Wake Vortex Tangential Velocity Adaptive Spectral (TVAS) Algorithm for Pulsed Lidar Systems

Hadi Wassaf
David Burnham
Frank Wang
Communication, Navigation, Surveillance (CNS) and Traffic Management Systems (RVT-70)

Coherent Laser Radar Technology CLRC XVI
June 20-24, 2011

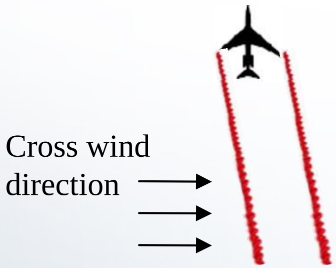
John A. Volpe National Transportation Systems Center

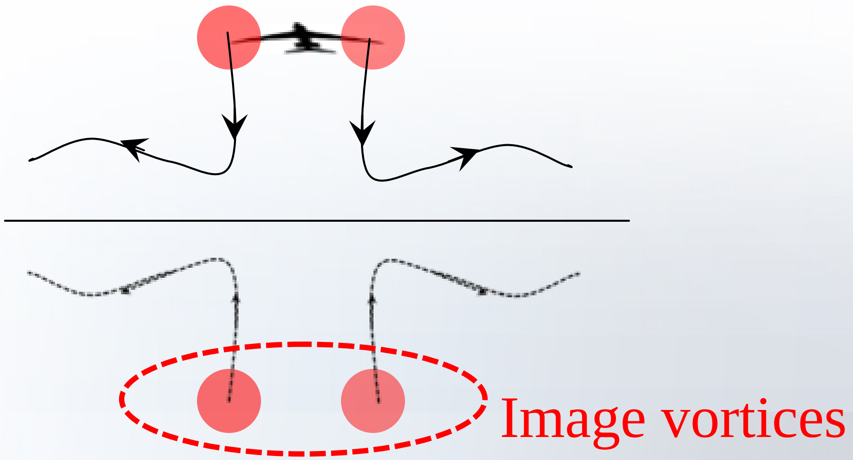
U.S. Department of Transportation
Research and Innovative Technology Administration

Background (1/3)

- Wake vortices are counter rotating flow structures that are an inevitable bi-product of generating lift.

- Wake encounters can be hazardous, and therefore, statistical characterization of measured wake motion and decay are important for designing new ATC procedures aimed at safely increasing airport capacities.



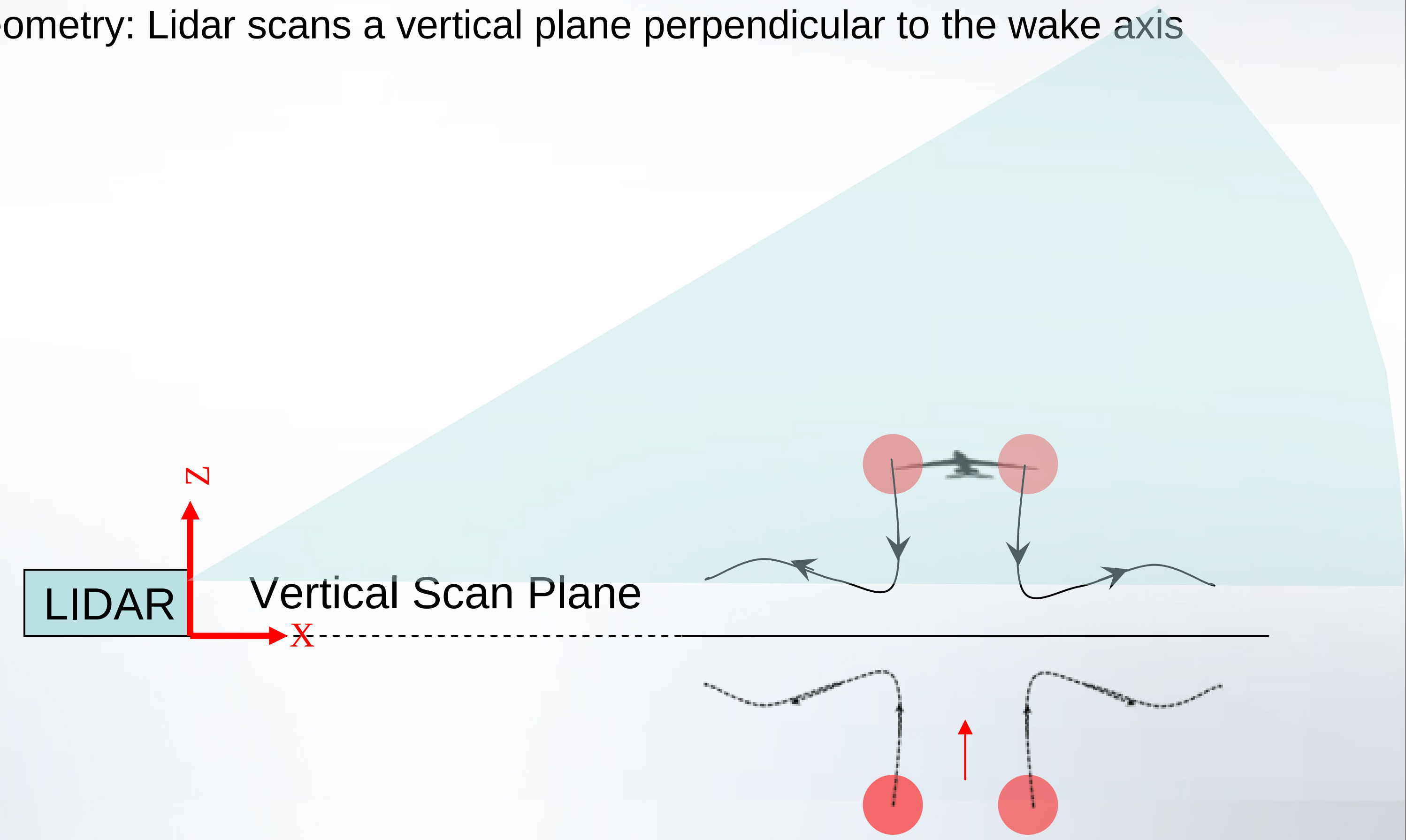


Background (2/3)

- Doppler Lidar is a major enabling technology for measuring aircraft wake vortices.
  - Continuous wave (CW) Lidars:
    - have good spatial resolution (on the order of few meters) and are effective for short range tracking and vortex strength characterization.
    - They suffer from short range on the order of 150 m after which the resolution is lost.
  - Pulsed Lidars:
    - Capable of providing long range measurements (Few km’s).
    - Range resolution is less than CW Lidars (~60 m), but is independent of distance to target.
    - Since the late 1990’s Pulsed Lidar has been the preferred technology for wake data collection. This data has been used for changing and establishing wake turbulence standards

Background (3/3)

- Scanning geometry: Lidar scans a vertical plane perpendicular to the wake axis



Motivation

- To date LMCT matched-filter software is the only commercially available wake vortex processing package. Having an alternative government owned processing package has the following advantages:
  - Outlier analysis can benefit from having more than one processing algorithm.
  - A Government owned software can be modified and improved in house to meet future processing needs.
  - Improving FAA future data processing capability and flexibility requires the decoupling of processing software from the Lidar hardware so that Lidars from different manufacturers can be more easily adapted for wake data collection.

- In 2008 the FAA Tasked the Volpe Center with the development of a processing package capable of wake detection, tracking and characterization. The result is the Tangential Velocity Adaptive Spectral (TVAS) algorithm.

First Section:

TVAS Description

TVAS Algorithm Description

- In order to complement rather than duplicate the LMCT processing, the decision was made to use the algorithm published by DLR in 2004 as a baseline for localization and circulation estimation with additional Enhancements. The main elements of the TVAS algorithm are:
  - Detection
  - Localization
  - Circulation Estimation
  - Kalman Filter (KF) Based Automated tracking← **Will be discussed in future publications.**

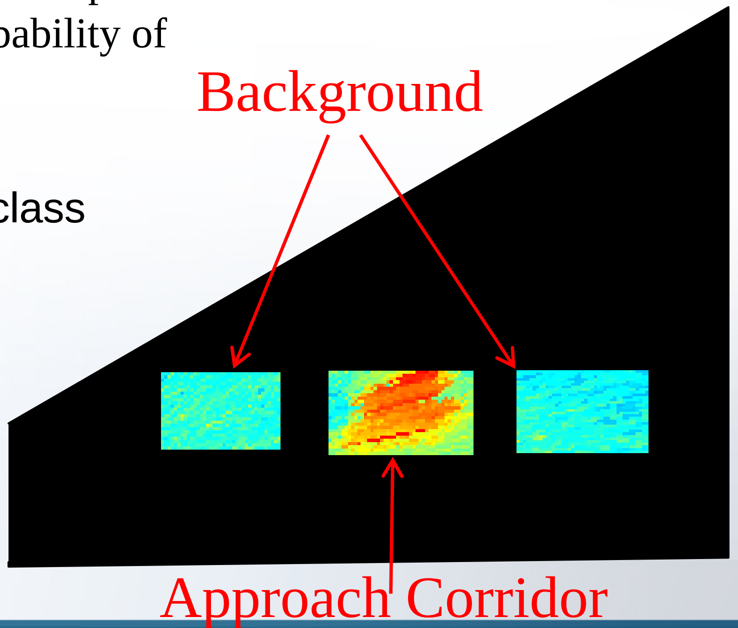
Detection

- The ratio D of the mean spectral width in the approach corridor to that of the background is compared against a threshold.

$$D = \frac{mean(\sigma_{fA})}{mean(\sigma_{fB})}$$

- This is tuned based on statistics of this ratio over an observation period when no wakes are present setting the threshold so that probability of false alarm $P_{FA}=10^{-3\sim-4}$.

- This approach proved robust for Medium ICAO wake class aircraft and larger.

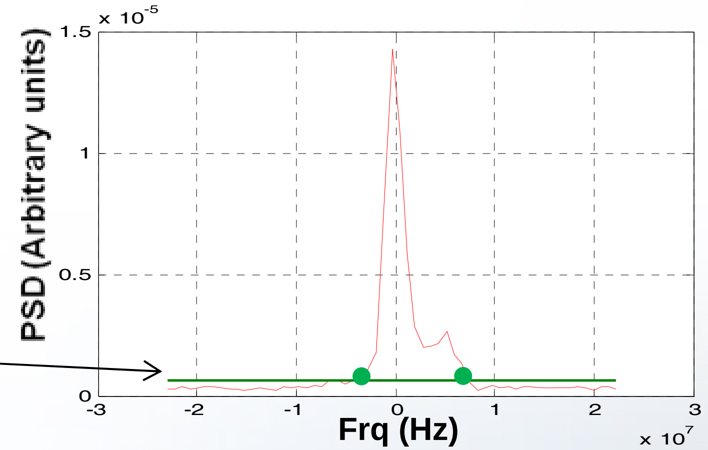


Localization (1/2)

First, calculate envelope velocities:

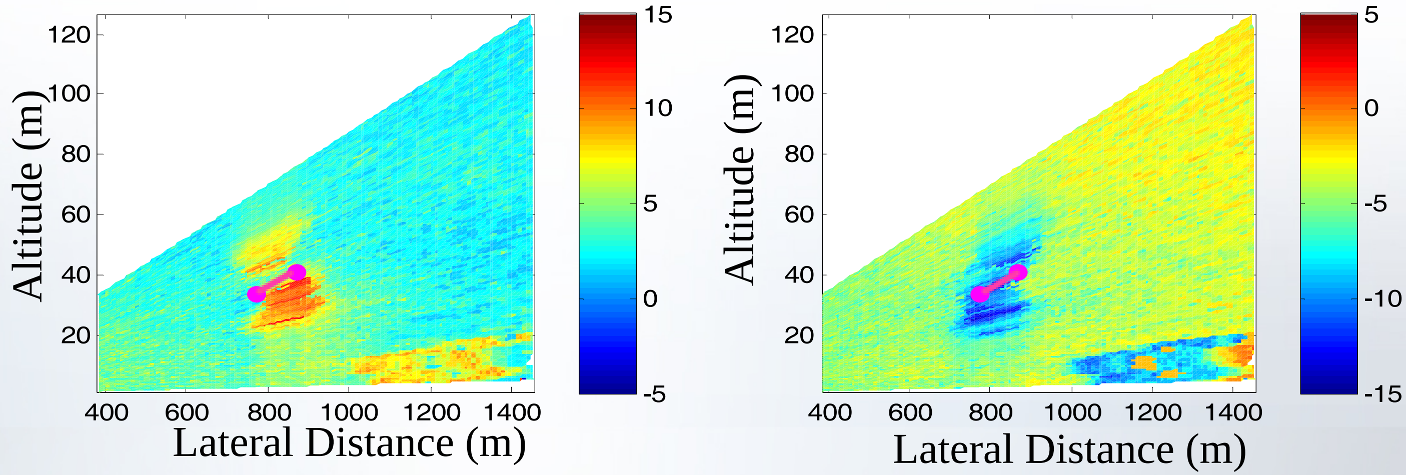
- The spectrum from each RG at location (R, ϕ) is considered
- A threshold that adapts to SNR is applied to generate a negative and positive envelope velocities.

$$T(R,\phi) = k.\hat{N}.\frac{SNR(R,\phi)}{SNR_o}$$



Localization (2/2)

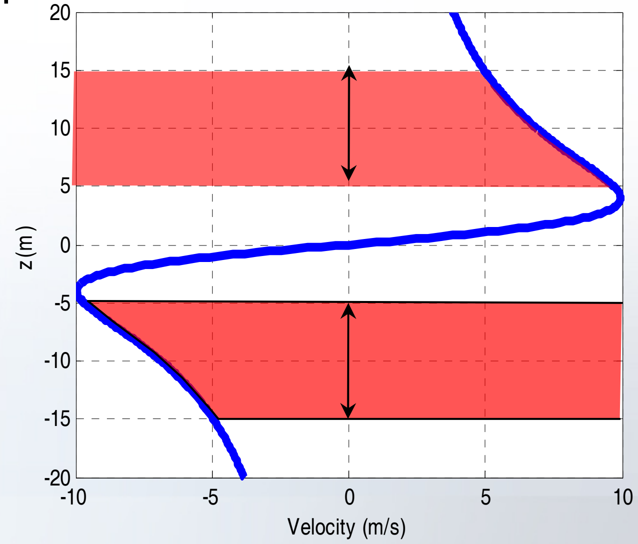
- Second, perform peak association and calculate the core position as the mid point between the maximum positive and negative velocities associated with each vortices
  - First Scan:
    - Image processing techniques are employed during the first scan to segment out large velocity regions that are potentially wake related
    - All possible positive/negative region associations are considered and the ranked based on separation and velocity magnitudes. The association that is most consistent with a wake structure is selected.
  - Subsequent scans: Search regions are predicted using a Kalman Filter with an optional manual override



Circulation Estimation (1/4)

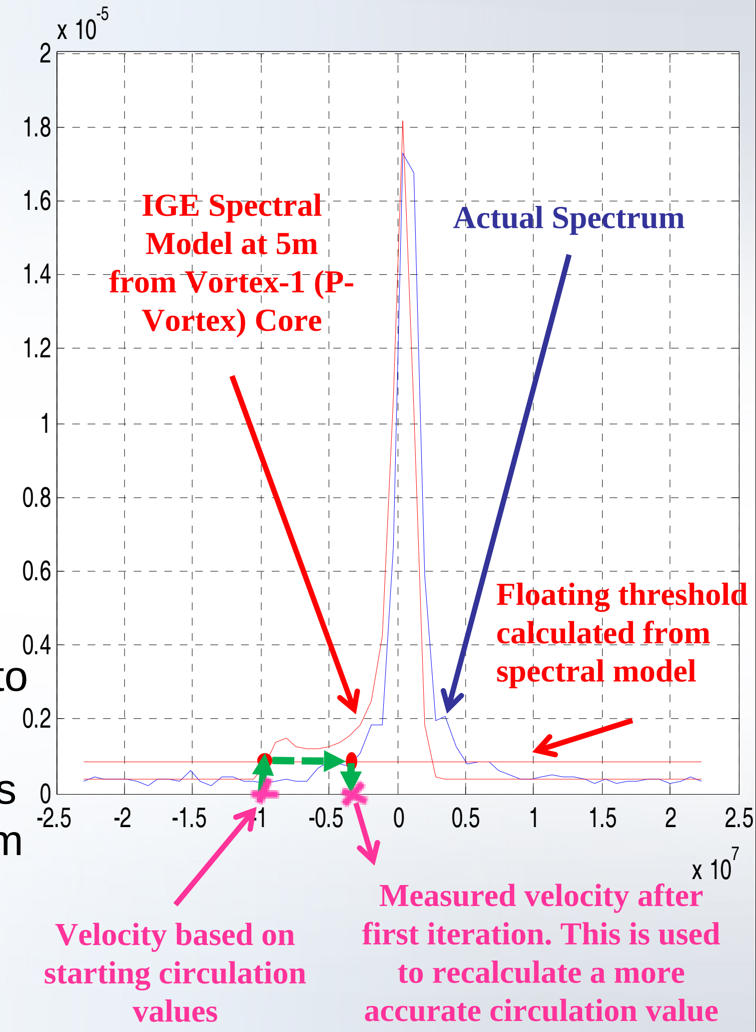
- Given the measured velocities below and above the core, the estimate of circulation is done as follows:
  - First, consider the velocities within a predefined region above and below the core. Usually 5-15 meters.
  - Second, remove the effects of the second vortex and image vortices based on initial estimate of their circulations.
  - Perform a fit, based on a pre-selected parametric model of the vortex flow field (such as Burnham-Hallock (BH) model). The only free parameter in the fit is circulation.

$$V(r) = \Gamma . \frac{z}{2\pi\left(z^2 + r_c^2\right)}$$



Circulation Estimation (2/4)

- The measurement of velocities that go into the estimation of circulation process is perform using 2 algorithms:
  - **Envelope Velocity Algorithm**: The 5-15 m velocities are calculated based on the SNR adaptive threshold. These are the same velocities used in localization.
  - **Peak Velocity Algorithm**: Only use the maximum velocities below and above the core to estimate circulation
  - **Floating Threshold (FT) Algorithm**: Velocities are calculated based on a refined threshold from a 4-vortex based spectral model.



Circulation Estimation (3/4)

- An additional algorithm is added that estimates circulation directly from the spectra associated with the points in the 5-15 m below and above the core:
  - **Minimum Mean Square Error (MMSE) Algorithm**: For each spectra find the circulation that minimizes the error between the observed spectrum and the 4-vortex model spectrum:

$$MSE(\Gamma_w) = \int_{f_i}^{f_f} \left(\hat{S}_{nz}(f \mid x_w, z_w, \Gamma_w) - S_{nz}(f) \right)^2 df$$

$$\Gamma_{MMSE} = Argmin_{\Gamma_w}\{MSE(\Gamma_w)\}$$

- **FT Algorithm + MMSE Algorithm = Hybrid Algorithm**
  - FT algorithm is fast and performs well for high velocities but presents a bias for high velocities.
  - MMSE is slow but is superior for low velocity measurements.
  - The hybrid algorithm calculates the envelope velocities using FT algorithm and if resulting velocities are below a predefined threshold it switches to the MMSE algorithm

Circulation Estimation (4/4)

- The primary algorithm for circulation estimation is the **Hybrid Algorithm**.

- The rest of the algorithms are used as an aide to the Hybrid Algorithm. This is done by replacing outliers in the hybrid algorithm with the corresponding result from one of the other 2 algorithms. This is done in the following manner:
  1. **Calculate an “outlier-immune” smooth curve**: Use an add-hoc smoothing spline fit of the Hybrid results.
  2. **Calculate an error matrix**: The difference between the results from each algorithm and the smooth curve are stored in an array. For N scans and 3 algorithm the result is Nx3 error matrix. T
  3. **Select “Best” algorithm:** For each scan (each row in the error matrix) choose the result from the algorithm corresponding to the minimum error along that row.

- Additional enhancements are described in more details in the paper….

Second section:

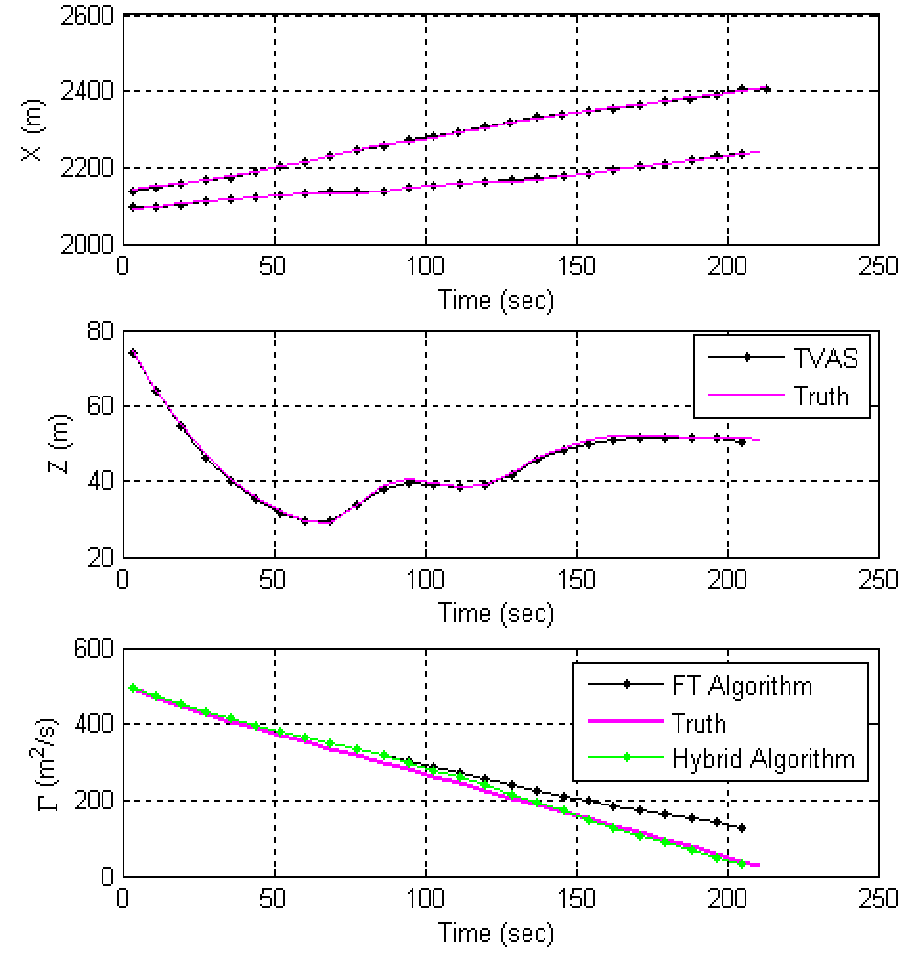
TVAS Validation

Validation Overview

- Two levels of validation:
  - **Simulation**: provides a known reference and help quantify the errors and assess the improvements provided by the hybrid algorithm under prestine conditions. The simulation parameters are:
    - Burnham-Hallock vortex model with 4 meter core for a B747-400 airplane.
    - Generation altitude= 79.3 m (260')
    - Cross Wind = 1 m/s
    - SNR=5 dB,
    - scan duration = 7.5 sec
  - **Field data**: TVAS results from 3 passages of a reference aircraft are compared to LMCT processing results in normalized form. Data was collected with an SNR on the order of 10 dB

Graphical Simulation Results (1/4)

- Good agreement in position.
- FT algorithm has a circulation bias for low circulations.
- Hybrid algorithm outperforms the FT algorithm by effectively removing the bias



Tabular Simulation Results

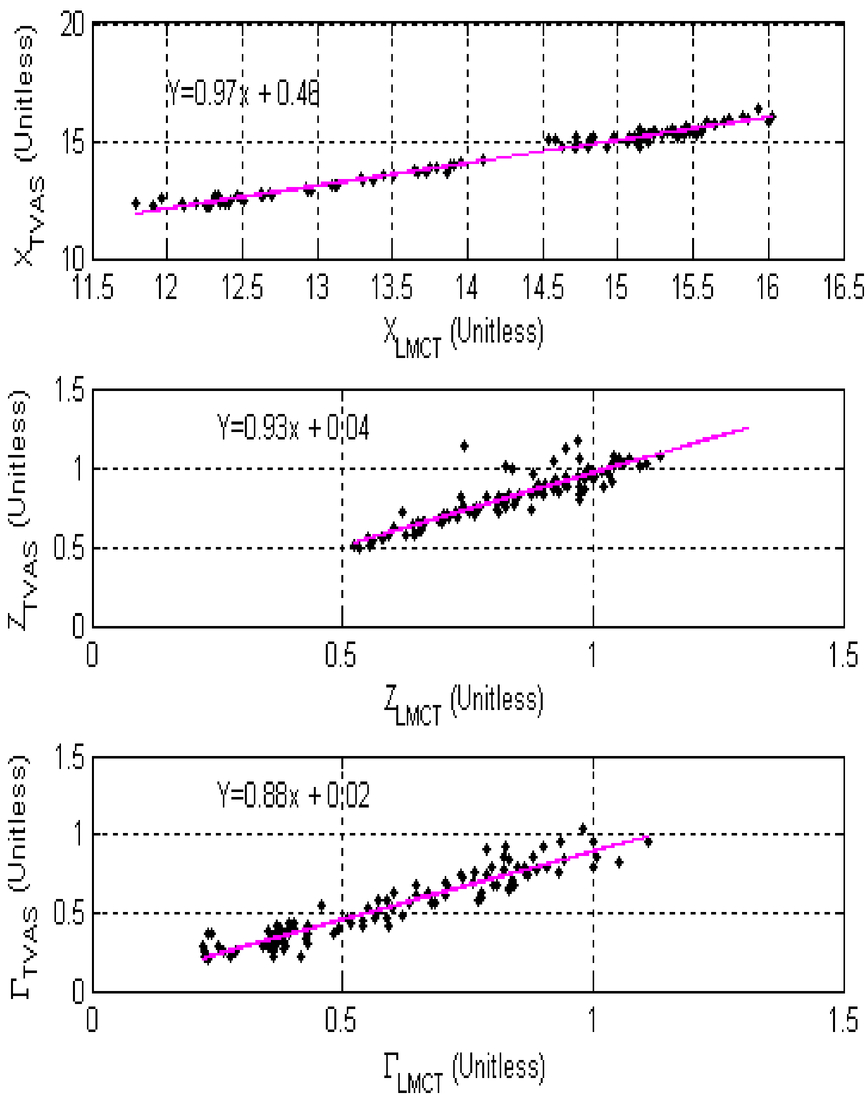
Simulation	Mean	Standard deviation
$X_{TVAS} - X_{True}$	-0.22 (m)	2.37 (m)
$Z_{TVAS} - Z_{True}$	-0.69 (m)	1.38 (m)
$\Gamma_{FT} - \Gamma_{True}$	31.27 (m^2/s)	25.53 (m^2/s)
$\Gamma_{Hybrid} - \Gamma_{True}$	4.87 (m^2/s)	8.34 (m^2/s)

- Good position accuracy. Errors are on the order of 2 to 3 meters.
- Circulation results show significant improvement provided by the Hybrid algorithm relative to the baseline FT algorithm.
- The circulation graphical results show that the bulk of the improvements presented by the hybrid algorithm are in estimating low circulation values.

Field Data

- The wake data output of both TVAS and LMCT processing packages are first normalized an presented in two forms:
  - Scatter plot form to evaluate the correlation between both algorithm results
  - Tabular relative uncertainty analysis

- Good agreement between the two results with the TVAS producing slightly lower circulations.



Tabular Uncertainty Results

P-Vortex	Mean	Std
$(\Gamma_{TVAS} - \Gamma_{LMCT})/\Gamma_o$	-7.1 e-2	7.3 e-2
$(X_{TVAS} - X_{LMCT})/b_o$	7.2 e-2	15.4 e-2
$(Z_{TVAS} - Z_{LMCT})/b_o$	-2.61 e-2	11.9 e-2

N-Vortex	Mean	Std
$(\Gamma_{TVAS} - \Gamma_{LMCT})/\Gamma_o$	4.3 e-2	7.6 e-2
$(X_{TVAS} - X_{LMCT})/b_o$	3.7 e-2	17 e-2
$(Z_{TVAS} - Z_{LMCT})/b_o$	-2.6 e-2	8 e-2

Conclusion & Future Work

- We have developed TVAS a new Wake vortex detection and tracking algorithm based on the DLR algorithm (Köpp et al. 2004 & Rahm et al. 2008) with additional enhancements.

- The algorithm was successfully validated in simulation as well as with field data relative to the commercially available LMCT algorithm.

- Future Work:
  - **Simulation**: enhance the simulation by adding wind turbulence effects and statistical model for speckle and optical turbulence induced noise. Evaluate these effects on the algorithm.
  - **Field Data**: Use a larger validation data set to investigate the small circulation bias relative to LMCT.
  - **Algorithm Enhancements**:
    - Complete the validation and tuning of the KF to improve automation
    - Incorporate new circulation and localization algorithms… Numerous ideas.

Acknowledgement

Authors would like to thank Steve Lang and Jeff Tittsworth of the FAA Wake Turbulence Program for sponsoring this development. They also acknowledge the support from Lockheed Martin Coherent Technologies for providing helpful details on the WindTracer system.