Lidar-Measurement-Integrated Simulation of Wake Turbulence

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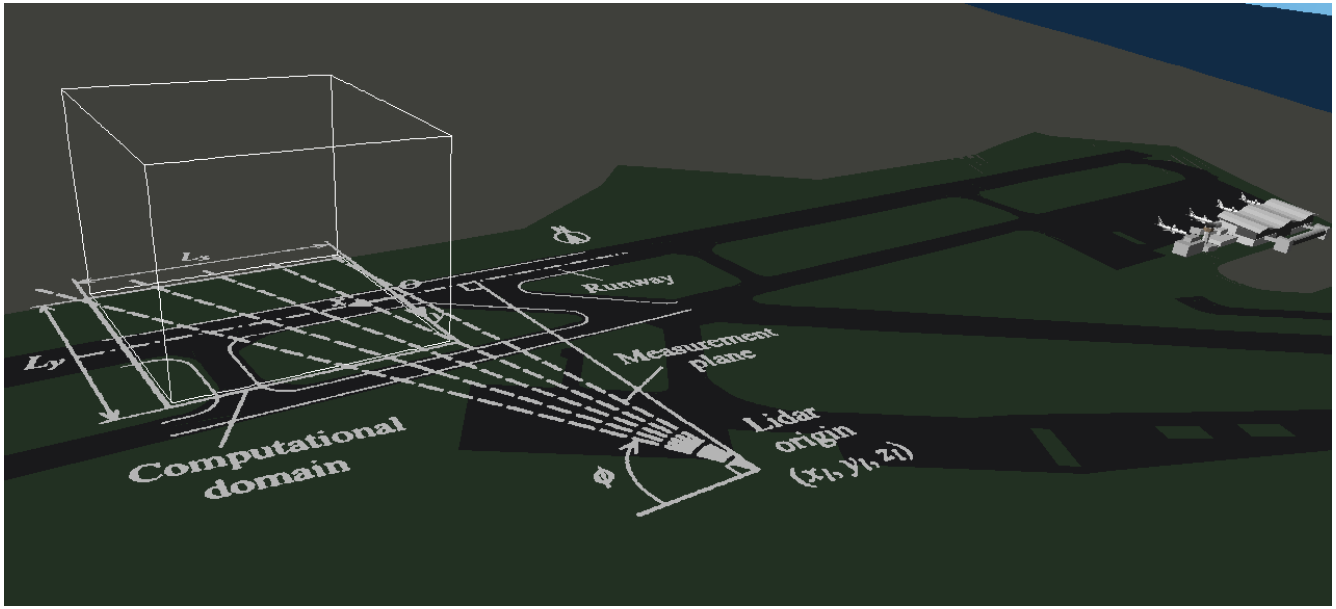
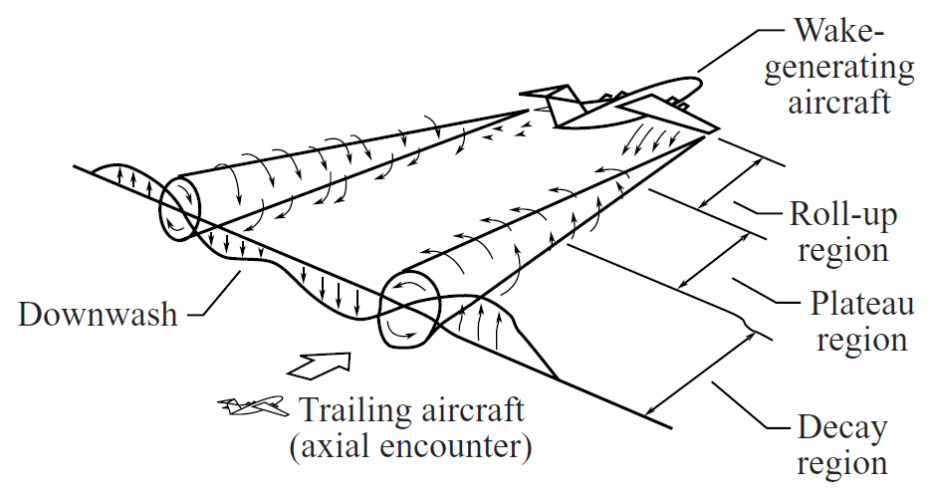
EULAG Model Users' Workshop
October 7th, 2008

Outline

- Wake turbulence: measurement & simulation
- Objective of this research
- Lidar data assimilation with 4D-Var method
- Results using lidar measurements at Sendai airport
- Conclusion



Background – Wake turbulence –



J. R. Chambers, NASA SP-2003-4529

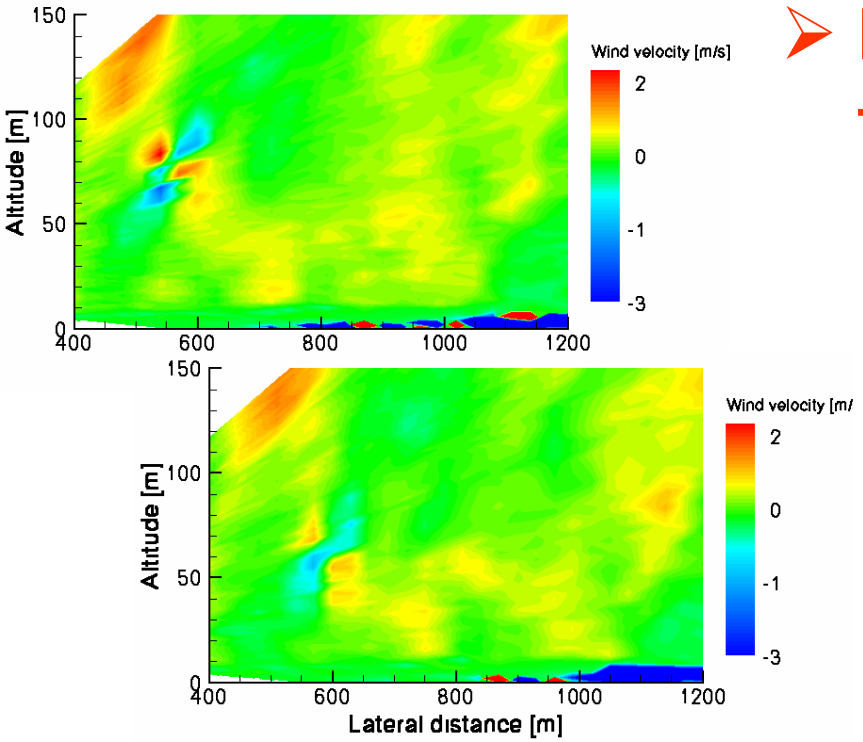
- Vortices mainly due to wing-tip and flap vortices
- Determine takeoff and landing separation at airport

- **Need for efficient control of airport traffic based on weather conditions including wake turbulence**

Queue for takeoff at Narita Airport in Japan

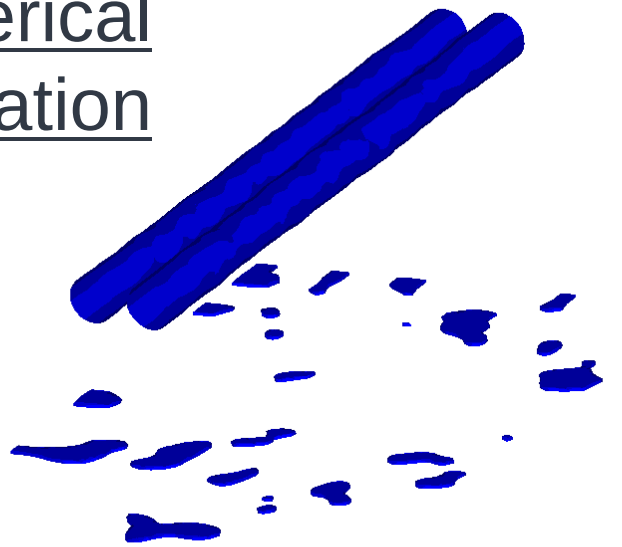
Background – Measurement and Simulation –

- Lidar measurement



- **Lack of spatial resolution and three-dimensional information**

- Numerical simulation



- **Difficulty in incorporating actual condition, e.g. ambient winds**

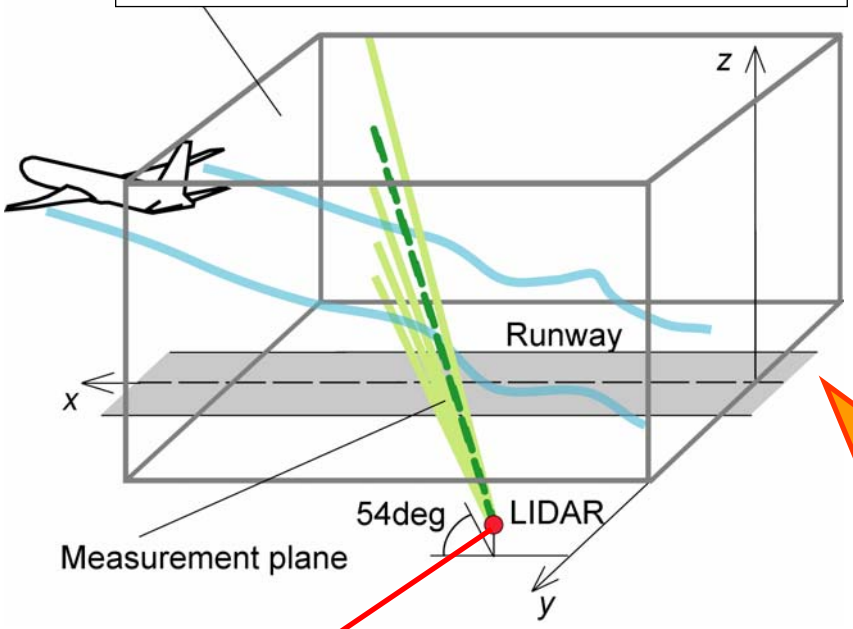
Objective

Simulate wake vortices under actual weather conditions based on lidar measurement with four-dimensional variational (4D-Var) method

- Approach: 4D-Var + Bogus vortex technique
- Validation: Assimilation exp. using virtual lidar data
- Application: Lidar measurements at Sendai airport

Overview of the Method

Large eddy simulation

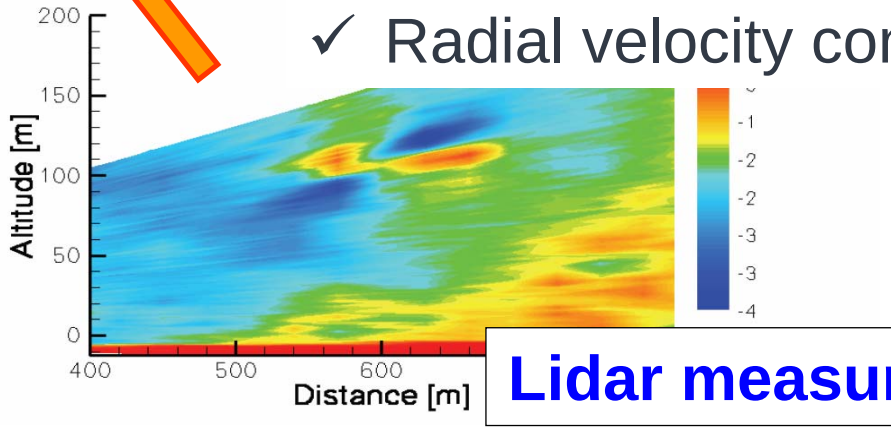


- ✓ Compressible Navier-Stokes Eqs.
- ✓ Computational domain: ～1km
- ✓ Mesh spacing: several meters to resolve vortex core

Data assimilation using four-dimensional variational method (4D-Var)

Lidar (ENRI)

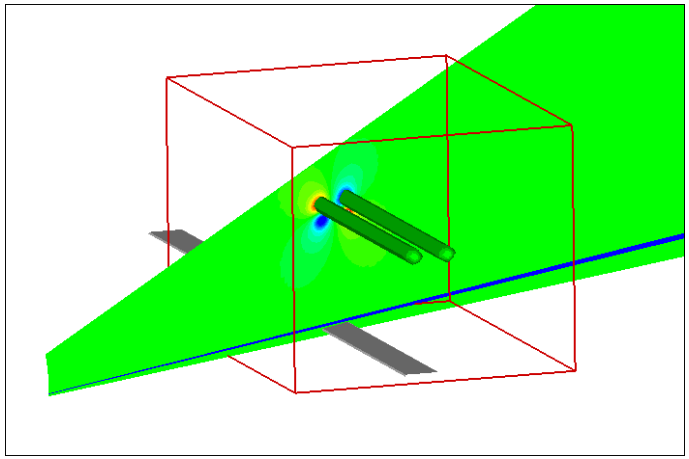
- ✓ Radial velocity component



Lidar measurements

4D-Var with Lidar Measurement (1)

➢ **Flowchart of 4D-Var method**



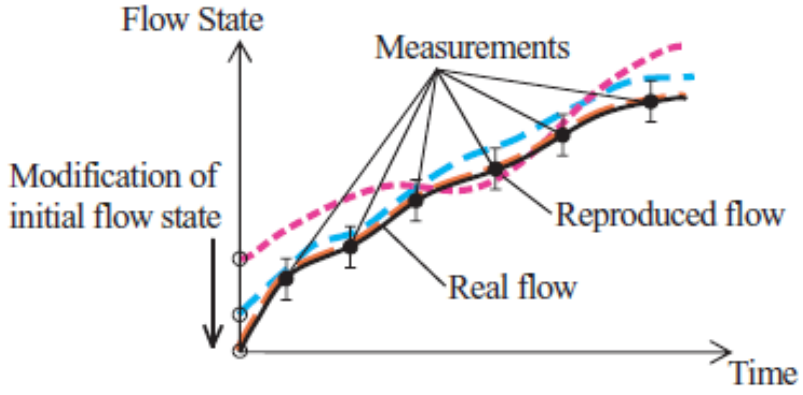
1. Simulate lidar measurement process during CFD computation (Acquiring virtual lidar measurement)

2. The difference is defined as a cost function:

$$J_L(\mathbf{Q}_0) = \frac{1}{2}\sum_{i=0}^{N}\left(H_i(\mathbf{Q}_i) - \mathbf{Y}_i\right)^T R_i^{-1}\left(H_i(\mathbf{Q}_i) - \mathbf{Y}_i\right)$$

3. Minimization of the cost function using adjoint equation method

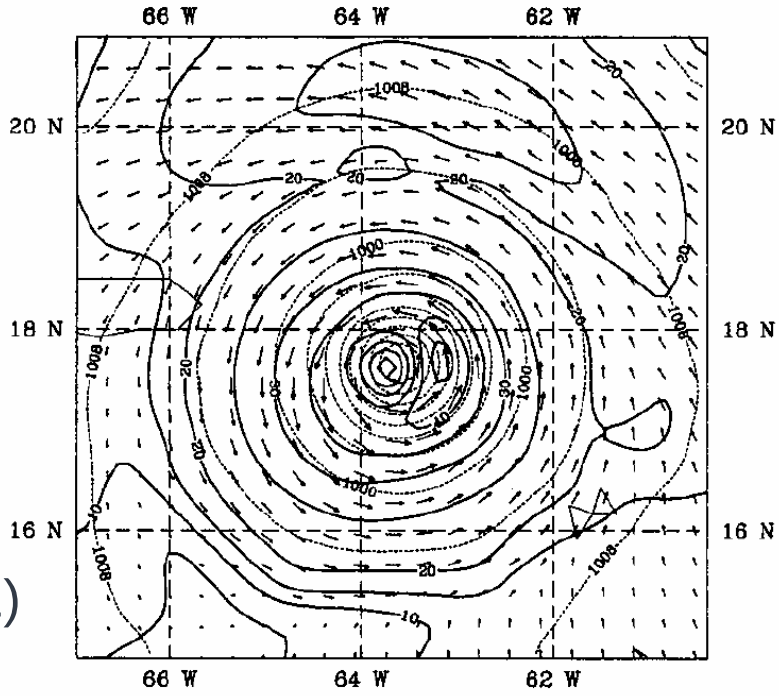
→ **Retrieval of unsteady flow field which agrees with time-series lidar measurements**



4D-Var with Lidar Measurement (2)

Bogus vortex technique: **assume a specific vortex structure in the flow field**

$$J_T(\mathbf{Q}_0, \mathbf{P}_v) = J_L(\mathbf{Q}_0) + \frac{1}{2}\left[\mathbf{Q}_0 - F_v(\mathbf{P}_v)\right]^T B^{-1}\left[\mathbf{Q}_0 - F_v(\mathbf{P}_v)\right]$$



Used to initialize a Hurricane:

Pu *et al. Monthly Weather Review* (2001)

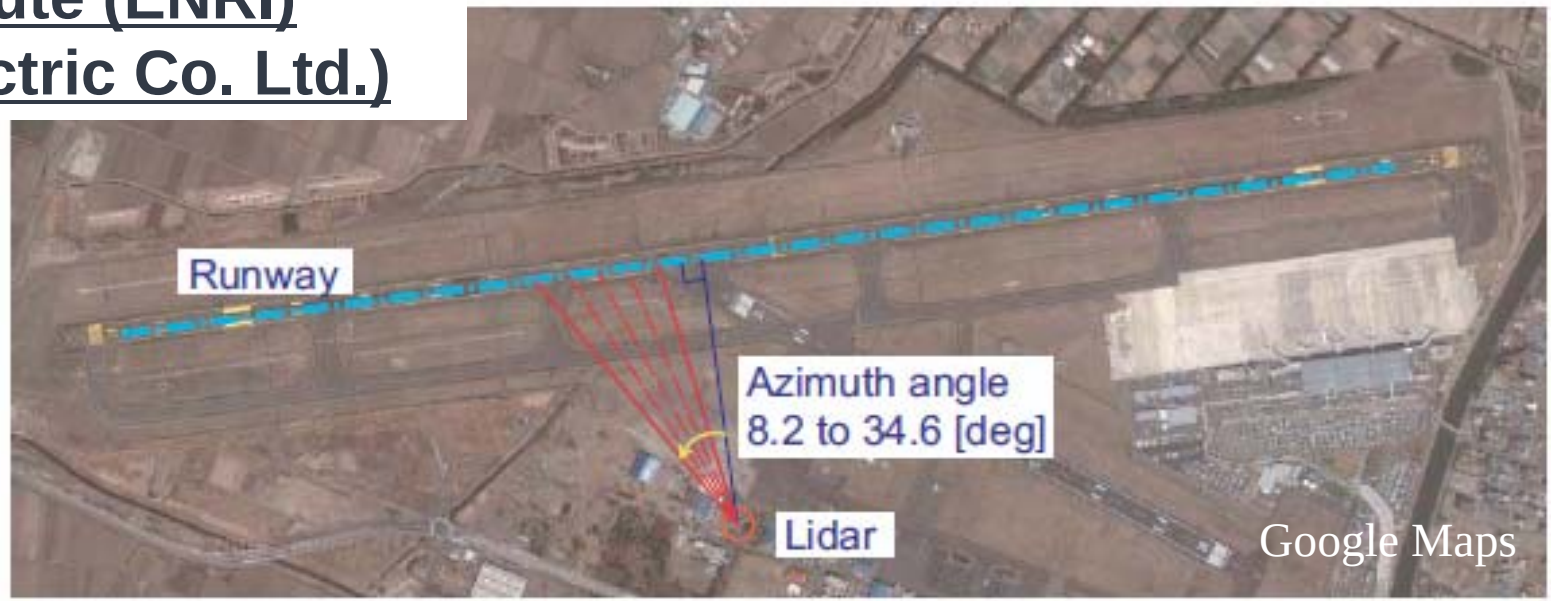
- Bogus vortex compensates insufficient velocity information due to line-of-site measurement of lidar

Sendai Airport

Lidar at Sendai Airport

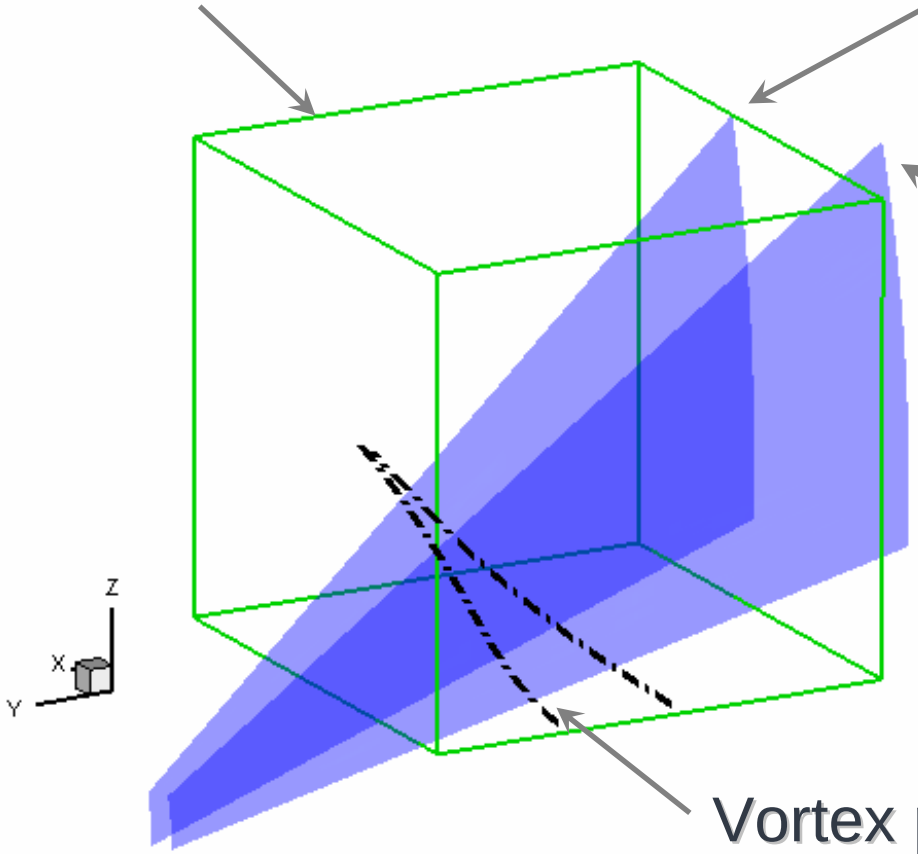
- ✓ Pulsed Doppler lidar
- ✓ 80 ranges with 30m interval
- ✓ Laser wave length: 1.5μm
- ✓ Laser power: 2W (average)
- ✓ Laser repetition freq: 4kHz

Owned by **Electric Navigation Research Institute (ENRI) (Mitsubishi Electric Co. Ltd.)**

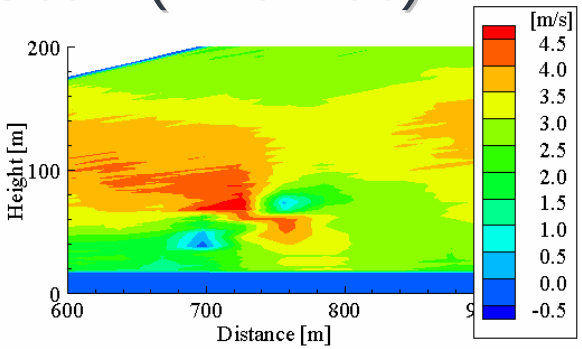


Computational Setting

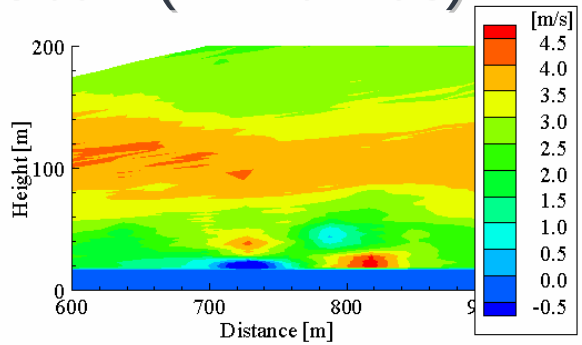
Computational domain
(400m^3 cube)



1st Scan (*T*=0-20s)

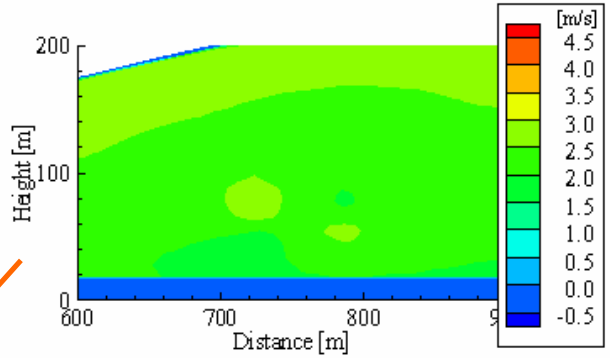


2nd Scan (*T*=20-40s)

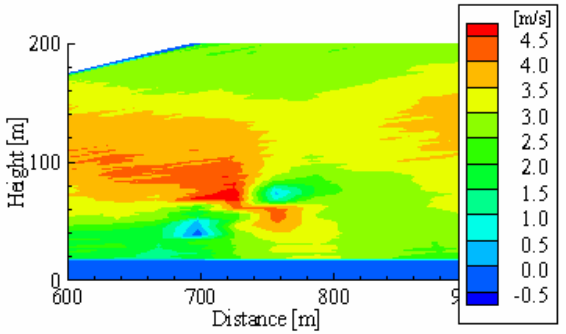


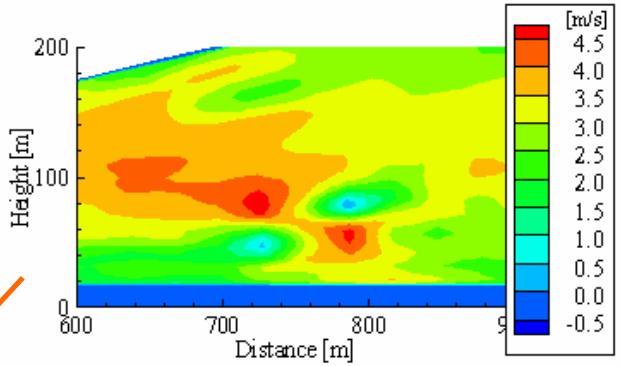
Vortex position is set as initial parameter of bogus vortex

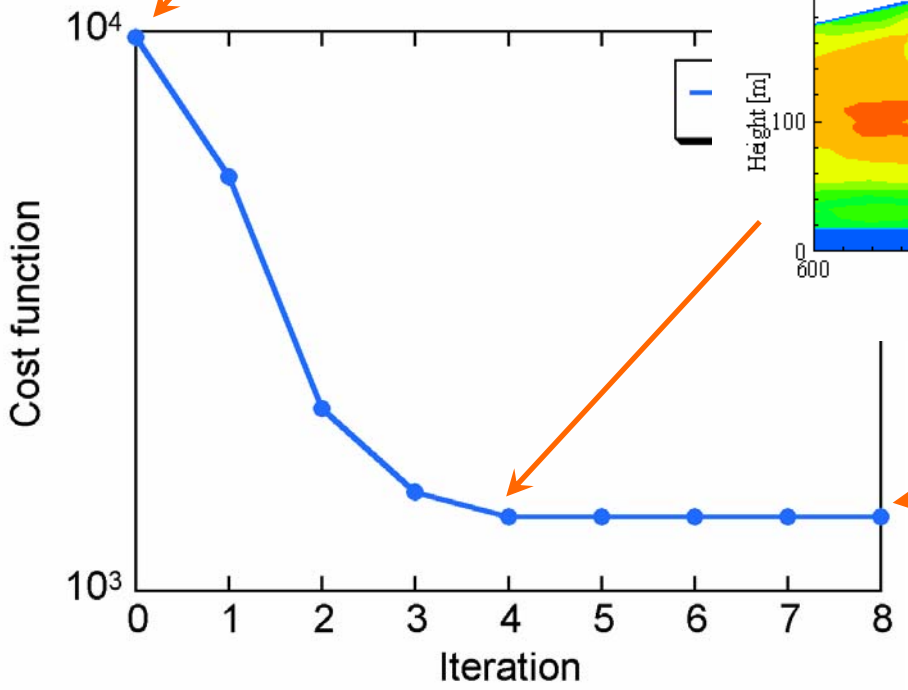
Velocity on Measurement Plane

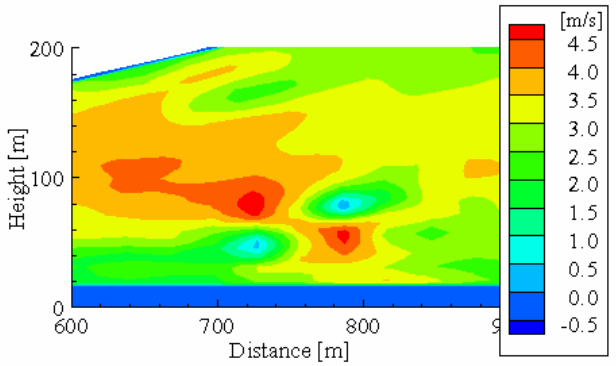


Real lidar data

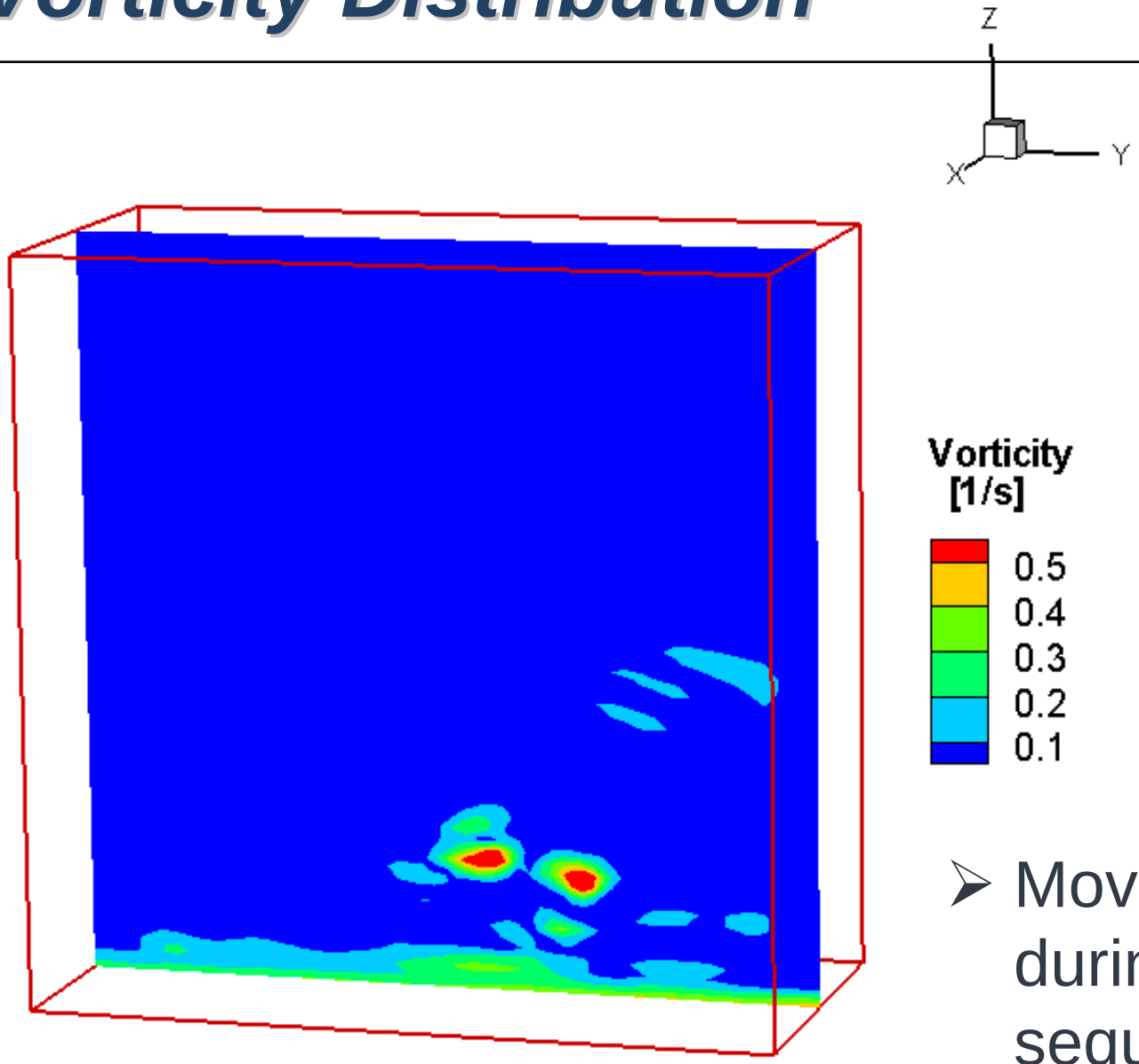






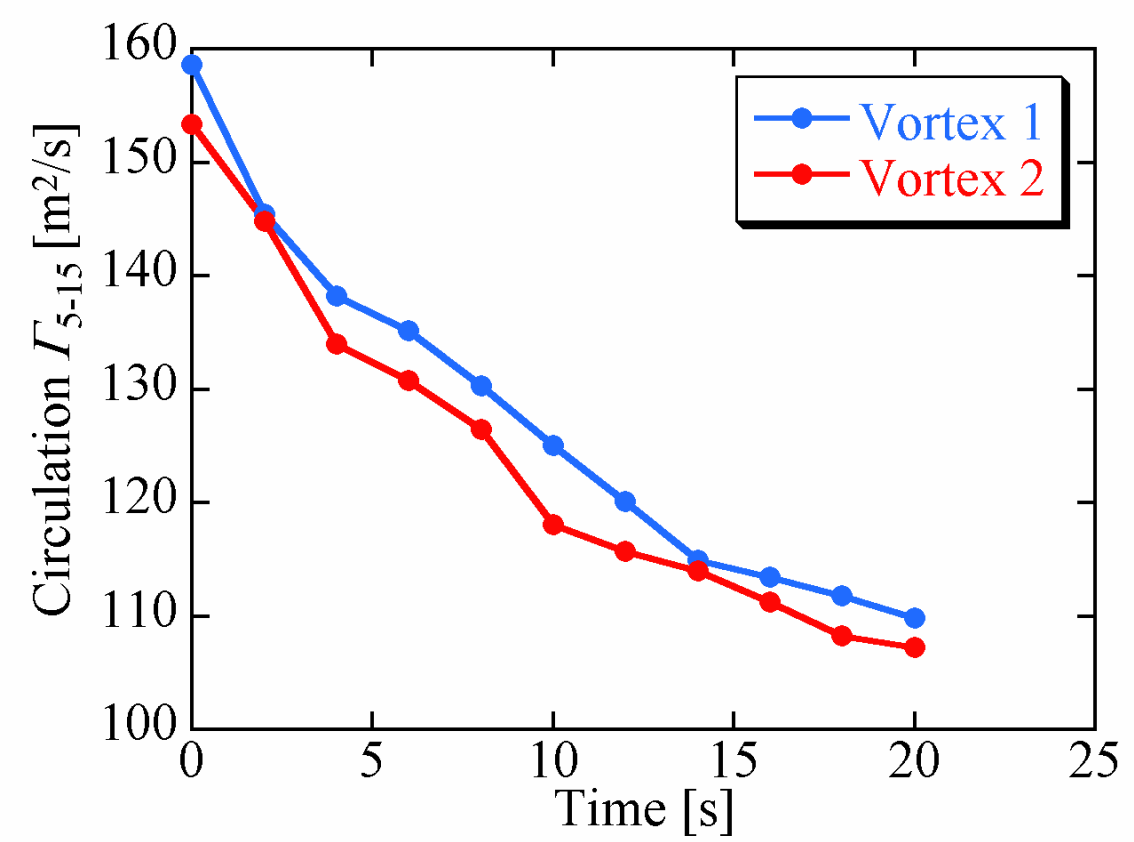


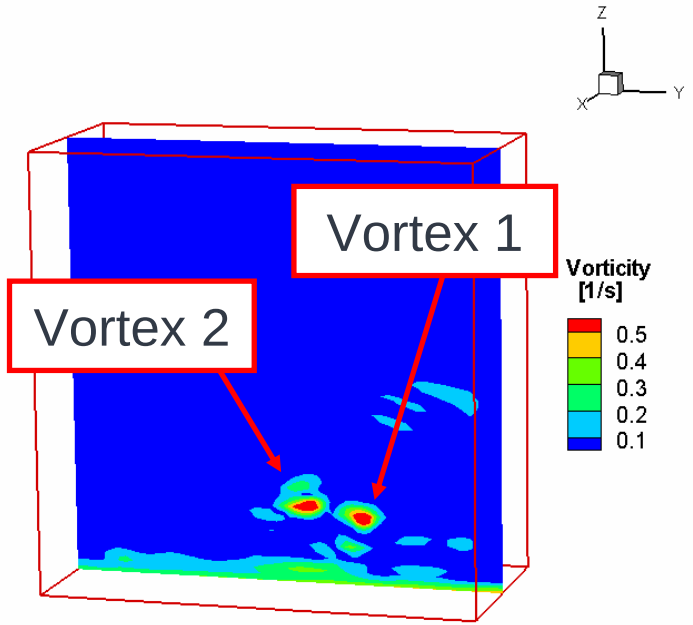
Vorticity Distribution



- Movement of vortices during a measurement sequence: 20s

Time History of Circulation





- Lidar Measurements

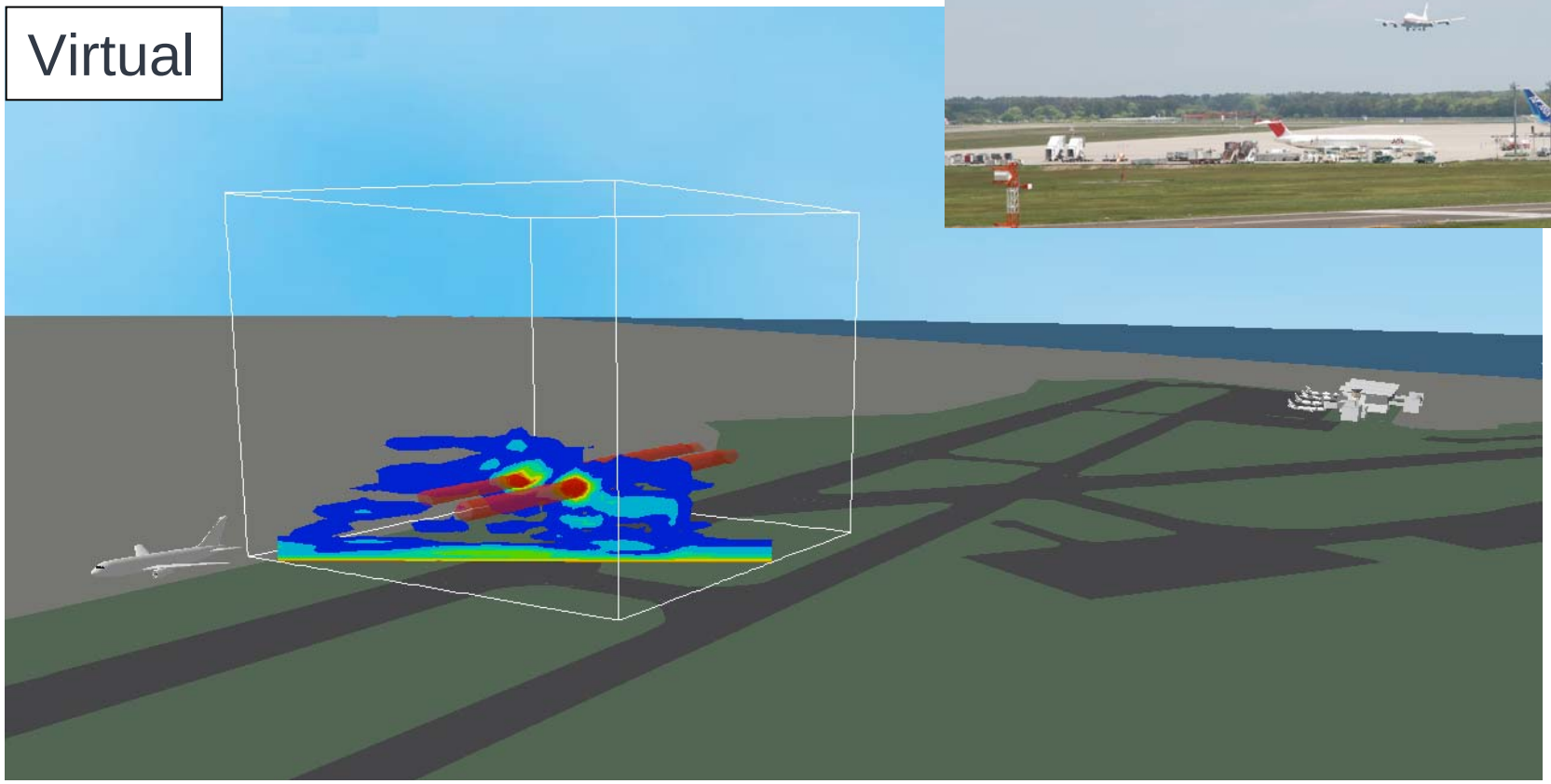
  → **Time history of circulation**

Modeling of Sendai Airport (1)

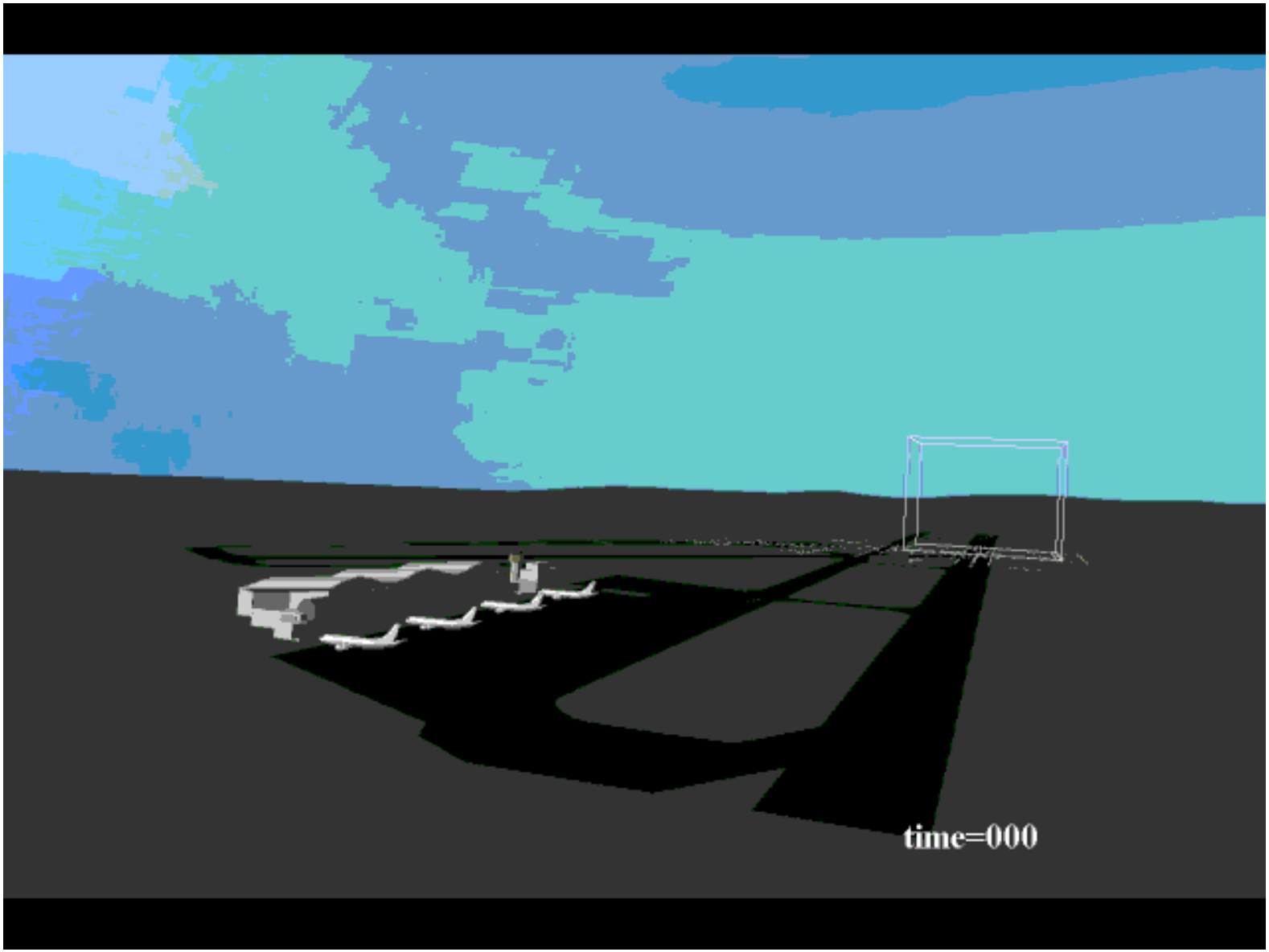
- ✓ **Reproduced flow field is superimposed on the virtual reality model of airport**

Real

Virtual



Modeling of Sendai Airport (2)



Conclusion

- 4D-Var: lidar + CFD
- Bogus vortex: compensation of LOS velocity
- **Lidar (sectional contour)**

  → CFD (3D unsteady flow field)