Advances in C-17 wing tip vortex investigations using the TODWL

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With material from Draper Laboratories

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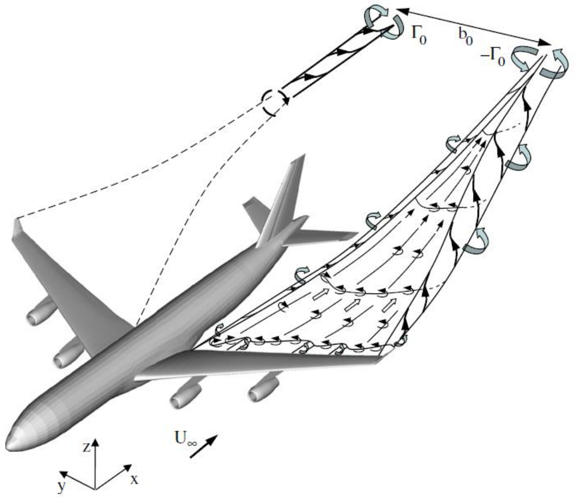
Program for Flight Separation Reduction during air deliveries

- Models are considered too ideal but still being pursued
- Need to express risk to personnel in probabilistic terms
- Most of what is known quantitatively has been obtained via groundbased DWLs with the exception of some DLR work in 2009.
- This work is funded by the US Army to obtain airborne DWL data to improve the existing WTV model being developed by Draper Laboratories and to explore alternatives to current aircraft spacing criteria.

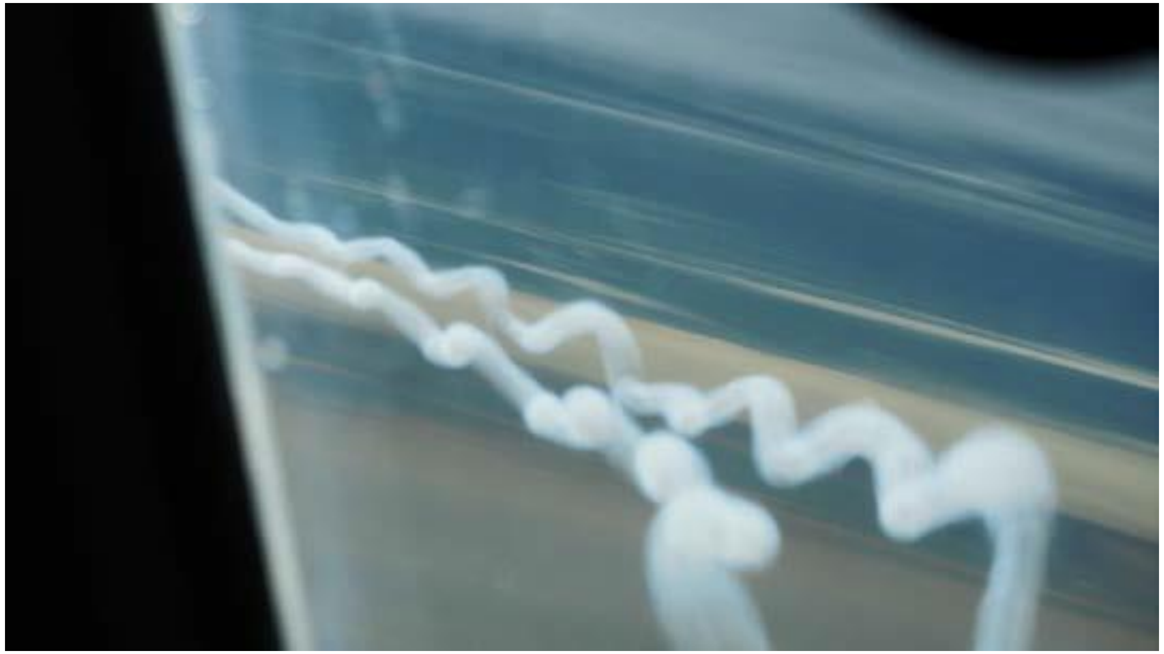
C-17 General Characteristics

Length: 174 feet (53.04 m)
Height at Tail: 55.1 feet (16.79 m)
Wing Span to Wingtips: 169.8 feet (51.74 m)
Maximum Payload: 164,900 lbs. (74,797 kg)
Range with Payload: 2,420 nautical miles
Cruise Speed: 0.74 – 0.77 Mach
Approach Speed: 130kts

Vortex concepts and photo realizations



As time goes on



Provided by Fred Proctor, NASA/LaRC

Also possible (likely?)

Provided by Fred Proctor NASA/LaRC

WTV Model

WTV model predictions

Lifetime (s)	Distance behind aircraft (m)	Core altitude (m)	Sink Rate (m/s)	Vortex core radius (m)	Max vtan (m/s)	Radius(m) where Vtan = 5 m/s
7.50	0.50	370.73	1.38	0.42	119.21	11.58
15.00	1.00	357.93	1.71	0.60	84.45	11.58
30.00	2.00	331.71	1.75	0.85	59.45	11.58
60.00	4.00	279.88	1.73	1.20	42.07	11.58
90.00	6.00	237.80	1.40	1.47	23.17	7.75
120.00	8.00	207.93	1.00	1.70	14.94	5.81
150.00	10.00	184.76	0.77	1.90	10.67	4.65
180.00	12.00	166.46	0.61	2.08	8.23	3.82
210.00	14.00	150.61	0.53	2.24	6.40	2.94
240.00	16.00	137.20	0.45	2.40	5.18	0.00
270.00	18.00	125.30	0.40	2.54	4.57	0.00
300.00	20.00	114.94	0.35	2.68	3.66	0.00

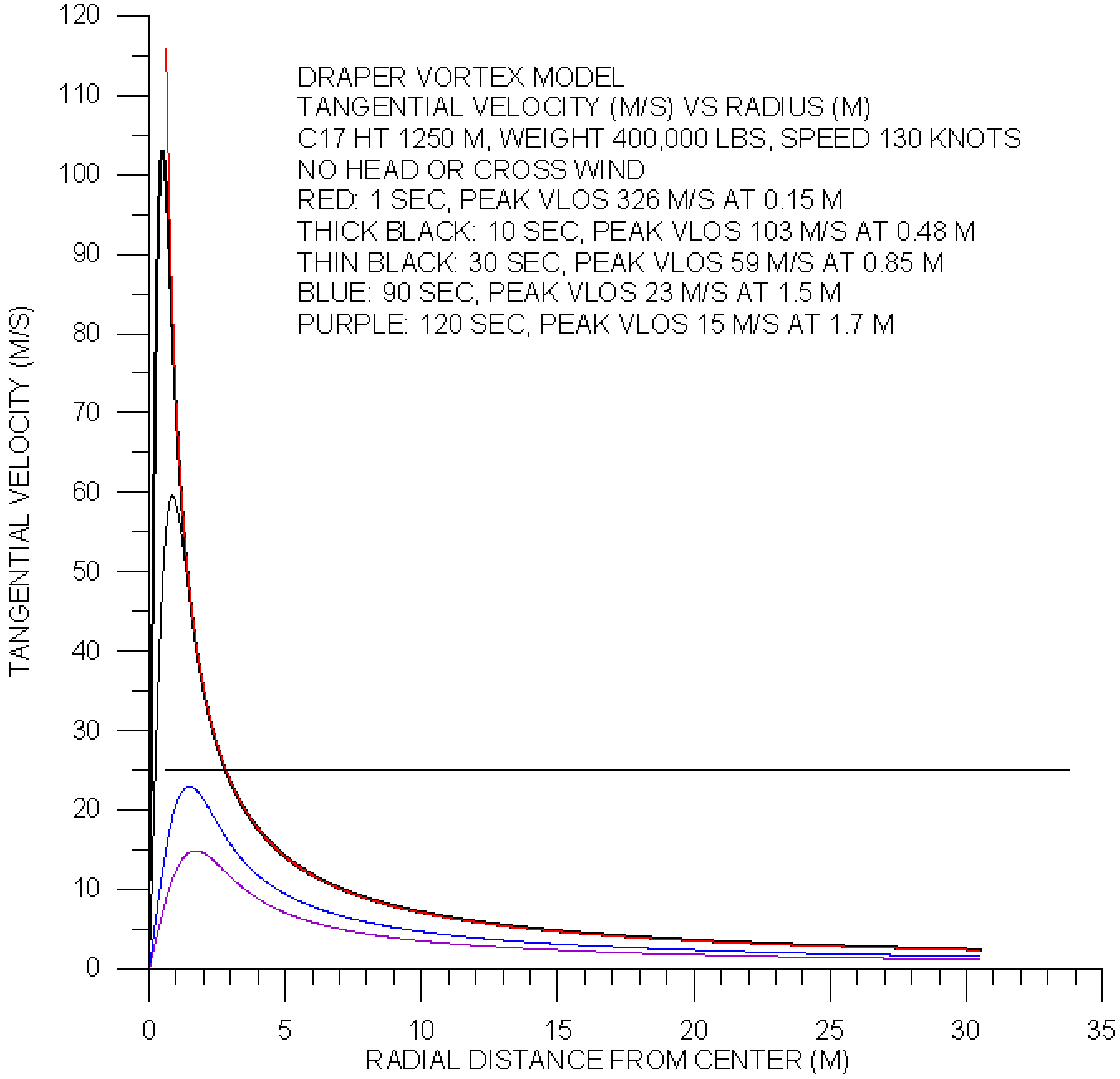
W= 400,000 lb, V = 130 knots, Altitude = 1250 ft

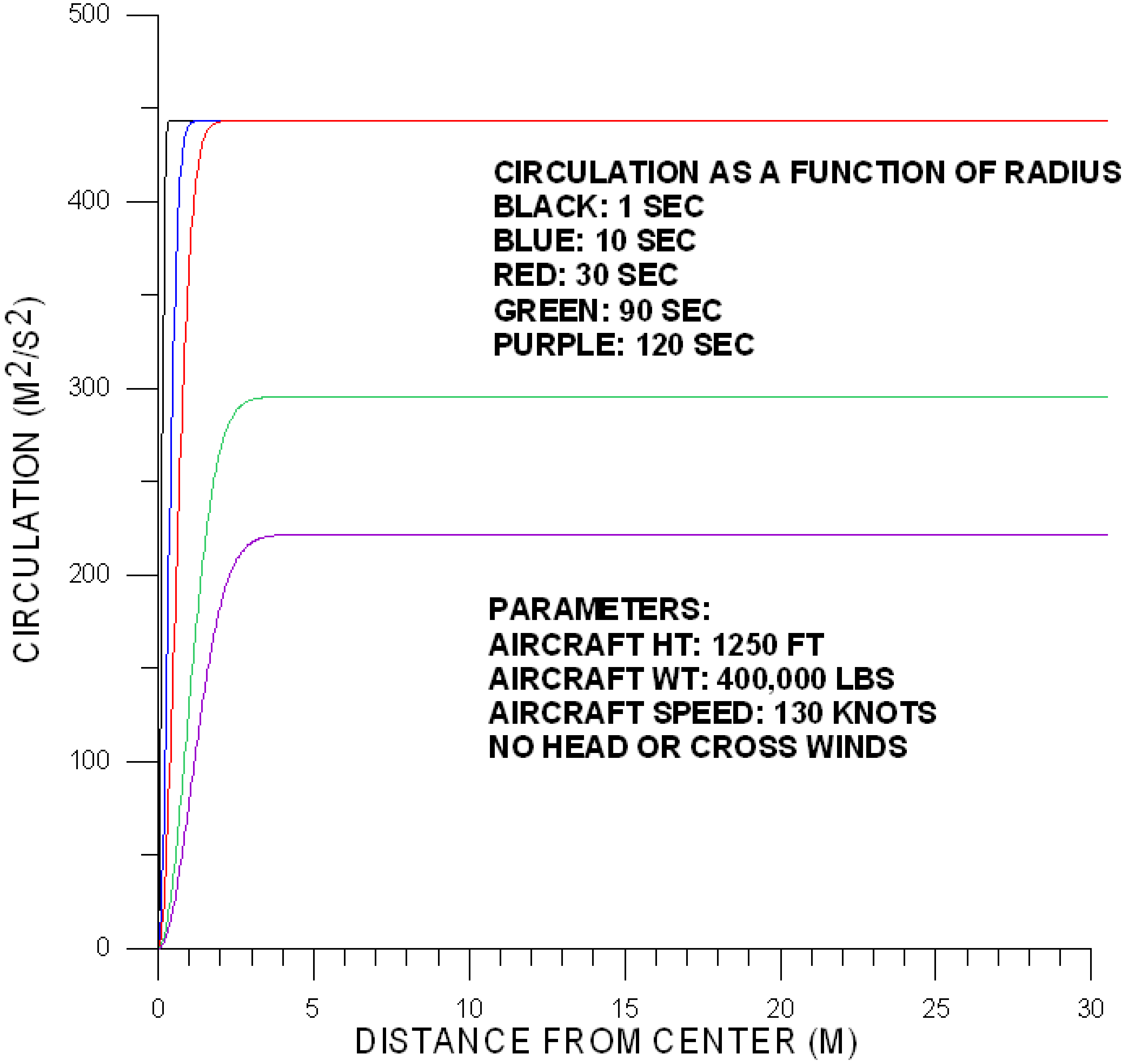
Circulation Calculation

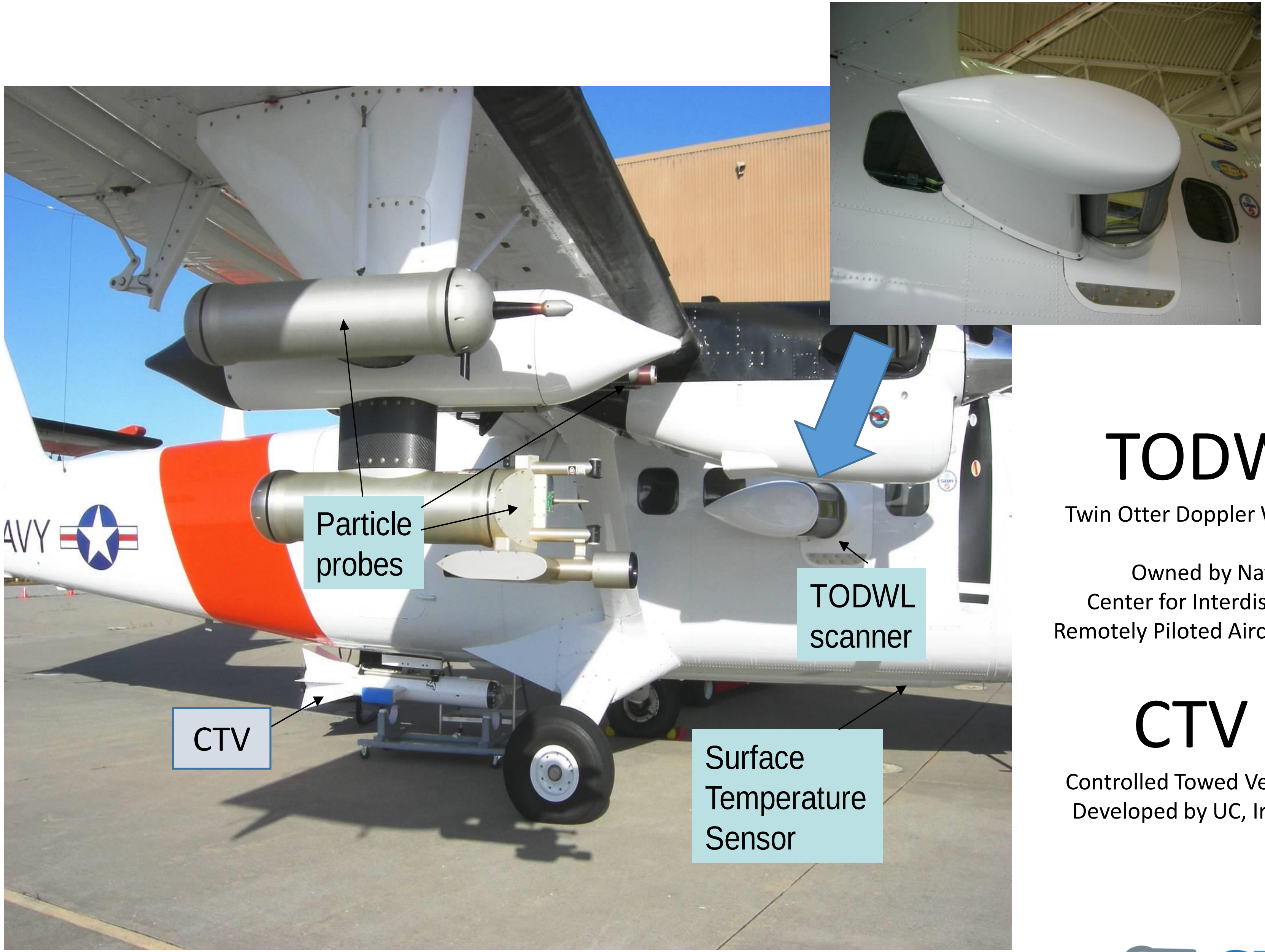
$$\Gamma = 2 * \pi * r * V(r)$$

r = distance from vortex core

V(r) = tangential speed at distance r


DRAPER VORTEX MODEL
TANGENTIAL VELOCITY (M/S) VS RADIUS (M)
C17 HT 1250 M, WEIGHT 400,000 LBS, SPEED 130 KNOTS
NO HEAD OR CROSS WIND
RED: 1 SEC, PEAK VLOS 326 M/S AT 0.15 M
THICK BLACK: 10 SEC, PEAK VLOS 103 M/S AT 0.48 M
THIN BLACK: 30 SEC, PEAK VLOS 59 M/S AT 0.85 M
BLUE: 90 SEC, PEAK VLOS 23 M/S AT 1.5 M
PURPLE: 120 SEC, PEAK VLOS 15 M/S AT 1.7 M
TANGENTIAL VELOCITY (M/S)
RADIAL DISTANCE FROM CENTER (M)
0
10
20
30
40
50
60
70
80
90
100
110
120
0
5
10
15
20
25
30
35


CIRCULATION AS A FUNCTION OF RADIUS
BLACK: 1 SEC
BLUE: 10 SEC
RED: 30 SEC
GREEN: 90 SEC
PURPLE: 120 SEC
PARAMETERS:
AIRCRAFT HT: 1250 FT
AIRCRAFT WT: 400,000 LBS
AIRCRAFT SPEED: 130 KNOTS
NO HEAD OR CROSS WINDS
CIRCULATION (M2/S2)
DISTANCE FROM CENTER (M)
0
100
200
300
400
500
0
5
10
15
20
25
30



TODWL

Twin Otter Doppler Wind Lidar

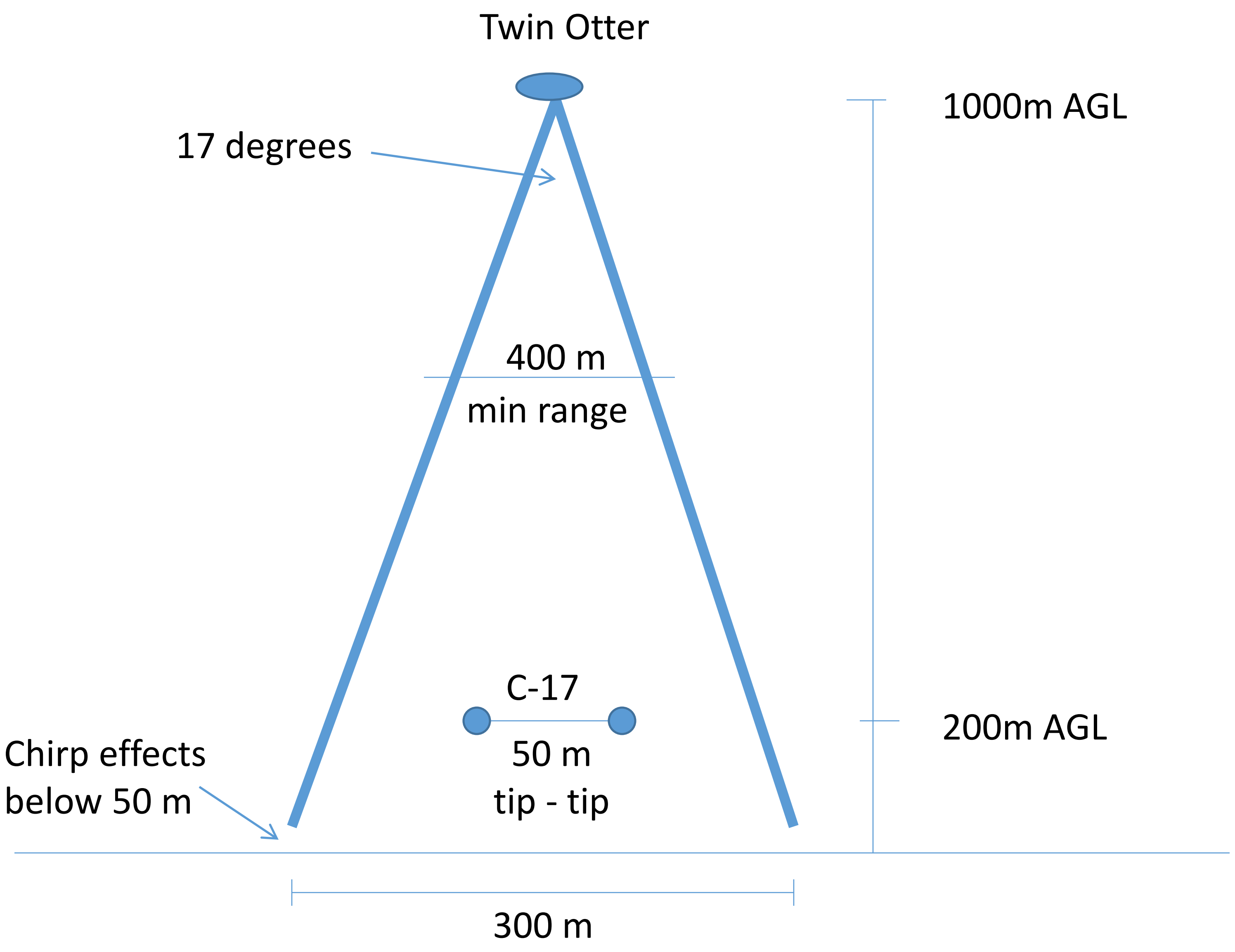
Owned by Navy's
Center for Interdisciplinary
Remotely Piloted Aircraft Studies

CTV

Controlled Towed Vehicle
Developed by UC, Irvine

Major considerations

- Differential speed between C-17 and Twin Otter. +-10 kts of 130 kts.
- Scanner slew rate
  - Maximum of 30 degrees/second
- What are the maximum tangential velocities expected?
  - TODWL’s bandwidth is +- 25 m/s
- What is the area of regard for life cycle monitoring?
  - Taking cross track drift into consideration
- Measurements of thermal stability and wind profiles between surface and 1000m



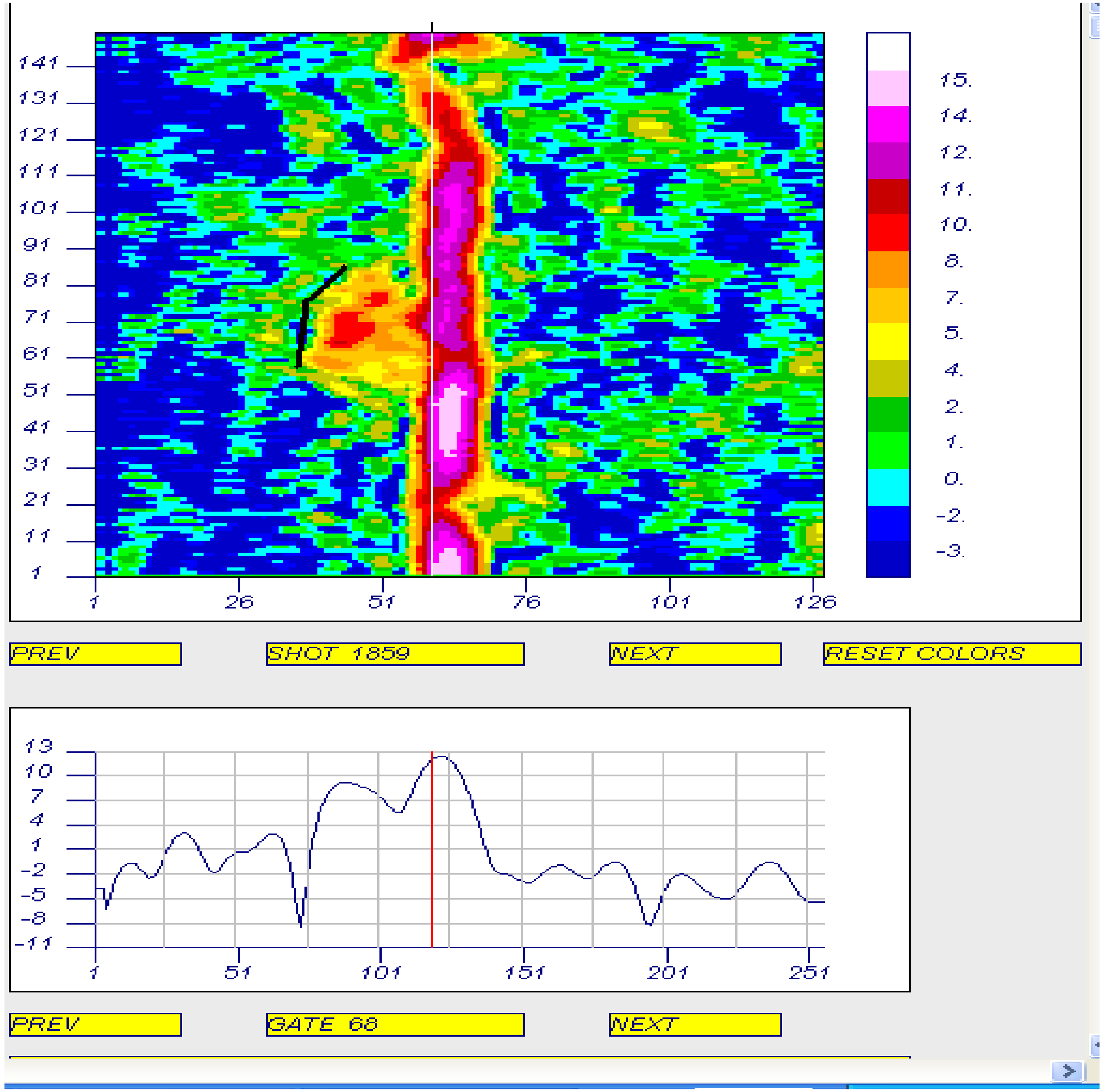
Aircraft positions and TODWL area of regard

TODWL Sampling Modes

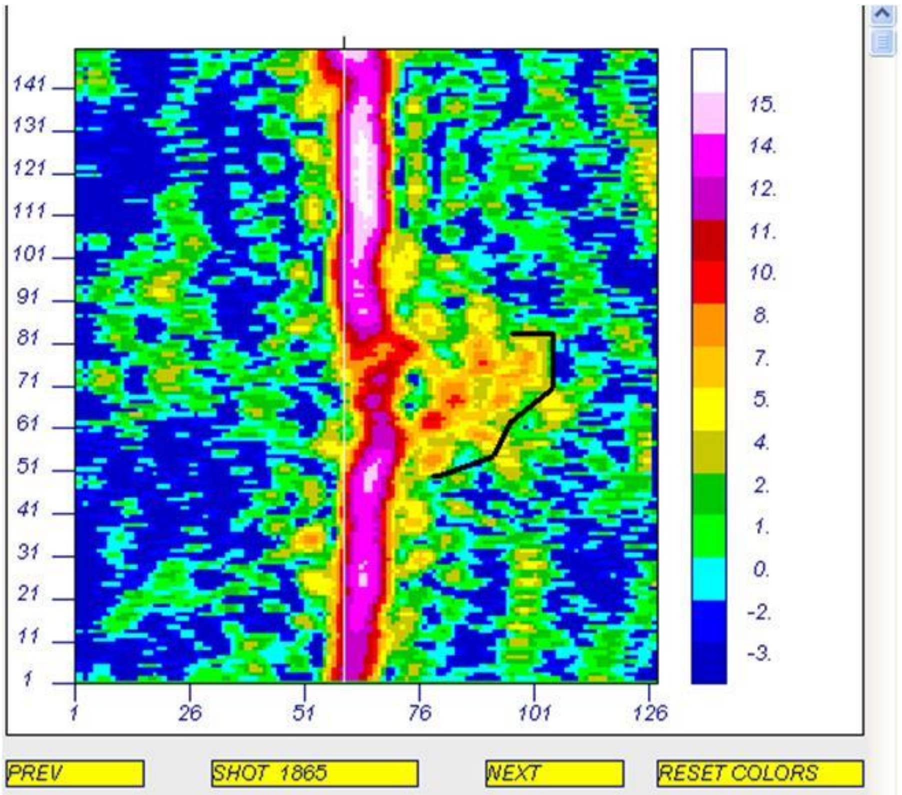
Mode Name	C - 17	T-Otter	Comments
Backslide	600’ (130K)	3000’ (110K)	Begin sampling with Twin Otter above and just forward of C -17; drift backwards while nadir raster scanning
Opposing	600’ (130K)	3000’ (140K)	Begin nadir raster sampling when TO is on opposing track to that just flown by C-17
Trailing	600’ (130K)	1000’ (130K)	Begin 3km behind C-17 and use dithered prospecting scan at – 6 degrees for 5 min.
Prospecting	600’ (130K)	1000’ (120K)	Begin 3km lateral to C-17 path and cross over DZ; do 180 and repeat going other direction.
DZ cross (GB)	600’ (130K)	Zero‘ (Zero)	Park the Twin Otter in a position to allow the lidar to scan the DZ from a side perspective to C-17 path.
DZ along (GB)	600’ (130K)	Zero‘ (Zero)	Park the Twin Otter in a position 3 -5 km “up approach” from the DZ to allow the lidar to scan the DZ along the C-17 path. C-17 would need to fly a J leg to avoid having vortexes hit the Twin Otter.

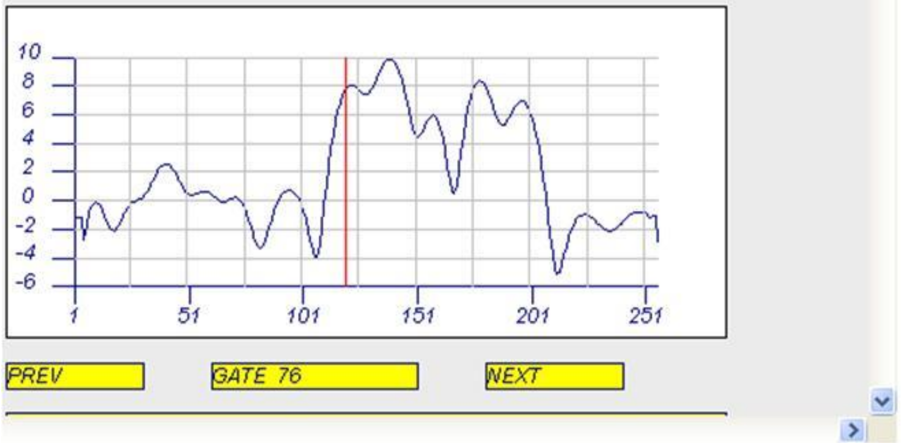
Key Issues addressed with TODWL

- Capturing signals from vortices over periods of several minutes using “opposing” flight paths and “fallback” sampling.
- Identifying region where vertical velocities are > 15 m/s (Danger Zone)
- Identifying and mapping individual vortices throughout several minutes of lifetime (location of vortex centers).
- Computing circulation values using lidar samples obtained at vortex radii ~ 10 – 20 meters.

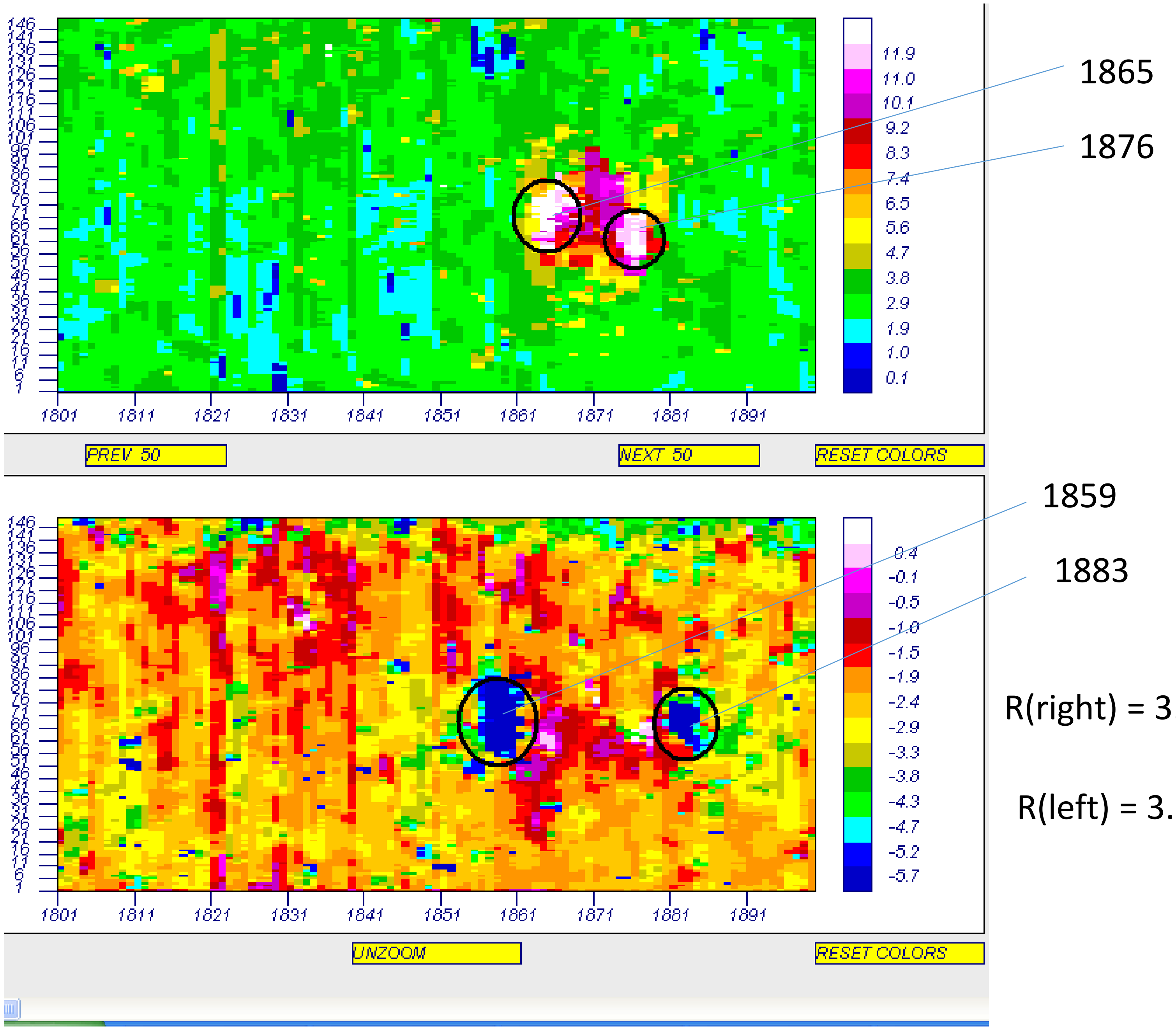

141
131
121
111
101
91
81
71
61
51
41
31
21
11
1
1
26
51
76
101
126
15.
14.
12.
11.
10.
8.
7.
5.
4.
2.
1.
0.
-2.
-3.
PREV
SHOT 1859
NEXT
RESET COLORS
13
10
7
4
1
-2
-5
-8
-11
1
51
101
151
201
251
PREV
GATE 68
NEXT

Vu(left) = 7 m/s


141
131
121
111
101
91
81
71
61
51
41
31
21
11
1
1
26
51
76
101
126
15.
14.
12.
11.
10.
8.
7.
5.
4.
2.
1.
0.
-2.
-3.
PREV
SHOT 1865
NEXT
RESET COLORS


10
8
6
4
2
0
-2
-4
-6
1
51
101
151
201
251
PREV
GATE 76
NEXT

Vd (left) = 10 m/s



R(right) = 3.5*2.5=8.75

R(left) = 3.0*2.5 = 7.5

Sink Rates

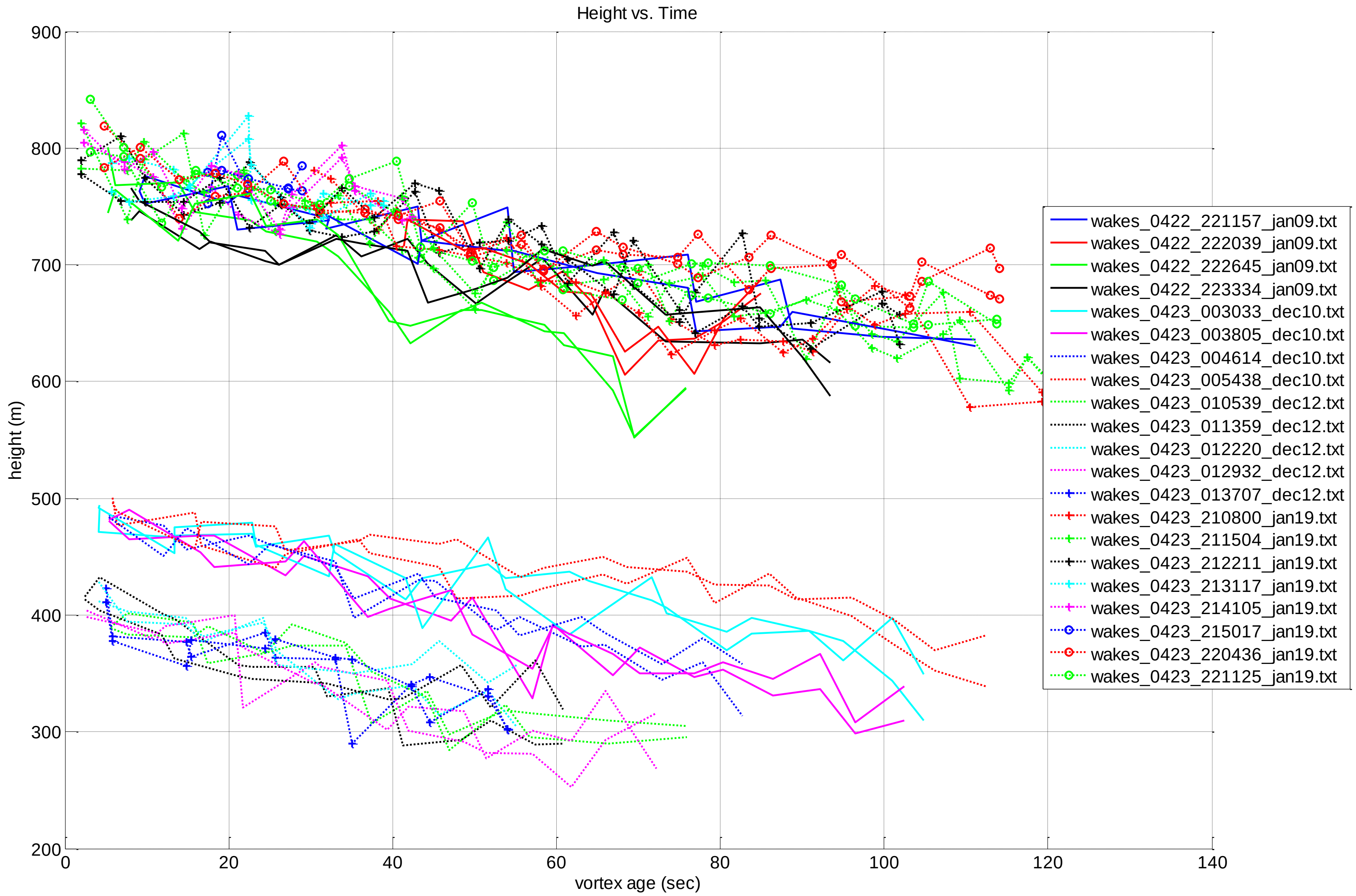
Priority Datasets

- 21 Data sets for opposing flights at night (4/22-4/23)
  - Most of the datasets have a data available for a vortex age between 60 to 120 seconds
- No major changes in aircraft weight from first pass to last pass on a given lift

Date	Initial Weight	Final Weight	Notes
4/22 Night	382280	374680	~800m altitude
4/23 Early morning	397080	384680	~500m altitude
4/23 Early morning	380080	369200	~400m altitude
4/23 Night	398800	375600	~800m altitude

- C17 speed relatively constant between passes
  - Most in the 130-132 knots range
  - 4 outside (143.3, 134.75, 136.5, 134.1)

All Datasets – Height vs. Vortex Age



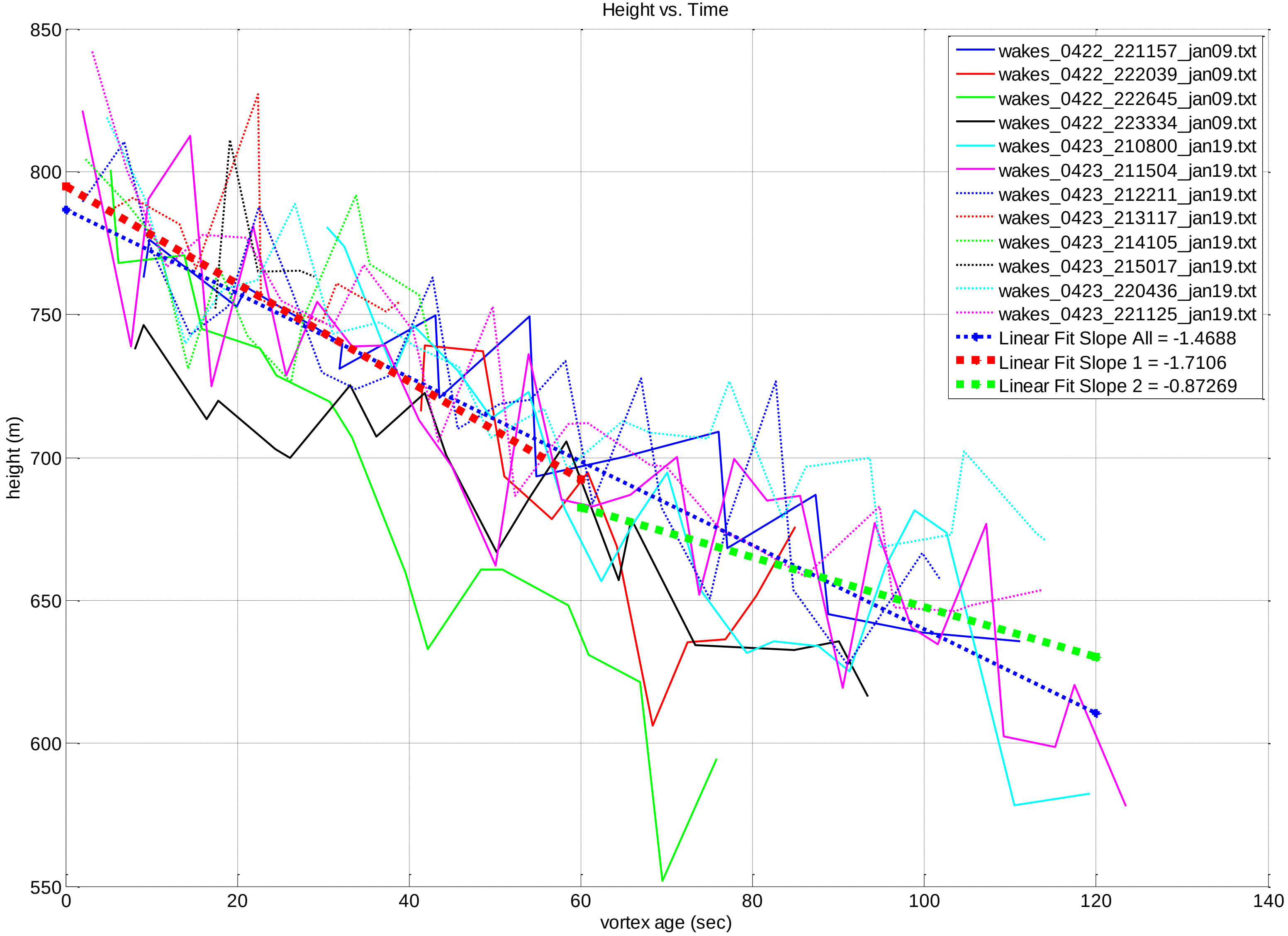
C17 Altitude ~800m

Tests conducted over two different nights

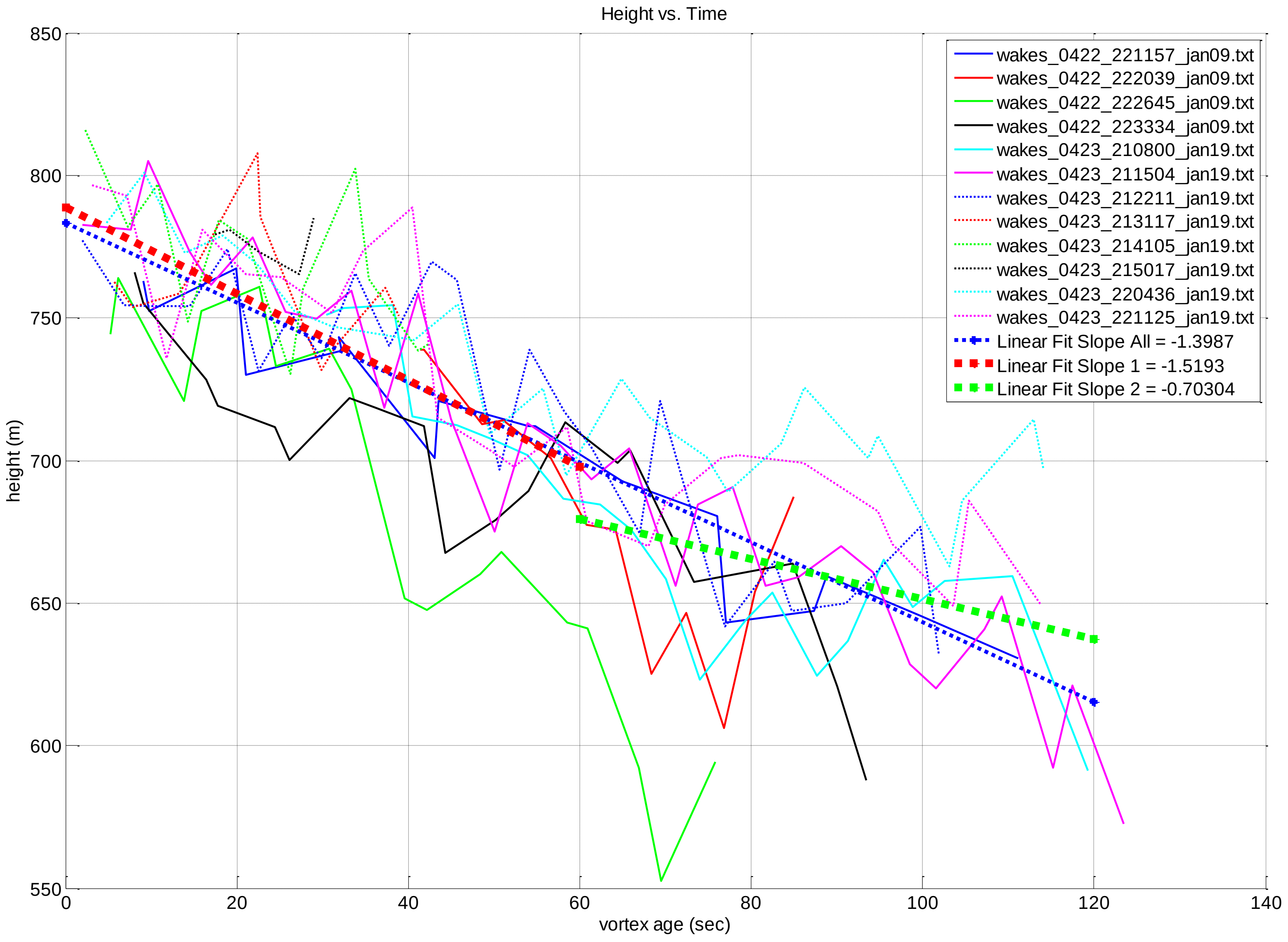
4/22/14 and 4/23/14

12 different flights passes

C17 Altitude ~ 800m – Height vs. Vortex Age – Right Vortex



C17 Altitude ~ 800m – Height vs. Vortex Age – Left Vortex



C17 Altitude ~ 800m – Height vs. Vortex Age

- Two descent rates can be seen in the data
  - The change in rates occur approximately around 60 seconds

  - First 60 second mainly a higher constant descent rate
    - 1.71 meters per seconds – right vortex
    - 1.52 meters per seconds – left vortex

  - After 60 seconds a slower descent rate
    - More variation
    - 0.87 meters per seconds – right vortex
    - 0.70 meters per seconds – left vortex

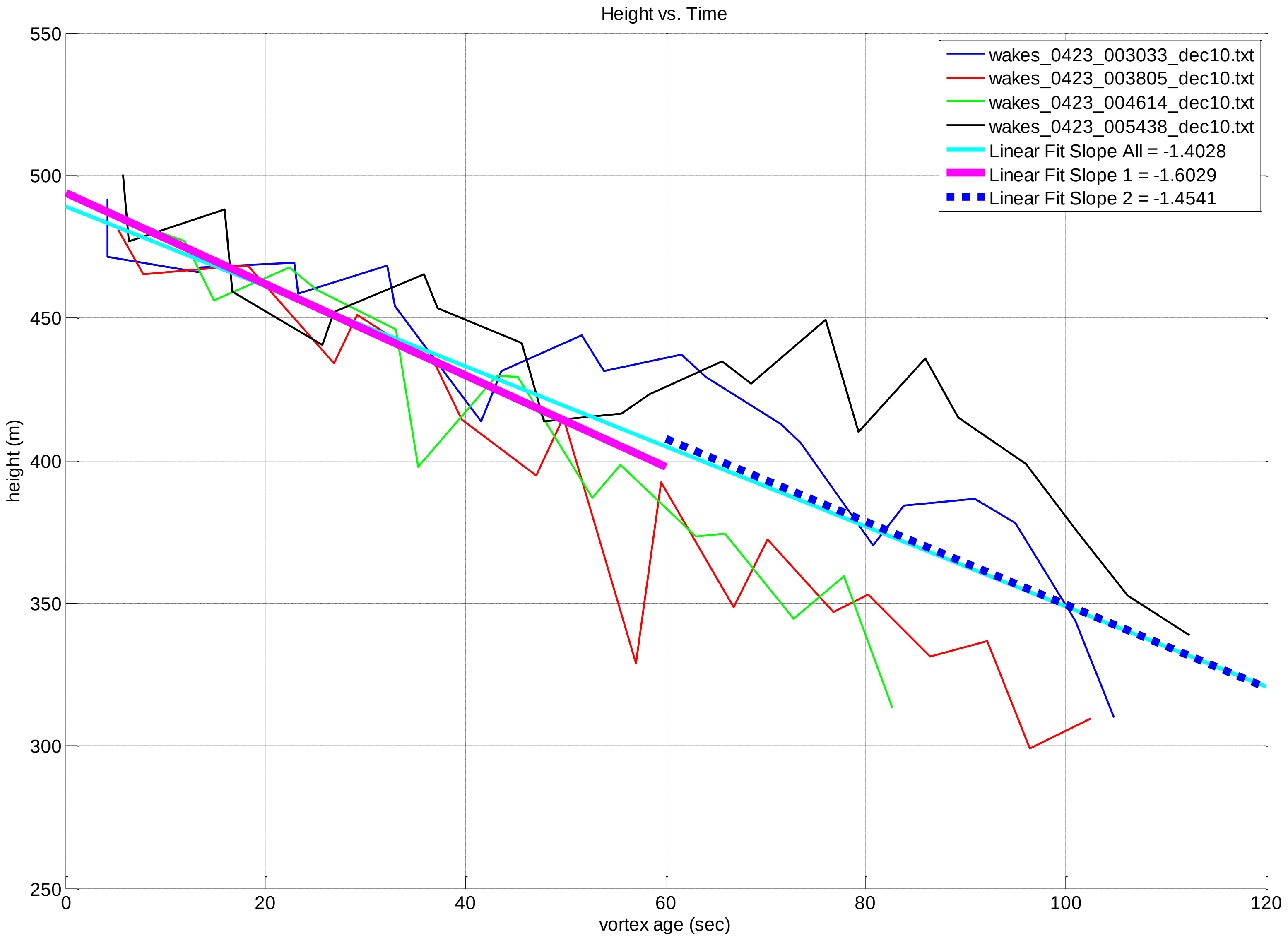
C17 Altitude ~500m

Tests conducted over one early morning

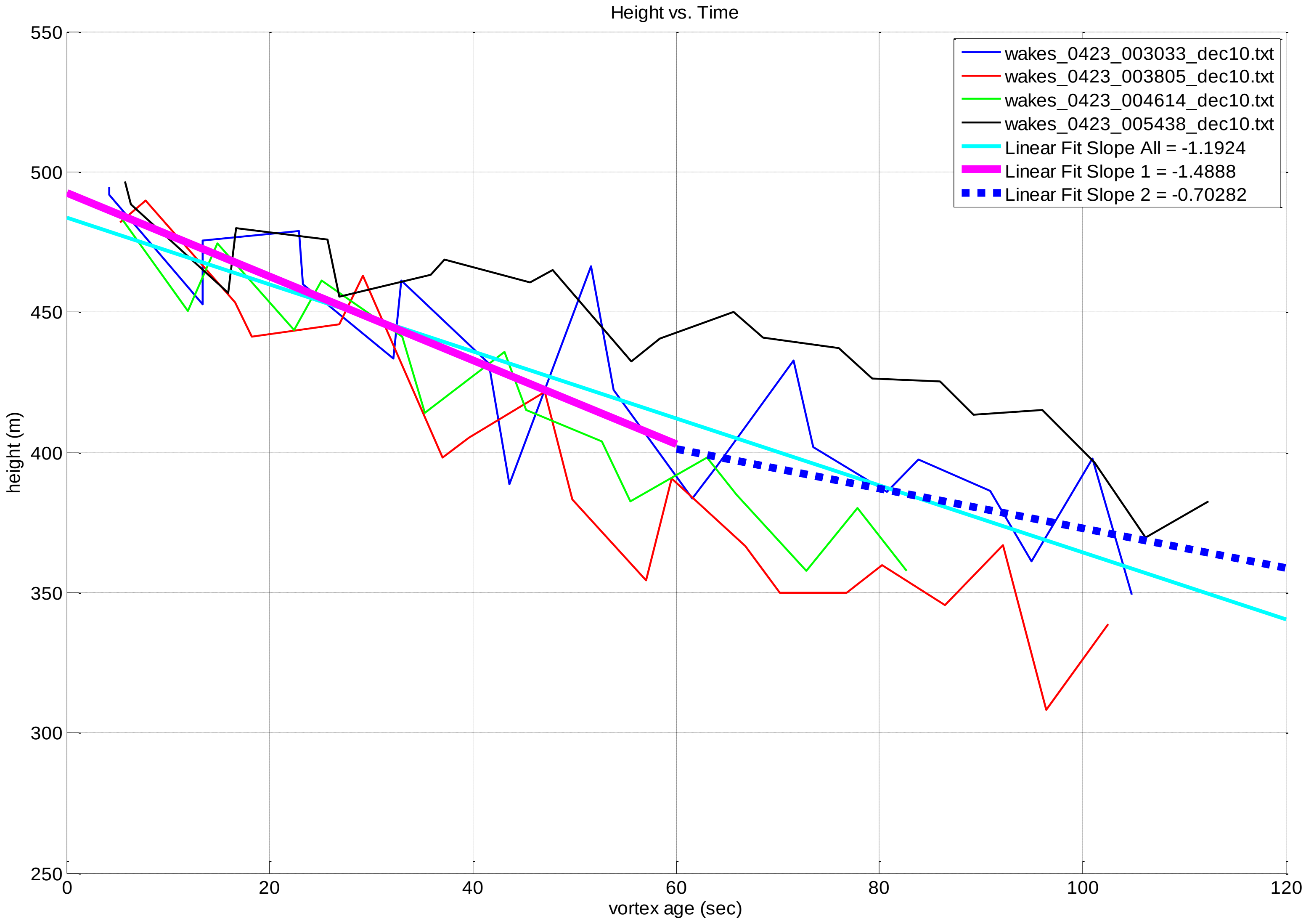
4/23/14

4 different flights passes

C17 Altitude ~ 500m – Height vs. Vortex Age – Right Vortex



C17 Altitude ~ 500m – Height vs. Vortex Age – Left Vortex



C17 Altitude ~ 500m – Height vs. Vortex Age

- Two descent rates can be seen in the data
  - The change in rates occur approximately around 60 seconds

  - First 60 second mainly a higher constant descent rate
    - 1.60 meters per seconds – right vortex
    - 1.49 meters per seconds – left vortex

  - After 60 seconds a slower descent rate
    - More variation
    - 1.45 meters per seconds – right vortex
    - 0.70 meters per seconds – left vortex

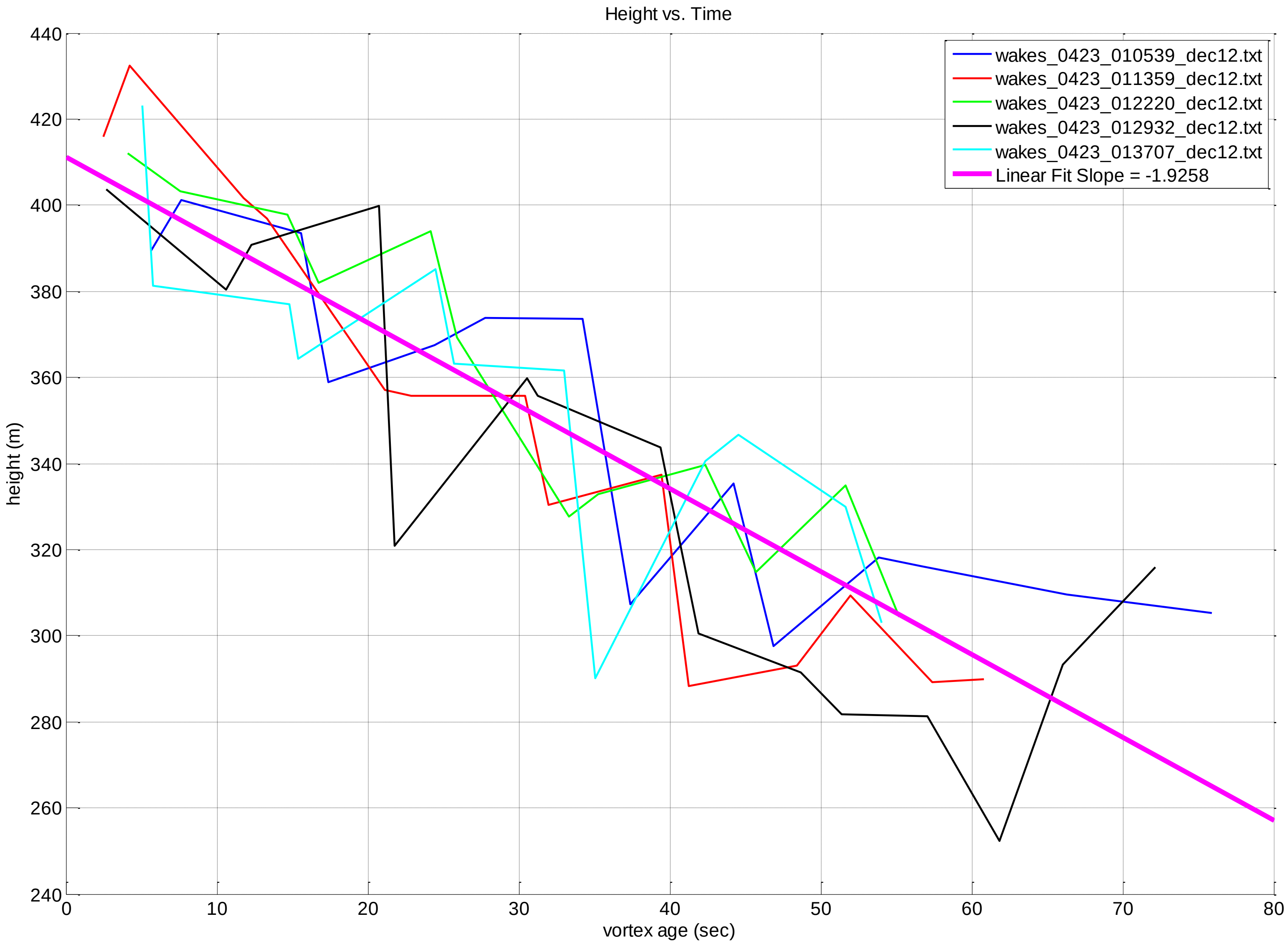
C17 Altitude ~400m

Tests conducted over one early morning

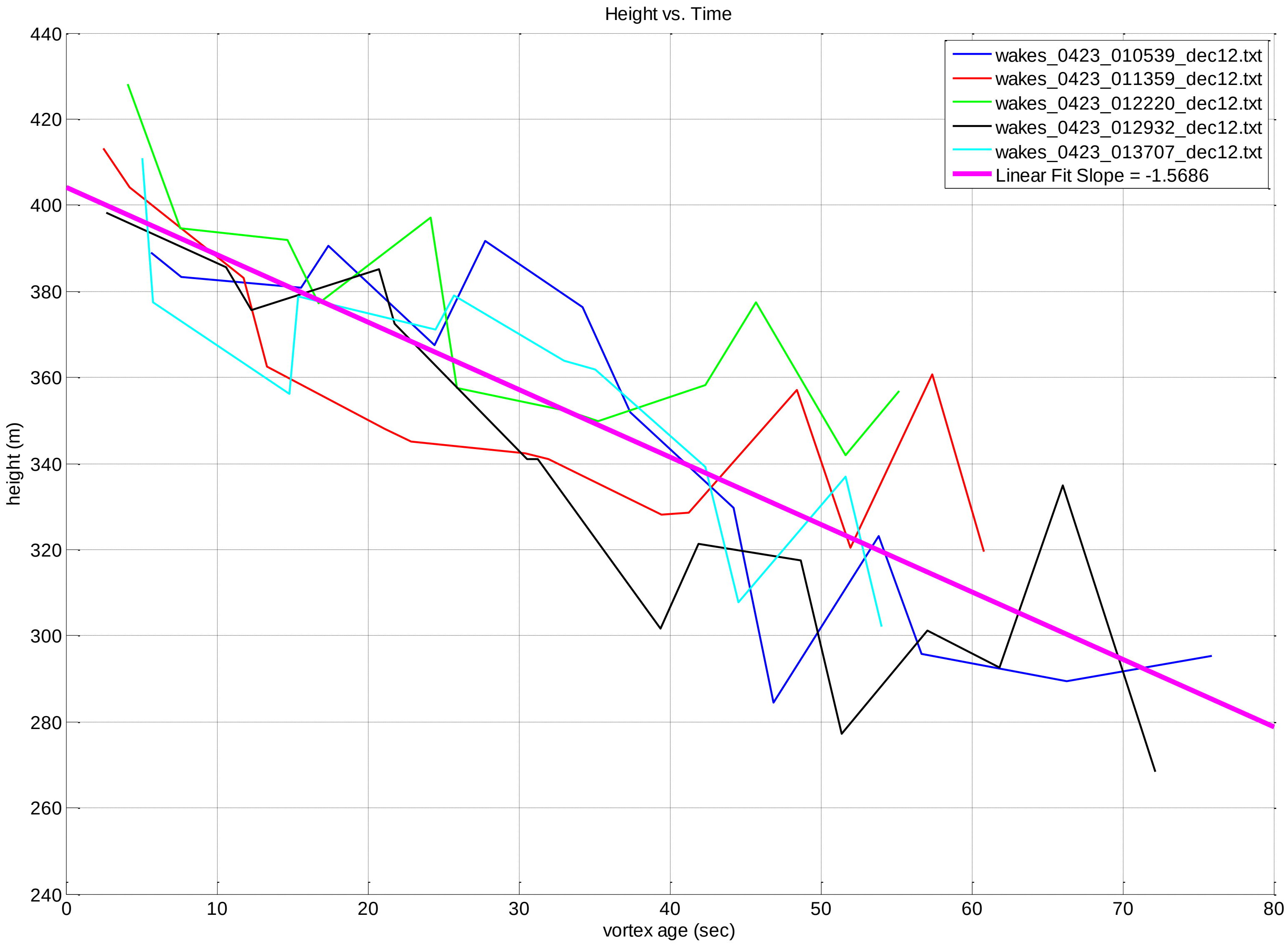
4/23/14

5 different flights passes

C17 Altitude ~ 400m – Height vs. Vortex Age – Right Vortex



C17 Altitude ~ 400m – Height vs. Vortex Age - Left Vortex



C17 Altitude ~ 400m – Height vs. Vortex Age

- Smaller time of data available – around 75 seconds
- Relatively constant descent rate
  - 1.93 meters per seconds – right vortex
  - 1.57 meters per seconds – left vortex
- We can start to see the change in the descent rate around 60 seconds

Summary of All the Data

Altitude (m)	Vortex Descent Rates (m/s)				Mean Velocity Decay (m/s^2)					
	First 60 Sec		After 60 Sec		Ascending		Descending		Both Cores	
	Right	Left	Right	Left	Right	Left	Right	Left	Right	Left
800	1.71	1.52	0.87	0.70	0.022	0.017	0.016	0.018	0.019	0.018
500	1.60	1.49	1.45	0.70	0.032	0.028	0.027	0.015	0.030	0.022
400	1.93	1.57	-	-	0.048	0.053	0.014	0.026	0.031	0.039

Working on calculating standard deviation for the decent and decays rates

Progress on computing circulation

Circulation calculations

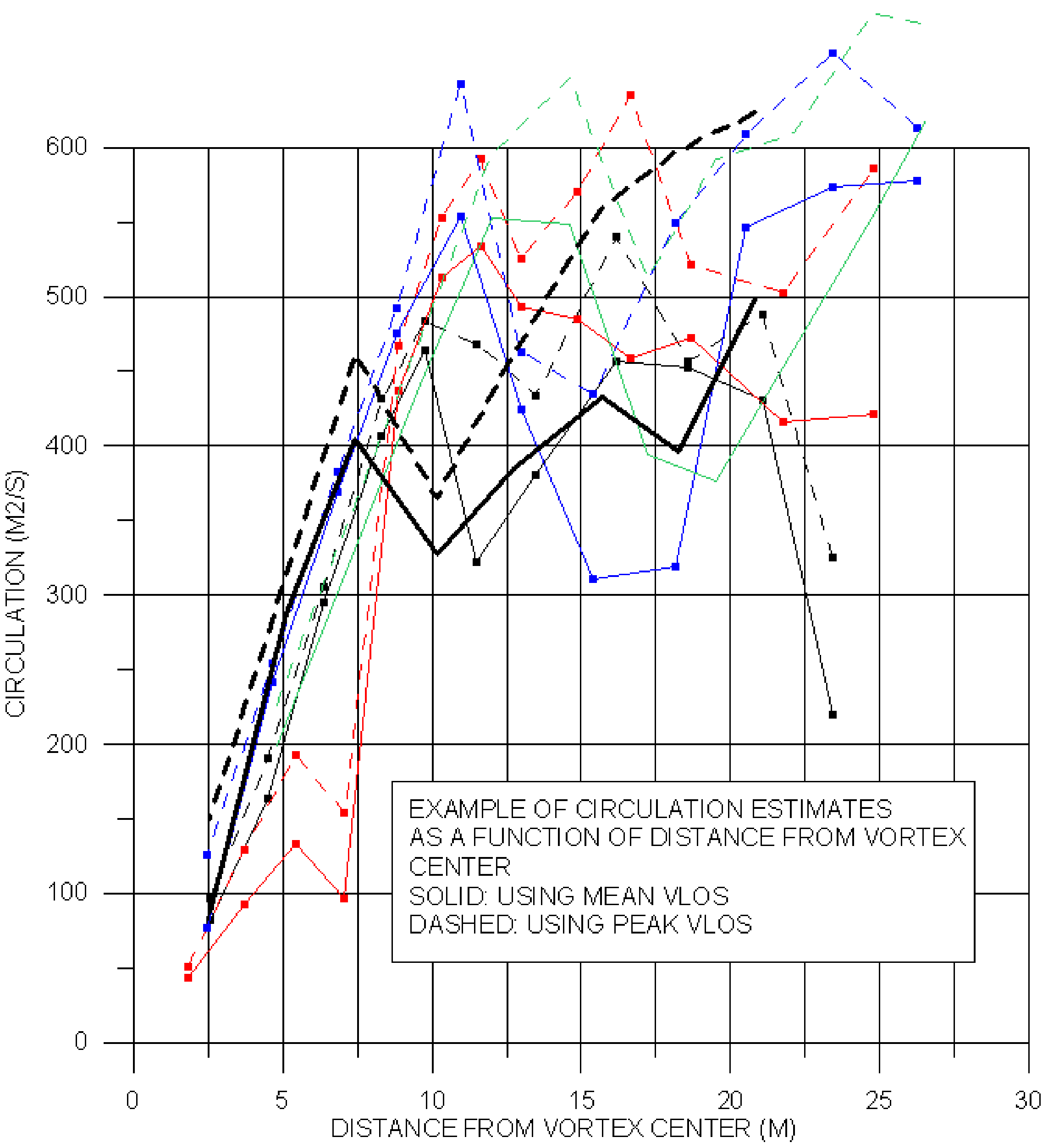
- The maximum tangential velocities may be ~ 100 m/s per various WTV models
- Since TODWL has a +- 25m/s receiver bandwidth and a ~80m Gaussian pulse length, we compute the circulation at radii where the tangential velocities are less than 10 -20 m/s.
- Using techniques developed in part by the DLR during similar airborne DWL investigations in 2009.
- SWA has expanded (and continues to do so) on the “spectral envelop” approach during this FSR project.

SWA Method*

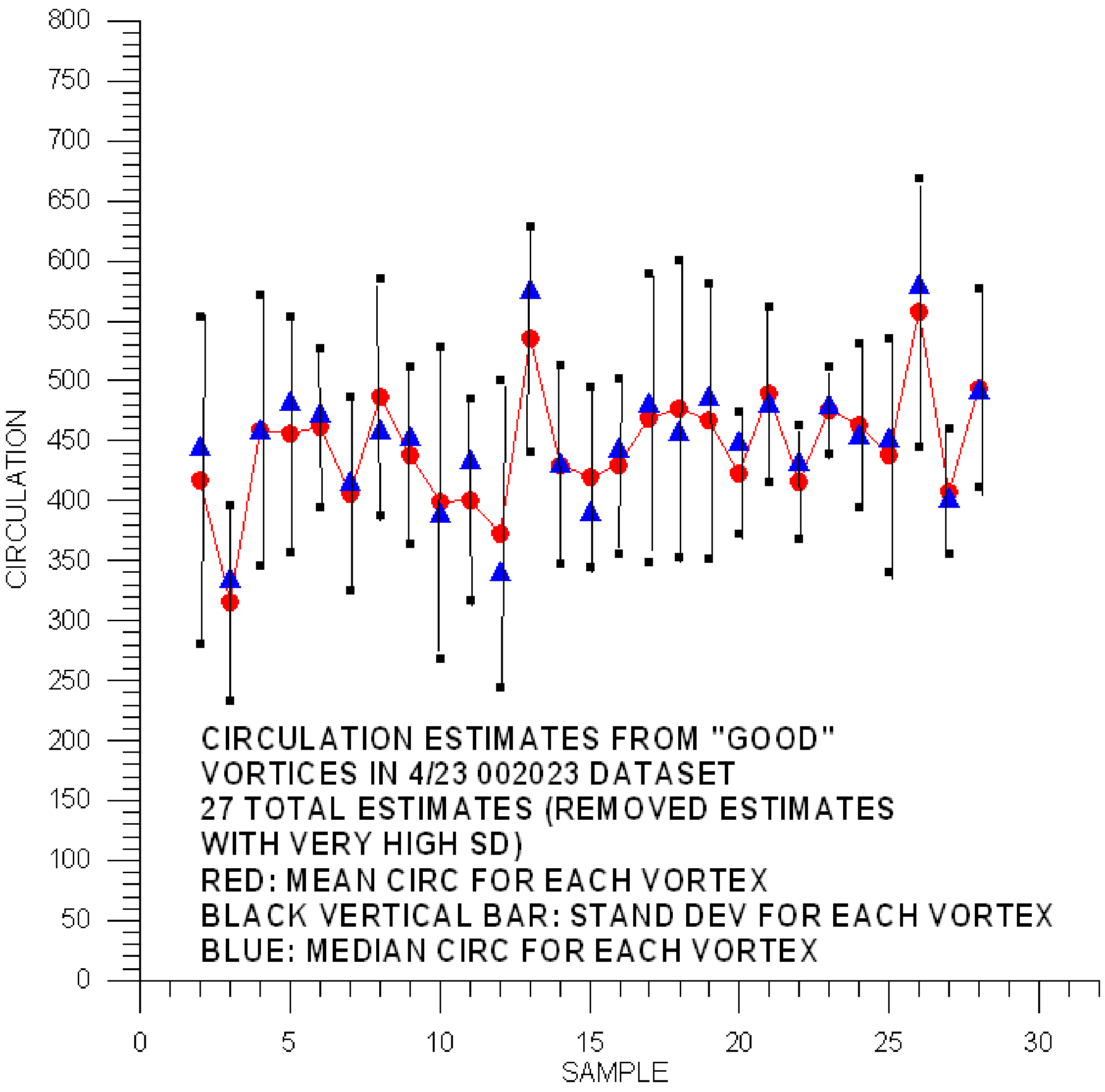
The method is as follows:

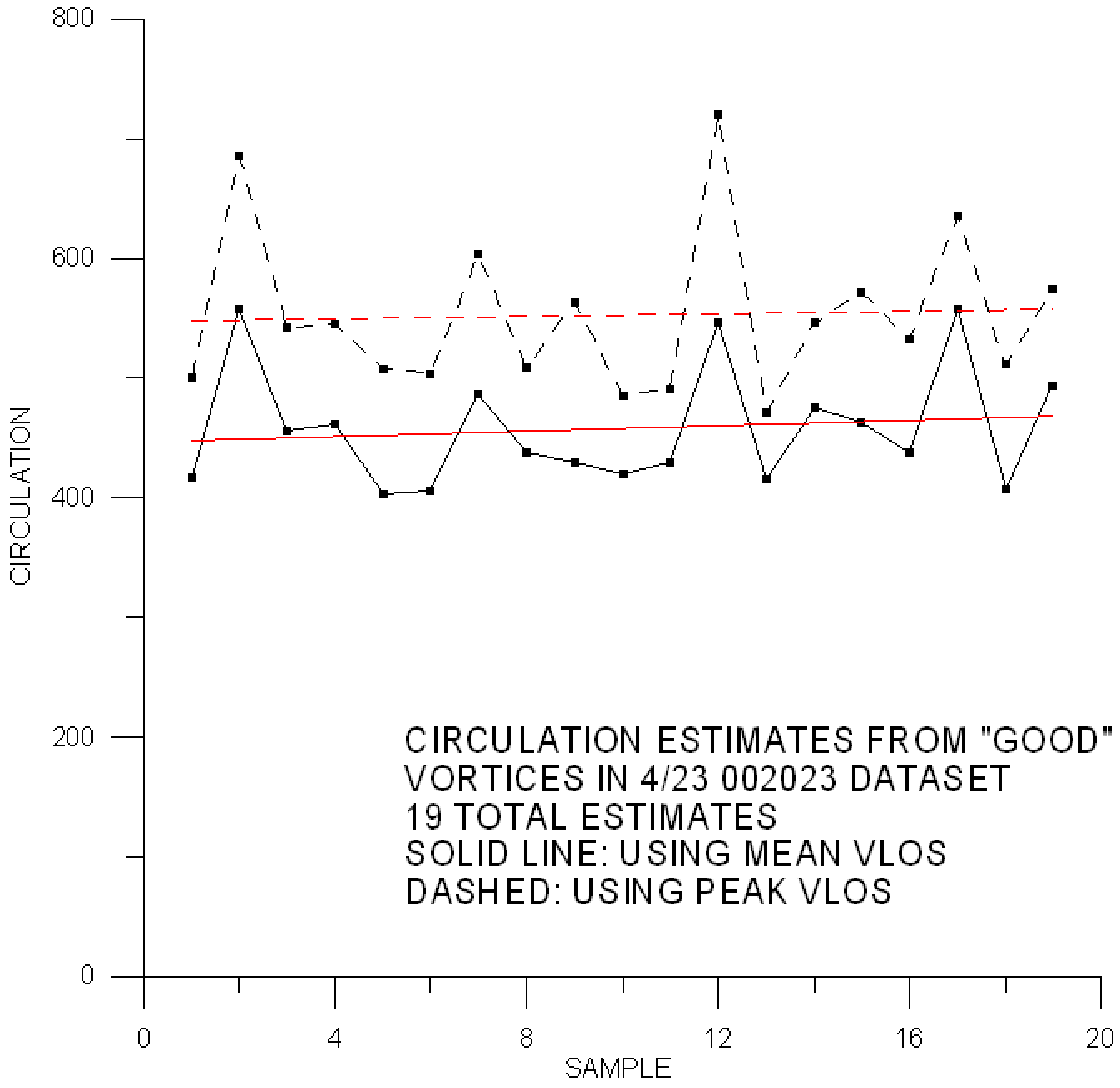
- Identify center of vortex (shot, gate)
- Using envelope velocities, calculate circulation moving outward from vortex center at each shot (average separation about 2 m but varies with scan angle)
- Circulation is estimated by examining a region within 10 gates of the core location.
- Tabulate the strongest envelope velocity and the average envelope velocity within that region, and then calculate a circulation from each, so two estimates per shot (distance)

* Base in part on work done by DLR


600
500
400
300
200
100
0
CIRCULATION (M2/S)
0
5
10
15
20
25
30
DISTANCE FROM VORTEX CENTER (M)
EXAMPLE OF CIRCULATION ESTIMATES
AS A FUNCTION OF DISTANCE FROM VORTEX
CENTER
SOLID: USING MEAN VLOS
DASHED: USING PEAK VLOS

First 10 seconds of WTV lifetime




CIRCULATION ESTIMATES FROM "GOOD"
VORTICES IN 4/23 002023 DATASET
19 TOTAL ESTIMATES
SOLID LINE: USING MEAN VLOS
DASHED: USING PEAK VLOS
CIRCULATION
SAMPLE
0
200
400
600
800
0
4
8
12
16
20

Radius sensitivity

- The computations are very sensitive. For example, if we've picked the wrong shot for the vortex center, everything shifts by an average of 2m.
- If you have a Vlos estimate of 6 m/s at 10 m, that's 377 m2/s. If you shift that 2 m you have a potential circulation range of 302 – 452 m2/s. That could possibly explain the outliers in the averaged data.

Summary

- Using our latest algorithms, the general estimates of WTV sink rates, vortex separation distances, drift angles and circulation values appear to pass the “reasonable” test when compared with the WTV model data from Draper. But…..
- There are occasions, however, where the sink rates differ between lifts conducted within the same (?) environment.
- There are cases where the separation between vortices is > 50m, somewhat counter to the expectation that vortices interact destructively and “pinch” together.
- There are cases where the sink rate for one vortex in a pair is consistently different that the other’s sink rate.

Summary of SWA algorithm errors

- Given the sampling limitations of the TODWL system, we expect:
  - Uncertainty in locating the centers of each vortex (+- 5 meters horizontal)
    - Running average location over 10 sweeps (10 – 20 seconds) seems to be very reasonable
  - Uncertainty in height assignment of individual vortex (+- 25 m vertical)
    - Running average vertical location over 10 sweeps seems to be very reasonable
  - Uncertainty in the estimation of the circulation (+- 30%)
    - 10 sweep running average circulation values are also quite reasonable and in agreement with model predictions
- Therefore, our focus is now shifting to:
  - Sink rates outside the envelope of expected values
  - Vortex separations that exceed 60m
  - Loss of detectable vortices in areas preceded and followed by detectable vortices.

Recommendations for next flight series

- Fly the C-17 well above the boundary layer to reduce convective interference with vortices. This will improve model validation for the basic physics of WTV generation and evolution.
- Fly within stable or neutral boundary layers. Marine boundary layers over the coast of California offer a good laboratory.
- Fly longer legs with the C-17 (3-5 minutes instead of 2).

Acknowledgements

- USArmy funding through Phase II SBIR to SWA
- Draper Laboratories for conducting model/data comparisons
- Kevin Godwin of KGS, LLC for assistance in operating TODWL in the Yuma field experiments and generating realtime/quicklook TODWL soundings used in planning the next day experiments.