \tag{20}$$

But in [25] **;**

$$\gamma_{dev}\,(rad) = 1.1641 * 10^{-6}\, T_{WP}^{1/2}\; L^{1/2}\; D_t^{-1/6} \quad \text{(where L in km and } D_t \text{ in cm)} \tag{21}$$

iii Turbulence Losses

* Fading loss (Scintillation loss) due to weak atmospheric turbulence ($\alpha_{turb\ fading}$) is defined as [23];

$$\alpha_{turb\ fading}\,(db) = abs\,\{10\log_{10}(1-\sigma_{weak})\} \tag{22}$$

With worst turbulence, α_{turb} can be estimated from the Rytov formula as [4], [7];

$$\alpha_{turb\ fading}\,(db) = \sqrt{\{75.3496\,\sigma_{weak}^2\}} = 8.68\,\sigma_{weak} \quad \text{(as defined in [7])} \tag{23}$$

The value of $\alpha_{turb\ fading}$ (from equation 22) < $\alpha_{turb\ fading}$ (from equation 23) until the value of σ =0.795.

As example 2;
At λ=0.85μm and L= 0.85km with $C_n^2 = 10^{-16}$, $10*10^{-16}$ and $100*10^{-16}$ (i.e. T_{WP} = 1, 10 and 100, respectively), the corresponding attenuation due to turbulence, $\alpha_{turb\ fading}$ (db) = 0.25, 0.82 and 3.2 db, respectively [9], [23].
From equation 11, σ_{weak}=0.05458434, 0.172611 and 0.5458434, respectively (i.e. weak turbulence). So, from equation 22, $\alpha_{turb\ fading}$ (db) = 0.243772, 0.8229 and 3.4279 respectively, as in [16].

Note 9: Optical Scintillation can be decreased by increasing the collecting area of the receiver lens (aperture averaging) [35] and so, the corresponding attenuation due to turbulence is lowered.

* Beam spreading Loss due to turbulence ($\alpha_{turb\ beam}$) is defined as [5], [25], [33].

$$\alpha_{turb\ beam}\,(db) = 20\log_{10}(D_{eff}\,/D_L) \tag{24}$$

From equation17, with L (km) , λ (μm), D_t (m) and θ (mrad), $\alpha_{turb\ beam}$ becomes;

$$\alpha_{turb\ beam}\,(db) = 20\log_{10}\left\{1 + 0.00162\,\sigma_{weak}^2\,\left|\frac{L\lambda}{(D_t + L\,\theta)^2}\right|^{\frac{5}{6}}\right\}$$

$$\text{(where L in km, } \lambda \text{ in } \mu m, D_t \text{ in cm and } \theta \text{ in mrad)} \tag{25}$$

From equation 25, the value of $\alpha_{turb\ beam}$ is decreased with θ, L and D_t but it increases with λ and σ (We should be noticed that the value of σ decreases with λ and increases with L)

The total turbulence attenuation ($\alpha_{turb\ total}$) is;

$$\alpha_{turb\ total} = \alpha_{turb\ fading} + \alpha_{turb\ beam} \tag{26}$$

Note 10**:** The fading at the receiver increases with higher data rate (tenths Gb/s) and so, the large receiver aperture is used to minimize the fading effect. Also, by using the receiver diameter (D_r) larger than the effective beam diameter ($D_{eff\ max}$), the effect of fading and beam wander becomes very leaky.

C. Attenuation of weather (α_w)

Attenuations due to the effect of all weather parameters, aerosols, fog, rain, snow, temperature and humidity are evident in the value of visibility. Where the total intrinsic attenuation (γ_t km^{-1}) for wither parameters together ($\gamma_t = \gamma_{Scat} + \gamma_{Fog} + \gamma_{Rain} + \gamma_{Snow}$) [14]. So, by measurement the value of visibility (V), the effect of total weather parameters are taken in the account. Therefore the total weather attenuation is calculated from Mie Scattering law and with transmittance (2%), the weather attenuation (α_w) is defined as [36], [37];

$$\alpha_w\ (db/km) = \frac{-13}{V}\left(\frac{0.550}{\lambda_{\mu m}}\right)^q \quad (where\ V\ in\ km) \tag{27}$$

Where V is the visibility in km, λ is the wavelength in μm, and with Kurluse model the parameter
q = 1.6 (with V > 50 km) ,
q=1.3 (with, 6km < V < 50 km) ,
q= 0.34+0.16 V (with 1< V < 6) ,
q= V- 0.5 (with 0.5 < V < 1 km) and
q=0 (with V< 0.5 km) [14].

D. Received power (P_r) [14],[19]

$$P_r = P_t\; G_t\; G_r\; \alpha_L\; \alpha_{Geom}\; e^{-L\,\alpha_w} \tag{28}$$

Where P_t is the transmitted power, G_t is the transmitter gain, G_r is the receiver gain, α_L is the free space losses, α_{geom} is the geometrical losses, L is the link distance and α_w is the weather attenuation;

$$G_t = (\pi D_t/\lambda)^2 \quad [19], [38]$$
$$G_r = (\pi D_r/\lambda)^2 \quad [19], [38]$$
$$\alpha_L = (\lambda/4\pi L)^2 \quad [19], [38]$$
$$\alpha_{Geom} = (D_r/D_{eff})^2 \quad [14] \tag{29}$$

D_t is the transmitter diameter, D_r is the receiver diameter and λ is the wavelength.
α_{geom} is ignored with $D_r > D_{eff\ max}$

The value of the received power P_r must be greater than the sensitivity of the optical detector ($P_{r\ mim}$) and smaller than the available maximum received power ($P_{r\ max}$).

$$P_r\,(Watt) = 0.0061685 * 10^{-0.1\,L\,\alpha_W}\,\frac{D_t^2\,D_r^2}{\lambda^2\,L^2}\;P_t \tag{30}$$

With L (km), G_t (cm), D_r (cm), λ (μm), $\alpha = \alpha_w$ (db/km) and P_t (Watt)

Also, P_r is defined as [13], [30]

$$P_r\,(Watt) = \eta\,(i/q_e)\,(h_p\,c/\lambda) = \eta N_p\,B_r\,(h_p\,c/\lambda) = 19.875 * 10^{-11}\,\eta N_p\,B_r/\lambda \tag{31}$$

Where η is the quantum efficiency of the receiver, i is the receiver current, q_e is the electronic charge, N_p is the average photons number per bit, B_r is the bit data rate (Gb/s), h_p is the Plank's constant ($h_p = 6.625*10^{-34}$ J.s) and c is the light velocity ($c = 3.*10^8$ m/s)

E. Signal to Noise Ratio (SNR), Q-parameter and Bit error rate (BER)

The OOK- NRZ modulation with wavelength 1.55μm is the most common used for FSO [19], [26], [39].
With the assumption that the typical value of receiver bandwidth equals half the bit rate (i.e. $\Delta F = 0.5\,B_r$), the SNR is defined for PIN receiver as [40];

$$SNR = \eta N_p \quad (32)$$

Therefore, from equations 30 and 31, the SNR becomes;

$$SNR = 31.0365 * 10^{6-0.1 L \alpha_w} \frac{D_t^2 D_r^2}{\lambda L^2} \frac{P_t}{B_r} \quad (33)$$

Where D_t (in cm), D_r (in cm), L (in km), B_r (in Gb/s) and λ (in μm) with notice that $D_r > D_{eff}$

The value of D_r is assumed as 1.2 $D_{eff\ max}$ to minimize the effect of turbulence,

From equation 32 into equation 31.b, the received power becomes;

$$P_t \ (Watt) = 19.875 * 10^{-11} (B_r/\lambda) \ SNR \quad (34)$$

From equation 33 we should notice that,

- SNR decreases with B_r (where with constant P_t, the value of N_p decrease with B_r)
- SNR increases with both D_t and D_r
- SNR decreases with L
- SNR decreases with λ (where P_r decreases with λ, also θ increases with λ)
- SNR decreases with scintillation index (σ) where $\alpha_{turb\ tot}$ increases with σ
- SNR decreases with lower visibility (α_w)
- SNR increases with the quantum efficiency of the PIN receiver (η)
- SNR decreases with the divergence angle (θ) (where, D_t decreases with θ while, D_L increases with θ)

Q-parameter is defined as [40];

$$Q = \sqrt{SNR} \qquad (\text{where SNR in ratio}) \quad (35)$$

Bit error rate (BER) is defined for OOK modulation scheme with Gaussian as [41];

$$BER = \frac{10^{-0.21715\ SNR}}{\sqrt{2\pi\ SNR}} = \frac{10^{-0.21715\ Q^2}}{\sqrt{2\pi Q^2}} \qquad (\text{where SNR in ratio}) \quad (36)$$

III. DESIGN A PROPOSED LINK BETWEEN Cairo tower to the big pyramids

* Operating parameters: data rate (B_r=10Gb/s) and wavelength (λ =1.55 μm).

* Structure parameters: distance (L=11.5 km) , height (h=130m), transmitter aperture (D_t =10 cm), so, from equations16.b and 18, the values of D_L = 15.67 cm, and $D_{eff\ max}$ = 18.489 cm

Therefore the receiver aperture, D_r becomes;

.D_r = 1.2 $D_{eff\ max}$ = 22.187 cm , we take D_r=23 cm.

* PIN receiver with: quantum efficiency (η=0.9), sensitivity ($P_{r\ min}$= 50nW= -43dB$_m$, $P_{r\ max}$ =50μW = -13 dB$_m$) , bandwidth (ΔF=5GHz).

* Transmitter: output power (P_t = 500mW = 27 dB$_m$), line width (Δλ=0.02 nm), divergence angle is calculated from Eqn.15, θ = 0.004934 mrad

* Weather data of temperature, pressure, wind velocity, relative humidity, and visibility from [29].

With L=11.5 km and λ=1.55μm, the value of σ^2 = 0.175255 T_{WP}, and the maximum allowable weak scintillation index (σ^2 =1), occurs at C^2_n = 5.706

So, equation 34, becomes;

$$SNR = 8 * 10^{9-1.15\alpha_w}\ P_t/B_r \qquad (\text{Where } \alpha_w \text{ in db/km}, B_r Br \text{ in Gb/s and } P_t \text{ in Watt}) \quad (37.a)$$

For P_t =500 mW and B_r =10 Gb/s, the SNR becomes;

$$SNR = 0.4 * 10^{9-1.15\alpha_w} \quad (37.b)$$

For minimum BER (10^{-9}), the corresponding value of SNR (SNR_{min}= 36 = 15.56db), so, from equation 37.b the maximum allowed weather attenuation ($\alpha_{w\ max}$) becomes 6.127 db/km, and from equation 27, the corresponding allowed minimum visibility (V_{min}) is 1.21 km.

We should notice that the received power (P_r) must be $P_{r\ min} < P_r < P_{r\ max}$. From equation 30,

$$P_r = 1.027 * 10^{-1.15\alpha_w} P_t \quad (38)$$

For high values of α (α_w) we need large value of P_t, with notice that the eye safety and $P_{r\ max}$.

For the availability of the proposed design, the values of weather attenuation must be realize the following three conditions;

$$\text{For SNR}: \quad \alpha_w < 6.3885 + 0.87 \log_{10}(P_t) \quad (39.a)$$

$$\text{For } P_{min}: \quad \alpha_w < 0.01 + 0.87 \log_{10}(P_t/P_{r\,min}) = 6.3588 + 0.87 \log_{10}(P_t) \ \ with\ P_{r\,min} = 50nW \quad (39.b)$$

$$\text{For } P_{max}: \quad \alpha_w > 0.01 + 0.87 \log_{10}(P_t/P_{r\,max}) = 3.75 + 0.87 \log_{10}(P_t) \ \ with\ P_{r\,min} = 50\mu W \quad (39.c)$$

Therefore, the value of $P_{r\ max}$ must be the maximum allowed value, and the value of P_t must be controlled by the predicted value of visibility from Egyptian meteorological authority.

The relationship between P_r and SNR (equation 34) with Br=10Gb/s and λ=1.55μm becomes;

$$P_r \ (Watt) = 128.226 * 10^{-11} \ SNR \quad (40.a)$$

$$P_r \ (dbm) = SNR - 58.92 \qquad (\text{where, SNR in db}) \quad (40.b)$$

IV Results and Discussion

A. Refractive index

The value of n_a decreases with both T, λ and h as evident in Table 1. The negative value of dn_a/dT decreases with both T, λ and h. The negative value of dn_a/dh decreases with both T , λ and h. The value of $D_{m\ air}$ decreases with λ, but the change of $D_{m\ air}$ with T and h is very weak

Table 1: The values of n_a at different values of λ , T and h

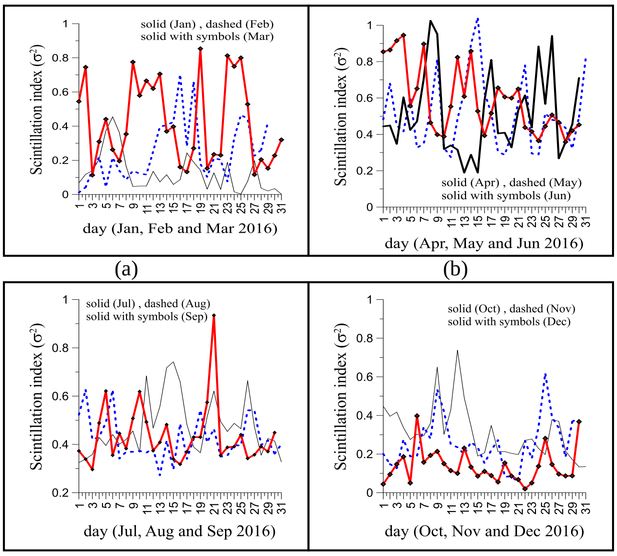
λ (μm)	T °K	h m	n_a
0.85	288	0	1.0002746
1.55	288	0	1.0002731
1.55	300	0	1.0002622

λ (μm)	T °K	h m	n_a
0.85	288	15	1.0002742
1.55	288	15	1.0002727
1.55	300	15	1.0002619

λ (μm)	T °K	h m	n_a
0.85	288	100	1.0002720
1.55	288	100	1.0002705
1.55	300	100	1.0002598

B Calculation of σ^2 at midday in Cairo through year 2016

The values of scintillation index (σ^2) at midday for all days of year 2016 are shown in Fig.4.



(c) (d)

Fig.4: Values of scintillation index (σ^2) at midday for all days of year 2016 (Note: C^2_n= 5.706*10^{-16} σ^2)

The scintillation index condition ($\sigma^2 \leq 1$) except, at 8 April 2016, the value of σ^2 = 1.025 and the maximum allowed length L_{max}=11.346 km. Also at 15May 2016, the value of σ^2 =1.043 and the maximum allowed length L_{max}=11.237 km. The values of C^2_n can evaluated from σ^2 as C^2_n= 5.706*10^{-16} σ^2.

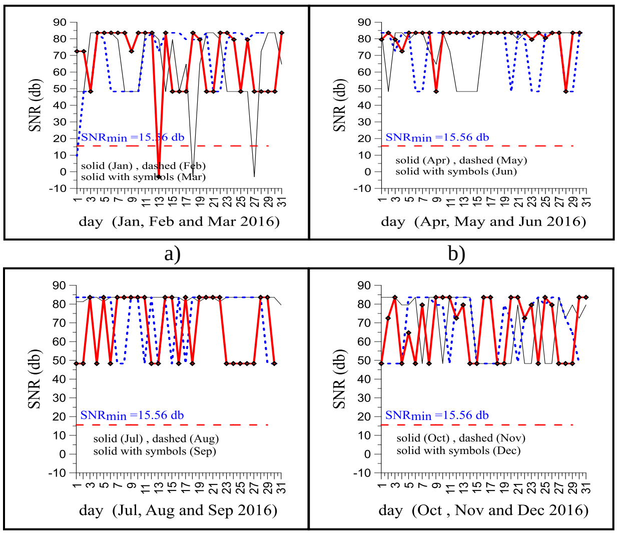
C Calculation of signal to noise ratio (SNR)

The values of SNR at midday for all days of year 2016 are shown in Fig.5. The required value of SNR (SNR $\geq$ 15.56 db) is realized for all days except, at midday of 18 and 27 January 2016, the value of SNR = -3.03 db , also at midday of 13 March 2016, the value of SNR = -3.03 db.

D. Calculation of the received power (P_r)

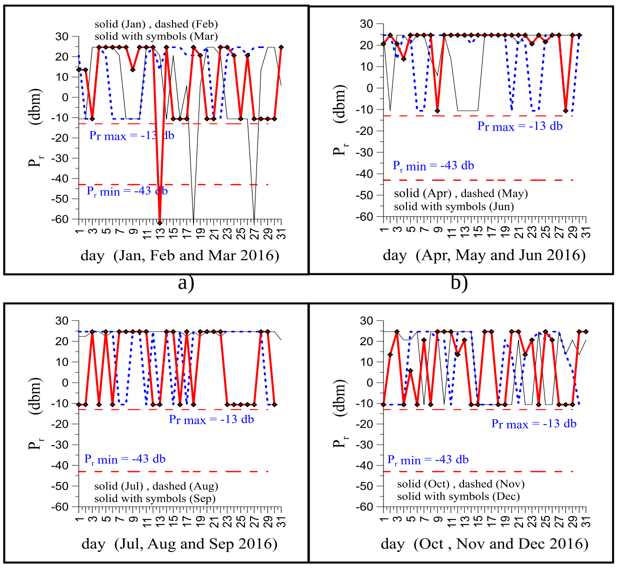
The values of received power (P_r db) at midday for all days of year 2016 are shown in Fig.6. The received power condition ($P_r \geq P_{r\,min}$ = - 43 db) is realized except , at midday of 18, 27 January 2016, and 13 March 2016, the received power $P_r \leq P_{r\,min}$,. Also, the received power greater than $P_{r\,max}$ for all days except, at midday of 18, 27 January 2016, and 13 March 2016, the received power P_r > $P_{r\,max}$, (-13 dbm)

Note, P_r (dbm) = SNR – 58.92



c) d)

Fig.5: Values of SNR at midday for all days of year 2016.



c) d)

Fig.6: Values of received power (P_r dbm) at midday for all days of year 2016 (P_r dbm = SNR – 58.92)

IV. Conclusion

A theoretical design of free space optical link between Cairo tower to the great pyramid is evaluated with 11.5km long, 130m altitude, 1.55µm wavelength and 10 Gb/s data rate.

During year 2016, the visibility usually greater than 2km, except it equals zero during 90 minutes only, but it becomes 1 km during 56.5 hr. Also weak atmospheric turbulence C^2_n < 6*10^{-16} $m^{-2/3}$ at altitude h=130 m, the scintillation index $\sigma^2 \leq$ 0.8, except three days, and the air dispersion very small around 0.47 ps km^{-1} nm^{-1}.

By considering the availability occurs if the SNR $\geq$ 36 $\equiv$ 15.56 db (i.e. BER $\leq 10^{-9}$ and Q-factor $\geq$ 6) also, received power P_r $\geq$ minimum received power ($P_{r\,min}$), the availability becomes 99.983% during year 2016. With visibility V $\leq$ 1km, or scintillation index (σ^2 >1), the link becomes not available.

SNR increases with the ratio of the transmitted power to the data rate (i.e. P_t /B_r).

The required transmitted power must be related to the expected visibility.

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Appendix A : Temporal Time Weight [31]

Table A.1: The values of temporal hour weight (W_{TH}) corresponding to current temporal hour (C_{TH})

event	night	night	night	night	night
C_{TH}	until -4	-4 to -3	--3 to -2	-2 to -1	-1 to 0
W_{TH}	0.11	0.11	0.07	0.08	0.06
event	day	day	day	day	day
C_{TH}	5 -- 6	6 -- 7	7 -- 8	8 -- 9	9 -- 10
W_{TH}	1.00	0.90	0.80	0.59	0.32

event	sunrise	day	day	day	day
C_{TH}	0 -- 1	1 -- 2	2 -- 3	3 -- 4	4 -- 5
W_{TH}	0.05	0.10	0.51	0.75	0.95
event	day	sunset	night	night	
C_{TH}	10 -- 11	11 --12	12 --13	over 13	
W_{TH}	0.22	0.1	0.08	0.13	

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