Assimilation of CYGNSS Delay-Doppler Maps by a Two- Dimensional Variational Analysis Method

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Outline

- 2D Variational Analysis Method (VAM)
- DDM forward model
- DDM assimilation result
- Summary
- Future work

2D Variational Analysis Method

- **Motivation:**
  - The direct measurement of CYGNSS is a 17×11 DDM (power)
  - CYGNSS baseline wind speed retrieval uses 3×5 window near the specular bin – lose much potential information from the measurement
  - CYGNSS 25 km wind speed retrieval is only at the specular point

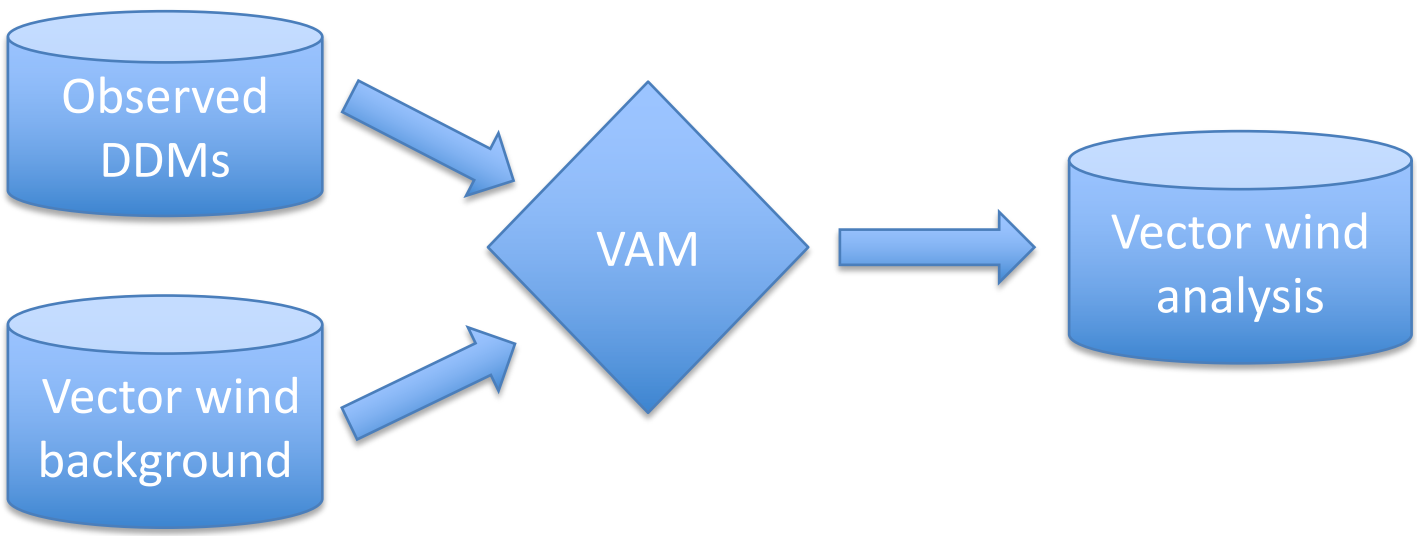
- **Goal:** direct assimilation of DDM into hurricane models using a forward model and Variational Analysis Method (VAM)
  - Use all information of the direct measurement
  - Can impact a non-uniform grid of wind speed with higher resolution

2D Variational Analysis Method

Two-dimensional Variational Analysis Method (VAM):

[Hoffman1982, 1984]

- VAM is a tool to assimilate measurements into wind vector field
- The observed DDMs are related to gridded wind speed by the forward model



2D Variational Analysis Method

- **VAM** finds the minimum of the objective cost function:

$$J(\boldsymbol{x}) = J_b(\boldsymbol{x}) + J_{ddm}(\boldsymbol{x}) + J_c(\boldsymbol{x})$$

- $J_b(\boldsymbol{x}) = \lambda_b \sum_{i=1}^{N} \frac{\left(x_i - x_i^b\right)^2}{\sigma_x^2}$ - **misfit between analysis and background**

- $J_{ddm}(\boldsymbol{x}) = \lambda_{ddm}(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y})^T R^{-1}(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y})$ - **misfit between analysis and observation**

  $\boldsymbol{y}$ - DDM observation; $\boldsymbol{h}(\boldsymbol{x})$ - simulated DDM; R - DDM covariance matrix

- $J_c(\boldsymbol{x})$ - **smoothness and physical constraints** including divergence, vorticity and Laplacian

2D Variational Analysis Method

- **VAM** finds the minimum of the objective cost function:

$$J(\boldsymbol{x}) = J_b(\boldsymbol{x}) + J_{ddm}(\boldsymbol{x}) + J_c(\boldsymbol{x})$$

To minimize it, the gradient of $J(\boldsymbol{x})$ has to be computed:

$$J_{ddm}(\boldsymbol{x}) = \lambda_{ddm}(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y})^T R^{-1}(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y})$$

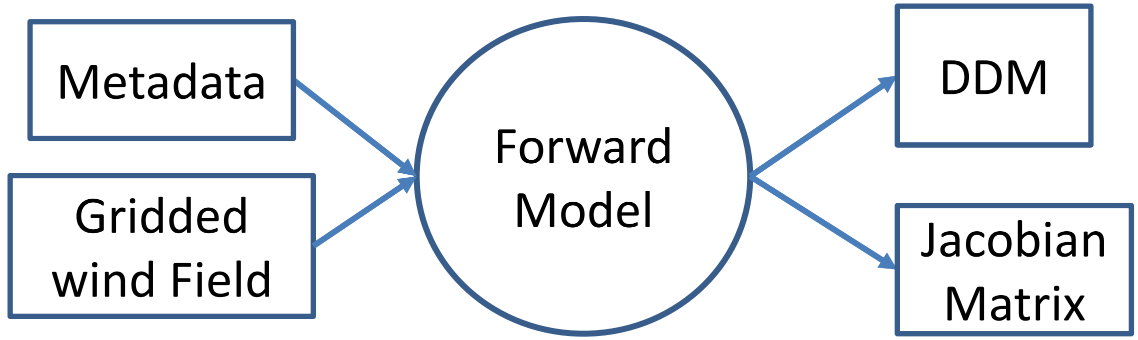
$$\frac{\partial J_{ddm}}{\partial \boldsymbol{x}} = 2H^T R^{-1}(\boldsymbol{h}(\boldsymbol{x}) - \boldsymbol{y})$$

So we need a DDM forward model for:

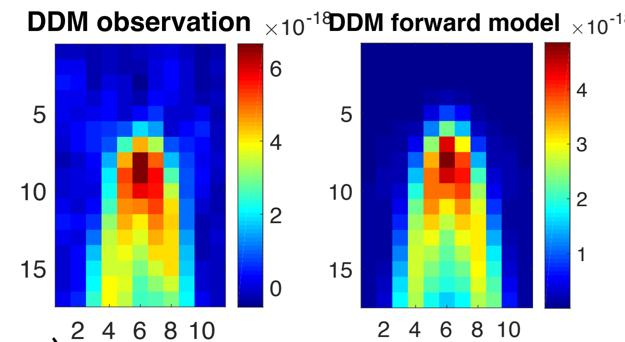
- $\boldsymbol{h}(\boldsymbol{x})$ - simulated DDM
- $H = \frac{\partial \boldsymbol{h}(\boldsymbol{x})}{\partial \boldsymbol{x}}$ - Jacobian matrix

DDM forward model

- Input:
  - Gridded wind field, $\boldsymbol{m}$
  - Metadata
- Output:
  - DDM, $h(\tau, f)$
  - Jacobian matrix, H



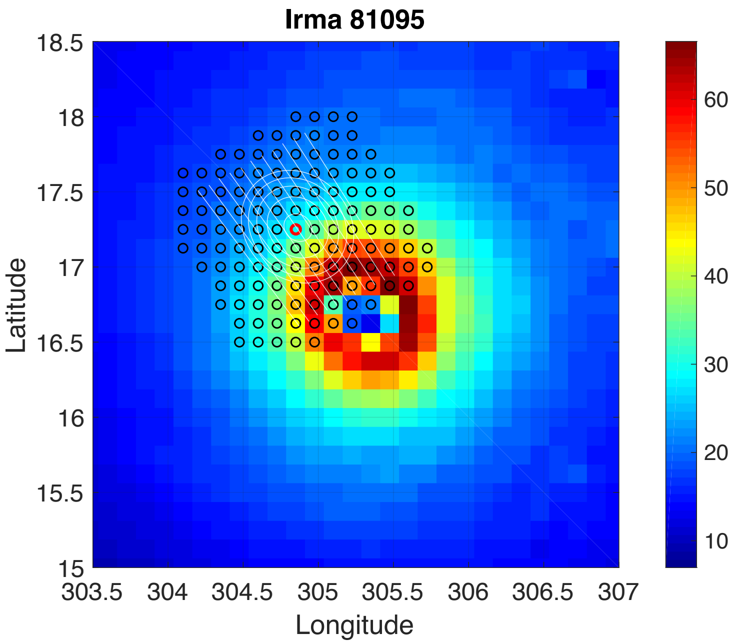
- Forward operator: $h(\tau, f, \boldsymbol{m}) = \frac{\lambda^2 P_t}{(4\pi)^3} \sum \frac{G_t(\overrightarrow{\rho_i}) G_r(\overrightarrow{\rho_i})}{R_t^2(\overrightarrow{\rho_i}) R_r^2(\overrightarrow{\rho_i})} \times \chi^2(\Delta\tau, \Delta f) \sigma^0(\overrightarrow{\rho_i}, m_i) dS_i$



- Jacobian matrix: $H = \begin{pmatrix} \frac{\partial h(\tau_1, f_{d_1}, \boldsymbol{m})}{\partial m_1} & \cdots & \frac{\partial h(\tau_1, f_{d_1}, \boldsymbol{m})}{\partial m_M} \\ \vdots & \ddots & \vdots \\ \frac{\partial h(\tau_N, f_{d_N}, \boldsymbol{m})}{\partial m_1} & \cdots & \frac{\partial h(\tau_N, f_{d_N}, \boldsymbol{m})}{\partial m_M} \end{pmatrix}$

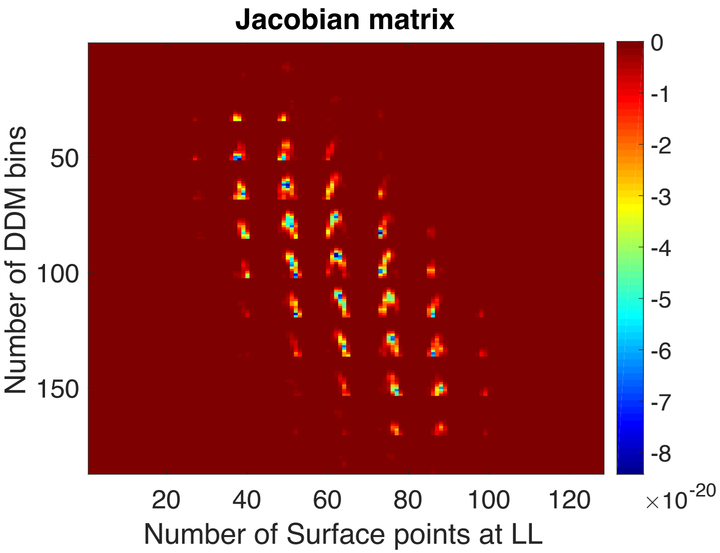
DDM forward model

- Jacobian matrix: sensitivity between grid points and DDM bins:



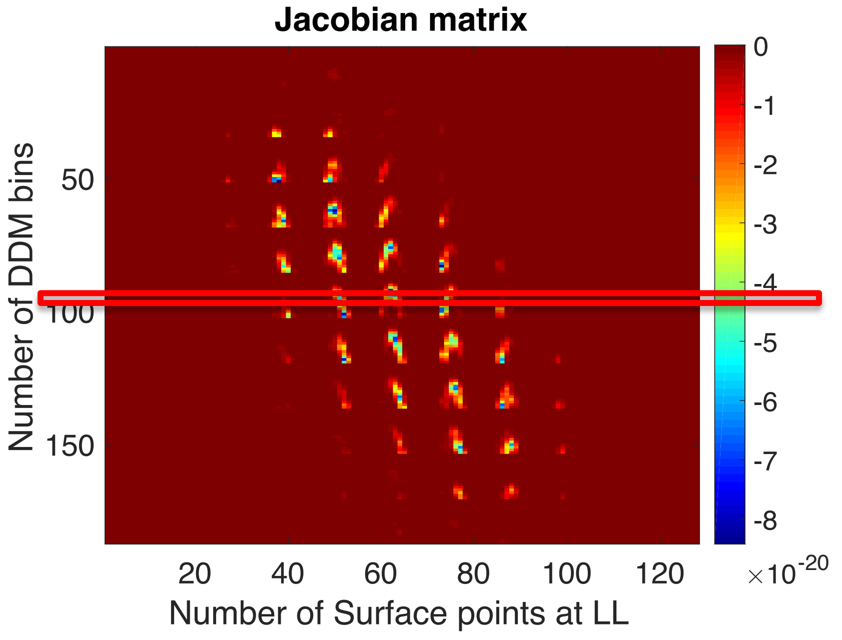
0.1 degree grid

$$H = \begin{pmatrix} \frac{\partial h(\tau_1, f_{d_1}, \boldsymbol{m})}{\partial m_1} & \cdots & \frac{\partial h(\tau_1, f_{d_1}, \boldsymbol{m})}{\partial m_M} \\ \vdots & \ddots & \vdots \\ \frac{\partial h(\tau_N, f_{d_N}, \boldsymbol{m})}{\partial m_1} & \cdots & \frac{\partial h(\tau_N, f_{d_N}, \boldsymbol{m})}{\partial m_M} \end{pmatrix}$$



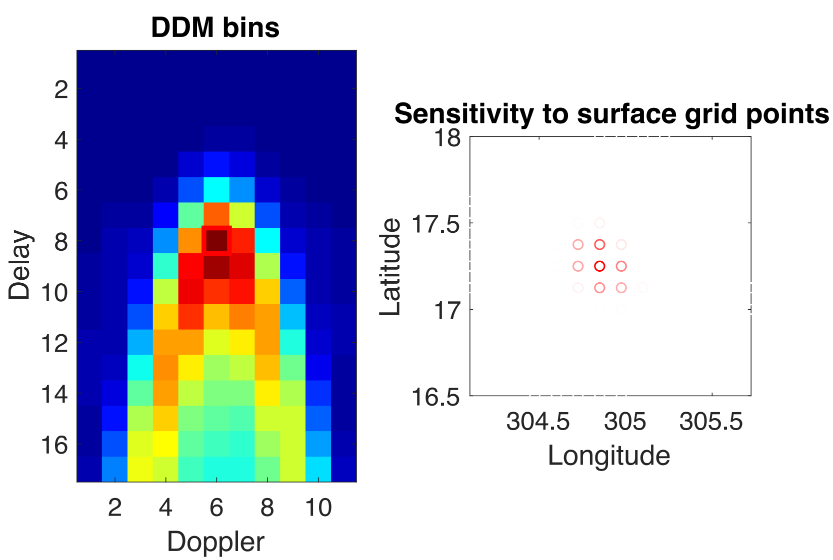
DDM forward model

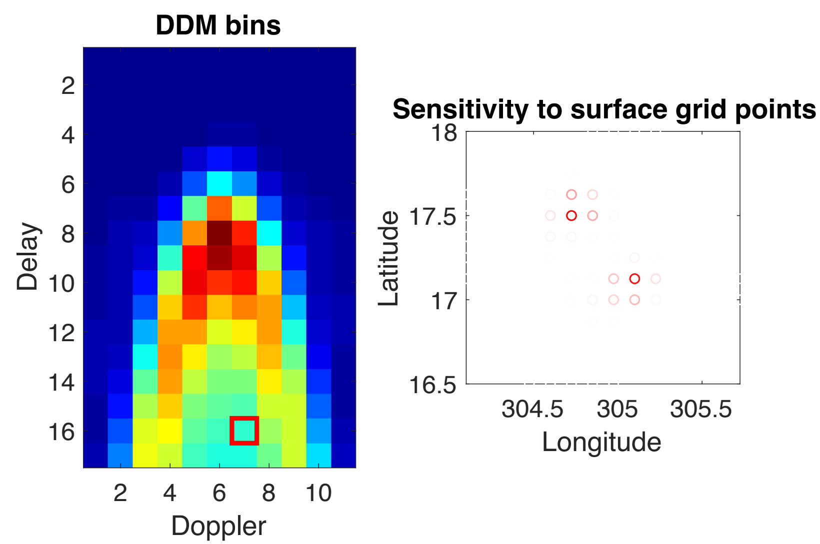
- Sensitivity of wind speed on the grid points respect to a DDM bin power
- Pick up a row



DDM forward model

- Sensitivity of wind speed on the grid points respect to a DDM bin power

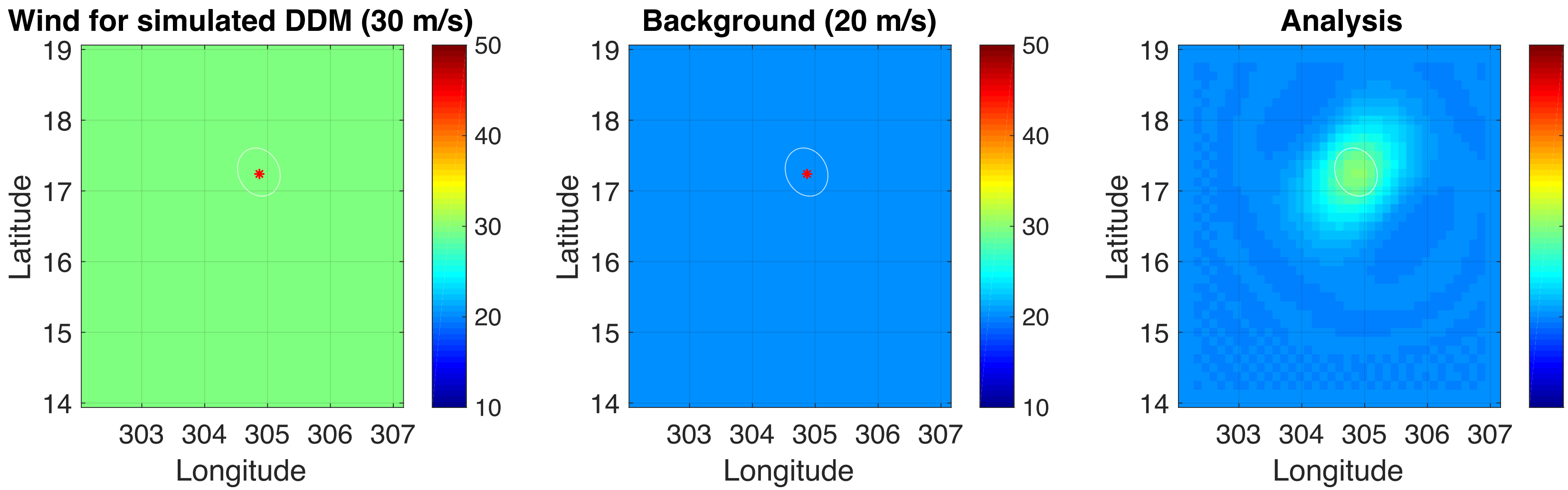




Delay-Doppler ambiguity

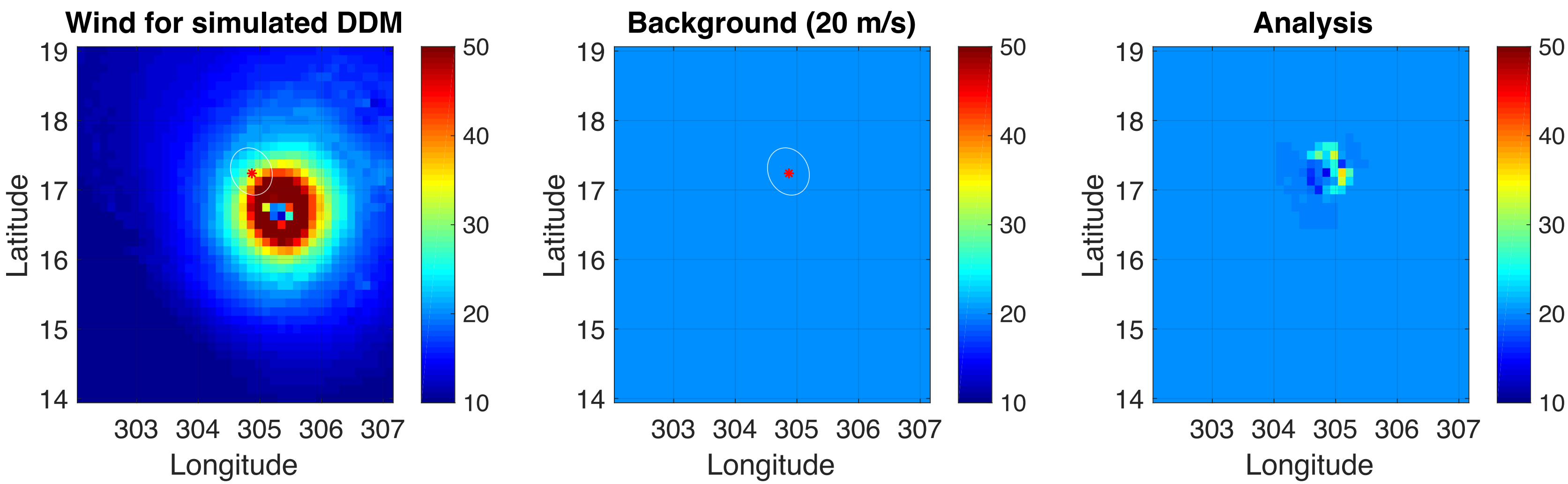
DDM assimilation result

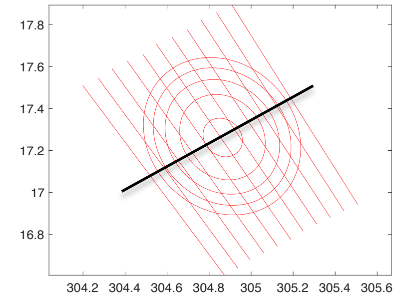
- Test on simulated data – assimilate a regular (17×11) DDM
- A simple case with uniform wind field



DDM assimilation result

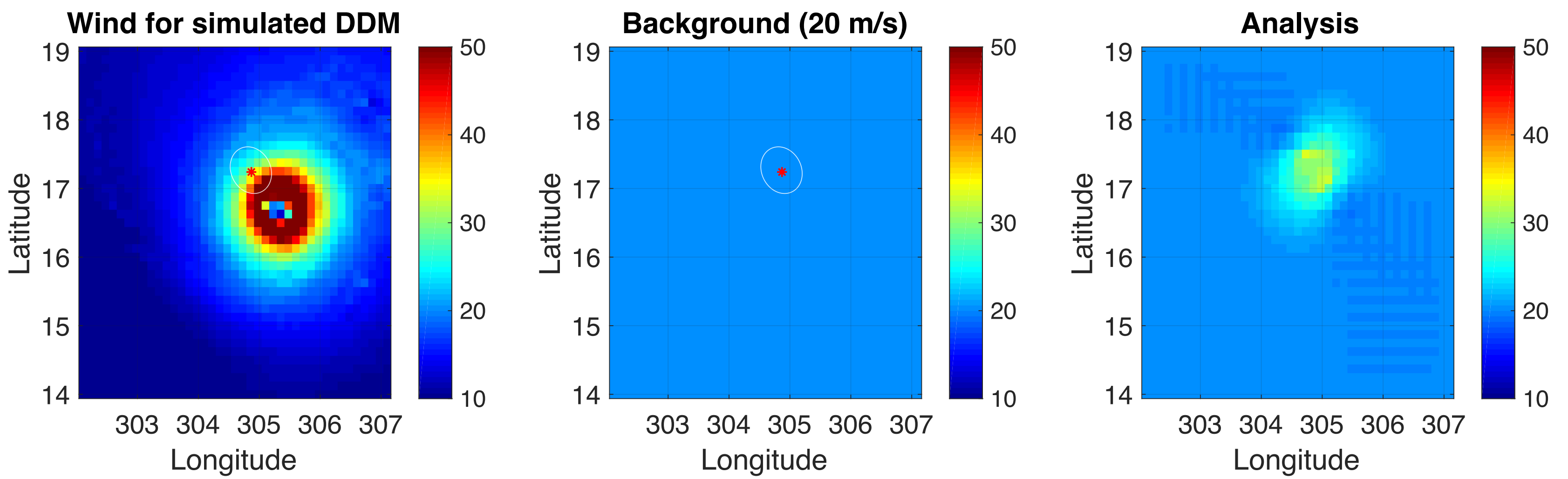
- Test on simulated data – assimilate a regular (17×11) DDM
- With no physical constraint terms (divergence, vorticity, Laplacian)





DDM assimilation result

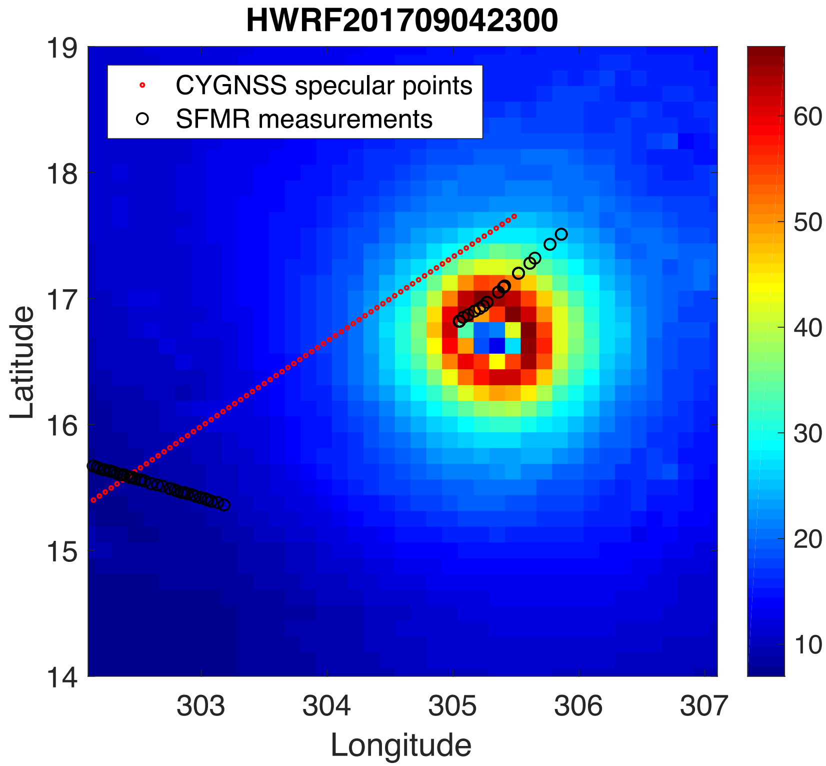
- Test on simulated data – assimilate the regular (17×11) DDM
- Add physical constraint terms (divergence, vorticity, Laplacian)



- The physical constrain terms smooth the result and extend it to a larger area but ambiguity still exists

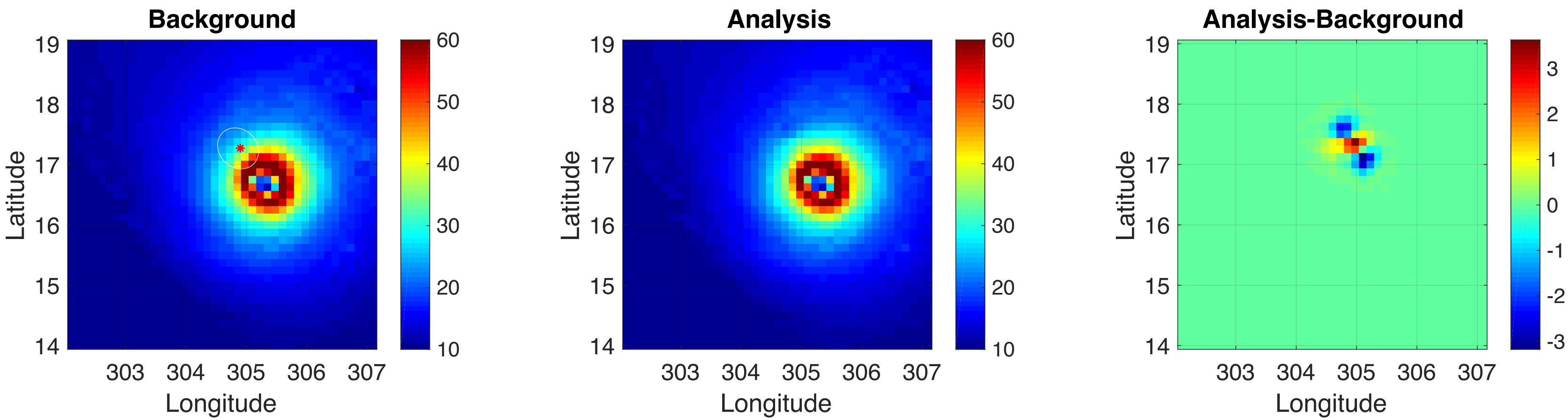
DDM assimilation result

- Test on real CYGNSS data – Hurricane Irma at 201709052300
  - Background: HWRF 5h forecast
  - Result validated by SFMR measurement



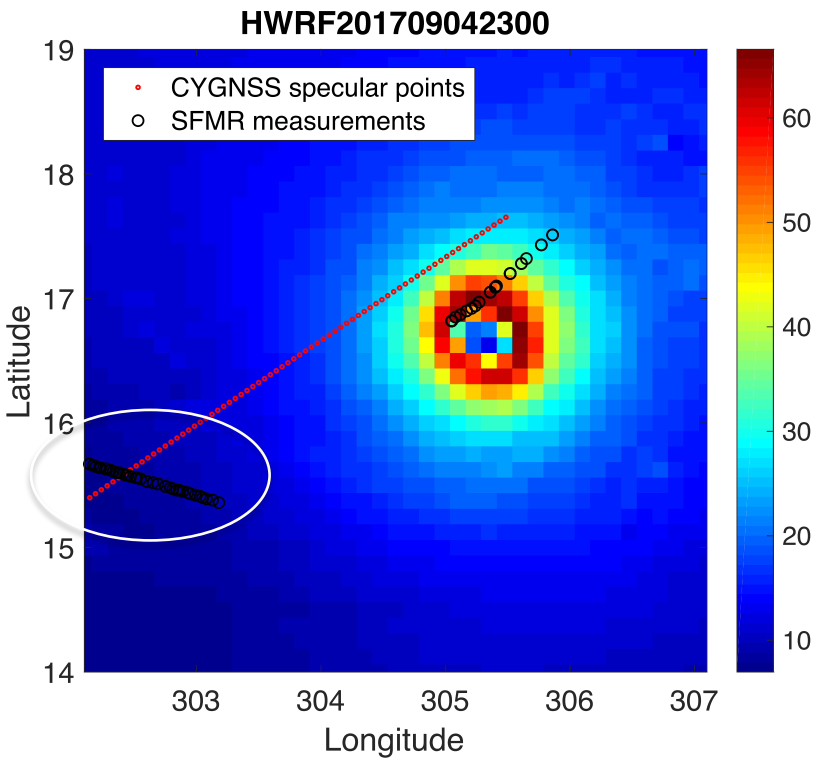
DDM assimilation result

- Test on real CYGNSS data – Hurricane Irma at 20170905z00
- Assimilate one DDM (17×11)



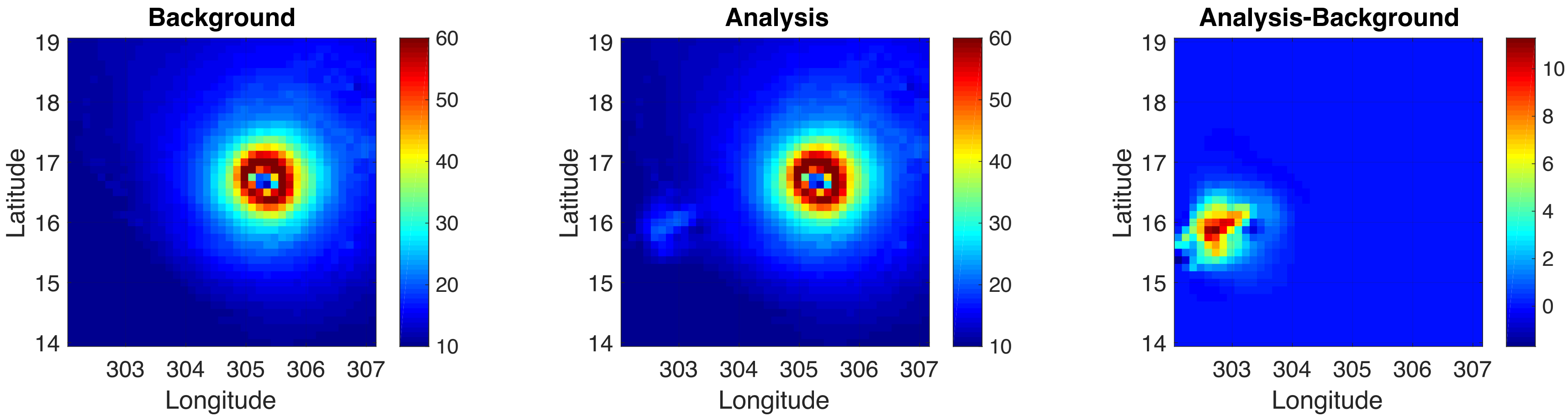
DDM assimilation result

- Assimilate a series of DDMs (17×11)
- low wind speed case

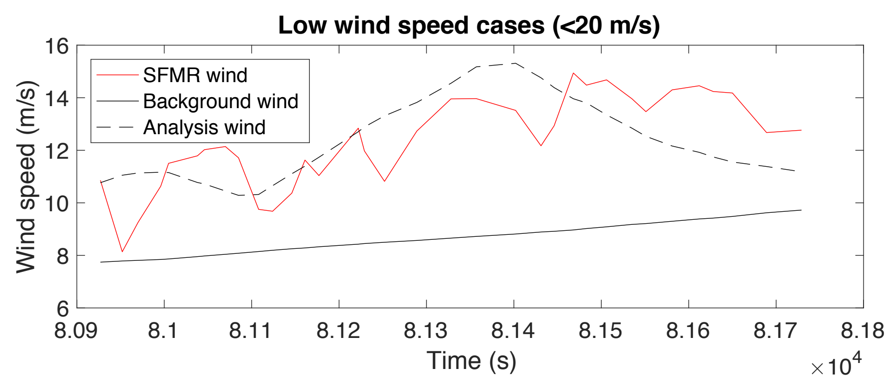


DDM assimilation result

- Assimilate a series of DDMs (17×11)
- low wind speed case

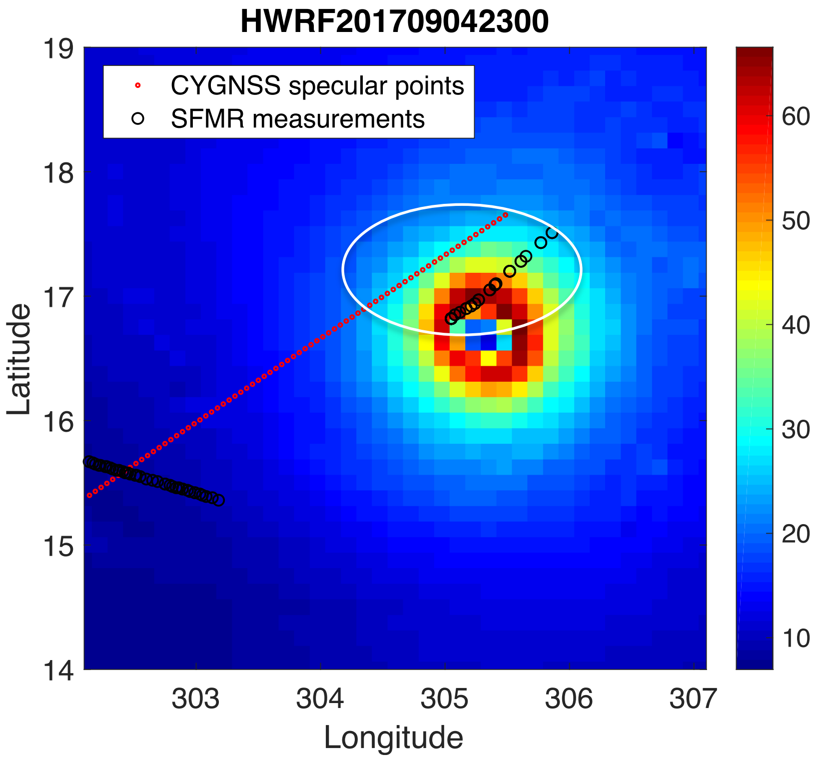


- Background RMS = 3.96
- Analysis RMS = 1.52



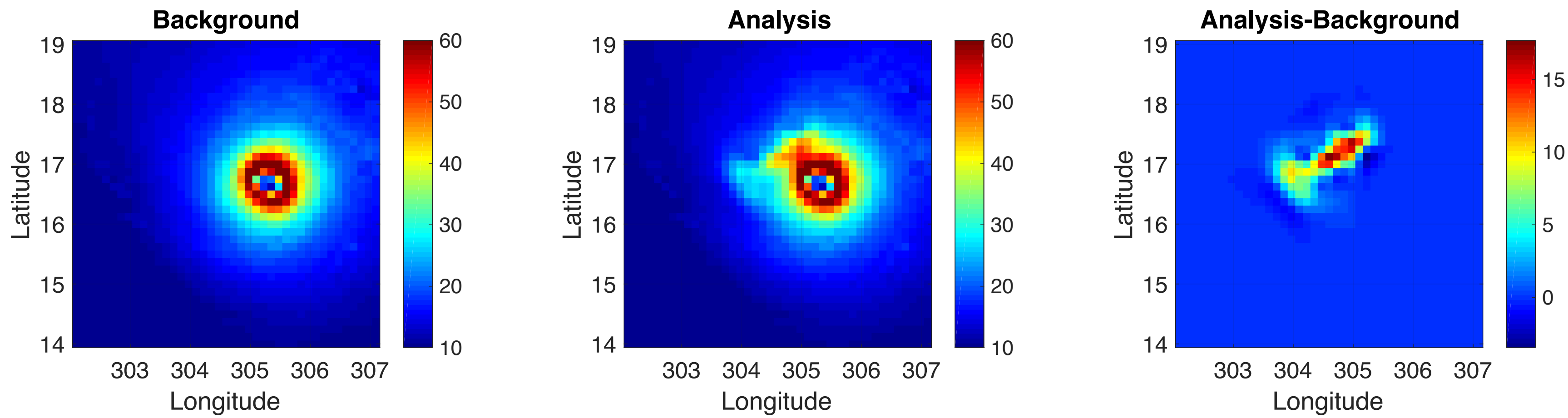
DDM assimilation result

- Assimilate a series of DDMs (17×11)
- high wind speed case

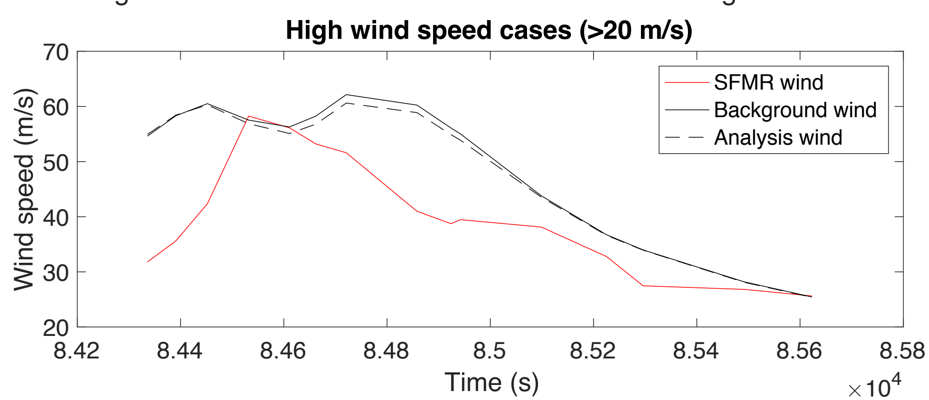


DDM assimilation result

- Assimilate a series of DDMs (17×11)
- high wind speed case

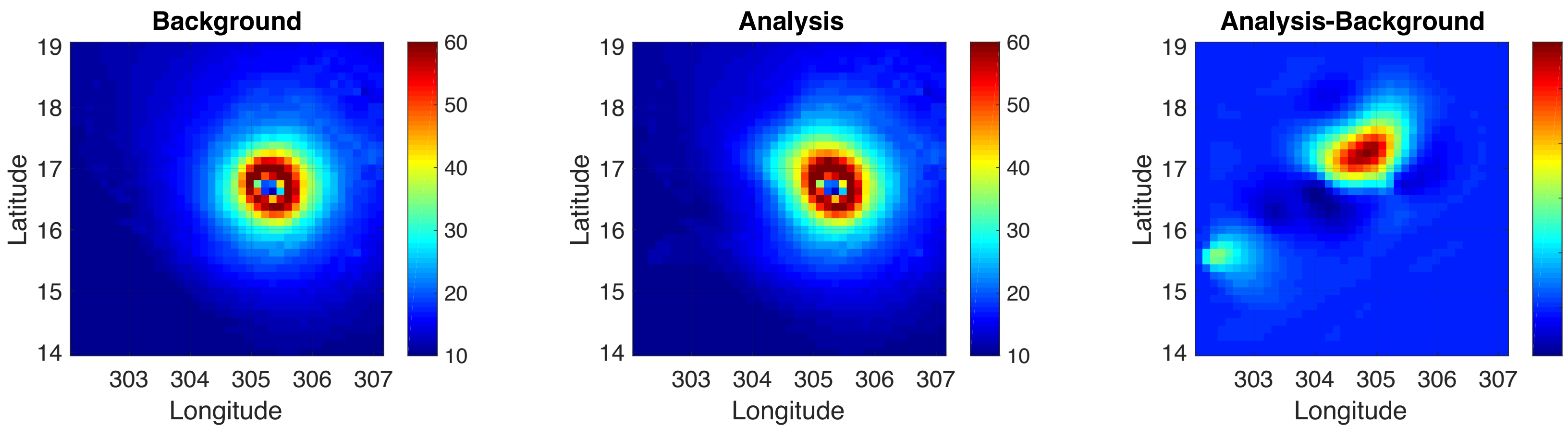


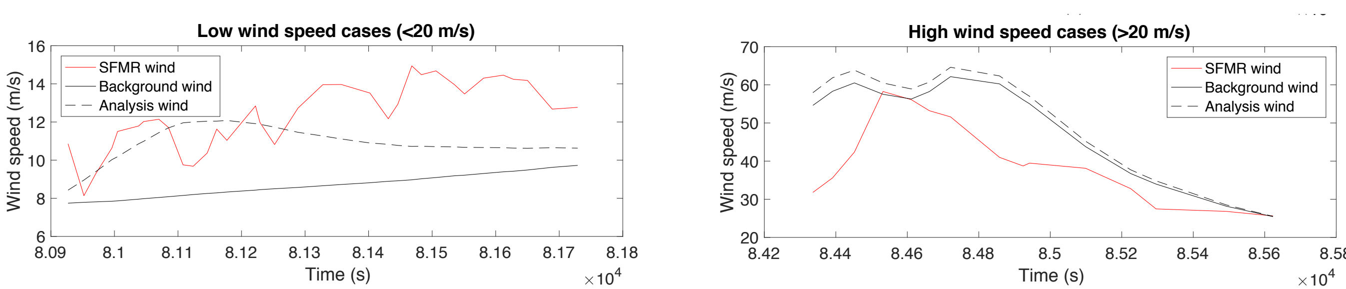
- Background RMS = 12.93
- Analysis RMS = 12.51



DDM assimilation result

- Assimilate a track of DDM (only specular bin)
- Avoid delay-Doppler ambiguity





Summary

- A variational analysis method (VAM) is used to assimilate DDMs into a wind vector field.
- Assimilation result using CYGNSS DDM observations shows improvement when comparing with the SFMR measurements
- The delay-Doppler ambiguity can impact the assimilation result when using the regular 17×11 DDM

Future work

- Study use of DDM measurements on the Ambiguity-free line
- Quality control on the observed DDMs
  - Speckle noise
  - Specular delay/Doppler shift
- Develop a model for DDM covariance
  - Accounting for wind speed, transmitter power, antenna pattern, incidence angle
- Process a larger set of data and validate the result by ASCAT