Marine boundary layer organized structures and their potential impact on fluxes

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WG Meeting, Boulder, CO

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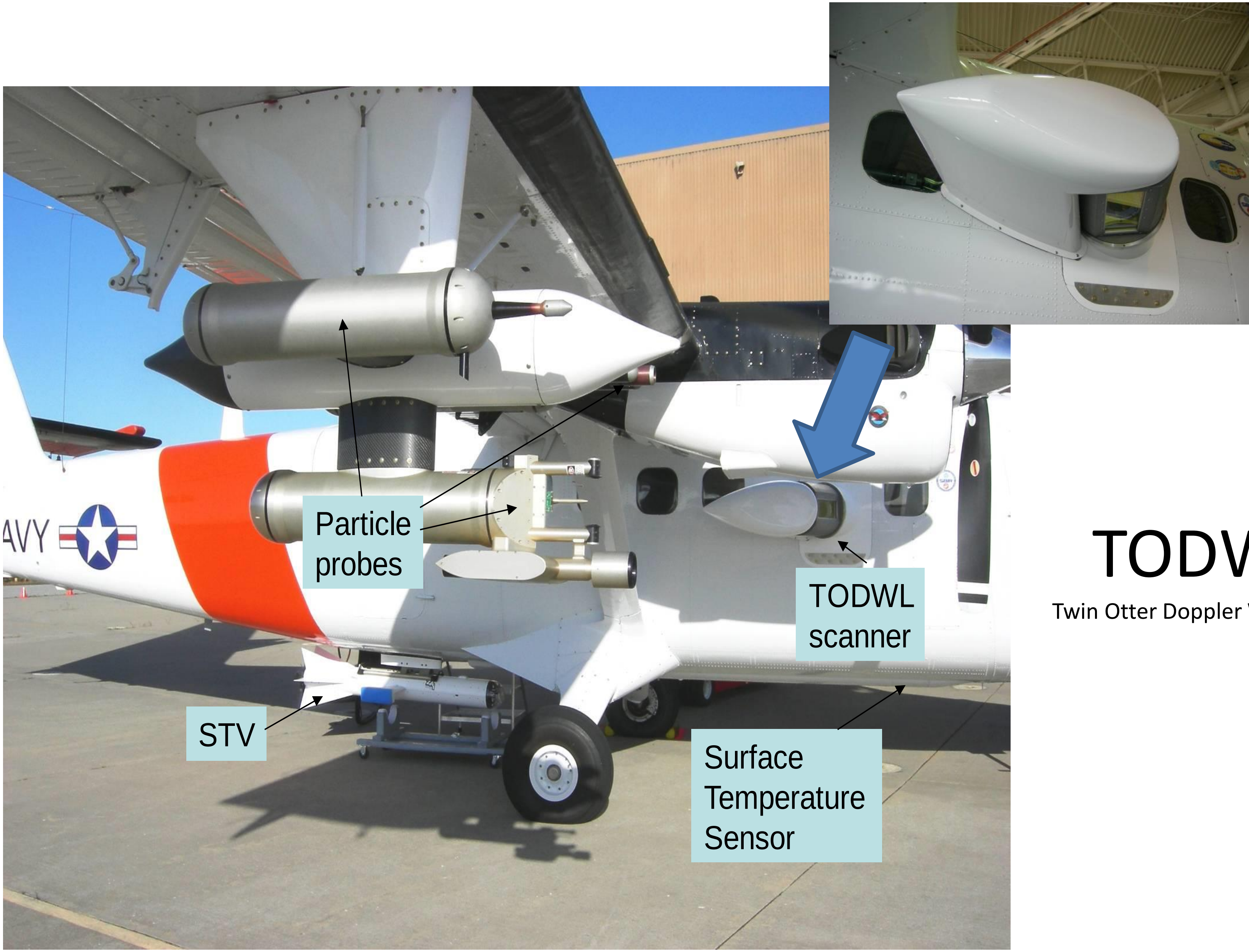
Overview

- Objectives of the September 2012 field campaign
- Description of observing system and data
- Summary of DWL data collection out of Monterey, CA
- Best day data 09/30/12 as example
  - Flight path
  - Clouds
  - Vertical position record
    - Twin Otter and CTV
  - Vertical soundings
- Additional case studies
- Modeling of rolls and their relative contributions to EDMF
- Near term plans

Objectives

- Extend prior airborne Doppler Wind Lidar investigations (2001-2008)of LLJs and OLEs in the MBL and PBLs.
- Investigate and characterize the degree of organization of rolls (OLEs) at the boundaries of stratocumulus topped MBLs.
- Explore the potential impact on the development and implementation of the EDMF into forecast models.

The observing systems and strategies



TODWL

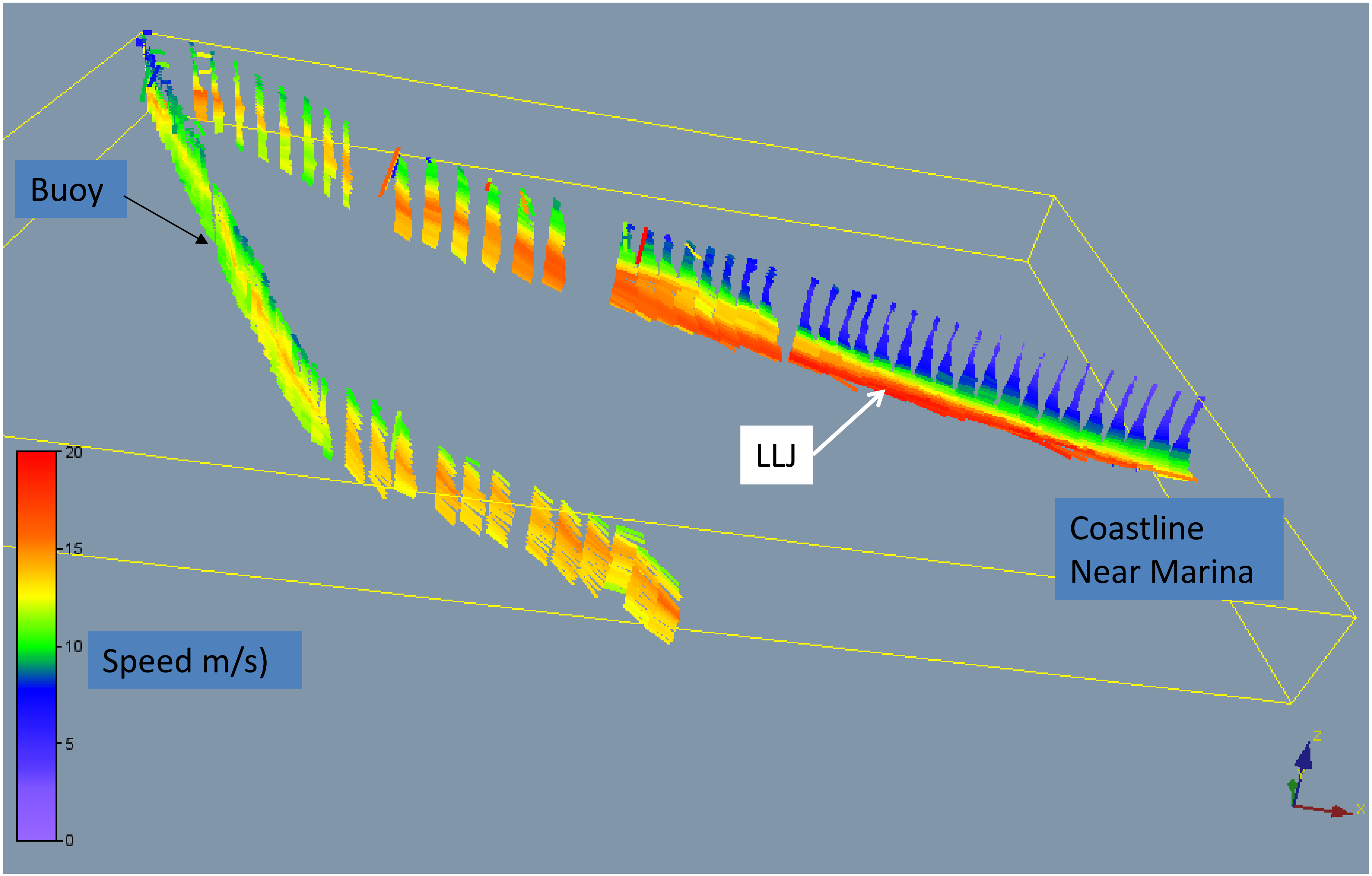
Twin Otter Doppler Wind Lidar

Pallet Wind Observing Lidar Facility (PWOLF)

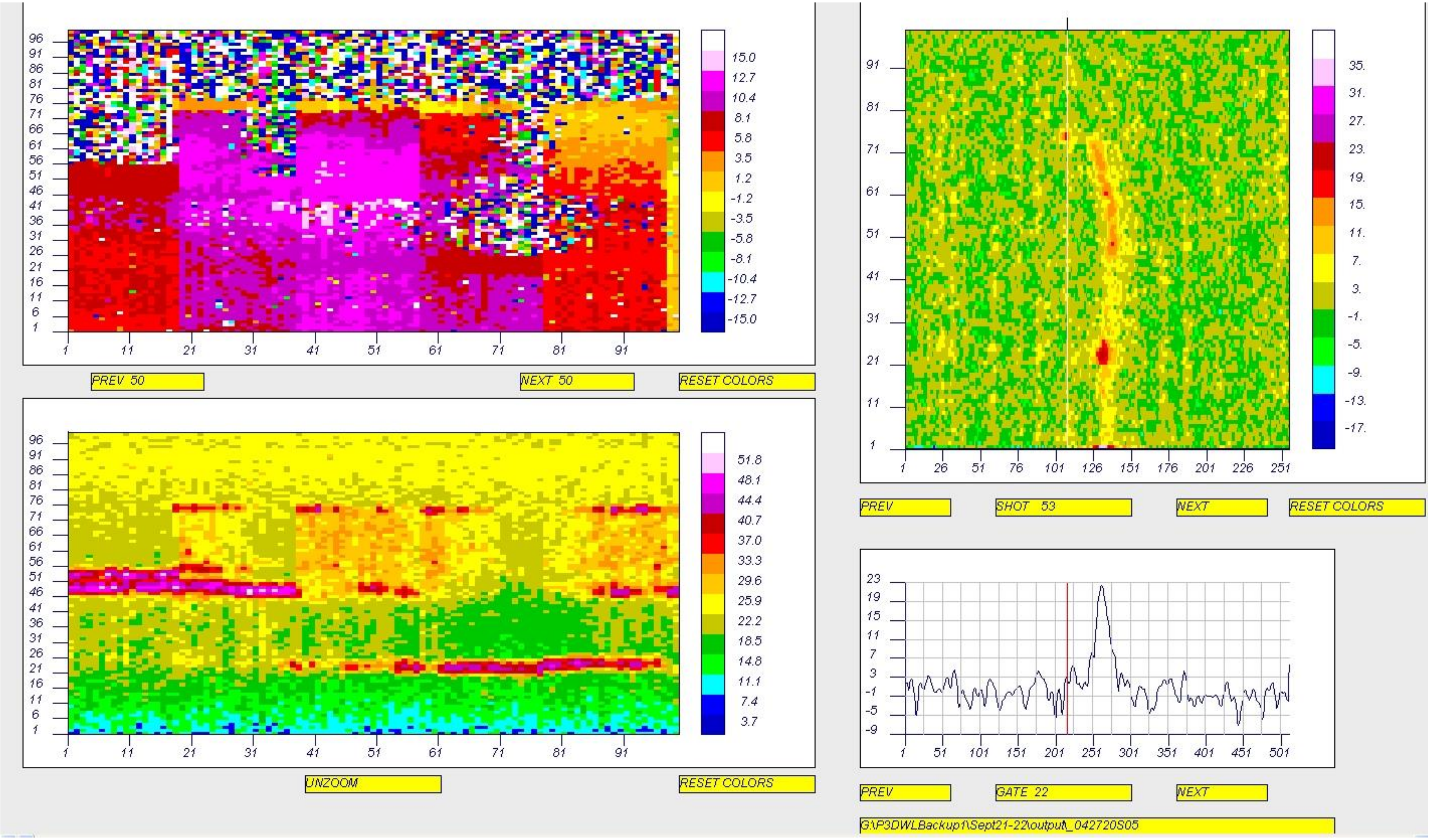
Attribute	Performance Metric	Comments
LOS resolution (applies to vertical profiles of 3D winds as well)	50 m	Range resolution to hard targets (ground or dense cloud) can be better than 10 meters.
U,V,W resolution	< 10 cm/s	< 5 cm/s for stationary groundbased operations
Maximum range	6 -30 km	Very dependent upon aerosols
Time to complete full step stare conical scan for wind profiles	~ 20 sec	12 point step stare with .5 - 2 second dwells
Sampling frequency	160 Hz	Integration of several shots is typical to improve range performance

Example of P3DWL "curtain" of wind profiles

TODWL flight 6:07 pm PST 18 April 2007
Monterey Bay, California



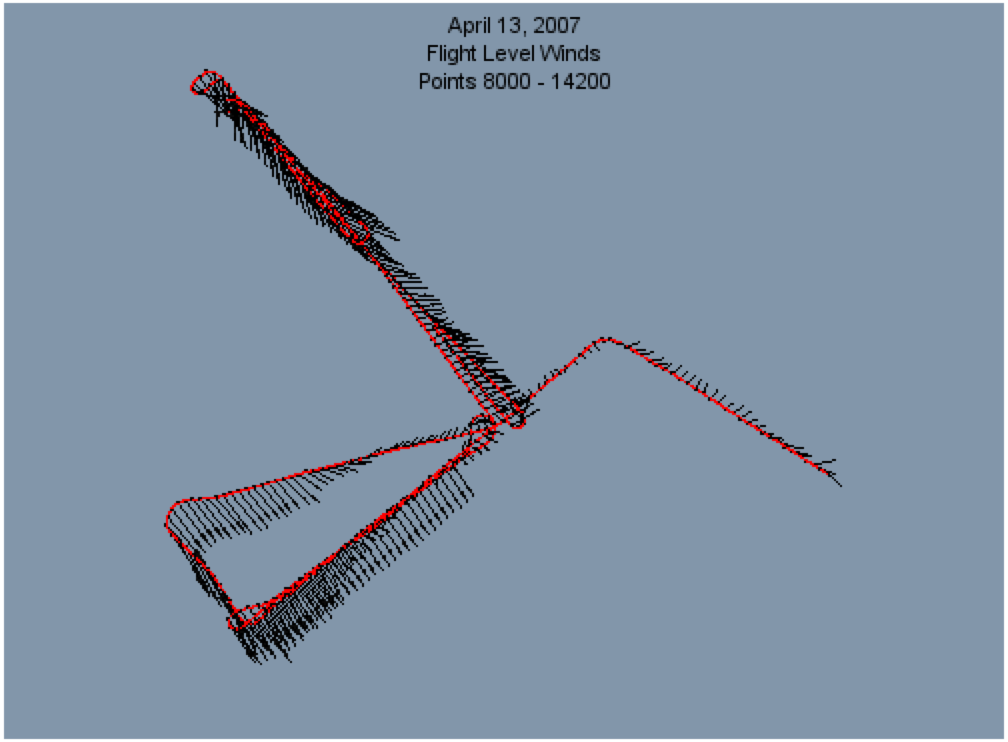
DWL over very disturbed water surface (~60 knots)

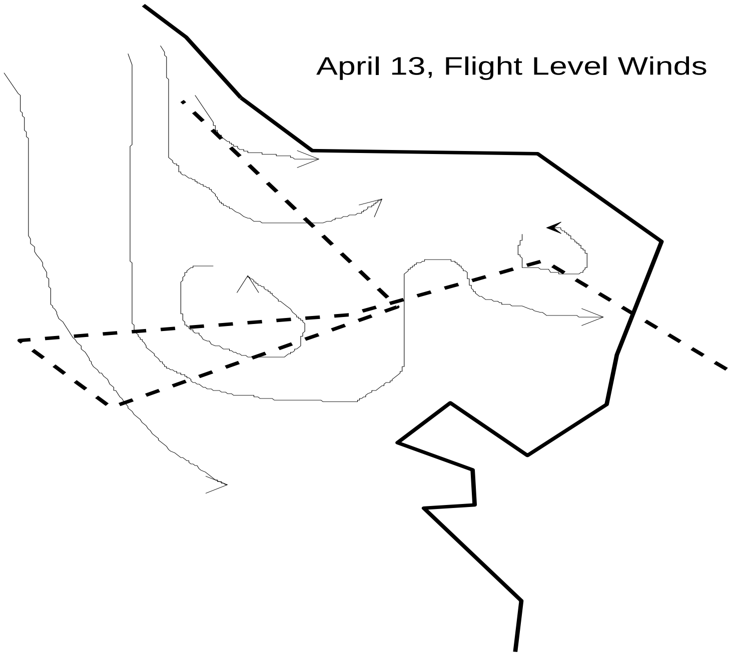


[Water Hagupit]()

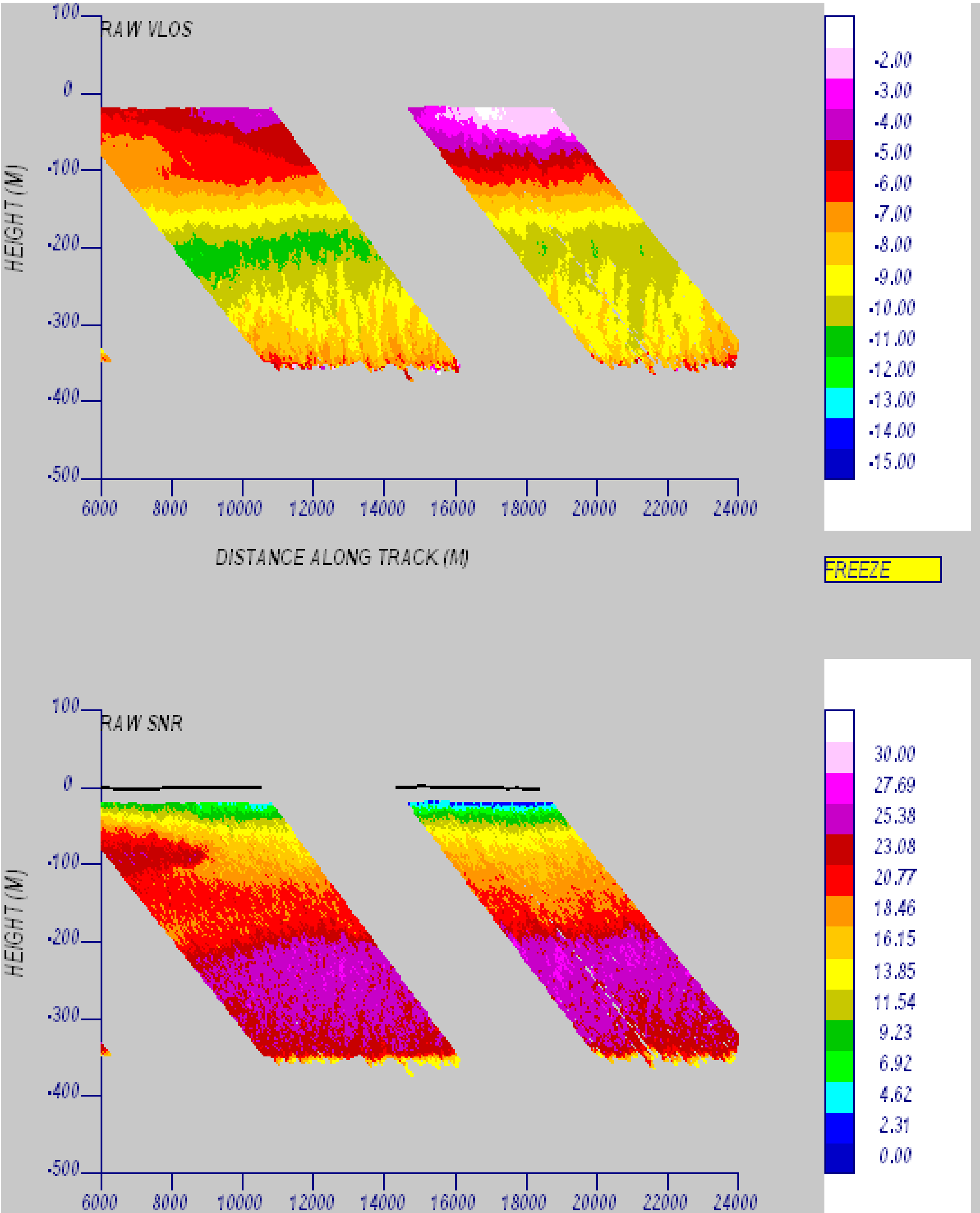
Prospecting Mode

- Feature prospecting uses a very shallow angle below the horizon (~ -1 -3 degrees down when at a 300m flight altitude).
  - Results in ~ 2 m vertical resolution and 50 m horizontal resolution with ~10 meter sliding sample.
  - It takes ~ 40 seconds to profile 100 meters below the aircraft.

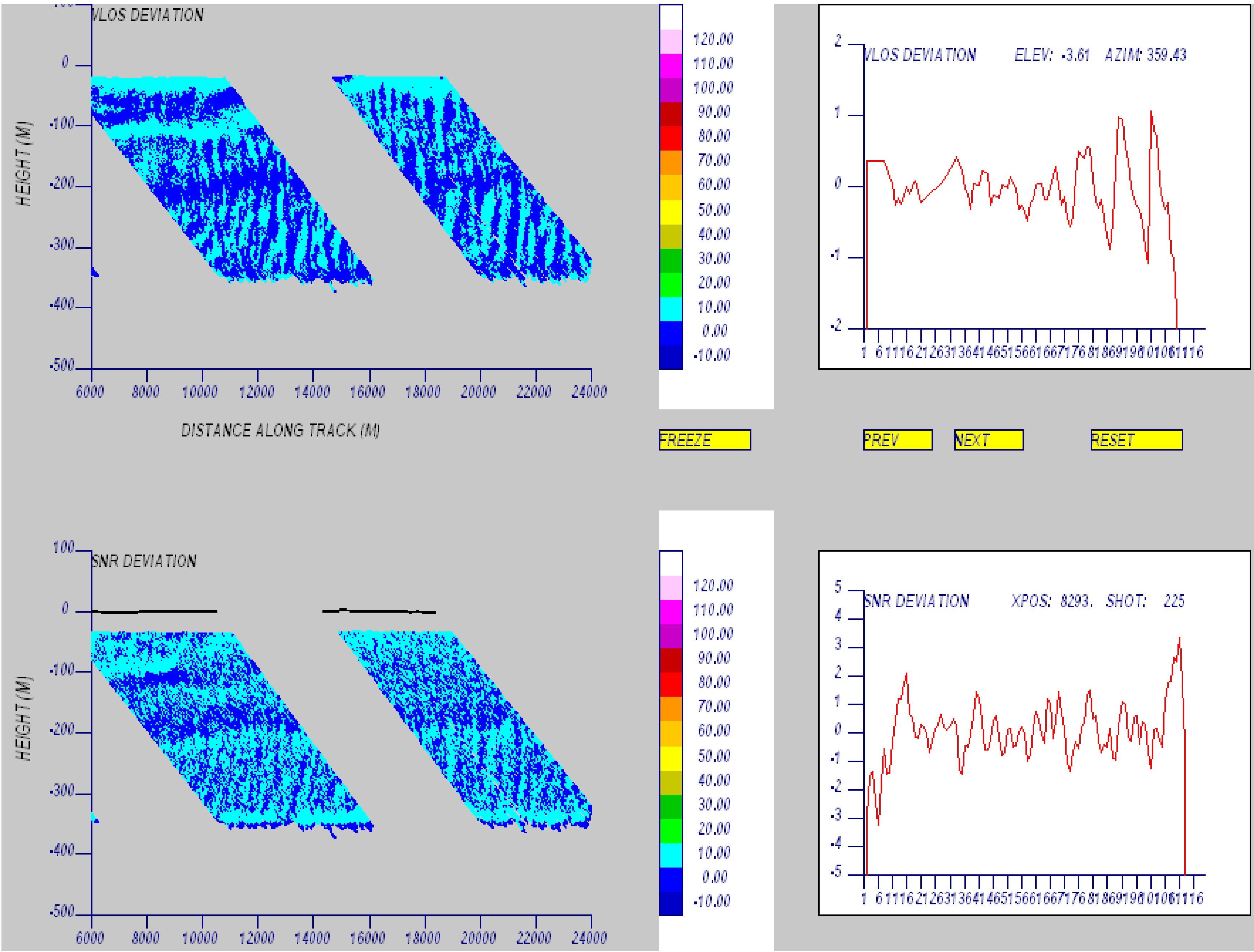


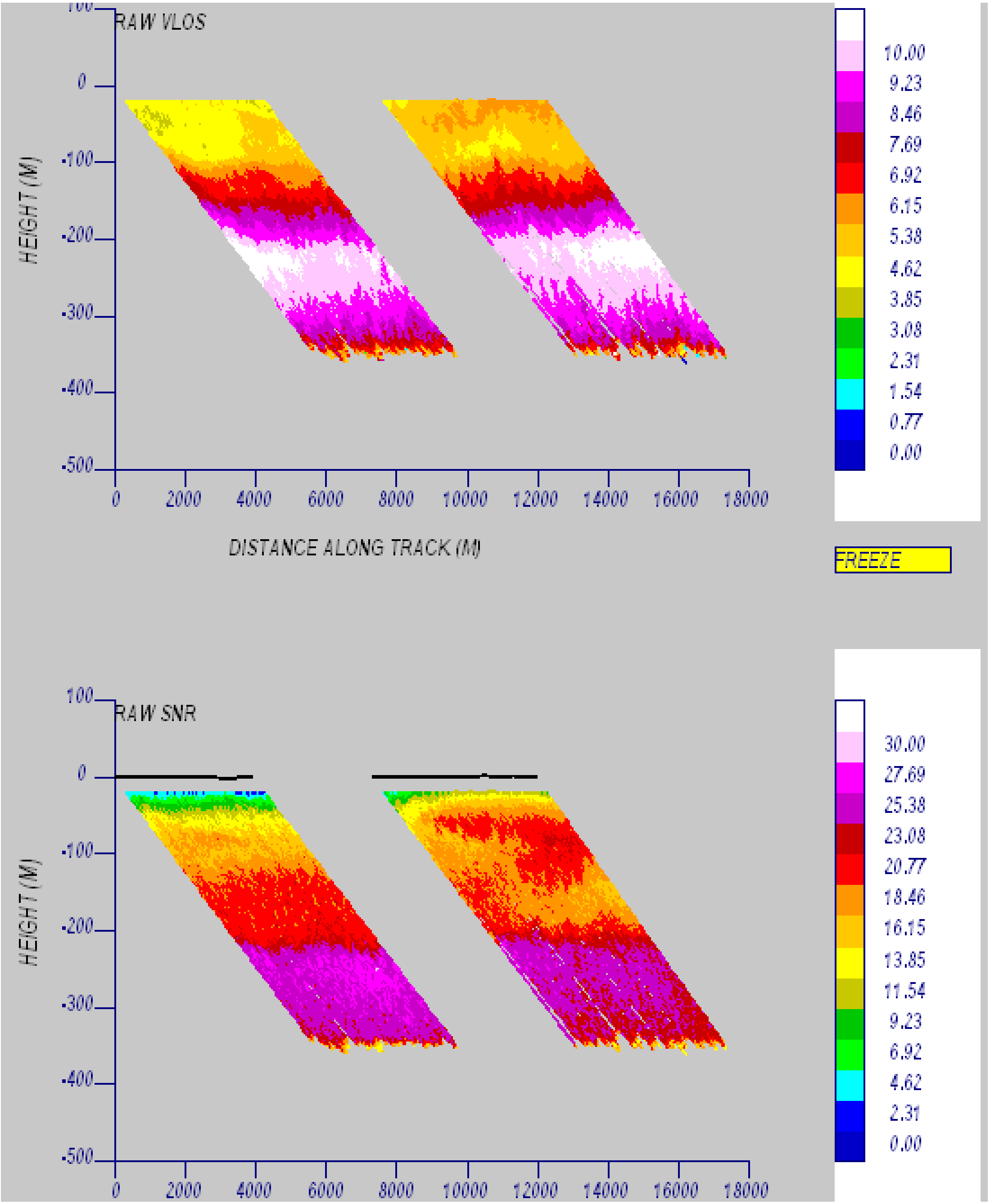


April 13, 2007 flights with CTV


RAW VLOS
HEIGHT (M)
100
0
-100
-200
-300
-400
-500
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
DISTANCE ALONG TRACK (M)
-2.00
-3.00
-4.00
-5.00
-6.00
-7.00
-8.00
-9.00
-10.00
-11.00
-12.00
-13.00
-14.00
-15.00
FREEZE
RAW SNR
30.00
27.69
25.38
23.08
20.77
18.46
16.15
13.85
11.54
9.23
6.92
4.62
2.31
0.00

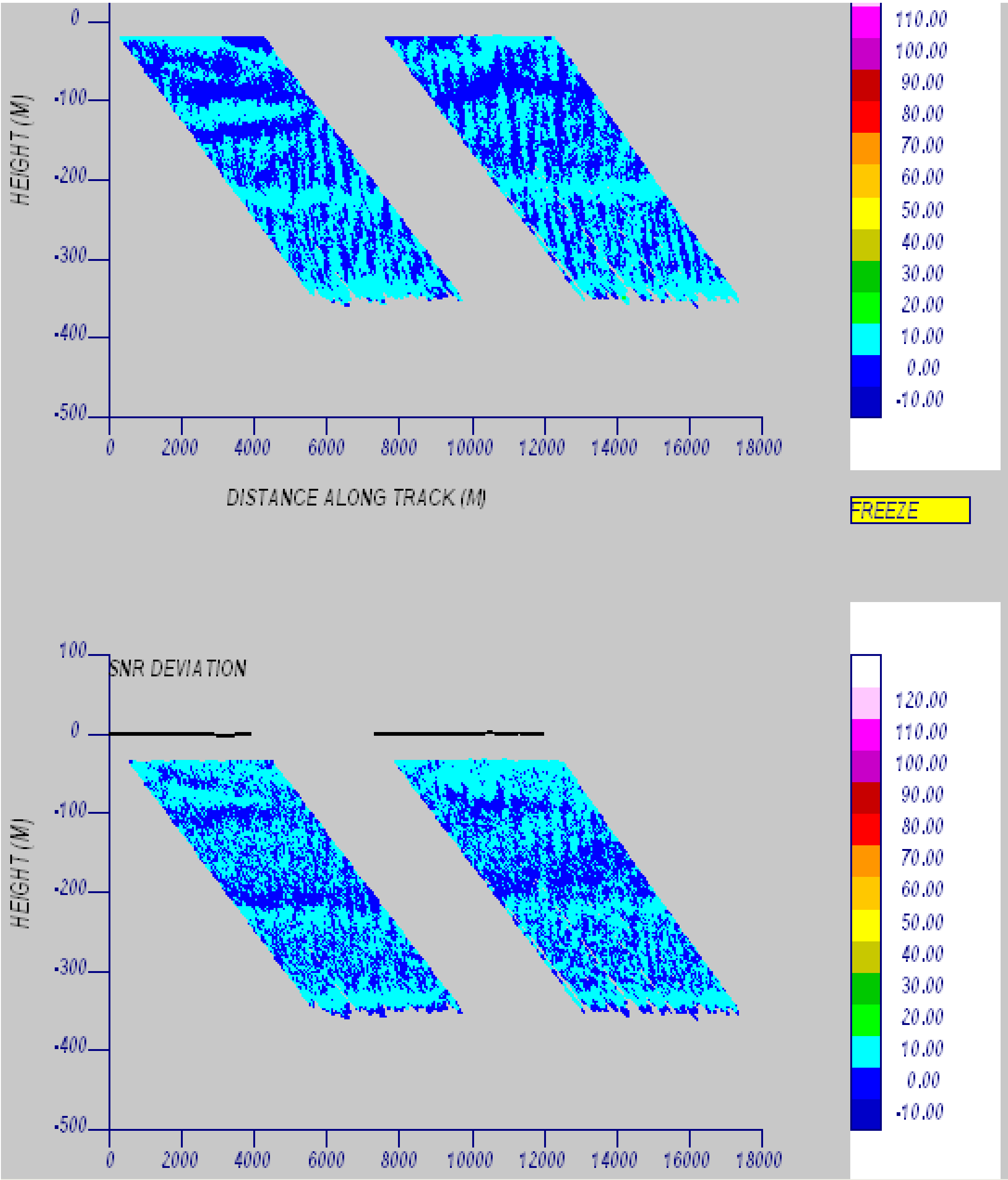
SE


VLOS DEVIATION
HEIGHT (M)
DISTANCE ALONG TRACK (M)
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
VLOS DEVIATION ELEV: -3.61 AZIM: 359.43
FREEZE
PREV
NEXT
RESET
SNR DEVIATION
SNR DEVIATION XPOS: 8293. SHOT: 225

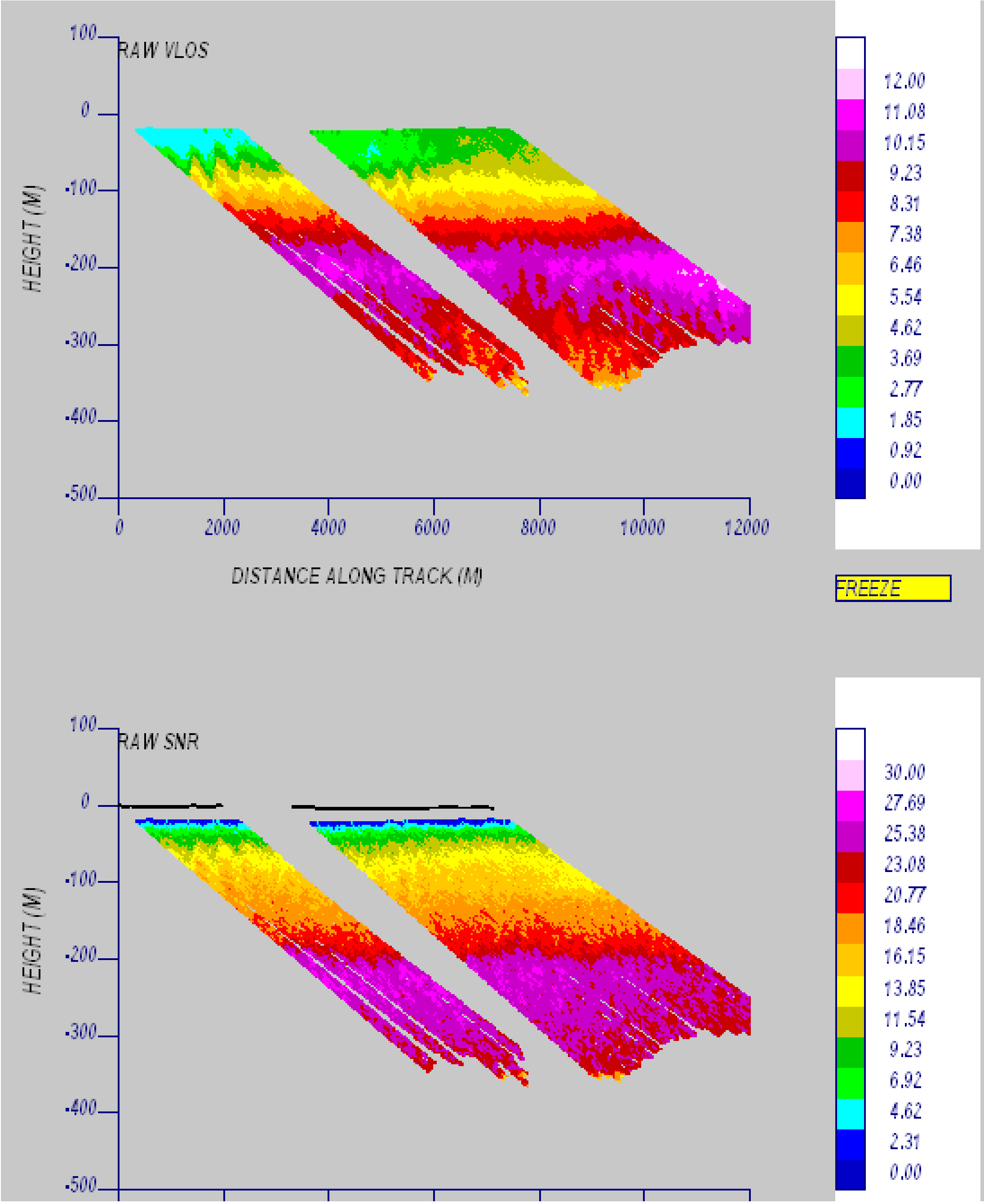


RAW VLOS
HEIGHT (M)
DISTANCE ALONG TRACK (M)
FREEZE
RAW SNR
HEIGHT (M)

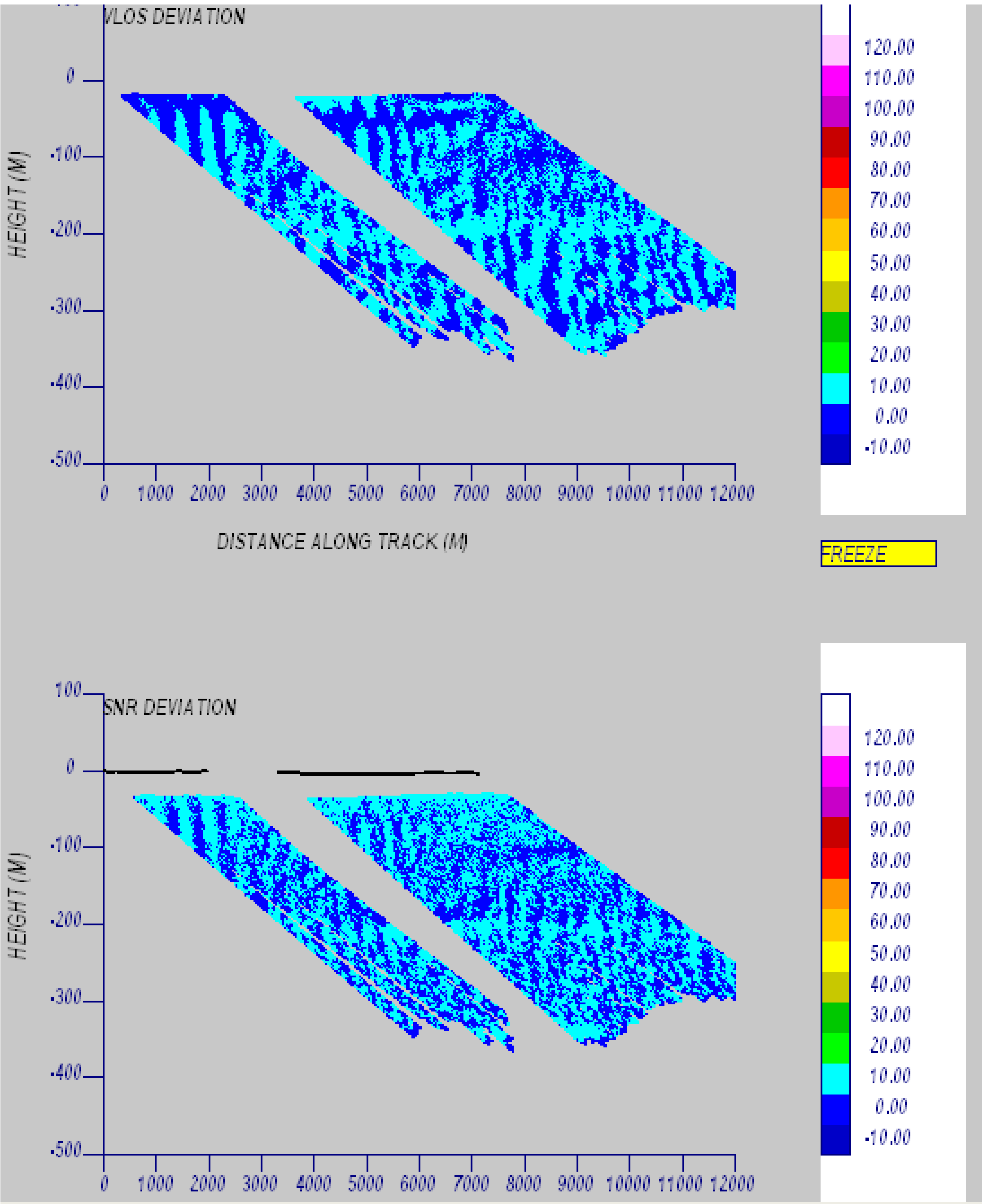
NW



"Stacked-OLEs" or rolls operating in both the negative and positive shear Layers associated with a PBL jet.


RAW VLOS
HEIGHT (M)
100
0
-100
-200
-300
-400
-500
0
2000
4000
6000
8000
10000
12000
DISTANCE ALONG TRACK (M)
12.00
11.08
10.15
9.23
8.31
7.38
6.46
5.54
4.62
3.69
2.77
1.85
0.92
0.00
FREEZE
RAW SNR
HEIGHT (M)
100
0
-100
-200
-300
-400
-500
30.00
27.69
25.38
23.08
20.77
18.46
16.15
13.85
11.54
9.23
6.92
4.62
2.31
0.00

NW



VLOS DEVIATION
HEIGHT (M)
0
-100
-200
-300
-400
-500
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000
DISTANCE ALONG TRACK (M)
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
FREEZE
SNR DEVIATION
HEIGHT (M)
100
0
-100
-200
-300
-400
-500
0 1000 2000 3000 4000 5000 6000 7000 8000 9000 10000 11000 12000
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00

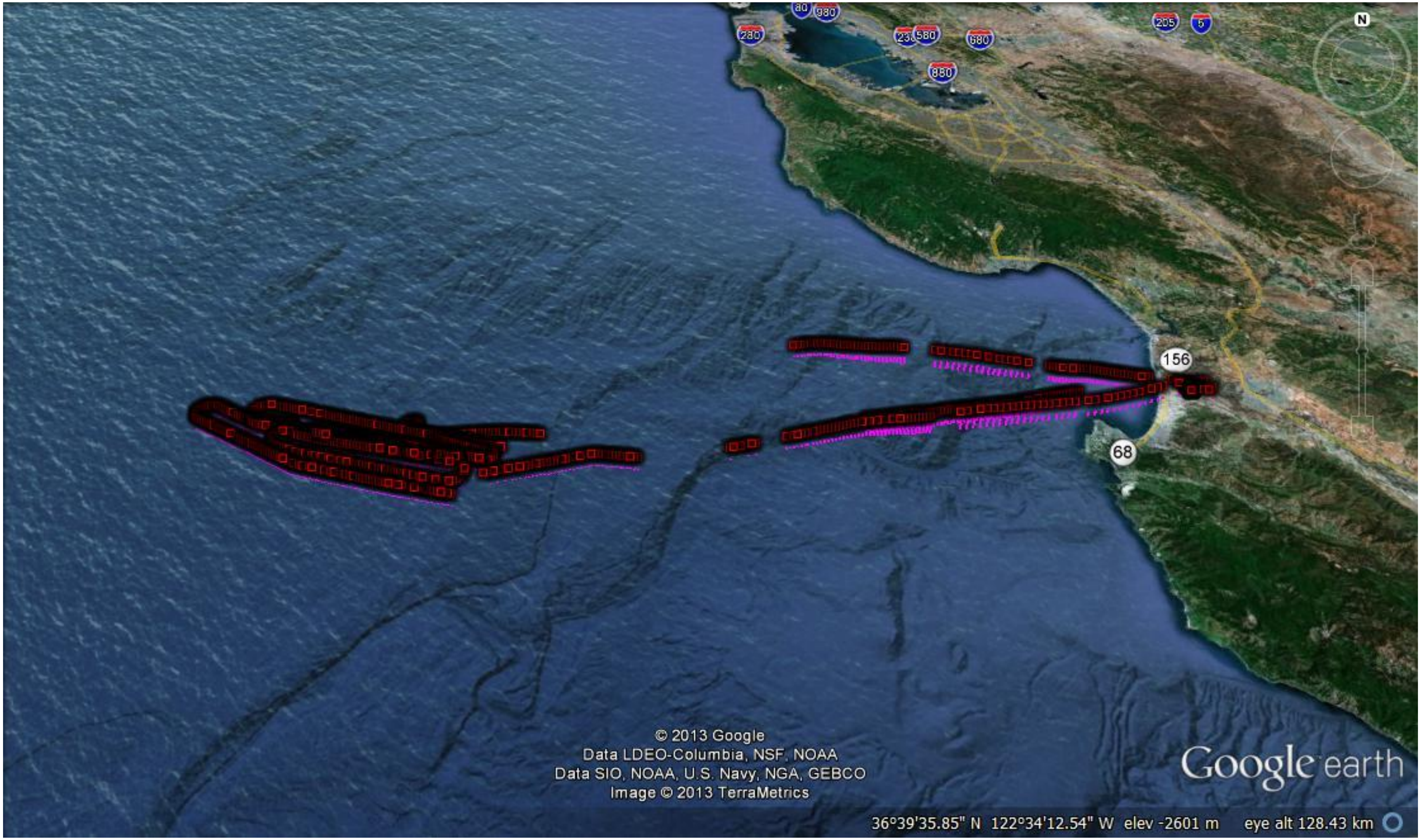
CIRPAS Twin Otter
with
CTV below

9/30/12 UPP: Monterey case study

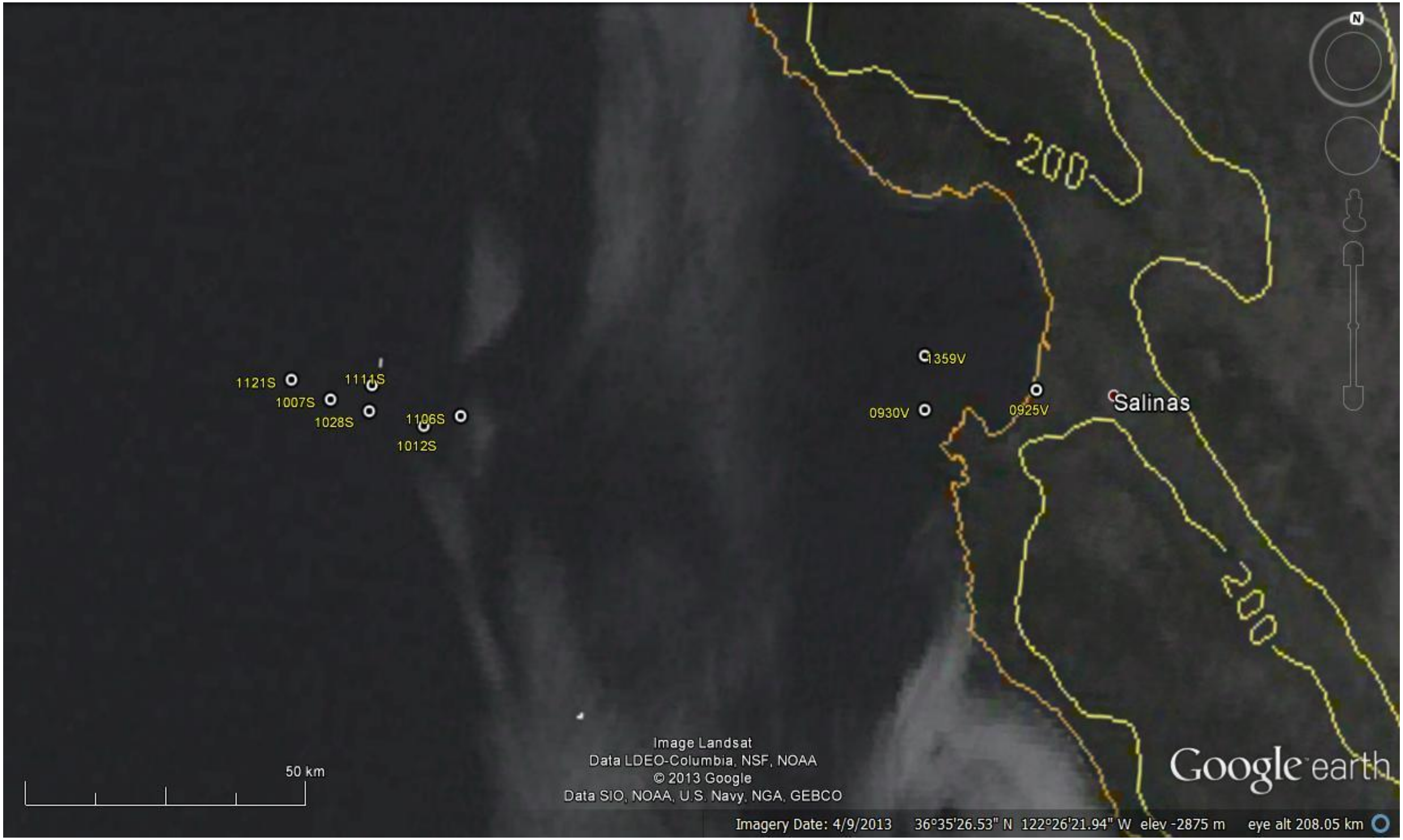
9/30/12 case study

- Process lidar data in search of organized aerosol/wind structures below the Twin Otter flight path
- Process Twin Otter “CABIN” data for time series of u, v, w, q, and ϴ.
- Process CTV data for u,v,w,q and ϴ.
- Match up times and then features from the TODWL and CABIN data sets near flight level.
- Match up times and features from TODWL and CTV at CTV cruise levels.

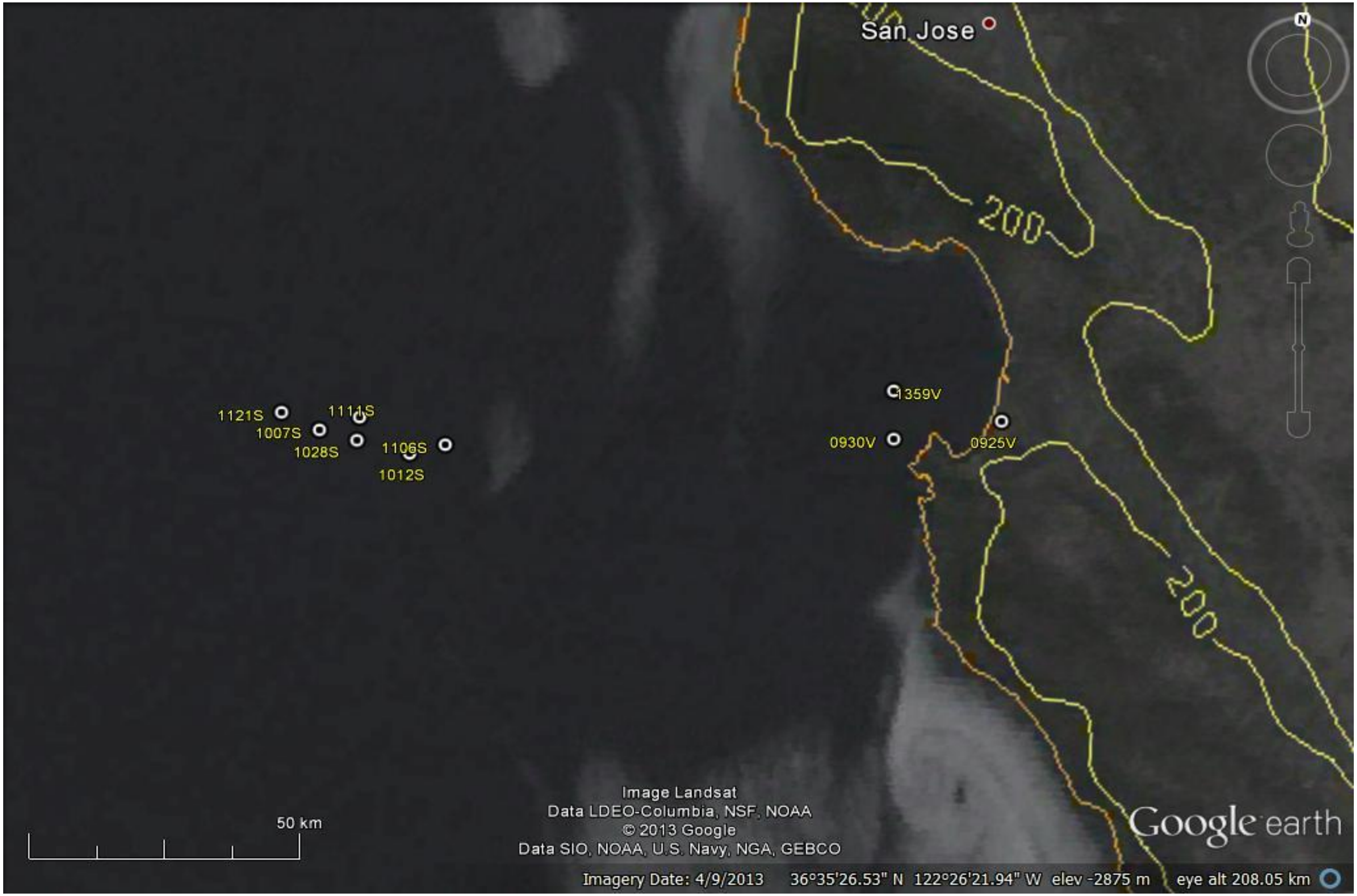
Flight path on 9/30 PM



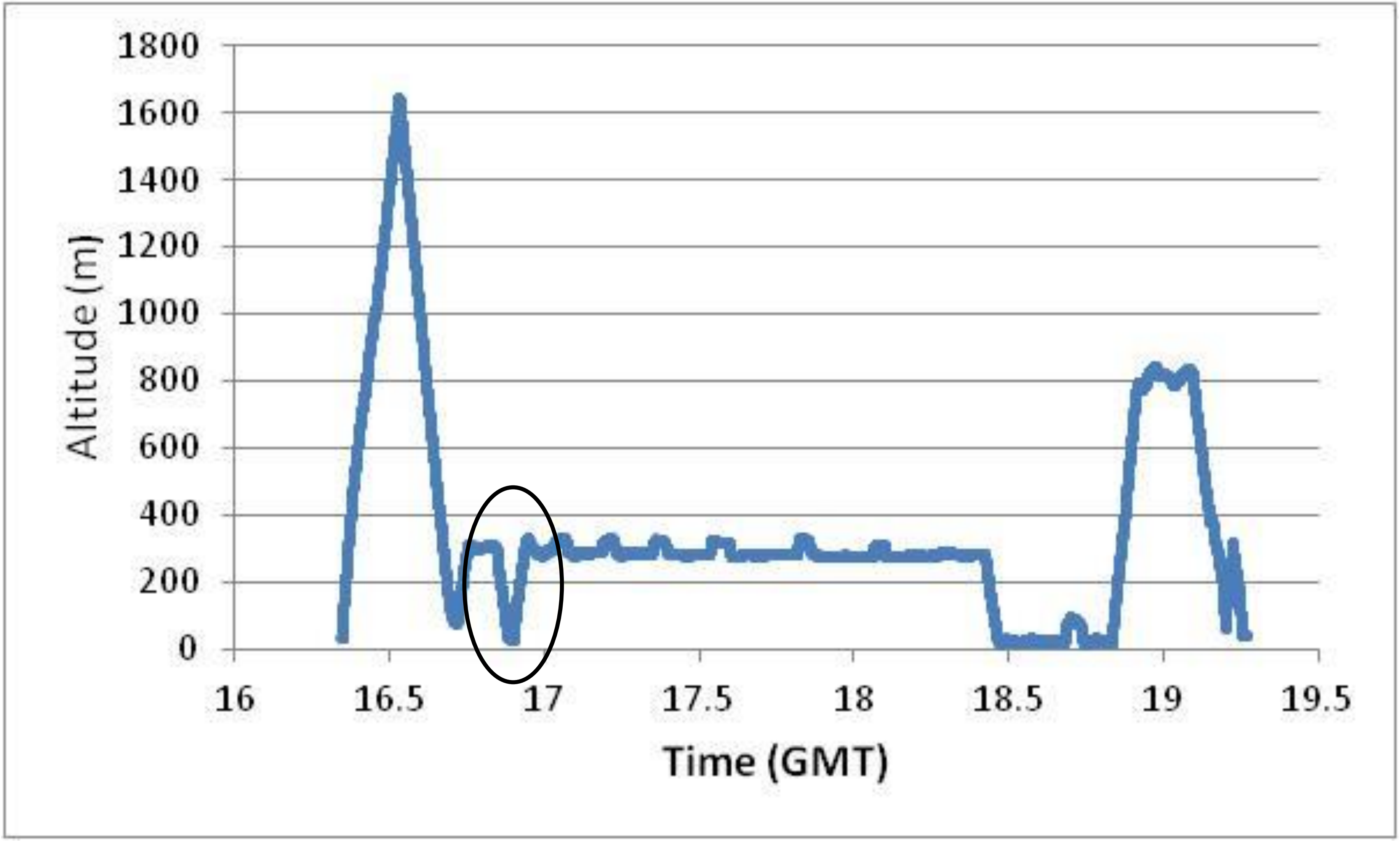
Time (LST) and Location of CTV/Lidar Data and 1045 LST GOESW Imagery

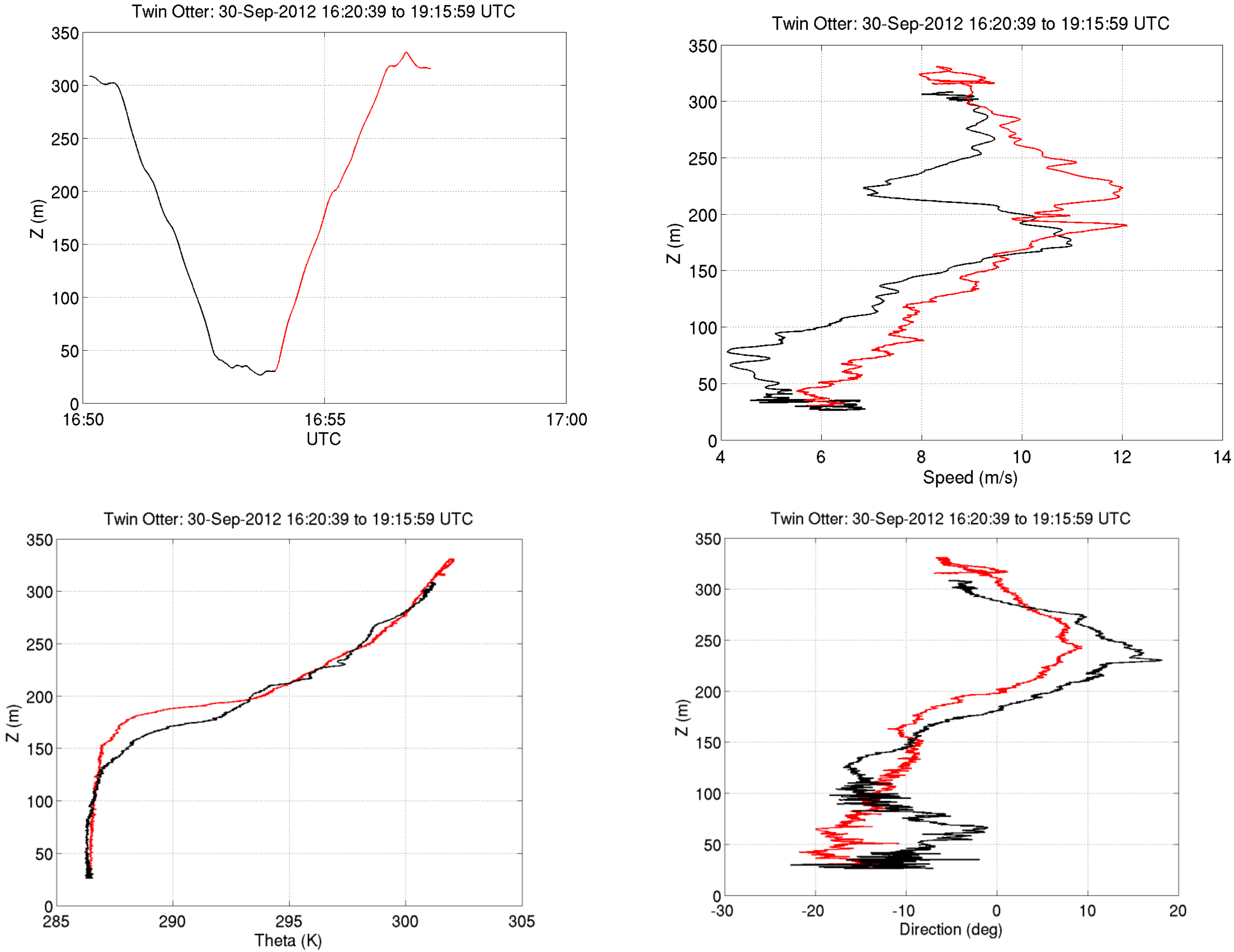


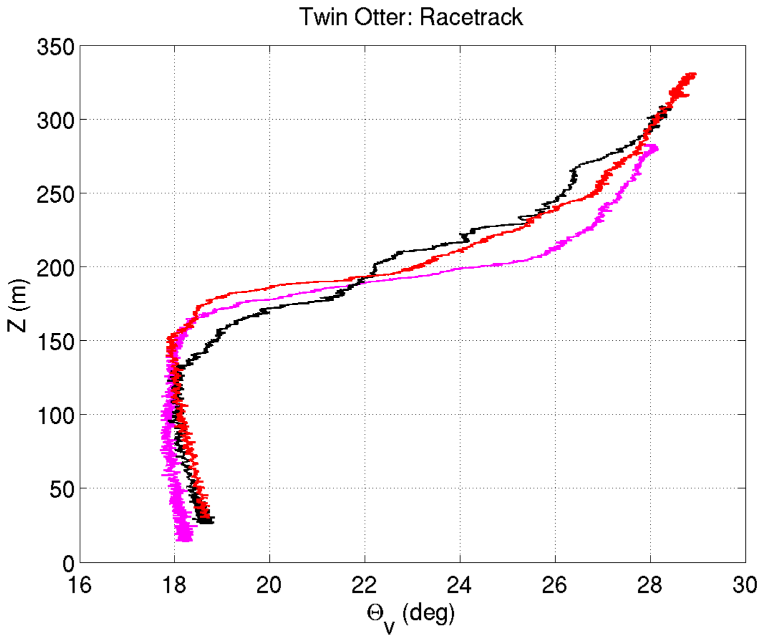
Time (LST) and Location of CTV/Lidar Data and 1145 LST GOESW Imagery



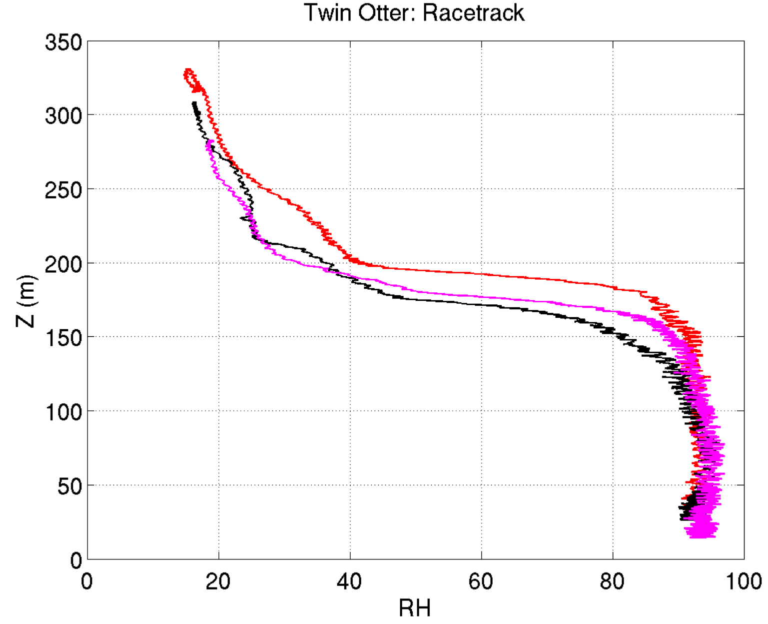
Flight level history



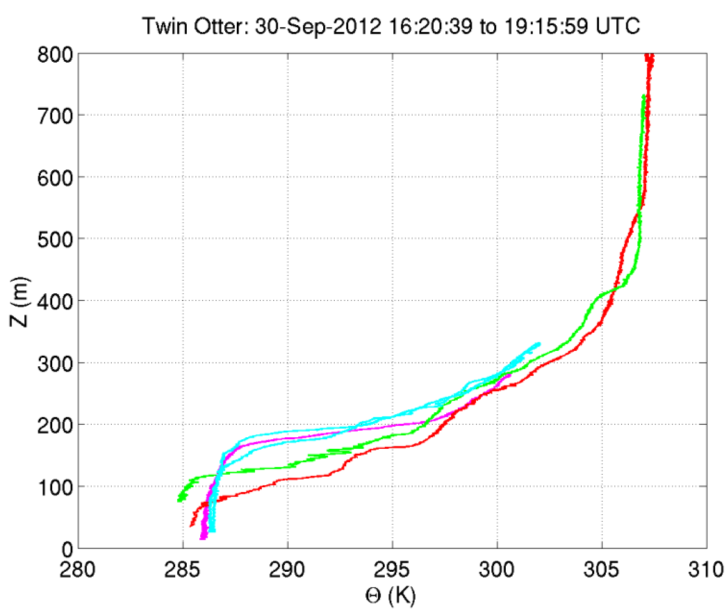

Twin Otter: 30-Sep-2012 16:20:39 to 19:15:59 UTC
Z (m)
UTC
16:50
16:55
17:00
Twin Otter: 30-Sep-2012 16:20:39 to 19:15:59 UTC
Z (m)
Speed (m/s)
Twin Otter: 30-Sep-2012 16:20:39 to 19:15:59 UTC
Z (m)
Theta (K)
Twin Otter: 30-Sep-2012 16:20:39 to 19:15:59 UTC
Z (m)
Direction (deg)



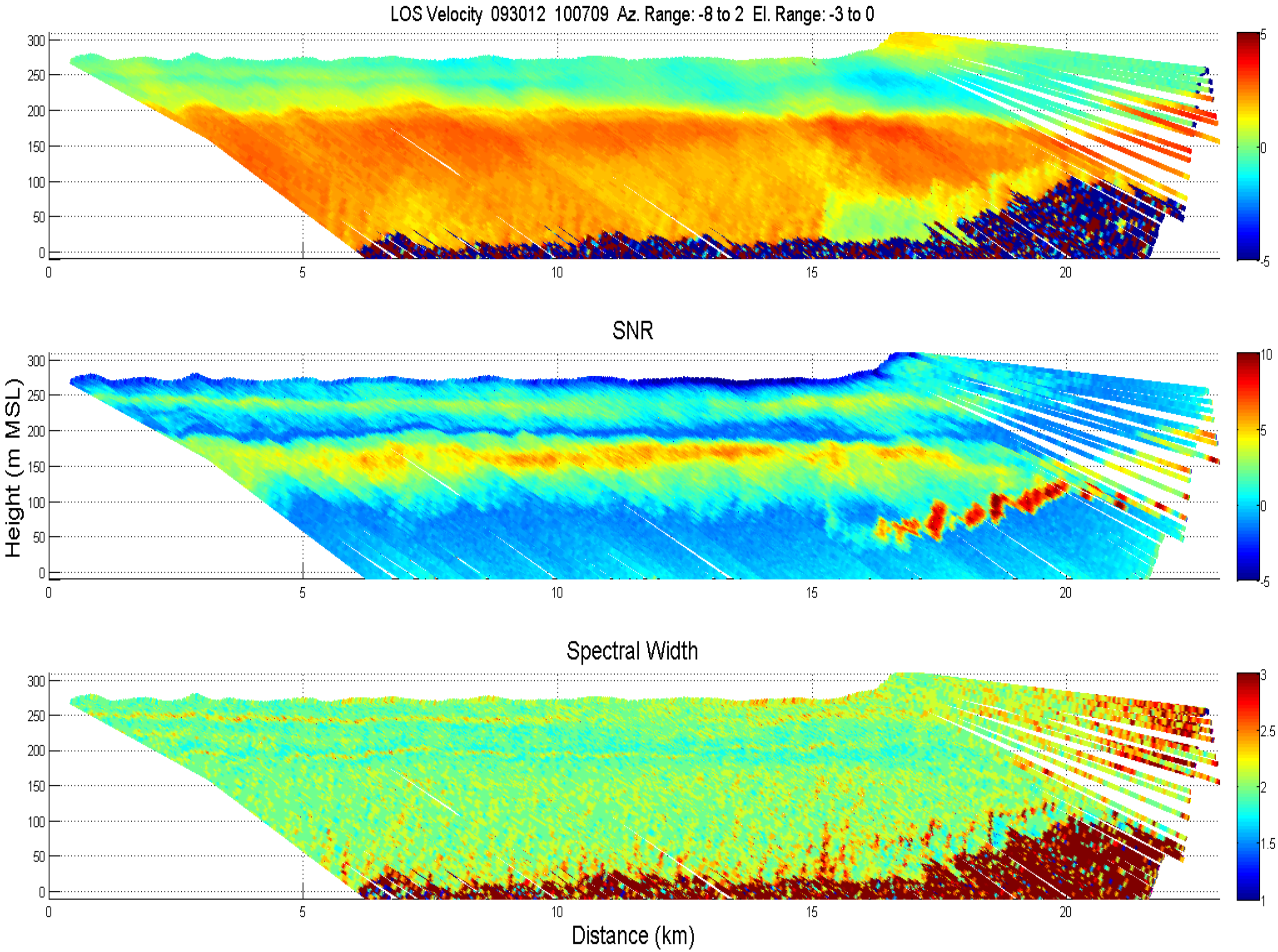
Twin Otter: Racetrack
350
300
250
200
150
100
50
0
16
18
20
22
24
26
28
30
Z (m)
Θ_V (deg)

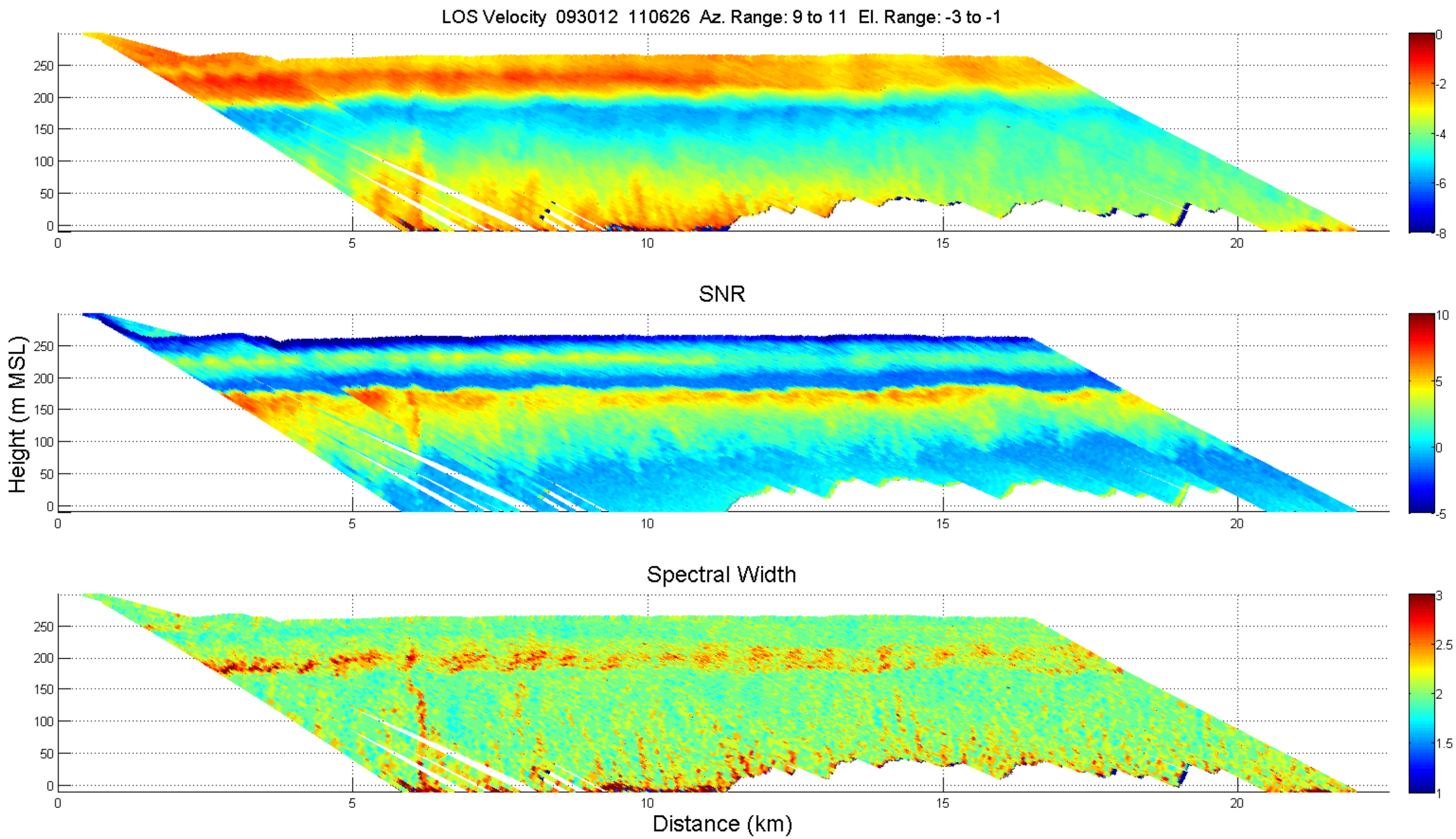


Twin Otter: Racetrack
350
300
250
200
150
100
50
0
0
20
40
60
80
100
Z (m)
RH

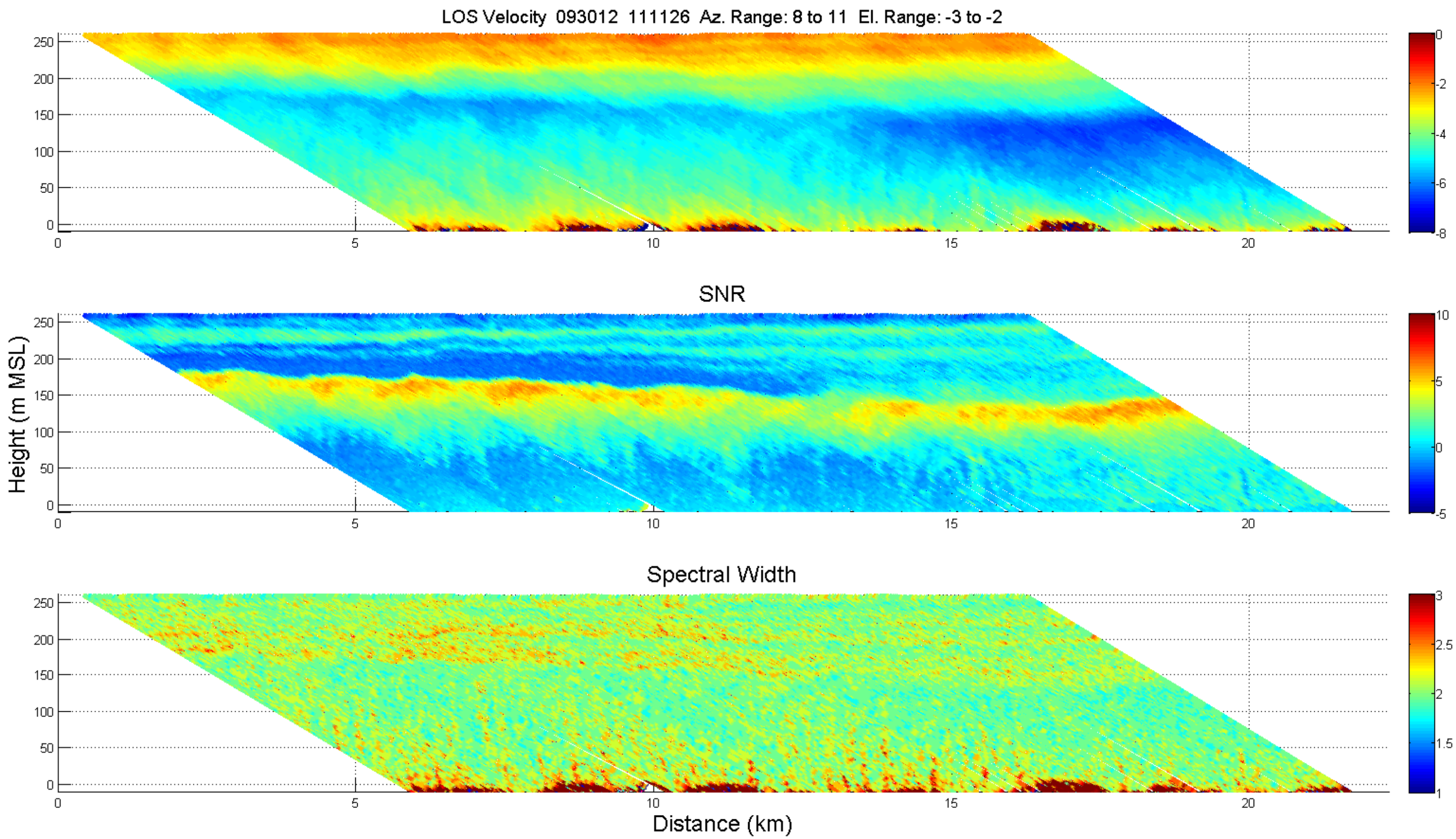


Twin Otter: 30-Sep-2012 16:20:39 to 19:15:59 UTC
800
700
600
500
400
300
200
100
0
280
285
290
295
300
305
310
Z (m)
Θ (K)

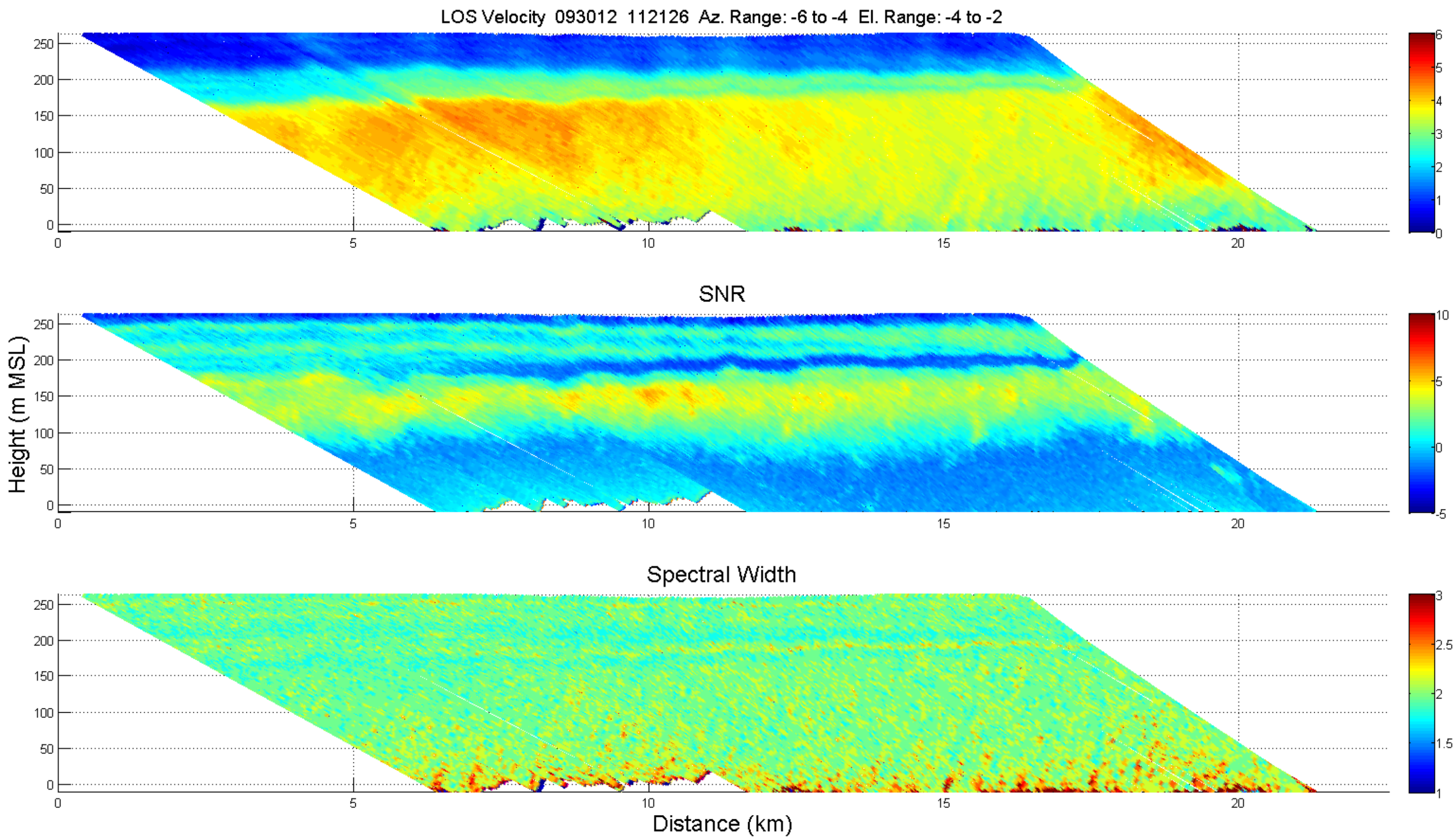

LOS Velocity 093012 100709 Az. Range: -8 to 2 El. Range: -3 to 0
SNR
Spectral Width
Height (m MSL)
Distance (km)
0
5
10
15
20
0
50
100
150
200
250
300
5
0
-5
10
5
0
-5
3
2.5
2
1.5
1

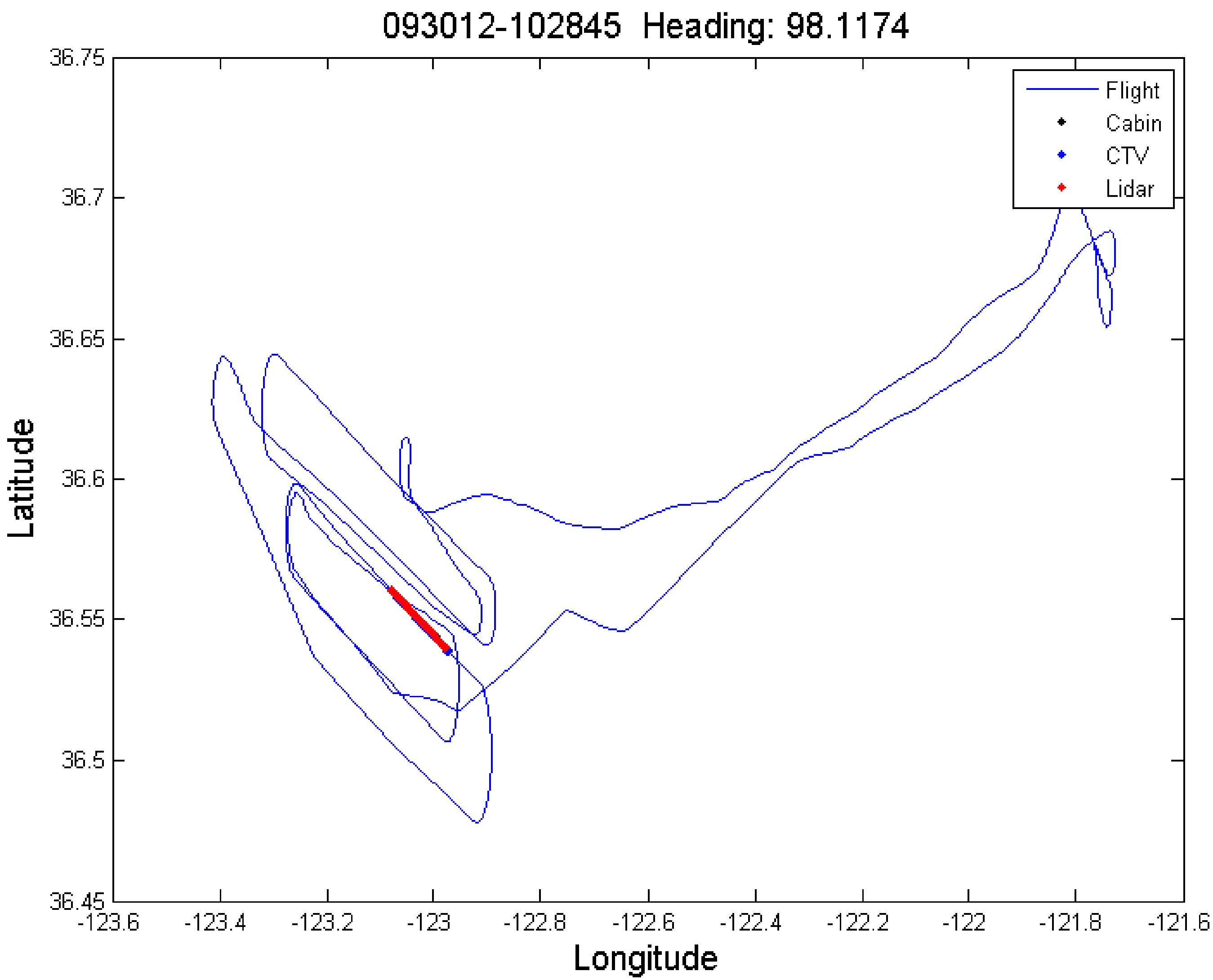


LOS Velocity 093012 110626 Az. Range: 9 to 11 El. Range: -3 to -1
SNR
Spectral Width
Height (m MSL)
Distance (km)
0
5
10
15
20
250
200
150
100
50
0
-2
-4
-6
-8
10
5
0
-5
3
2.5
2
1.5
1

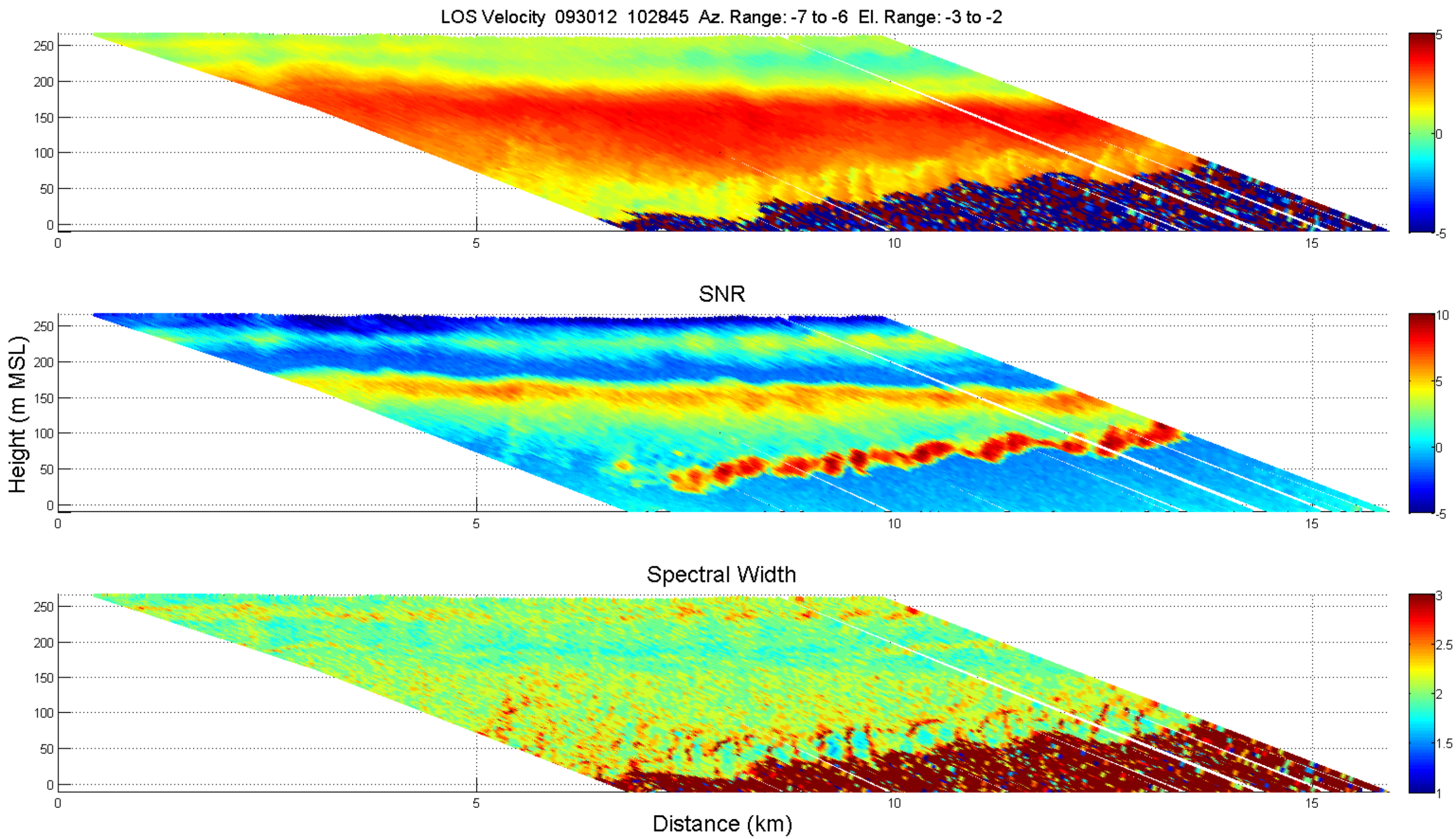


LOS Velocity 093012 111126 Az. Range: 8 to 11 El. Range: -3 to -2
SNR
Spectral Width
Height (m MSL)
Distance (km)

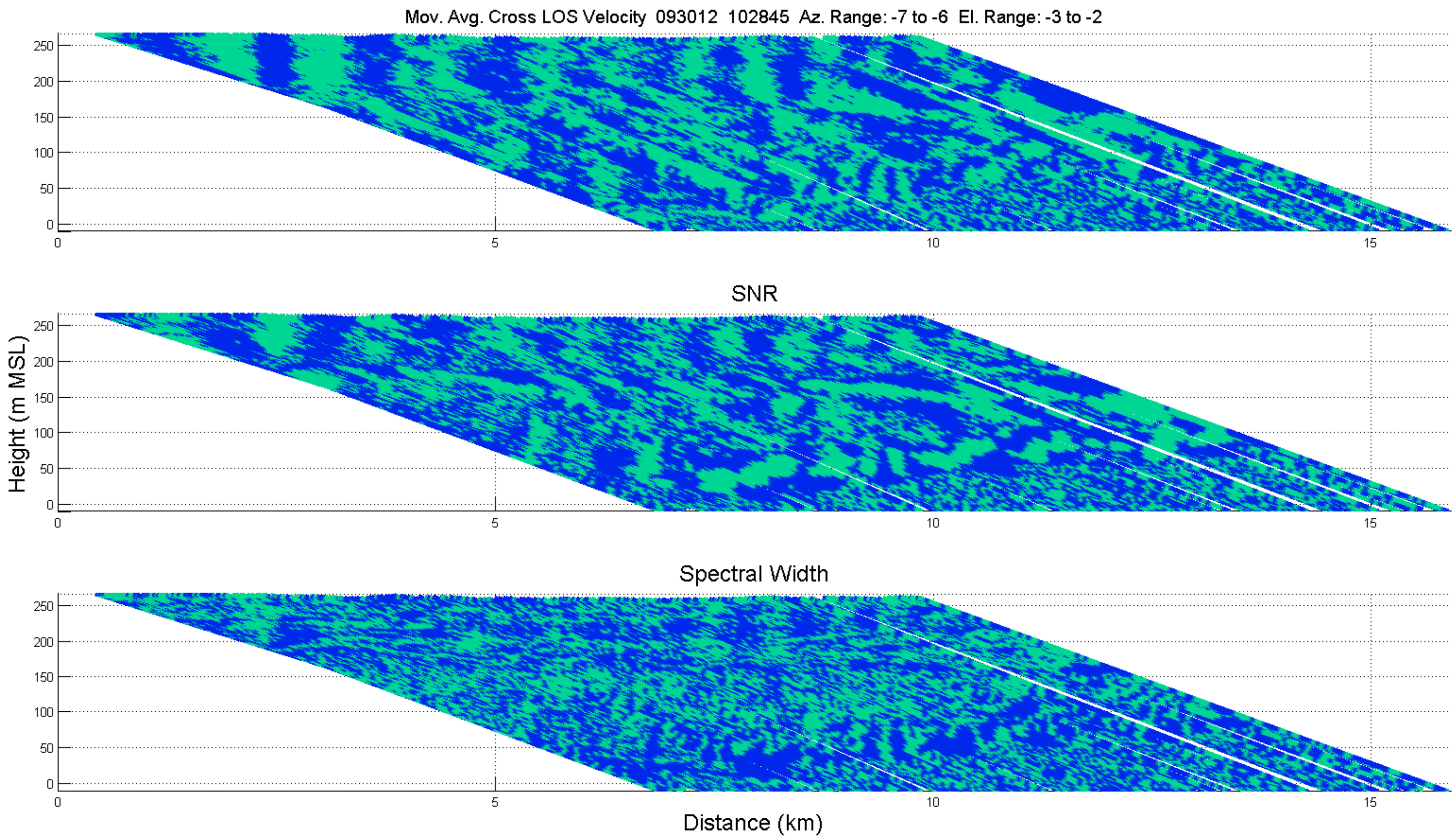

LOS Velocity 093012 112126 Az. Range: -6 to -4 El. Range: -4 to -2
SNR
Spectral Width
Height (m MSL)
Distance (km)
0
5
10
15
20
0
50
100
150
200
250
6
5
4
3
2
1
0
10
5
0
-5
3
2.5
2
1.5
1



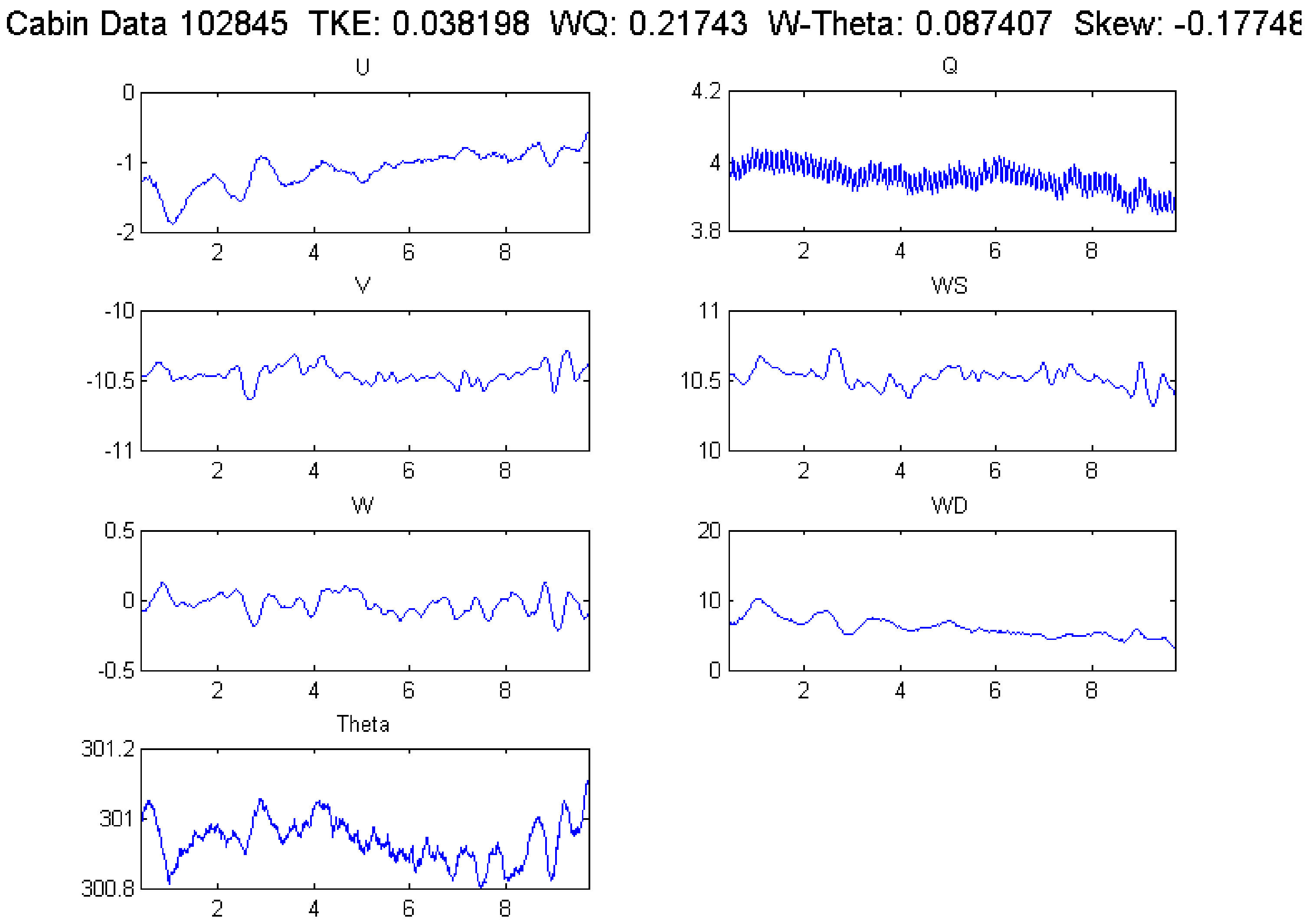
093012-102845 Heading: 98.1174
Flight
Cabin
CTV
Lidar
Latitude
Longitude
36.75
36.7
36.65
36.6
36.55
36.5
36.45
-123.6
-123.4
-123.2
-123
-122.8
-122.6
-122.4
-122.2
-122
-121.8
-121.6



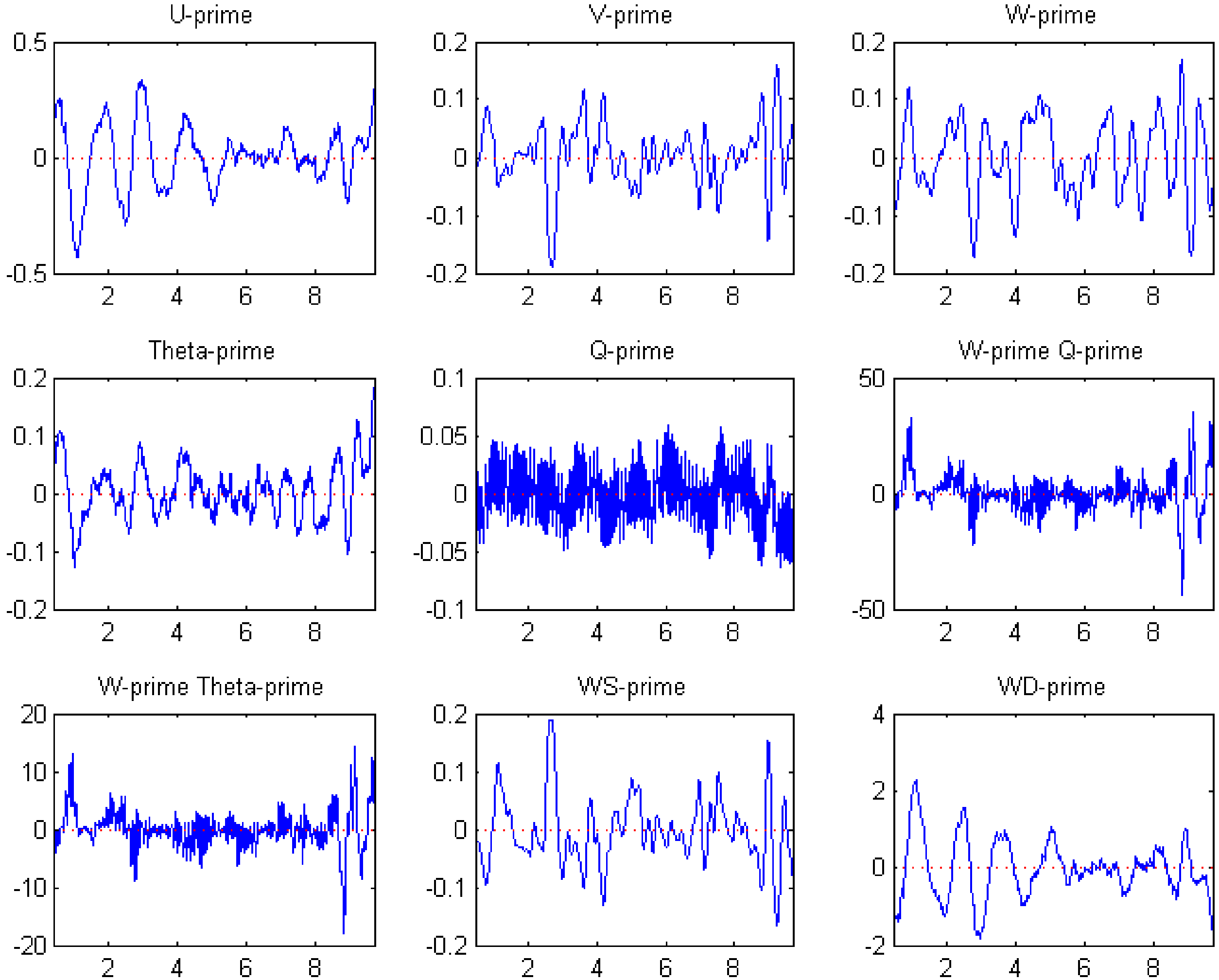
LOS Velocity 093012 102845 Az. Range: -7 to -6 El. Range: -3 to -2
SNR
Spectral Width
Height (m MSL)
Distance (km)
0
5
10
15
250
200
150
100
50
0
-5
2.5
2
1.5
1
3

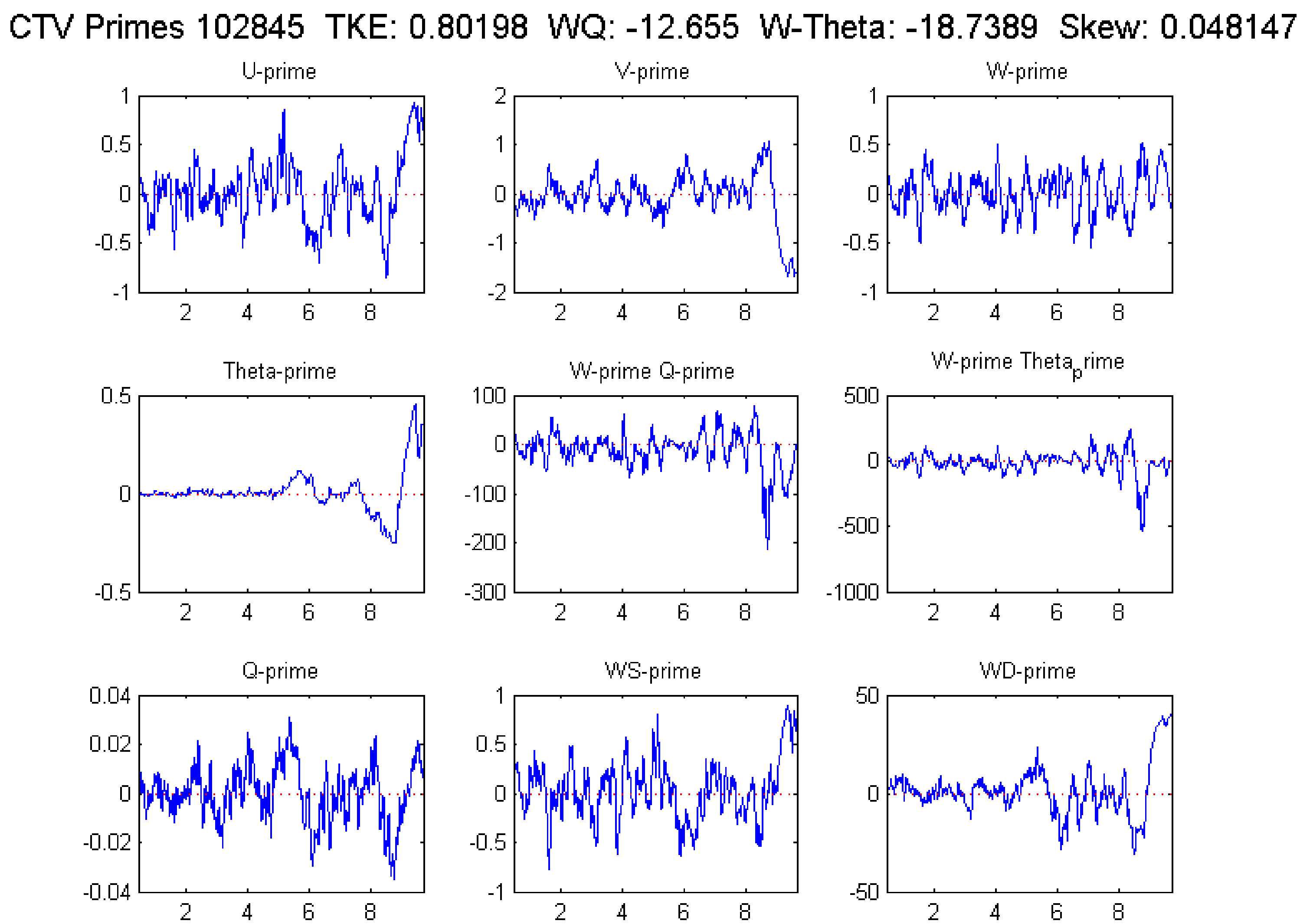


Mov. Avg. Cross LOS Velocity 093012 102845 Az. Range: -7 to -6 El. Range: -3 to -2
SNR
Spectral Width
Height (m MSL)
Distance (km)
0
50
100
150
200
250
0
5
10
15


Cabin Data 102845 TKE: 0.038198 WQ: 0.21743 W-Theta: 0.087407 Skew: -0.17748
U
Q
V
WS
W
WD
Theta

Cabin Primes 102845 TKE: 0.038198 WQ: 0.21743 W-Theta: 0.087407 Skew: -0.1774

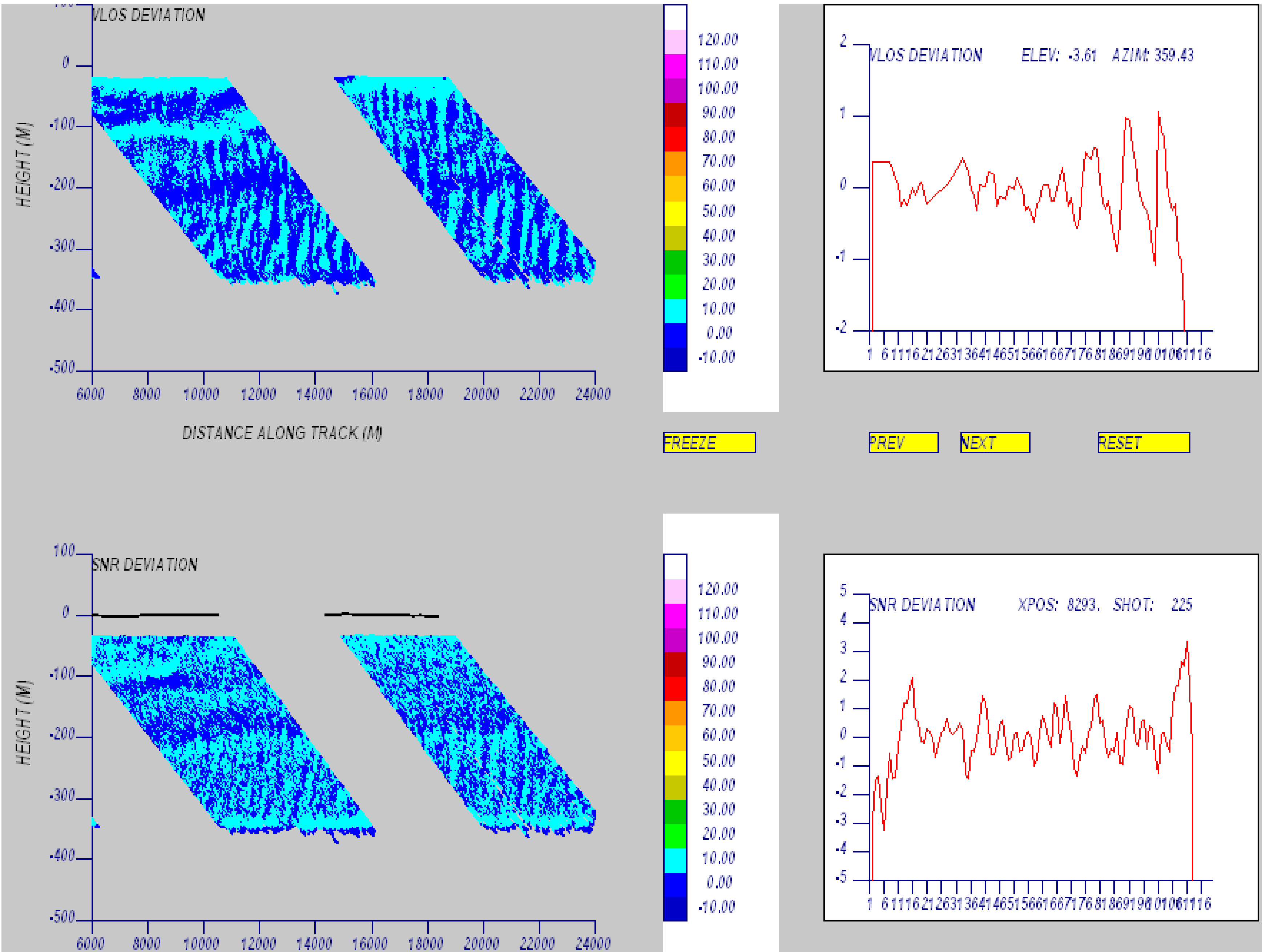




CTV Primes 102845 TKE: 0.80198 WQ: -12.655 W-Theta: -18.7389 Skew: 0.048147
U-prime
V-prime
W-prime
Theta-prime
W-prime Q-prime
W-prime Theta_prime
Q-prime
WS-prime
WD-prime

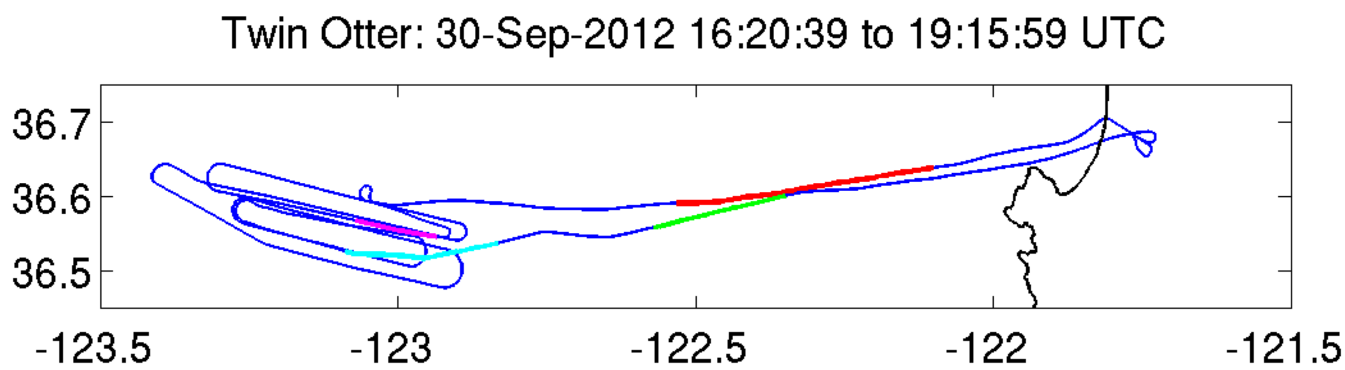
Summary of segment statistics

Flight Segment	TODWL Altitude	CTV Altitude	Heading	TKE	Sensible Heat (W)	Latent Heat (W)	Skewness
1007	284	60	94	.19	8.55	3.43	-.40
				1.92	-1.28	15.15	.90
1028	292	25	98	.04	.22	.09	-.18
				.80	-12.6	-18.7	.05
1106	286	75	294	.05	3.02	1.21	-.51
				1.1	-3.36	-1.19	-.17
1111	290	75	293	.24	1.98	.80	-.37
				.29	-.74	.55	.22
1121	288	climbing	98	.14	-1.11	-.44	.90

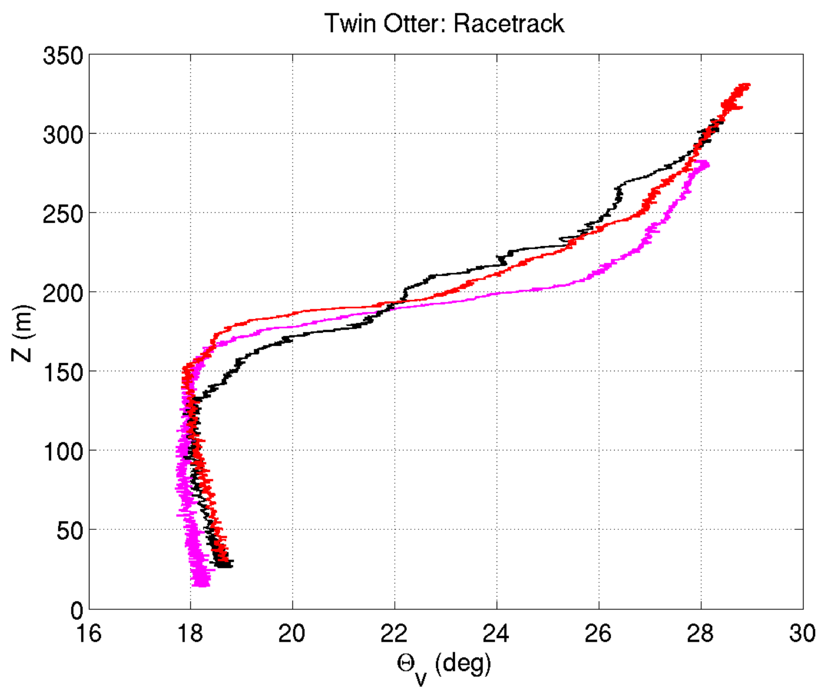

VLOS DEVIATION
HEIGHT (M)
0
-100
-200
-300
-400
-500
6000
8000
10000
12000
14000
16000
18000
20000
22000
24000
DISTANCE ALONG TRACK (M)
120.00
110.00
100.00
90.00
80.00
70.00
60.00
50.00
40.00
30.00
20.00
10.00
0.00
-10.00
VLOS DEVIATION
ELEV: -3.61
AZIM: 359.43
FREEZE
PREV
NEXT
RESET
SNR DEVIATION
100
SNR DEVIATION
XPOS: 8293.
SHOT: 225

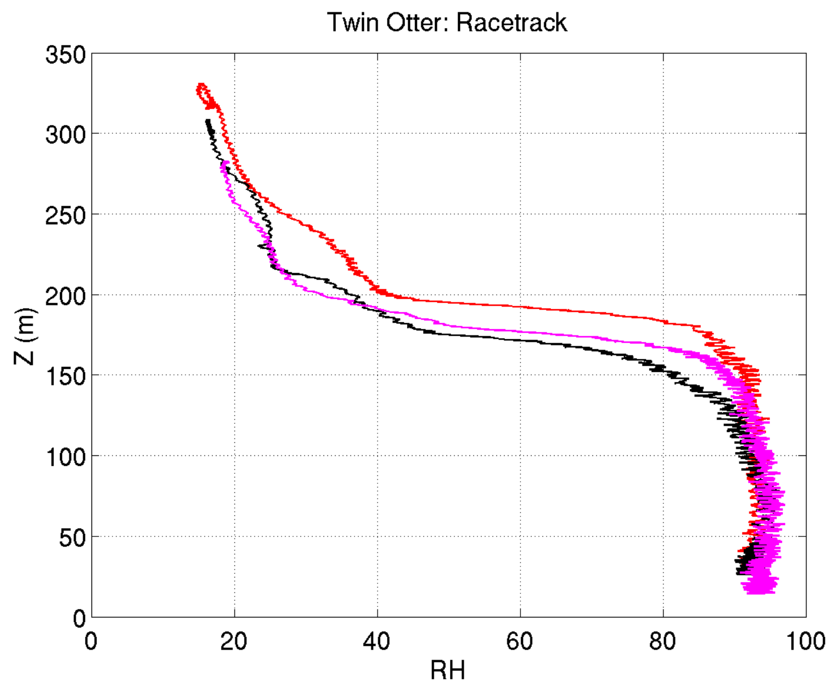
Is our “stacked-OLEs” interpretation reasonable?

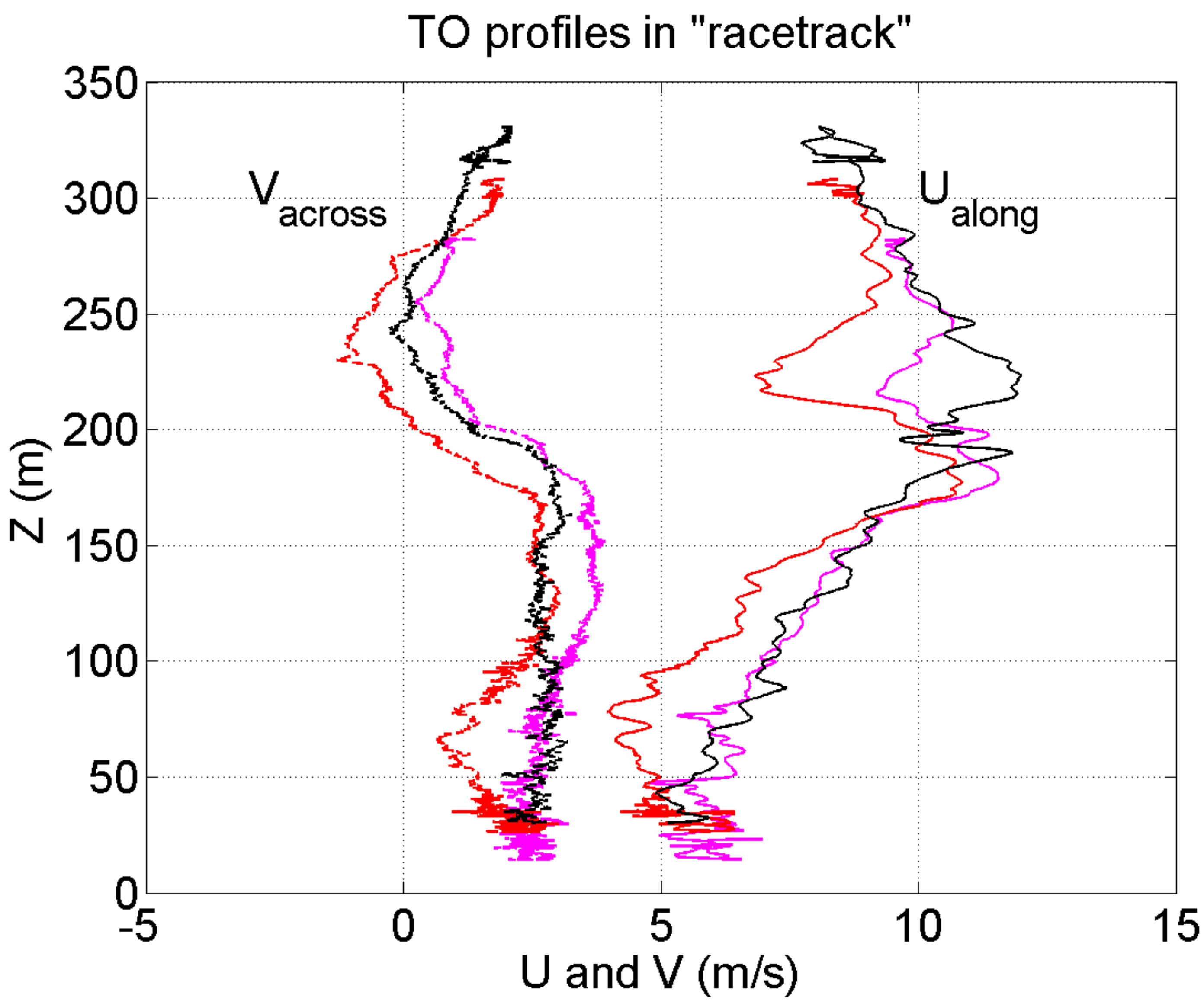
- Simplify Problem:
  - Neutral stratification
    - Shear effects only
    - Omit effect of stratification above jet
    - No surface buoyancy flux
  - Elevated, thin baroclinic layer
  - Variable K(z) (akin to MRF/YSU)
- Non-linear stability model
- Interacting triads

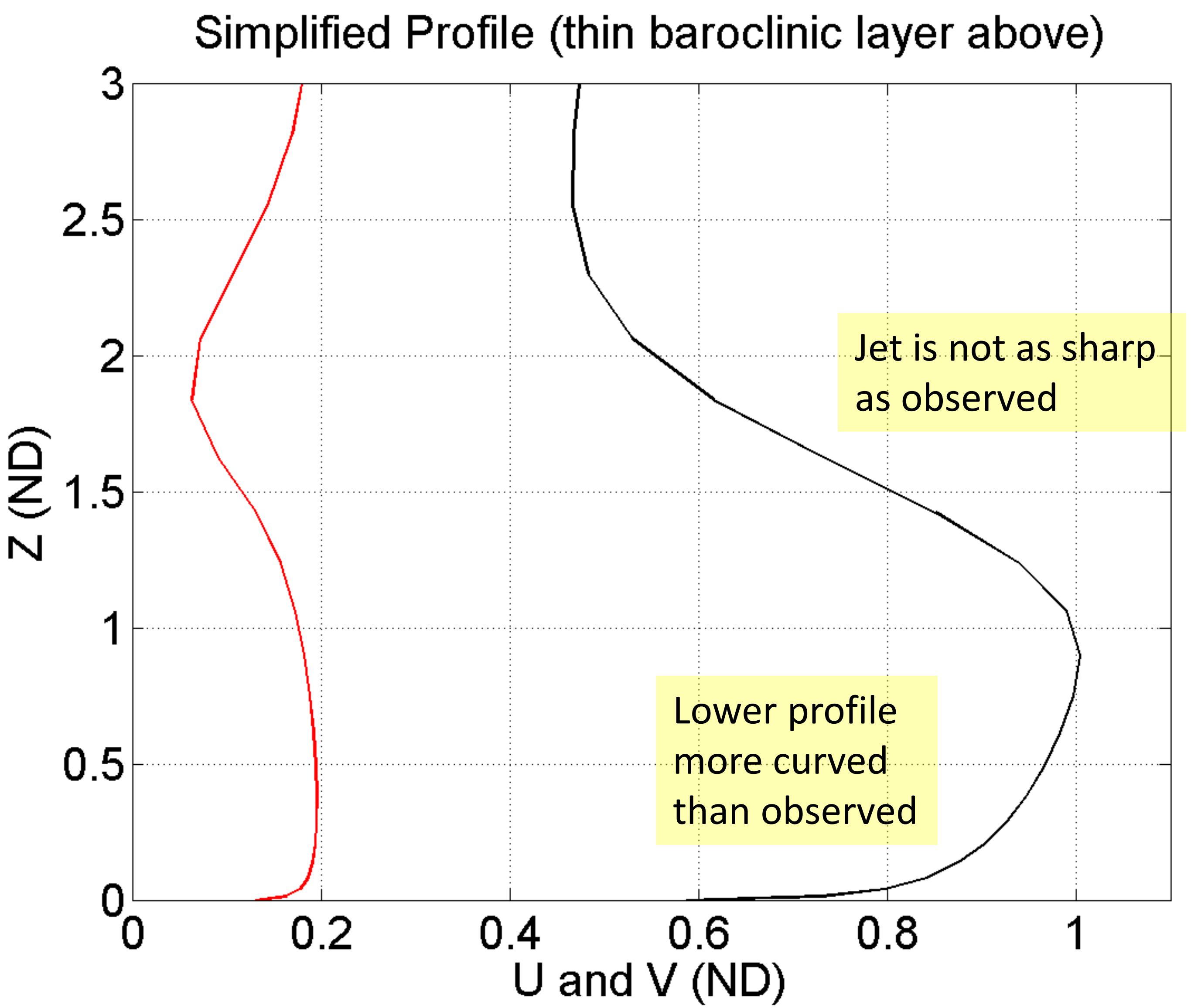


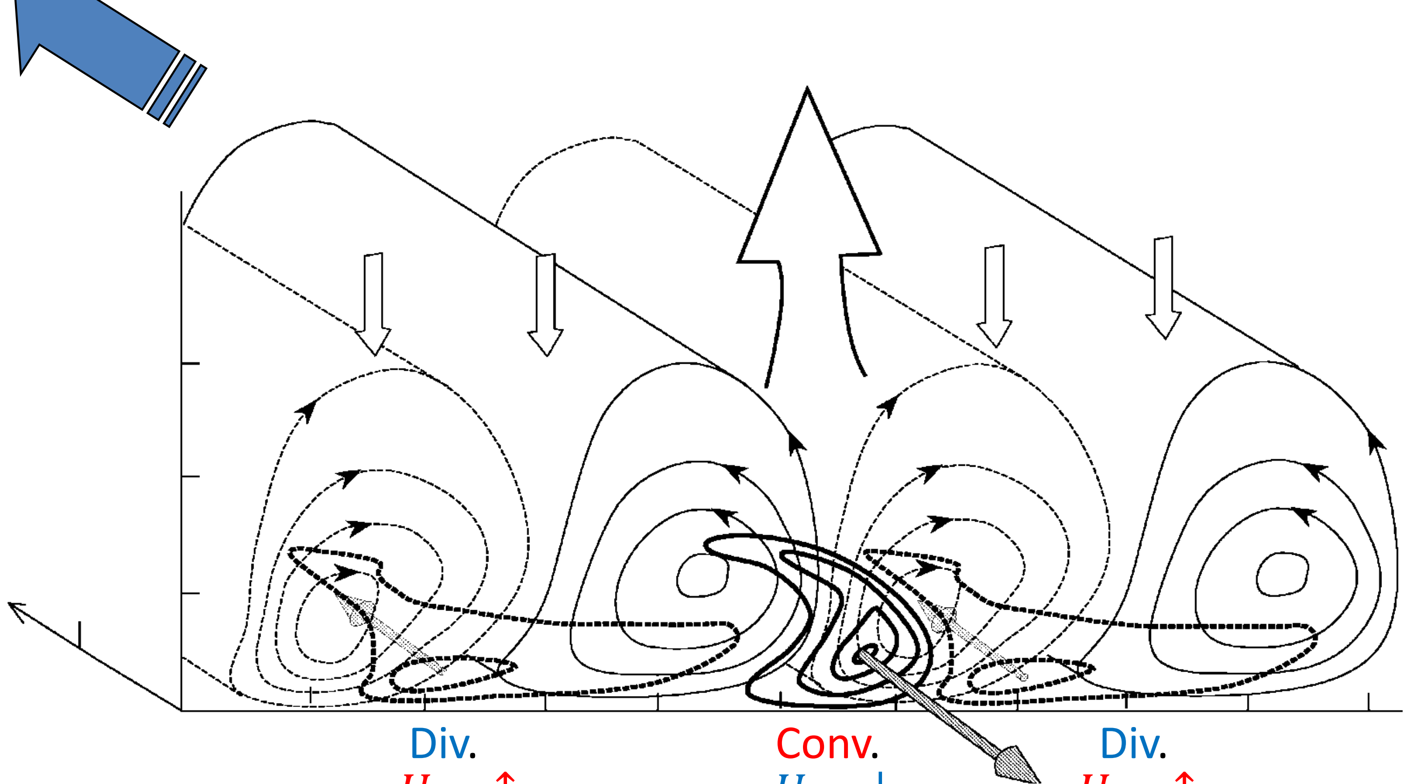
Mean wind at flight level is generally from the north






TO profiles in "racetrack"
V_{across}
U_{along}
Z (m)
350
300
250
200
150
100
50
0
-5
0
5
10
15
U and V (m/s)


Simplified Profile (thin baroclinic layer above)
Z (ND)
U and V (ND)
0
0.5
1
1.5
2
2.5
3
0
0.2
0.4
0.6
0.8
1
Jet is not as sharp as observed
Lower profile more curved than observed

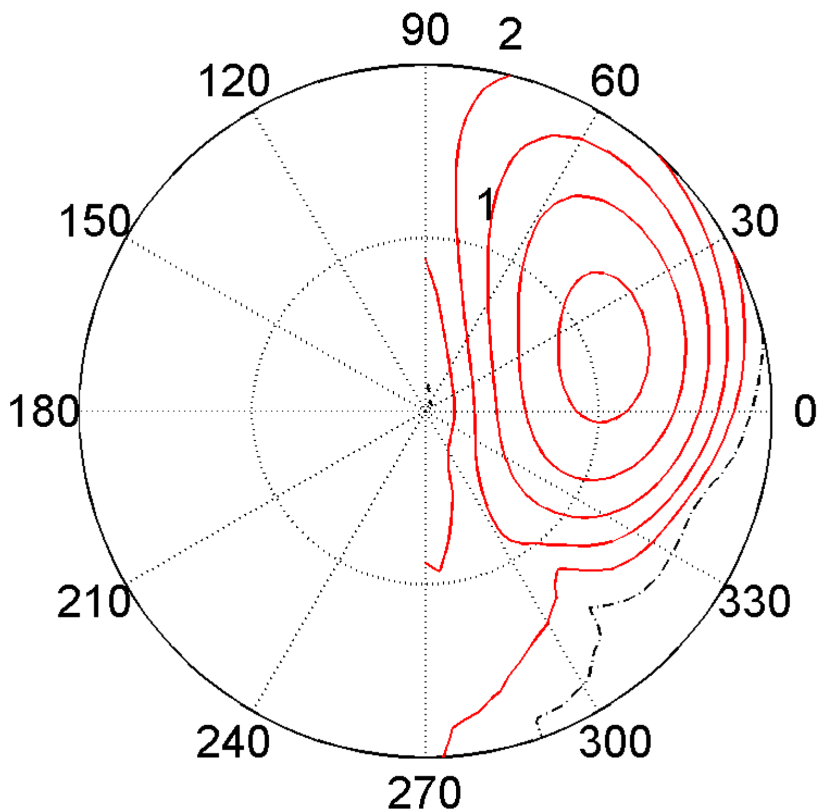


Wavelength: Larger-scale structures ~ 1.5 to 2.5 km
Smaller-scale structures ~ 300 to 700 m

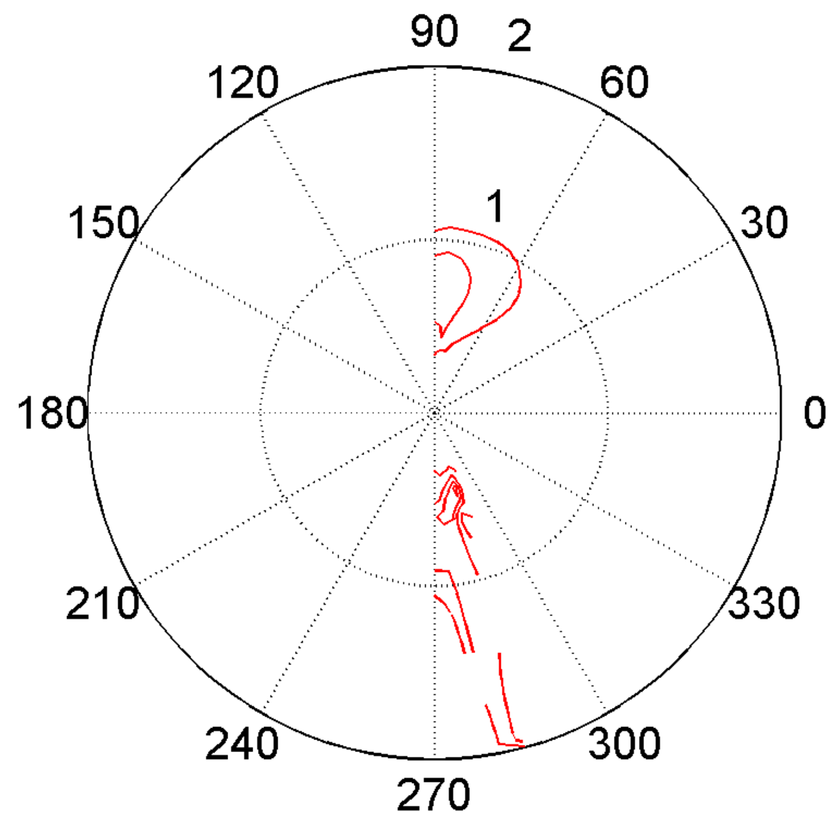
Along-roll velocity Perturbations: +/- 20-25 %
Note; largest near surface

Orientation: Typically aligned along shear

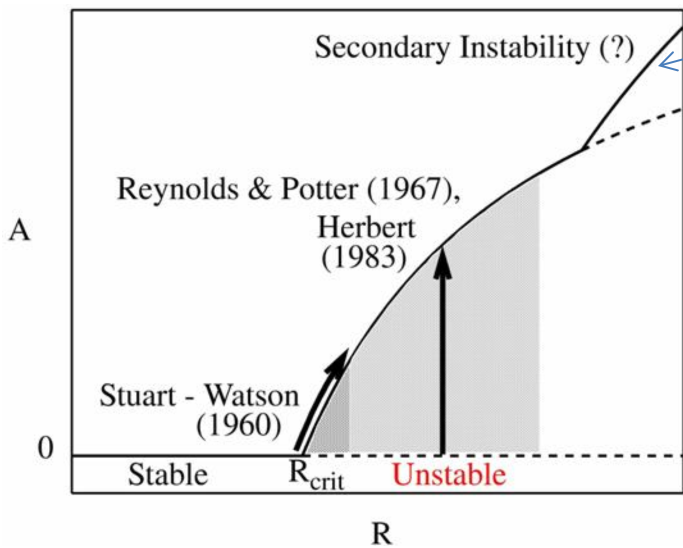
Dominant mode



Secondary mode associated with above-jet layer



Single-Wave Roll Theory
Nonlinear Stability



Multi-wave theory

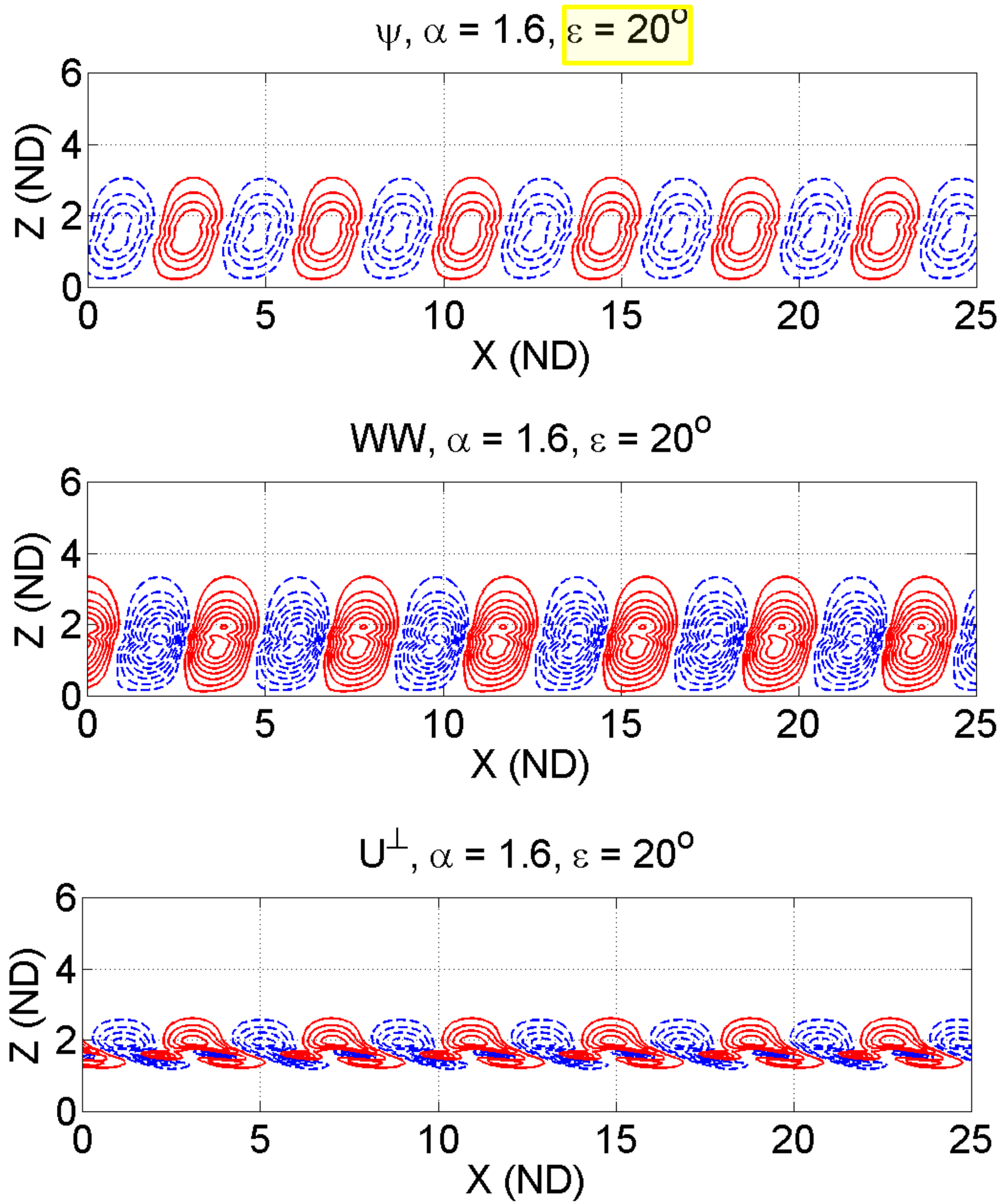
$$\lambda = a + i\omega = \frac{1}{A}\frac{dA}{dt} + i\frac{d\eta}{dt} = \lambda_0 + A^2\lambda_1 + A^4\lambda_2 + \cdots$$

$$\underset{\sim}{q} = 2real\left[\sum_{n=0}^{\infty} A^n e^{in(\alpha x-\omega t)} \sum_{m=0}^{\infty} A^{2m} \underset{\sim}{q}_{nm}(z)\right]$$

- "Stretch" eigenvalue, λ_0, in powers of nonlinear amplitude, *A(t)*.
- Expand eigenfunction, q_{10}, in harmonics of fundamental wavenumber, α, and forced modifications
  - Forced fundamental modifications are orthogonal to linear mode
  - Determine Landau Coefficients (the λ_i)
- Estimate equilibrium Amplitude (dA/dt = 0) & structure, $\mathbf{q = [u,v,w,T]^T}$

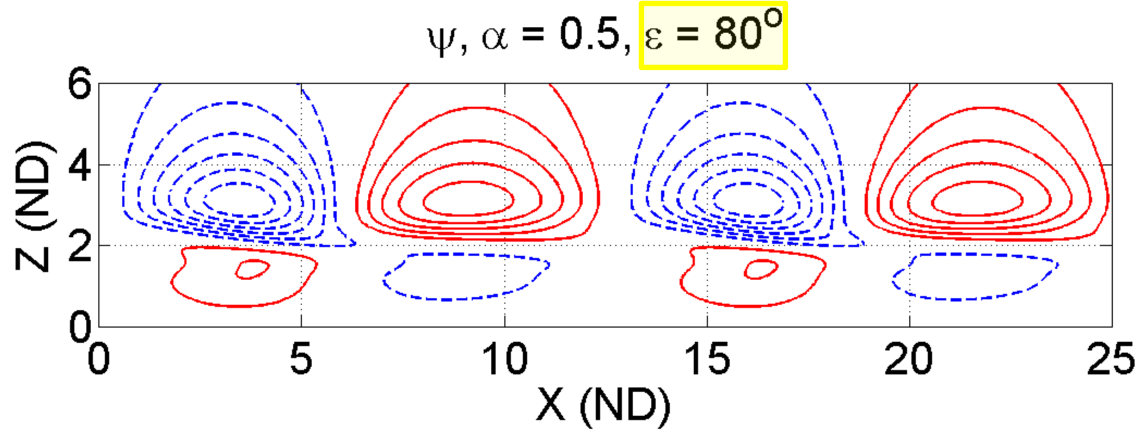
Primary Mode

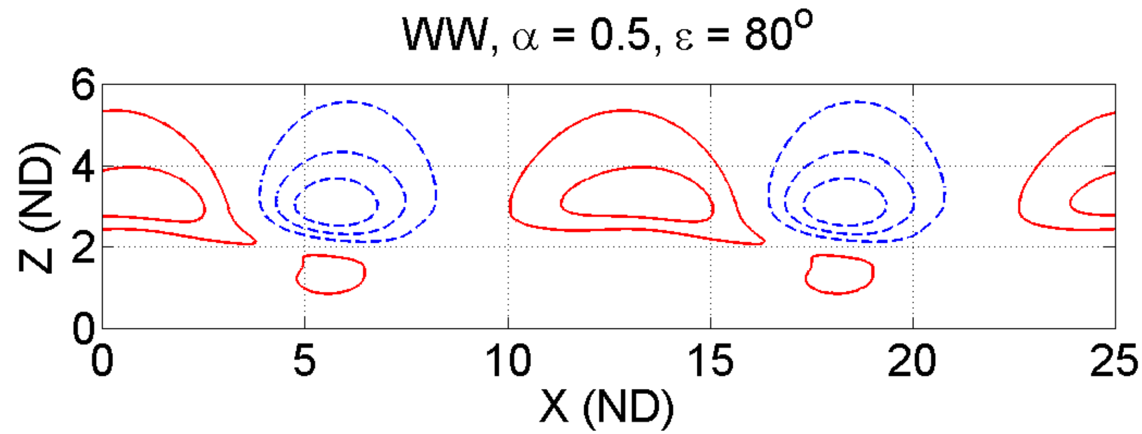
- Mostly in the sub-jet layer
- Along-roll velocity strongest near jet as compared to std. rolls
- Oriented at large angle to dominant rolls

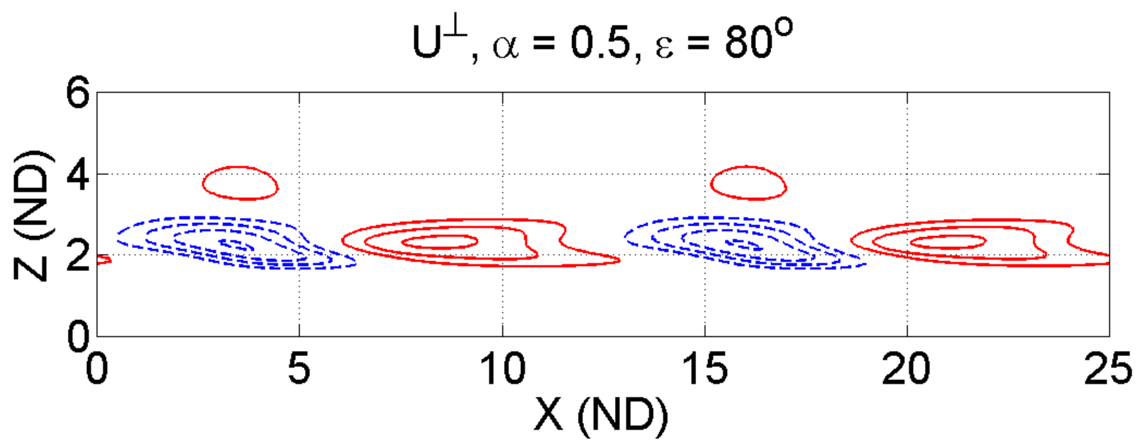


Weaker, secondary mode

- Similar to STD rolls, but based on jet top
- Along-roll velocity max near jet
- Oriented at large angle to dominant rolls







Resonant Triad Interaction Between OLE

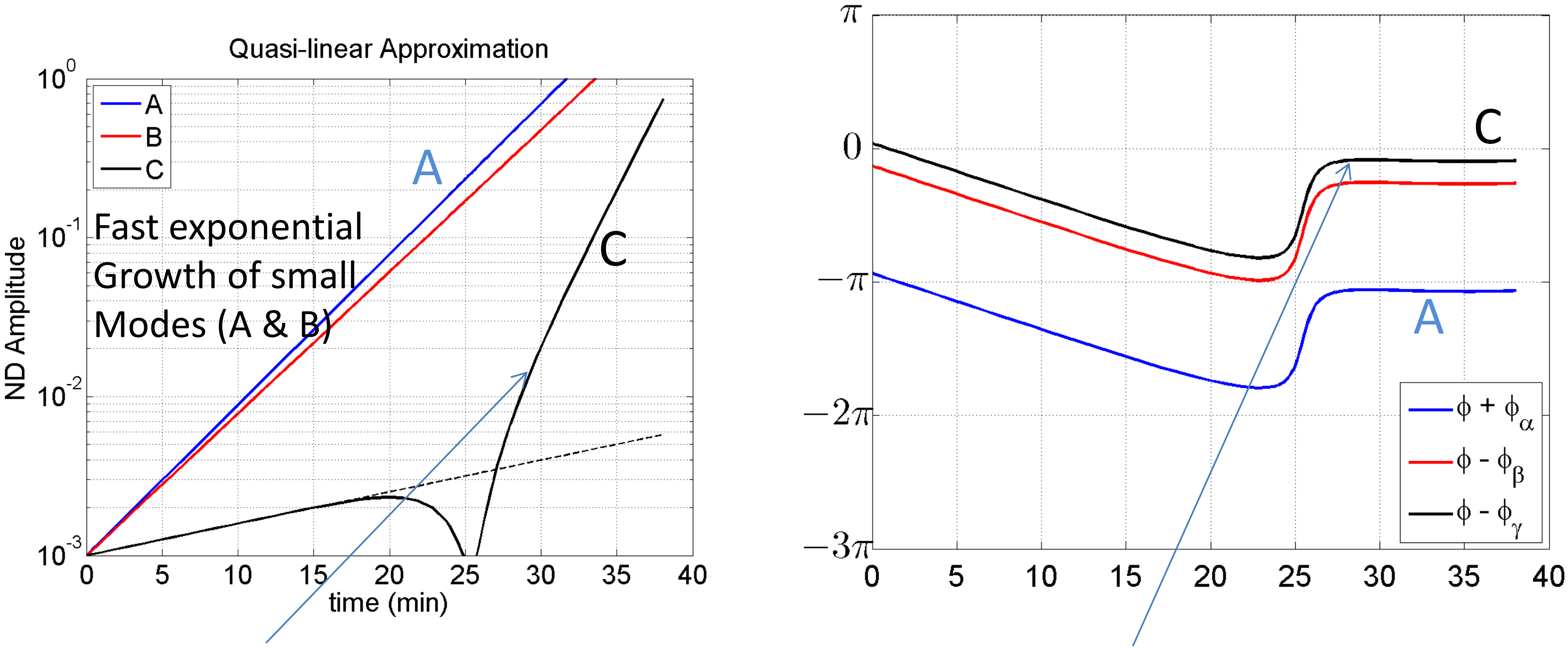
- $\alpha = \beta + \gamma$ (mode A, mode B, mode C) wavenumber relationship
- Require at least one wavenumber at fastest growing mode (A)
- Exchange of energy between OLE modes
- Often energizes weak modes
- At present, require co-linear modes (can be relaxed)

Truncated Model
Amplitude (real) and Phase (imaginary)

- $\frac{1}{A}\frac{dA}{dt} - i\,\frac{d\theta_A}{dt} = a_0 + a_1 \frac{BC}{A} e^{i\phi} + [a_2 A^2 + a_3 B^2 + a_4 C^2]$
- $\frac{1}{B}\frac{dB}{dt} - i\,\frac{d\theta_B}{dt} = b_0 + b_1 \frac{AC}{B} e^{-i\phi} + [b_2 A^2 + b_3 B^2 + b_4 C^2]$
- $\frac{1}{C}\frac{dC}{dt} - i\,\frac{d\theta_C}{dt} = c_0 + c_1 \frac{AB}{C} e^{-i\phi} + [c_2 A^2 + c_3 B^2 + c_4 C^2]$
- $\phi = \theta_A - \theta_B - \theta_C$ (Wave phase imbalance)
- $\alpha = \beta + \gamma$ (resonant triad wavenumbers)

- The a_i, b_i, c_i are complex, generalized Landau coefficients, calculated via an orthogonalization assumption (nonlinear wave-wave & wave-mean flow interactions)
- Highest-order (bracketed) terms force equilibrium; dominated by single-wave contributions (a_2A^2, b_3B^2, c_4C^2)
- Lower-order phase coupling allows inter-scale energy transfer, ENHANCES GROWTH RATE OF SLOWEST-GROWING MODE, ESPECIALLY DURING QUASI-LINEAR PHASE

How is the slowly-growing mode energized? Examine quasi-linear, early-time behavior



Accelerated growth of slow mode (C)

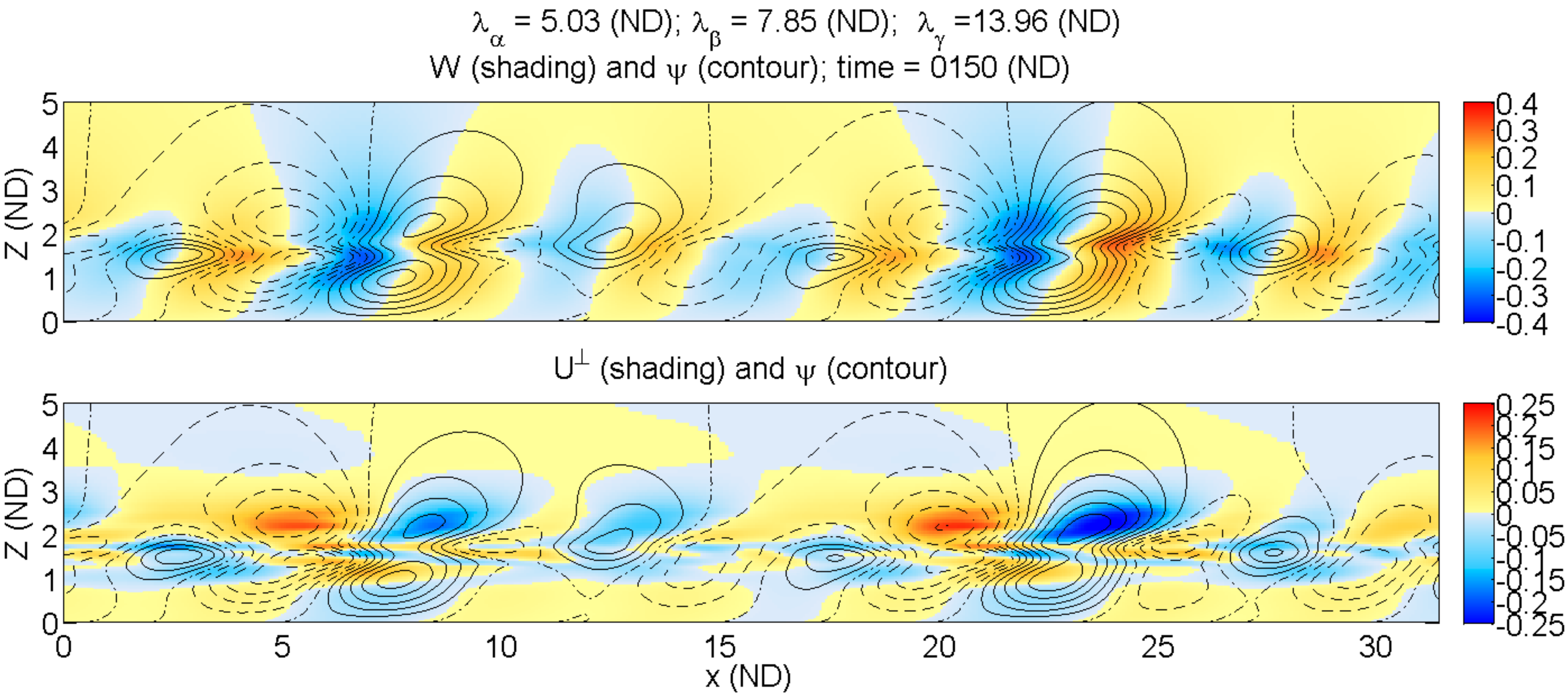
Starts when $(\phi - \phi_{c1}) \rightarrow 2\pi n$

Phase Imbalance:

$\phi = \theta_A - \theta_B + \theta_C$

QL Landau Coefficient:

$c_1 = |c_1| \, e^{i\phi_\gamma}$



λα = 5.03 (ND); λβ = 7.85 (ND); λγ =13.96 (ND)
W (shading) and ψ (contour); time = 0150 (ND)
Z (ND)
U⊥ (shading) and ψ (contour)
x (ND)

Summary

- **It appears that a PBL jet can induce "stacked" OLEs**
  - Caveat: test case is neutral stratification
    - In model, but examine neutral first
- **Co-linear OLE triads can generate complex structure**
- **There is a weaker, larger-scale, oblique above-jet mode**
  - Can it be energized by nonlinear triad mechanism?

Summary

- EDMF-type schemes attempt to capture non-local contributions to PBL fluxes
  - Implicitly assumes such transport is due to narrow, skewed updrafts
  - Quite unstable stratification
- OLE rolls are very common
  - low skewness
  - Likely significant flux contributions
  - Near-neutral to moderately unstable stratification
    - Possible also slightly stable?

Future plans

- Focus on the fluxes (Emmitt)
  - De-trending
  - Scale separations
  - Skewness calculations
- Use processing techniques developed with the 9/30 cases to explore the UPP/Dugway PBL structure cases. (de Wekker)
- Modeling work (Foster)
  - Modify triad code for non-co-linear OLE
  - Include stratification and thermal wind effects on OLE
- Design a series of TODWL/CTV flights that would focus on cloud free and partly cloudy MBLs where the CTV is deployed per in-flight findings using the TODWL.

Extra Slides

Truncated 3-Mode Roll Solutions

$$q_\alpha = Aq_{0,\alpha} + BCq_{1,\alpha}e^{i\phi} + A[A^2q_{2,\alpha} + B^2q_{3,\alpha} + C^2q_{4,\alpha}] + A^2q_{20,\alpha} + A^3q_{30,\alpha}$$

$$q_\beta = Bq_{0,\beta} + ACq_{1,\beta}e^{-i\phi} + B[A^2q_{2,\beta} + B^2q_{3,\beta} + C^2q_{4,\beta}] + B^2q_{20,\beta} + B^3q_{30,\beta}$$

$$q_\gamma = Cq_{0,\gamma} + ABq_{1,\gamma}e^{-i\phi} + C[A^2q_{2,\gamma} + B^2q_{3,\gamma} + C^2q_{4,\gamma}] + C^2q_{20,\gamma} + C^3q_{30,\gamma}$$

$$\phi = \theta_A - \theta_B - \theta_C,$$

- **YELLOW**: contributions from single-wave theory; e.g. $q_{2,\alpha} = q_{11,\alpha}$.
- **BLUE**: new wave-wave & wave-mean flow interaction contributions.
- **RED:** Low-order phase-coupling terms.
- Also: mean-flow modifications due to each wave.

Standard Non-Linear Single-Wave PBL Roll Model

Table 5.1 Contributions to the nonlinear perturbation up to the fifth Landau Coefficient

Order	Landau	q_0	q_1	q_2	q_3	q_4	q_5	q_6	q_7	q_8	q_9	q_{10}	q_{11}
1		MF											
A	λ_0		q_{10}										
A^2		q_{01}		q_{20}									
A^3	λ_1		q_{11}		q_{30}								
A^4		q_{02}		q_{21}		q_{40}							
A^5	λ_2		q_{12}		q_{31}		q_{50}						
A^6		q_{03}		q_{22}		q_{41}		q_{60}					
A^7	λ_3		q_{13}		q_{32}		q_{51}		q_{70}				
A^8		q_{04}		q_{23}		q_{42}		q_{61}		q_{80}			
A^9	λ_4		q_{14}		q_{33}		q_{52}		q_{71}		q_{90}		
A^{10}		q_{05}		q_{24}		q_{43}		q_{62}		q_{81}		q_{100}	
A^{11}	λ_5		q_{15}		q_{34}		q_{53}		q_{72}		q_{91}		q_{110}

Truncated Contributions to Multi-Wave Roll Model

$$\mathbf{q} = [u, v, w, T]^T$$

To 1st Nonlinear Landau Term:

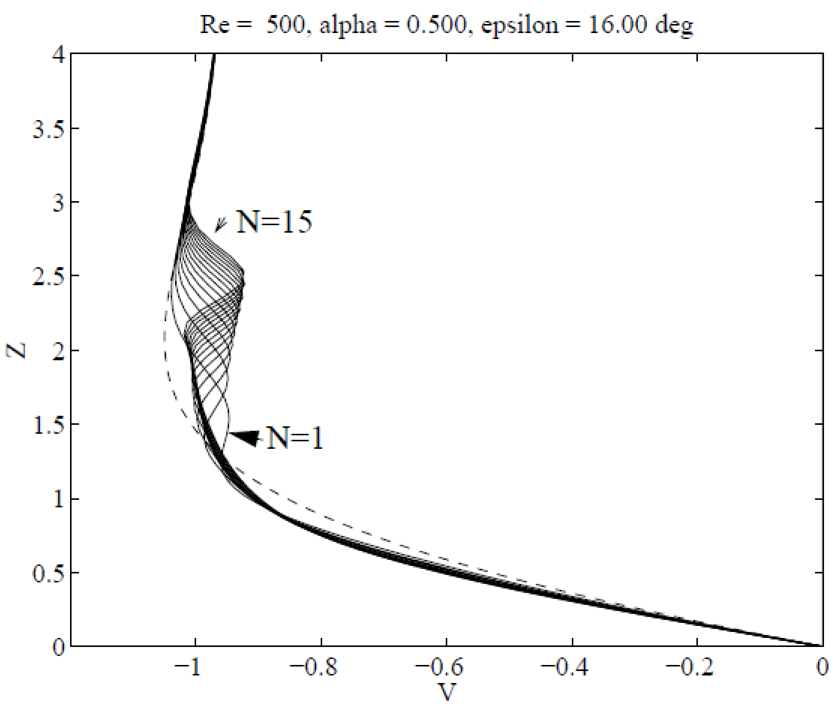
$0 \quad + A^2 q_{01}$ (mean flow modification)

$Aq_{10} + 0 \quad + A^3 q_{11}$ (fundamental wavelength)

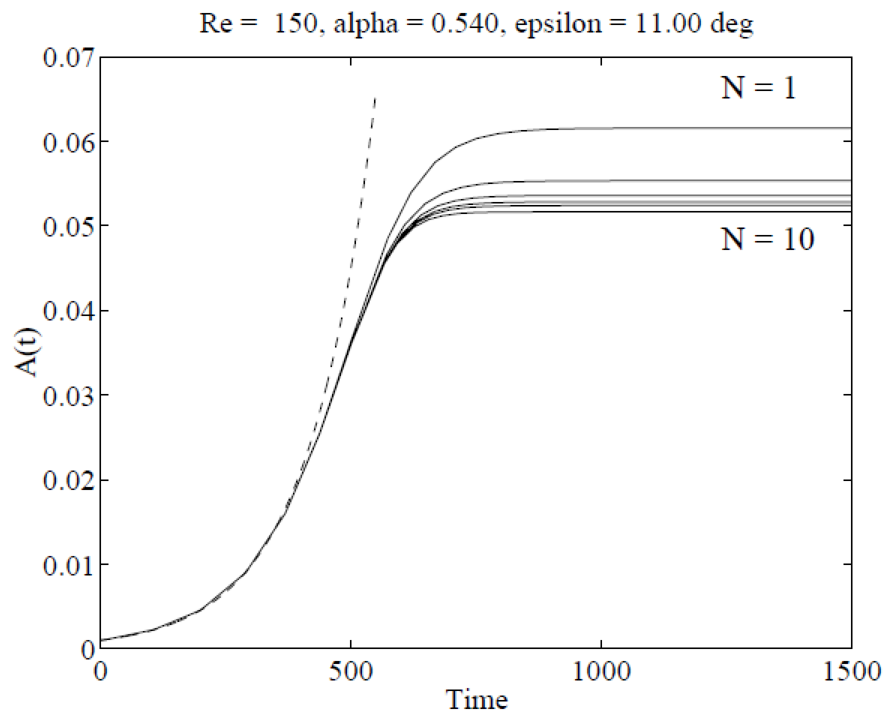
$0 \quad + A^2 q_{20}$ (1st harmonic)

$0 \quad + 0 \quad + A^3 q_{30}$ (2nd harmonic)

Low-Order Truncation Errors



Mean-flow Modification



Amplitude Estimation

Low-order truncation problems:

- Over-estimated amplitude
- “S-shaped” MF modification