ReVAR: A data-driven algorithm for generating aero-optic phase screens

[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

Approved for public release; distribution is unlimited. Public Affairs release approval # AFRL-2026-0502

Light Detection and Transmission from an Aircraft

Goal: *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).

Light Detection and Transmission from an Aircraft

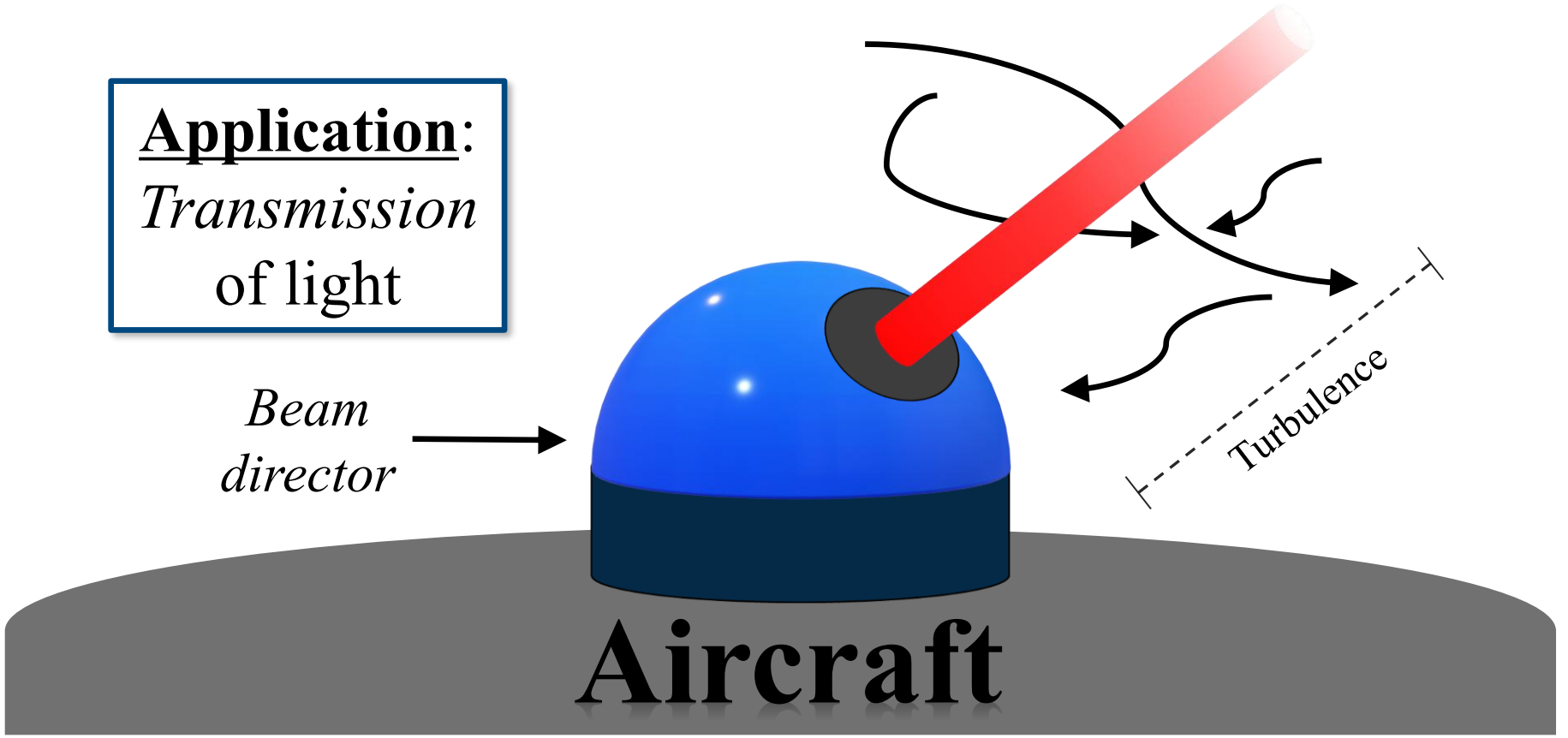
Goal: *Detect* and *transmit* light from the side of a high-speed aircraft.

https://aero-optics.nd.edu/research/aaol/

Turbulence Near the Aircraft

Problem: Light passes through **turbulence** *near* the aircraft.

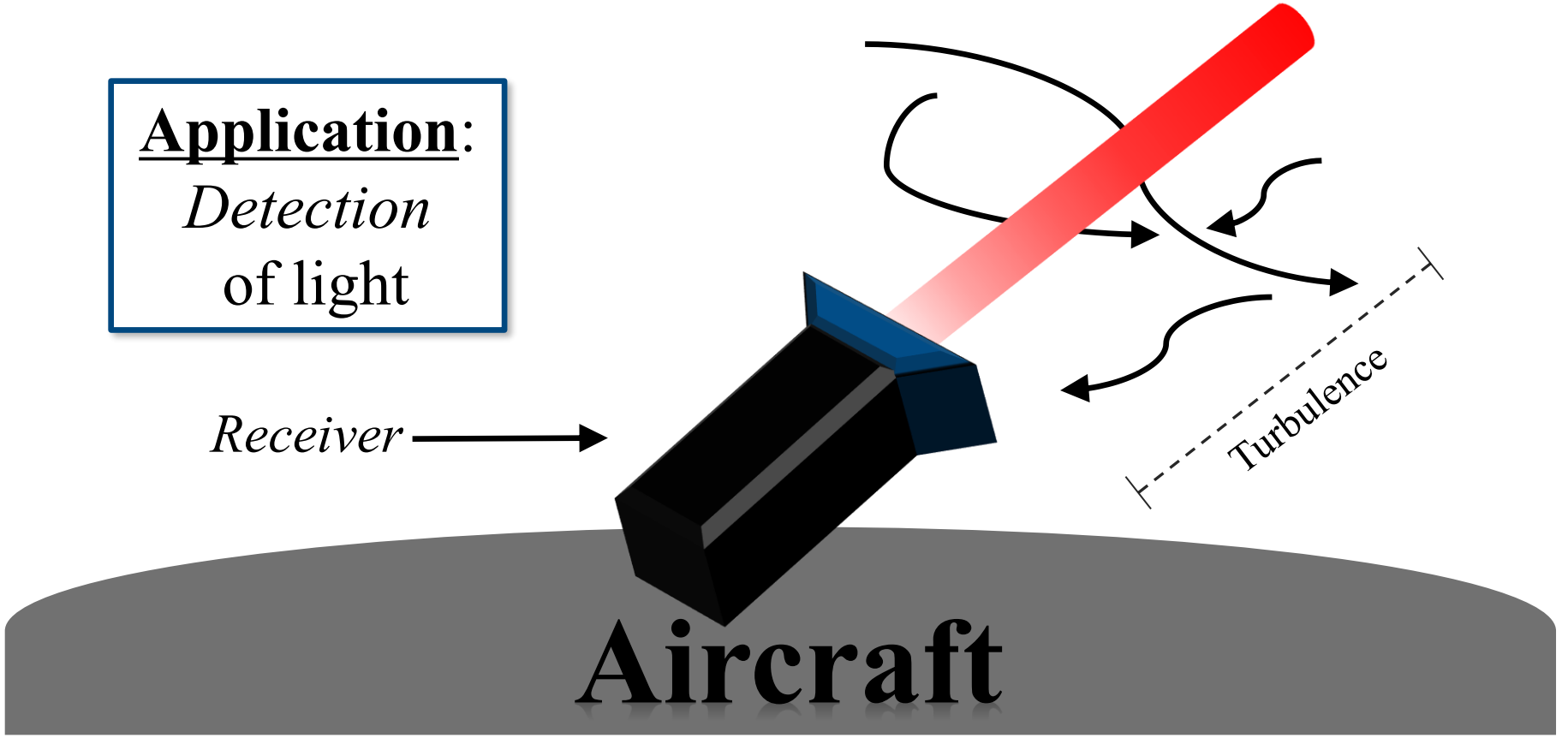
Application:
Transmission
of light



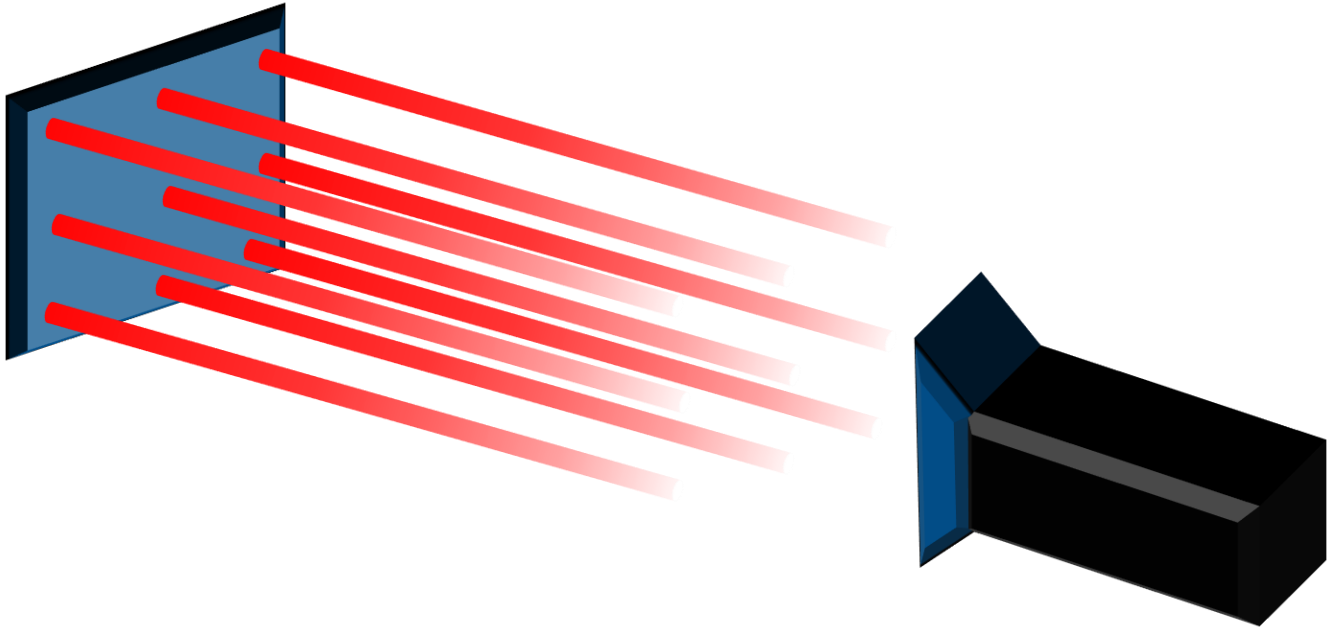
Turbulence Near the Aircraft

Problem: Light passes through **turbulence** *near* the aircraft.

Application:
Detection
of light



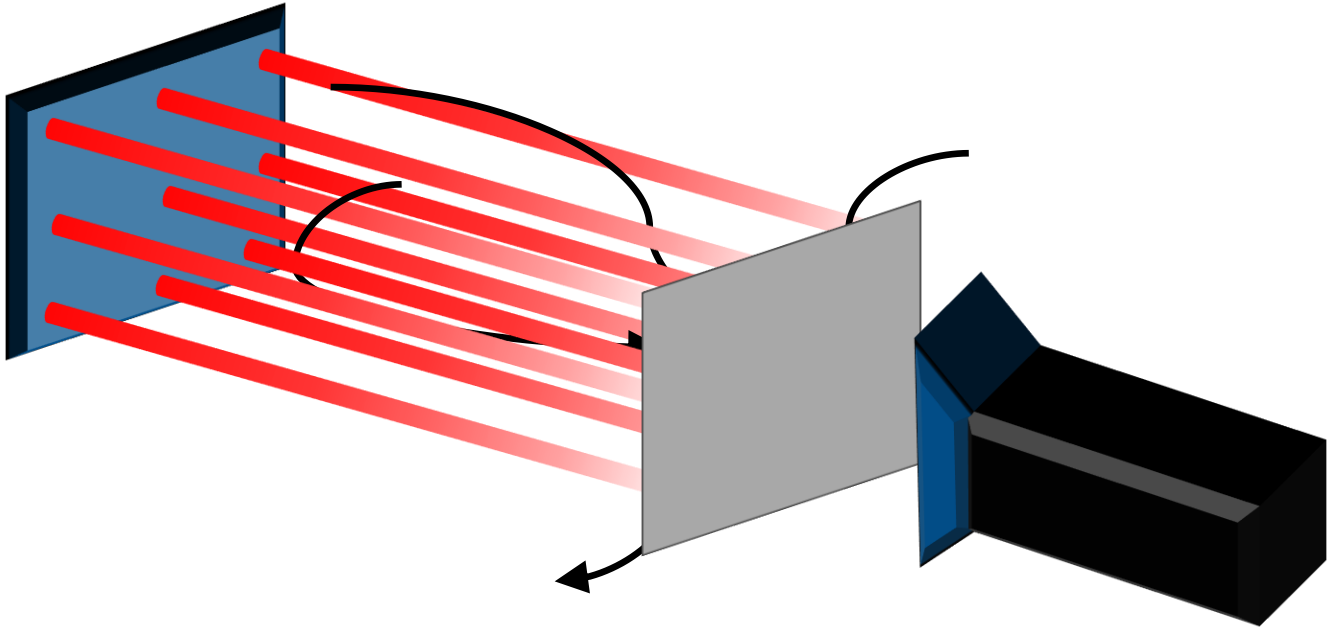
Effect of Turbulence on Light: Aero-Optic Effects



Receiver/target

Without turbulence, light moves *uniformly*.

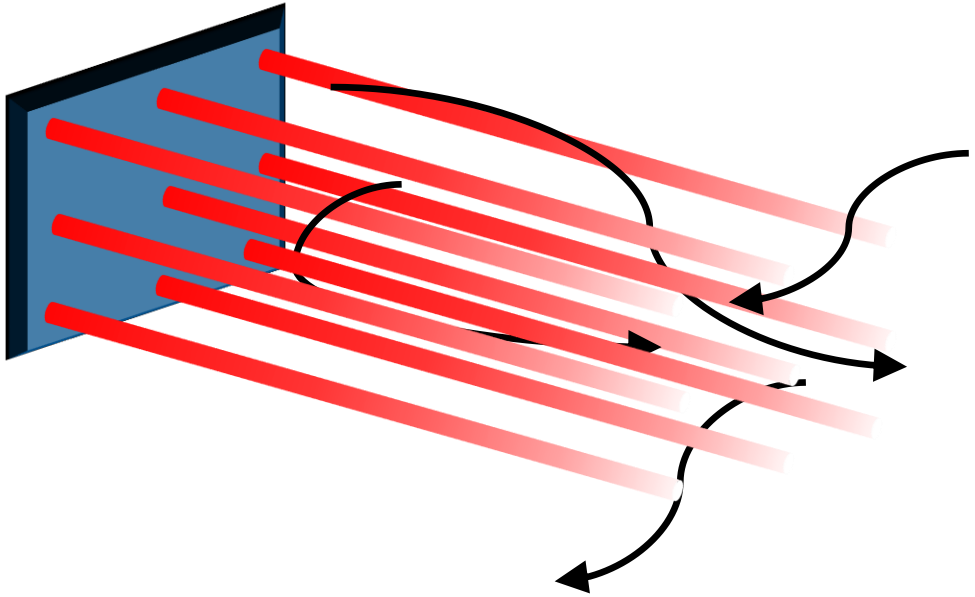
Effect of Turbulence on Light: Aero-Optic Effects

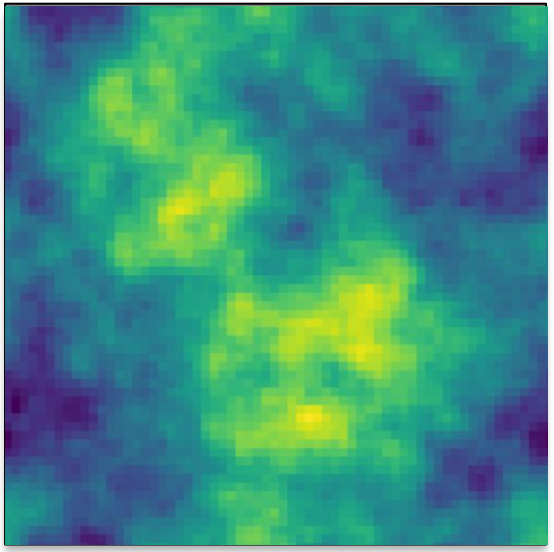


Receiver/target

Velocity changes result in **phase aberrations** in detected light.

Measuring Aero-Optic Effects: Phase Screens



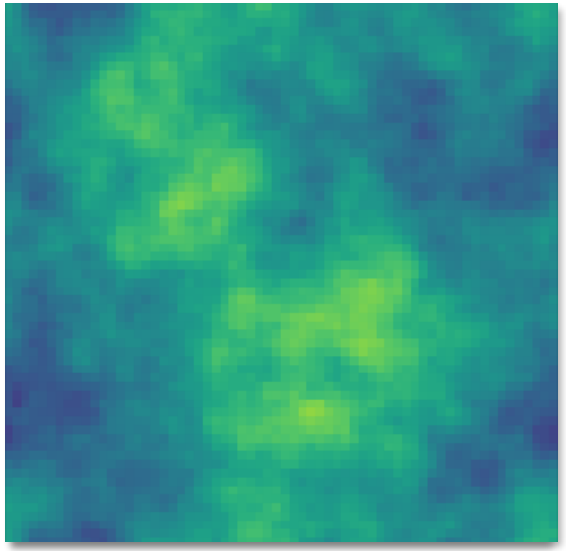


Velocity changes result in **phase aberrations** in detected light.

Phase screens *measure* and *simulate* these phase aberrations.

Measuring Aero-Optic Effects: Phase Screens

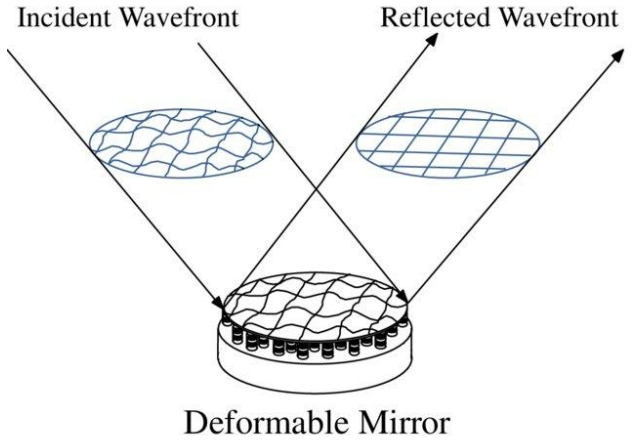
- In addition to *spatial non-uniformity*, these phase aberrations **vary in time**.
- *Time series* of phase screens **capture** this temporal variation.
- These time series *measure aero-optic effects*, giving us **aero-optic data**.



Phase screens *measure* and *simulate* these phase aberrations.

We Need Aero-Optic Data!

- **Adaptive-optic (AO)** systems can *compensate* for phase aberrations.

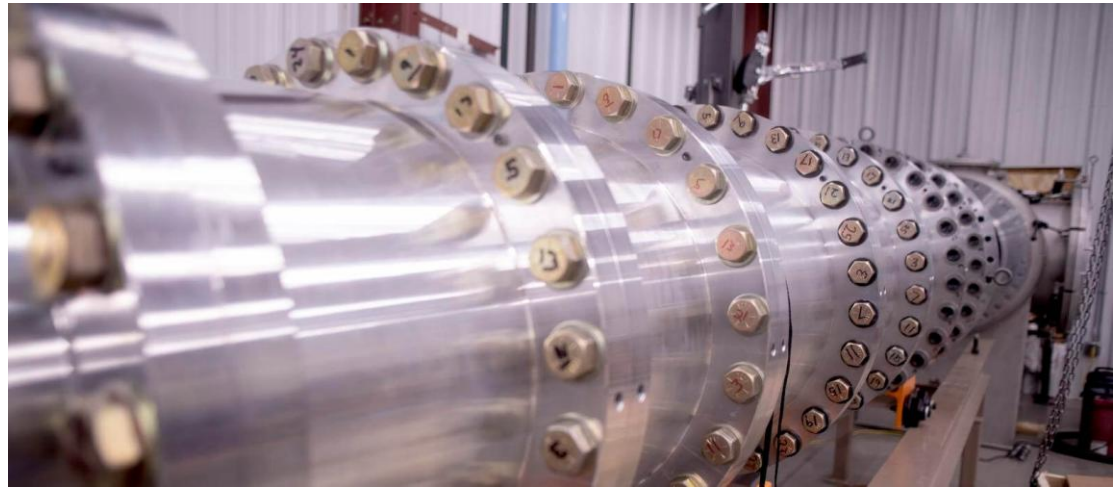


- **<u>Problem</u>**: To address aero-optic effects, more sophisticated AO systems must be developed.
- This development ***requires aero-optic data***.

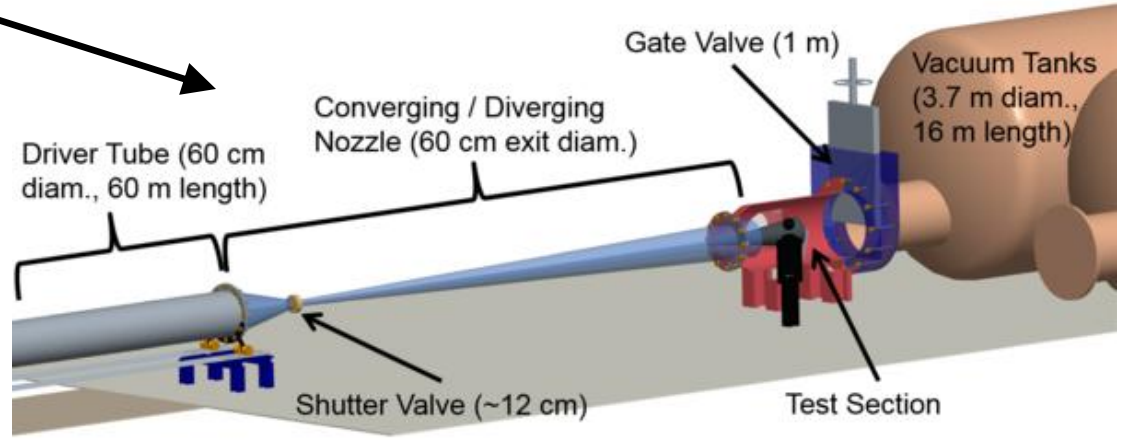
[2] Steinbock, M. J. (2012). *Implementation of branch-point-tolerant wavefront reconstructor for strong turbulence compensation* (No. AFITGEENG1245).

Measuring Aero-Optic Data

Physical experiments are **expensive**!



- **Wind tunnel** experiments are most common for measuring this data.
- They require a lot of ***time and money***.



https://hyperlab.nd.edu/facilities/

Generating Aero-Optic Data

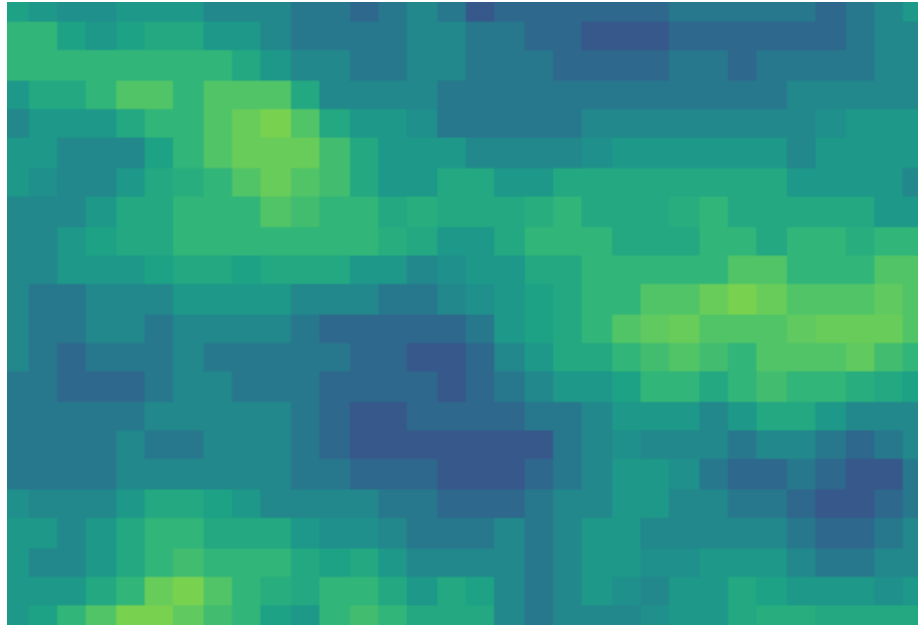
- Simulations can ***generate*** this data without the montetary expense of physical experiments.
- As of now, existing simulation methods ***still have drawbacks***.

- **Solution**: We develop **ReVAR (Re-whitened Vector Auto-Regression)**, a *data-driven algorithm* that generates *aero-optic data* which match the statistics of measured data.

ReVAR: Re-whitened Vector AutoRegression

ReVAR:

- Take in a **short video** of *measured data*.
- Create a **much longer** video of *synthetic data*.



Match the *spatial* and *temporal* **statistics** of the measured data.

Presentation Outline

1. Measured Data Sets

2. ReVAR

3. Results

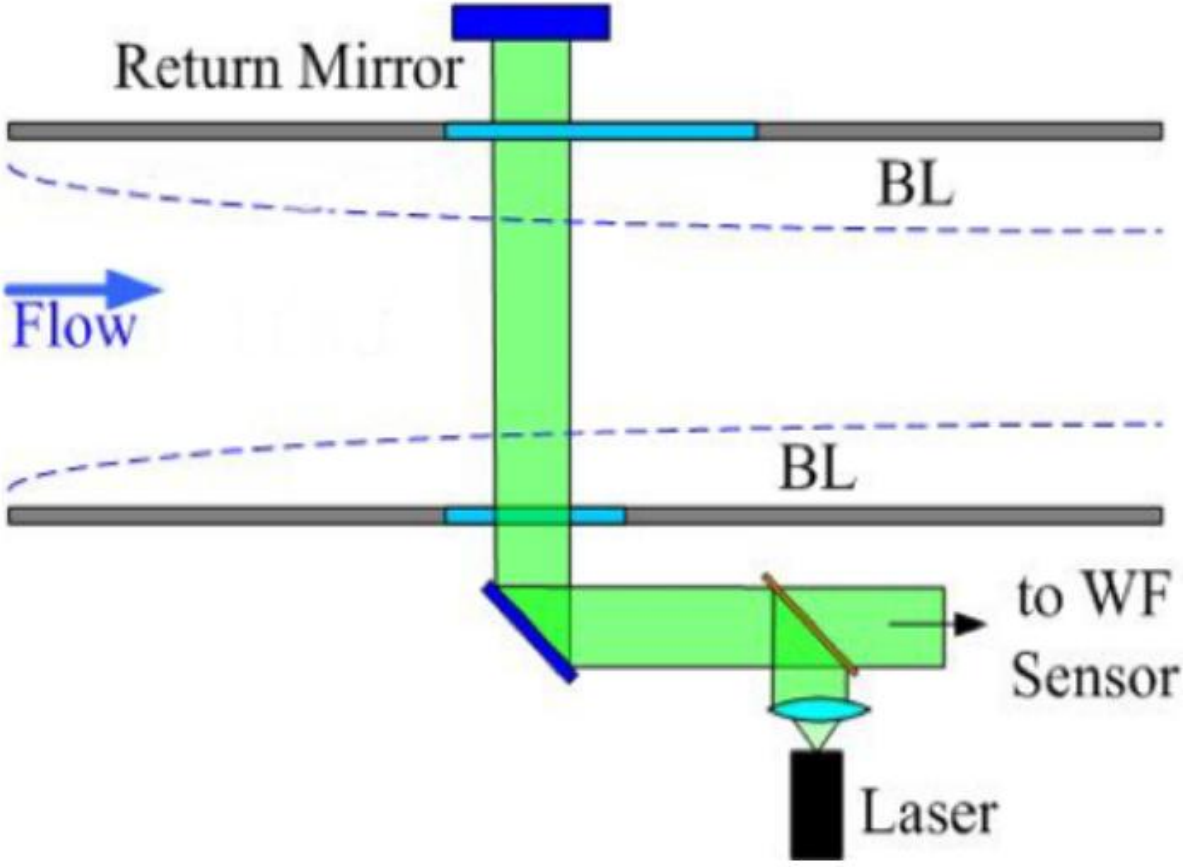
Presentation Outline

1. **Measured Data Sets**

2. ReVAR

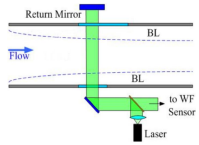
3. Results

Measured Data: Wind Tunnel Experiment

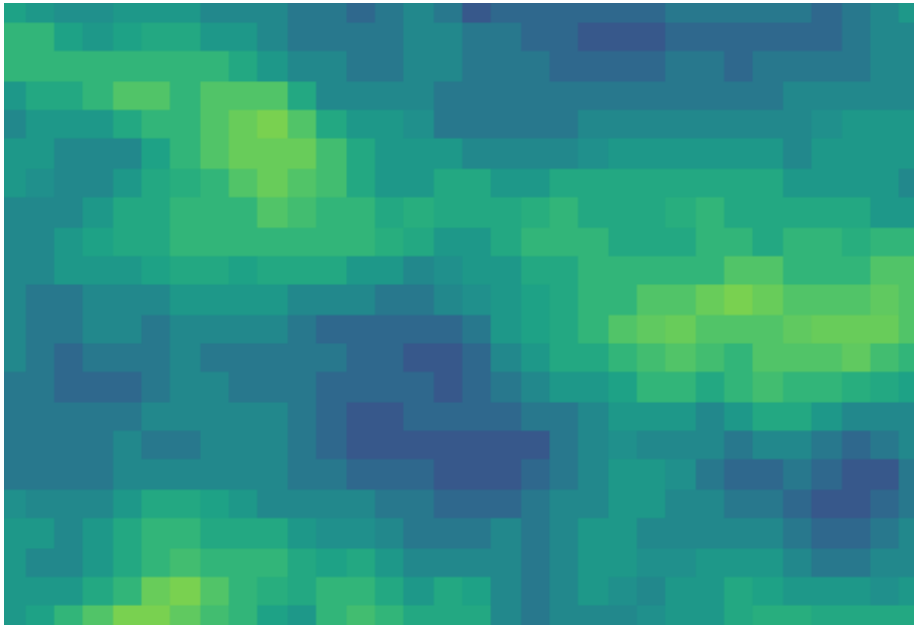


[3] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures", *54th AIAA Aerospace Sciences Meeting*, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.

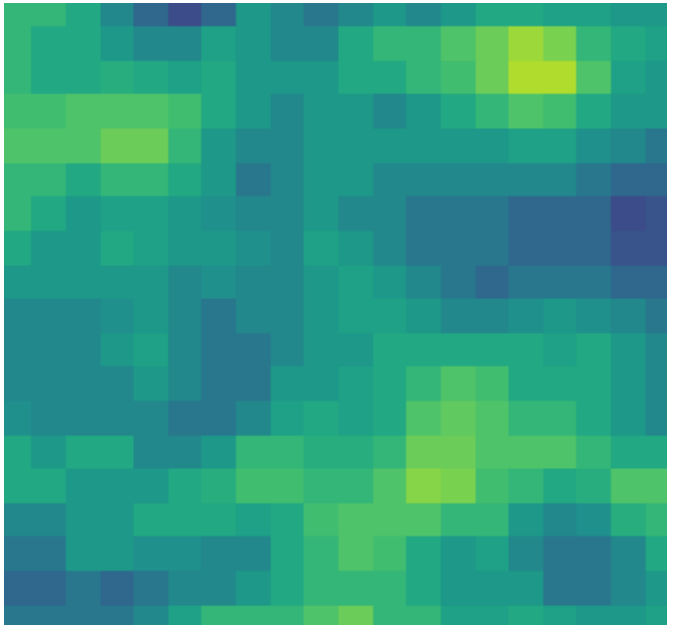
Measured Data: Wind Tunnel Experiment



Dataset 1



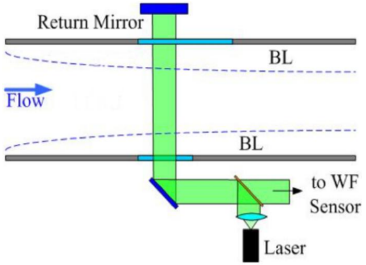
Dataset 2

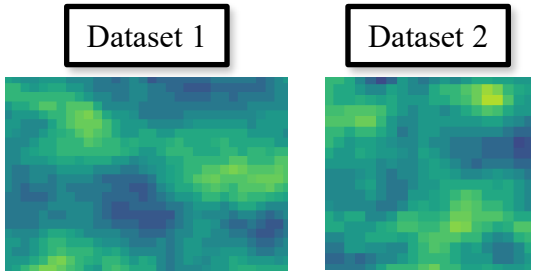


[3] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures", *54th AIAA Aerospace Sciences Meeting*, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.

Presentation Outline

1. **Measured Data Sets**



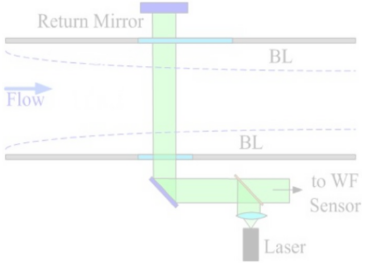


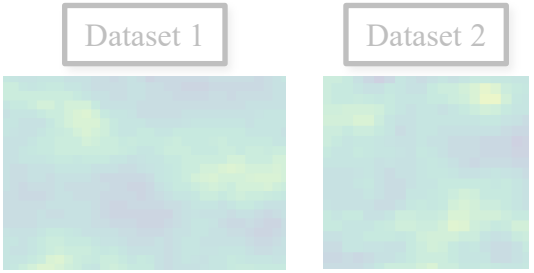
2. ReVAR

3. Results

Presentation Outline

1. Measured Data Sets



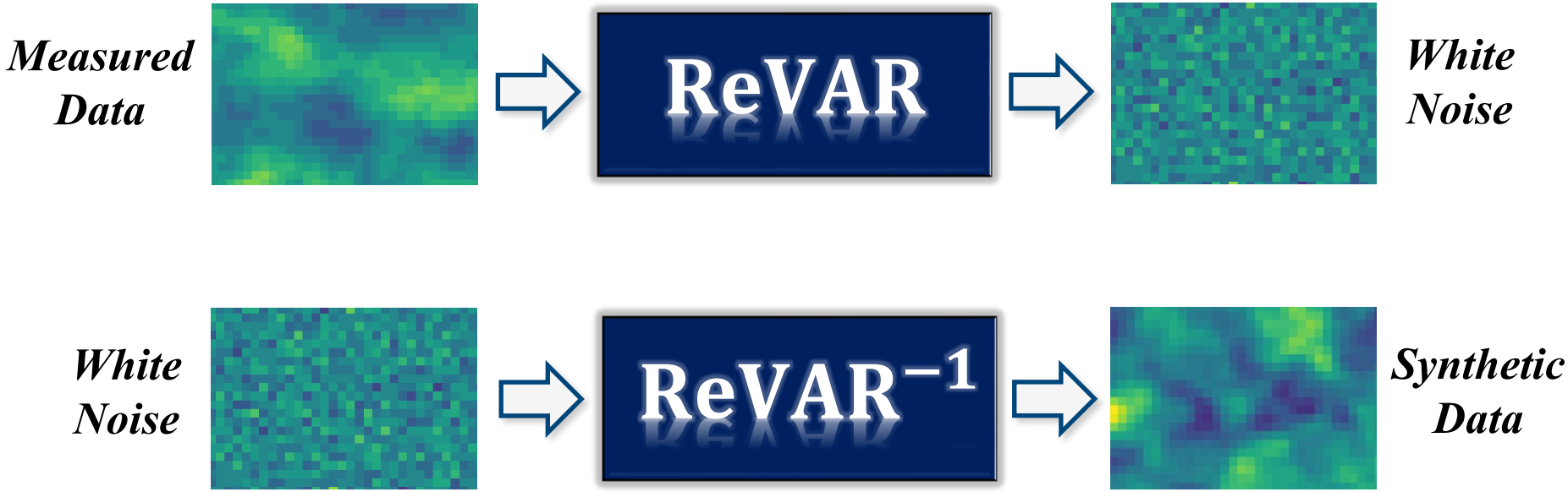


2. **ReVAR**

3. Results

ReVAR: Re-whitened Vector AutoRegression

Transform input data into **white noise** in a way that is **invertible**.

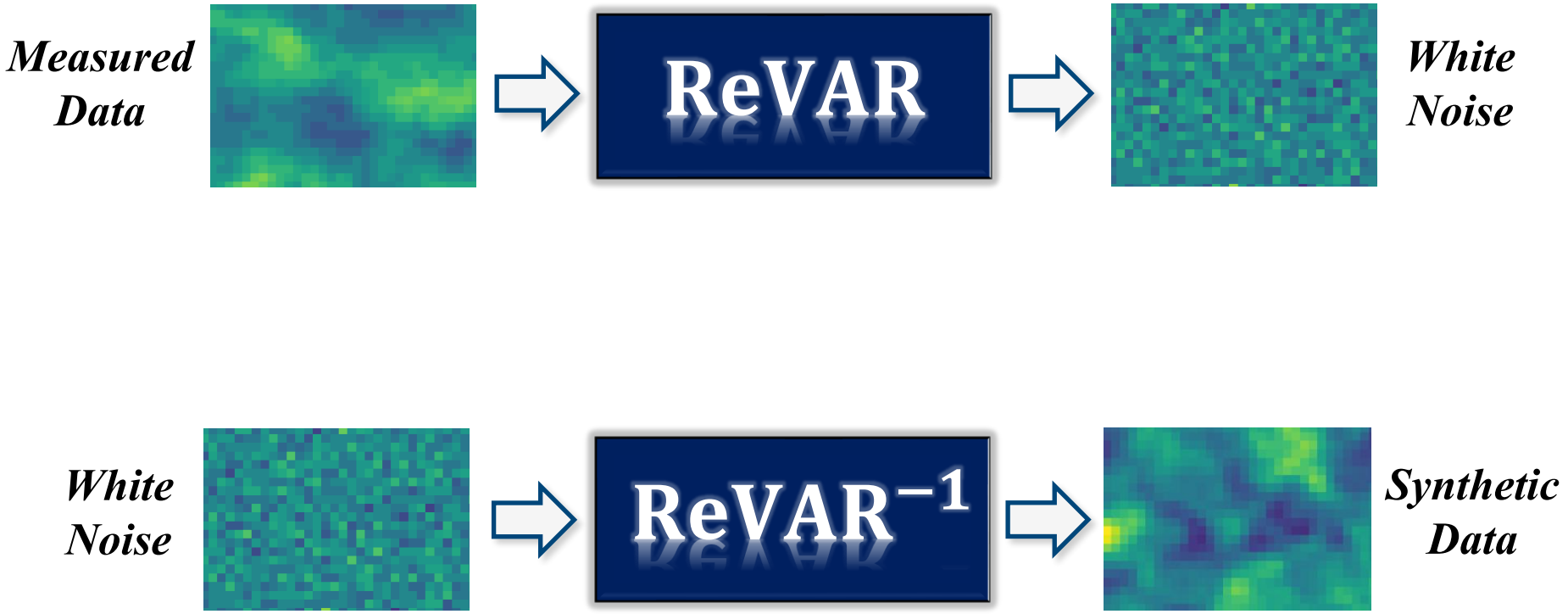


ReVAR: Re-whitened Vector AutoRegression

1. Parameter Estimation

2. Data Synthesis

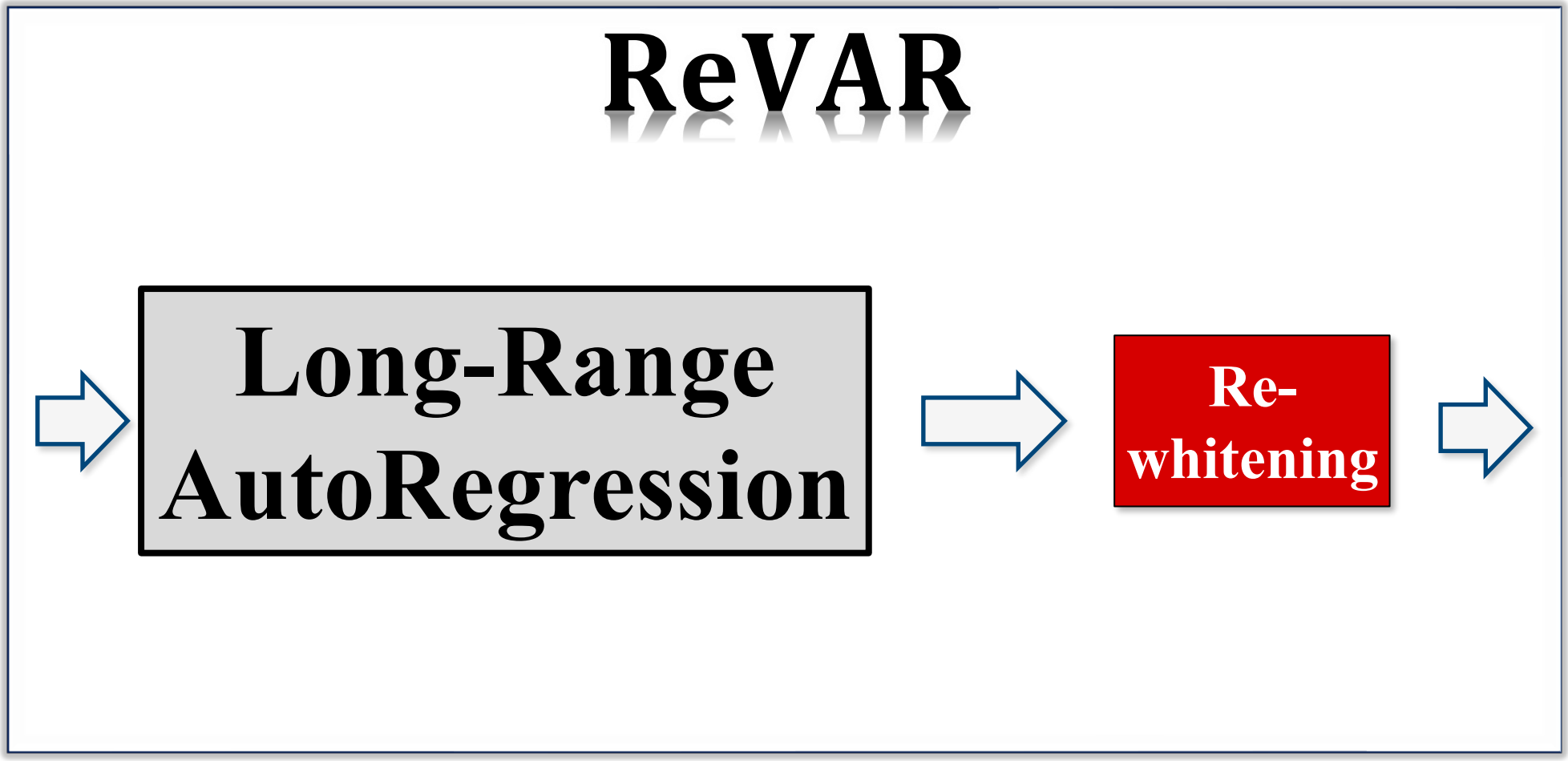
ReVAR: Re-whitened Vector AutoRegression



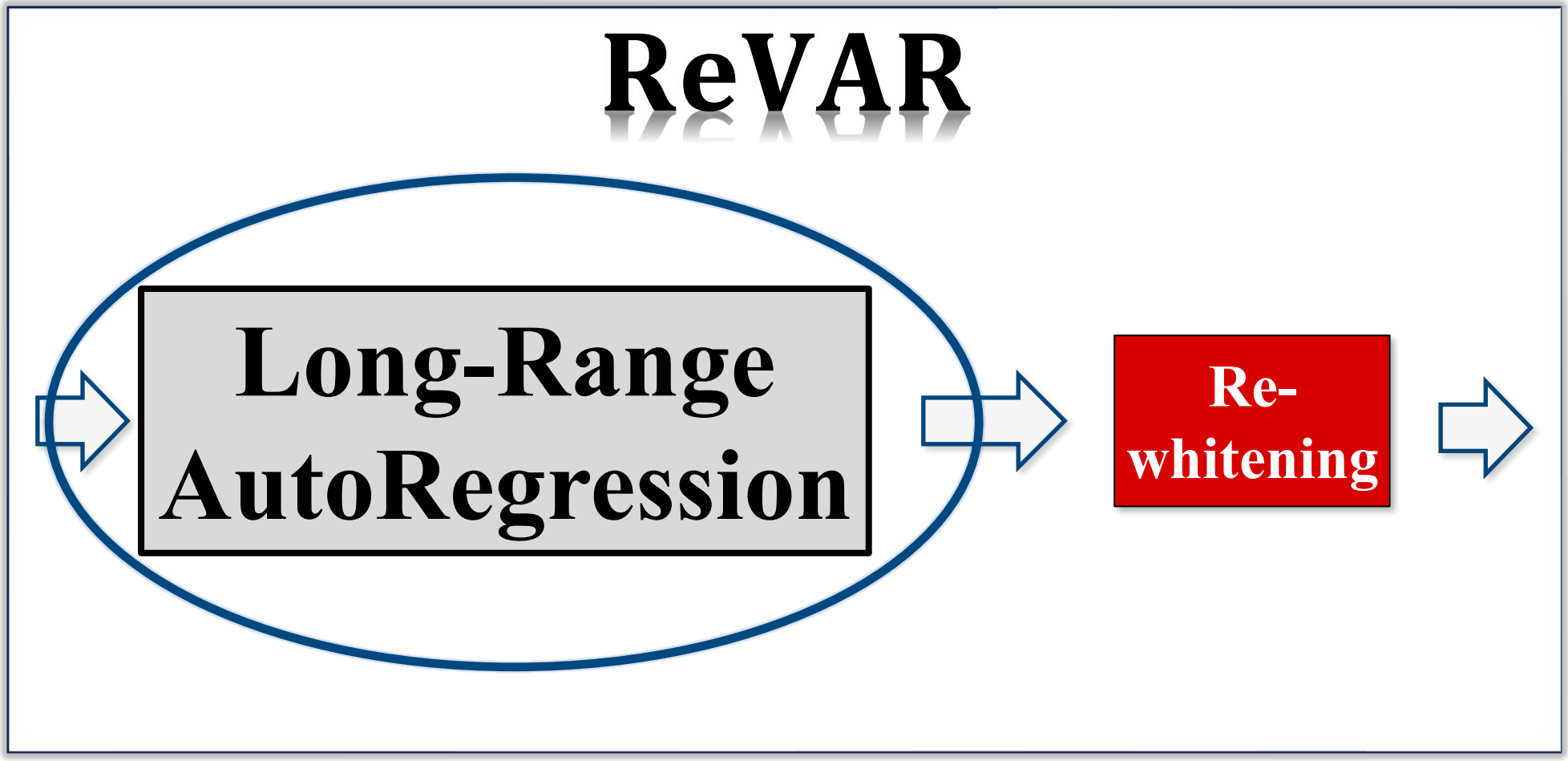
ReVAR: Re-whitened Vector AutoRegression

ReVAR

ReVAR: Re-whitened Vector AutoRegression

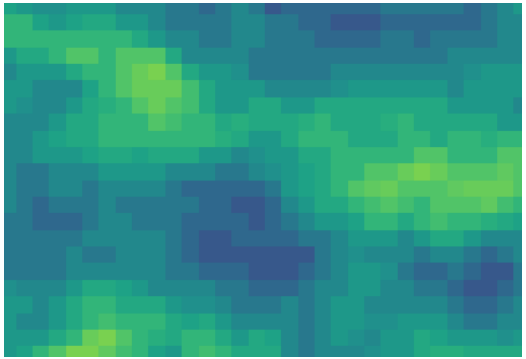


ReVAR: Re-whitened Vector AutoRegression



Long-Range AutoRegression

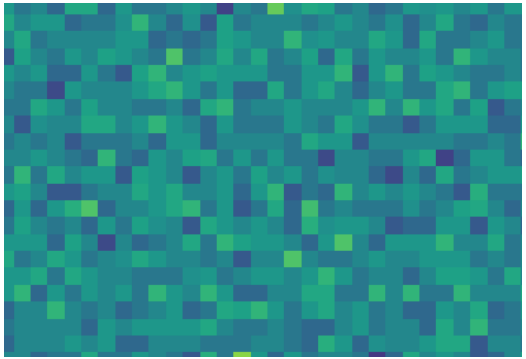
➢ **Idea**: At each time, represent the data through ***some linear prediction*** of previous data, plus *some noise*.



=

Linear Prediction

+



Long-Range AutoRegression

➢ **Idea**: At each time, represent the data through ***some linear prediction*** of previous data, plus *some noise*.

$$X_n = \hat{X}_n + \xi_n$$

Long-Range AutoRegression

- **Idea**: At each time, represent the data through ***some linear prediction*** of previous data, plus *some noise*.
- For this linear predictor, we use a ***long-range predictor***.

$=$

Long-Range Predictor

$+$

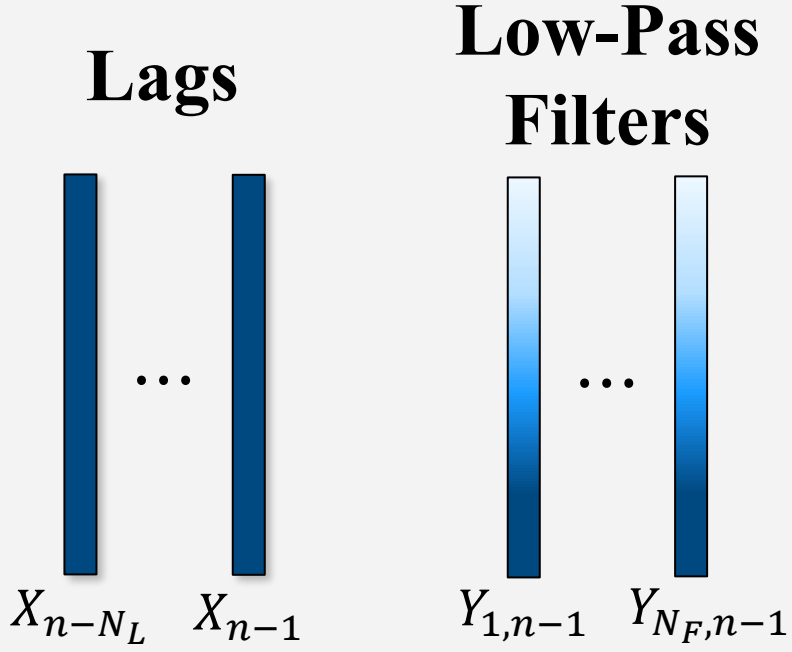
$X_n = \hat{X}_n + \xi_n$

Long-Range Predictor

➢ Send the following ***components*** into a **linear predictor:**

1. ***Lags***: Most recent time-steps $X_{n-N_L}, \cdots, X_{n-1}$.
2. ***Low-Pass Filters***: A collection of LPFs of the entire time history: $Y_{1,n-1}, \cdots, Y_{N_F,n-1}$.

➢ **(1)** captures ***short-range*** temporal correlations and **(2)** captures ***long-range*** correlations.



Long-Range Predictor

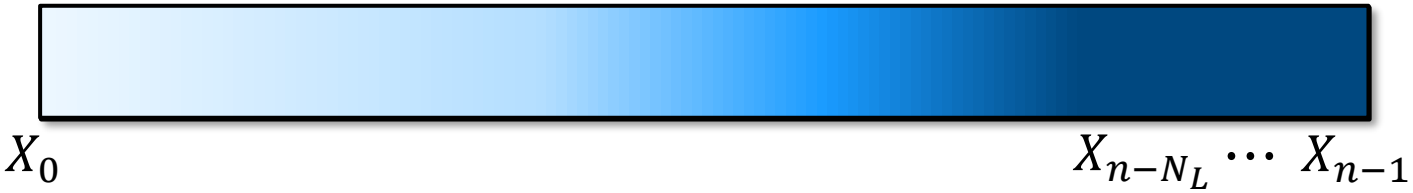
Low-Pass Filters

$\cdots$

$Y_{1,n-1} \cdots Y_{N_F,n-1}$

Lags

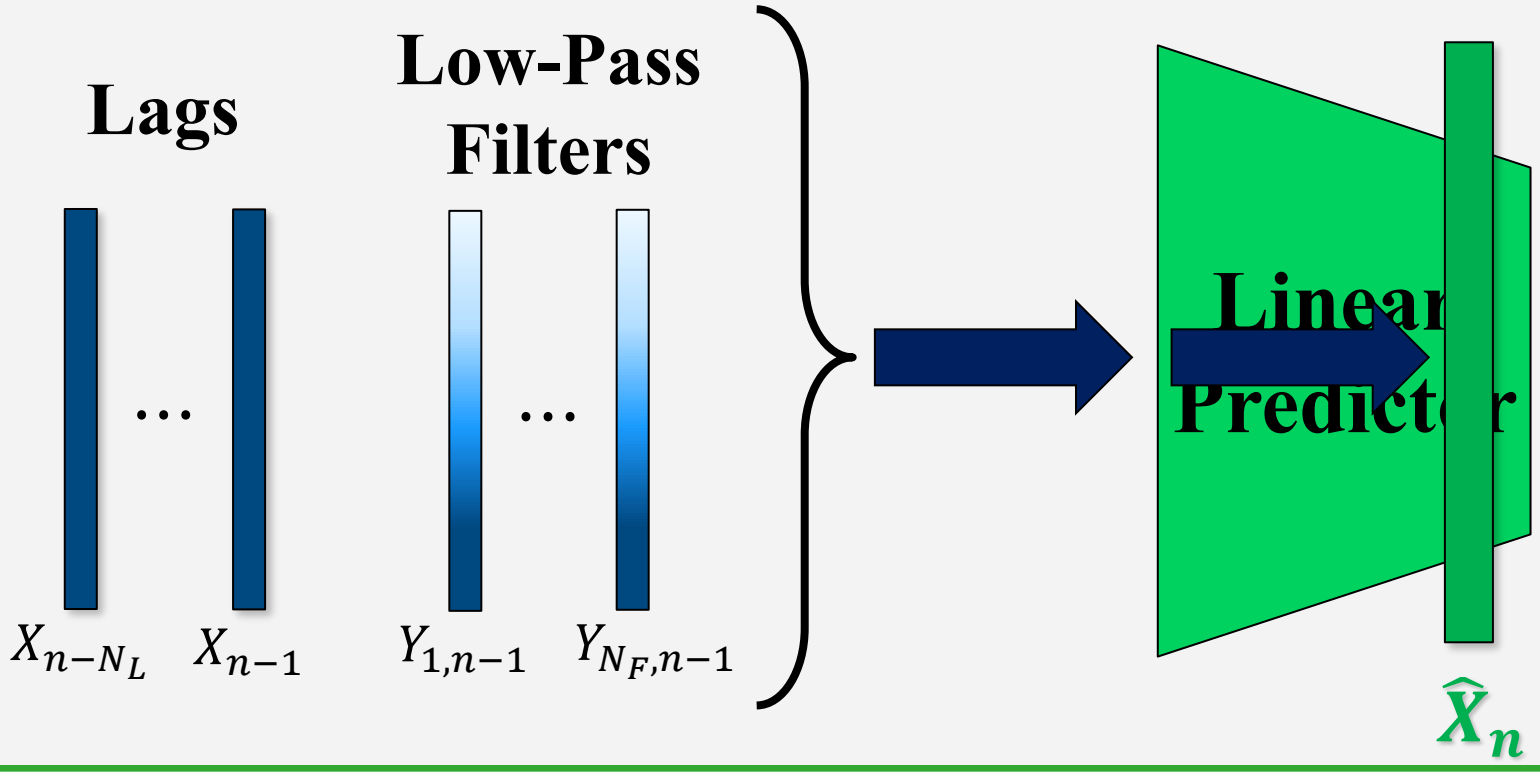
Linear Predictor



Time History

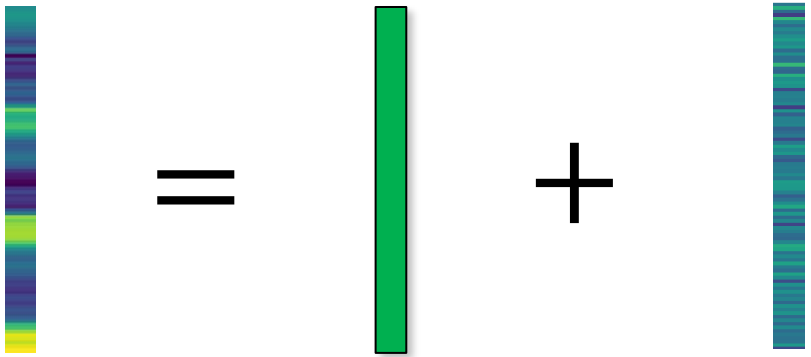
Long-Range Predictor

The **linear predictor** determines the next time-step.



Long-Range AutoRegression

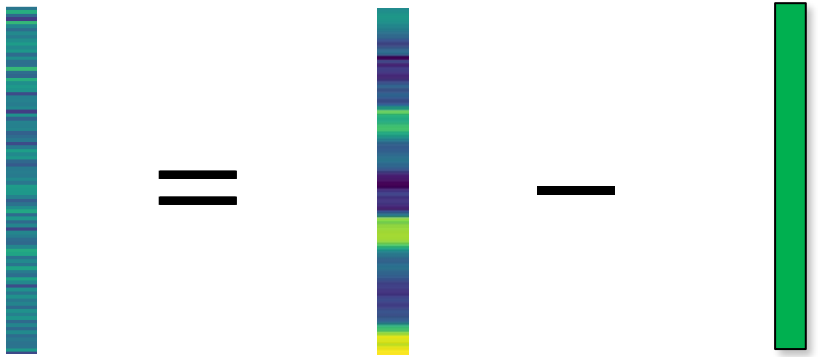
➢ **Long-Range Predictor** $\hat{X}_n$: Use a linear prediction that captures ***both*** short- and long-range temporal correlations.



$$X_n = \hat{X}_n + \xi_n$$

Long-Range AutoRegression

- **Long-Range Predictor** $\hat{X}_n$: Use a linear prediction that captures ***both*** short- and long-range temporal correlations.
- **Additive Noise** ξ_n: The ***residuals*** of the long-range predictor.



$$\xi_n = X_n - \hat{X}_n$$

Long-Range AutoRegression

ξ_n

What are the **statistics** of the **residuals** ξ_n?

Long-Range AutoRegression

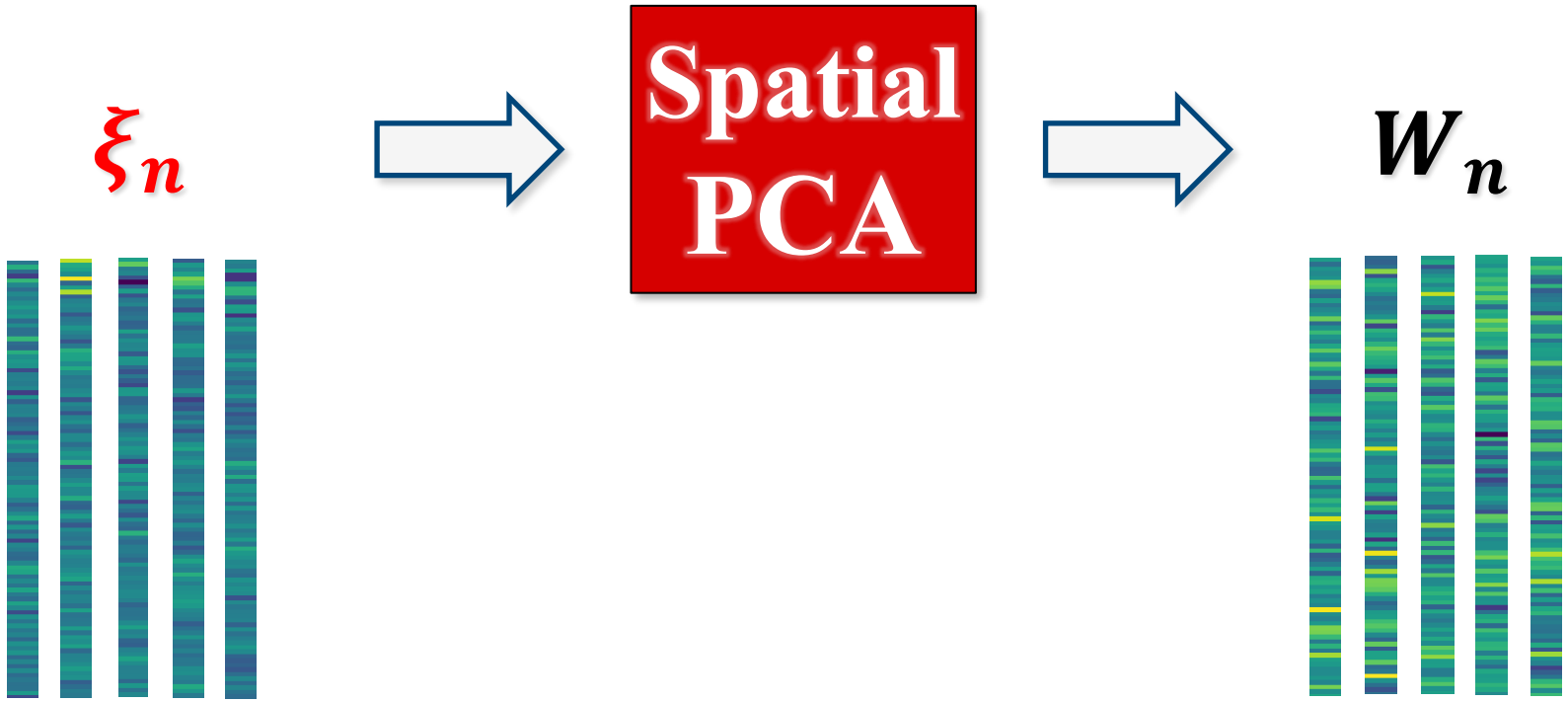
ξ_n

What are the **statistics** of the **residuals** ξ_n?

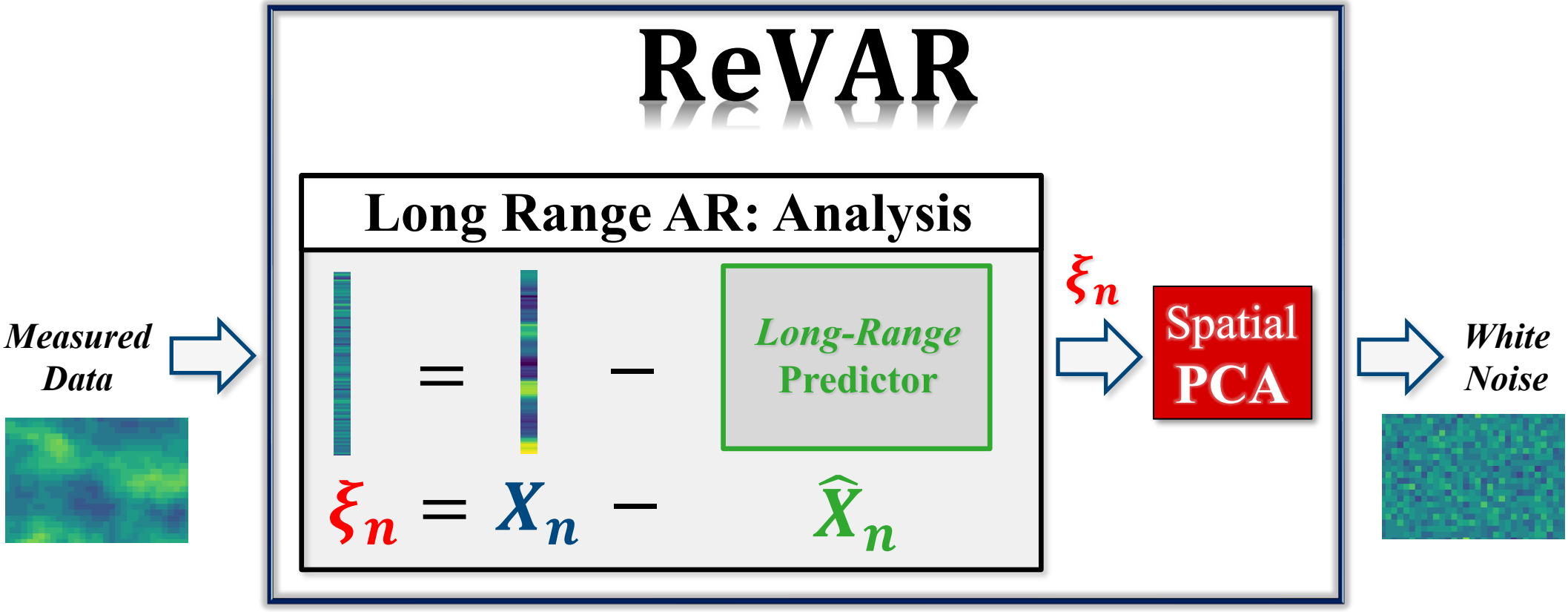
ξ_n is **white** in *time* but **correlated** in *space*.

Parameter Estimation: Re-whitening

A **spatial PCA** *whitens* ξ_n in *space.*

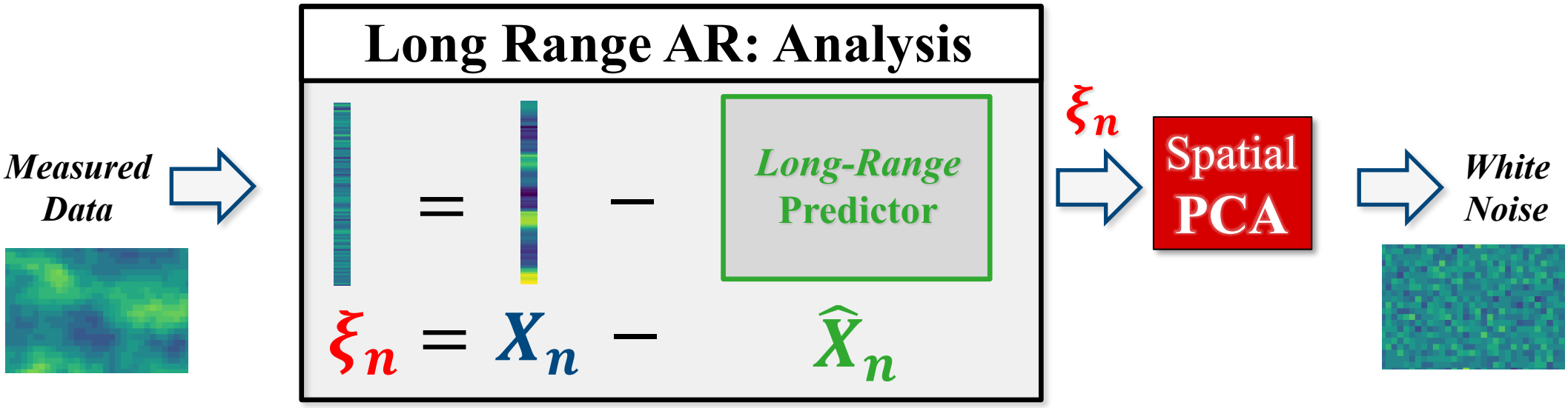


ReVAR: Parameter Estimation

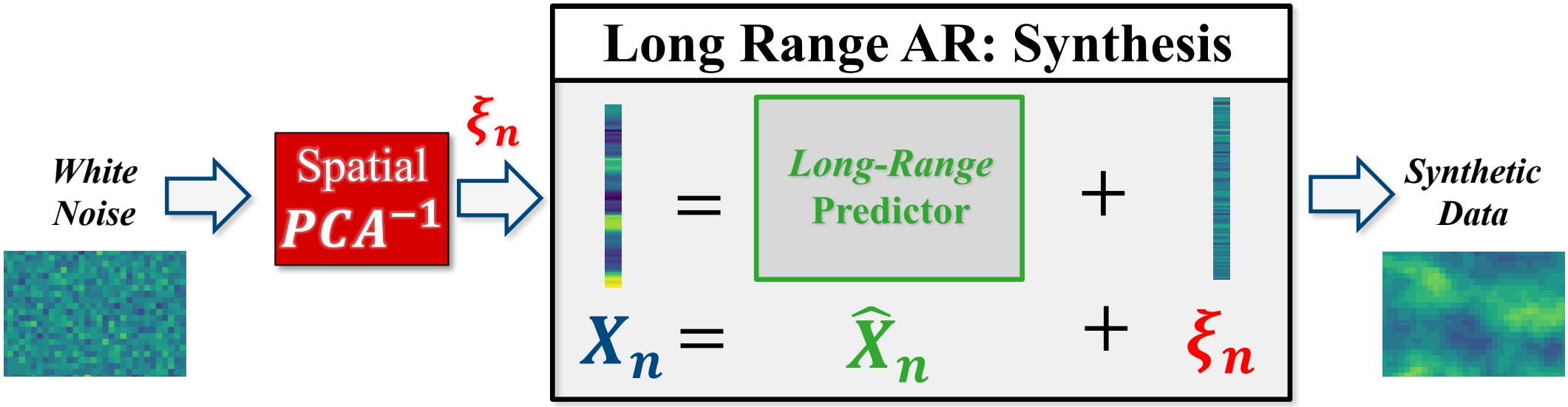


$$\xi_n = X_n - \hat{X}_n$$

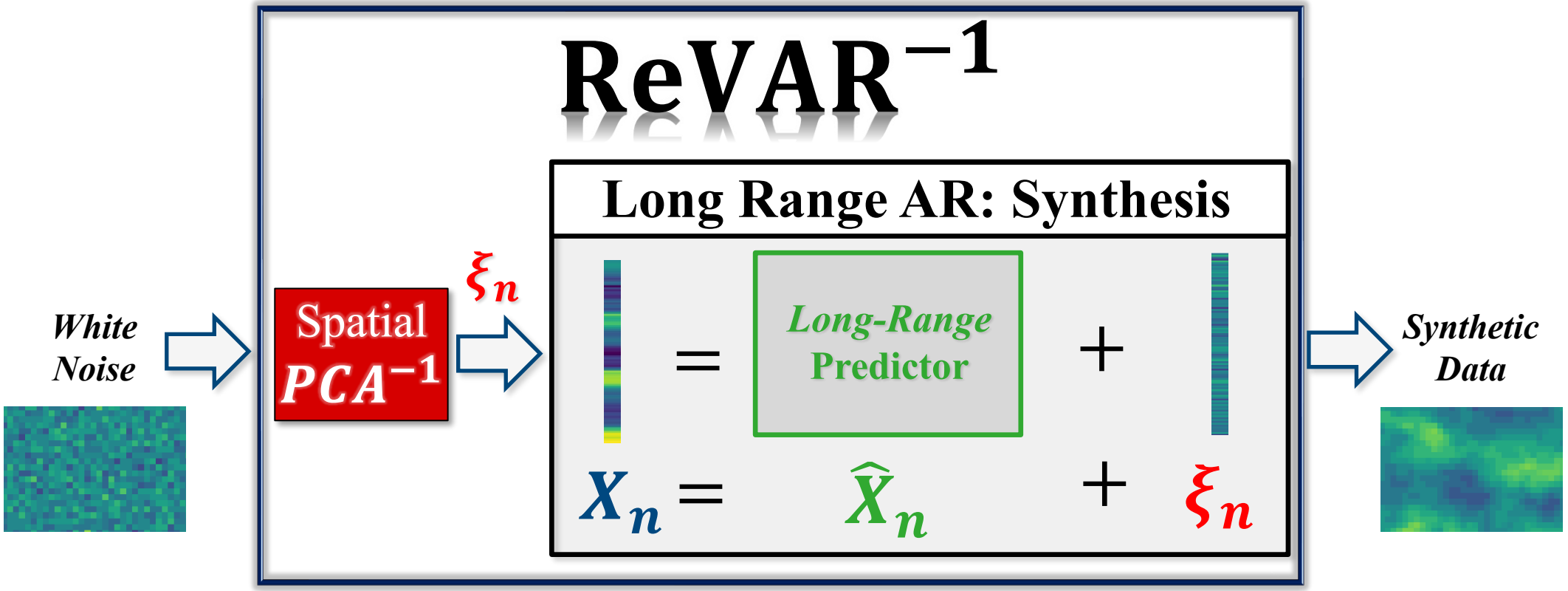
ReVAR: Parameter Estimation



ReVAR: Data Synthesis

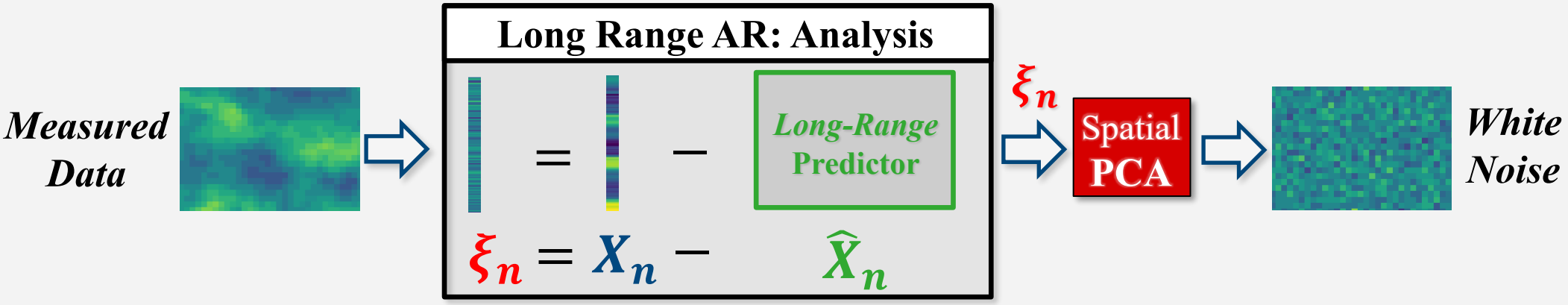


ReVAR: Data Synthesis

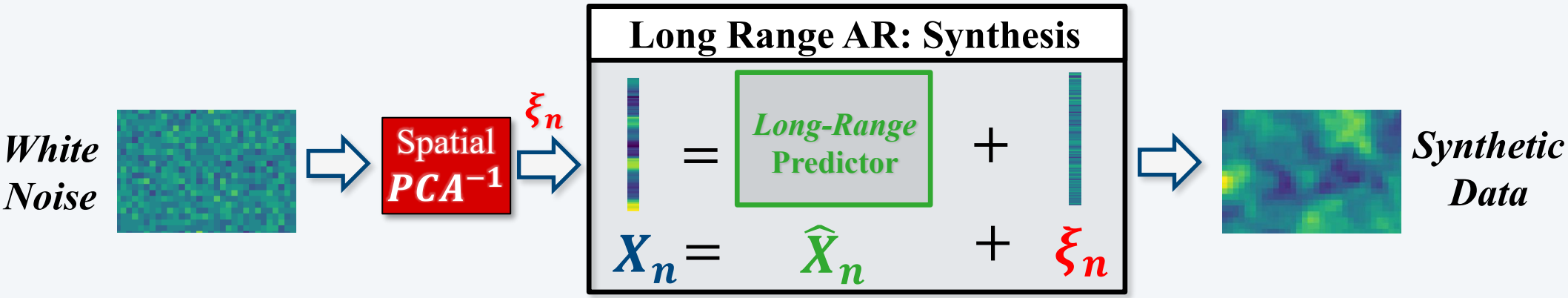


ReVAR: Algorithm Overview

1. Parameter Estimation

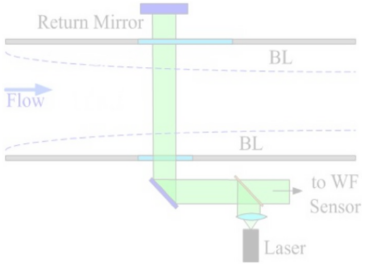


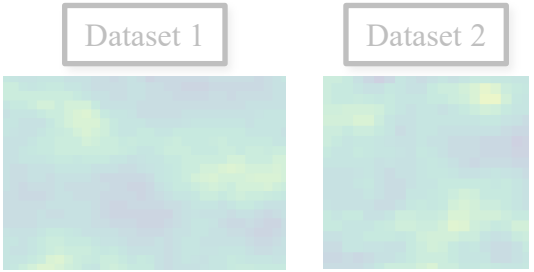
2. Data Synthesis



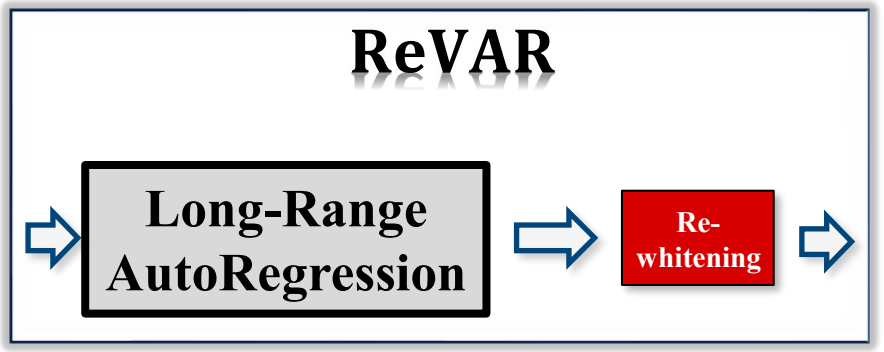
Presentation Outline

1. Measured Data Sets





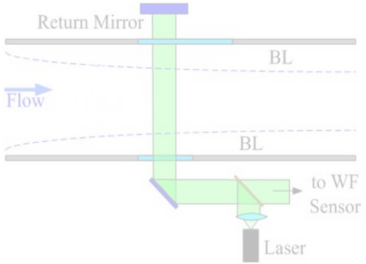
2. **ReVAR**

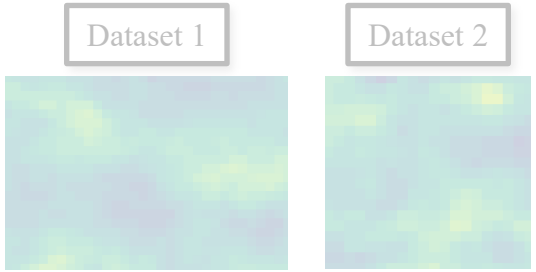


3. Results

Presentation Outline

1. Measured Data Sets

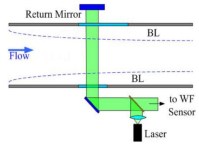




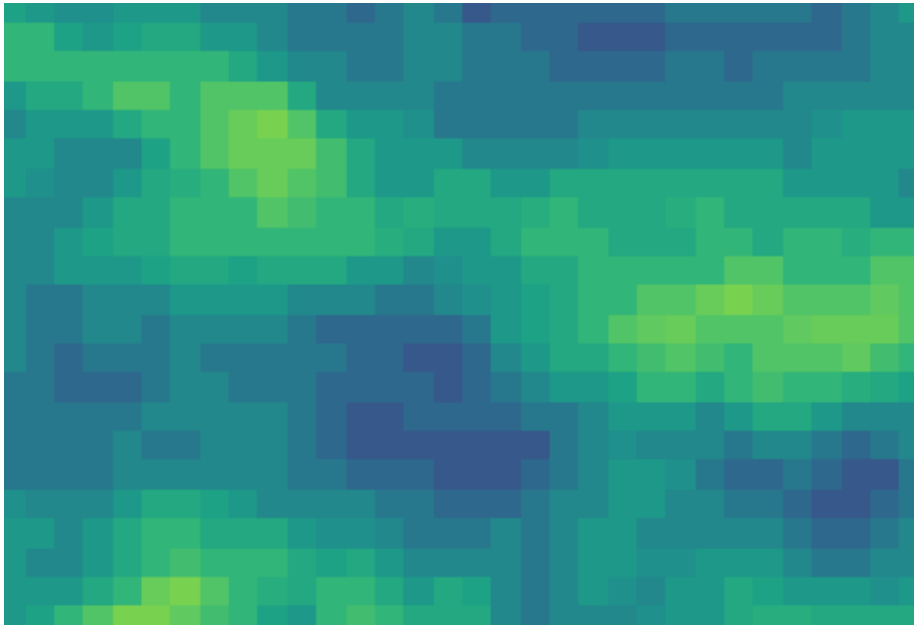
2. ReVAR

3. **Results**

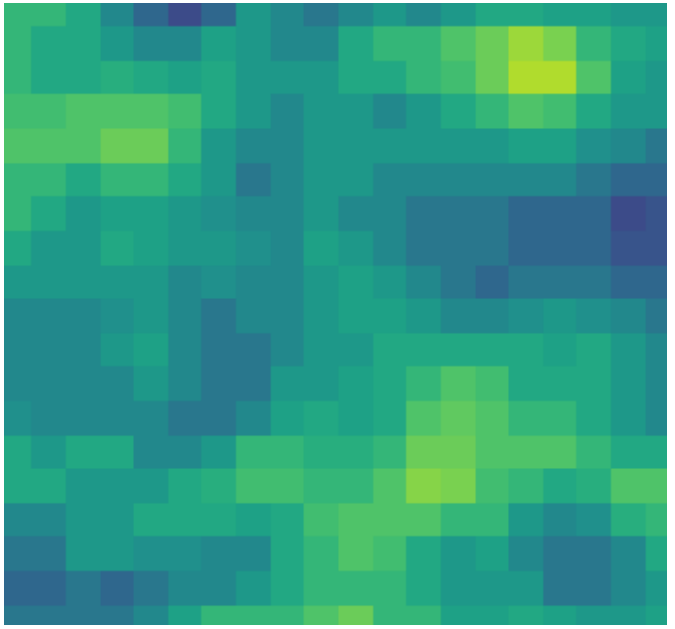
Measured Data: Wind Tunnel Experiment



Dataset 1

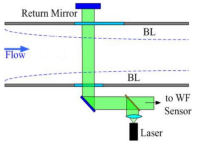


Dataset 2

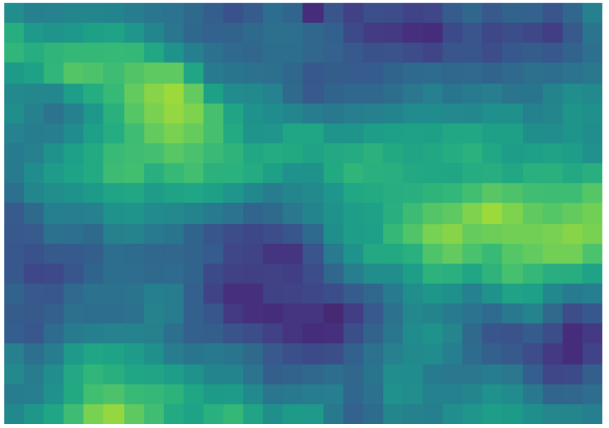


[3] M. R. Kemnetz and S. Gordeyev, "Optical investigation of large-scale boundary-layer structures", *54th AIAA Aerospace Sciences Meeting*, 4 - 8 Jan 2016, San Diego, California, AIAA Paper 2016-1460.

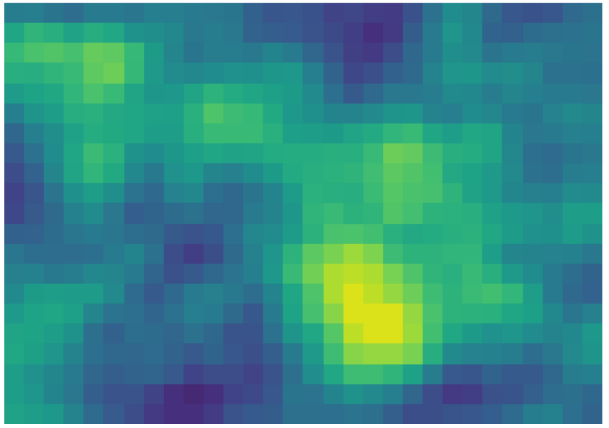
Results: Dataset 1



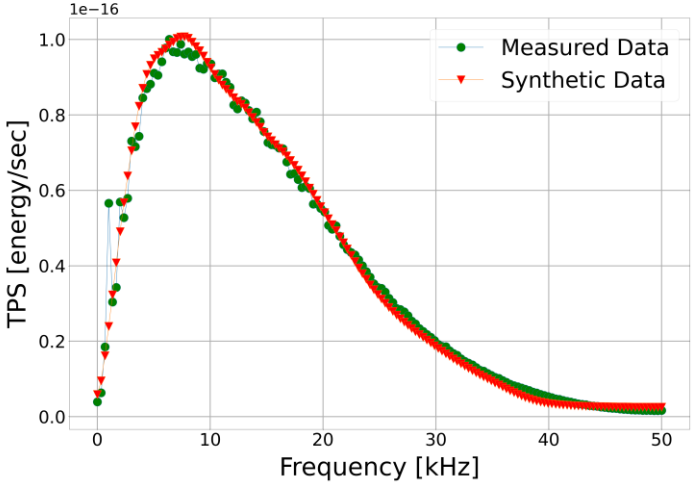
Measured data



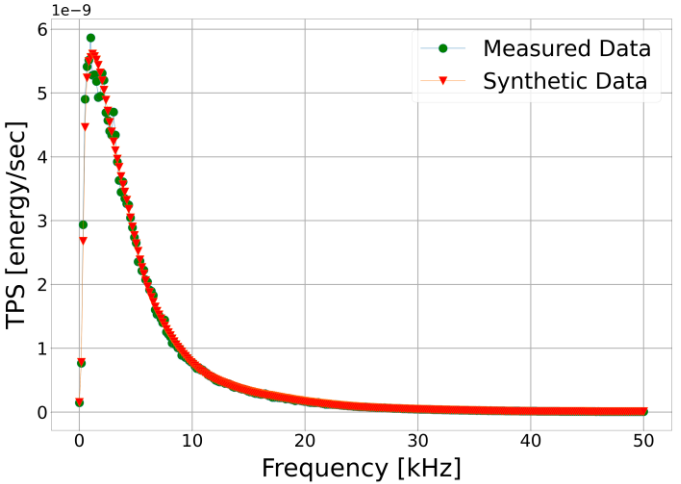
Synthetic data



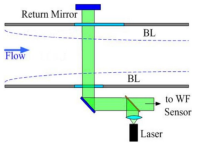
Temporal Power Spectrum: Streamwise Slopes



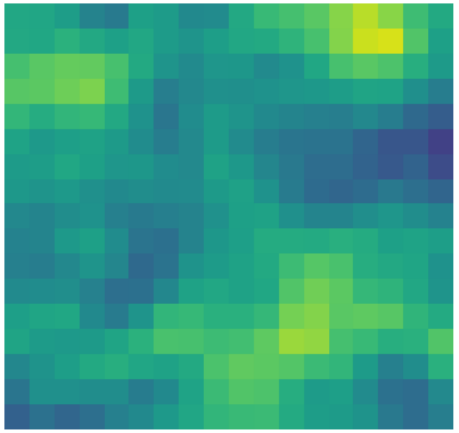
Temporal Power Spectrum: Phase Screens



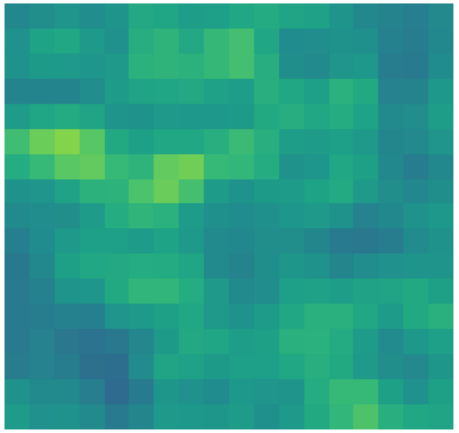
Results: Dataset 2



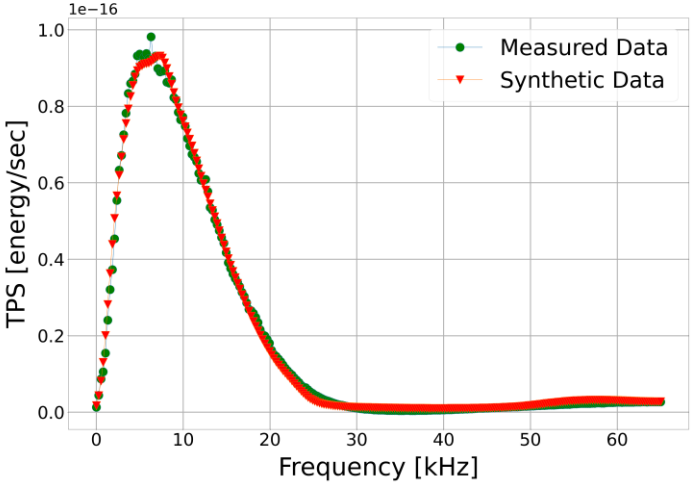
Measured data



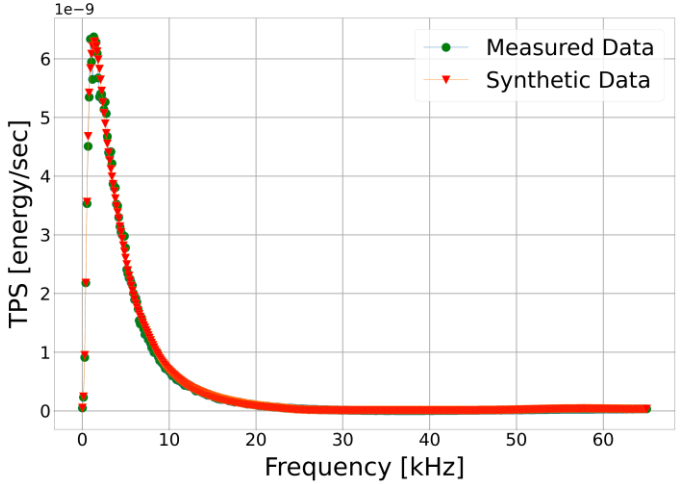
Synthetic data



Temporal Power Spectrum: Streamwise Slopes

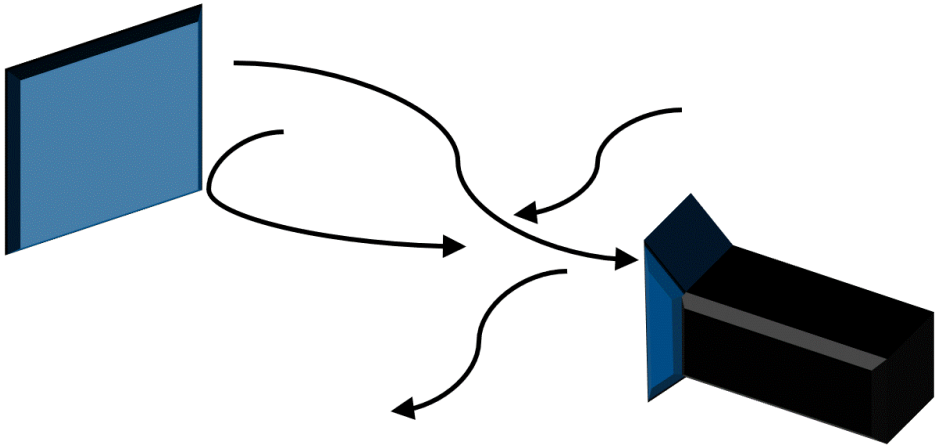


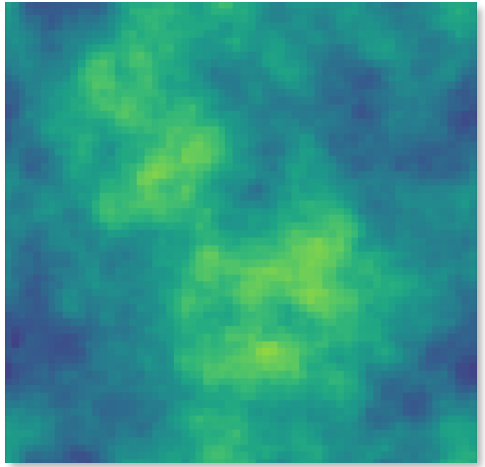
Temporal Power Spectrum: Phase Screens



Summary

- Aero-optic effects **degrade** imaging and communication **performance** from a high-speed aircraft.
- We **need aero-optic data** to develop AO systems, but *existing* ways of getting this data have ***significant drawbacks***.

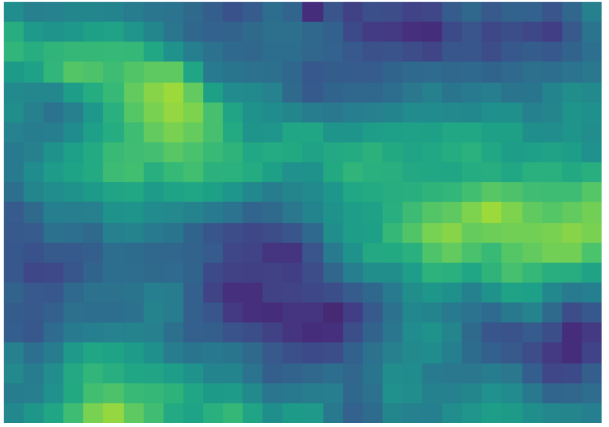




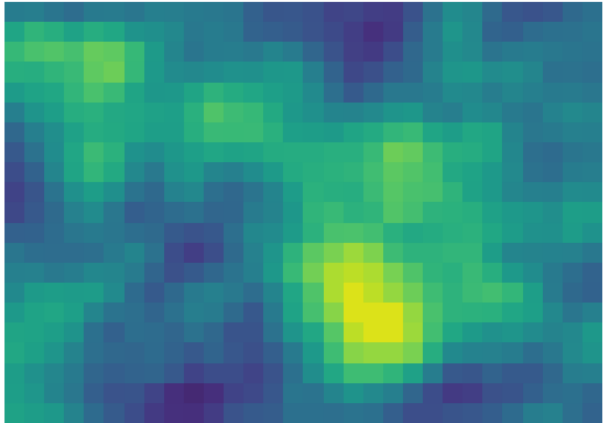
Conclusion

We introduce **ReVAR**: a data-driven algorithm that generates aero-optic data which match the statistics of measured data.

Measured data



Synthetic data



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] Steinbock, M. J. (2012). *Implementation of branch-point-tolerant wavefront reconstructor for strong turbulence compensation* (No. AFITGEENG1245)

[3] 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.