LASERCOM PATHFINDER

For operators aiming to deploy an Optical Ground Stations (OGS) network, the first step consists in the selection of sites with the best potential for direct to Earth Laser Communications. The LaserCom Pathfinder modelling of the atmospheric optical transfer function leverages historical weather data, advanced turbulence simulation and in situ validation to assist in this selection.

It is very cost effective to test potential OGS deployment sites to reveal potential adverse atmospheric conditions before any equipment installation and operational testing.

It also saves time by eliminating the need for extensive commissioning. Engineers can evaluate all global potential sites simultaneously and select the most suitable one for actual on-site instrumental characterization.

Miratlas offers a site pre-selection tool which uses global modelling, based on the ECMWF ERA5 dataset, and provides a model of the turbulence parameters.

ERA5 DATA

The model uses European Centre for Medium-Range Weather Forecasts (ECMWF) ERA5 data[1], which is a re-analysis of the global climate. Note that even though this is a European-based center, the sources of data are multiple, and include north American- or Asian-based agencies data (e.g. NASA or JAXA).

The data has a **temporal resolution of 3h and a geographical of 0.3°** (about 33kmx33km at the equator). It represents the vertical profiles of parameters at surface level, and on the vertical axis on a 137-levels model.

We use the following metrics at surface level:

- Boundary layer height
- Total cloud cover
- 10m (U,V) wind components
- 2m temperature
- Land-sea mask
- Forecast surface roughness

For the vertical layers, we download the following metrics:

- Temperature
- Humidity
- (U,V) wind components
- Geopotential

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[1] https://www.ecmwf.int/en/forecasts/dataset/ecmwf-reanalysis-v5

The current analysis use data **from January 1st, 2018 to December 31st, 2023**. We aim to increase the database over time to provide better modeling, but also global trends.

TURBULENCE PARAMETERS

FRIED PARAMETER

r_0, Fried parameter, represents the size of the isoplanatic patch, which is the region in the atmosphere where the wavefront of the light remains relatively undistorted. It is a key measure of the strength of the turbulence integrated over the whole airmass between the ground and the top of the atmosphere. **A large r_0 value indicates low atmospheric turbulence**, resulting in a more stable and clearer optical signal.

The r_0 depends on temperature and pressure of the atmosphere, wind speed and direction and the distribution of turbulence along the atmosphere height. It is also proportional to the wavelength of the optical signal, in other words a larger wavelength means a larger r_0 value with the same other conditions. **Its values lie from a few to several dozens of centimeters, with a typical 4 cm in mild low altitude areas**.

ISOPLANATISM ANGLE

θ_0, isoplanatism angle, refers to the maximum angle over which the wavefront (or Fried parameter) remains approximately valid over the entire distance between the transmitter and receiver. **It is the spatial validity domain of a given turbulence**.

The isoplanatic angle depends on the atmospheric conditions, the distance between the transmitter and receiver, and is inversely proportional to the wavelength of the optical signal. **Its values are usually comprised within 10 ArcSec**.

COHERENCY TIME

τ_0, coherency time, refers to the duration over which the received optical signal maintains a coherent phase relationship with the transmitted signal. It is the temporal validity domain of the turbulence. Random fluctuations in the optical signal lead to signal distortion, including scintillation and fading. These fluctuations vary rapidly, making it challenging to maintain an accurate mitigation **The coherence time is important as it determines the maximum time response of the mitigation technology to compensate the distortion of the signal**.

The coherence time depends on the atmospheric conditions, the distance between the transmitter and receiver, and it inversely proportional to the wavelength of the signal. **It values are typically of a few milliseconds**.

REFRACTIVE INDEX STRUCTURE CONSTANT C_N^2

The refractive index structure constant C_n^2 is the distribution of the turbulence strength along the altitude. The optical refractive index of air varies with temperature, pressure, and humidity fluctuations, causing light to deflect as it propagates through the atmosphere. The C_n^2 characterizes these fluctuations and their distribution over the airmass.

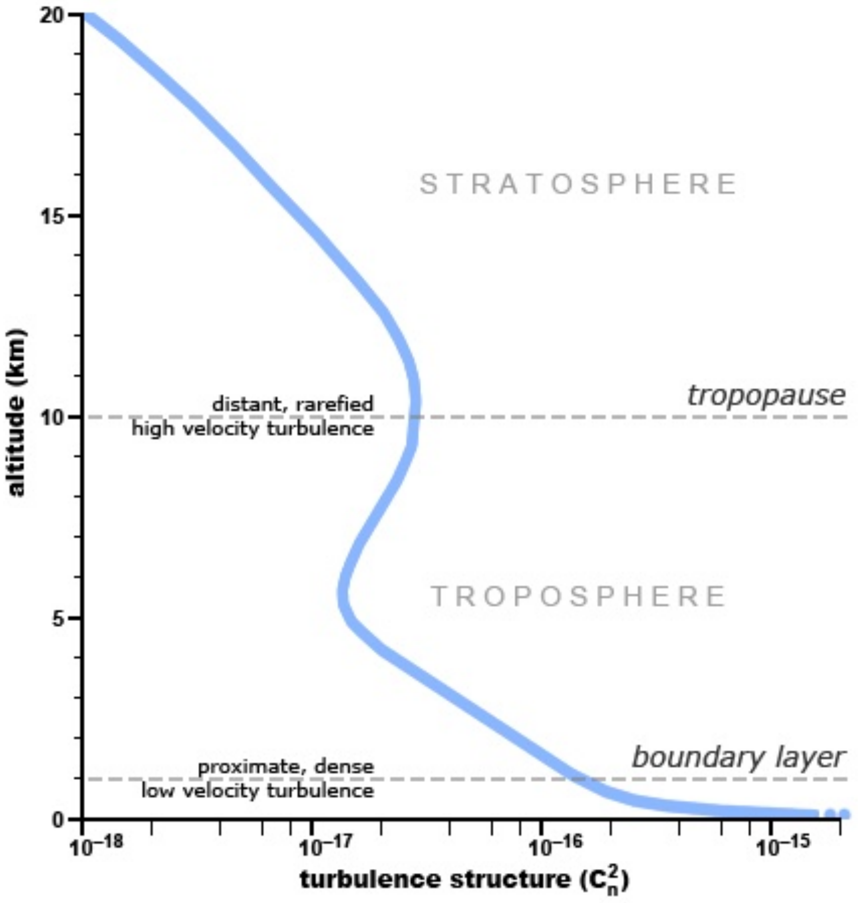

FIGURE 1 A TYPICAL C_n^2 PROFILE PRESENTS A PEAK AT THE TROPOPAUSE AND A STRONG TURBLENCE IN THE GROUND LAYER.

TURBULENCE MODELING

In collaboration with Durham university, Miratlas has developed a turbulence modelling algorithm, able to provide a characterization of the turbulence based on atmospheric parameters. For every cell in the geographical grid, and at every point in the time sampling, a local C_n^2 vertical profile is computed[2], and from this profile, the turbulence parameters can be derived. The whole processed is illustrated in the figure 2 below.

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[2] Osborn, James & Communal, Jean-Edouard & Jabet, Frédéric. (2023). Global atmospheric turbulence forecasting for free-space optical communications. 51. 10.1117/12.2649795.

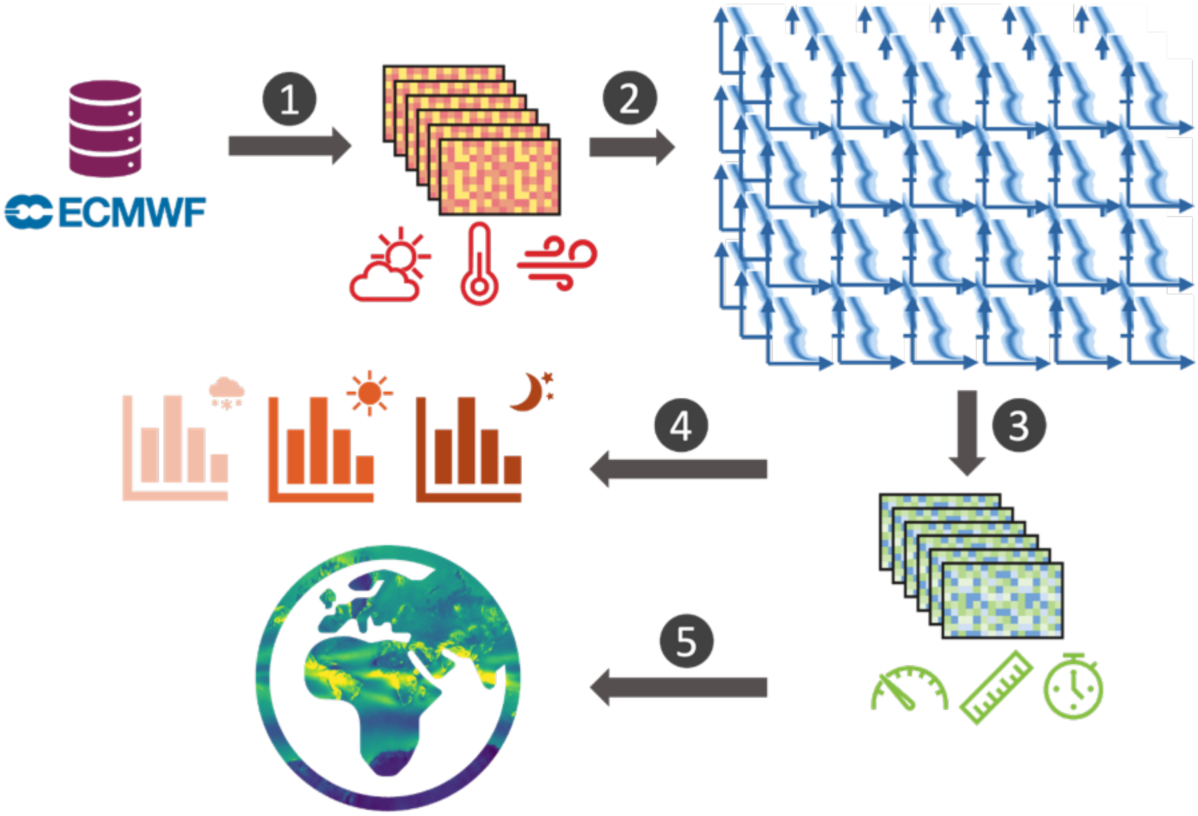

FIGURE 2 THE FLOW OF DATA FROM THE ECMWF SOURCE TO THE STATISTICS AND VISUALIZATION WE PROVIDE (RIGHT).

ATMOSPHERIC METRICS EXTRACTION

The first step is our analysis is to download the data from the ECMWF database, using the CDS API (step 1 of figure 2). The files are in the GRIB format, each one containing either an hourly set of data for a calendar day (surface-level data) or a snapshot of a specific time for all the vertical layers of the model (vertical layers data). Although it is possible to restrict the data to a certain window or latitude/longitude, we request the whole globe at all points in time.

TURBULENCE PROFILE ESTIMATION

From the GRIB files, we can extract arrays of data representing snapshots of the globe at a single point in time, over the 137 levels that the model provides. For each cell of the surface array, we use our model to estimate the C_n^2 profile at that point, using the local atmospheric parameters if we want to generate a map (this is step 2 of figure 2). If we want to model specific sites, we will take the subset of (lat, lon) coordinates provided by the user, and compute an adjusted Cn2 profile based on the altitude of the site.

INTEGRATED PARAMETERS COMPUTATION

Each of the three integrated parameters described above can be derived from the refractive index structure, using the following formulas:

$$r_0 = \left[0.423 * k^2 \int_{Path} C_n^2(z')dz'\right]^{-3/5}, \mathrm{k} = \frac{2\pi}{\lambda}$$

$$\theta_0 = \lambda^{\frac{6}{5}} \left[\int_{Path} C_n^2(z')z'^{\frac{5}{3}}\mathrm{dz}'\right]^{\frac{-3}{5}}$$

$\tau_0 = \lambda^{\frac{6}{5}} \left[\int_{\mathrm{Path}} \mathrm{C_n}^2(z')\mathrm{w_s}(\mathrm{z}')^{\frac{5}{3}}\,\mathrm{dz}'\right]^{\frac{-3}{5}}$, where w_s is the wind speed profile.

LOCAL SITE CHARACTERIZATION

Using that data generated at each point in time, we can then perform statistical analysis on the turbulence parameters, and obtain the local characteristics of the site: is the turbulence strong or weak, is it a good site by daytime or nighttime, in winter or summer, etc. Looking at averages over the years per day and time of the year is a great way to gather information on seasonal patterns.

Figure 3 presents such an example, where the r_0 parameter has been computed. We can see that the values are low around mid-day (higher temperatures), but that this effect is stronger in the summer months and weaker in winter.

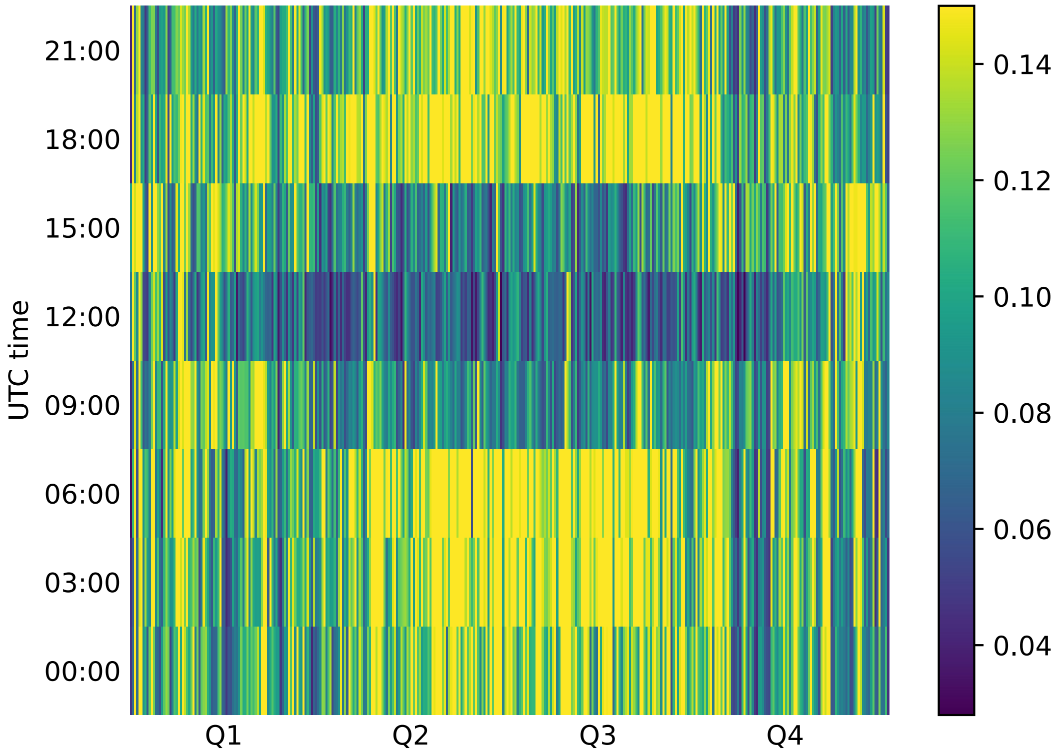

FIGURE 3 TEMPORAL AVERAGES OF R0 FOR A SITE IN WESTERN EUROPE

GLOBAL MAPS

Another way to visualize the output of our model is to generate a map of the world for a parameter, to see the global patterns that can emerge. The figure 4 below demonstrates this with a global view of the cloud cover during the northern hemisphere summer and the southern hemisphere winter.

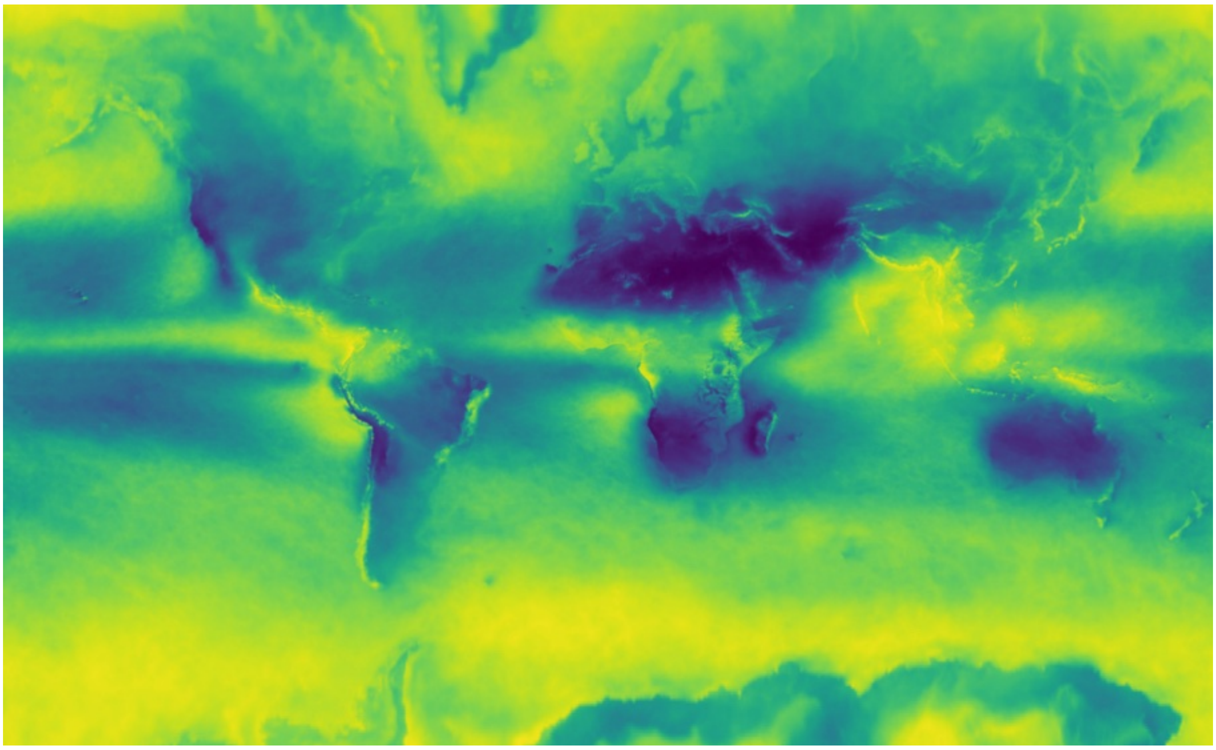

FIGURE 4 (CROPPED) GLOBAL MAP OF THE PERCENTAGE OF CLOUD COVER IN DAYTIME DURING THE 3RD QUARTER OF A CALENDAR YEAR

SITE COMBINATION

Combining both turbulence and cloud cover analysis, we can dismiss the worst locations for Laser Comms. Then, based on the weather decorrelation, we can provide the best and minimum subset of potential sites necessary to achieve a specific overall network availability (e.g. 99.9%).

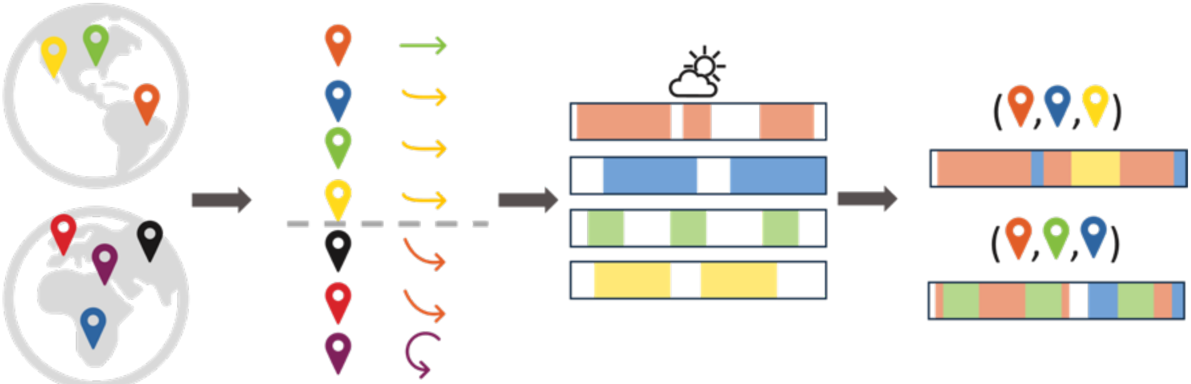

FIGURE 5 – FROM THE GLOBAL TURBULENCE MODELING, WE EXTRACT LOCAL METRICS (LEFT), FROM WHICH WE CAN EXCLUDE UNWANTED SITES (CENTER LEFT). THE REMAINING SITES AVAILABILITY (BASED ON CLOUD COVER, CENTER RIGHT) CAN THEN BE USED TO COMPUTE THE BEST COMBINATION OF SITES TO OBTAIN THE BEST COVERAGE (RIGHT)

SITE VALIDATION

Our model provides an efficient way to exclude potential sites from a selection, however, modelling is limited in temporal and spatial resolution and daytime turbulence is an inherently very local phenomenon where a few meters can make a very large difference depending on the immediate environment of the optical ground station.

Furthermore, pollution, aerosols and dust can also have a large impact on the real-world result and are impossible to account for by modeling only.

For all these reasons, LaserCom Pathfinder site selection should be followed by in-situ analysis, using the Sky Monitor which will need to be installed as close as possible to the future OGS location to gather seasonal variations of all the parameters with the necessary precision.

Only in situ measurements by the Sky Monitor can confirm the potential availability and capacity of a location for direct to Earth Laser Comms.

ABOUT MIRATLAS

Miratlas, characterizes clouds and atmospheric turbulence by deploying a global network of instruments relying on the analysis of the light from the stars and sun.

Derived from astronomy, these high-precision and real-time data are critical for direct to earth free-space optical telecommunications.

Miratlas sells its data to equipment manufacturers, satellites, and telecom operators, optimizing routing of information within their telecommunication network. Miratlas enables them to ensure the continuity and efficiency of operation regardless of atmospheric conditions.

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