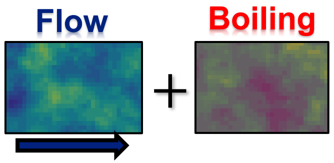
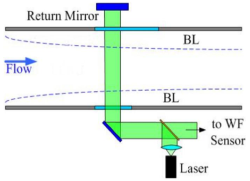
Boiling flow parameter estimation from boundary layer data





[1]Jeffrey Utley, [1]Gregery Buzzard, [2]Charles Bouman, and [3]Matthew Kemnetz

[1]Department of Mathematics, Purdue University
[2]Departments of Electrical and Computer Engineering, and Biomedical Engineering, Purdue University
[3]Department of Engineering Physics, Air Force Institute of Technology

INTEGRATED IMAGING

AFIT
AIR FORCE INSTITUTE OF TECHNOLOGY

Light Detection and Transmission

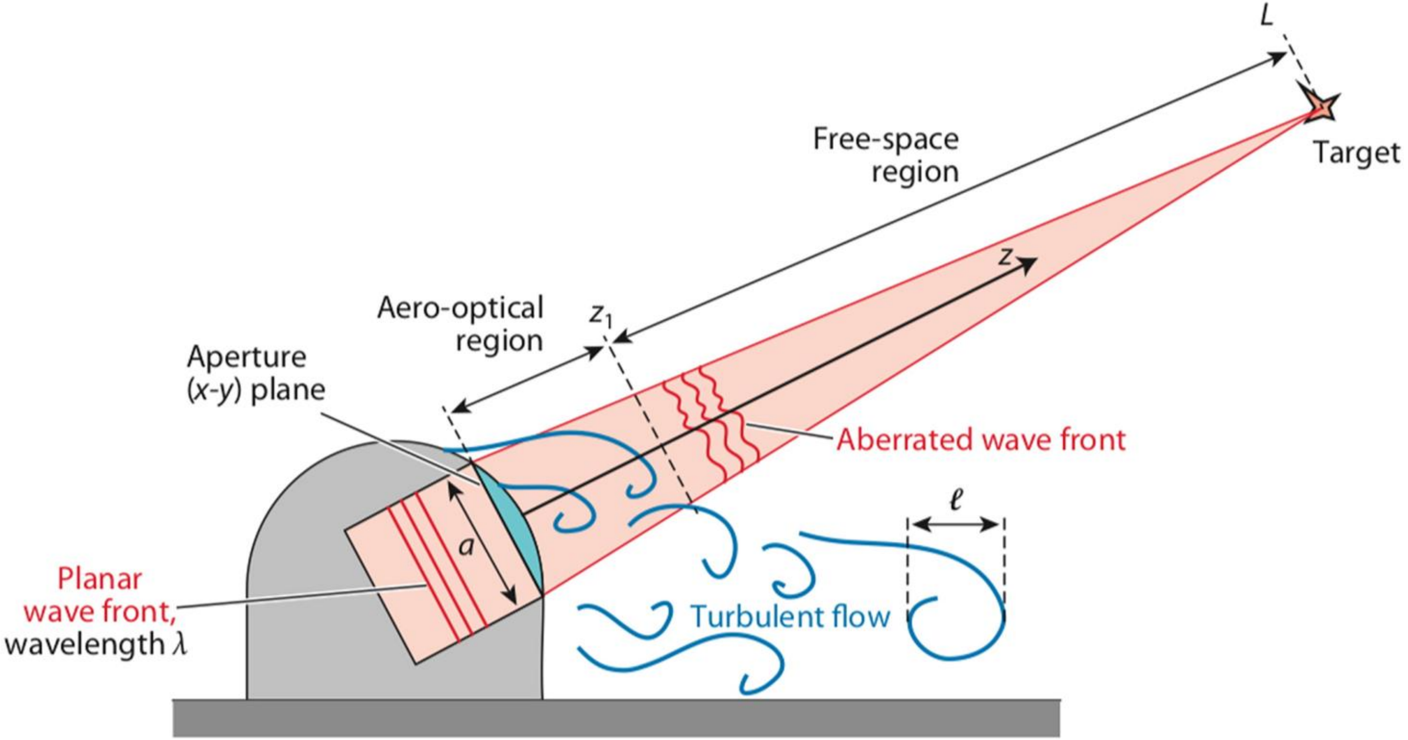
<u>Goal</u>: *Detect* and *transmit* light from the side of a high-speed aircraft.

https://aero-optics.nd.edu/research/hemispherical-turret-beam-directors/

[1] E. J. Jumper, S. Gordeyev, and M. R. Whiteley, "Aero-optical effects," in Aero-Optical Effects, (John Wiley Sons, Incorporated, United States, 2023).

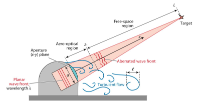
The Aero-Optics Problem

<u>Problem</u>: Turbulent flow near the aperture **distorts light propagation**.

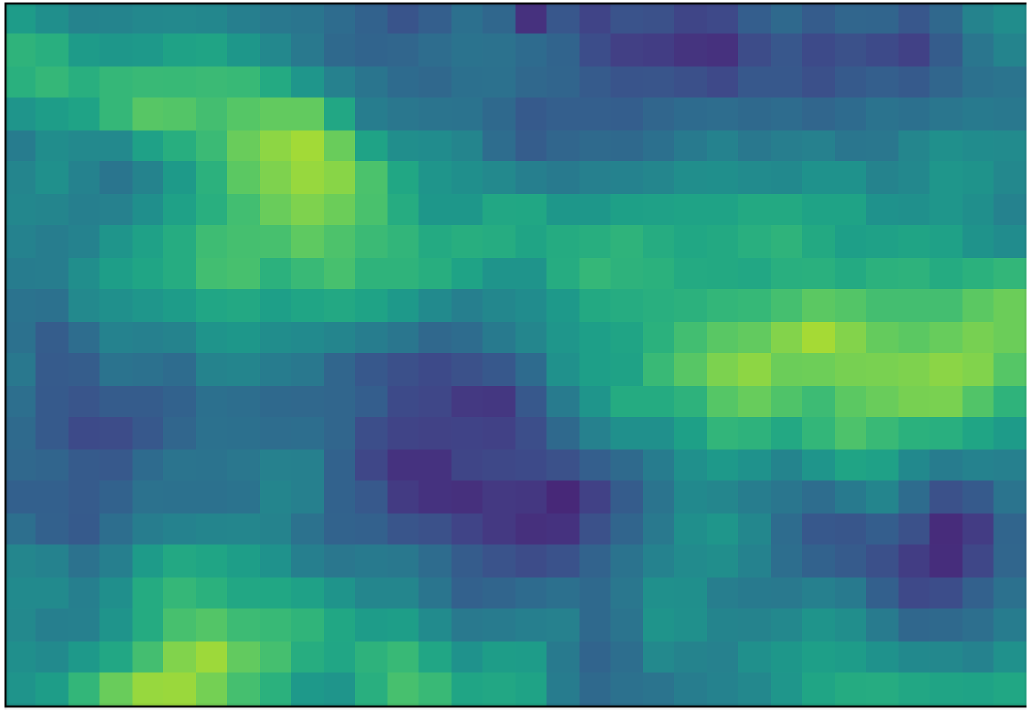


[2] M. Wang, A. Mani, and S. Gordeyev, “Physics and Computation of Aero-Optics,” *Annual Review of Fluid Mechanics*, Vol. 44, No. 1, 2012, pp. 299–321.

Phase Screen Generation for Aero-Optic Effects



- We quantify aero-optic effects as *time-series of* ***phase screens***.



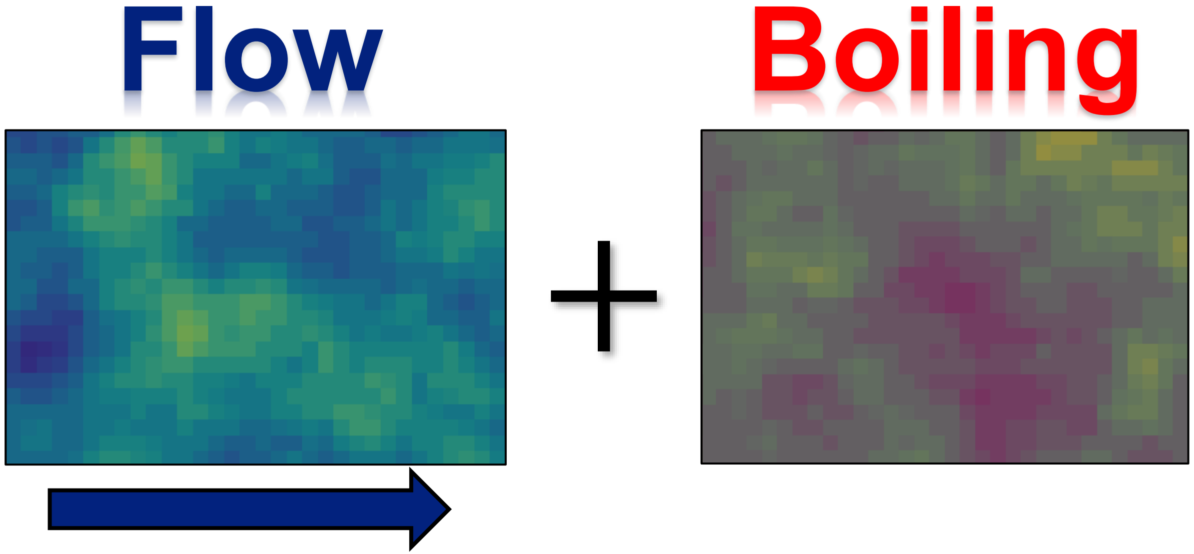
- Phase screens can be *measured* by experiment (**expensive**) or *simulated* (**less expensive**).

Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2025-3569

Phase Screen Simulation: Boiling Flow

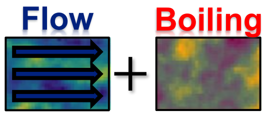
Boiling Flow adds two components at each time-step:

1. **Flow**: *Shift* the previous phase screen according to some *flow velocity*.
2. **Boiling**: A *new* random Kolmogorov phase screen.

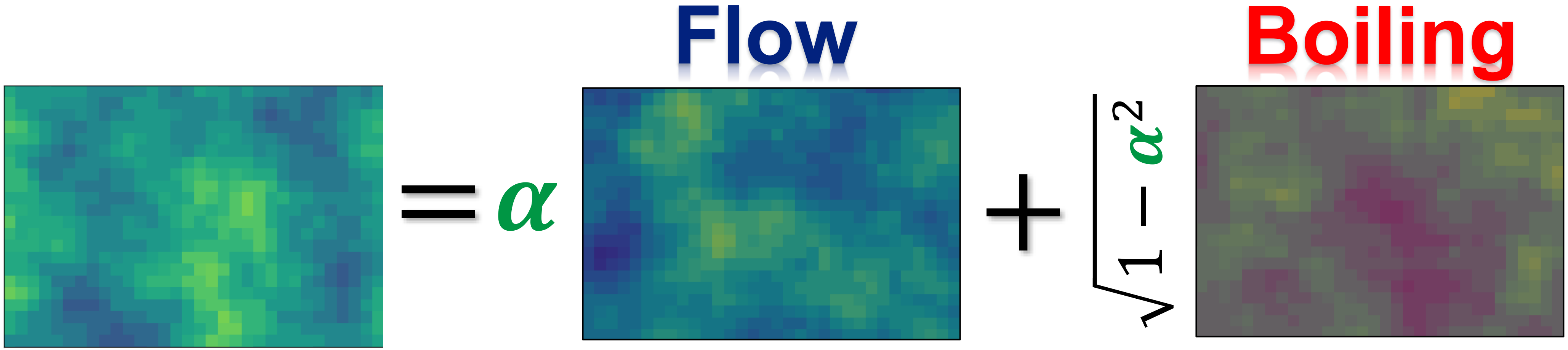


[3] Srinath, S., Poyneer, L. A., Rudy, A. R., and Ammons, S. M., "Computationally efficient autoregressive method for generating phase screens with frozen flow and turbulence in optical simulations," Opt. Express 23, 33335–33349 (Dec 2015)

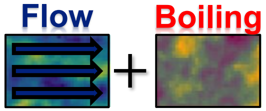
Phase Screen Simulation: Boiling Flow



$$\phi_n = \alpha \, \mathbf{Flow}(\phi_{n-1}) + \sqrt{1-\alpha^2} \, \mathbf{Boiling}$$



Boiling Flow Parameters

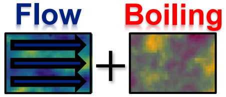


$$\phi_n = \alpha\, \mathbf{Flow}(\phi_{n-1}) + \sqrt{1-\alpha^2}\, \mathbf{Boiling}$$

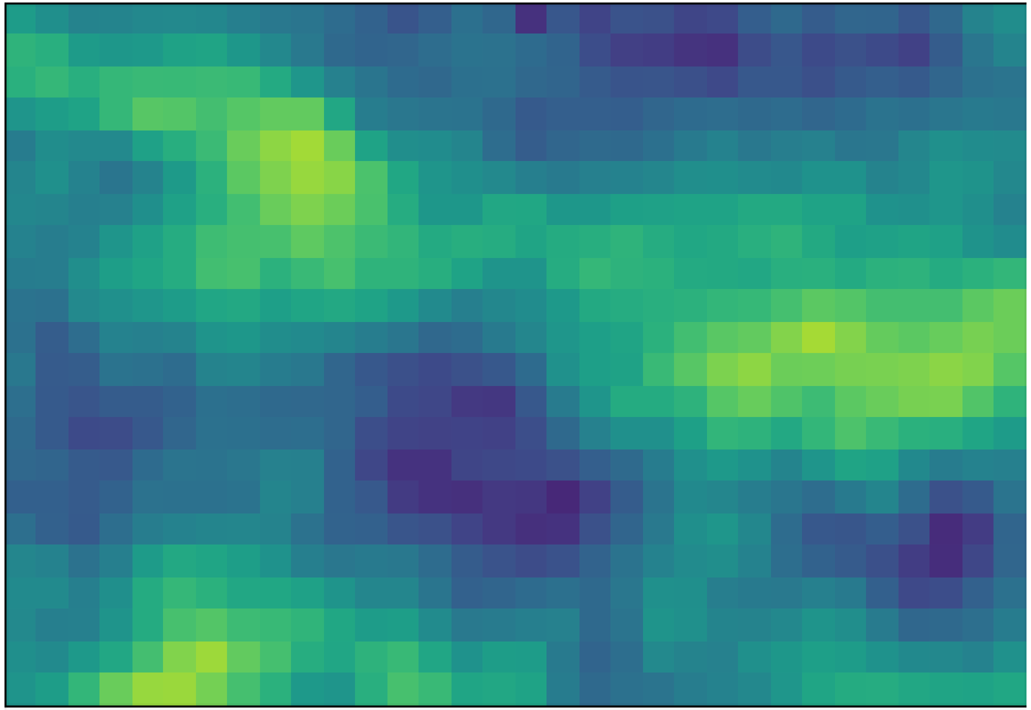
Parameters:

- L_0: outer scale (m)
- r_0: Fried coherence length (m)
- (v_x, v_y): flow velocity components (pixels/time-step)
- α: ***boiling coefficient*** (unit-less)

Phase Screen Generation for Aero-Optic Effects

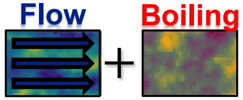


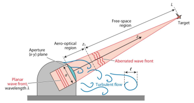
➢ **<u>Problem</u>**: Boiling flow depends on ***physical parameters***, some of which are **undefined for aero-optic effects**.



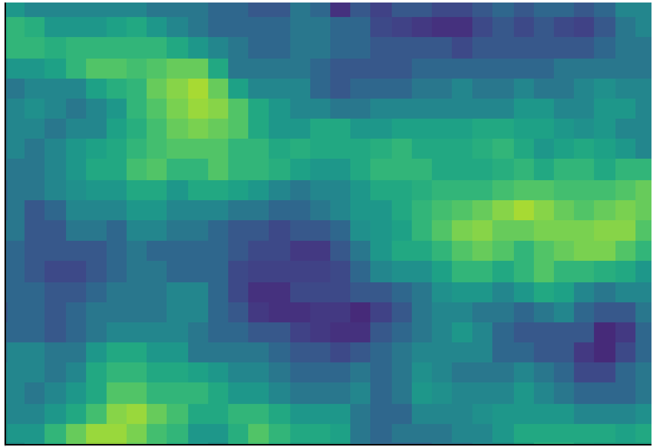
➢ **<u>Solution</u>**: We develop an algorithm to **estimate** these parameters **from measured aero-optic phase screens.**

Parameter Estimation from Measured Data

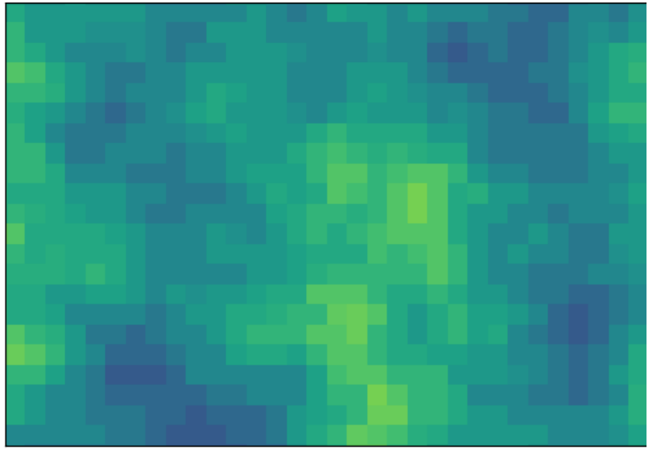




***Measured* Phase Screens**



***Synthetic* Phase Screens**



Compare

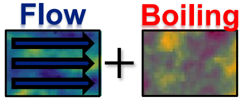
Estimate

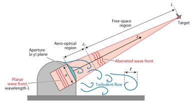
$$(\hat{L}_0, \hat{r}_0, \hat{v}_x, \hat{v}_y, \hat{\alpha})$$

Generate

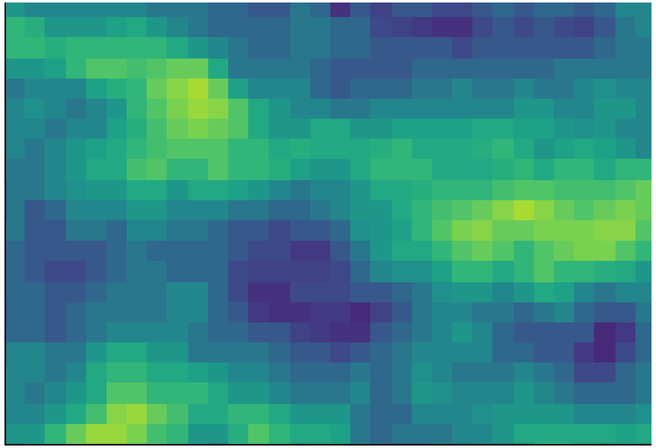
Boiling Flow

Parameter Estimation from Measured Data



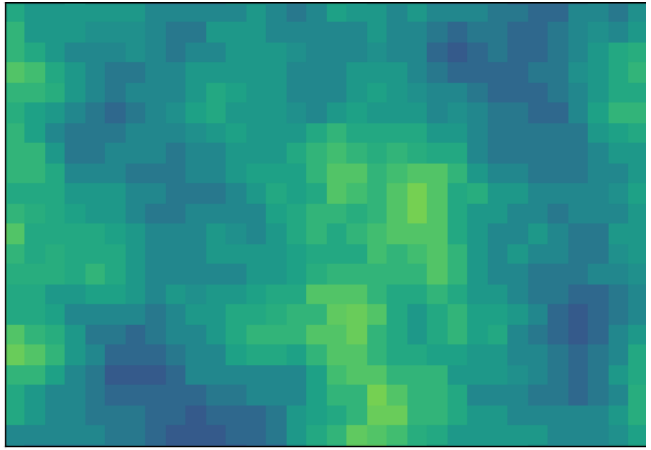


Measured **Phase Screens**



Compare

Synthetic **Phase Screens**



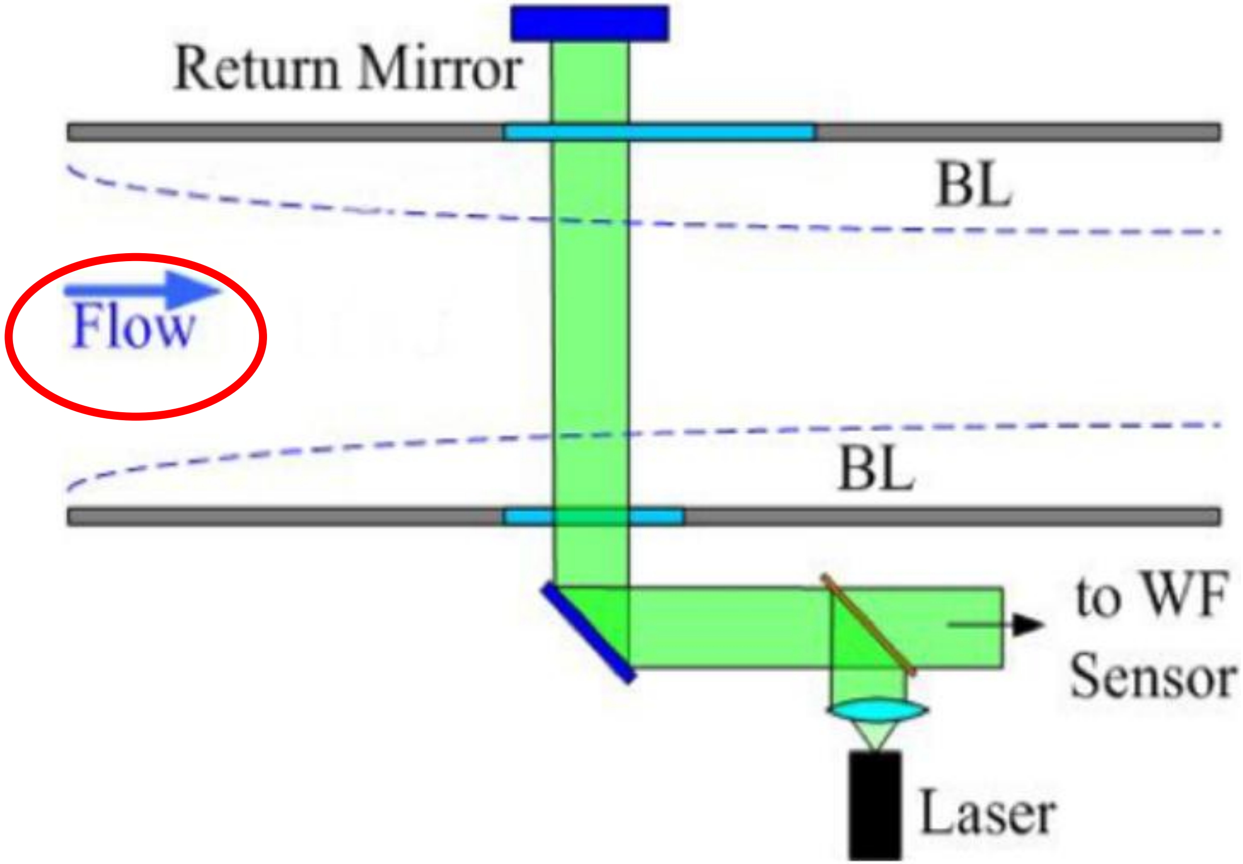
Estimate

$$\left(\hat{L}_0, \hat{r}_0, \hat{v}_x, \hat{v}_y, \hat{\alpha}\right)$$

Generate

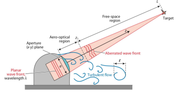
Boiling Flow

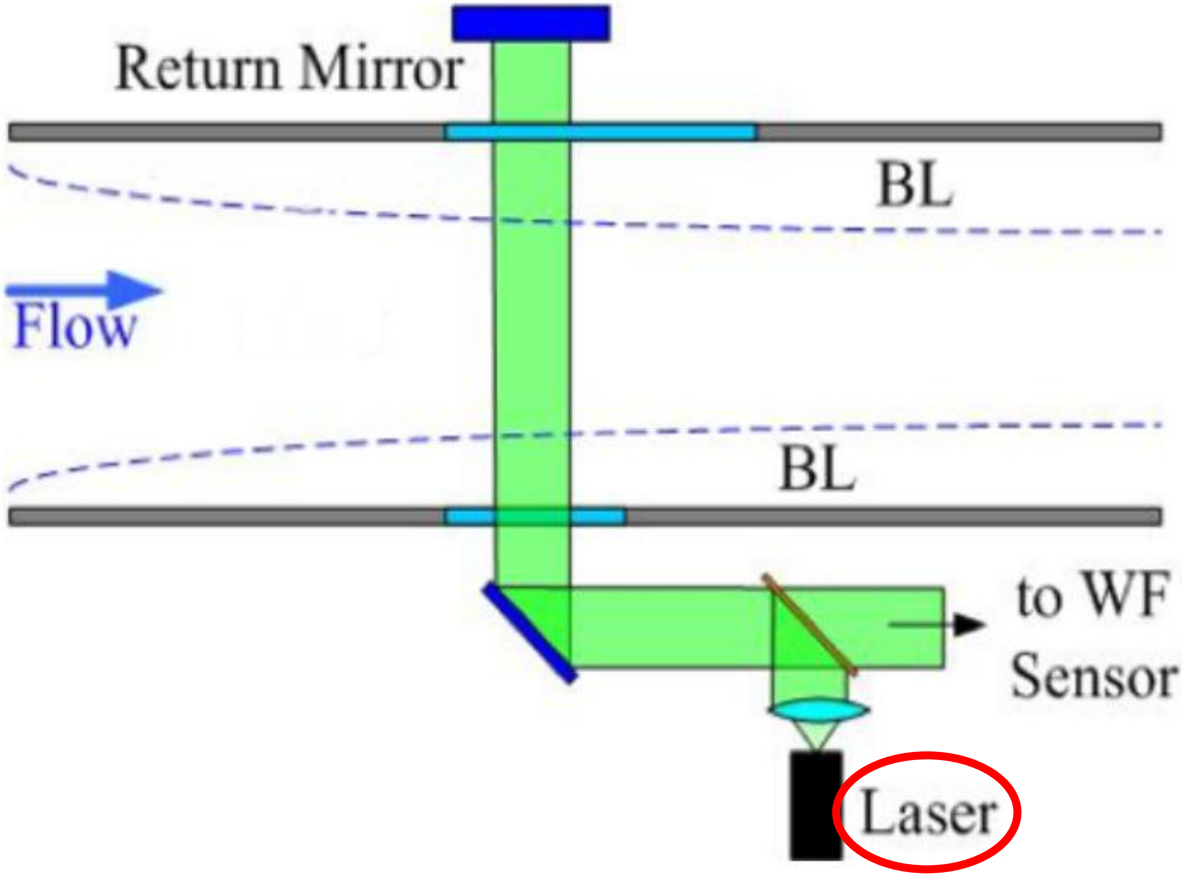
Measured Data: Wind Tunnel Experiment



[4] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures",
54th AIAA Aerospace Sciences Meeting, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.

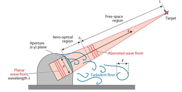
Measured Data: Wind Tunnel Experiment



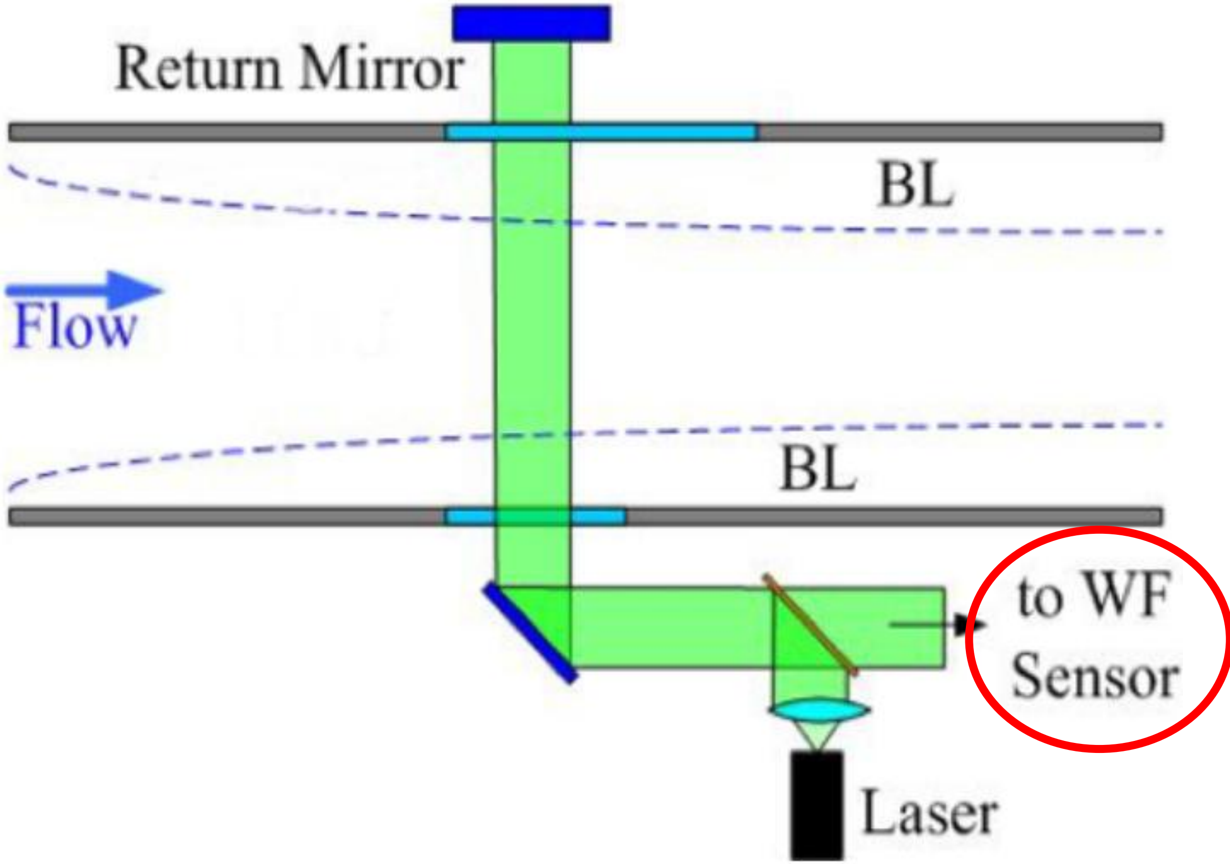


[4] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures",
54th AIAA Aerospace Sciences Meeting, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.

Measured Data: Wind Tunnel Experiment

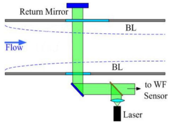


The result of the experiment is a **time-series** of ***aero-optic phase screens***.



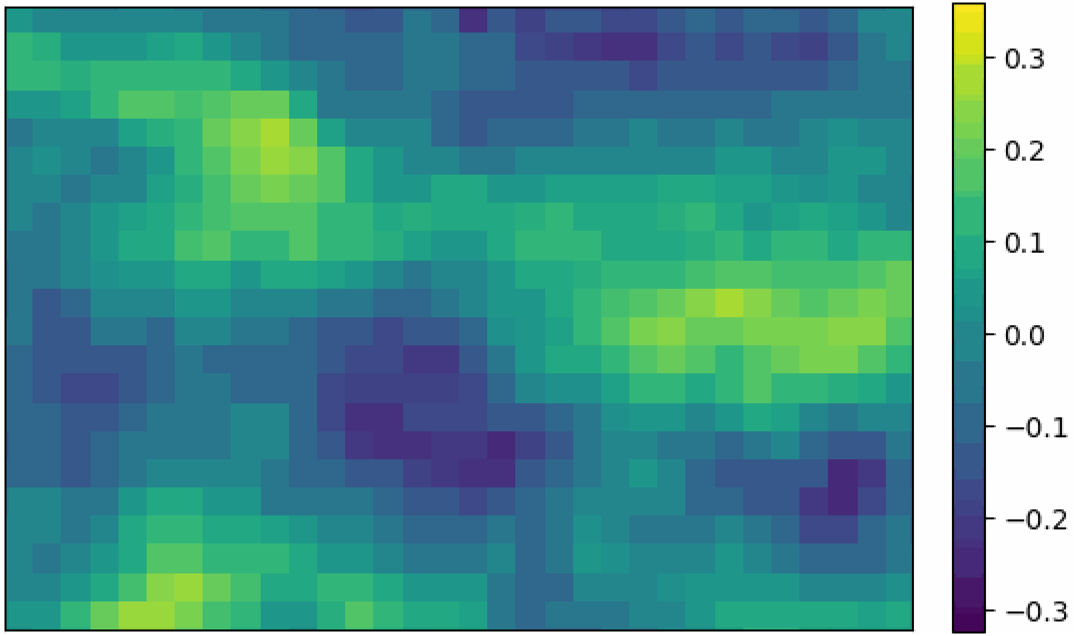
[4] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures", *54th AIAA Aerospace Sciences Meeting*, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.

Experimental Data: Visualization

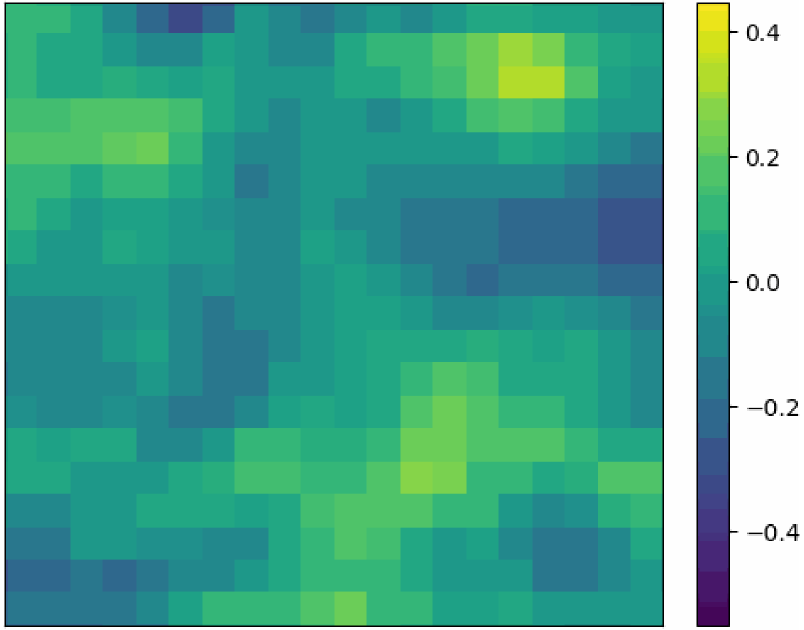


The boundary layer data is ***highly convective***.

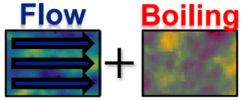
Data Set F06

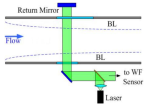


Data Set F12

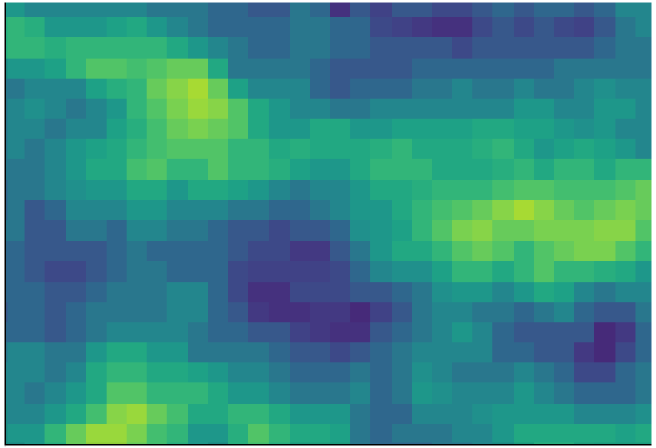


Parameter Estimation from Measured Data



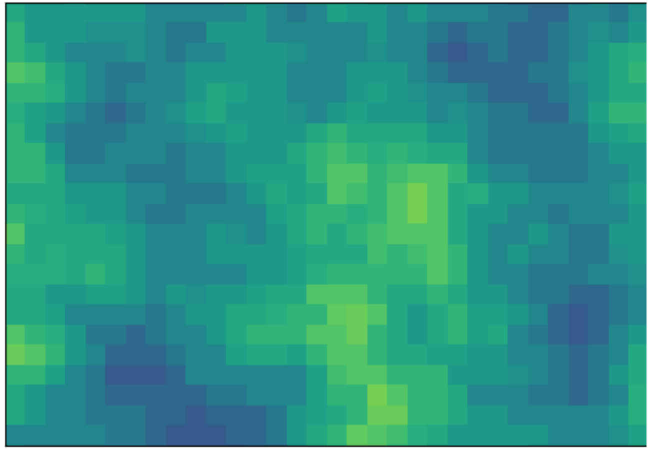


Measured **Phase Screens**



Compare

Synthetic **Phase Screens**



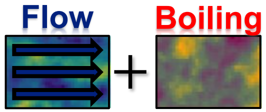
Estimate

$(\hat{L}_0, \hat{r}_0, \hat{v}_x, \hat{v}_y, \hat{\alpha})$

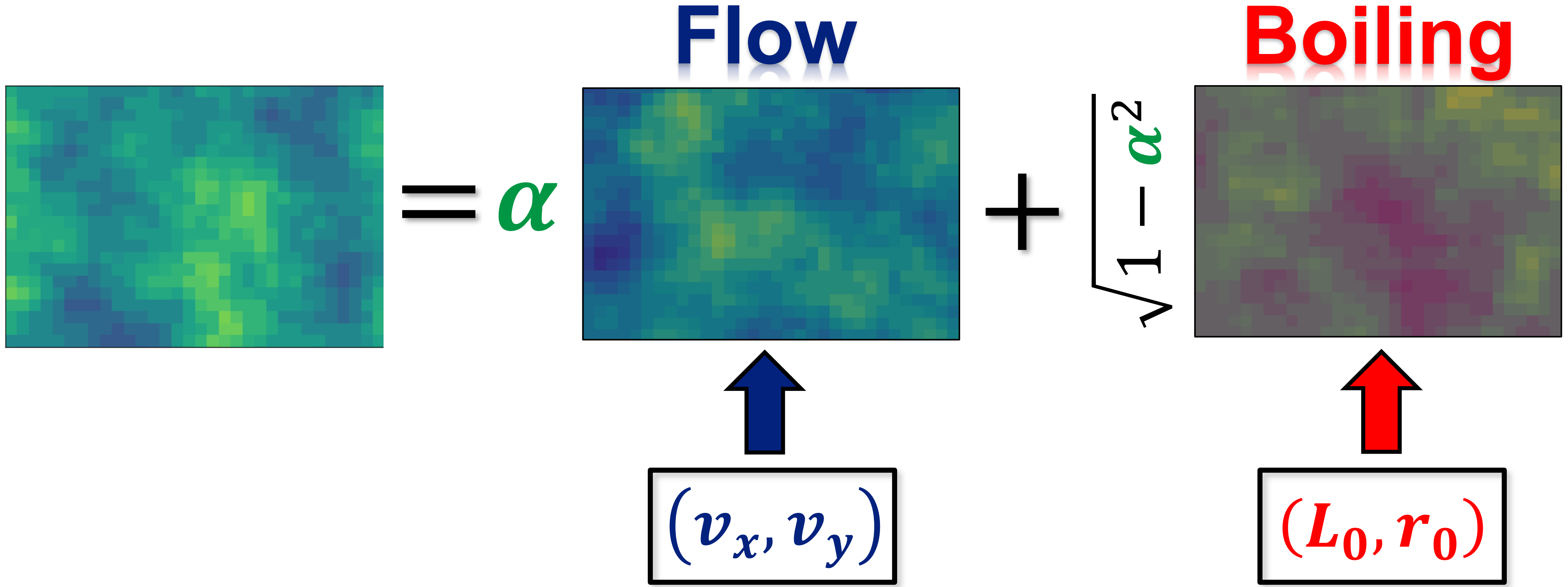
Generate

Boiling Flow

Boiling Flow Parameters

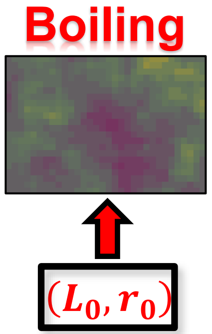


- L_0: outer scale
- r_0: Fried coherence length
- (v_x, v_y): flow velocity components
- α: ***boiling coefficient***

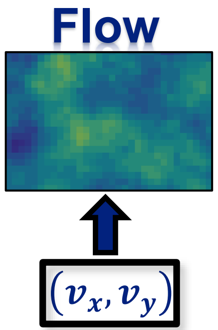


Parameter Estimation Algorithm: Outline

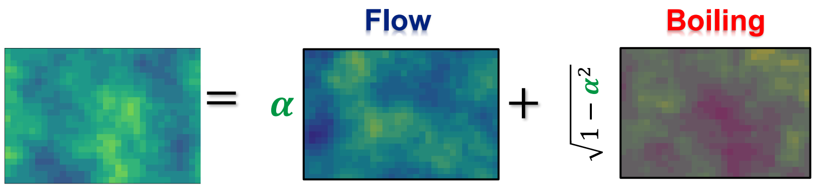
1. Boiling parameters (L_0, r_0)



2. Flow parameters (v_x, v_y)

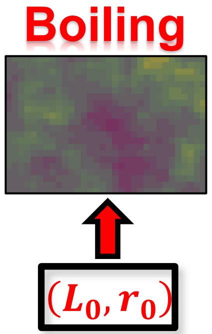


3. Boiling coefficient α

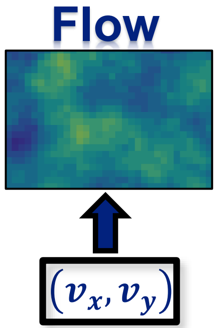


Parameter Estimation Algorithm: Outline

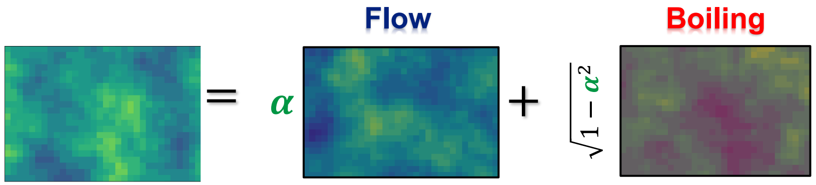
1. Boiling parameters (L_0, r_0)



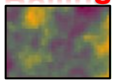
2. Flow parameters (v_x, v_y)



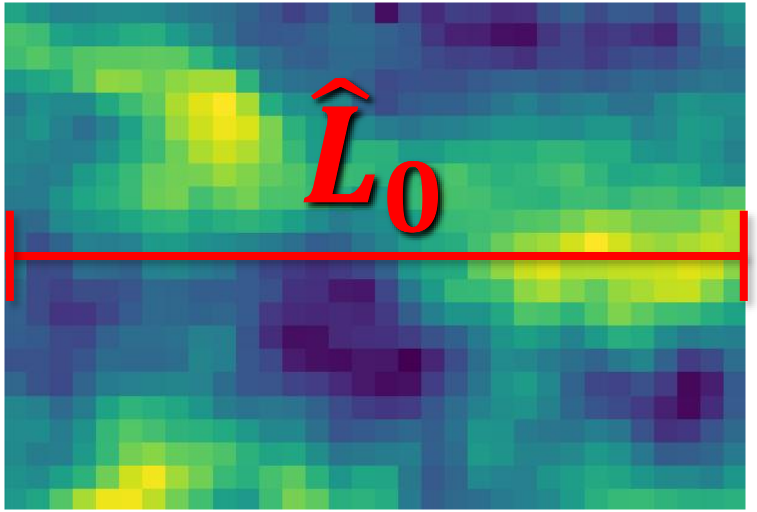
3. Boiling coefficient α

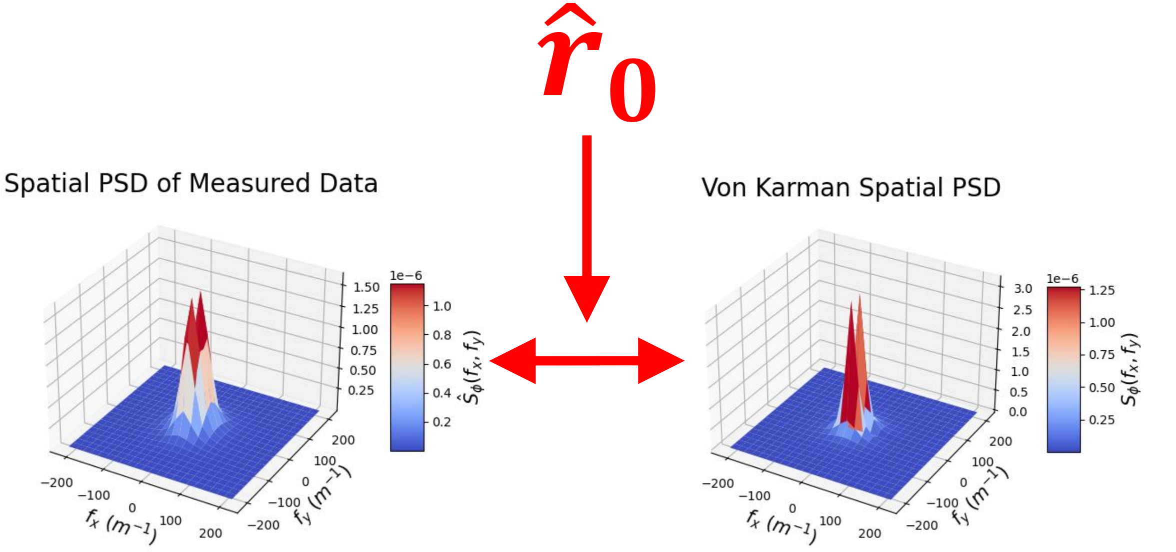


Estimating the Boiling Parameters (L_0, r_0)



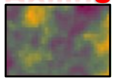
- Set $\hat{L}_0$ to the length of the aperture (m).
- Estimate $\hat{r}_0$ to *fit* the *von Karman PSD* to the *measured data's* spatial PSD, $\hat{S}_\phi(f_x, f_y)$.



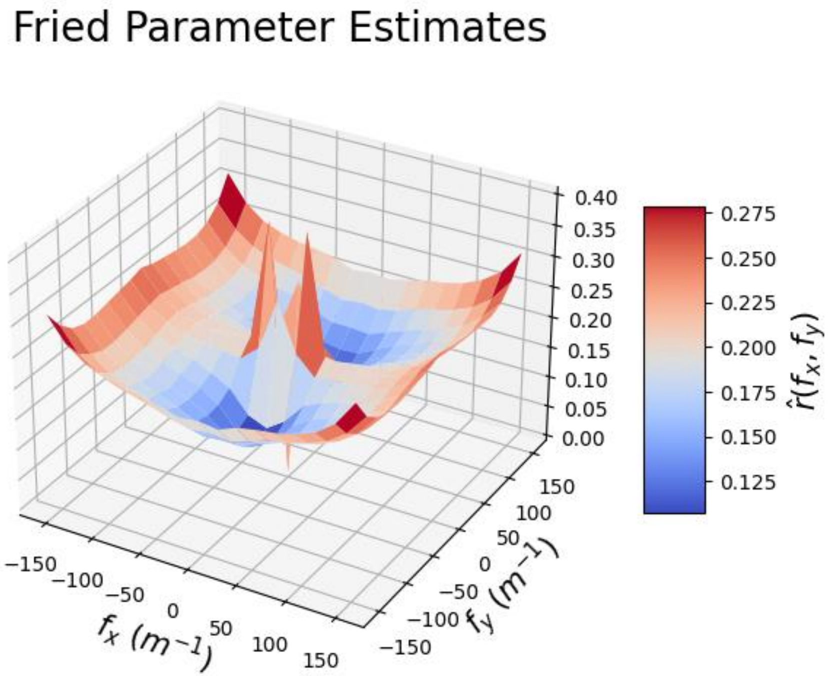


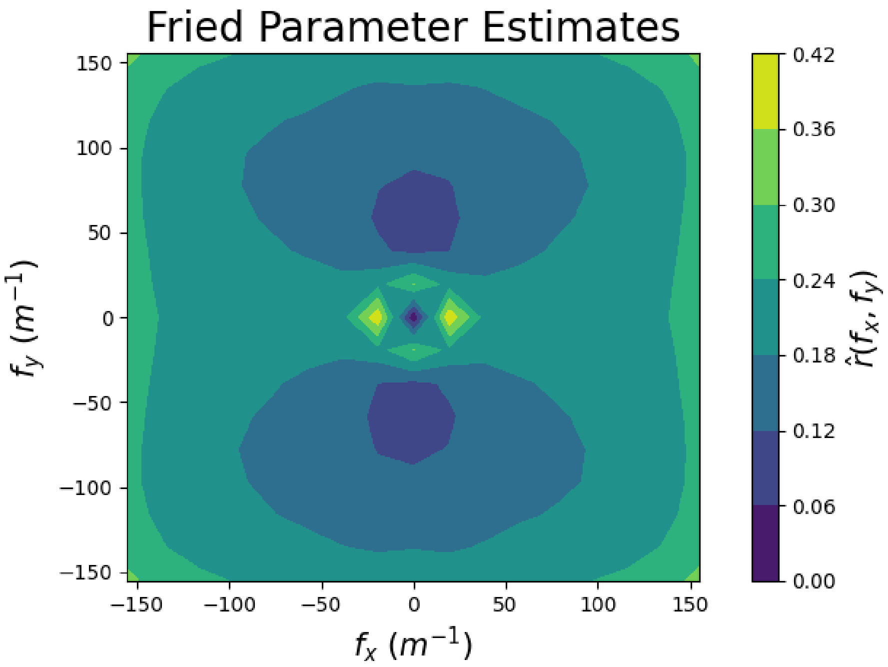
Estimating the Boiling Parameters (L_0, r_0)

Boiling



- This gives us an estimate $\hat{r}(f_x, f_y)$.
- We take $\hat{r}_0$ as the *average* of $\hat{r}(f_x, f_y)$ over (f_x, f_y).

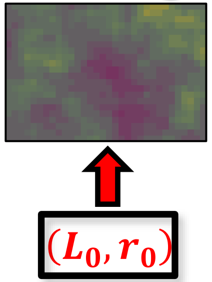




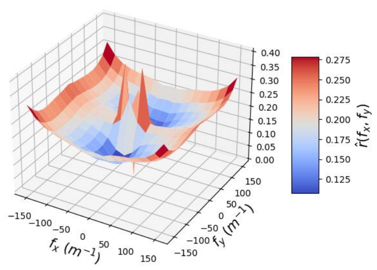
Parameter Estimation Algorithm: Outline

1. Boiling parameters (L_0, r_0)

Boiling

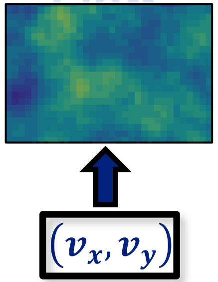


Fried Parameter Estimates



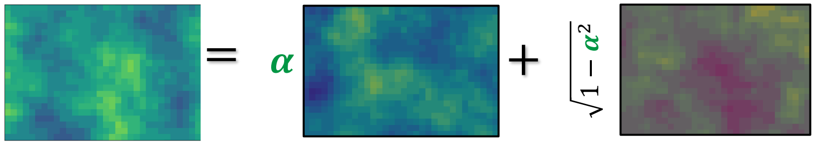
2. Flow parameters (v_x, v_y)

Flow



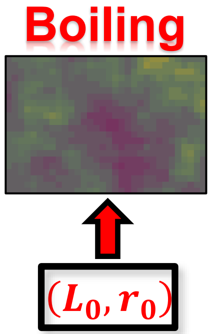
3. Boiling coefficient α

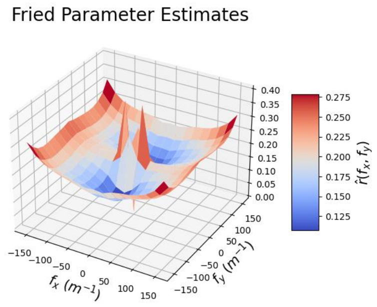
Flow Boiling



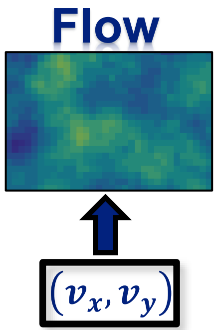
Parameter Estimation Algorithm: Outline

1. <u>Boiling</u> parameters (L_0, r_0)

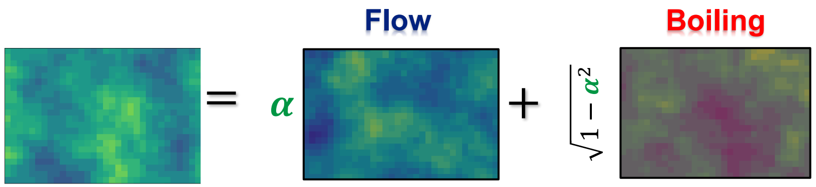




2. <u>Flow</u> parameters (v_x, v_y)

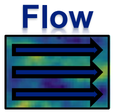


3. Boiling <u>coefficient</u> α

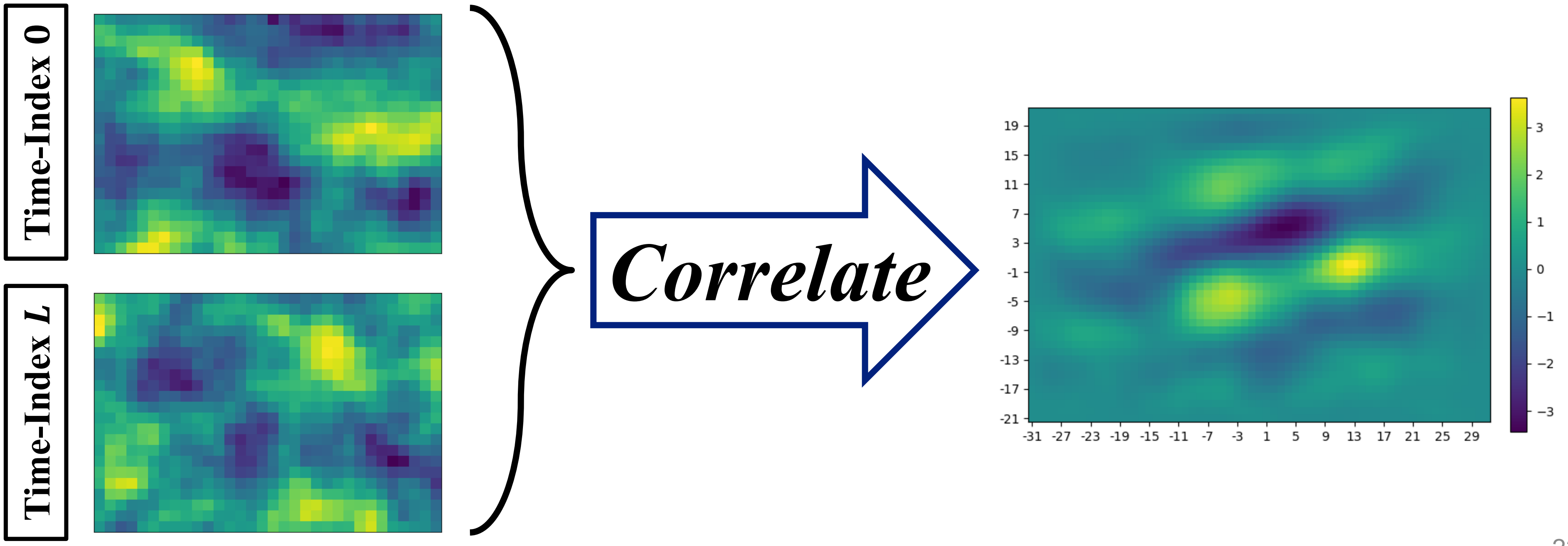


Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2025-3569

Estimating the Flow Parameters (v_x, v_y)

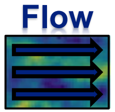


Search for the ***pixel shifts*** $(\boldsymbol{i}, \boldsymbol{j})$ which <u>maximize</u> the ***cross-correlation*** $\boldsymbol{R}(\boldsymbol{i}, \boldsymbol{j}; \boldsymbol{L})$ (with time-lag L).



Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2025-3569

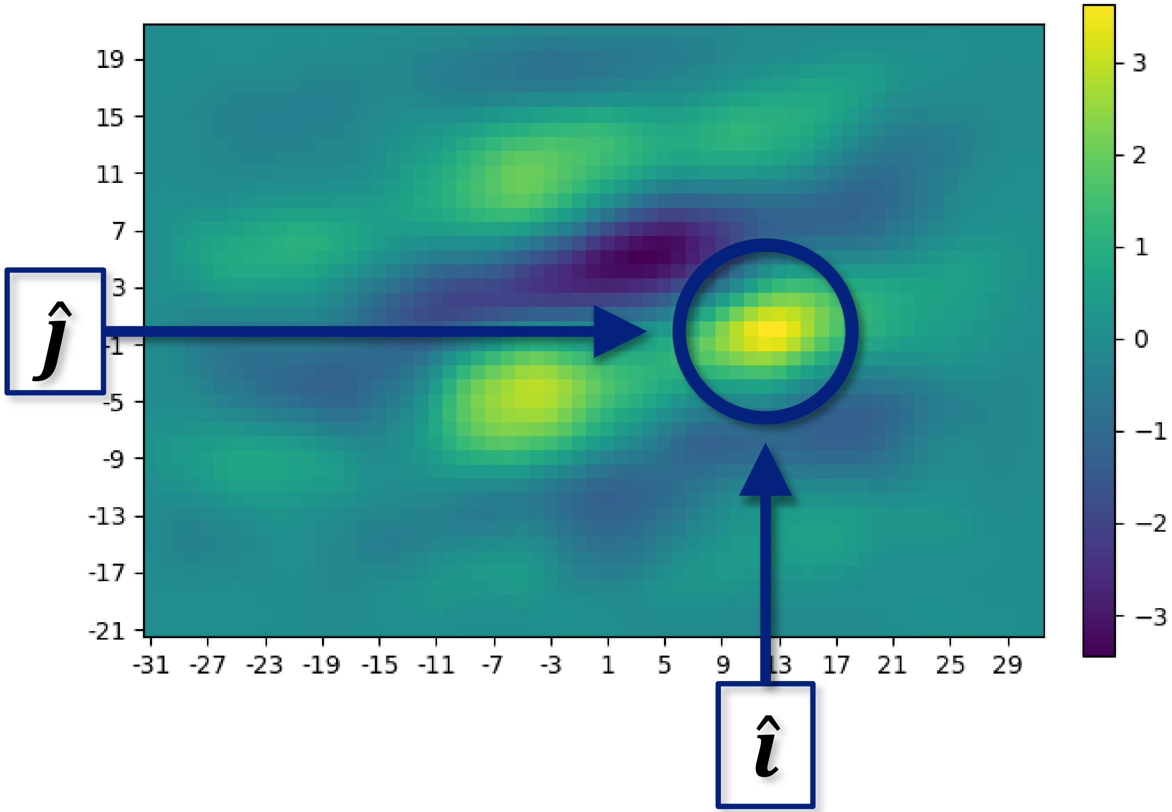
Estimating the Flow Parameters (v_x, v_y)



- The maximal *pixel shift* $(\hat{\imath}, \hat{\jmath})$ is where the *correlation is the* *largest*.

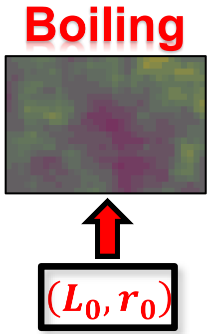
- The *flow velocity* estimates divide by the time-lag L:

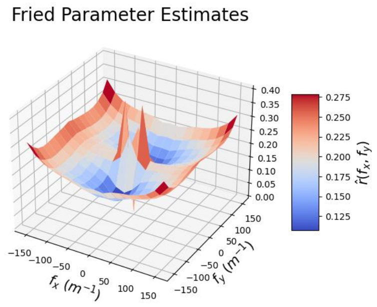
$$(\hat{v}_x, \hat{v}_y) = \frac{1}{L}(\hat{\imath}, \hat{\jmath})$$



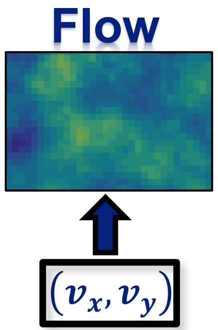
Parameter Estimation Algorithm: Outline

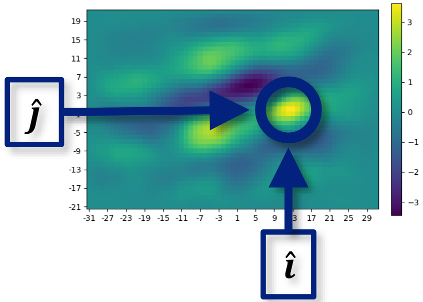
1. Boiling parameters (L_0, r_0)



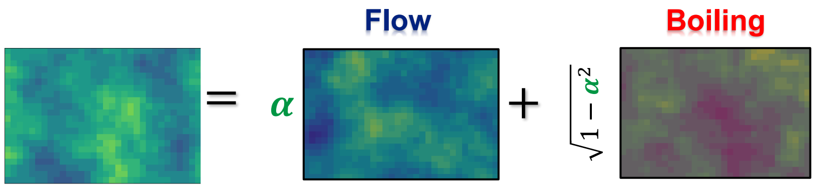


2. Flow parameters (v_x, v_y)



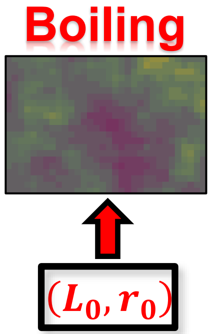


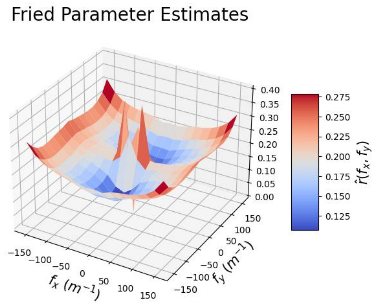
3. Boiling coefficient α



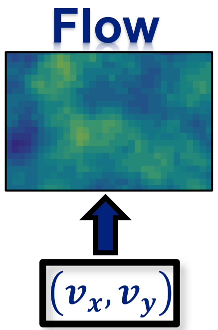
Parameter Estimation Algorithm: Outline

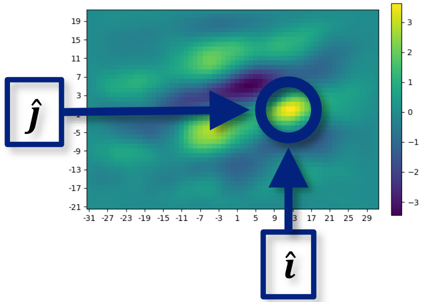
1. Boiling parameters (L_0, r_0)



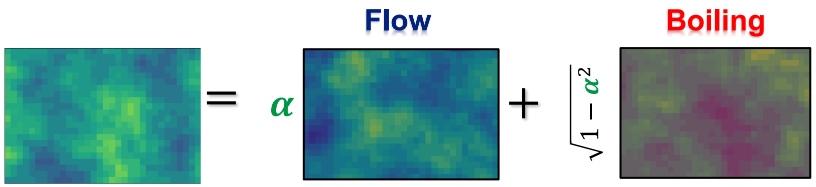


2. Flow parameters (v_x, v_y)

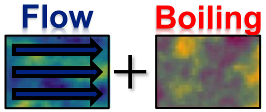




3. Boiling coefficient α



Estimate the Boiling Coefficient α



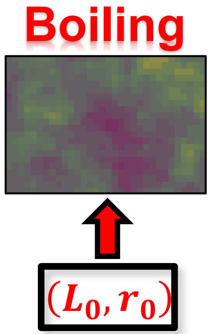
- We use a **least-squares fitting** to compute $\hat{\alpha}$, *given the flow velocity* components $(\hat{v}_x, \hat{v}_y)$:

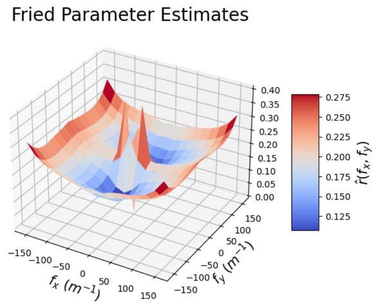
$$\hat{\alpha} = \underset{\alpha}{\operatorname{argmin}} \left\{ \sum_n \| \phi_n - \alpha \, \boldsymbol{Flow}(\phi_{n-1}) \|^2 \right\}$$

- $(\hat{v}_x, \hat{v}_y, \hat{\alpha})$ *fit the temporal statistics* of the measured data.

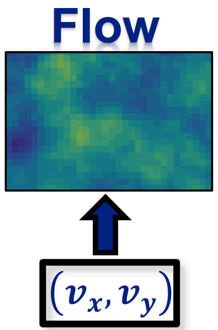
Parameter Estimation Algorithm: Outline

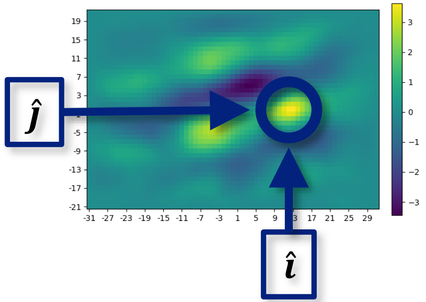
1. Boiling parameters (L_0, r_0)



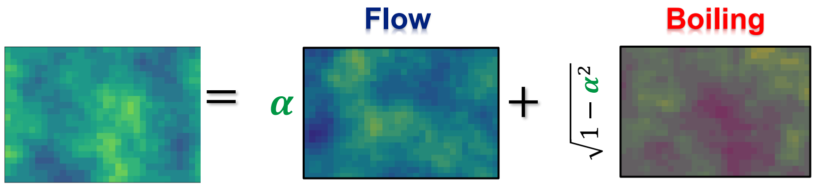


2. Flow parameters (v_x, v_y)



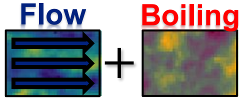


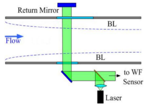
3. Boiling coefficient α



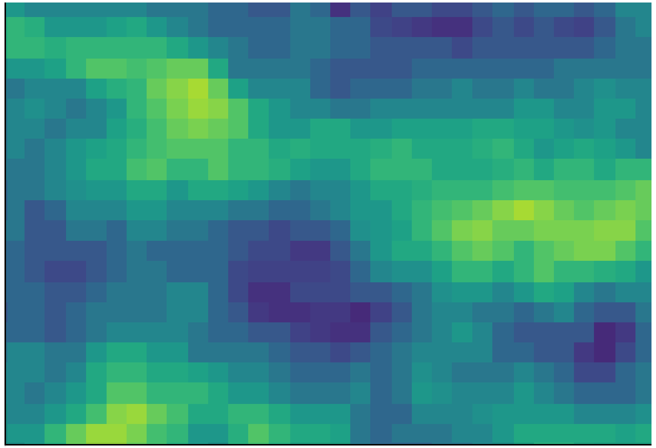
$$\hat{\alpha} = \underset{\alpha}{\operatorname{argmin}} \left\{ \sum_n \left\| \phi_n - \alpha\, \boldsymbol{Flow}(\phi_{n-1}) \right\|^2 \right\}$$

Parameter Estimation from Measured Data

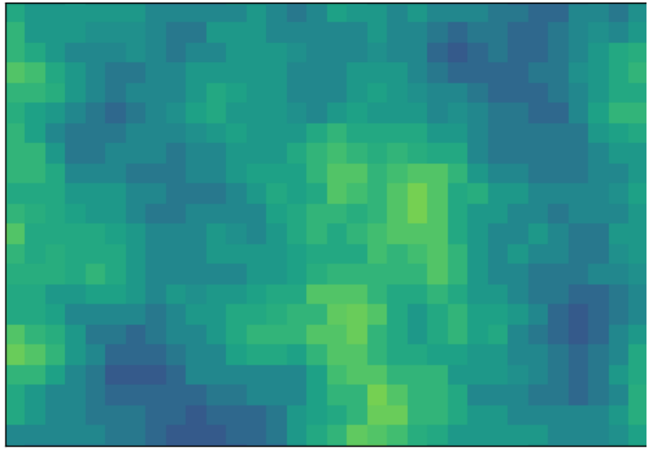




Measured Phase Screens



Synthetic Phase Screens



Compare

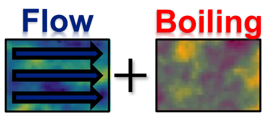
Estimate

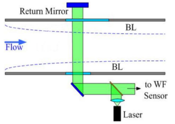
$$\left(\hat{L}_0, \hat{r}_0, \hat{v}_x, \hat{v}_y, \hat{\alpha}\right)$$

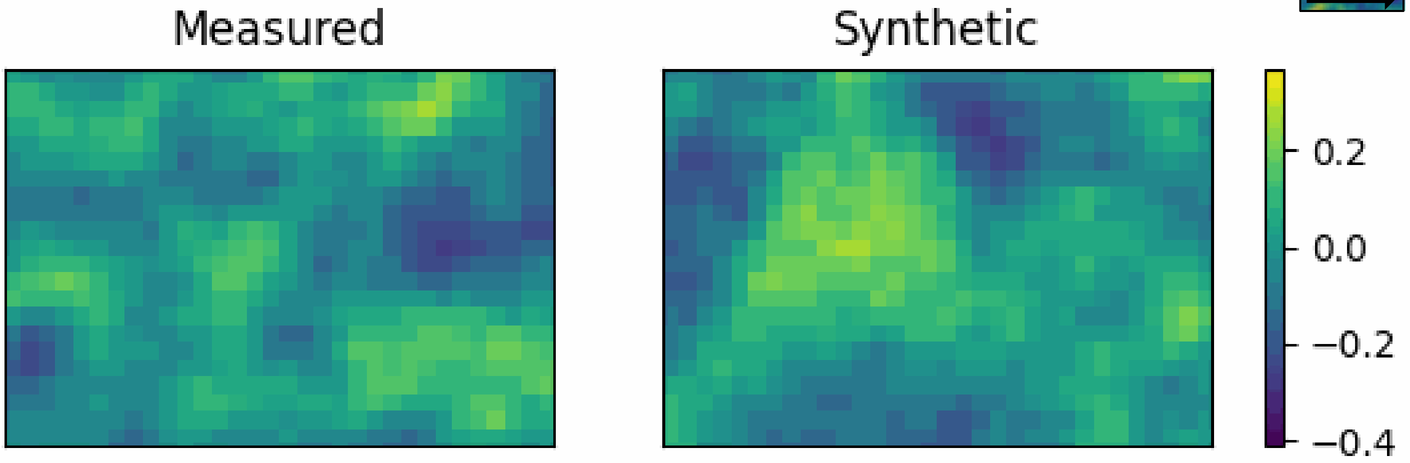
Generate

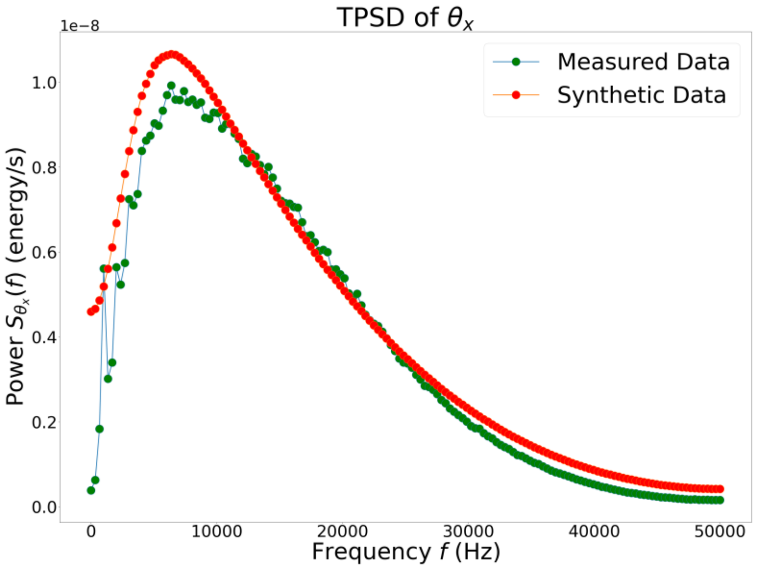
Boiling Flow

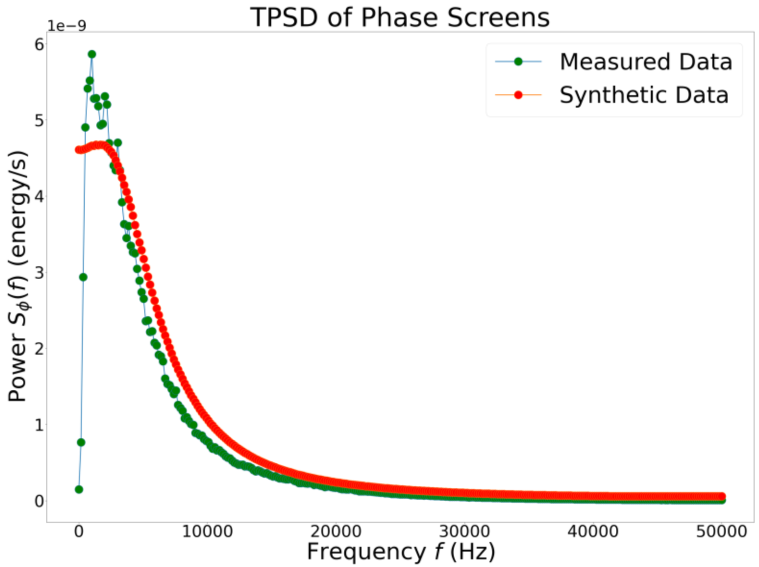
Results: Data Set F06



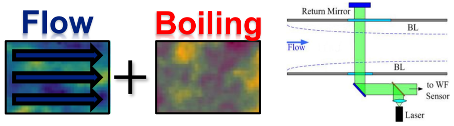


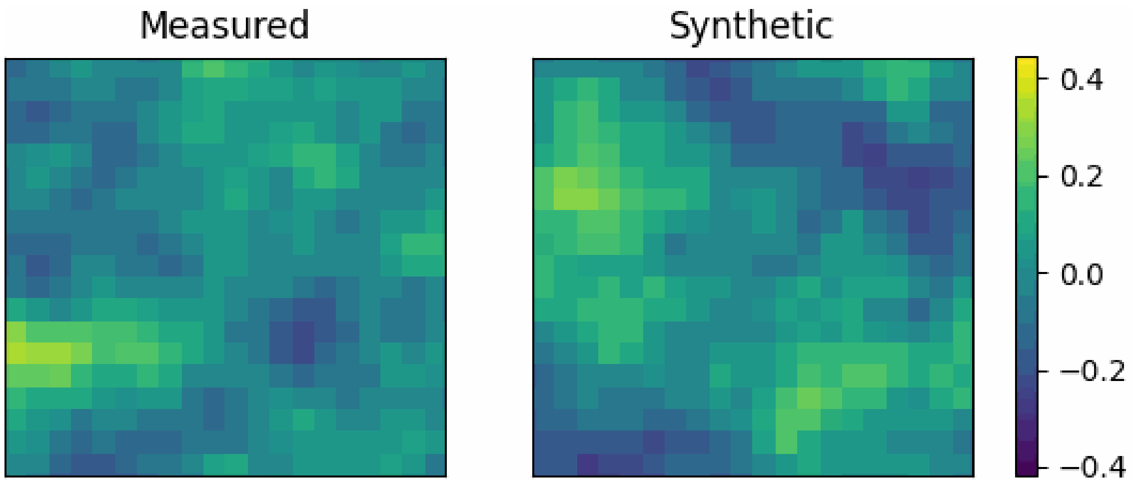


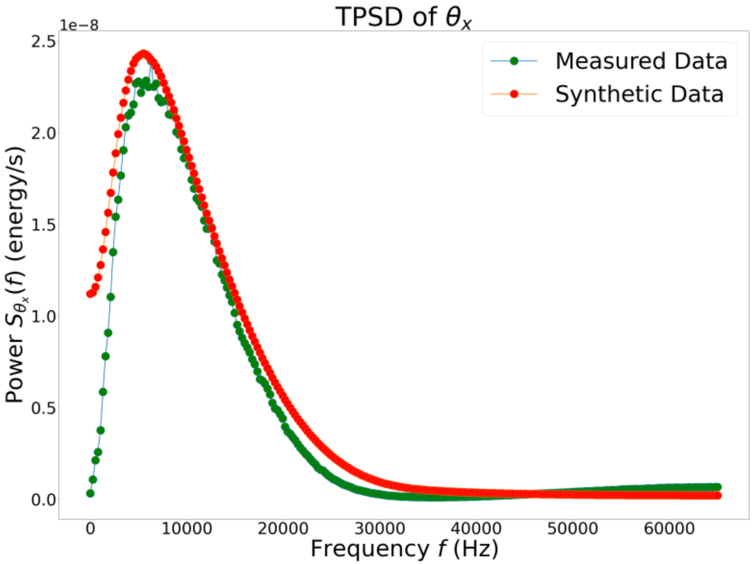


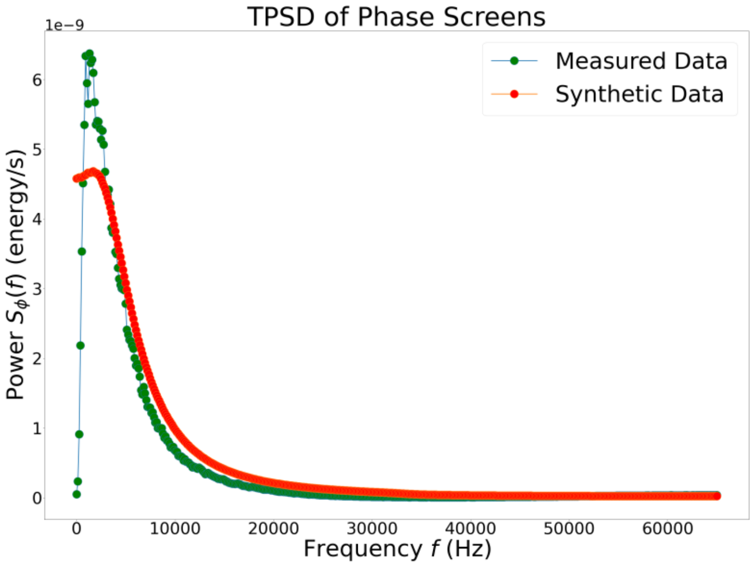


Results: Data Set F12

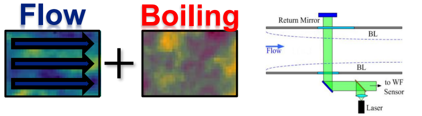








2-D Kolmogorov Spatial Structure Function

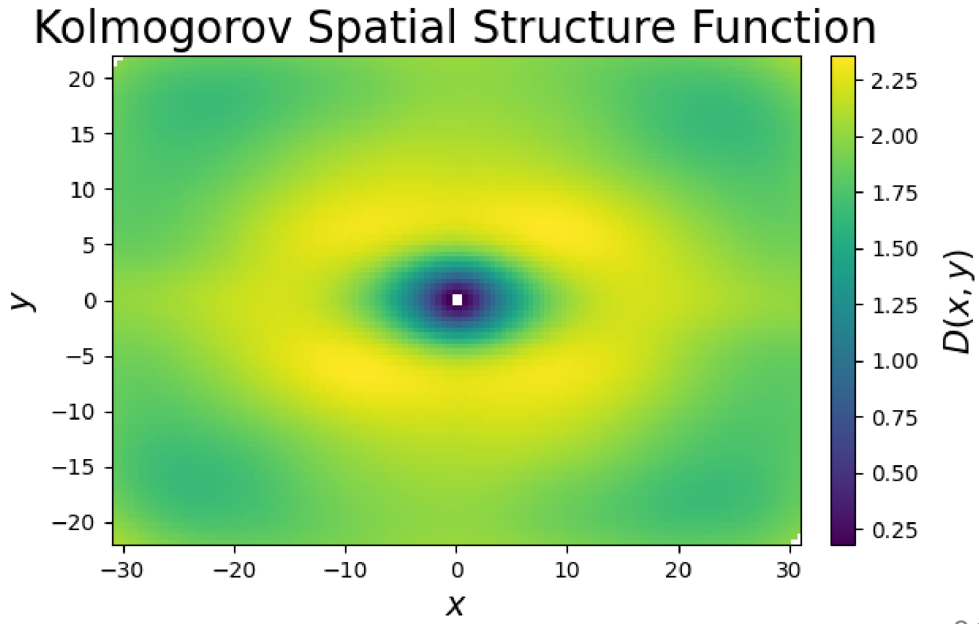


➢ The **2-D Kolmogorov spatial structure function**

$$D_\phi(x, y) = \mathbb{E}\left[\left(\phi(x_0 + x, y_0 + y) - \phi(x_0, y_0)\right)^2\right]$$

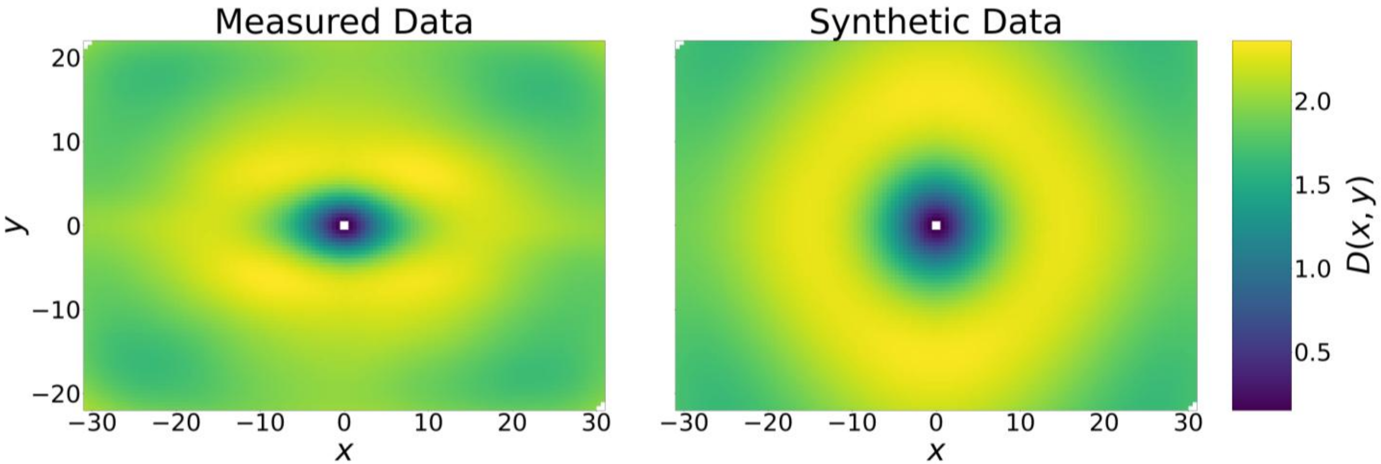
evaluates the *spatial statistics* of the phase screens.

➢ This function depends on the $(\boldsymbol{x}, \boldsymbol{y})$ **difference**, instead of just the **separation distance** $\boldsymbol{r}$.

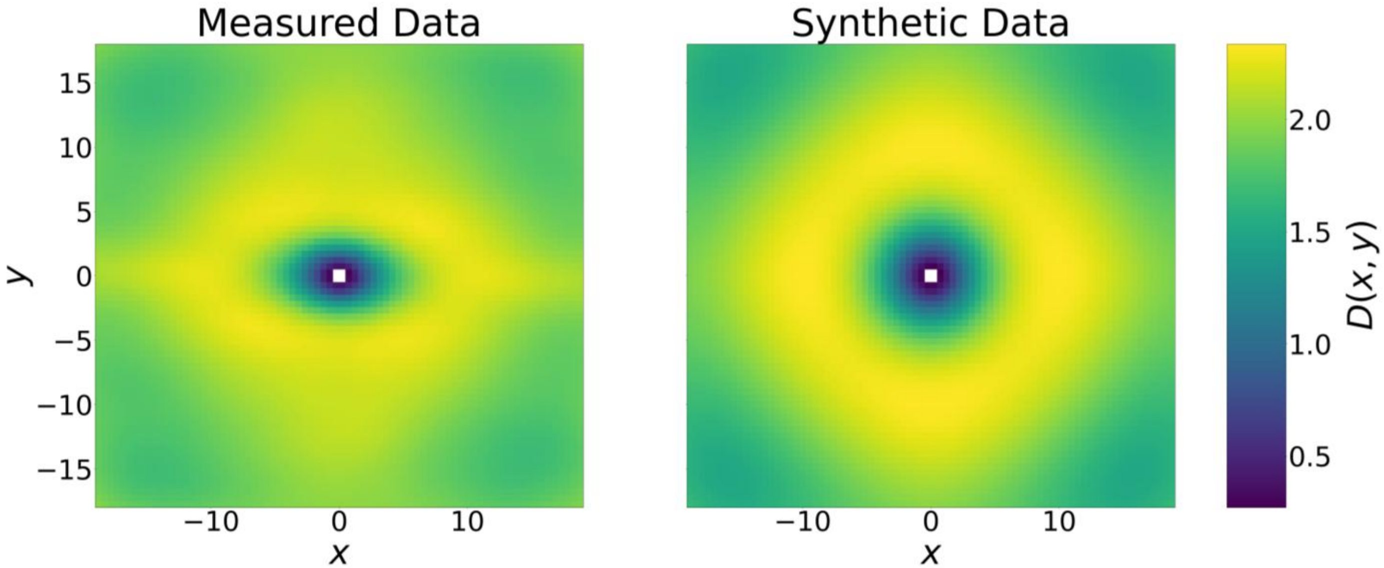


Spatial Statistics of Measured and Synthetic Data

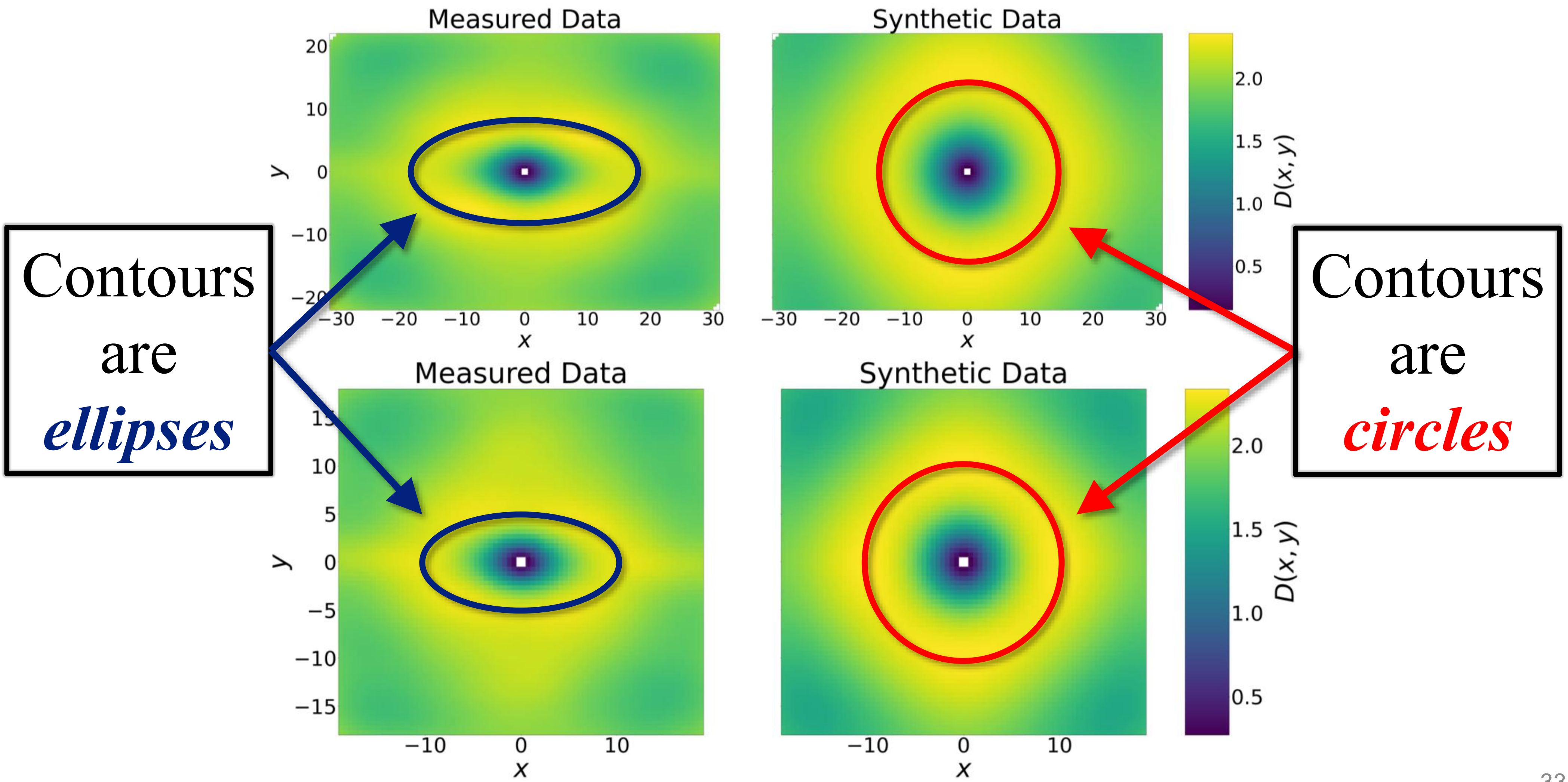
Data Set F06



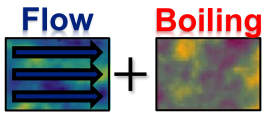
Data Set F12

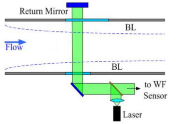


Spatial Statistics of Measured and Synthetic Data



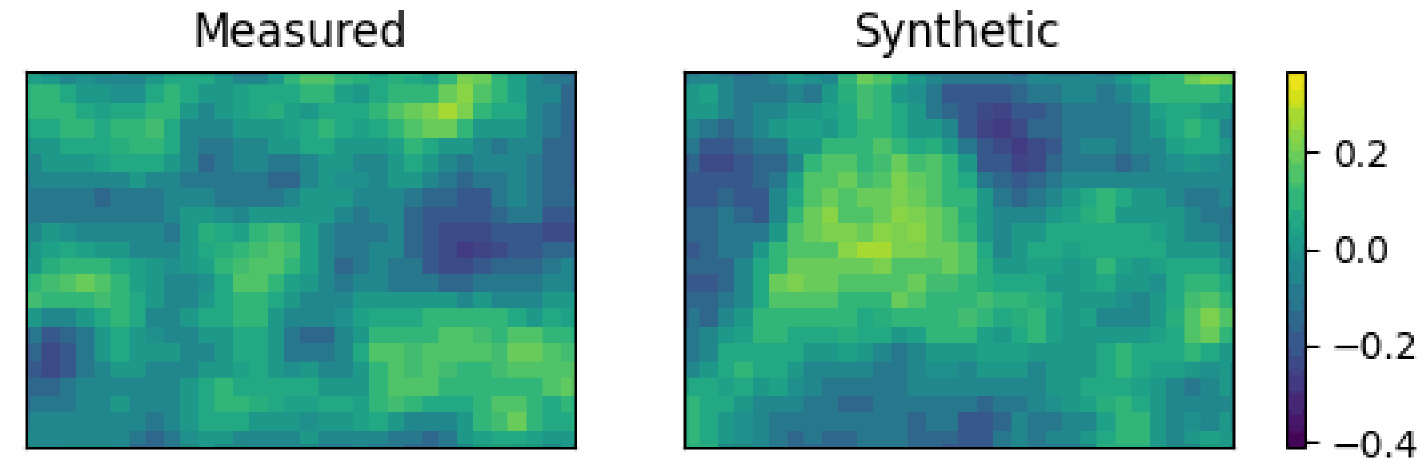
Conclusion





➢ We *estimated* the ***Boiling Flow*** parameters from measured *aero-optic* phase screens.

➢ The resulting synthetic phase screens **reasonably match the temporal statistics** of the *slopes of* the measured phase screens, but **do not match the spatial statistics** of the measured phase screens.



References

[1] E. J. Jumper, S. Gordeyev, and M. R. Whiteley, “Aero-optical effects,” in Aero-Optical Effects, (John Wiley Sons, Incorporated, United States, 2023)

[2] M. Wang, A. Mani, and S. Gordeyev, “Physics and Computation of Aero-Optics,” *Annual Review of Fluid Mechanics*, Vol. 44, No. 1, 2012, pp. 299–321.

[3] Srinath, S., Poyneer, L. A., Rudy, A. R., and Ammons, S. M., “Computationally efficient autoregressive method for generating phase screens with frozen flow and turbulence in optical simulations,” Opt. Express 23, 33335–33349 (Dec 2015)

[4] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures", *54th AIAA Aerospace Sciences Meeting*, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.