NWRA *NorthWest Research Associates, Inc.*
Redmond, WA

Development of the VIPER Fast-Time Wake Vortex Model

(Development, Assumptions, Examples, and Plans)

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Acknowledgements

- VIPER is being developed for the U.S. Federal Aviation Administration
  - Will be used to predict the evolution of aircraft-generated wake vortices under a variety of atmospheric conditions and aircraft flight regimes for evaluating new, proposed operational procedures
- Steve Barnes at AFS-440 is the Program Manager
- Wayne Bryant is also involved
- The support of both Steve and Wayne is gratefully acknowledged

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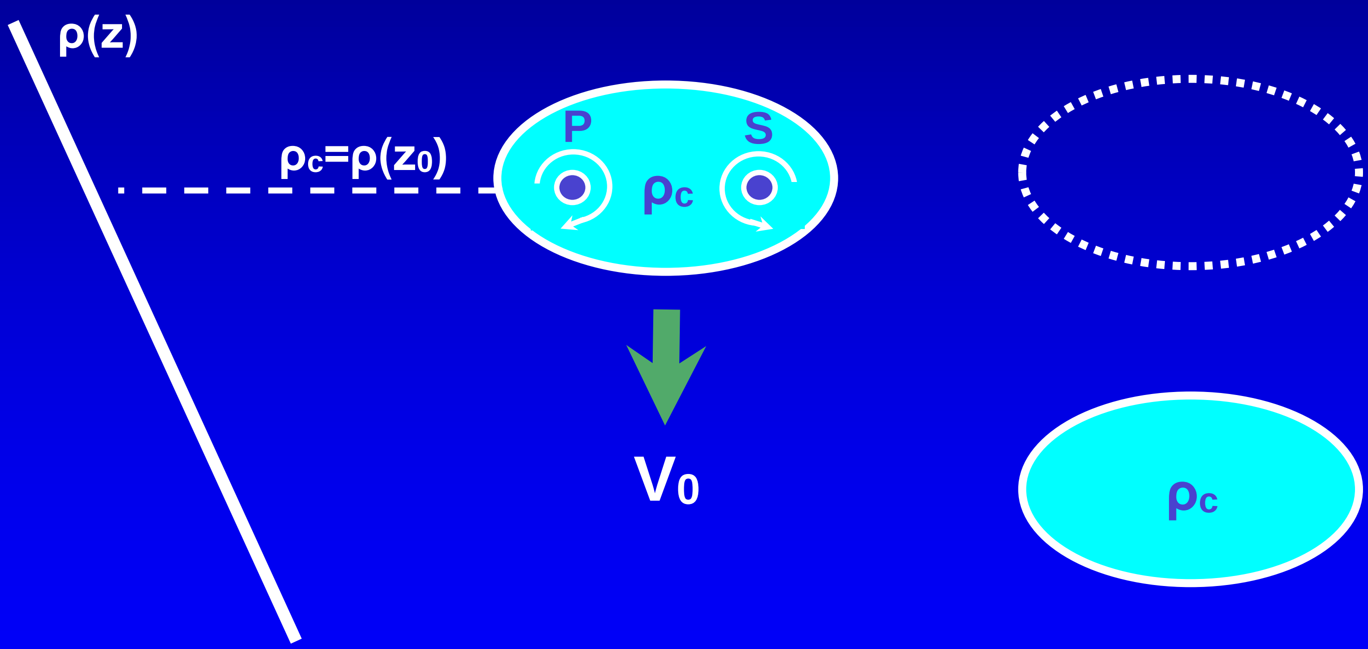
What Is VIPER?

- A new fast-time wake vortex model
- VIPER stands for Vortex algorithm Including Parameterized Entrainment Results
- Self-consistent model based on control-volume analyses and the fluid laws for conservation of mass, momentum, and angular momentum

Why a New Fast-Time Wake Model?

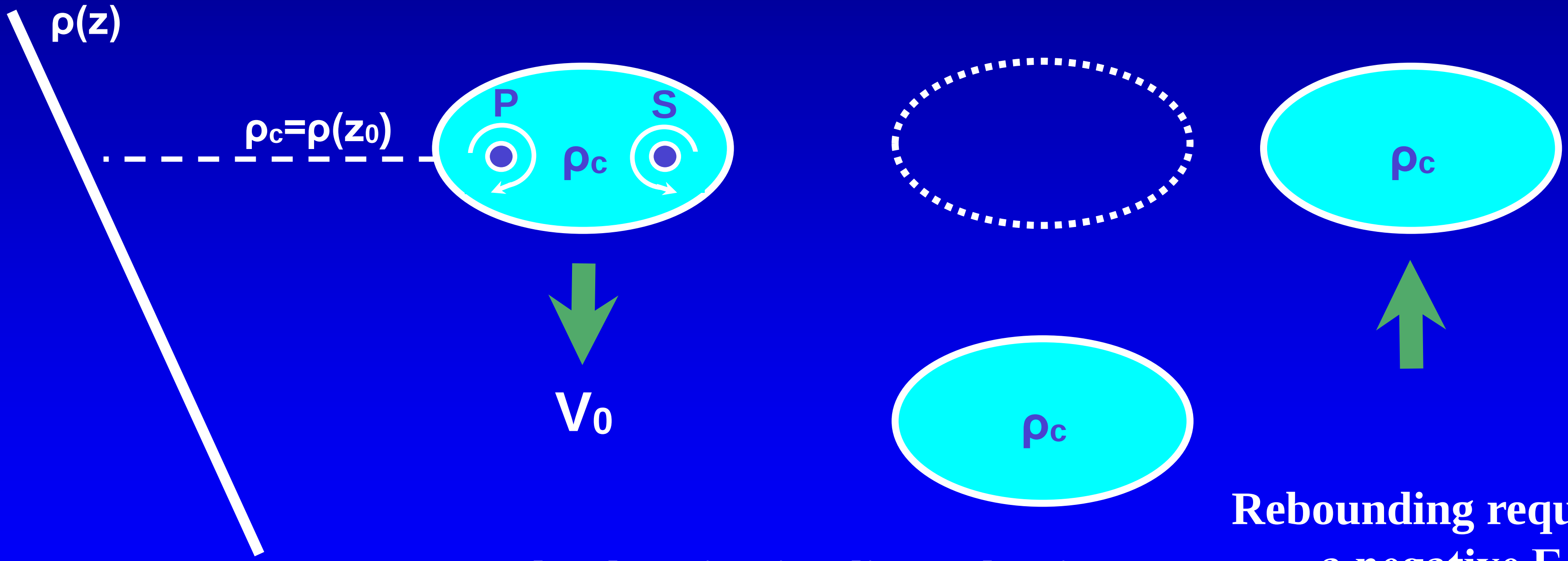
- Want consistent treatment of stratification and entrainment/detrainment of fluid from the wake oval
  - Use recent advances in our understanding from lab experiments, LES simulations, and field observations
- Example: Nearly all models assume the wake cell density is constant with time
  - But, we know this is not true

Many Models Assume Constant Wake Cell Density



Many Models Use Circulation to Get V

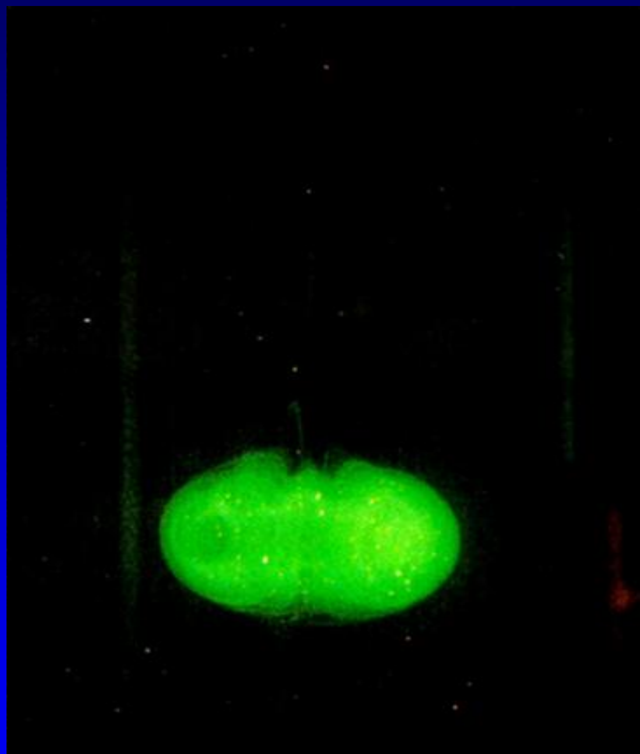
- $V = \Gamma / (2\pi\, b)$ $\quad \therefore\ \Gamma \rightarrow 0$ as $V \rightarrow 0$
- Not consistent with buoyancy



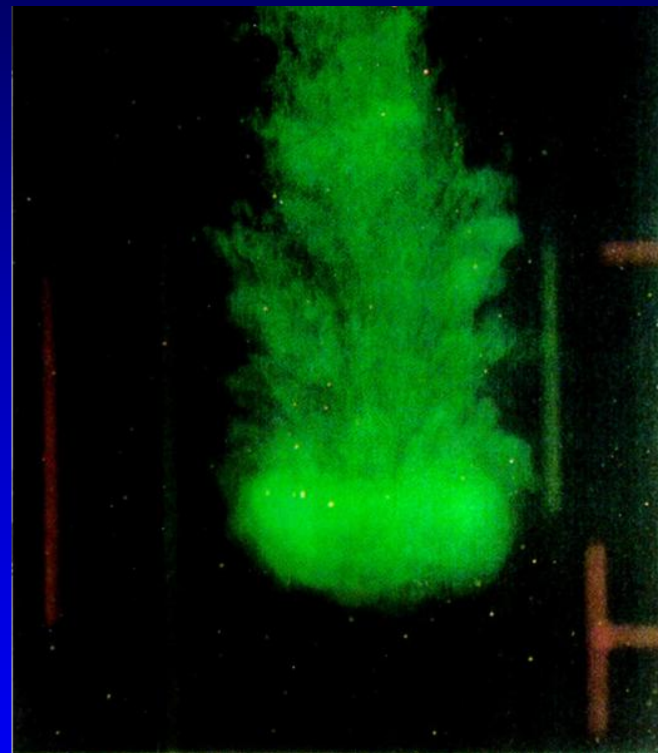
Buoyant deceleration implies reduction in Γ as wake oval descends

Rebounding requires a negative Γ

NWRA Lab Experiments Demonstrate Importance of Entrainment and Detrainment



Laminar Vortex Ring
Re=3,000

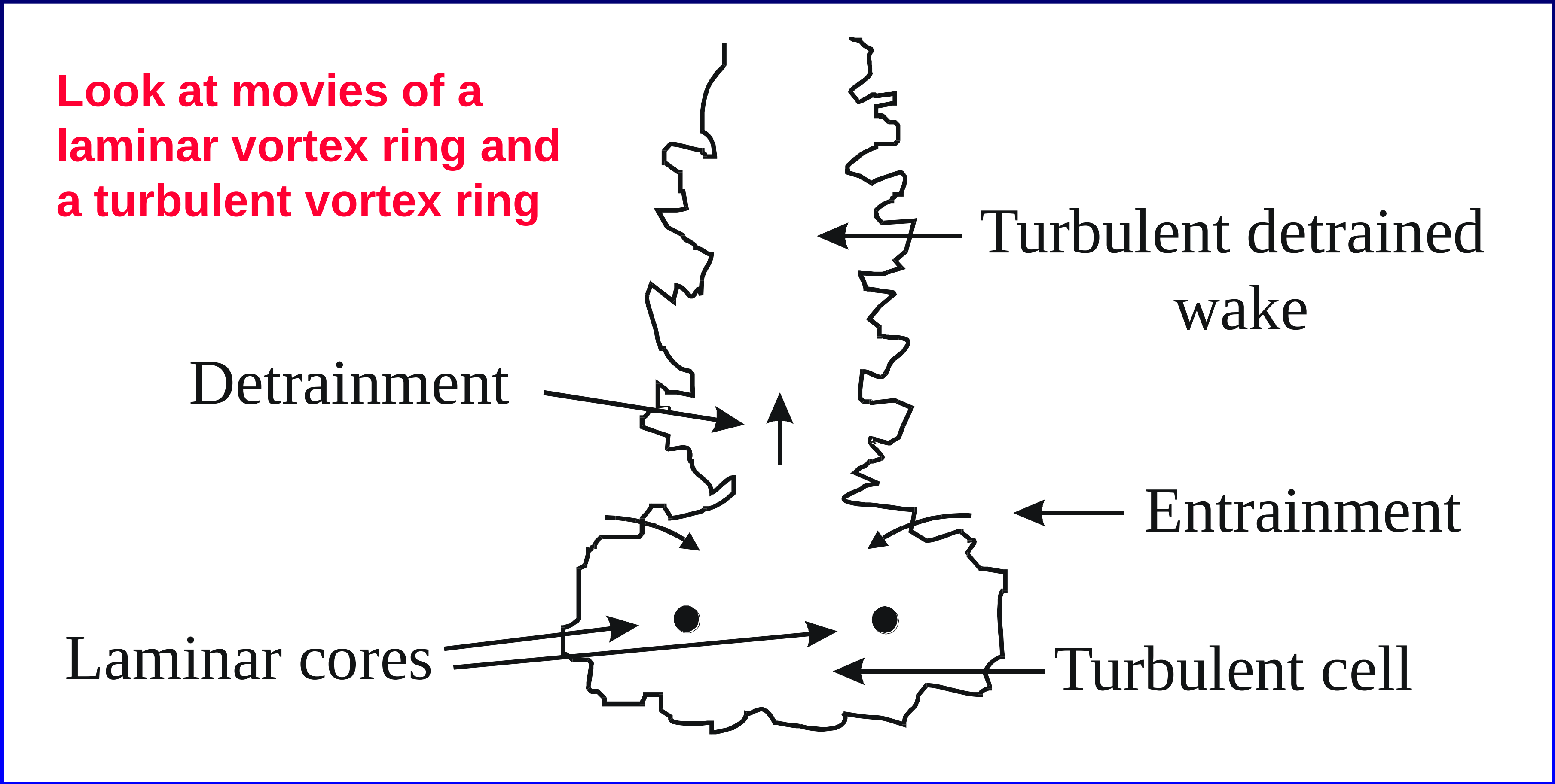


Turbulent Vortex Ring
Re=12,000

Fluid exchange must be modeled to properly characterize buoyancy

(Delisi and Pierce 2011, Circulation Measurements of Merging Vortex Rings, AIAA 2011-3033)

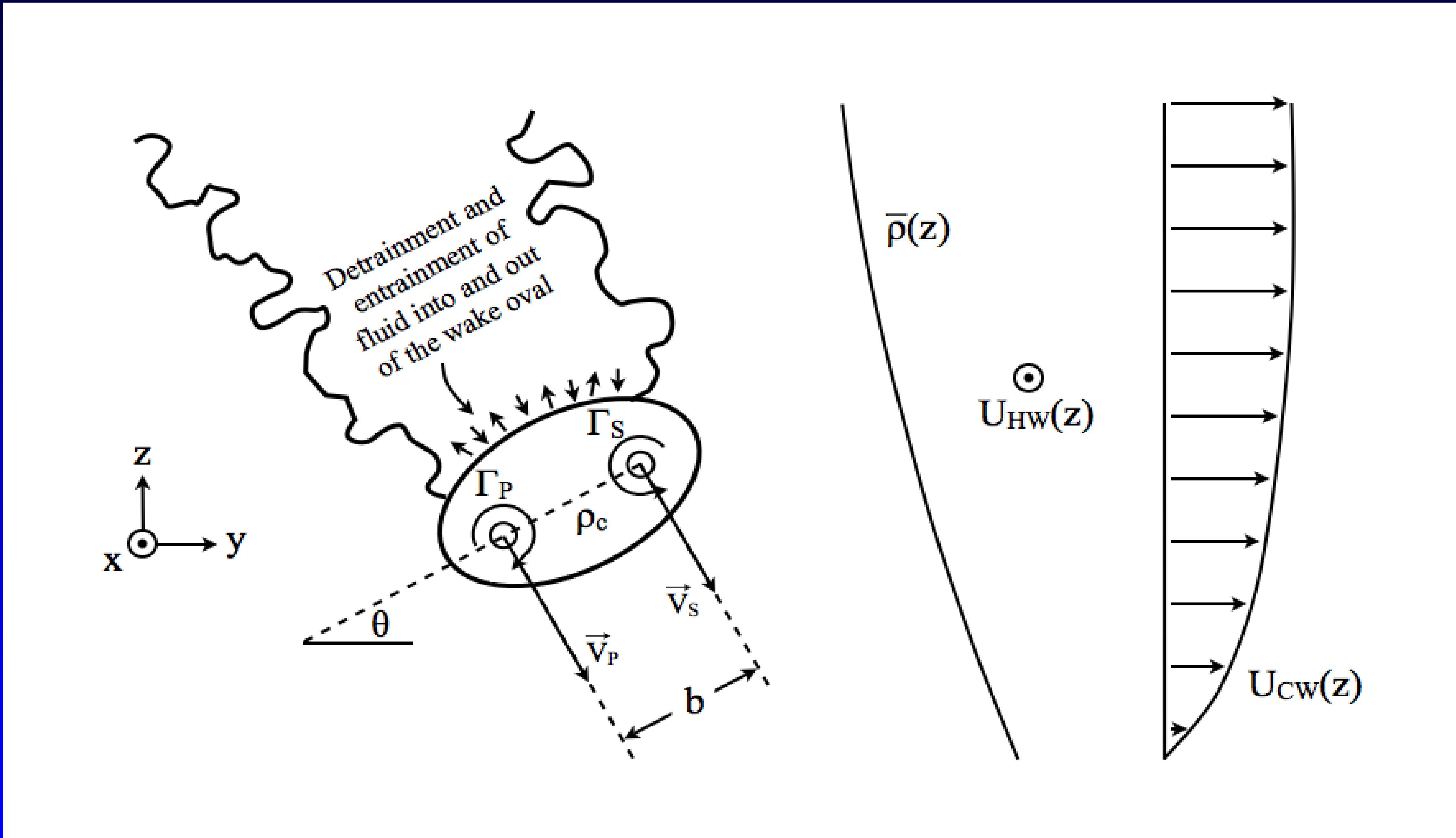
Our Current Picture of the Turbulent Vortex Cell



Entrainment-Based Modeling Approach (What We Did)

- Introduced an entrainment model to detrain wake momentum and buoyancy from the wake vortex cell with turbulent vortices
- Self-consistent treatment of mass, momentum, and angular-momentum conservation laws
- Self-consistent treatment of ambient meteorological data (HW, CW, stratification, and turbulence)
- Allows V=0 at finite Γ
- Obtained model constants from aircraft landing data

The Model



Includes: Entrainment/detrainment from trailing edge of wake oval, stratification, headwind, crosswind and crosswind shear gradients

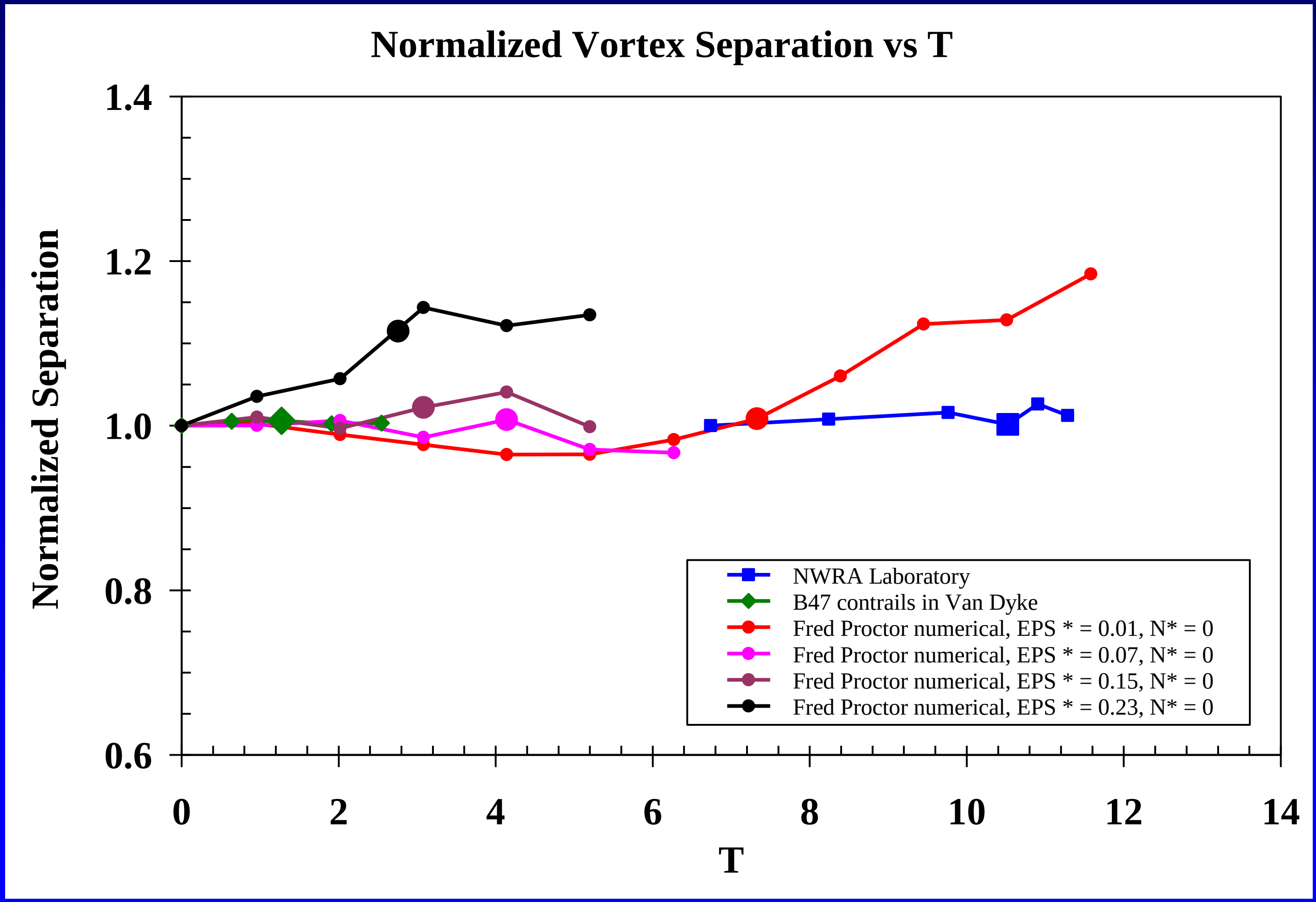
Model Assumptions (1 of 5)

- The wake oval density, ρ_c, varies with time as ambient fluid is entrained into and wake cell fluid is detrained out of the wake oval
- The wake oval density is rapidly mixed and is, therefore, taken to be spatially uniform throughout the wake cell
  - We know this is wrong since the cores and cell detrain at different rates. This will be modified in the next version.

Model Assumptions (2 of 5)

- Wake oval cross sectional area, A, is approximately constant during the wake cell evolution
  - Found from NWRA lab experiments; also seen in LES simulations
  - Also implies b does not change with time (see next slide)

Average b vs. T from Lab, Field Data, and Numerical Simulations



Model Assumptions (3 of 5)

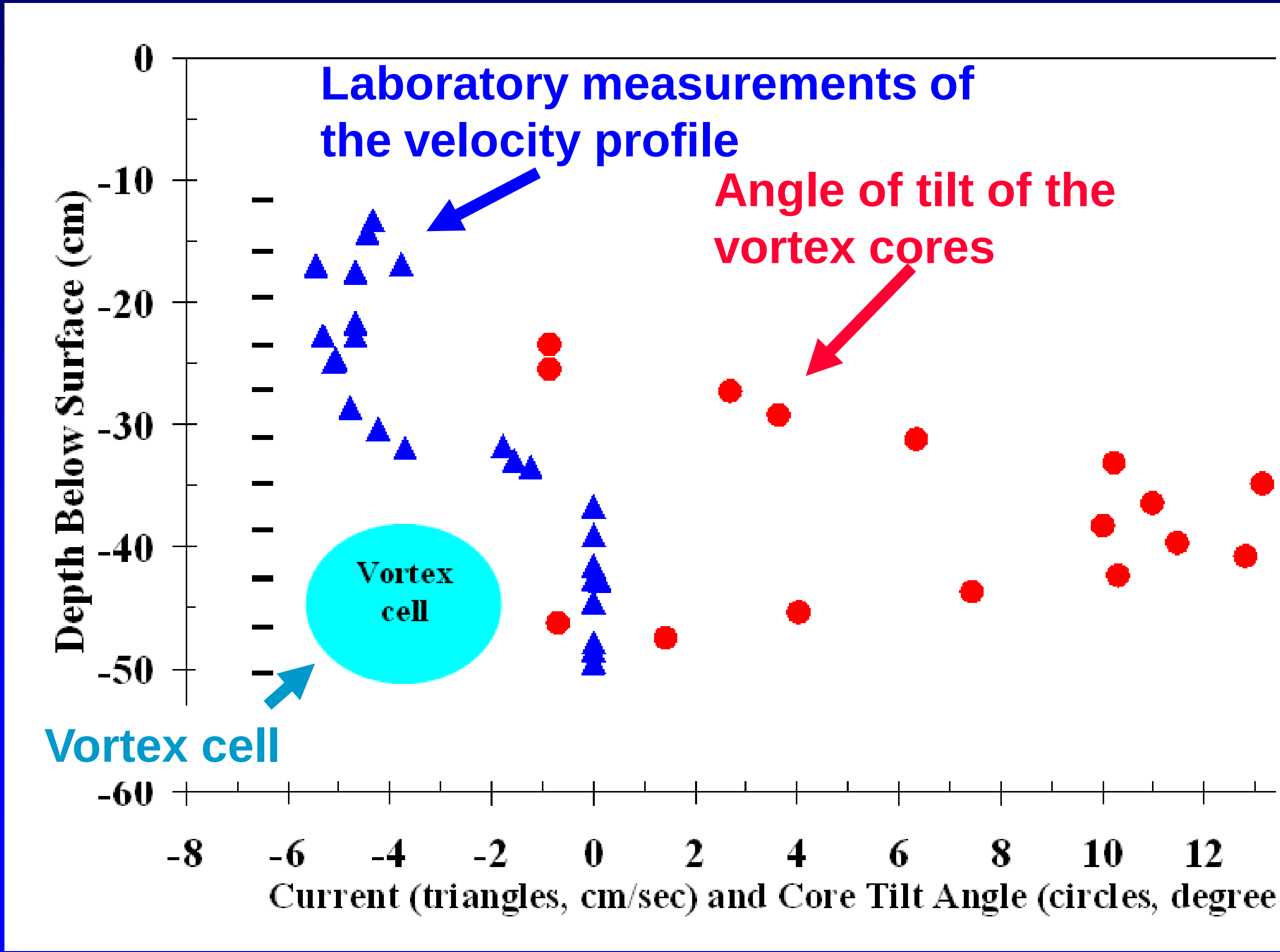
- Entrainment and detrainment occur at the trailing edge of the propagating wake cell
  - Inferred from the movie earlier
- Entrainment and detrainment can be quantified in terms of an entrainment velocity, u_e, which is proportional to the shear velocity, ΔU, at the edge of the wake cell ($u_e = c_e \Delta U$)

Model Assumptions (4 of 5)

- Entrainment rates for mass, momentum, and angular momentum are allowed to be different from each other
- Variations in the atmospheric wind profile are gradual compared to the size of the wake cell
  - Shown to be justified from NWRA lab experiments with vortices in crosswind shear

NWRA Lab Experiments on Vortex Tilting in a Shear Flow

(Delisi and Robins, 2006, Effects of Crosswind Shear on Trailing Vortex Evolution, AIAA 2006-1075)

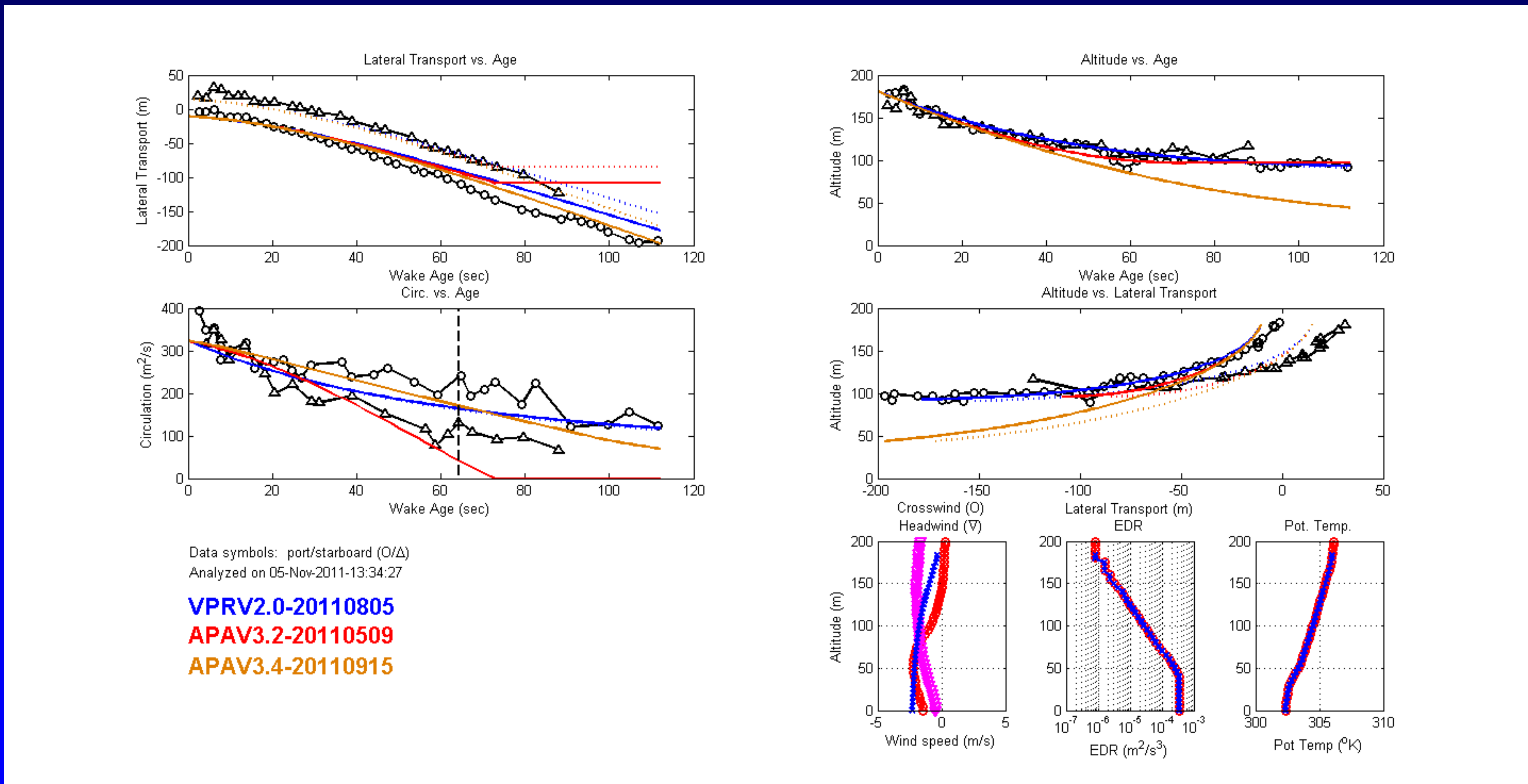


Tilt of vortex cores begins when the vortex cell first enters the region where the shear gradient is non-zero, and returns to zero when the vortex cell leaves the region where the shear gradient is non-zero. Thus, the shear gradient acts on the entire vortex cell, not just the vortex cores, and small perturbations not important.

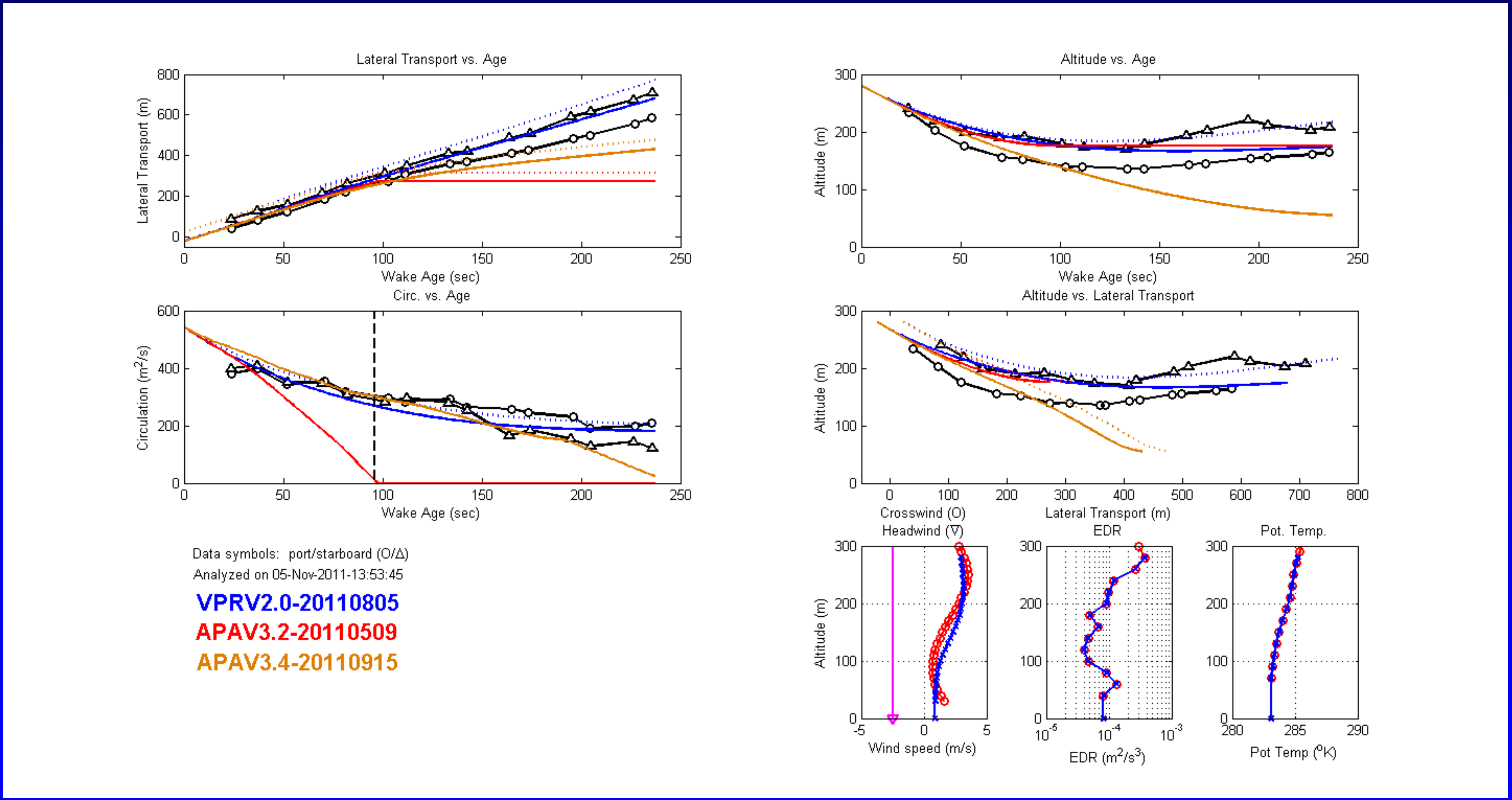
Model Assumptions (5 of 5)

- The aircraft glide slope angle is 3°
  - 3° is a typical glide slope angle
- The direction of propagation of the vortex pair is perpendicular to their separation
- The vortex pair is completely rolled up by the time we model it
  - Does not include detailed vortex rollup

Example #1: Low Shear Gradient, High Stratification, Low EDR



Example #2: Shear Gradient, Moderate Stratification, Moderate EDR



Development of an IGE Model

- The APA model is not a physics-based IGE model
  - In the APA-series of numerical models, the IGE region is modeled with a series of point vortices. These vortices are numerically efficient, but are not physically realistic, since they do not decay unless a user-defined circulation decay is prescribed. These vortices also ignore the effects of stratification and EDR.
- A physics-based IGE numerical model is currently being developed to combine with the OGE model

Future Plans (1 of 2)

- Continue IGE development
- Improve OGE model:
  - Include Magnus effect for spinning objects in mean wind
    - Why? Differing descent rates for vortices with identical circulation magnitudes are observed in the field data

Future Plans (2 of 2)

- Model vortex cores separately from their wake half-cell
  - Why? We know from NWRA lab experiments that entrainment rates, and therefore densities, differ for vortex cores and the wake oval
  - (Delisi and Lai, 2011, Detrainment from a Vortex Pair in a Nonstratified Fluid, Recent Progress in Fluid Dynamics Research, American Institute of Physics Press)

Questions for This Workshop

- What are the important aspects of OGE to model that are not being modeled?
- What are the important aspects of IGE to model?
- How much can we use field data and/or LES simulations as “truth”?

Questions?