Sensor Signal Processing for Defence Conference

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Simulation of Anisoplanatic Turbulence for Images and Videos

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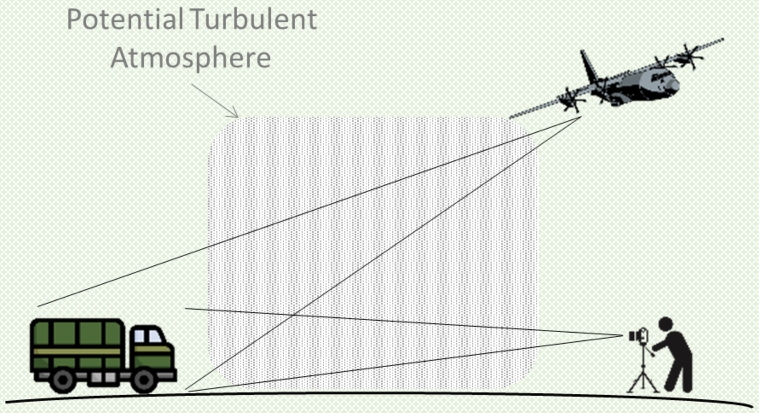
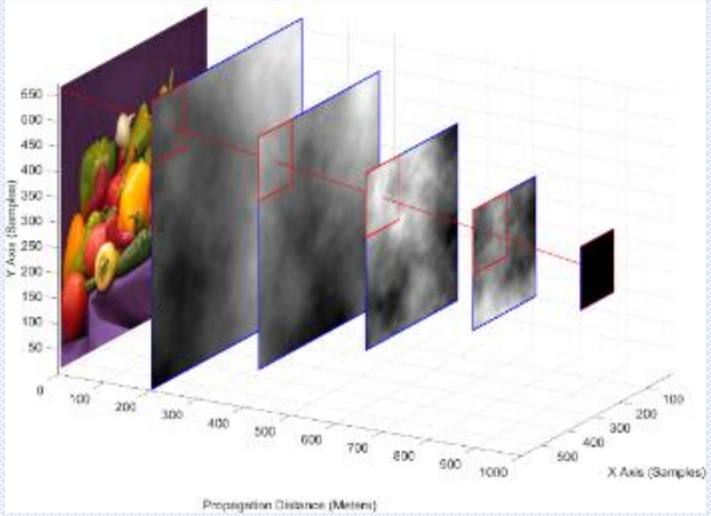
SSPD 2023

Presentation Contents

Long Range Imagery



Turbulence Simulator



Dataset Creation

Long Range Imagery

Sources of Image Degradation

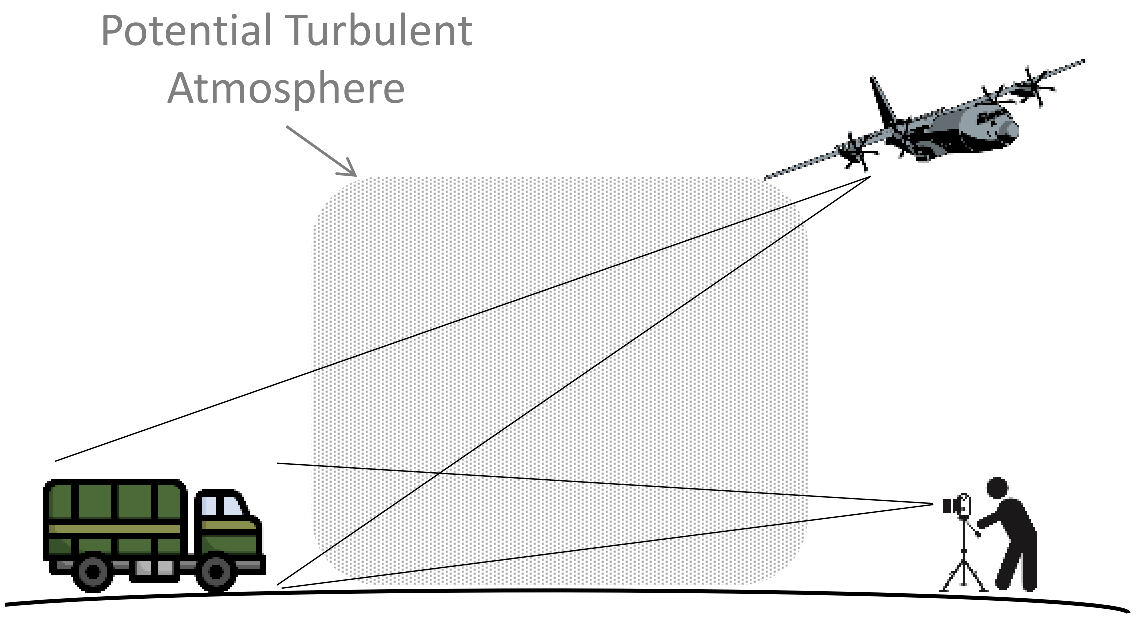
- Camera system
  - Motion blur
  - Limitations in camera technology
  - Limitations in optics – Diffraction
- Turbulent atmosphere
  - Distortion applied before reaching the operator

Outcomes

Distorted imagery that cannot be fully relied upon for further decision-making processes, such as classification or tracking.

Solutions

- Get closer to the target (Not always possible)
- Perform post processing to remove unwanted effects

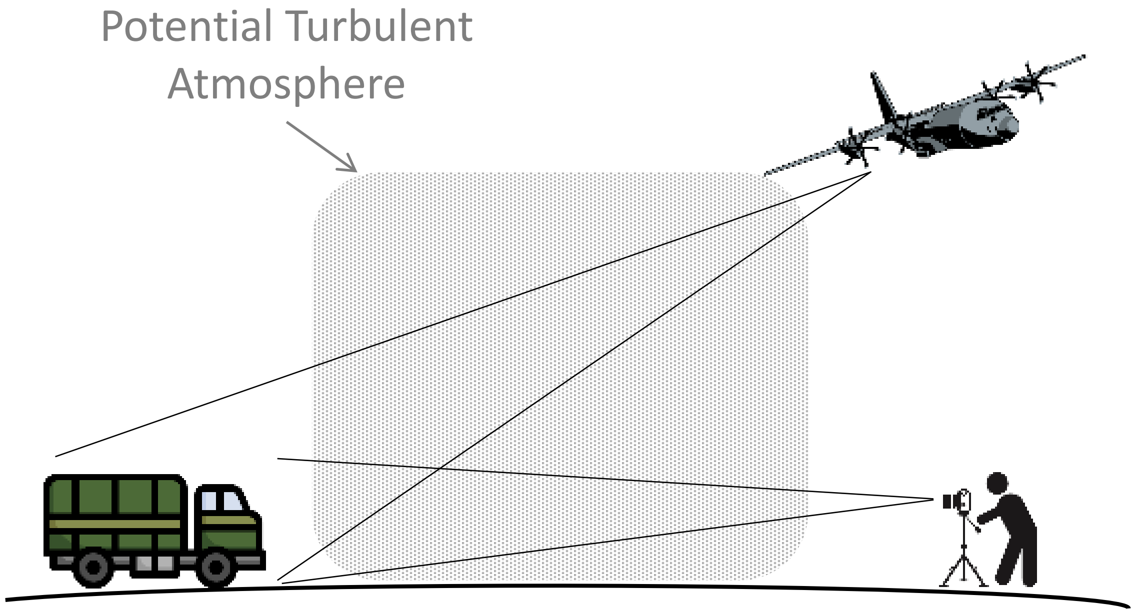


Long Range Imagery

Need for Data
- In order to improve post processing algorithms, a suitable amount of data is first required.
- Examples are a key tool in the development of algorithms.
- Especially true in the field of machine learning.

Difficulties
- Not as simple as obtaining images degraded by a turbulent atmosphere.
- Ground truth images are often required.
    - How to obtain this?

Solutions
- Gain control over the atmosphere.
- Employ a simulation tool, allowing data to be generated.
    - Allows greater control over atmosphere parameters
    - Provides access to large amounts of data



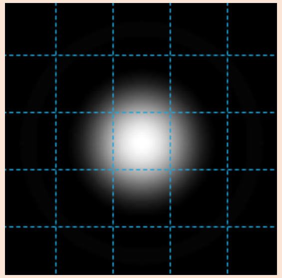
Previous Works

Image Degradation Function

- The Optical Transfer Function (OTF) of an imaging system can be described as a product of
  - Atmospheric OTF (H_{atm})
  - Camera OTF (H_{diff})

$$H = H_{atm} H_{diff}$$

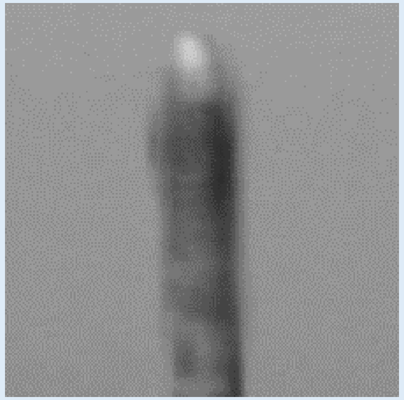
- Resulting impulse response is known as the Point Spread Function (PSF).



How best to represent H_{atm}?

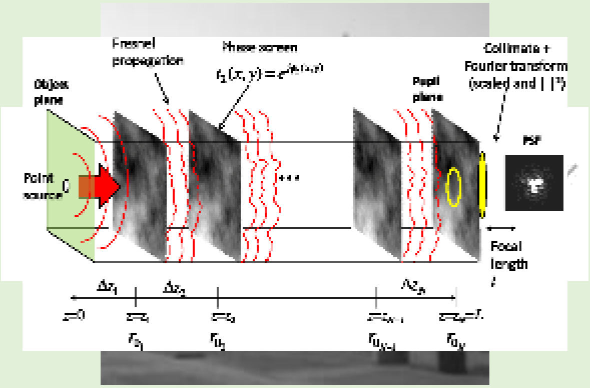
Physical Simulation

Gas Burners
Heat Plates
Hair Dryers
Heat Vents



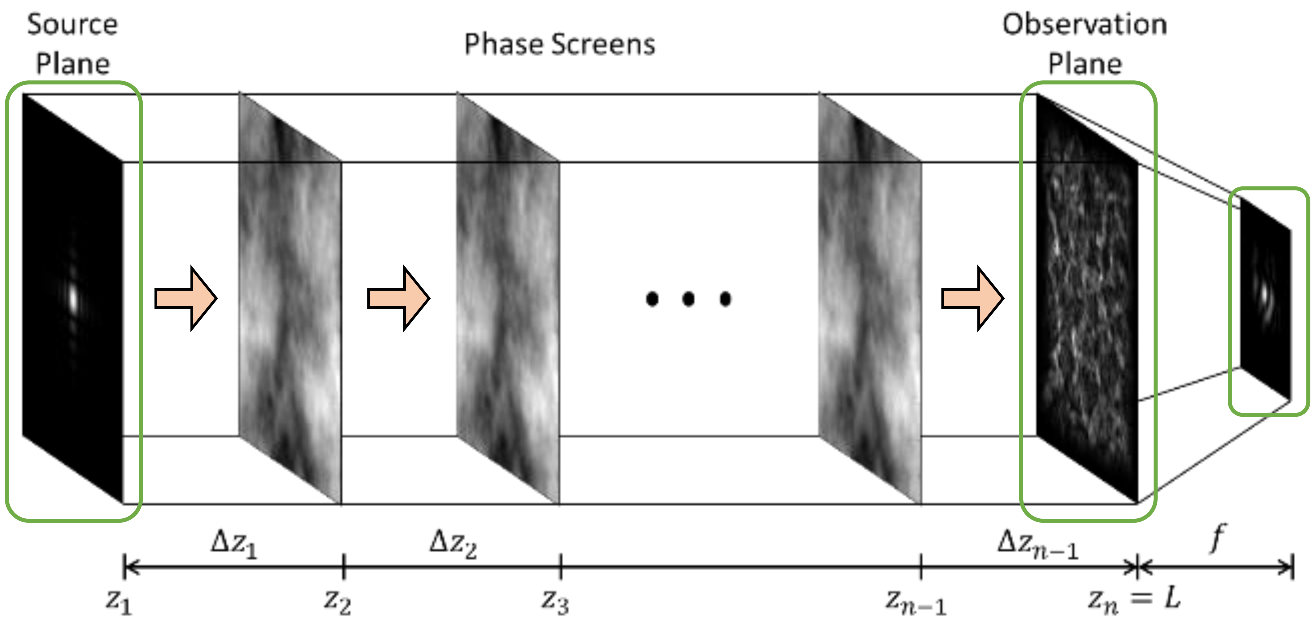
Computer Simulation

Warp and Blur
Application of OTF Equation
2D Simulation
Propagation Simulation



Layered Atmosphere Model

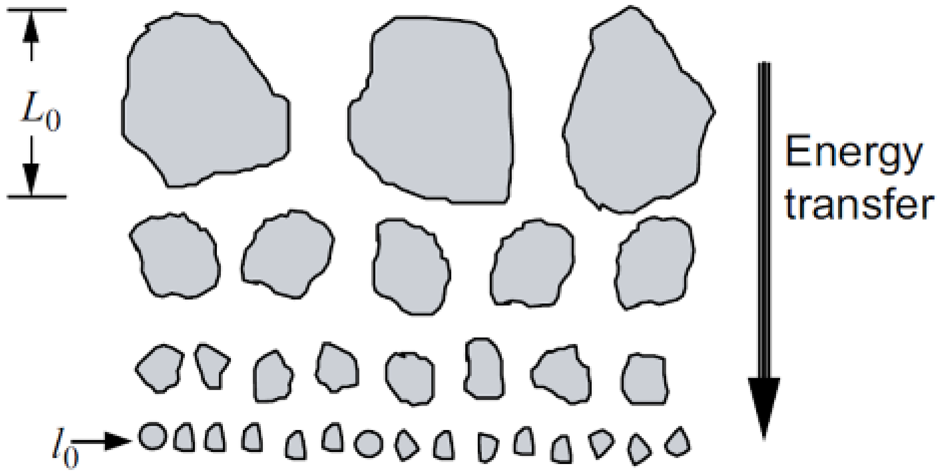
- For simulation, a turbulent atmosphere can be treated as a finite number of discrete layers.
  - **Phase screens**.
- Once the phase screens have been generated, a point source can be propagated through each one in turn.
- At the observation plane (Front of the camera lens) exists a complex plane.
- Using Fourier optics, a point spread function can then be realised.



Turbulence Theory

Kolmogarov Statistical Model of Turbulence

- Within turbulent flow, kinetic energy is transferred from large to small eddies
  - Beginning at size L_0
  - Ending at size l_0
- This range is known as the **inertial subrange**.
- It is assumed that, within this range, the eddies are statistically
  - Homogenous (Consistent in space)
  - Isotropic (Consistent in orientation)



Andrews, L.C., 2005. *Laser Beam Propagation Through Random Media*, SPIE.

- Kolmogarov refractive index Power Spectral Density (PSD)

$$\boxed{\Phi_n^K(\kappa) = 0.033 C_n^2 \kappa^{-11/3}}$$

- modified Von Karman PSD

$$\boxed{\Phi_{\phi_i}^{mvK}(f) = \frac{0.023 \mathrm{e}^{-f^2/f_m^2}}{r_{0_i}^{5/3}\left(f^2 + f_0^2\right)^{11/6}}}$$

$\boldsymbol{C_n^2}$ - Refractive Index Structure Parameter

$$\boxed{r_{0_i} = \left[0.423 k^2 C_{n_i}^2 \Delta z_i\right]^{-3/5}}$$

$\boldsymbol{r_{0_i}}$- Fried parameter for the i^{th} phase screen

Phase Screen Generation

$$\Phi_{\phi_i}^{mvK}(f) = \frac{0.023e^{-f^2/f_m^2}}{\boxed{r_{0_i}^{5/3}}(f^2+f_0^2)^{11/6}}$$

- In order to realise the PSD, we first need the values of $r_{0_i}^{-5/3}$
- Three parameters of turbulence are utilised for this task

$$\hat{r}_{0,sw} = \left[\sum_{i=1}^{n} \boxed{r_{0_i}^{-5/3}} \left(\frac{z_{i+1}}{L}\right)^{\frac{5}{3}}\right]^{-\frac{3}{5}}$$

$$\hat{\sigma}_{x,sw}^2 = 1.311k^{-\frac{5}{6}}L^{\frac{5}{6}}\sum_{i=1}^{n} \boxed{r_{0_i}^{-5/3}} \left(\frac{z_{i+1}}{L}\right)^{\frac{5}{6}}\left(1-\frac{z_{i+1}}{L}\right)^{\frac{5}{6}}$$

$$\hat{\theta}_0 = \left[\sum_{i=1}^{n} L^{\frac{5}{3}}\left(1-\frac{z_{i+1}}{L}\right)^{\frac{5}{3}} 6.8794\boxed{r_{0_i}^{-5/3}}\right]^{-3/5}$$

r_0 - Atmospheric Coherence Diameter (Fried Parameter)

A measure of the quality of optical transmission through the atmosphere.

θ_0: Isoplanatic Angle

The extent of anisoplanatism within the simulation. If two point sources are separated by less than this angle, their path through the atmosphere can be assumed to be the same (i.e. Isoplanatic).

σ_x^2: Log-Amplitude Variance

Describes the fluctuations in the wave function amplitude. It is a common measure of scintillation.

Phase Screen Generation

Step 1

From the PSD, evaluate the Fourier series coefficients

$$\boxed{c_{n,m}} = \sqrt{\boxed{\Phi_{\phi_i}\left(f_{x_n}, f_{y_m}\right)}\Delta f}$$

Step 2

Multiply the Fourier coefficients with gaussian random samples

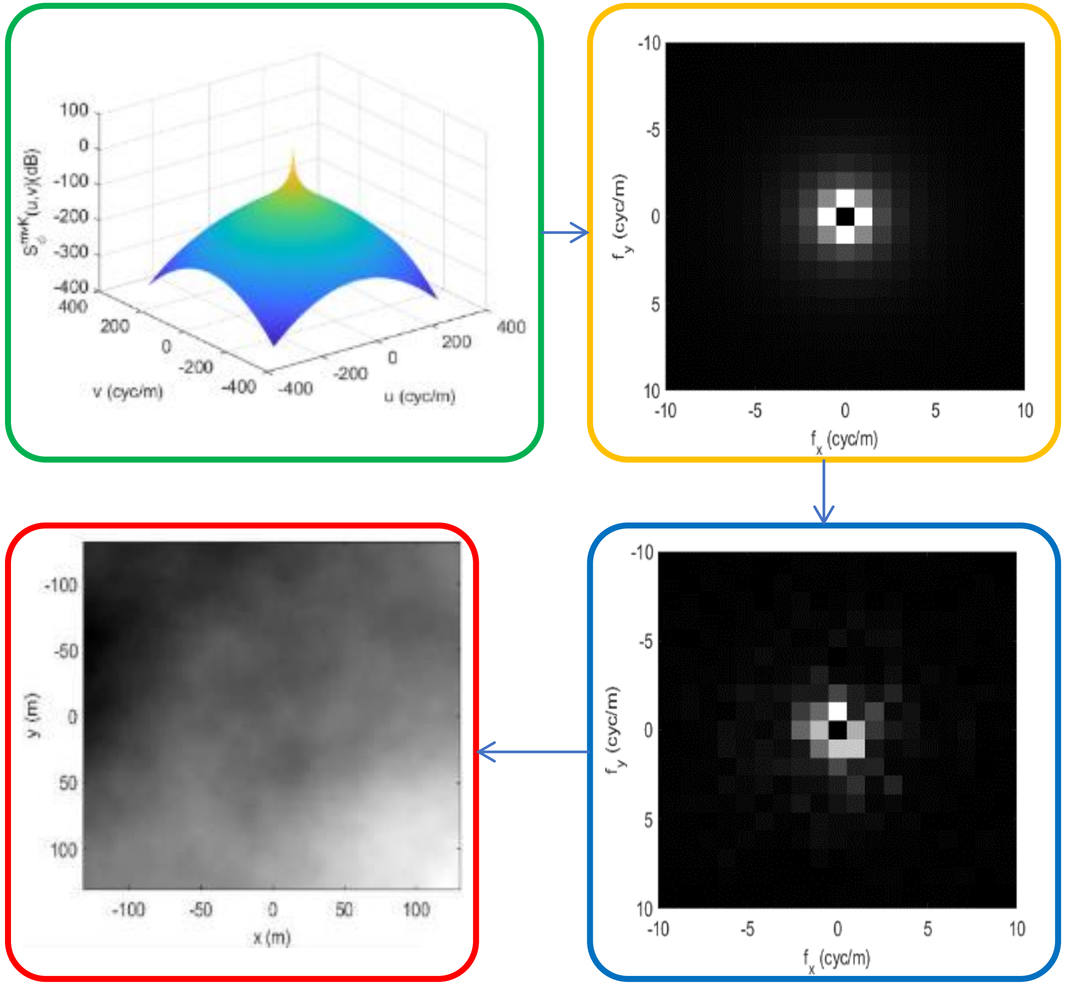
$$\boxed{\hat{c}_{n,m}} = \mathcal{N}\left(f_{x_n}, f_{y_m} | 0,1\right)\boxed{c_{n,m}}$$

Step 3

Calculate the turbulent induces phase (Phase screen) using an Inverse Fourier Transform

$$\boxed{\phi(x,y)} = \sum_{n=-\infty}^{\infty} \sum_{m=-\infty}^{\infty} \boxed{\hat{c}_{n,m}} e^{i2\pi\left(f_{x_n}x + f_{y_m}y\right)}$$

Repeat for each screen along the propagation path

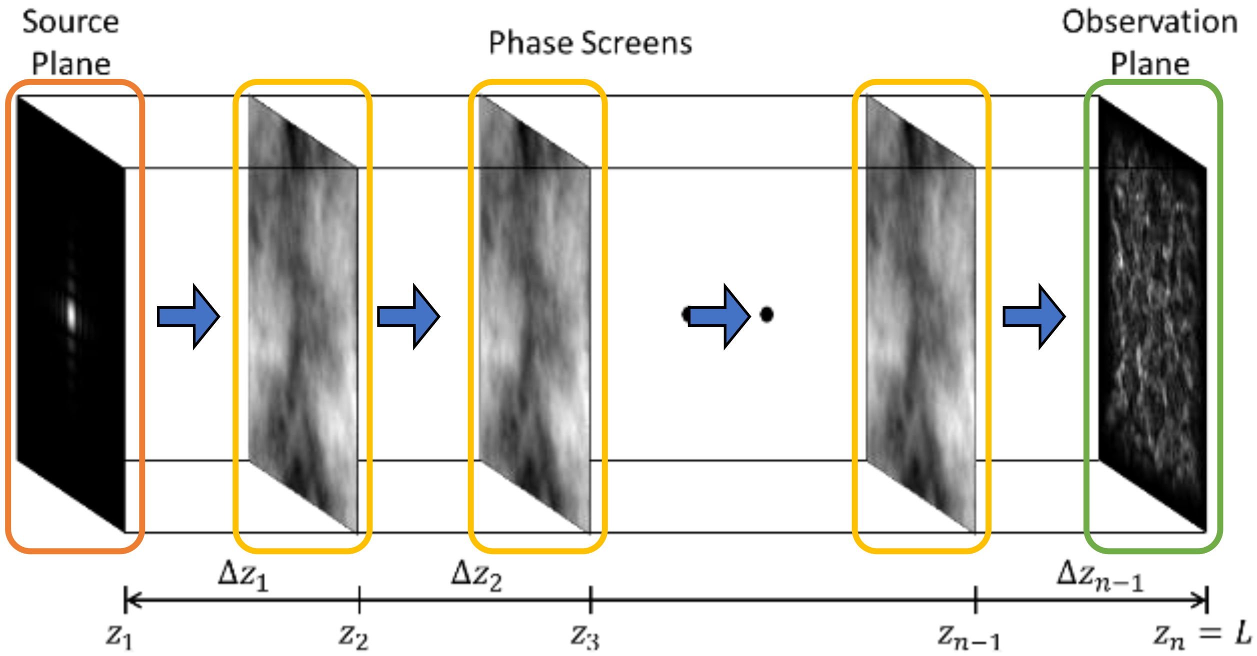


Propagation

The Propagation equation can be separated into four elements

- Complex Point Source
- Phase Screens
- Fresnel Diffraction
- Output complex plane

$$\boxed{U(\boldsymbol{r}_n)} = \boxed{Q\left[\frac{m_{n-1}-1}{m_{n-1}\Delta z_{n-1}}, \boldsymbol{r}_n\right]} \times \prod_{i=1}^{n-1}\left\{\boxed{\mathcal{T}[z_{i+1}]}\,\boxed{\mathcal{F}^{-1}\left[\boldsymbol{f}_i, \frac{\boldsymbol{r}_{i+1}}{m_i}\right] Q_2\left[-\frac{\Delta z_i}{m_i}, \boldsymbol{f}_i\right] \mathcal{F}[\boldsymbol{r}_i, \boldsymbol{f}_i]\left(\frac{1}{m_i}\right)}\right\} \times \left\{\boxed{Q\left[\frac{1-m_1}{\Delta z_1}, \boldsymbol{r}_1\right]}\,\boxed{U(\boldsymbol{r}_1)}\right\}$$



Lens Equations

- The result after propagation is a 2D complex plane.
- To produce a PSF, the OTF of the camera lens needs to be applied

- This consists of three main processes
    - Aperture Mask

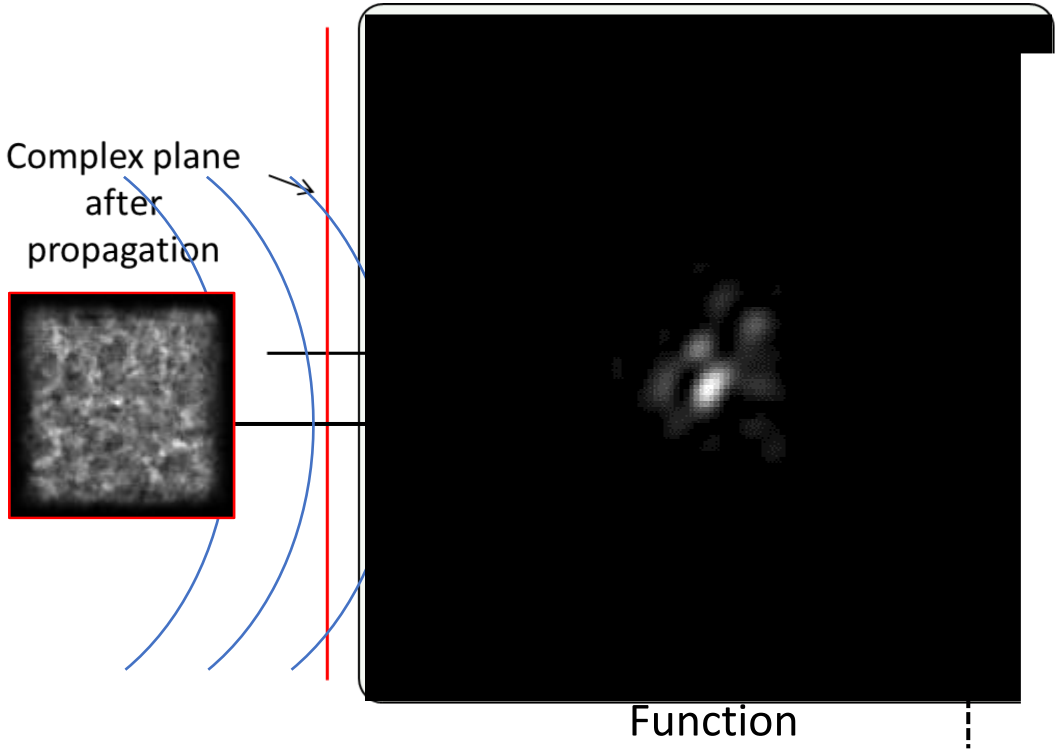
$$p(x,y) = a(x,y)\,U_0(x,y)$$

    - Collimation

$$p(x,y) = a(x,y)\,U_0(x,y)\,exp\left[\frac{-i\pi\left(x^2+y^2\right)}{\lambda R}\right]$$

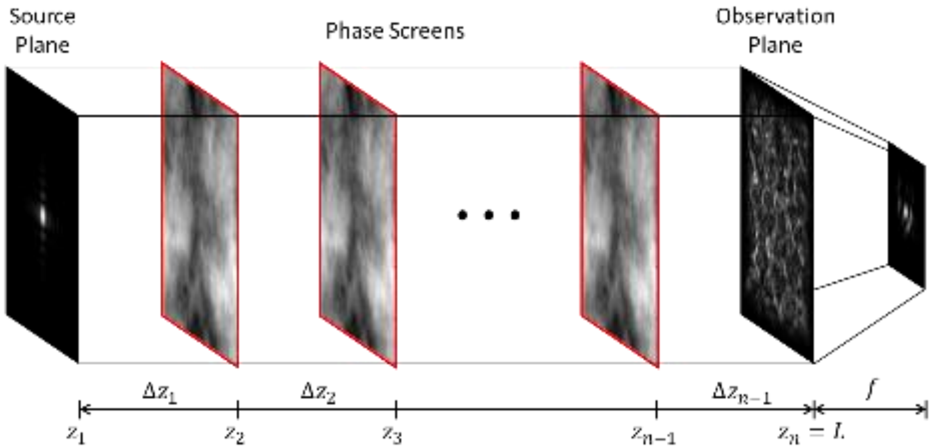
    - Focusing

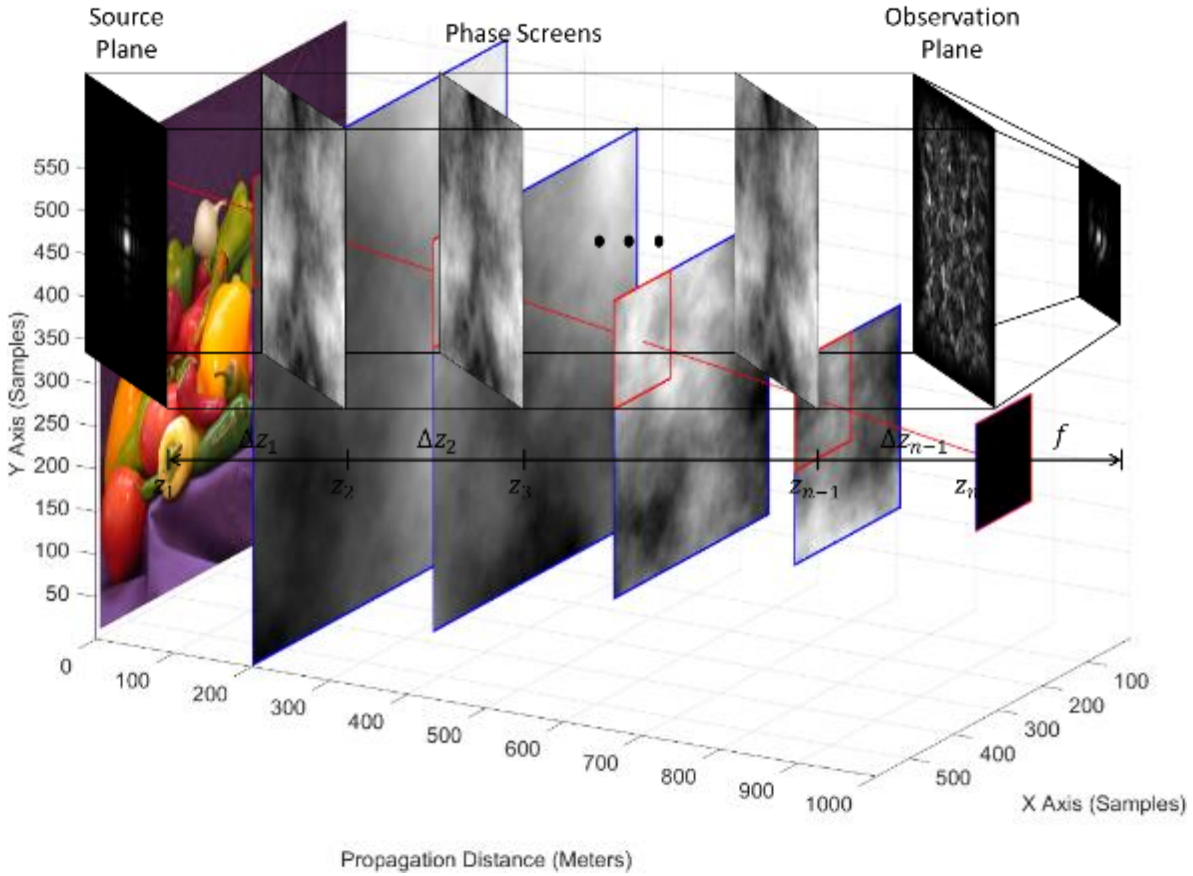
$$h(x,y) = \left(|\mathrm{FT}\{p(x,y)\}|^2\right)\Big|_{u=\frac{x}{\lambda l},\,v=\frac{y}{\lambda l}}$$



Anisoplanatic Simulation

- Thus far, only a with a single propagation has been considered, leading to a single PSF.
- The result of using this PSF would be an image with **spatially invariant** distortion
  - Isoplanatic simulation.
- To simulate anisoplanatic turbulence, the simulation environment needs expansion.



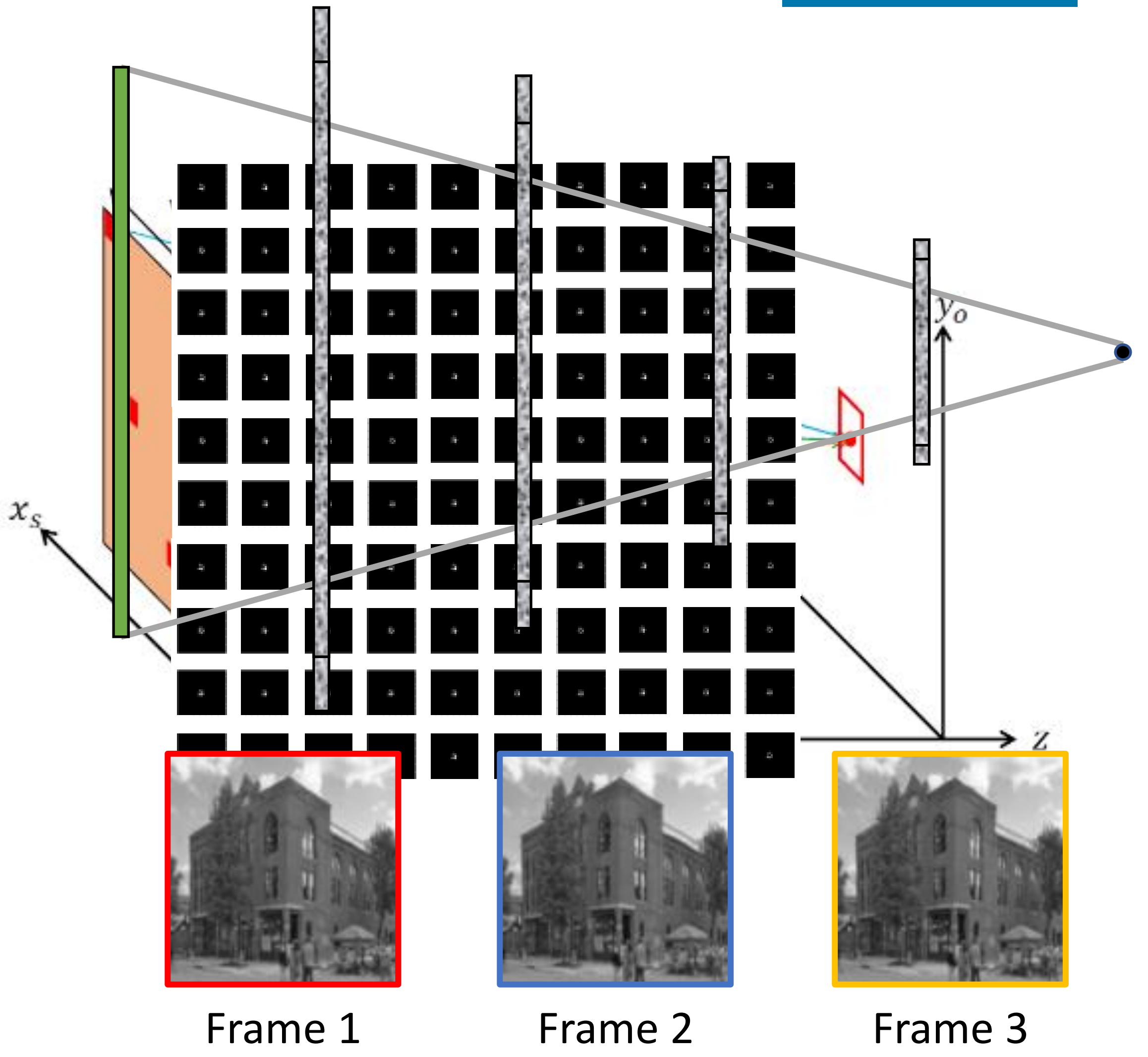


Anisoplanatic Simulation

- A propagation is performed for each pixel in the image
- Providing each pixel with a bespoke PSF
- These can then be applied to the image with a spatial varying convolution

$$y[m,n] = \sum_j \sum_i x[i,j] \cdot h_{m,n}[m-i, n-j]$$

- Video simulation also possible
  - Generate the phase screens at a larger scale,
  - For each frame, translate the screens laterally in a chosen direction



Input Dataset

In order to perform useful simulation, suitable data was required.

The Places dataset consists of natural images consisting of

- 205 Categories
- 1,469,373 Images

Cathedral

Aqueduct

Skyscraper

Of the 201 Categories in the ‘Places’ dataset, 31 of them are images of scenes that *could* be affected by turbulence.

'abbey'	'bridge'	'highway'	'palace'
'alley'	'building_facade'	'inn/outdoor'	'runway'
'apartment_building/outdoor'	'butte'	'islet'	'skyscraper'
'aqueduct'	'canyon'	'kasbah'	'temple/east_asia'
'arch'	'castle'	'lighthouse'	'temple/south_asia'
'badlands'	'cathedral/outdoor'	'mansion'	'tower'
'basilica'	'church/outdoor'	'monastery/outdoor'	'wind_farm'
'bayou'	'courthouse'	'pagoda'	

Zhou, B. et al., 2014. Learning deep features for scene recognition using places database. *Advances in neural information processing systems*, 27.

Simulator Settings

Scenario Parameters

Input	Description	
D2	Diameter of the camera aperture	0.1m
L	Propagation Distance	5km
nscr	Number of phase screens used	8
Image_Pixels	Size of the output Image	257 x 257
Skip	Number of skipped pixels	4
Speed	Speed that screens move between frames	~
Direction	Direction in which the screen will translate	~
Frame Count	How many turbulent frames to simulate	15

Turbulence Parameters

Input	Description	
Cn2	Atmospheric structure parameter	~
$l0$	Inner Turbulence Scale	0.01m
L0	Outer Turbulence Scale	300m
Lambda	Wavelength of light	525nm
I	Input Image	~

Resulting Dataset

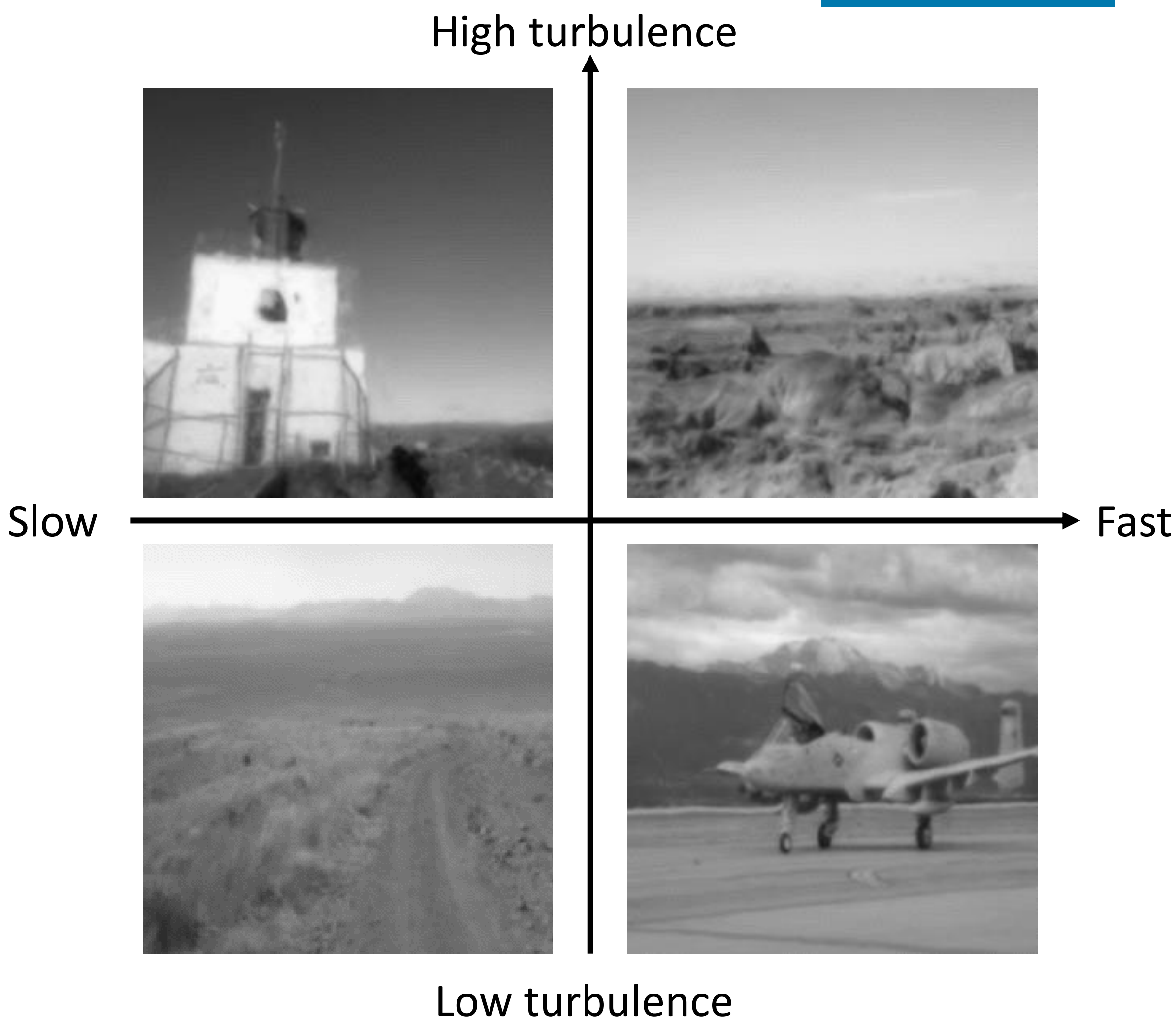
Using the simulator, a dataset of **148,884** turbulent videos was generated

15 frames generated per video

5 levels of turbulence (Cn2)
4 values of 'Speed'
8 turbulence 'directions'

Input	Description
Cn2	$(0.25, 0.65, 0.87, 1.18, 1.5) \times 10^{-15}$

160 different configurations



Conclusion

Due to lack of control over the atmosphere, it is very difficult to obtain a suitable dataset of turbulent imagery where the ground truth image is also available

The use of simulation allows
- Full control over the desired outcome
- Any data type to be simulated

Propagation Simulation
- Accurate – No compromises made
- Flexible – Can define the atmosphere exactly as required

Publicly available dataset
- Allows access to a large, diverse dataset to further improve turbulence mitigation algorithms
- In the world of deep learning, this will be invaluable

Input

Output

Anantrasirichai, N., Achim, A. & Bull, D., 2018. *Atmospheric turbulence mitigation for sequences with moving objects using recursive image fusion*, IEEE.

Thank You

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