Airborne DWL investigations of wing tip vortices and their dissipation

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WG Meeting , Boulder, Co.

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DoD funded study

- 1st in a series of tests conducted at Yuma Proving Grounds, Arizona in April 2014
- Partners:
  - US Army ATEC at Yuma (host and co-ordination)
  - US Air Force from McCord AFB (C-17)
  - ONR CIRPAS (Twin Otter with TODWL)
  - Draper Labs (Vortex Model)
  - Simpson Weather Associates (TODWL operations, data processing and model validation)

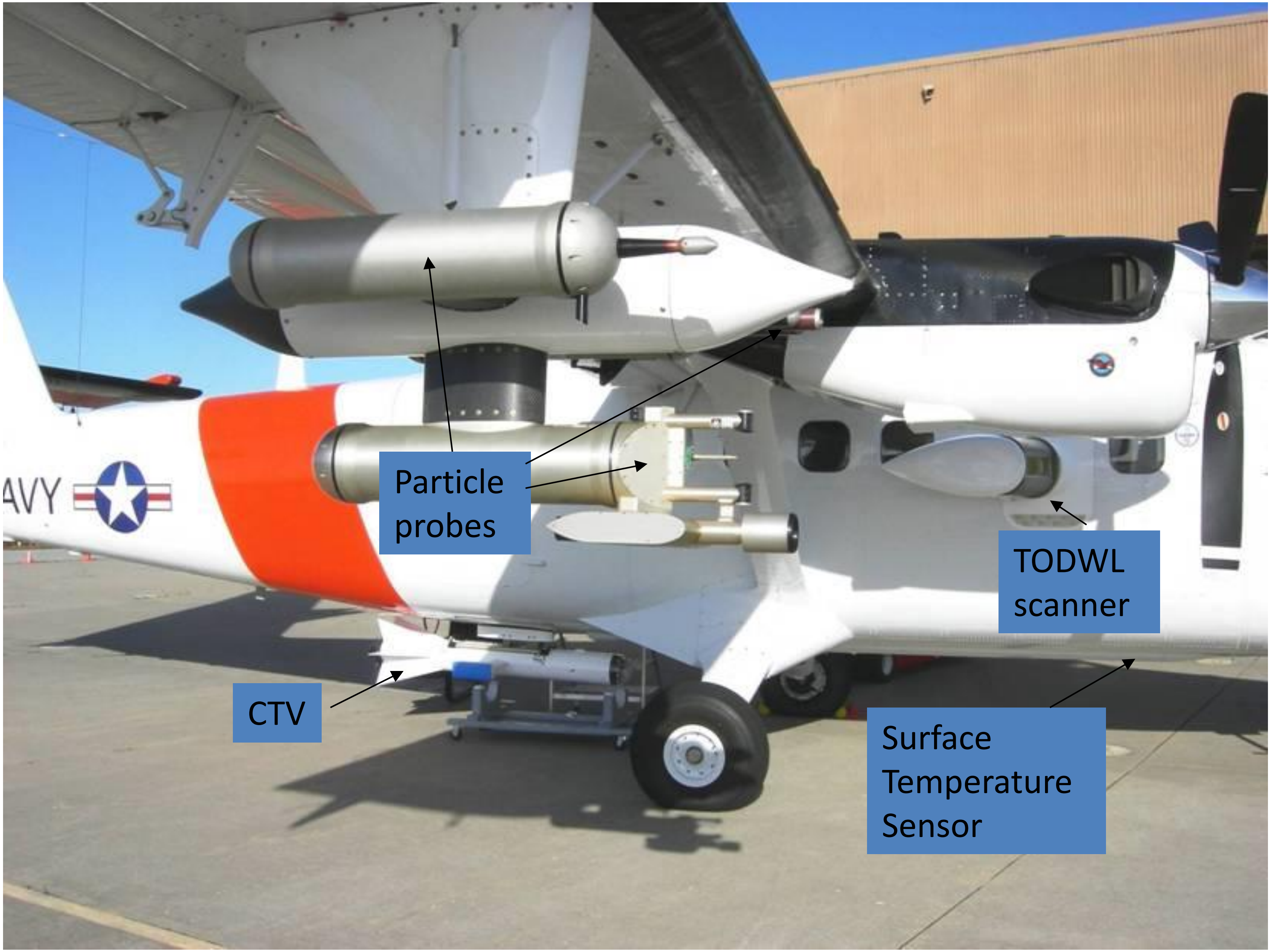
Motivation

- C-17 Wing Tip Vortices generate tangential speeds of 100+ m/s .
- WTVs represent significant danger to paratroopers
- Current spacing of trailing C-17's is thought to be much greater than necessary. DoD not comfortable trusting models.
- Ground based DWLs have been used to investigate WTVs (LMCT, NASA, DLR, DoD…….)
- Airborne DWL offers significant flexibility in monitoring WTVs in a variety of aircraft configurations, atmospheric conditions and topographical regions.

Wing Tip Vortices

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


AVY
Particle probes
TODWL scanner
CTV
Surface Temperature Sensor

Major considerations

- Differential speed between C-17 and Twin Otter. +-10 kts of 130 kts.
- Scanner slew rate
- Six sampling modes
- What are the maximum tangential velocities expected?
- What are the time/space requirements for life cycle monitoring?
- Measurements of thermal stability and wind profiles between surface and 1000m

Vortex Model

- The flow field behind a lift-generating aircraft can be approximated by a pair of fully rolled up vortices a few wing spans behind the aircraft,

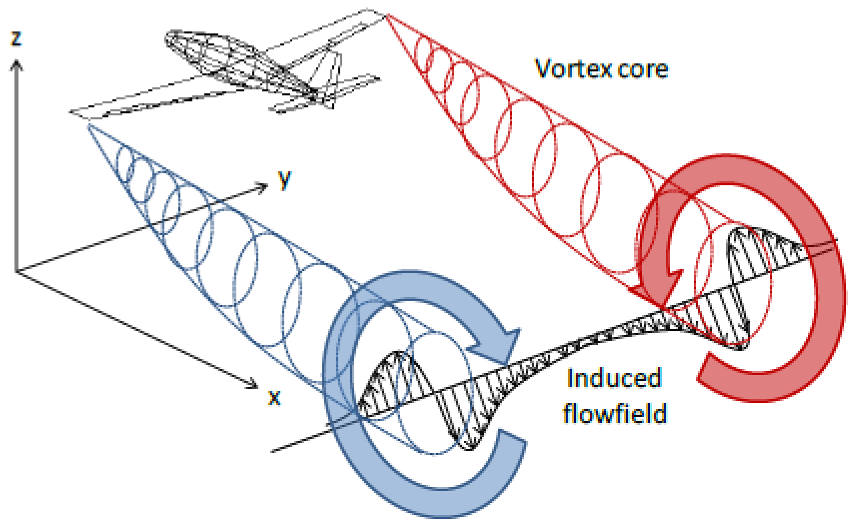


Figure 1: Wake vortex flowfield behind a lift-producing aircraft.[4]

Vortex Model

- As the trailing wake rolls up, the vortices move inward from the wingtips and are eventually separated by an effective span, b_{eff}. For an elliptic loading,

$$b_{eff} = \pi b/4$$

- The initial vortex strength is given by,

$$\Gamma_0 = \frac{kW}{\rho V_\infty b_{eff}} = \frac{4kW}{\pi \rho V_\infty b}$$

- The vortex strength decays over time according to the empirically-derived vortex decay time t_d. t_v is the current vortex age

$$\Gamma = \Gamma_0, \quad t_v \le t_d$$
$$\Gamma = \Gamma_0 \frac{t_d}{t_v}, \quad t_v > t_d$$

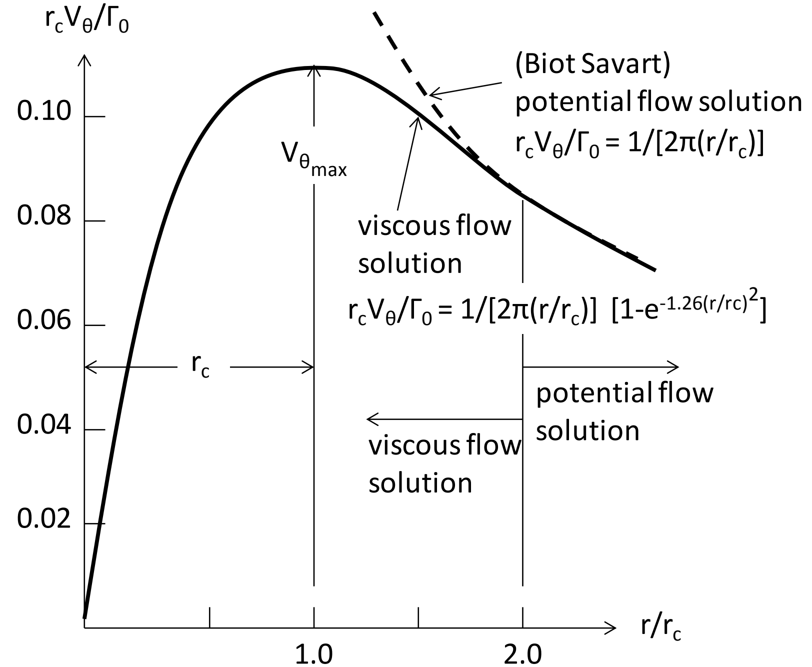
Vortex Model

- The induced velocity is maximum at some distance from the vortex core.

$$r_c = 36.2\sqrt{\frac{\nu t_v}{\cos^2 \Lambda}}$$

- Induced velocity from Biot-Savart law with corrections to model zero velocity at vortex core
  - Velocity profile based on Kurylowich model
- Numerical model generates new vortex at each time step at each wing tip

$$V_\theta = \frac{\Gamma}{2\pi r}\left[1 - e^{-1.26(r/r_c)^2}\right].$$



Vortex Calculations – 1250 ft. AGL

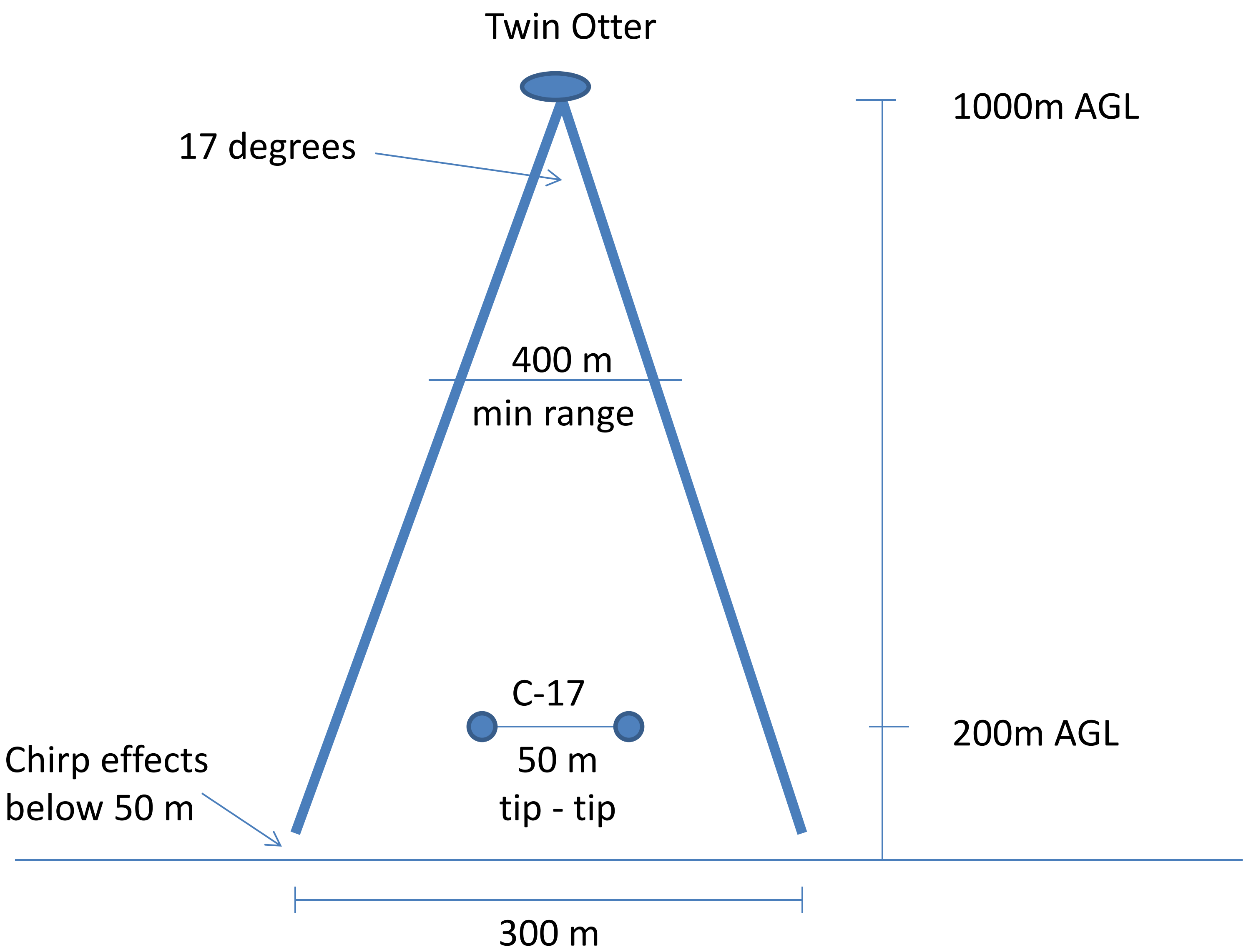
Time (s)	Distance from a/c (ft)	Altitude (ft)	Vortex Core Radius (ft)	Max Vtan (ft/s)	Radius (ft) with Vtan of 20 ft/s
7.5	1640 (0.5 km)	1216	1.39	391	37.99
15	3281 (1km)	1174	1.97	277	37.99
30	6561 (2km)	1088	2.78	195	37.99
60	13123 (4km)	918	3.93	138	37.98
90	19685 (6km)	780	4.81	76	25.41
120	26247 (8km)	682	5.56	49	19.06
150	32808 (10km)	606	6.22	35	15.24
180	39370 (12km)	546	6.81	27	12.53
210	45932 (14km)	494	7.36	21	9.64
240	52493 (16km)	450	7.86	17	
270	59055 (18km)	411	8.34	15	
300	65616 (20km)	377	8.79	12	

W= 400,000 lb, V = 130 knots, Altitude = 1250 ft, td = 60s

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
Overtake	600’ (130K)	3000’ (140K)	Begin nadir raster sampling when TO is 1 -2 km behind C-17 and then overtake the 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.

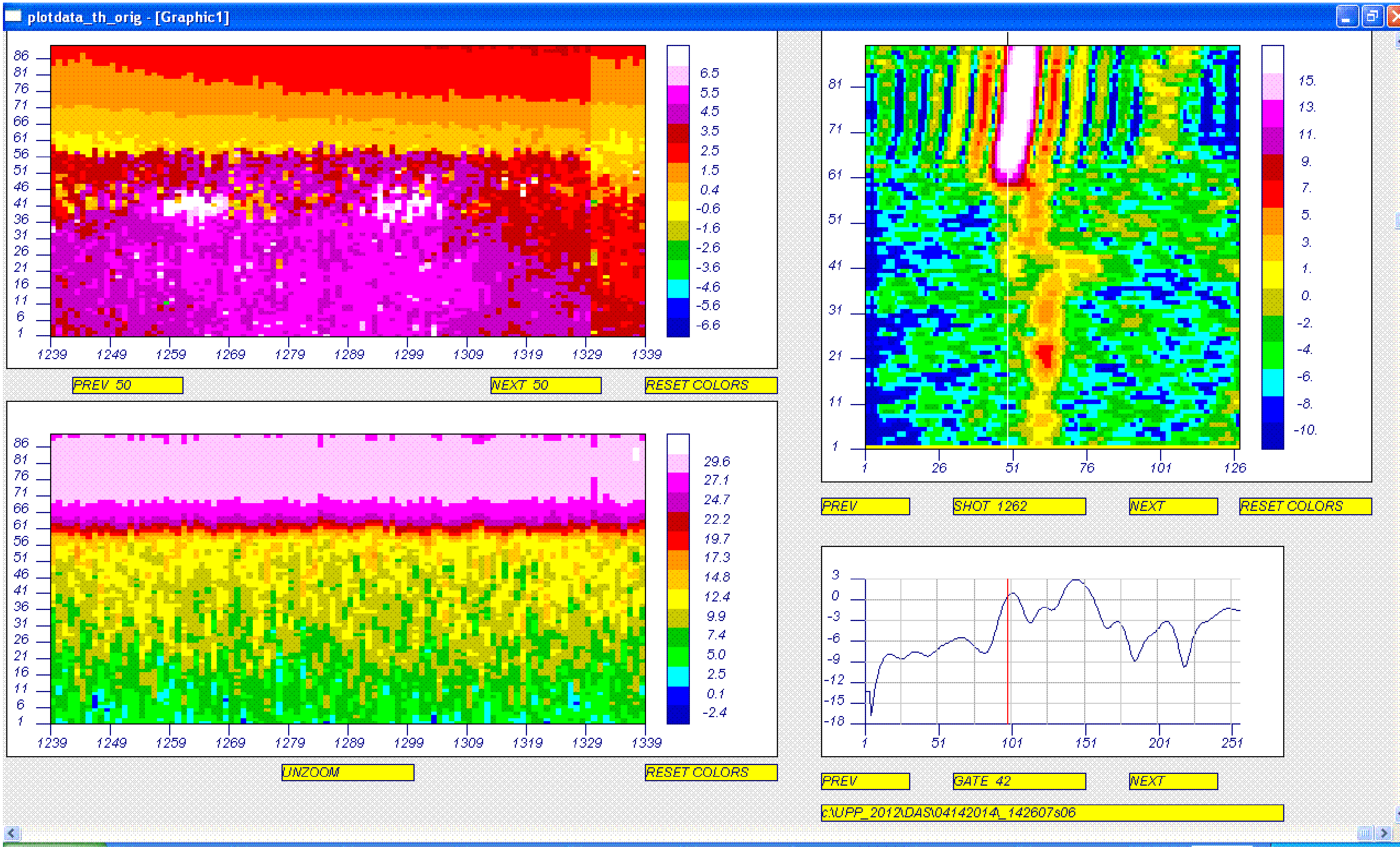
SWA contribution



Aircraft positions and lidar cone of regard for “backslide” and “overtake” modes

Challenges

- Getting and keeping C-17 and Twin Otter aligned during 8km “runs” in cross winds and heavy turbulence
  - C-17 at 130 Kts with FL 550’ or 1250’ AGL
  - Twin Otter at 130 Kts with FL 3500’ - 5500’ AGL
- Keeping vortex pair within TODWL’s field of regard
  - Want a small field of regard to increase spatial and temporal resolution
- Sample features with spatial dimensions of a few 10’s of meters with a pulse length ~ 75m.
- Extract velocities in the presence of strong chirp returns from surface.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86 81 76 71 66 61 56 51 46 41 36 31 26 21 16 11 6 1
1239 1249 1259 1269 1279 1289 1299 1309 1319 1329 1339
6.5 5.5 4.5 3.5 2.5 1.5 0.4 -0.6 -1.6 -2.6 -3.6 -4.6 -5.6 -6.6
PREV 50
NEXT 50
RESET COLORS
86 81 76 71 66 61 56 51 46 41 36 31 26 21 16 11 6 1
1239 1249 1259 1269 1279 1289 1299 1309 1319 1329 1339
29.6 27.1 24.7 22.2 19.7 17.3 14.8 12.4 9.9 7.4 5.0 2.5 0.1 -2.4
UNZOOM
RESET COLORS
81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
15. 13. 11. 9. 7. 5. 3. 1. 0. -2. -4. -6. -8. -10.
PREV
SHOT 1262
NEXT
RESET COLORS
3 0 -3 -6 -9 -12 -15 -18
1 51 101 151 201 251
PREV
GATE 42
NEXT
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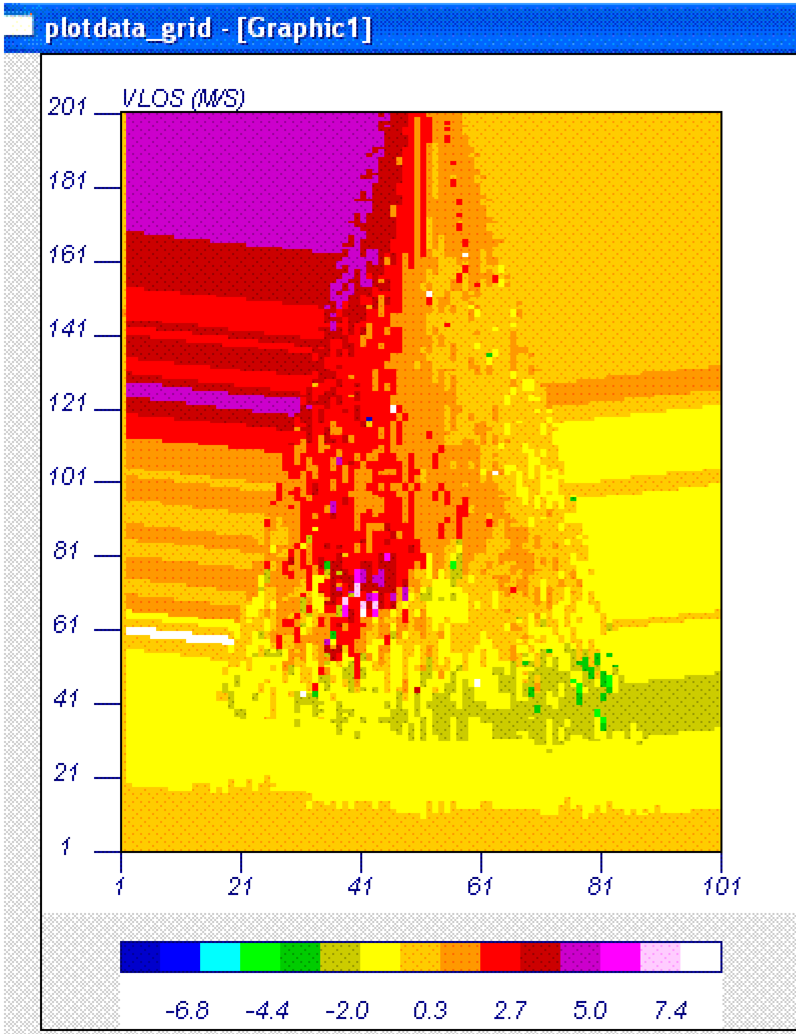
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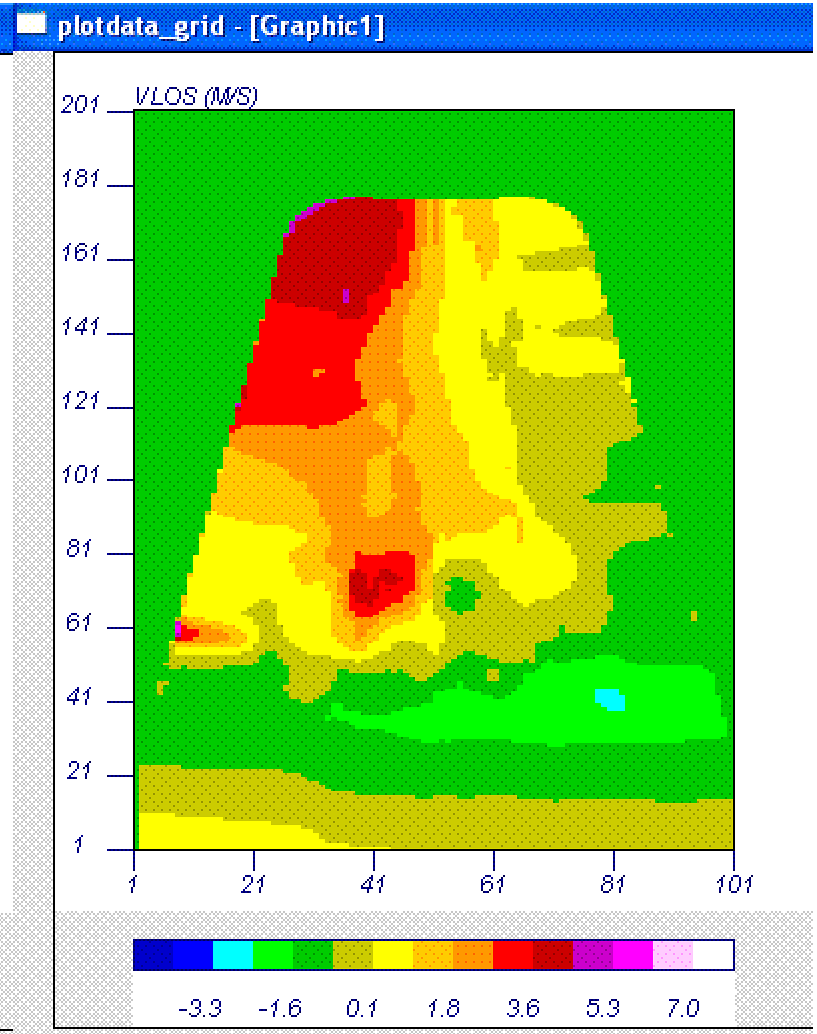
VLOS (M/S)
201
181
161
141
121
101
81
61
41
21
1
1
21
41
61
81
101
-6.8
-4.4
-2.0
0.3
2.7
5.0
7.4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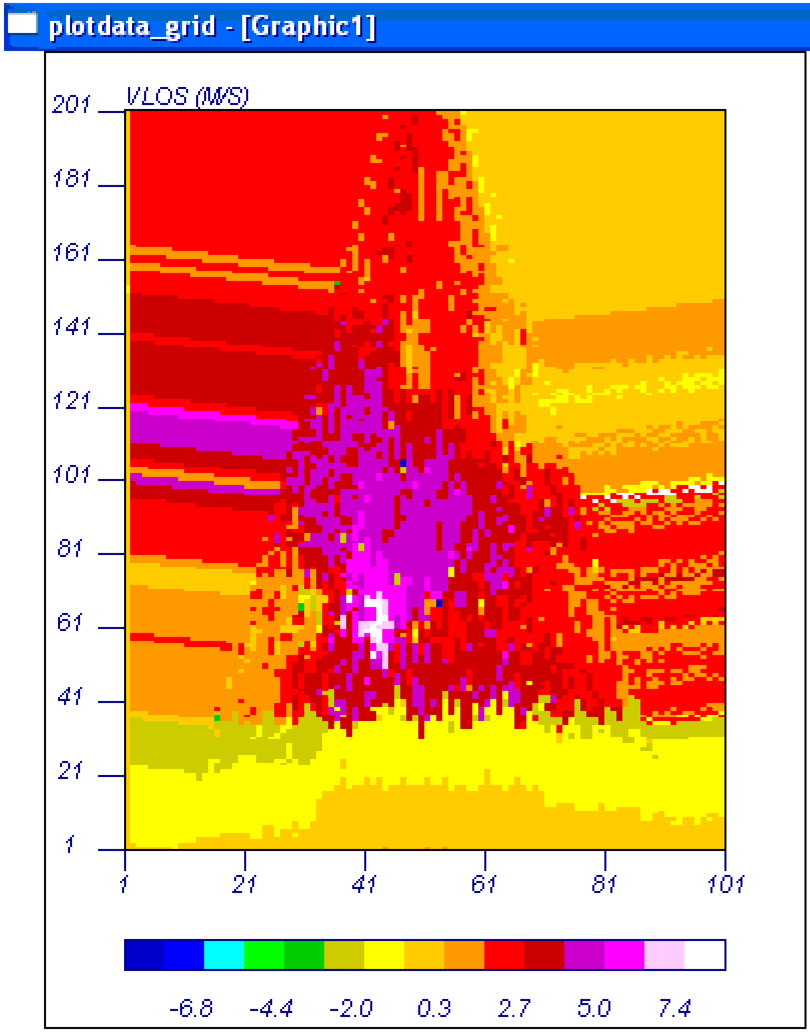
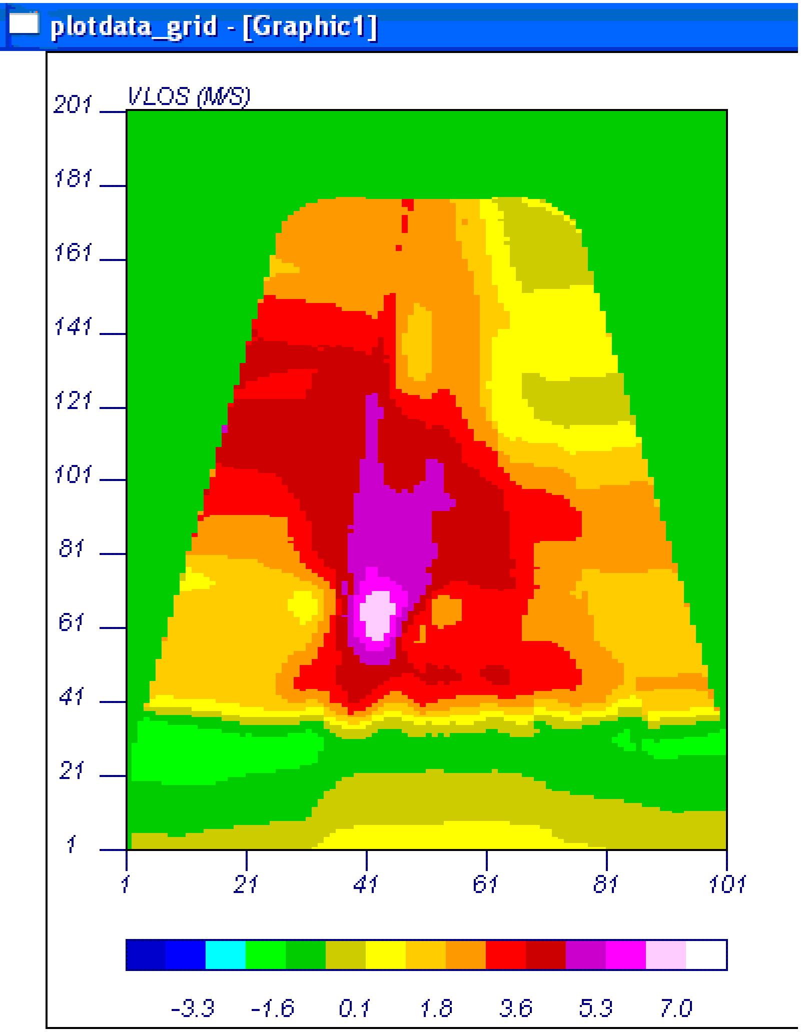
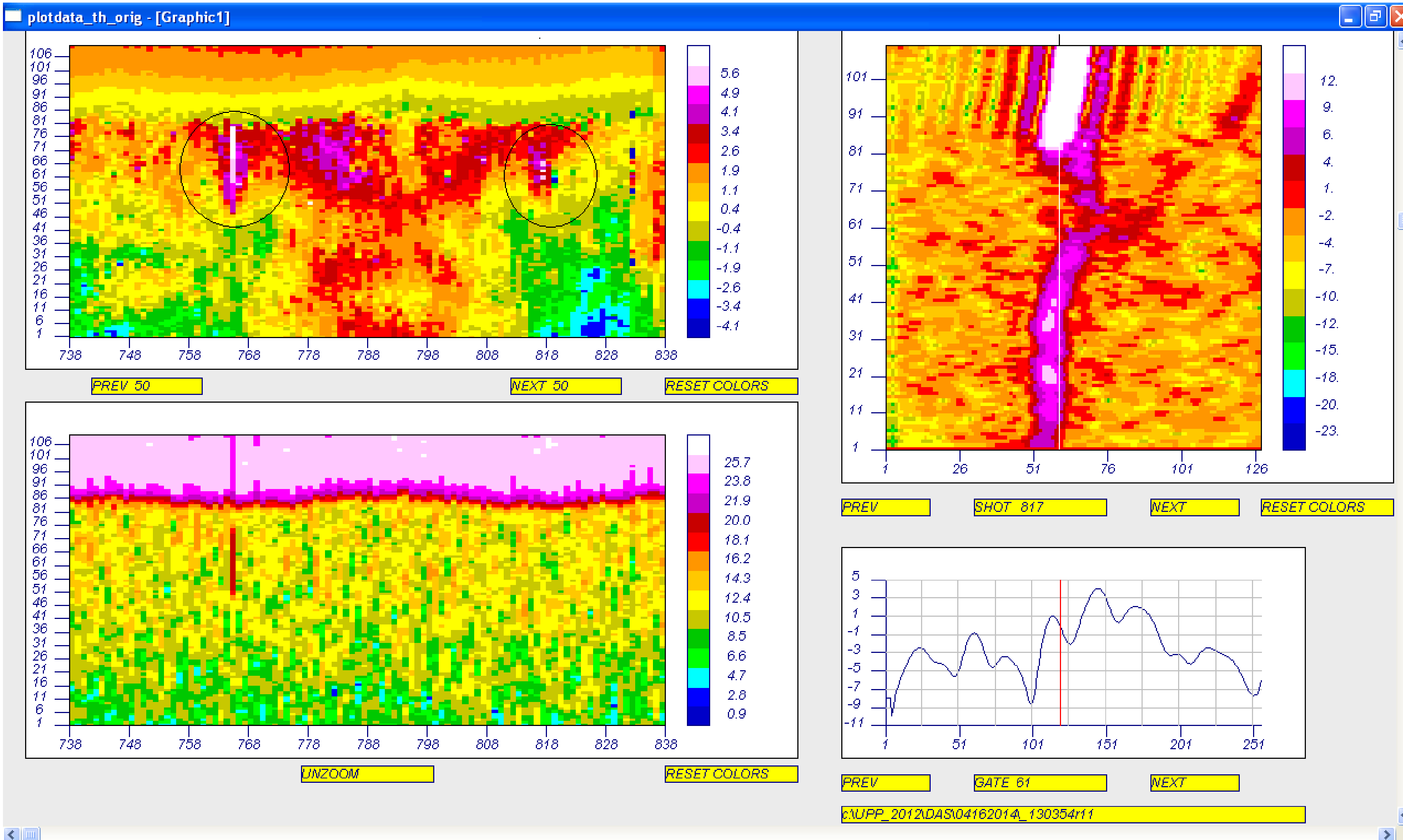
VLOS (M/S)
201
181
161
141
121
101
81
61
41
21
1
1
21
41
61
81
101
-3.3
-1.6
0.1
1.8
3.6
5.3
7.0


plotdata_grid - [Graphic1]
VLOS (M/S)
201
181
161
141
121
101
81
61
41
21
1
1 21 41 61 81 101
-6.8 -4.4 -2.0 0.3 2.7 5.0 7.4


plotdata_grid - [Graphic1]
VLOS (M/S)
201
181
161
141
121
101
81
61
41
21
1
1 21 41 61 81 101
-3.3 -1.6 0.1 1.8 3.6 5.3 7.0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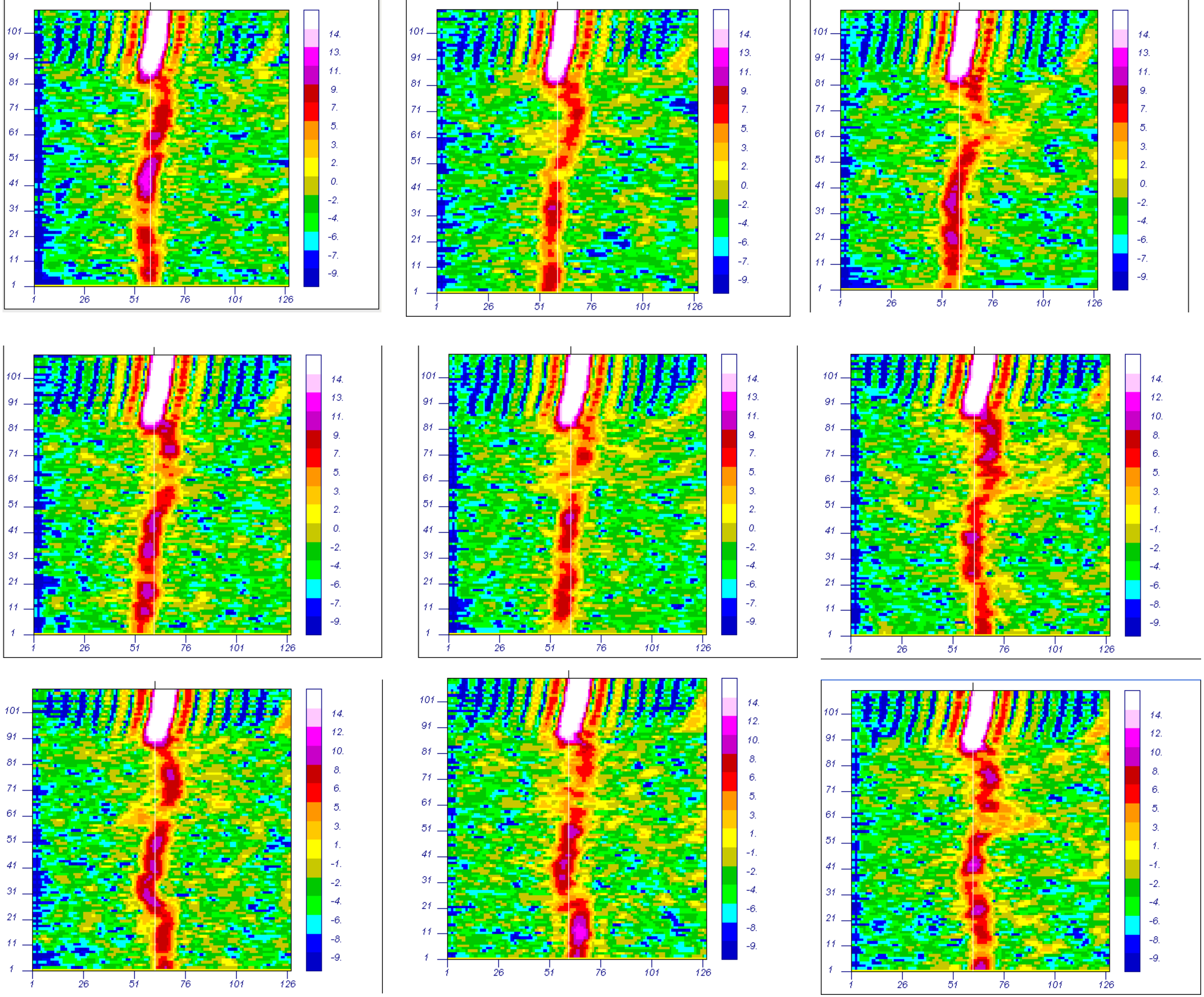
5.6
4.9
4.1
3.4
2.6
1.9
1.1
0.4
-0.4
-1.1
-1.9
-2.6
-3.4
-4.1
738 748 758 768 778 788 798 808 818 828 838
PREV 50
NEXT 50
RESET COLORS
25.7
23.8
21.9
20.0
18.1
16.2
14.3
12.4
10.5
8.5
6.6
4.7
2.8
0.9
UNZOOM
RESET COLORS
12.
9.
6.
4.
1.
-2.
-4.
-7.
-10.
-12.
-15.
-18.
-20.
-23.
1 26 51 76 101 126
PREV
SHOT 817
NEXT
RESET COLORS
1 51 101 151 201 251
PREV
GATE 61
NEXT
c:\UPP_2012\DAS\04162014_130354r11



101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 13. 11. 9. 7. 5. 3. 2. 0. -2. -4. -6. -7. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 13. 11. 9. 7. 5. 3. 2. 0. -2. -4. -6. -7. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 13. 11. 9. 7. 5. 3. 2. 0. -2. -4. -6. -7. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 13. 11. 9. 7. 5. 3. 2. 0. -2. -4. -6. -7. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 13. 11. 9. 7. 5. 3. 2. 0. -2. -4. -6. -7. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 12. 10. 8. 6. 5. 3. 1. -1. -2. -4. -6. -8. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 12. 10. 8. 6. 5. 3. 1. -1. -2. -4. -6. -8. -9.
101 91 81 71 61 51 41 31 21 11 1
1 26 51 76 101 126
14. 12. 10. 8. 6. 5. 3. 1. -1. -2. -4. -6. -8. -9.
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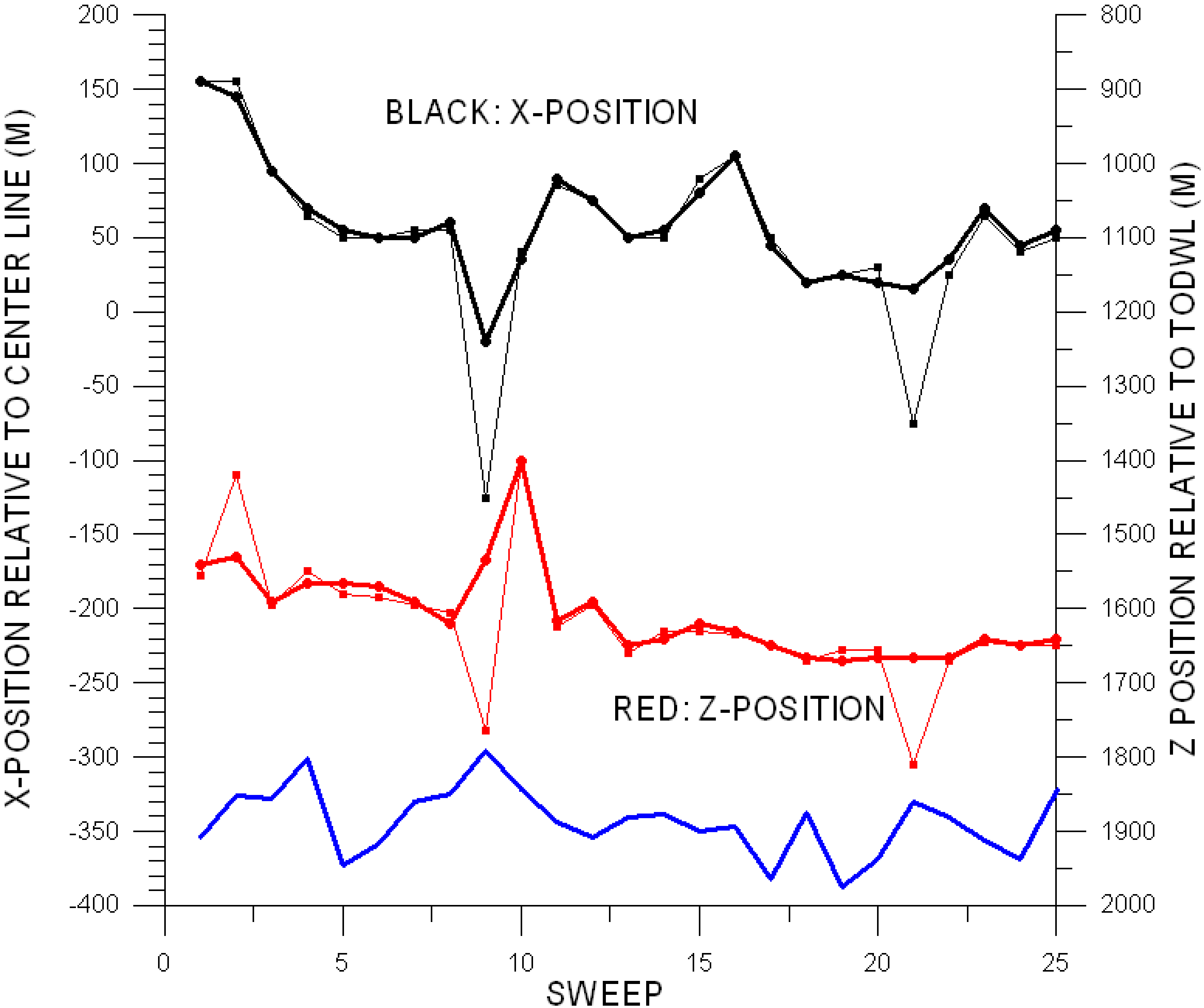
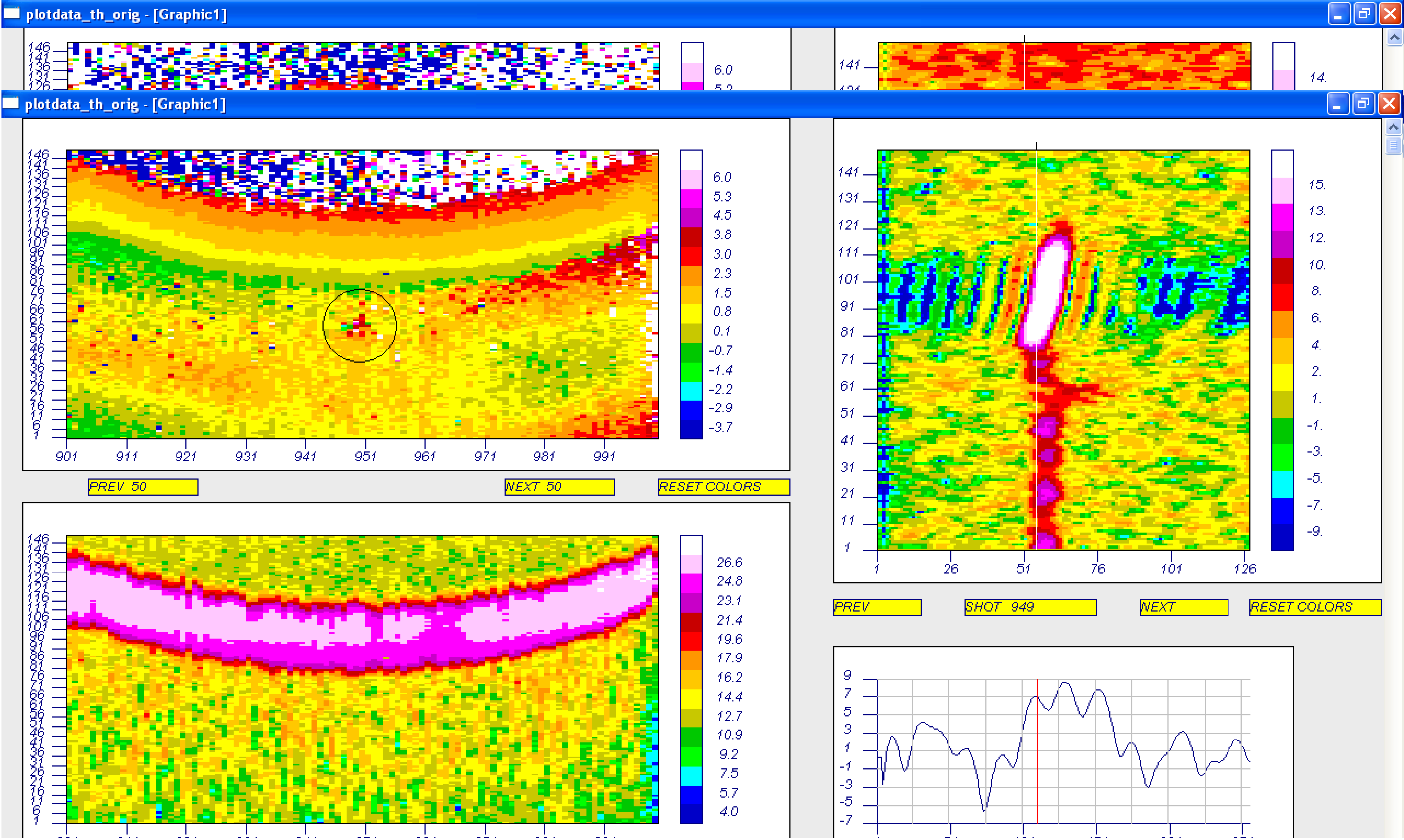
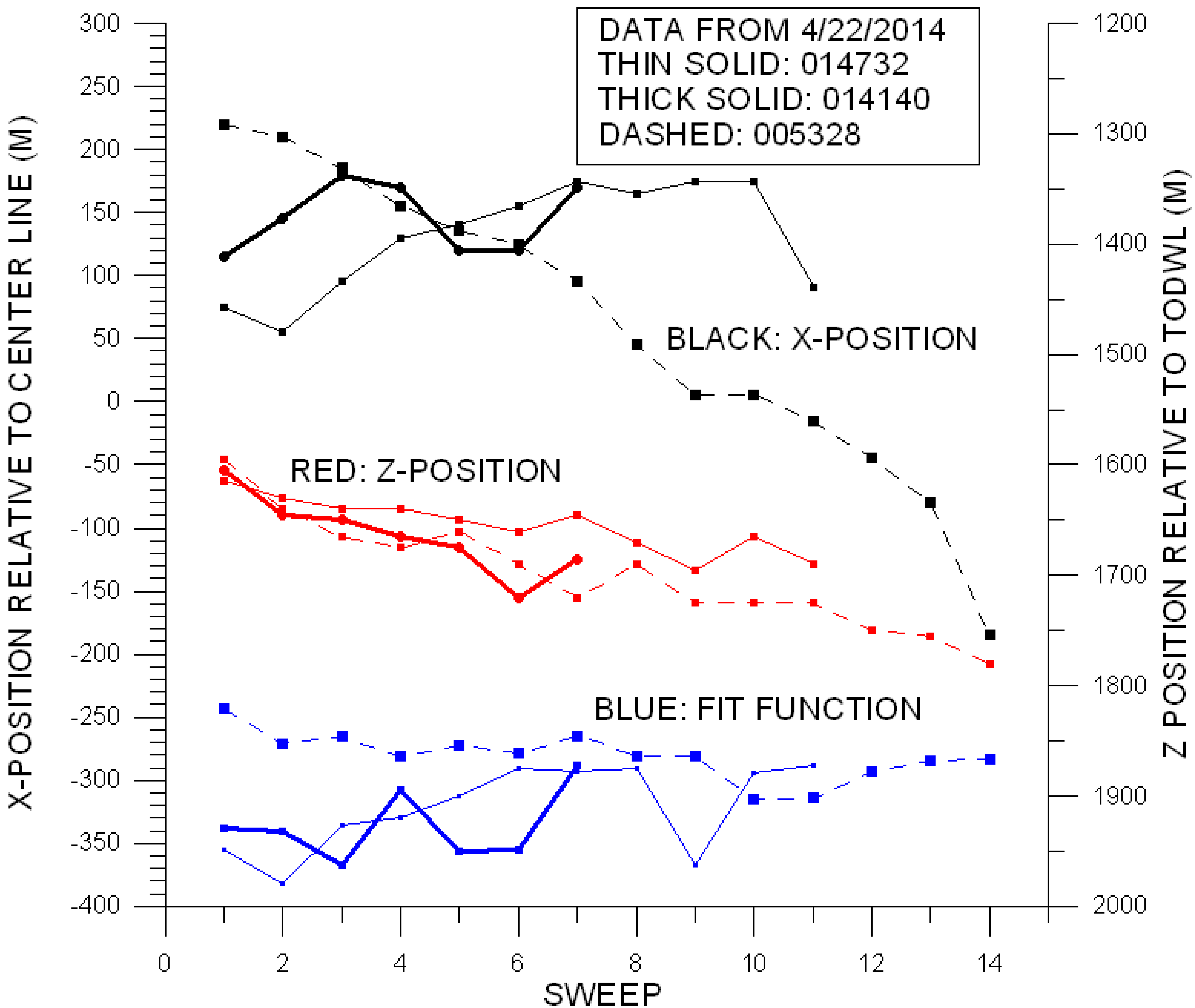
1 26 51 76 101 126
14. 12. 10. 8. 6. 5. 3. 1. -1. -2. -4. -6. -8. -9.


BLACK: X-POSITION
RED: Z-POSITION
X-POSITION RELATIVE TO CENTER LINE (M)
Z POSITION RELATIVE TO TODWL (M)
SWEEP
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
800
900
1000
1100
1200
1300
1400
1500
1600
1700
1800
1900
2000
0
5
10
15
20
25


plotdata_th_orig - [Graphic1]
plotdata_th_orig - [Graphic1]
6.0 5.3 4.5 3.8 3.0 2.3 1.5 0.8 0.1 -0.7 -1.4 -2.2 -2.9 -3.7
901 911 921 931 941 951 961 971 981 991
PREV 50
NEXT 50
RESET COLORS
26.6 24.8 23.1 21.4 19.6 17.9 16.2 14.4 12.7 10.9 9.2 7.5 5.7 4.0
15. 13. 12. 10. 8. 6. 4. 2. 1. -1. -3. -5. -7. -9.
1 26 51 76 101 126
PREV
SHOT 949
NEXT
RESET COLORS
9 7 5 3 1 -1 -3 -5 -7


DATA FROM 4/22/2014
THIN SOLID: 014732
THICK SOLID: 014140
DASHED: 005328
BLACK: X-POSITION
RED: Z-POSITION
BLUE: FIT FUNCTION
X-POSITION RELATIVE TO CENTER LINE (M)
Z POSITION RELATIVE TO TODWL (M)
SWEEP
300
250
200
150
100
50
0
-50
-100
-150
-200
-250
-300
-350
-400
1200
1300
1400
1500
1600
1700
1800
1900
2000
0
2
4
6
8
10
12
14

Summary

- The airborne DWL documentation of WTV life cycles has been successfully demonstrated. CIRPAS pilots deserve much credit for positioning the Twin Otter in prescribed locations relative to the C-17.
- The initial data sets (35 hours, >150 runs) cover extremely convective, neutral and nocturnal stable boundary layer conditions.
- SWA will work with Draper Labs to add statistical envelopes to its deterministic parametric model.
- This work may provide justification for the use of DWLs on C-17’s to directly detect WTVs.