# Wake Vortex Separation Reduction Systems and Large Eddy Simulation of Wake Vortex during Approach

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**National CNS/ATM Key Laboratory**

**School of Electronic Information Engineering**

**Beihang University**

**(Beijing University of Aeronautics and Astronautics)**

**for WakeNet-3**

# A Brief Introduction of Professor XU Xiao-Hao and National Key Lab of Air Traffic Operation Safety

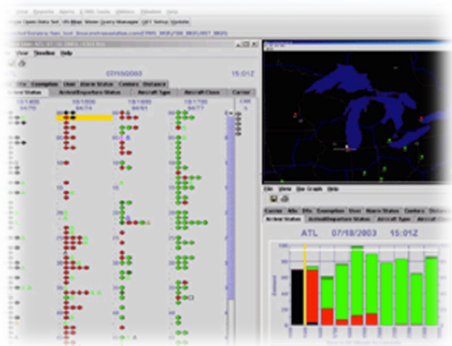
- Chief Scientist of Expert Committee for the Key National High-Tech R&D Program of New Air Traffic Management System of China.
- Chief Scientist of Several National Nature Science Key Program
- Ex-Vice President of Civil Aviation University of China

Prof. XU Xiao-Hao, Director of the National Key Lab of Air Traffic Operation Safety(Air Traffic Management Research Base of Civil Aviation of China)

Located in Civil Aviation University of China, Tianjin City, China

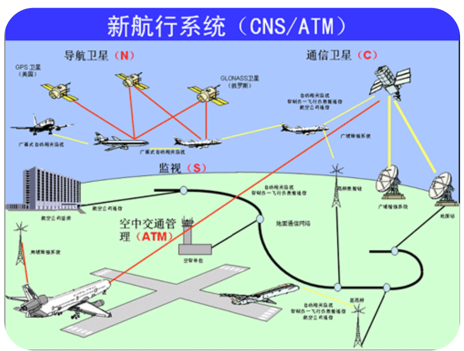
中国民航大学
Civil Aviation University of China

# A Brief Introduction of Professor XU Xiao-Hao and National Key Lab of Air Traffic Operation Safety



## Air Traffic Management Lab,

- ✓ Collecting real-time information of flight in national air space
- ✓ Coordinate the air traffic flow, cut the cost for air holding pattern… and more




## Lab of Communication Navigation and Surveillance

- ✓ Research of the theory, algorithm to tackle the problem in CNS new tech and facility development .
- ✓ Envision and plan the next generation national air traffic system.

## Control Tower View Simulation Lab.

- ✓ 360 degree dynamic simulation of control tower view
- ✓ Compatible controller training system development

# A Brief Introduction of Professor ZHANG Jun and National Key Lab of CNS/ATM

- Leading Scientist of a Key National High-Tech R&D Program of New Air Traffic Management System of China & Leading Scientist of a National Basic Research Program .
- Vice President of Beijing University of Aeronautics and Astronautics (Now: Beihang University)

Prof. ZHANG Jun, Director of the National Key Lab of CNS / ATM

北京航空航天大學
BEIHANG UNIVERSITY

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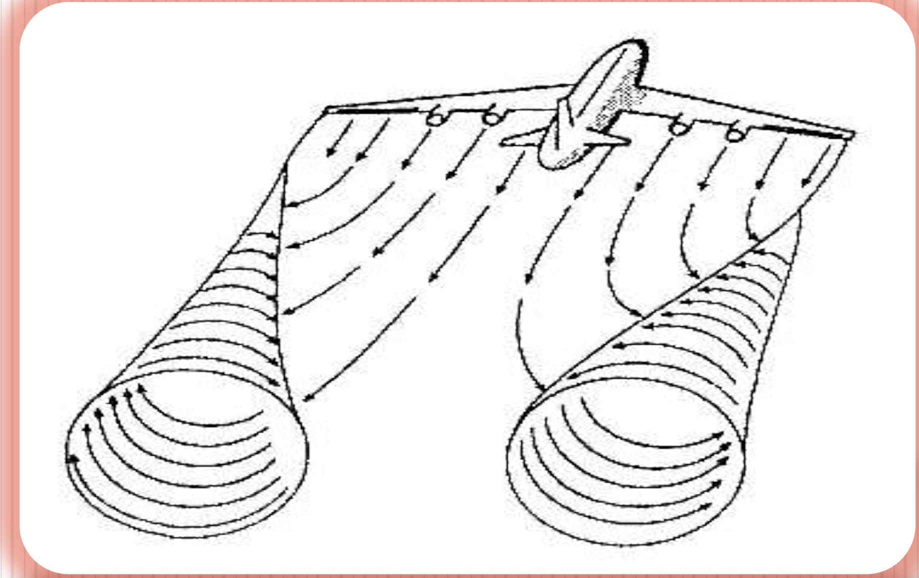
- **Extra Part** :Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

# Part I-Large Eddy Simulation of Short Field Wake Vortex

- Brief Introduction to The Concept of Wake Vortex and Its Threat to The Safety of Flight Operation



# Part I-Large Eddy Simulation of Short Field Wake Vortex

- Theory of Large Eddy Simulation of Turbulence

  - *Direct Numerical Simulation*

  - *Why LES (Large Eddy Simulation)*
    - *Governing Equations*

$$\frac{\partial \overline{u}_i}{\partial t} + \frac{\partial \overline{u_i u_j}}{\partial x_j} = -\frac{1}{\rho}\frac{\partial \overline{p}}{\partial x_i} + \nu \frac{\partial^2 \overline{u}_i}{\partial x_j \partial x_j}$$

$$\frac{\partial \overline{u}_i}{\partial x_i} = 0$$

# Part I-Large Eddy Simulation of Short Field Wake Vortex

- Theory of Large Eddy Simulation of Turbulence

  - Let : $\overline{u_i u_j} = \bar{u}_i \bar{u}_j + (\overline{u_i u_j} - \bar{u}_i \bar{u}_j)$

  - Define: $-(\overline{u_i u_j} - \bar{u}_i \bar{u}_j)$ *as sub-grid stress*

  - *Thus, governing equations become:*

$$\frac{\partial \bar{u}_i}{\partial t} + \frac{\partial \bar{u}_i \bar{u}_j}{\partial x_j} = -\frac{1}{\rho} \frac{\partial \bar{p}}{\partial x_i} + \nu \frac{\partial^2 \bar{u}_i}{\partial x_j \partial x_j} - \frac{\partial (\overline{u_i u_j} - \bar{u}_i \bar{u}_j)}{\partial x_j}$$

$$\bar{\tau}_{ij} = \bar{u}_i \bar{u}_j - \overline{u_i u_j}$$

# Part I-Large Eddy Simulation of Short Field Wake Vortex

- Theory of Large Eddy Simulation of Turbulence

  - *Smargorinsky Eddy-viscosity Model*

$$\overline{\tau}_{ij} = (\overline{u}_i \overline{u}_j - \overline{u_i u_j}) = 2(C_s \Delta)^2 \overline{S}_{ij} (2\overline{S}_{ij} \overline{S}_{ij})^{1/2} - \frac{1}{3} \overline{\tau}_{kk} \delta_{ij}$$

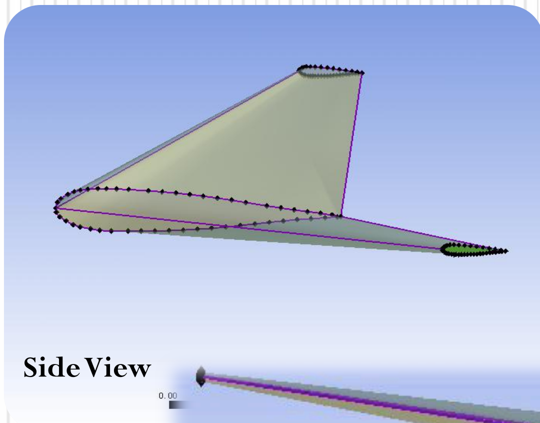
# Part I-Large Eddy Simulation of Short Field Wake Vortex

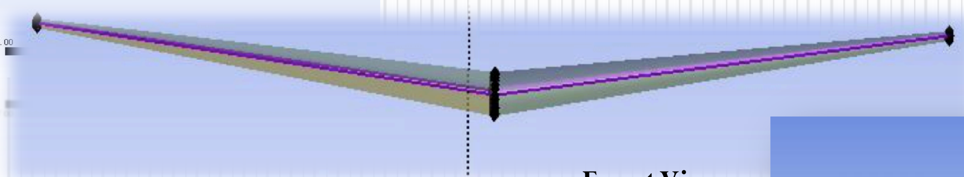
- 3-Dimension Wing Model of Boeing-737A Airfoil

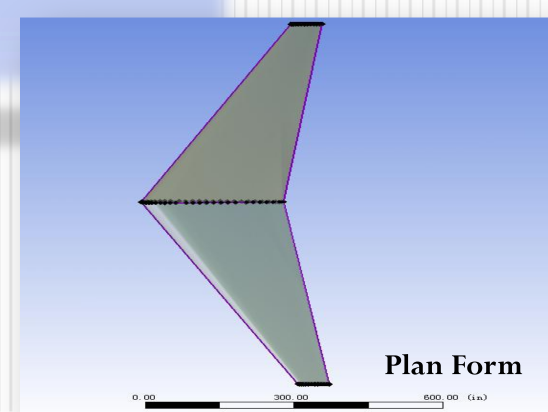
| Parameter | Value | Unit |
| --- | --- | --- |
| Wing Span | 1116.0000 | inch |
| Root Chord | 288.1000 | inch |
| Tip Chord | 63.2900 | inch |
| Dihedral | 6 | degree |
| Swept Angle | 25 | degree |
| Incidence at Root | 1 | degree |
| Incidence at Tip | 1 | degree |
| Taper Ratio | 0.2197 | — |

# Part I-Large Eddy Simulation of Short Field Wake Vortex

- 3-Dimension Wing Model of Boeing-737A Airfoil

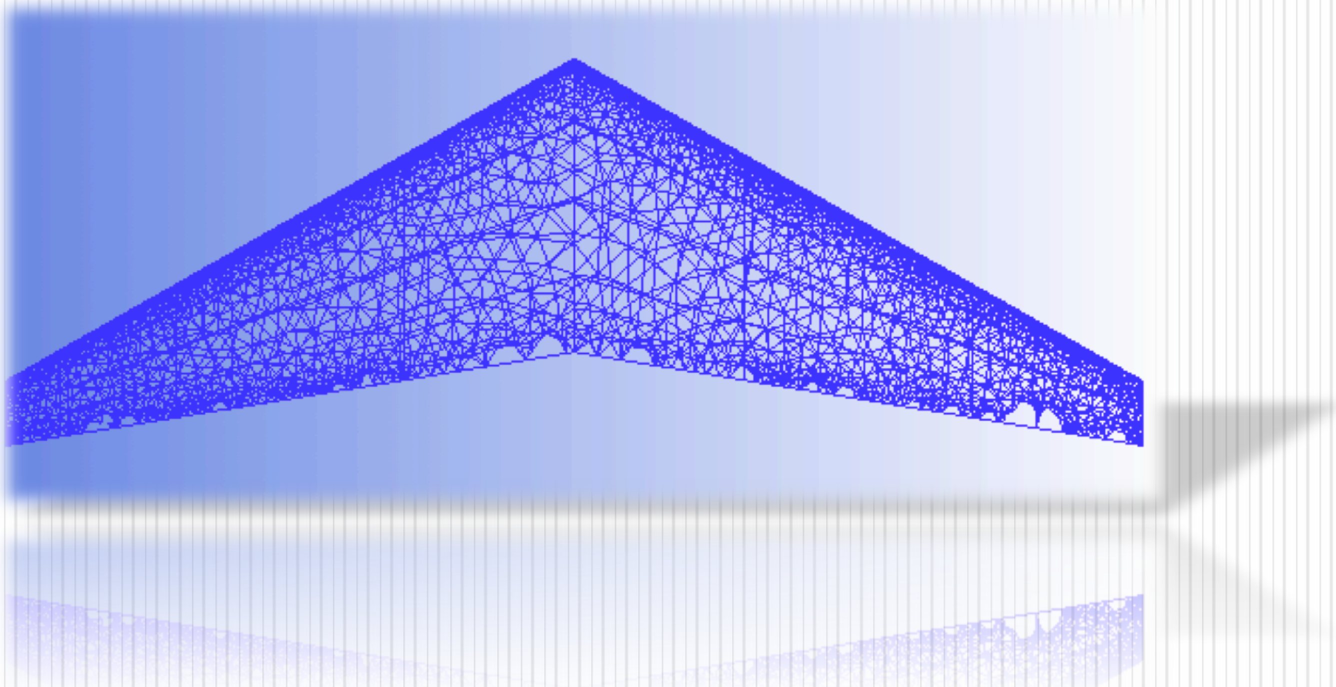


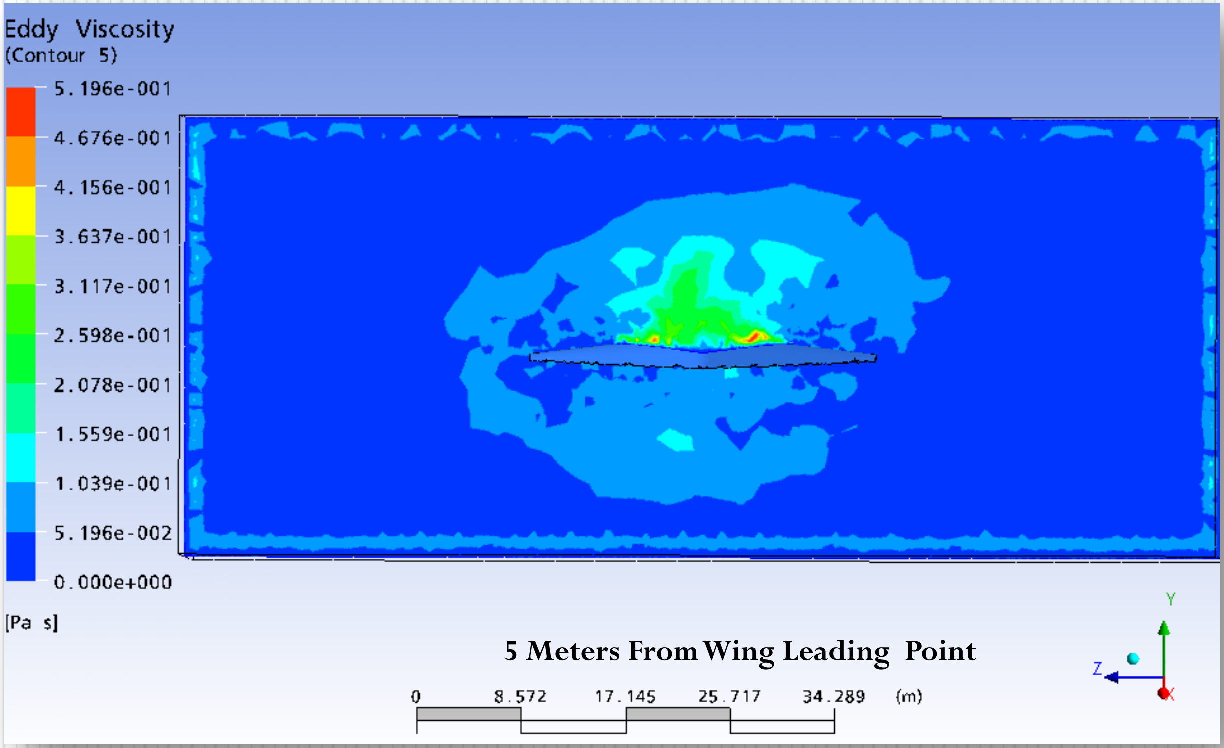
# Part I-Large Eddy Simulation of Short Field Wake Vortex

- 3-Dimension Wing Model of Boeing-737A Airfoil Warped with Tetrahedral Mesh (Finite Element Method)



# Part I-Large Eddy Simulation of Short Field Wake Vortex

- Visualized Eddy-Viscosity Contour Graph



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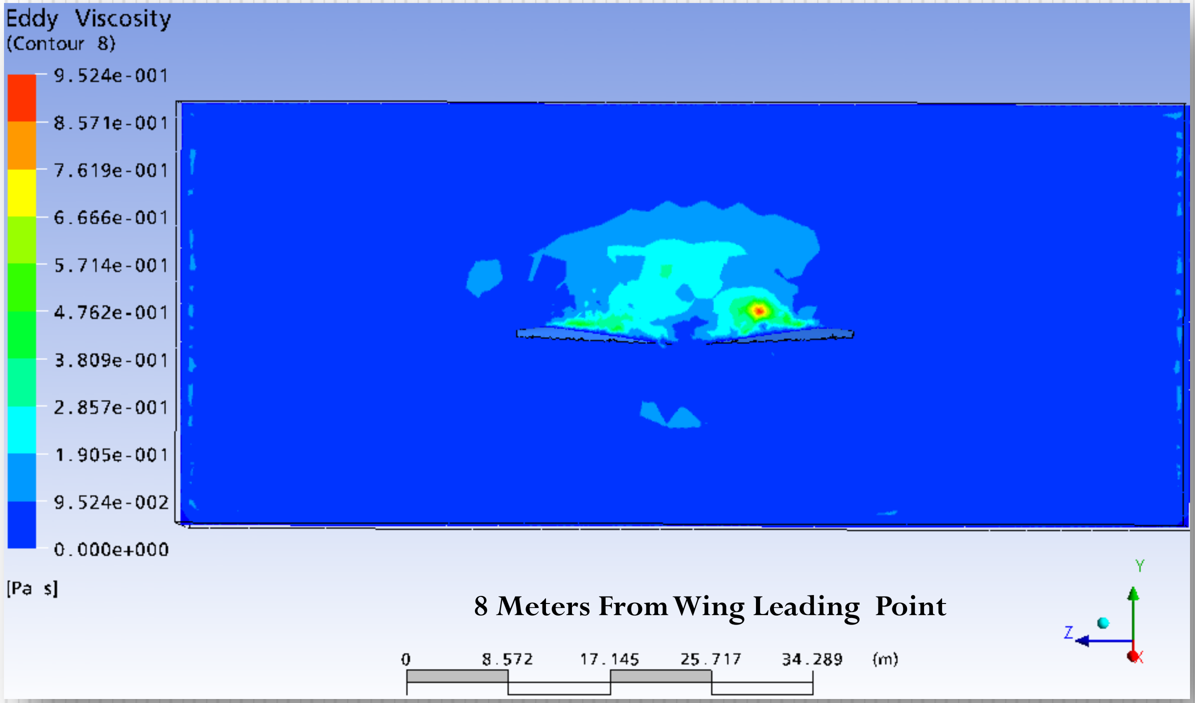

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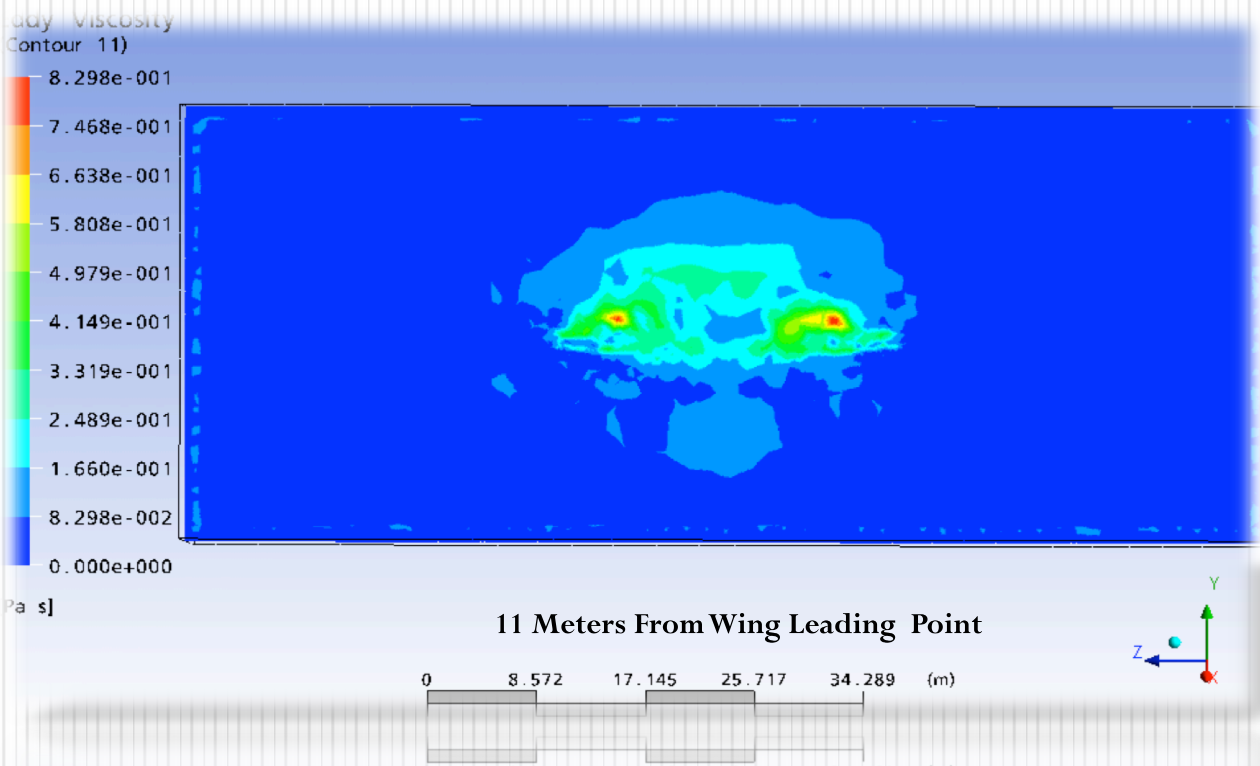

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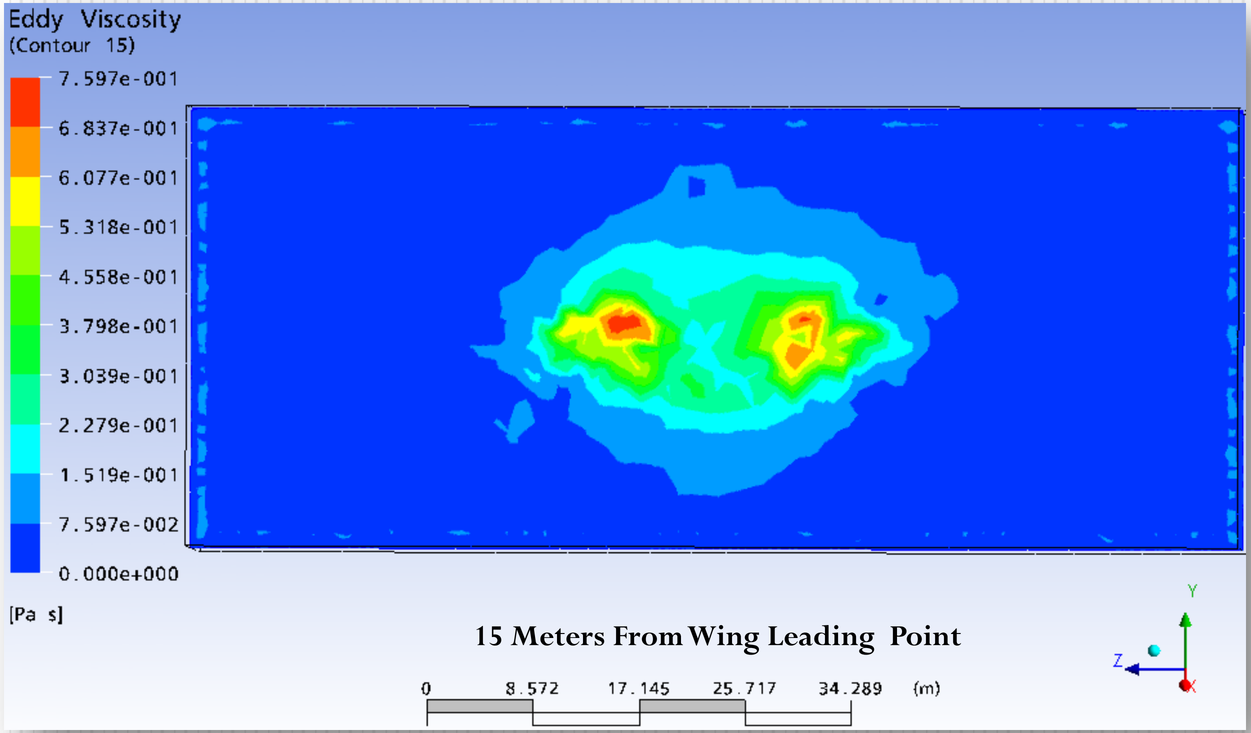

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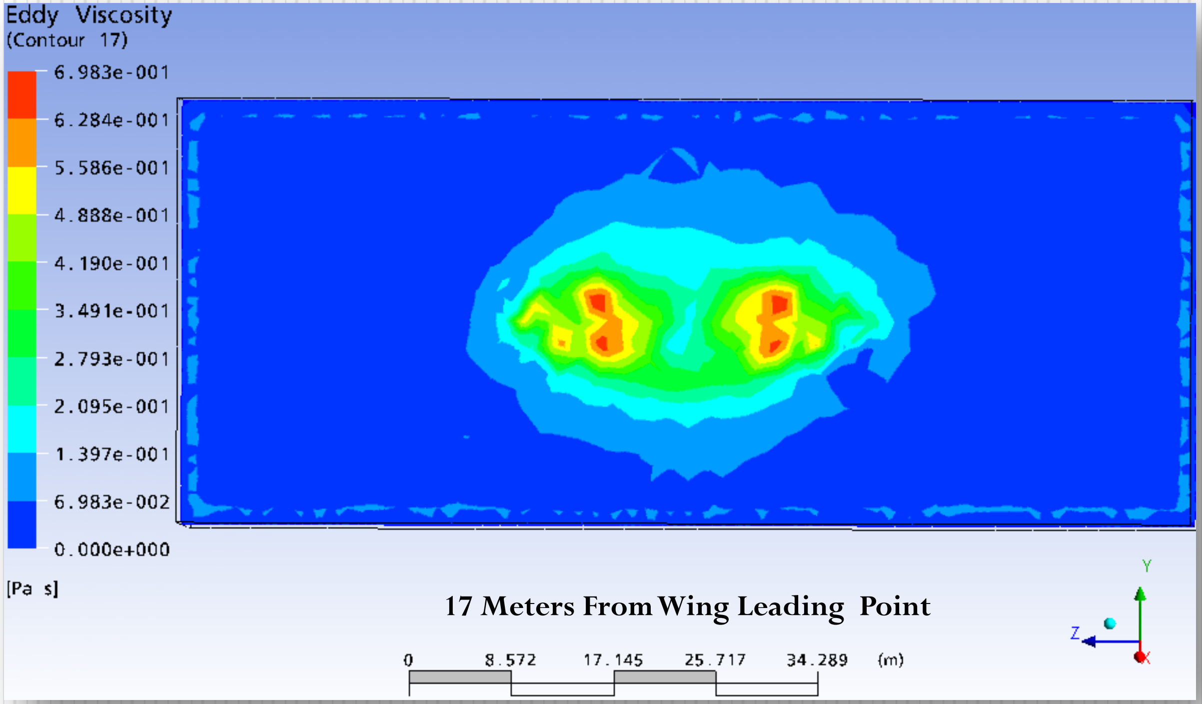
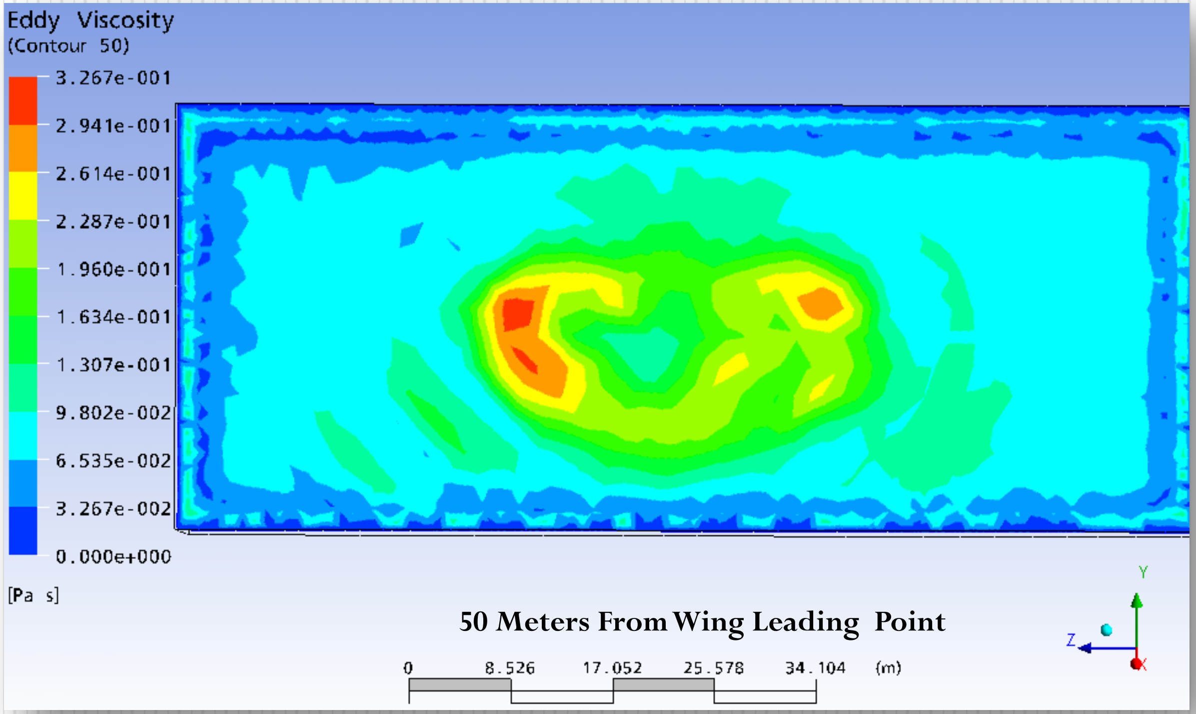


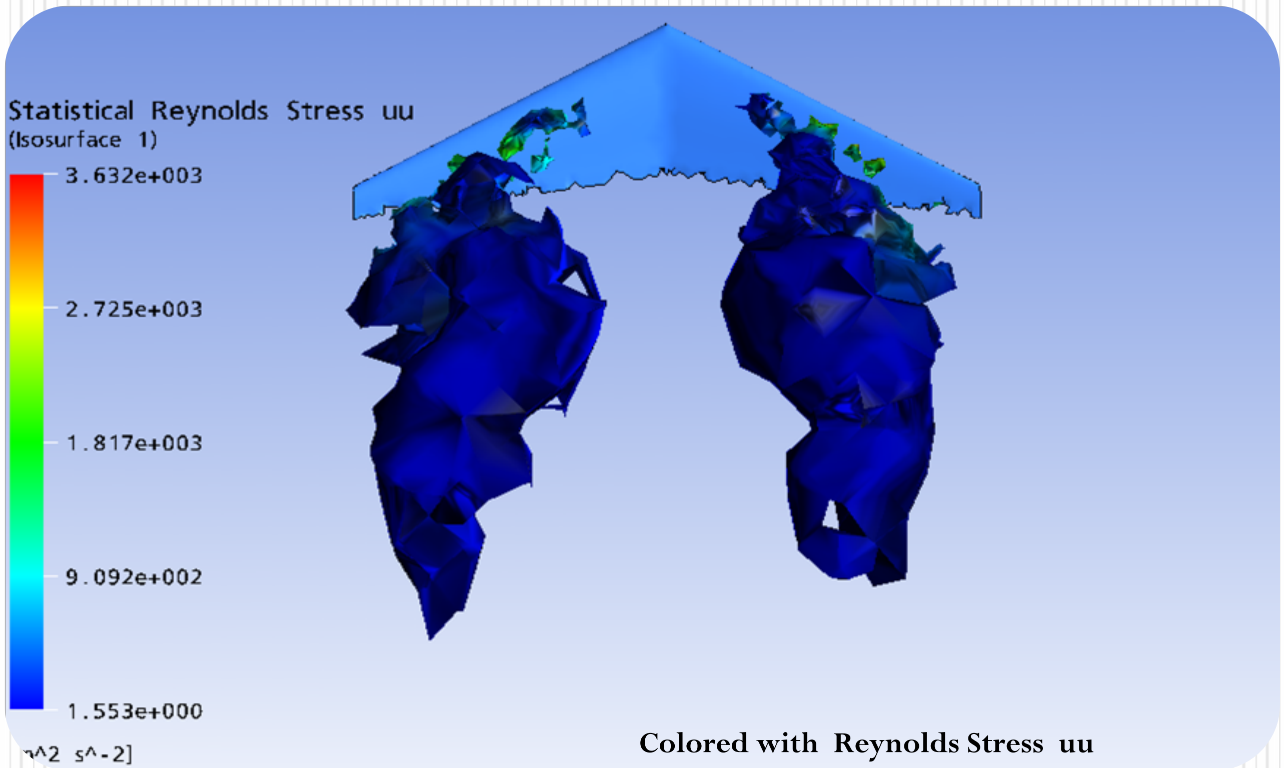
# Part I-Large Eddy Simulation of Short Field Wake Vortex

- Visualized Eddy-Viscosity Contour Graph



# Part I-Large Eddy Simulation of Short Field Wake Vortex

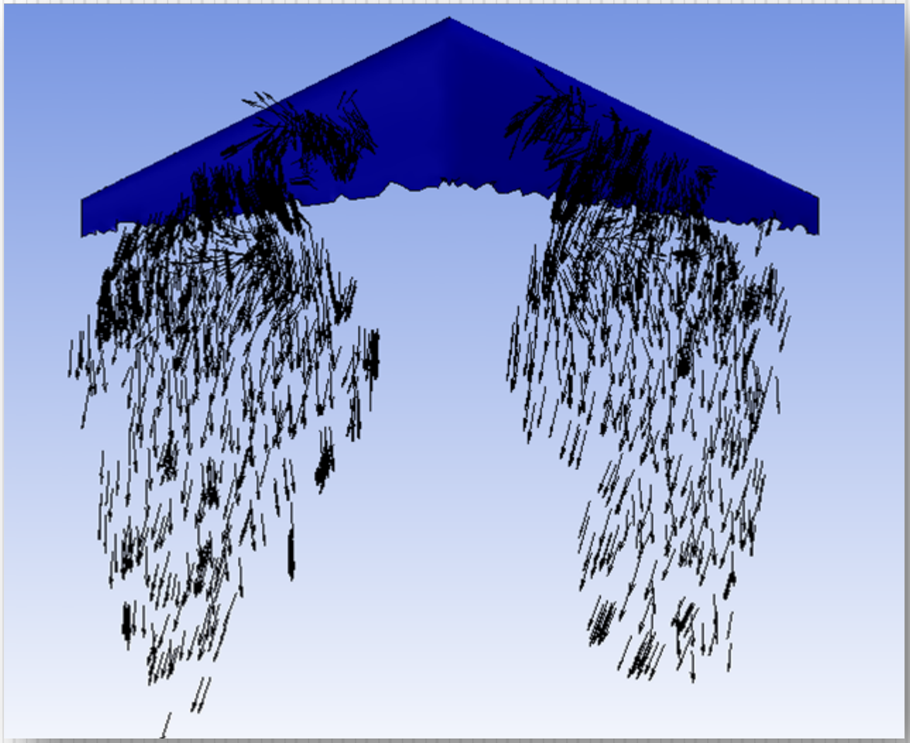
- Iso-surface with Eddy-Viscosity=0.4



Colored with Reynolds Stress uu

# Part I-Large Eddy Simulation of Short Field Wake Vortex

- 3-Dimensional Velocity Vectors on the Iso-surface with Eddy-Viscosity=0.4



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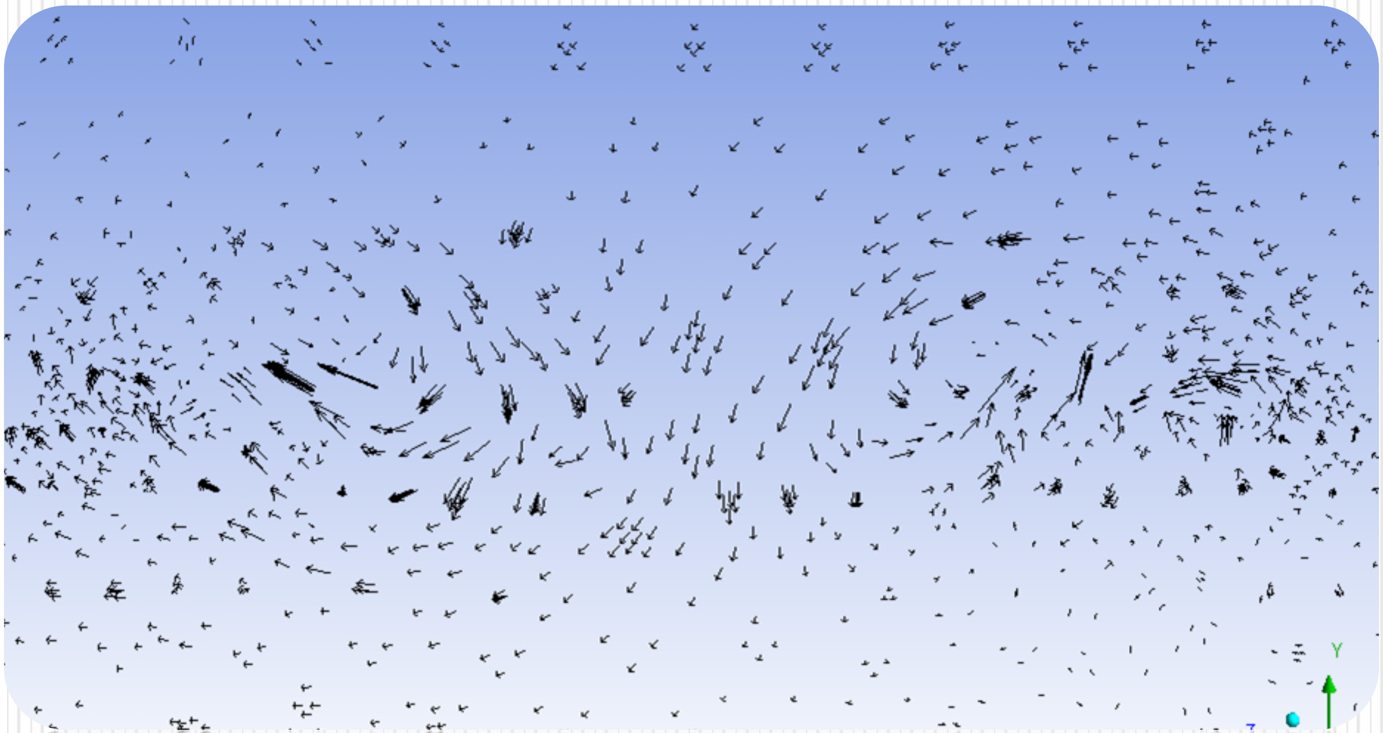


# Part I-Large Eddy Simulation of Short Field Wake Vortex

- We expect to use the generated data through LES simulation for different aircraft type
- Then, build a database using the simulation data for quick reference according to the aircraft pair information in practical approach operation.
- The database is in the form of wake turbulence separation consultative matrix for different aircraft pair
- Intended to be capable of acquiring more landing and take-off slots using the suggestion system

(a lot of work underway)

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Purpose of the Improved Dynamical Prediction Algorithm

  - *Dynamically calculate vertical position, separation history between port wake vortex and starboard wake vortex, as well as the circulation of the vortices and the lateral position increment.*

  - *Using backward difference to discretize the continuous linear differential equations to facilitate exploitation of numerical algorithm.*

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Basic Idea of the Improved Dynamical Prediction Algorithm

  - *Parameter inputs: cross wind profile, temperature profile, eddy dissipation rate (EDR), and other parameters such as: Brunt-Vaisala frequency, wing-span of aircraft etc. These are parameters abstracted from environment as well as the interested aircraft.*

  - *Divide the whole process of wake vortex dissipation as four phases with different strategy to treat them*

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Basic Idea of the Improved Dynamical Prediction Algorithm- introduction to 4 phases of dissipation

  - *Phase I: Vortex behavior during this phase is described by the turbulence governing equations presented by Sarpkaya in 2000. Thus dissipation rate mainly depends on the EDR according to the environmental temperature profile as well as cross-wind profile.*

  - *Phase II: The influence of ground effect on vortex pair is initiated in this phase but the vortices are still high enough in the air to prevent from generation of secondary vortices.*

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

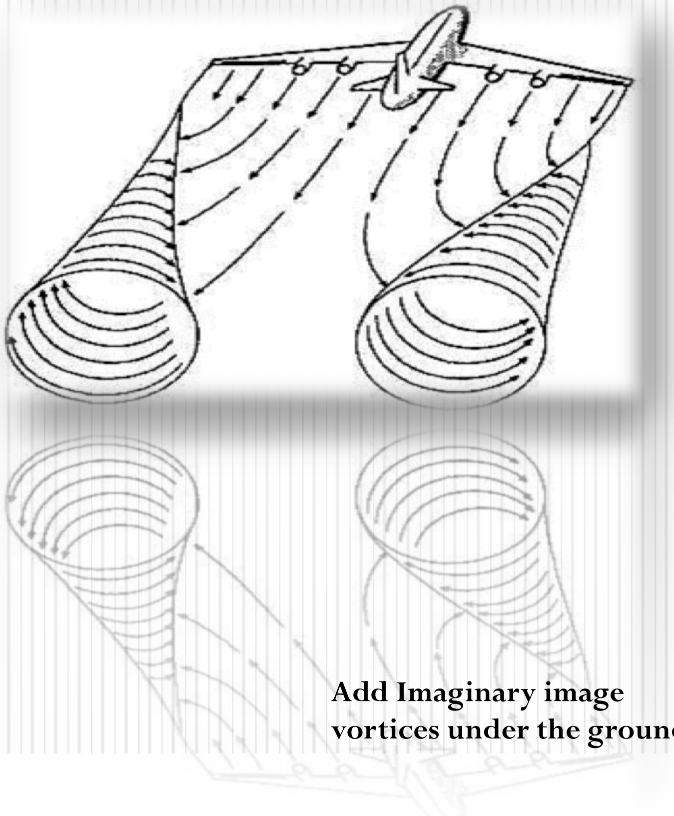
- Basic Idea of the Improved Dynamical Prediction Algorithm- introduction to 4 phases of dissipation

  - *Phase III: begins when the vortices approach close enough to the ground that their interaction with the ground produces secondary vorticity.*

  - *Phase IV: this is an extension of Phase III, but the secondary vorticity is strong enough to slow down the sink of original vortex pair.*

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- The Scheme Exploited to Generate Equivalent Effect of Secondary Vortices



Add Imaginary image vortices under the ground

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Continuous Differential Equations of Dynamic Dissipation Prediction of Wake vortex

$$\begin{cases} \dfrac{d}{dt}(Vb^2) = -b^2 C_2 B(z) - \dfrac{1}{2\pi}\dfrac{d}{dt}(b\Gamma_Q) \\ \dfrac{dz}{dt} = V \\ \dfrac{dy}{dt} = U(z) \end{cases}$$

$$Where \qquad \Gamma_Q(z) = \Gamma_0 \exp\left[-(C + 0.25N^2(z))\frac{T}{T^*(\varepsilon^*)}\right]$$

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Synthesized Continuous Differential Equations of Dynamic Dissipation Prediction of Wake vortex

  (to facilitate discretize using backward difference)

$$
\begin{cases}
\dfrac{dV}{dt} = -C_2 B(z) - 2V\left(\dfrac{1}{b}\dfrac{db}{dt}\right) + \dfrac{b_0}{b}\left[M\dfrac{V_0^2}{b_0} - V_0\left(\dfrac{1}{b}\dfrac{db}{dt}\right)\right] \cdot e^{-MT} \\
\dfrac{dz}{dt} = V \\
\dfrac{dy}{dt} = U(z)
\end{cases}
$$

# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Discrete Differential Equations of Dynamic Dissipation Prediction of Wake vortex

$$\begin{cases} \dfrac{\Delta V(n)}{\Delta t} = -C_2 B(n-1) - 2V(n-1)\dfrac{\Delta b(n)}{b} + \dfrac{b_0}{b(n-1)}\Delta\left(M\dfrac{V_0^2}{b_0} - V_0\dfrac{\Delta b}{b}\right)e^{-MT} \\ Z(n) = Z(n-1) - \dfrac{\Delta V(n-1)}{\Delta t}\Delta t = Z(n-1) - \Delta V(n-1) \\ Y(n) = Y(n-1) + U(n-1) \end{cases}$$

$$\textit{Where} \quad \Gamma_Q(n) = \Gamma_0 \exp\left\{-[C + 0.25N^2(n-1)]\frac{T}{T^*}\right\} \quad \textit{and} \quad n \in Z^+$$

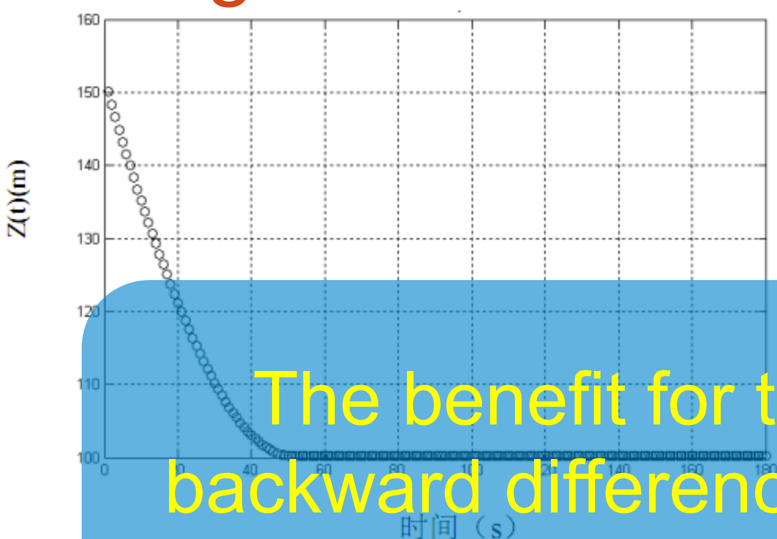
# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex

- Simulation of Boeing-747 Landing to 180 Runway in Beijing International Airport (ZBAA)  Using Discrete Algorithm

  - *The results of the simulation validated the sinkage phenomenon of wake vortex pair and also the linear accumulation of the lateral position of the vortices ,which is under the influence of crosswind.*

  - *Remark: The Temperature Profile as well as Cross-wind Profile used in simulation are in accordance with that of  NWRA AVOSS Wake Vortex Prediction Algorithm Version 3.1.1,  NASA STI Program Office, 2002.*

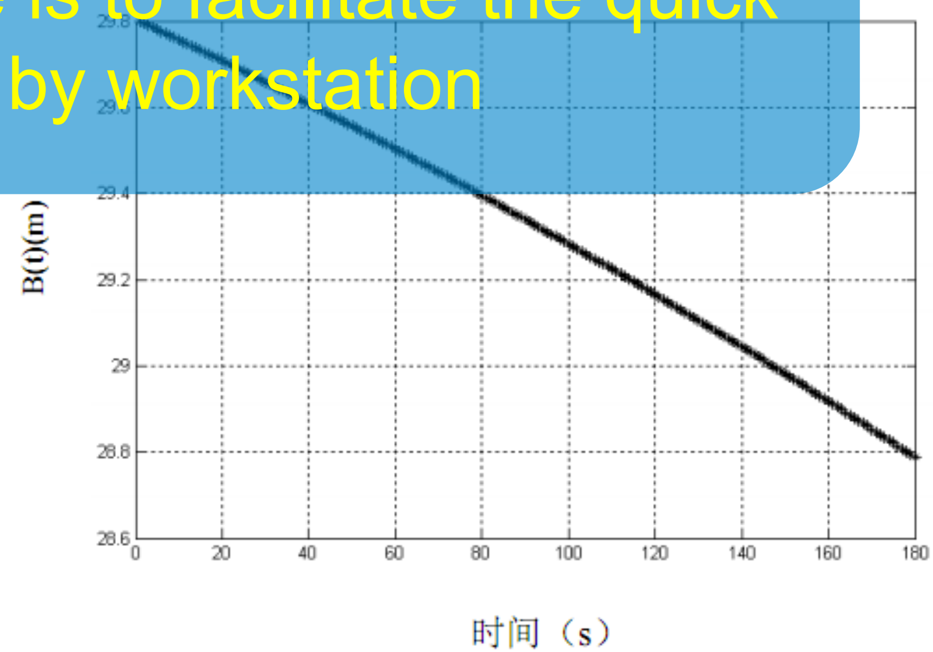
# Part II-Improved Dynamical Prediction Algorithm of Dissipation of Jet Wake Vortex




Altitude change of the vortices

The benefit for the discretization using backward difference is to facilitate the quick calculation by workstation

Distance between starboard vortex core and port vortex core



# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

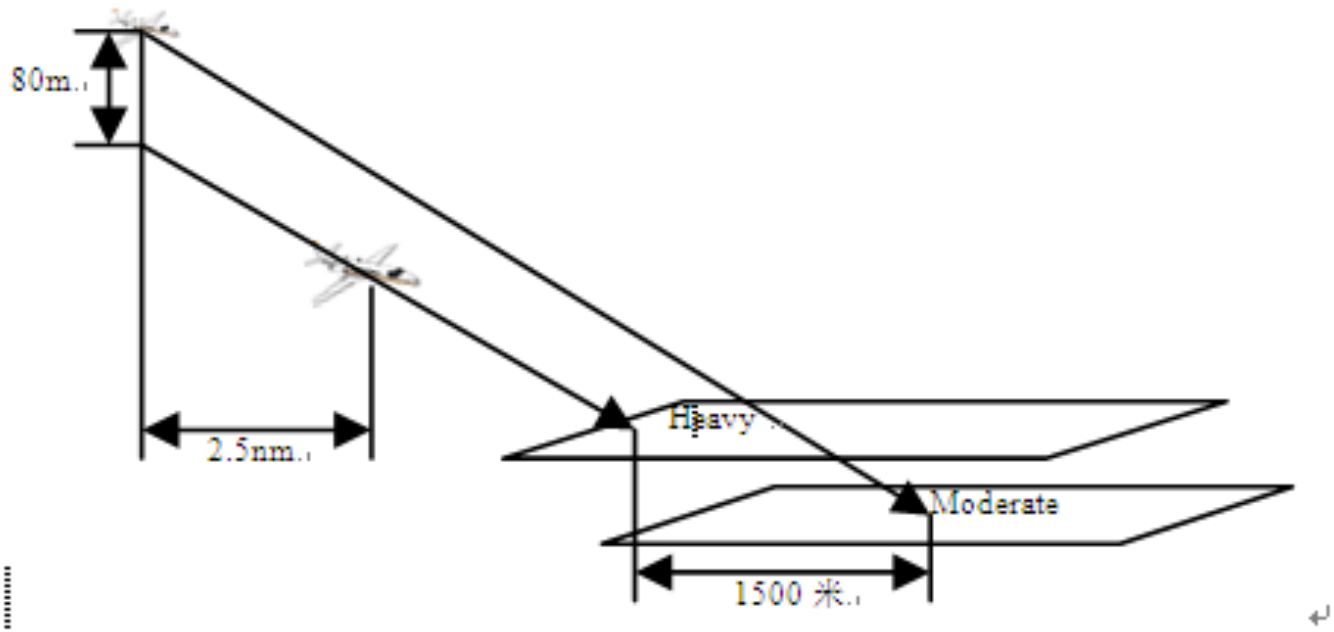
- Background & Motivation
- Flight delay is nowadays one of the most critical curbing factors in aviation industry.
- Massive research work on wake vortex separation reduction has been done by researchers all around the world.
- One of the developed technologies to date is to modify flight procedure aiming at the reduction of the wake vortex separation of closely spaced parallel runways.
- The other is to build wake turbulence prediction model in order to anticipate the dissipation and transportation of wake vortex.

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

- Wake vortex separation systems based on offset approach procedure

  - *HALS/DTOP: The high approach landing system/ dual threshold operation has been developed for Frankfurt Airport by DFS (Deutsche Flugsicherung GmbH) in 2000. Two aircrafts, staggered by radar separation, approach the parallel runways along two glide paths which are separated 80 m vertically and 518 m laterally. The aircraft approaching along the higher path lands at a new runway threshold which is installed 1500 m behind the first threshold. The system has been tested to work in CAT-1 with IMC conditions.*

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems



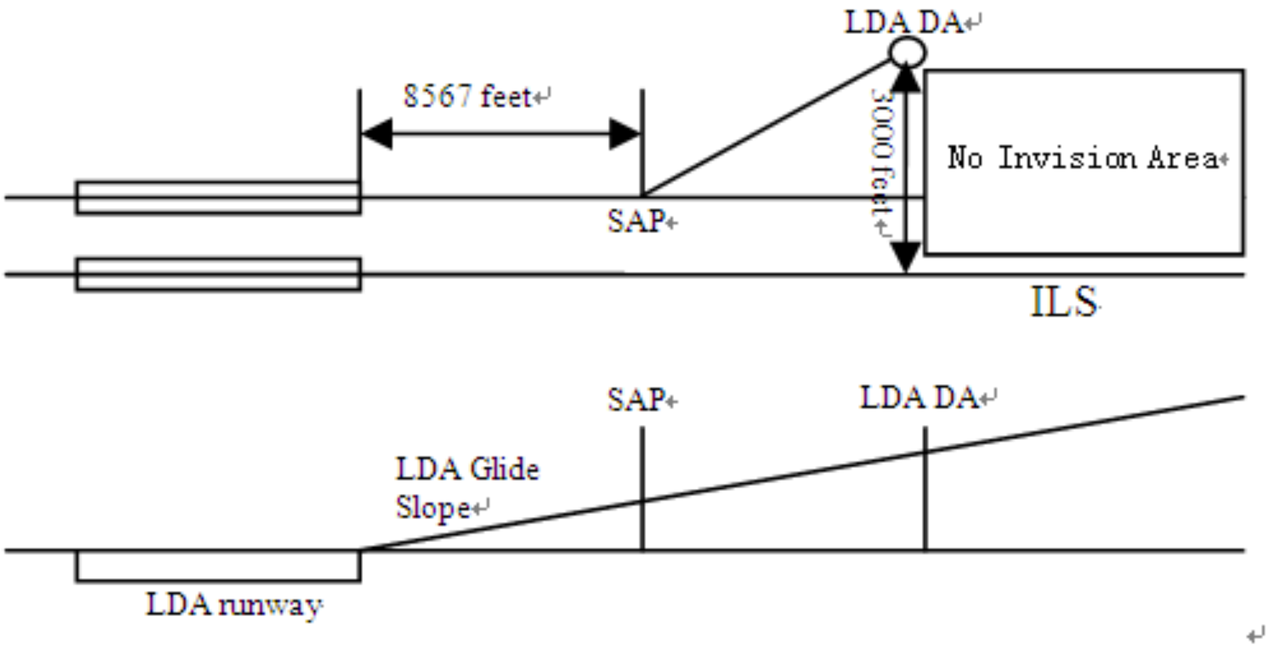

Capacity Gain 2.5% for FrankFort Airport

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

- Wake vortex separation systems based on offset approach procedure

  - *SOIA: The simultaneous offset instrumented approach is developed by FAA for San Francisco Airport where two runways separated by 255 m only prohibit independent operation under IMC. The system aims at simultaneous operations under IMC when the cloud ceiling is not lower than 1600 feed: Two aircraft approach non-staggered but safely separated by 3000 feet laterally until they reach the missed approach point at about 100 feed height and 3.3 nautical miles before the threshold. The final approach is then flown under VMC. Flight-simulator tests and trainings and wake-turbulence monitoring have been performed.*

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems




25% extra arrival flights allowed

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

- Wake vortex separation systems based on dynamic prediction

  - *WVWS: The Wirbelschleppen-Warnsystem initiated by DFS in the 1980s, has been developed for Frankfurt Airport where two closely spaced parallel runways (518 m apart) cannot be operated independently because wake vortices may be advected to the adjacent runway. The WSWS uses data from a wind line, a statistical wind forecast, and a vortex decay and transport model to predict minimum non-hazard times for the two runways at appropriated winds in IMC.*

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

- Wake vortex separation systems based on dynamic prediction

  - *SYAGE: The systeme Anticipatif de Gestion des Espacements was developed by CERFACS and STNA and uses ground-based wind measurements and the wake vortex model VORTEX to predict reduced separations for single runway departure. The system is implemented for tests at Toulouse-Blagnac Airport.*

3 more flights per hour with the probability of 80%

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

- Wake vortex separation systems based on dynamic prediction

  - *AVOSS: The Aircraft Vortex Spacing System is developed by NASA to produce weather dependent wake vortex spacing criteria in IMC for single runway approach. AVOSS provides current and predicted weather conditions and predicted wake vortex transport and decay. The functionality of the system was demonstrated in July 2000 at Dallas-Fort Worth Airport.*

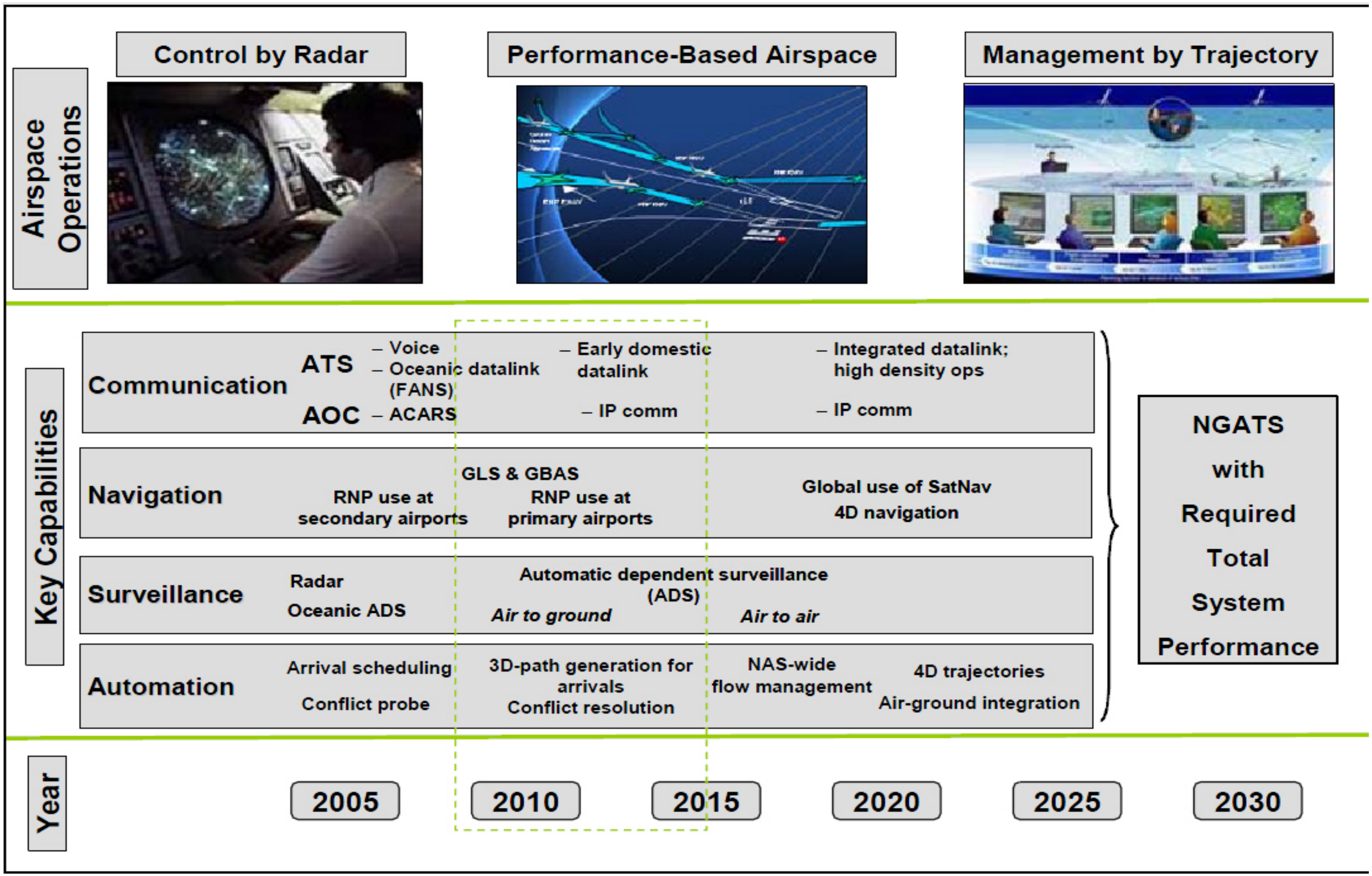
  - *Remark: This is a brief introduction of the wake vortex separation reduction systems and technology, for thorough analysis and in-depth evaluation refer to Xu Xiao-hao, Zhao Hong-sheng, Wang Zhen-yu, 2009, Overview of Wake Vortex Separation Reduction Systems, Acta Aeronautica et Astronautica Sinica,*

# Part III-Overview of Wake Vortex Separation Reduction Technology and Systems

6% (on average) capacity gain
0% to 16% capacity gain depending on weather
When 16% capacity gain is achieved, the wake vortex separation is almost the minimum separation for runway occupation

All of the work introduced before is part of the program directed by Prof. XU Xiao-Hao. The title is:
Analysis Model and Evaluation Method Research of Safety Separation in Air Traffic Control
(funded by national natural funds)

# Extra-Part: The error estimation in Performance Based Navigation and wake vortex



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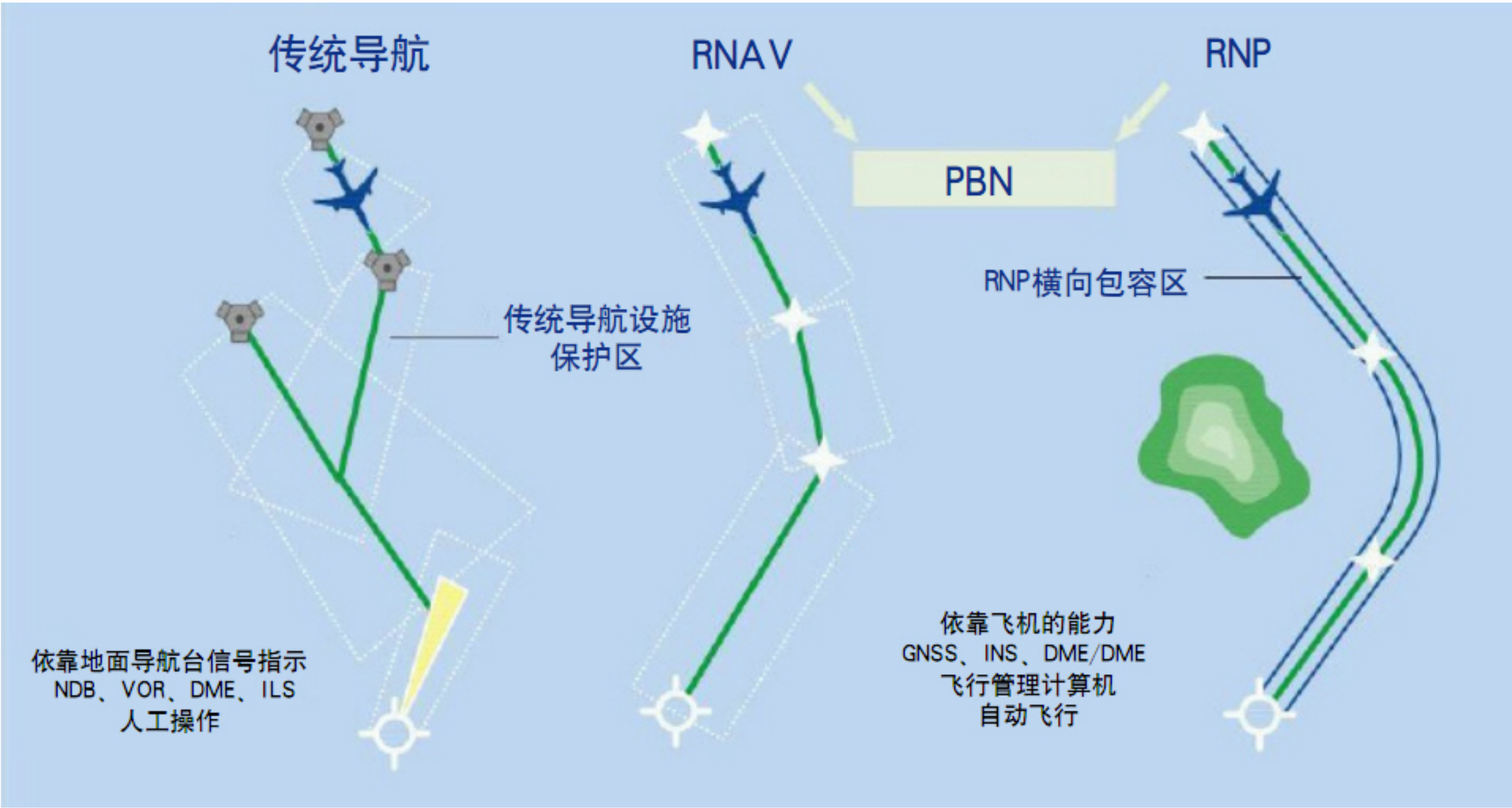

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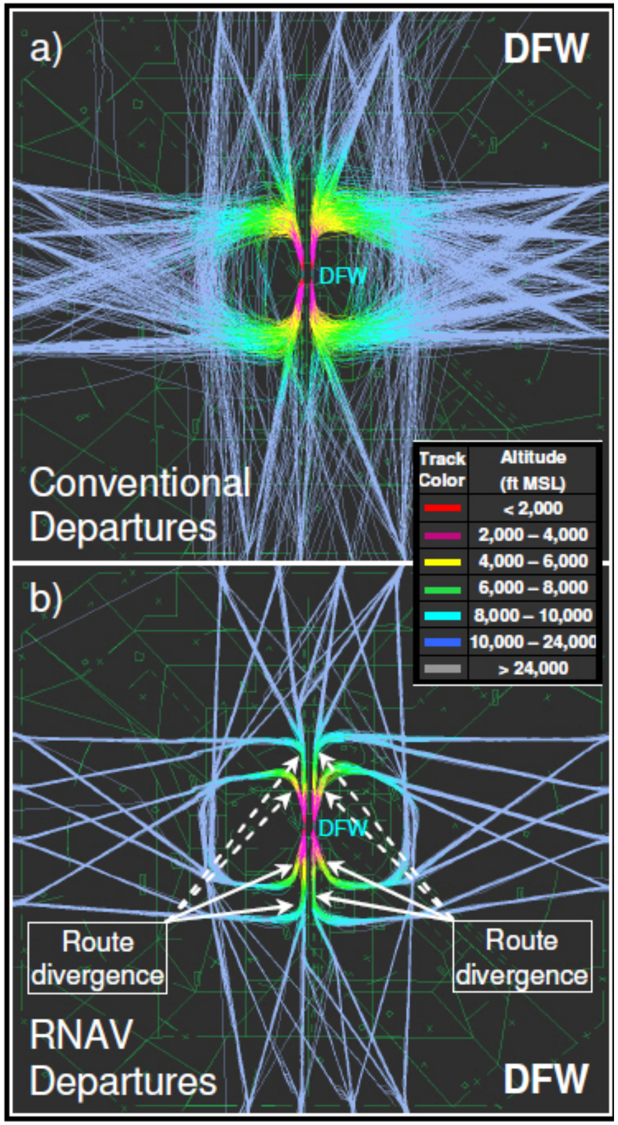
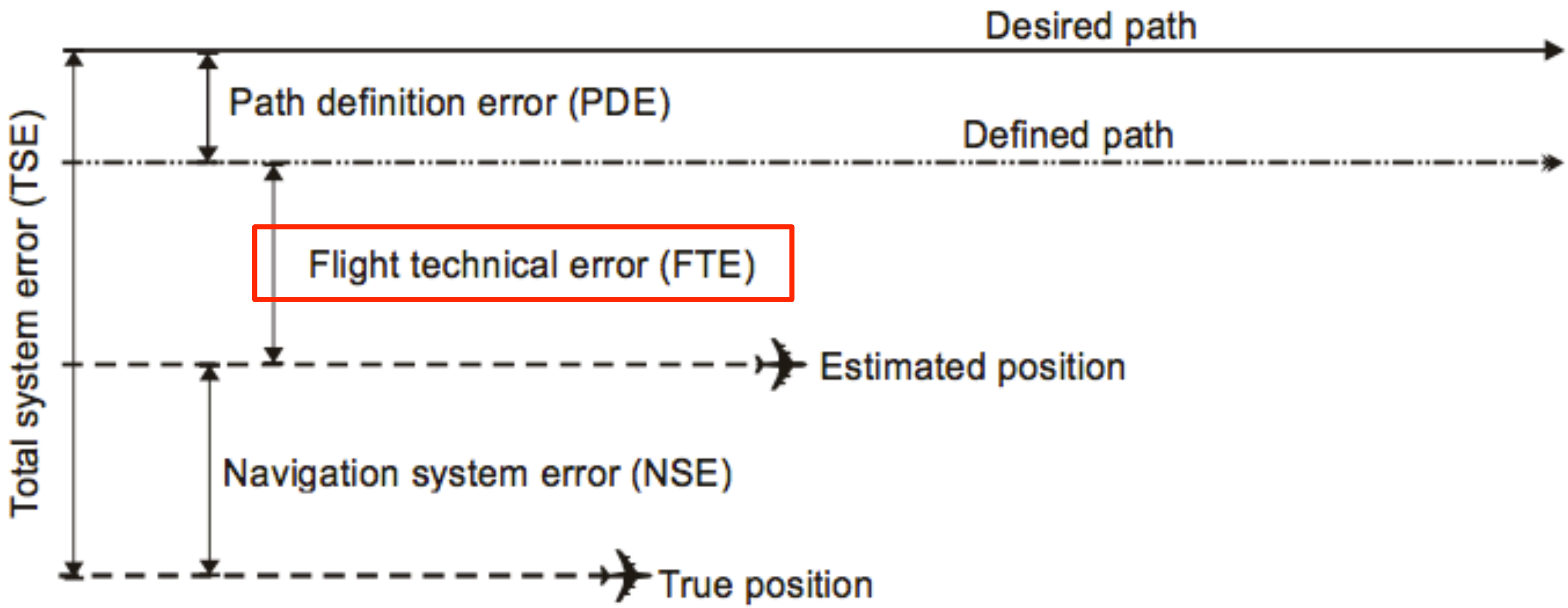



More accurate air route implementation, smaller protection area
Hence, keep separation better, more safe.

# Extra-Part: The error estimation in Performance Based Navigation and wake vortex



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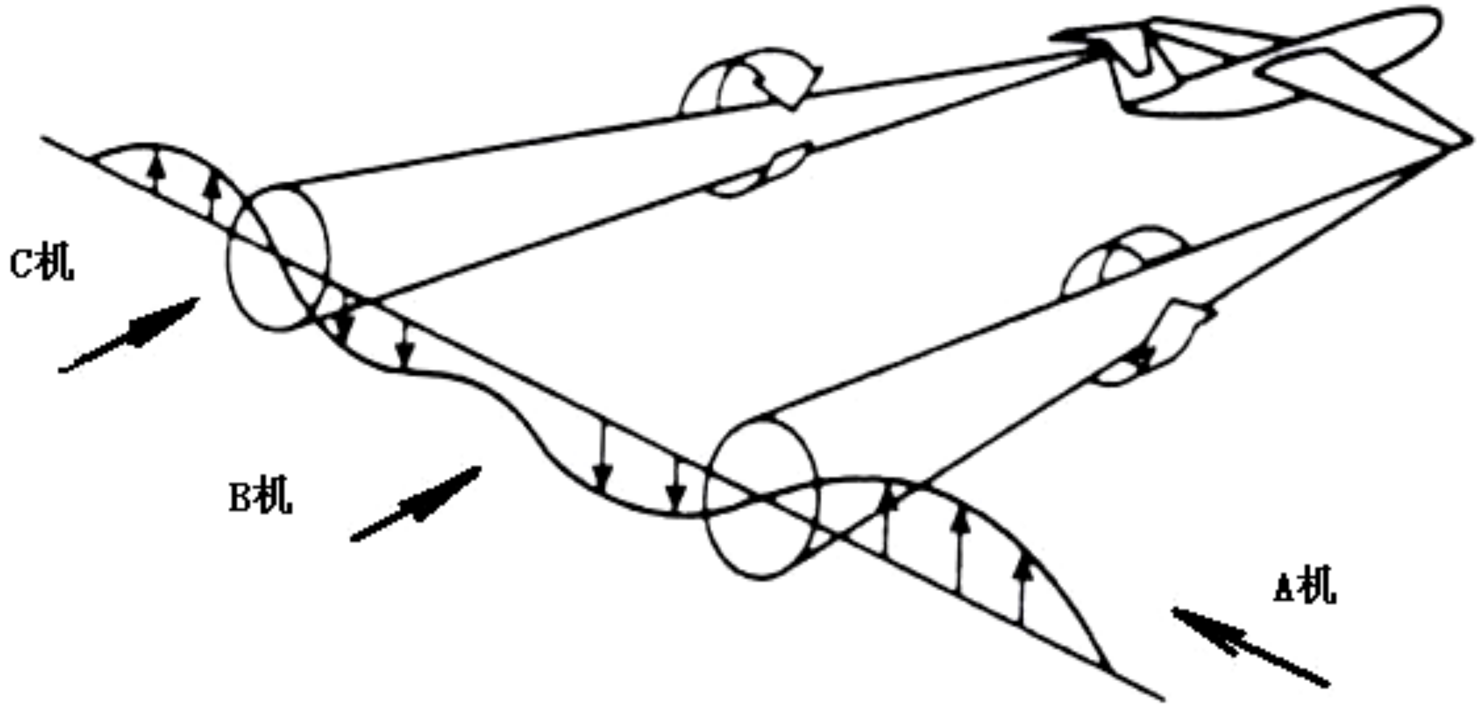

# Extra-Part: The error estimation in Performance Based Navigation and wake vortex

Possible Solution: wake turbulence inform on primary display in advance to enable crew to prepare for probable RNP on-board navigation performance alerting.
If the info of wake turbulence includes intensity indication, there will be better effect and

Encounter with wake turbulence causes the flight technical error of following aircraft increase greatly and unexpectedly, thus hinders the PBN (performance based navigation) implementation.

*This is the end*

*Thanks for your patience.*