Prediction of Wake Turbulence under Actual Atmospheric Condition

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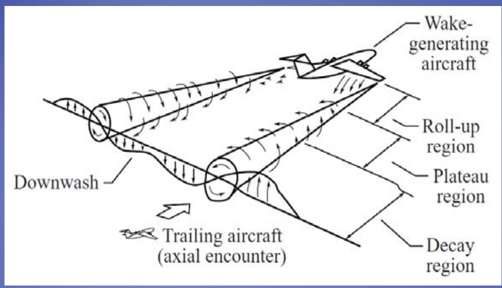
Outline

- Background
  - Wake turbulence
  - Data assimilation for realistic environmental simulation
  - Data utilization in CFD and NWP
  - Toward prediction of wake turbulence
- Objective of this research
- Approach for wake turbulence simulation
  - Doppler lidar at Sendai airport
  - Attempt to predict of wake turbulence
- Results
  - Retrieved background wind field
  - Behavior of a vortex pair in assimilated wind field
- Conclusions

Background -Wake turbulence-



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

Discovery Channel

Wake turbulence

■ Wake turbulence, which generated two vortices from wing tip stay behind, is dangerous for a following aircraft.

■ Strength of wake turbulence is proportional to the lift and the inverse of velocity. That is, wake turbulence is most strong at takeoff and landing conditions, especially in the case of a heavy aircraft.

$$\Gamma = \frac{L}{\rho V b}$$

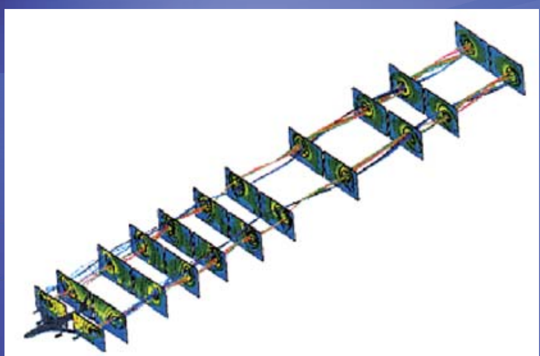
L: lift, ρ: air density
V: velocity, *b*: wing span

Wake turbulence-related accidents

■ There were 3 accidents during the past half decade in Japan, and 200 accidents during the past two decades in the United States.

Background -Need for realistic conditions-

Calculation of whole aircraft



K. Hueneche, AIAA2001-2427

- Detailed analysis of wake turbulence's behavior
- Difficulty in incorporating actual condition

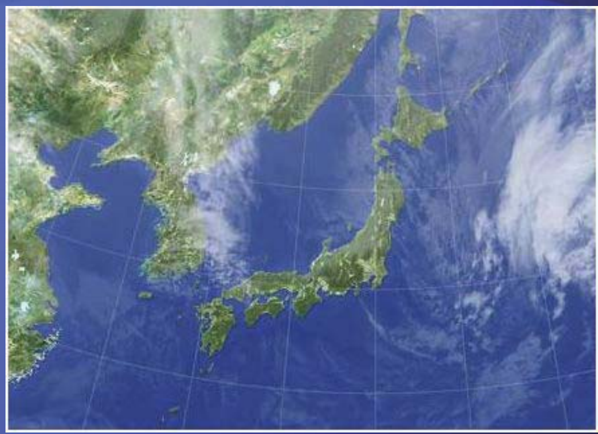
Without turbulence

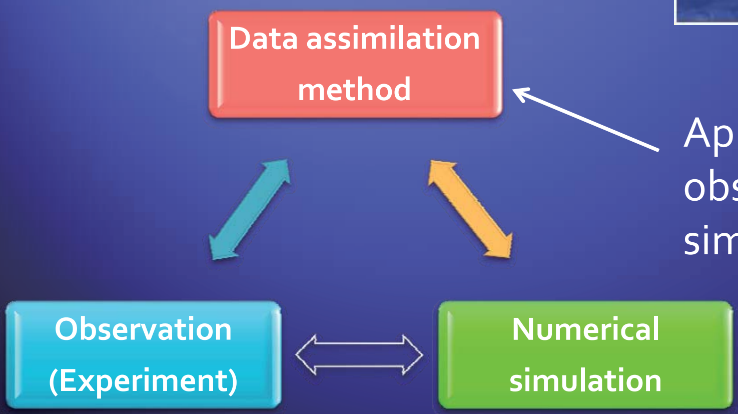
With turbulence

- Disturbance in a flow field significantly affects the decay of wake turbulence

Background -Data assimilation method-

- Developed in meteorological and oceanic from the 1990s onward
- Method for accurately estimating the complex time evolutional system, such as atmosphere, with observations (experiments) and a numerical model





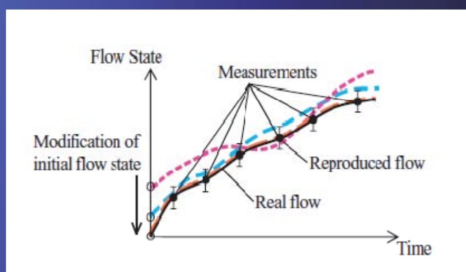
Approach method to integrate observation and numerical simulation research

Background

-Two major approach for data assimilation-

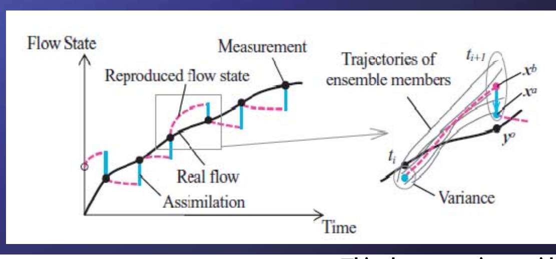
Variational approach (e.g. four-dimensional variational method)

- Initial flow state is modified based on measurements within certain period of time



Sequential approach (e.g. ensemble Kalman filter)

- Flow field is modified when measurement are obtained



Back ground - Data utilization in CFD and NWP -

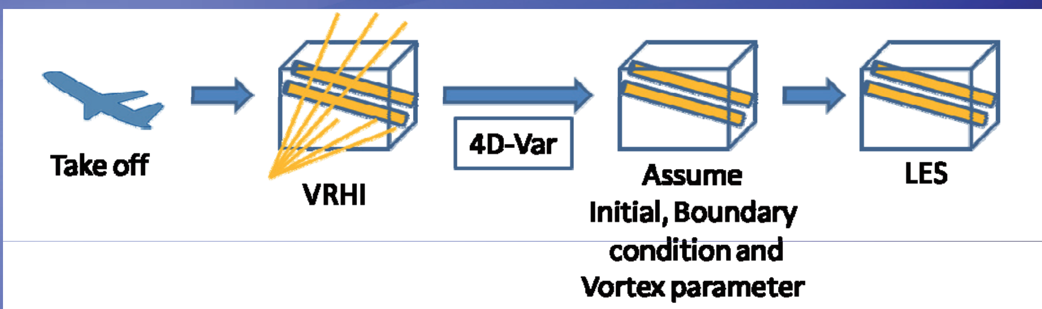
	Numerical Weather Prediction (NWP)	Computational Fluid Dynamics (CFD)
Flow scale	A few hundreds meters to several tens kilometer	***A few millimeters to several tens meters***
Application	Weather forecast	Aircraft design
Relationship with measurement data	Comparison (validation), ***ASSIMILATION***	Comparison (validation of CFD code)

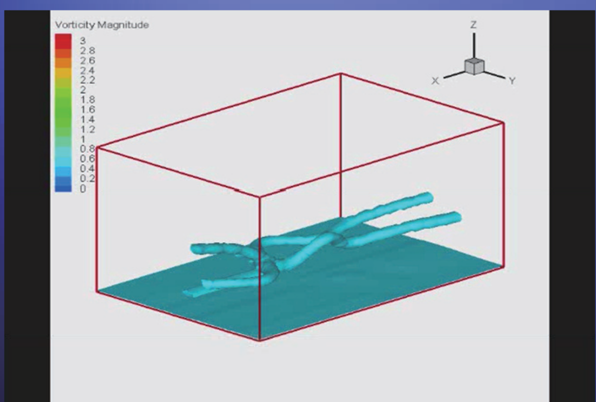
Can we effectively utilize measurement data to improve the reliability of CFD simulation?

Back ground

- Toward prediction of wake turbulence -

Previous method





Iso surface (Vorticity magnitude)

- Able to retrieve wake turbulence in detail by using its lidar measurements after take off
- Difficulty in wake turbulence before the takeoff of a following aircraft, due to the large computational cost

Objective of this research

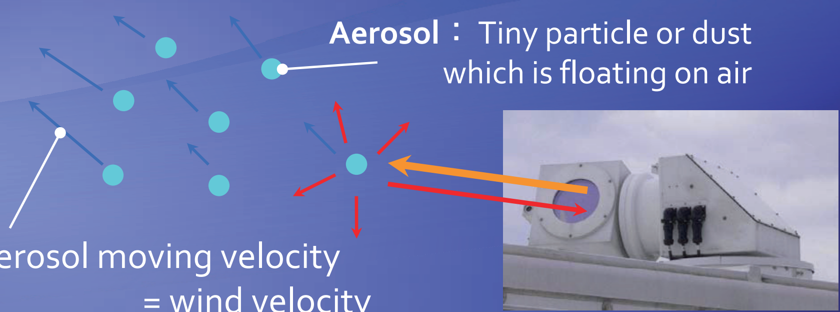
<u>Prediction of wake turbulence</u>
<u>under actual atmospheric conditions</u>
<u>before the aircraft's take off</u>

- Approach : Data assimilation method (CFD + Experiment)
  (four-dimensional variational method)

If analysis of wake turbulence can finish before the aircraft's take off, we can determine the separation time of a following aircraft's take off or landing in advance.

Approach for wake turbulence simulation

- Doppler lidar at Sendai airport -

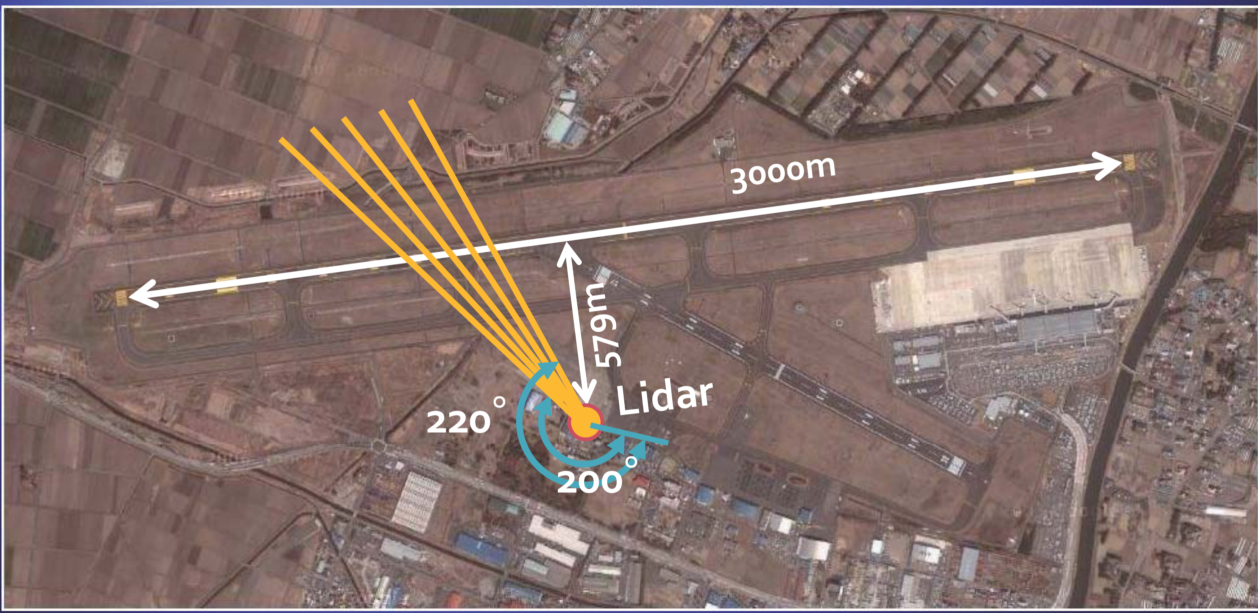


Scanner

Doppler lidar (ENRI)

- Distance resolution
  30m (High accuracy compared to radar)
- Maximum measurement wind velocity
  more than equal to 30m/s
- Laser wave length
  less than equal to 0.5m/s
- Scanning velocity
  maximum 20m/s
- Eye-safe wavelength
- Available to measure in fine days

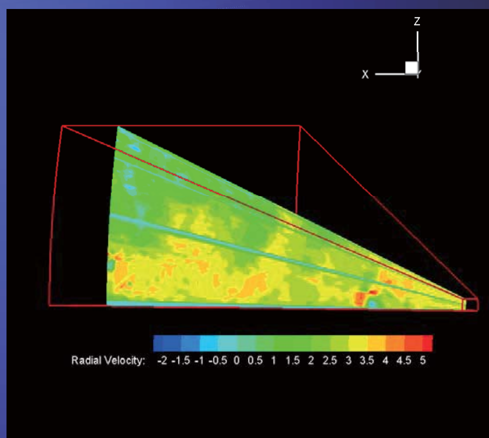
Measured velocity distribution at Sendai airport



Sendai airport

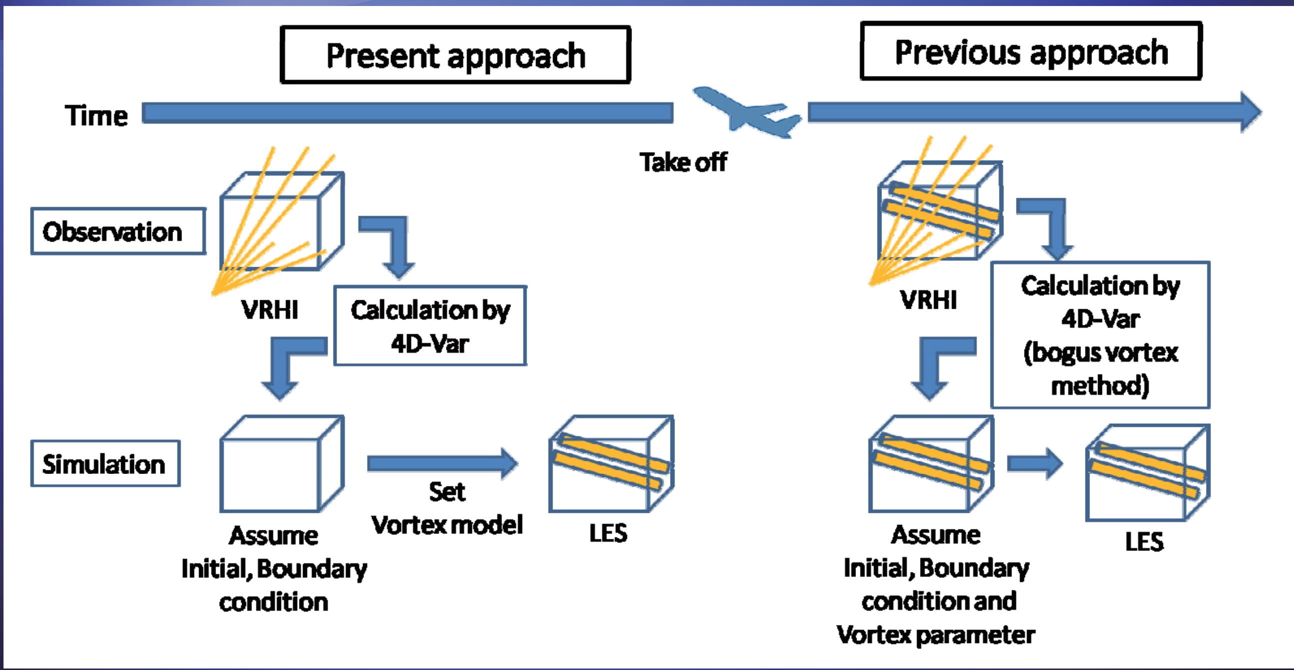
Measured velocity distribution at Sendai airport

Take off at Sendai airport



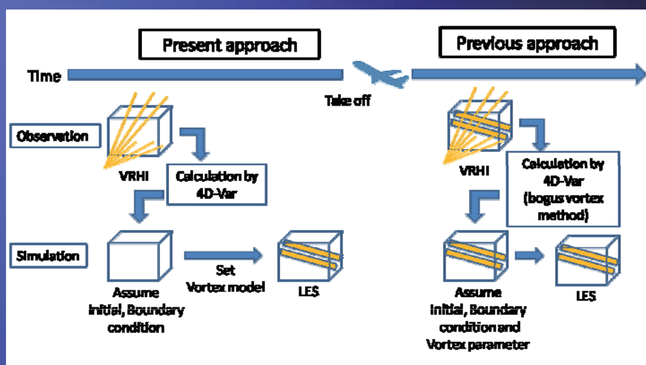
Radial velocity

Approach for wake turbulence simulation
- Attempt to predict of wake turbulence -

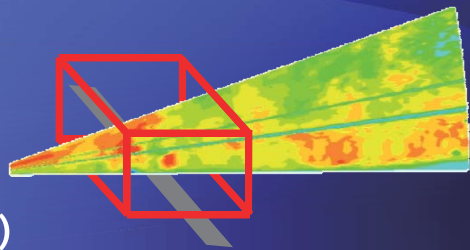


Approach for wake turbulence simulation
- Attempt to predict of wake turbulence -

- Advantage of this approach
  - When the change in atmosphere is little for a long time, we can determine the separation time of a following aircraft's take off or landing based on the simulation outcome of a few hours ago.
  - We don't need high accurate wind detection system such as Doppler lidar because the target of data assimilation in this method is not vortex pair (wake turbulence) .



Flowchart of 4D-Var method

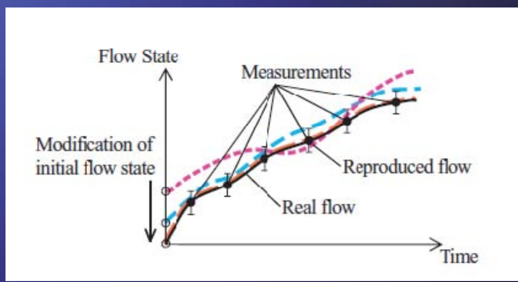


1. Simulate lidar measurement process during CFD computation (Acquiring virtual lidar measurement)
2. The difference is defined as a cost function:

[illegible]

3. Minimization of the cost function using adjoint equation method

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



Measurement conditions for data assimilation

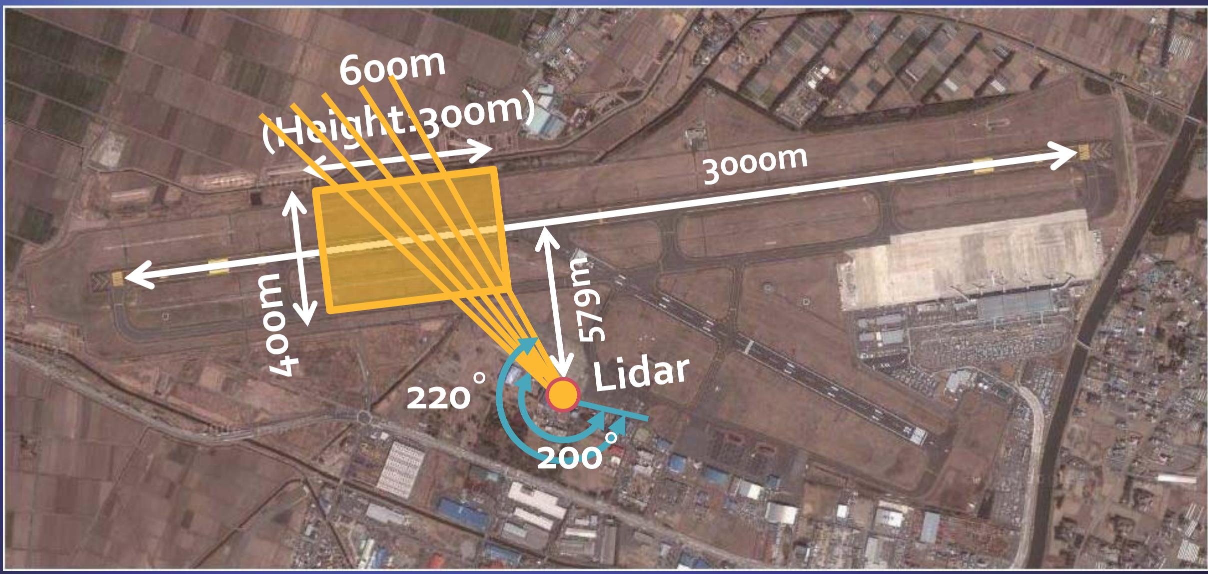
- Observation date for data assimilation
  December 11 2008 16:07 (For about 90[s])
- Observation date for wake turbulence
  December 11 2008 16:15
- Target aircraft
  Boeing 777-200 (relief service)
- Weather condition
  Weather cloudy
  Wind velocity 4[m/s]*
  Wind direction SSW*
  Pressure 1007[hPa]**
  Temperature 14.5° **

Boeing 777-200

Category	Heavy
Wing span	60.9 m
Length	63.7 m

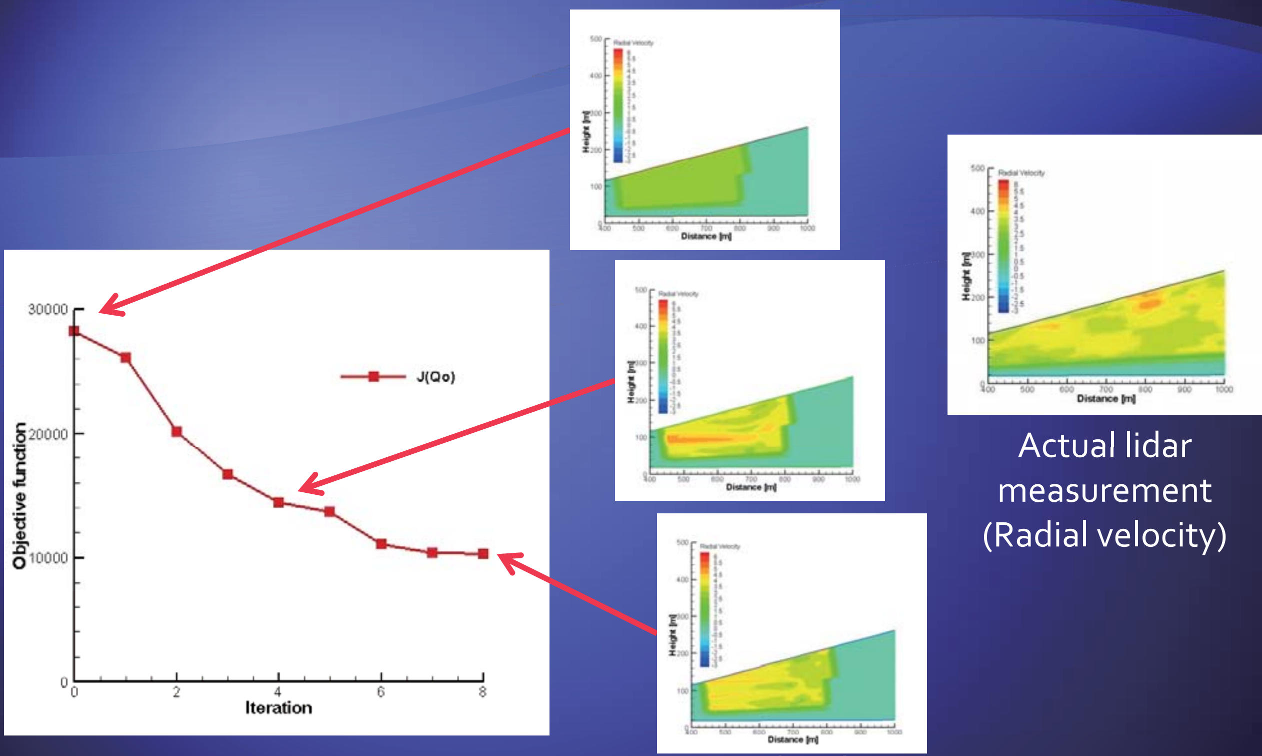
* Japan Meteorological Agency
** METAR

Setting of computational domain and lidar azimuth angle



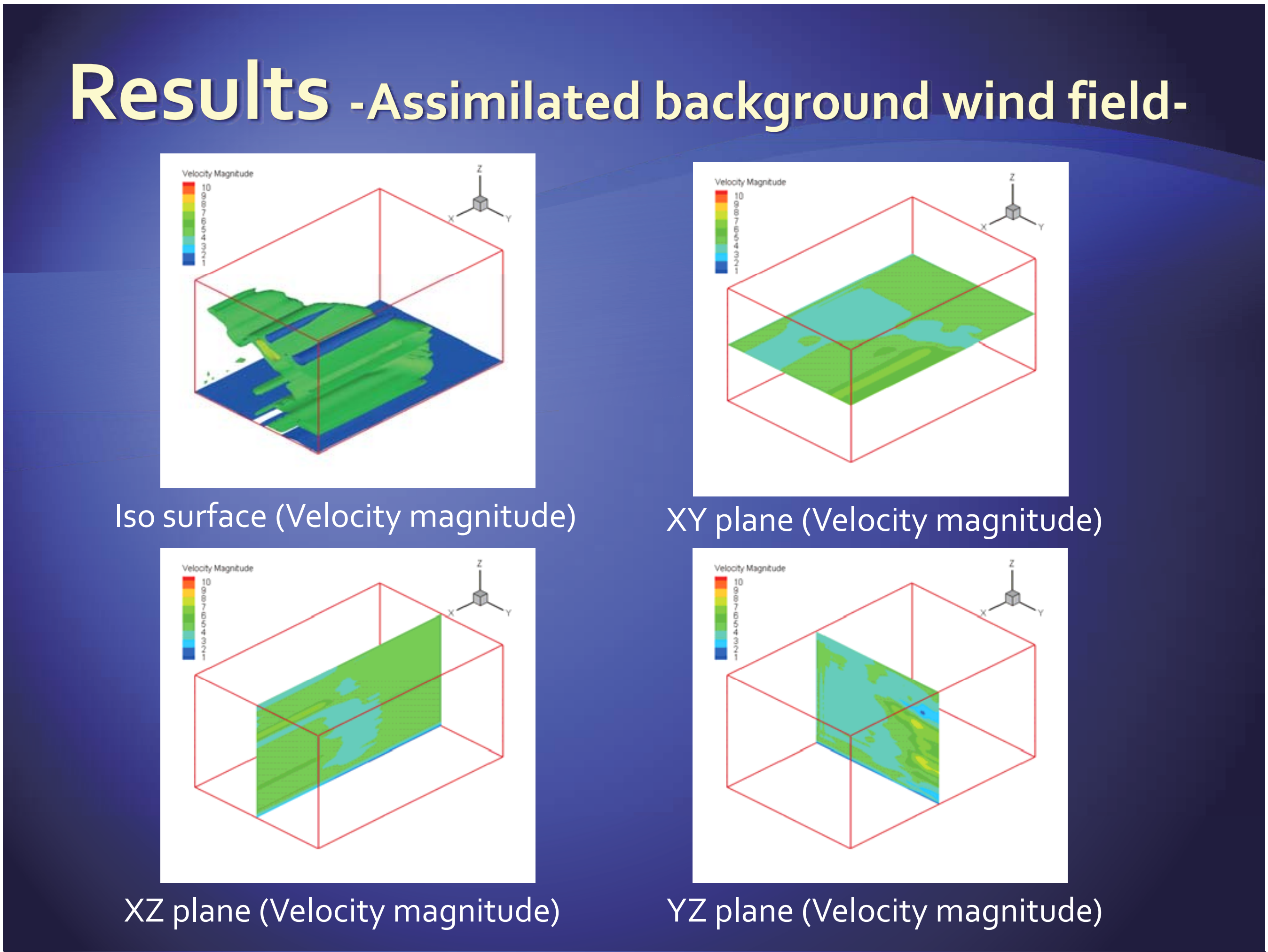
Sendai airport

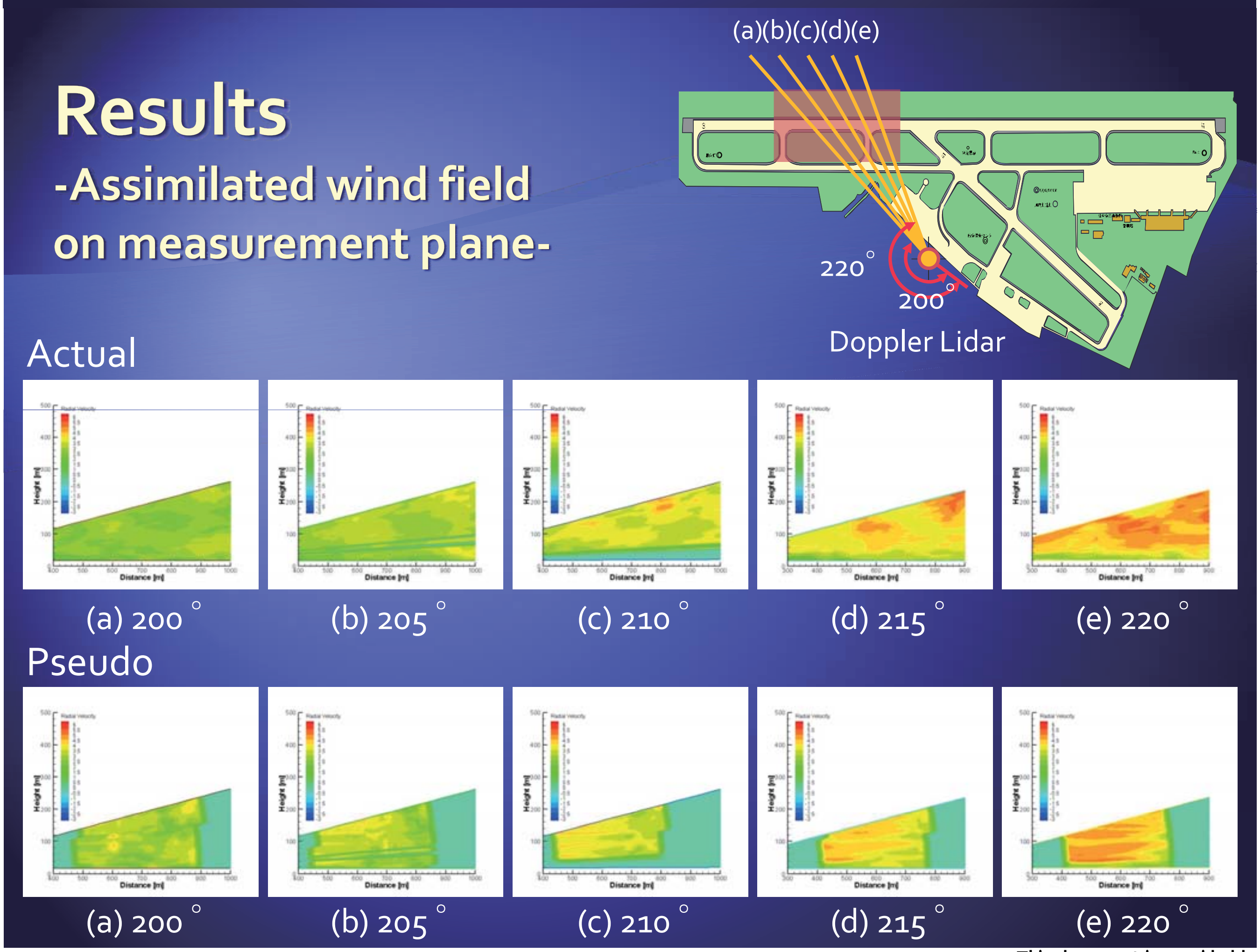
Results - Minimization history of cost function -

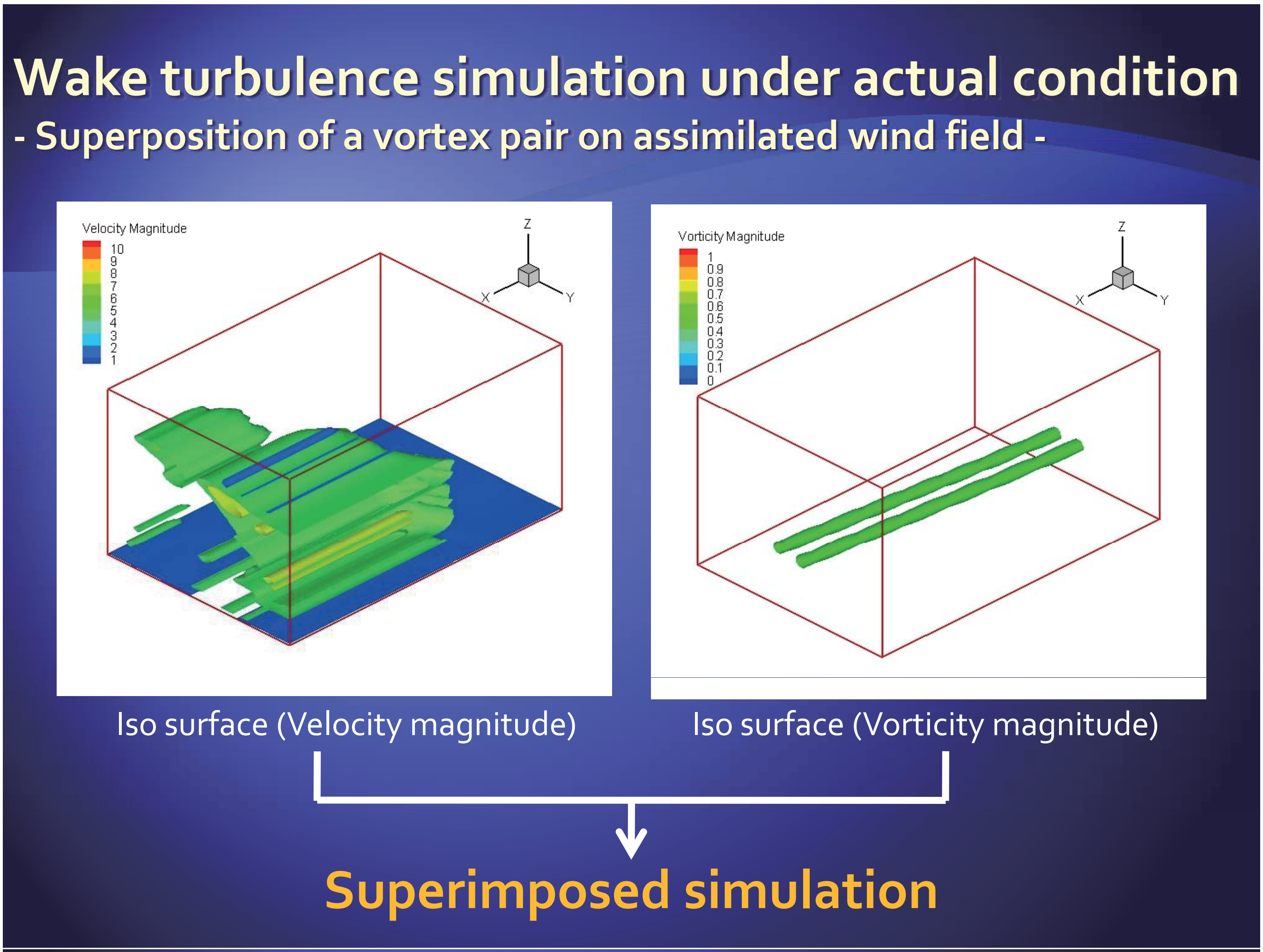


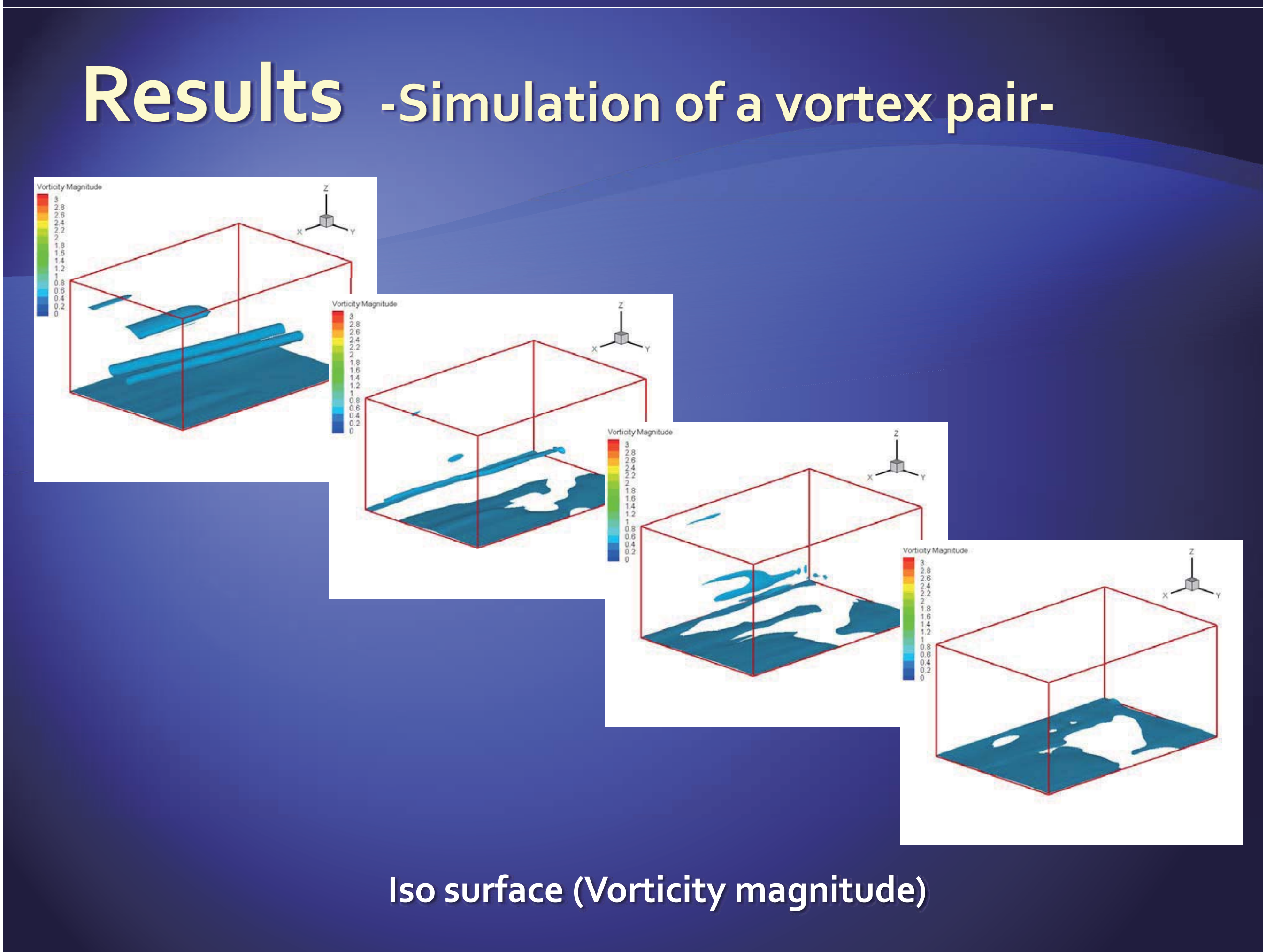
Actual lidar measurement (Radial velocity)

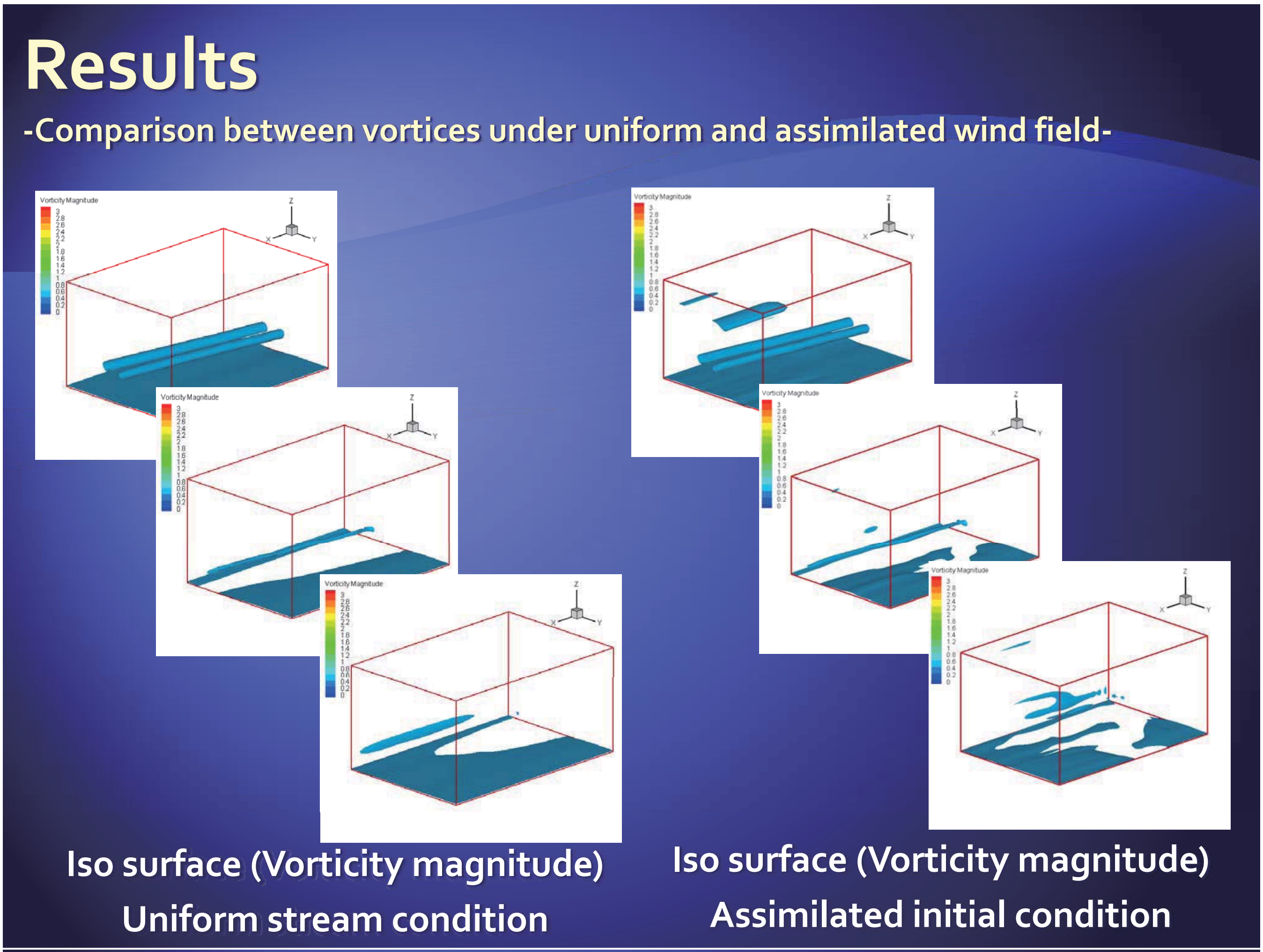
Pseudo lidar measurement (Radial velocity)

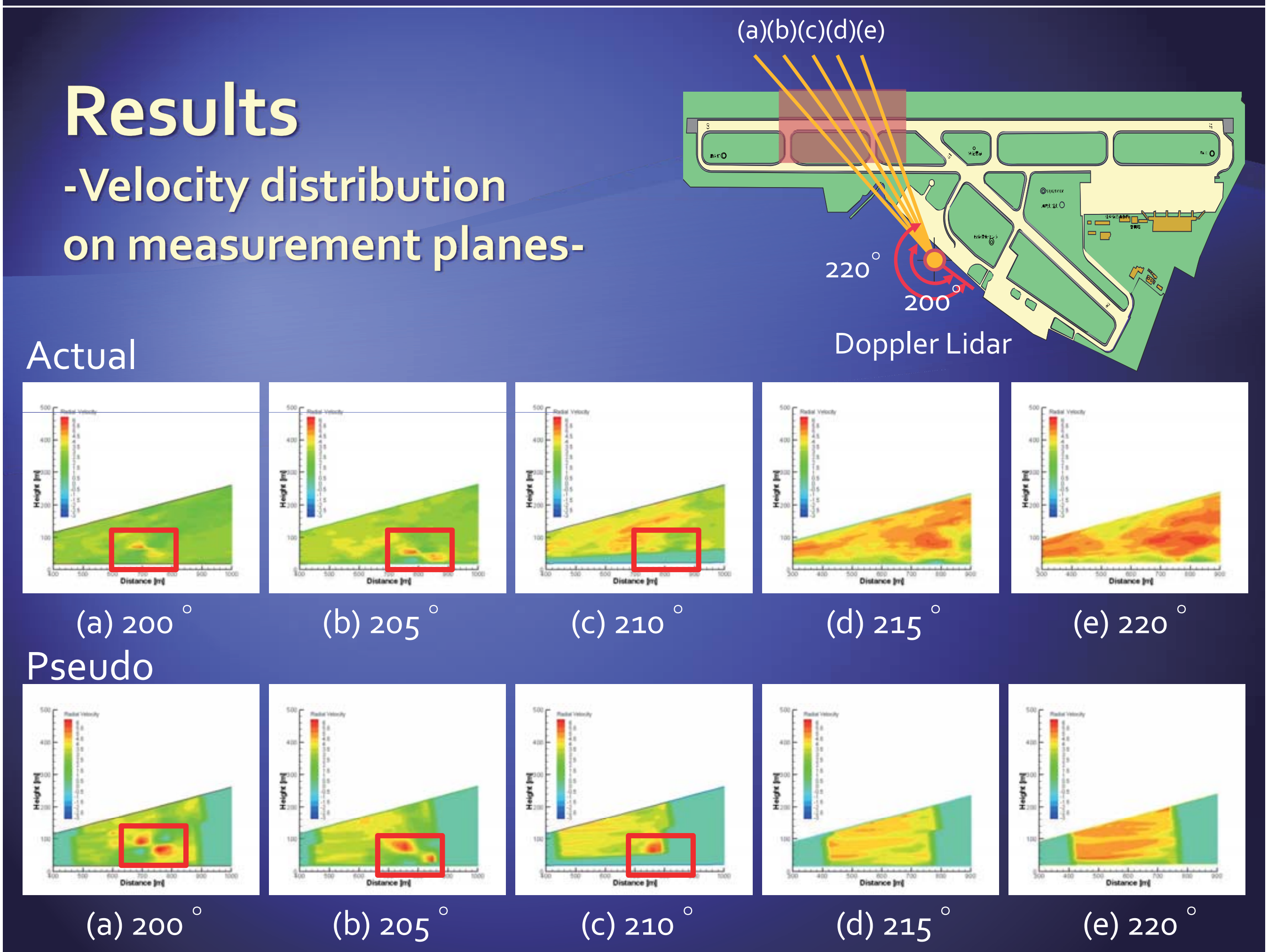

Results -Assimilated background wind field-
Velocity Magnitude
Iso surface (Velocity magnitude)
XY plane (Velocity magnitude)
XZ plane (Velocity magnitude)
YZ plane (Velocity magnitude)


Results
-Assimilated wind field
on measurement plane-
(a)(b)(c)(d)(e)
220°
200°
Doppler Lidar
Actual
(a) 200°
(b) 205°
(c) 210°
(d) 215°
(e) 220°
Pseudo
(a) 200°
(b) 205°
(c) 210°
(d) 215°
(e) 220°


Wake turbulence simulation under actual condition
- Superposition of a vortex pair on assimilated wind field -
Velocity Magnitude
10
9
8
7
6
5
4
3
2
1
Z
X
Y
Vorticity Magnitude
1
0.9
0.8
0.7
0.6
0.5
0.4
0.3
0.2
0.1
0
Iso surface (Velocity magnitude)
Iso surface (Vorticity magnitude)
Superimposed simulation


Results -Simulation of a vortex pair-
Vorticity Magnitude
Iso surface (Vorticity magnitude)


Results
-Comparison between vortices under uniform and assimilated wind field-
Iso surface (Vorticity magnitude)
Uniform stream condition
Iso surface (Vorticity magnitude)
Assimilated initial condition


Results
-Velocity distribution
on measurement planes-
(a)(b)(c)(d)(e)
220°
200°
Doppler Lidar
Actual
(a) 200°
(b) 205°
(c) 210°
(d) 215°
(e) 220°
Pseudo
(a) 200°
(b) 205°
(c) 210°
(d) 215°
(e) 220°

Conclusions

Wake turbulence has been simulated by using a back ground wind field prior to takeoff aiming to predict the wake turbulence in advance.

- Retrieval of a background wind field prior to takeoff was performed to predict a behavior of wake turbulence in advance.
- Advection of simulated vortex pair was similar to the actual advection of wake turbulence.
- Difference of vortex pair's decay between in uniform and assimilated wind fields showed the effect of actual conditions.

Thank you for your kind attention