ELDORA TPARC/TCS08 Dataset

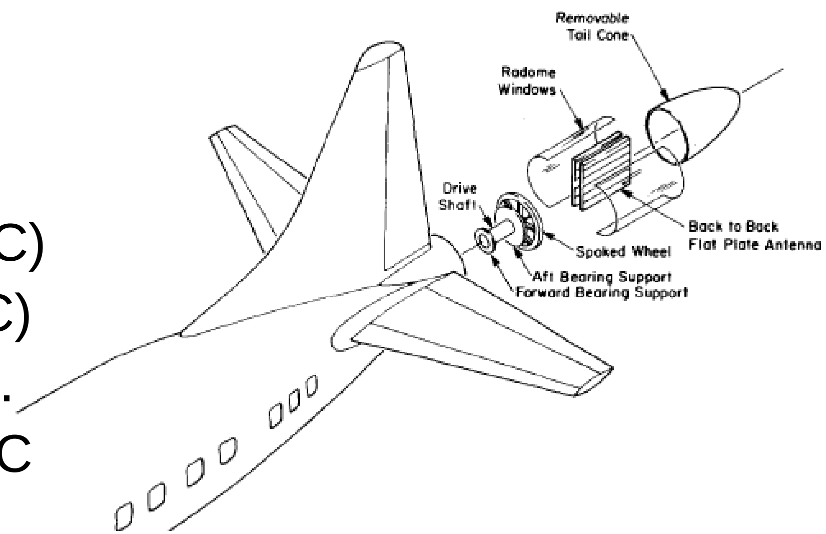
Wen-Chau Lee and Michael M. Bell

NCAR NCAR/NPS

http://www.eol.ucar.edu/instrumentation/airborne-instruments/eldora/eldora-help-center

ELDORA Airborne Doppler Radar

- NRL-P3 ~~ELectra DO~~ppler RAdar
  - 3.2 cm, 1.8° beam, 38.7 dB Gain
  - 2 Antennas & Tx
  - 40 kW Peak Power
  - 2 PRF in 4:5 ratio (62 m/s NV in TPARC)
  - Scan rate up to 144°/s (87°/s in TPARC)
  - Complex ‘chirp’ w/4 (3 in TPARC) Freq.
  - ~500 m along track resolution in TPARC
  - Unambig. Range ~75 km (Convective)



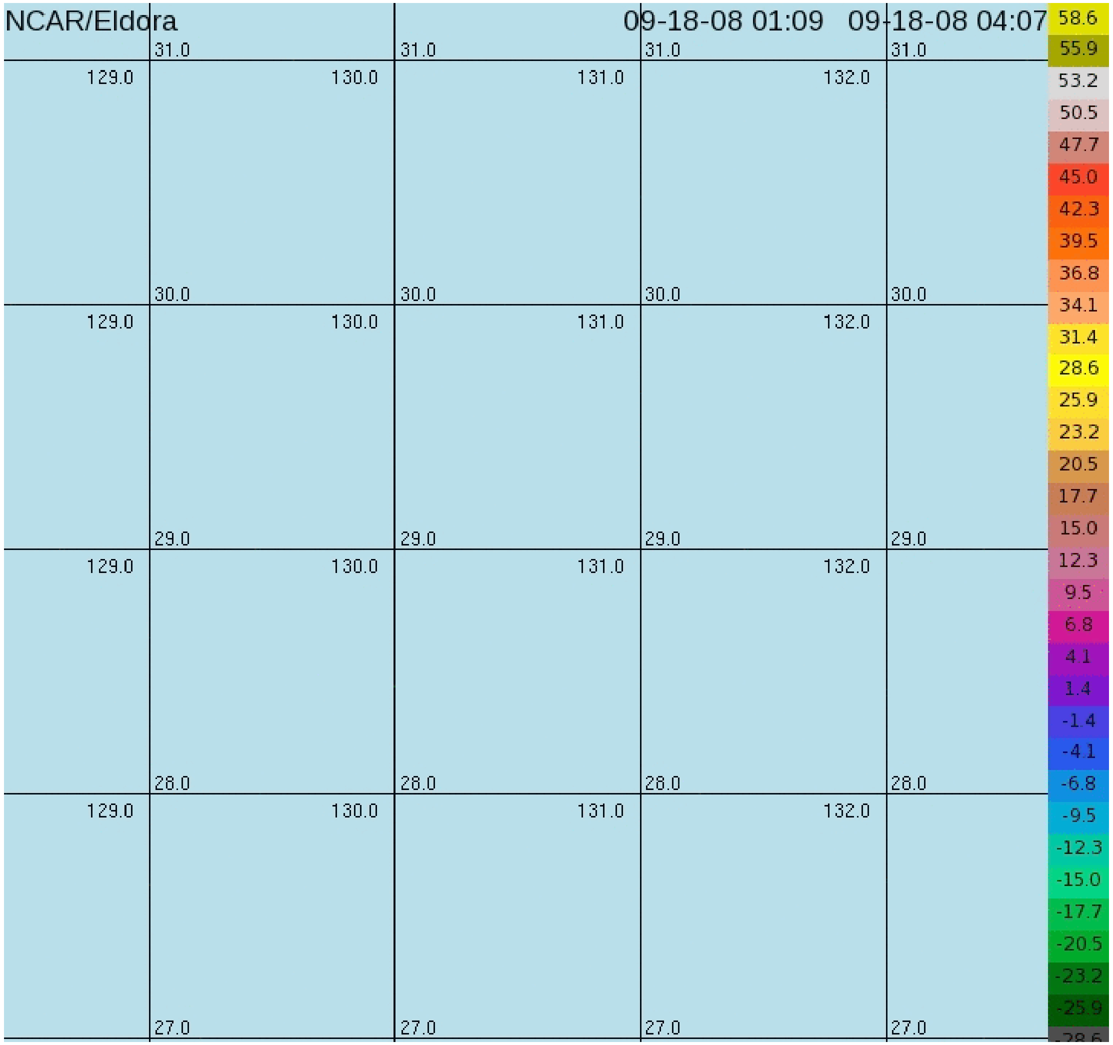
- TOGA COARE (93),VORTEX 95, FASTEX (97), LAKEICE (97/98), MAP (99), IHOP (02), CRYSTAL-FACE (02), BAMEX (03), RAINEX (05), TCS-08/TPARC (08)

EOL
Deployment
Development
Data Services

ELDORA Data Fields

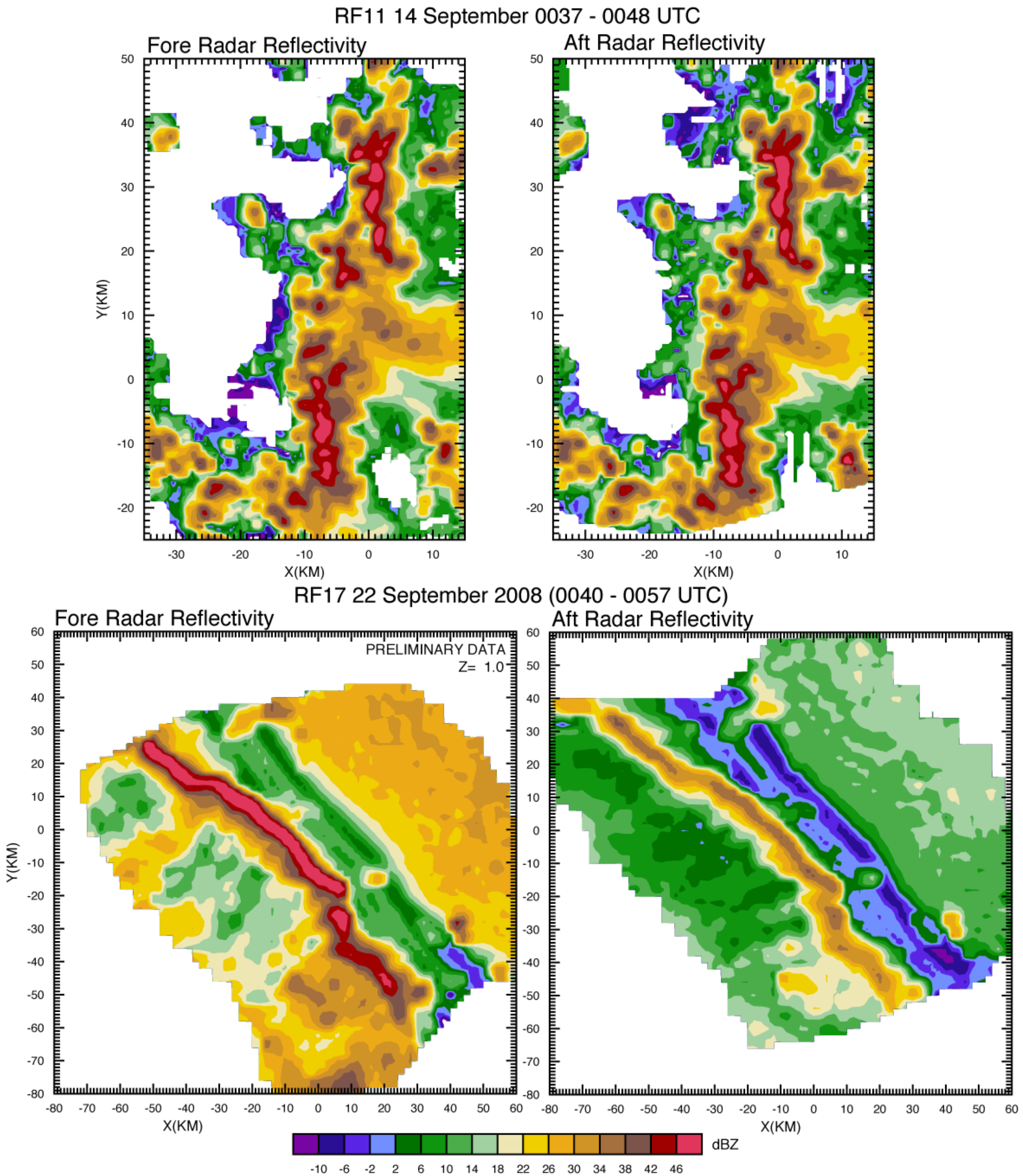
Field Name	Description
DBZ	Radar Reflectivity
VG	Ground-relative, navigation corrected, Doppler velocity
NCP	Normalized Coherent Power
SW	Spectrum Width
VT	VG thresholded with NCP below 0.25
VS	Short-pulse Doppler velocity
VL	Long-pulse Doppler velocity
VR	Aircraft-relative Doppler velocity

CAPPI Movies Bonus Dataset

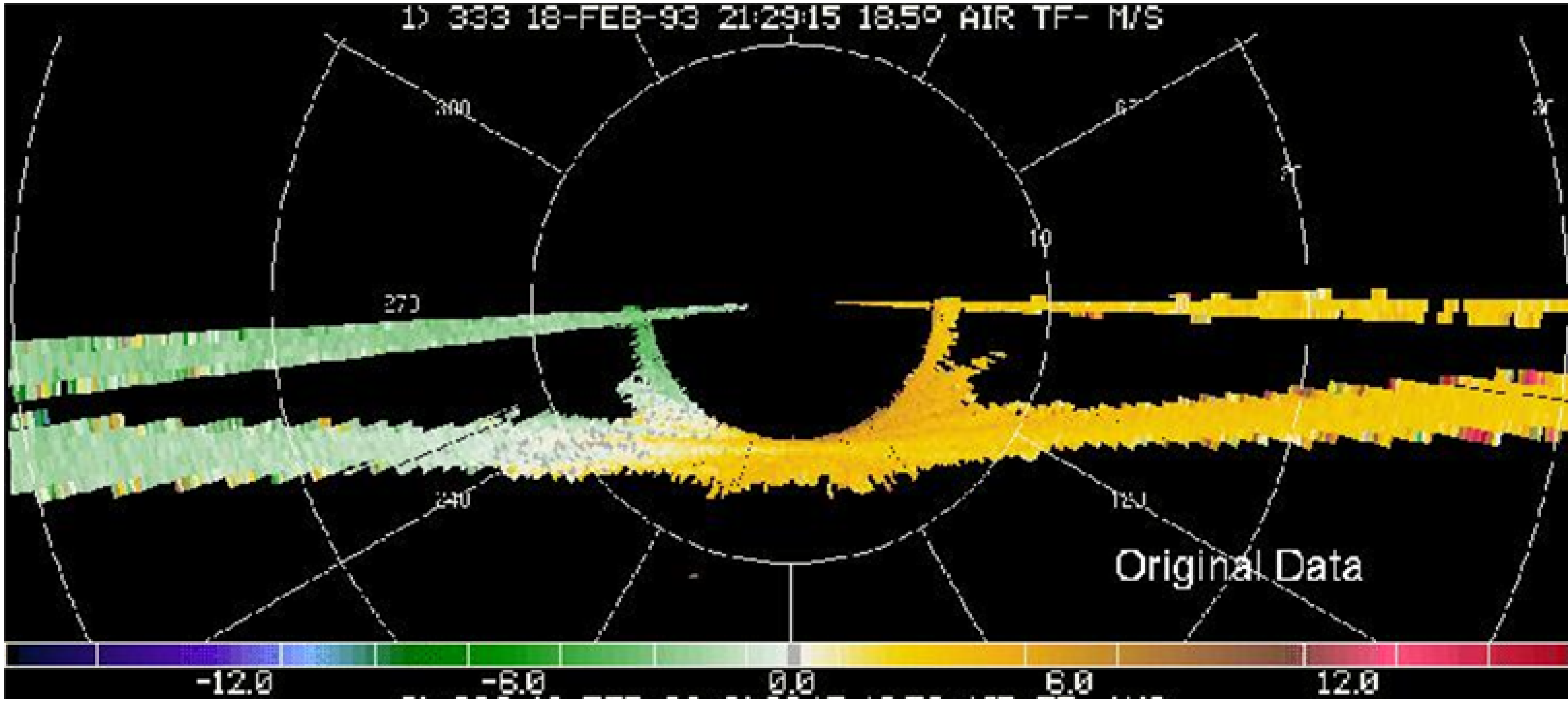


Dataset Summary

- Velocity data appears very good throughout project
- INS Navigation corrections were stable
- Aft Reflectivity is low from RF16 – RF21, reduced sensitivity in cloudy & clear air
- 165 GB dataset ready, on CODIAC soon
  - Dorade sweep files in ~200 MB 10-minute tar files (netCDF translator available)
  - Navigation correction factors (cfac files)


RF11 14 September 0037 - 0048 UTC
Fore Radar Reflectivity
Aft Radar Reflectivity
Y(KM)
X(KM)
RF17 22 September 2008 (0040 - 0057 UTC)
Fore Radar Reflectivity
Aft Radar Reflectivity
PRELIMINARY DATA
Z= 1.0
dBZ
-10 -6 -2 2 6 10 14 18 22 26 30 34 38 42 46

Problems in Raw Data



1. Earth surface is tilted.
2. Earth surface is not stationary.
3. Earth surface moves at different speeds.

Testud et al 1995

ELDORA Navigation Corrections

- Accurate knowledge of the aircraft orientation and radar beam pointing angle is essential to airborne Doppler analysis

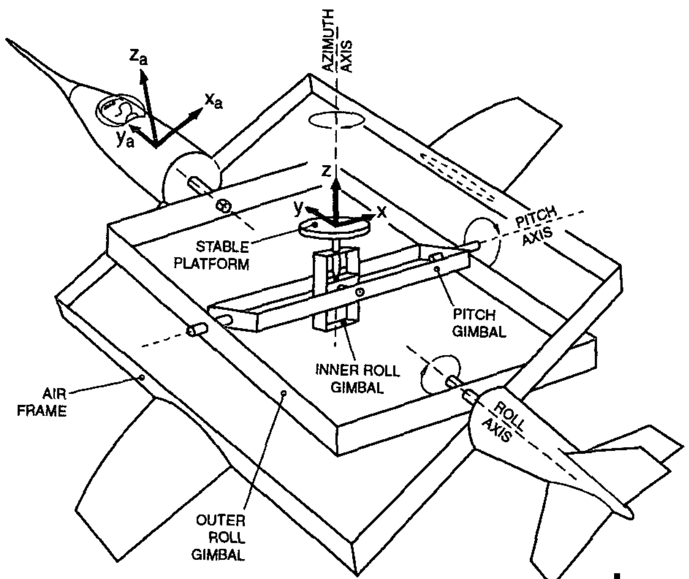
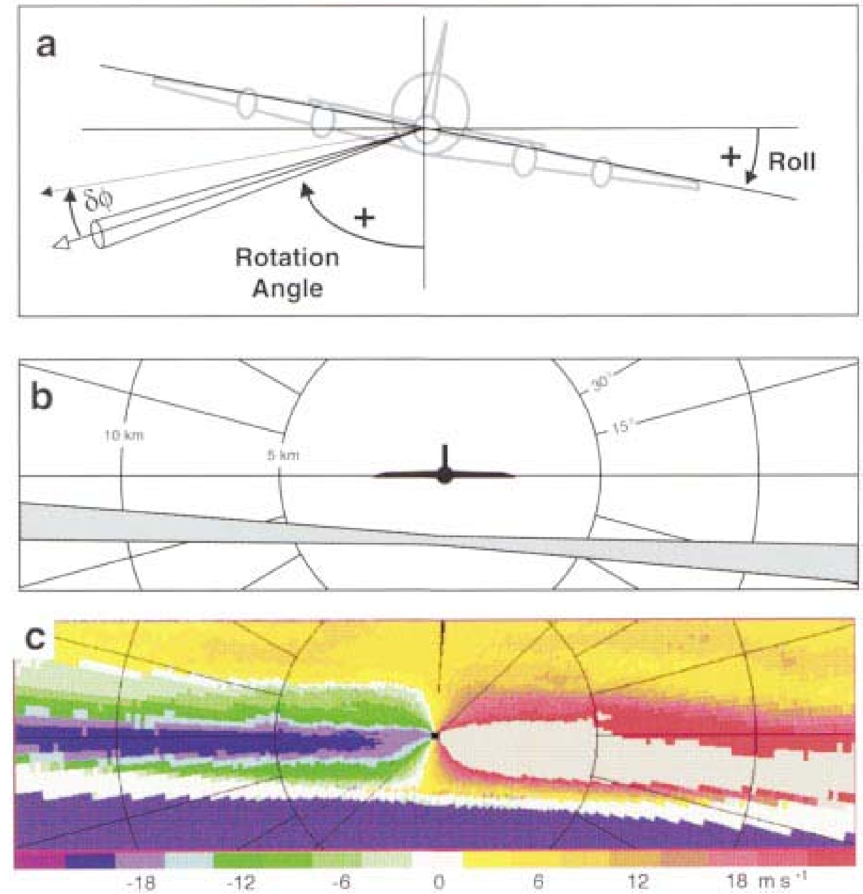


FIG. 1. Platform gimbals and reference frame [adapted from Axford (1968)].

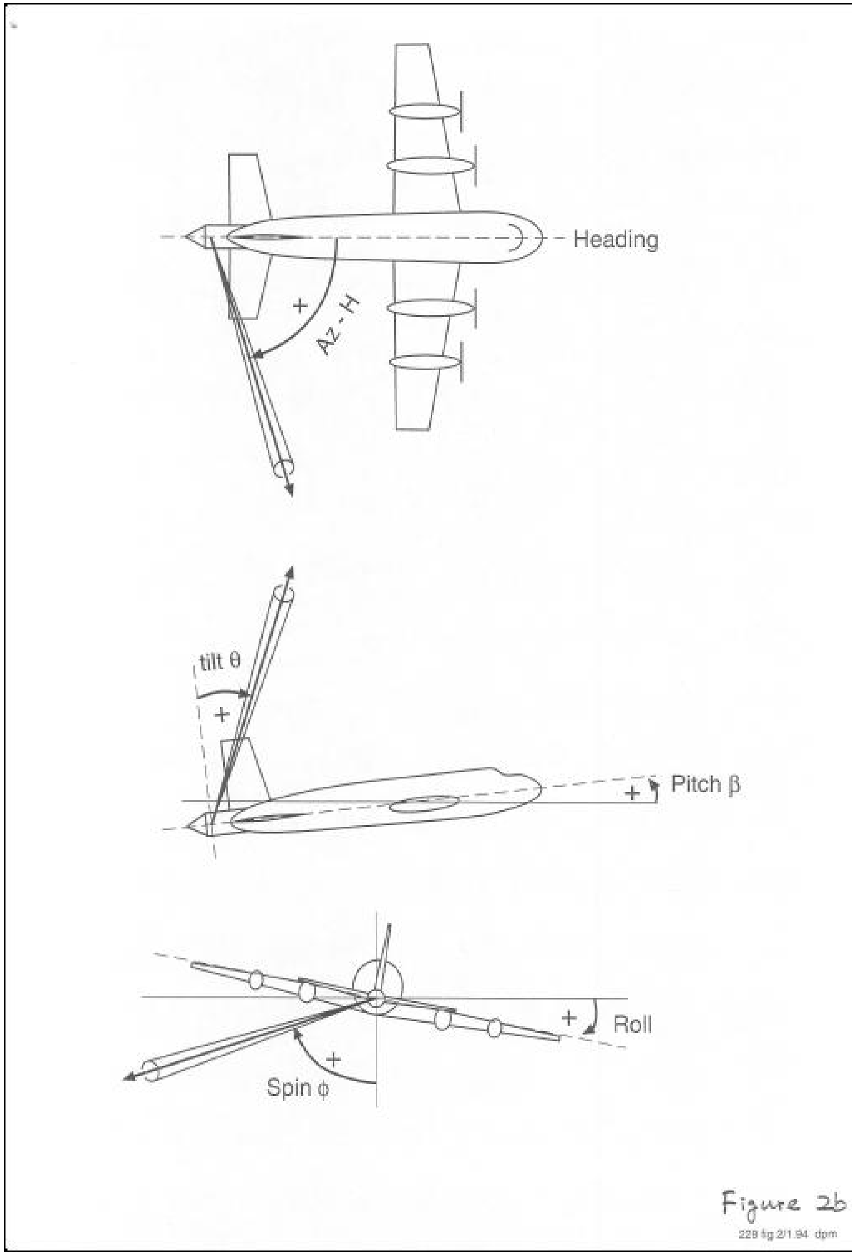
Roll/Rotation Angle Error



Lee et al, 1994; Testud et al, 1995; Georgis et al, 2000; Bosart et al, 2002

Definitions of INS Attitude Angles

- Meteorological coordinates-positive clockwise
- Drift is the angle between track and heading (T=H+D), a positive drift angle is defined as the track is more clockwise than the heading
- Pitch is the angle that the aircraft longitudinal axis makes with the horizontal plane, nose up is positive pitch
- Roll is the angle that the wings make with the horizontal plane, right wing down is positive
- Through these three sequential rotation, **X is transformed in**to $\mathbf{X_a}$



Uncertainties in INS and Antenna Pointing Angles

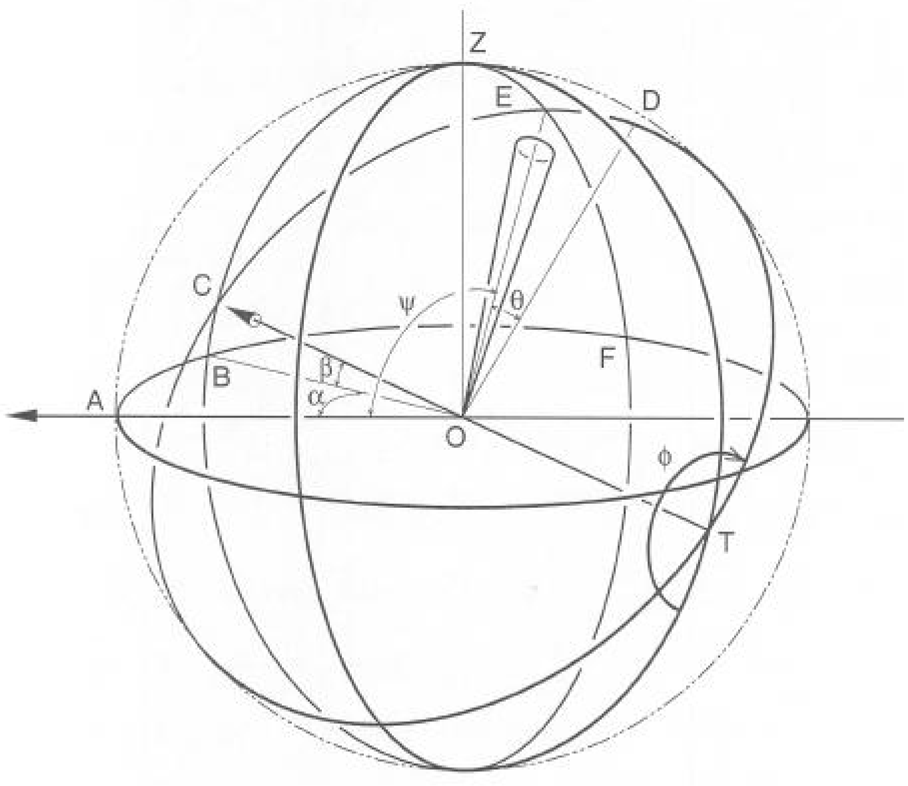
Measurement/Instrument Errors:

- Horizontal velocity (V_H): $\pm$ 2 m s^{-1}
- Drift angle (α): $\pm$ 1°
- Aircraft vertical velocity (W): $\pm$ 0.15 m s^{-1}
- Pitch angle (β): $\pm$ 0.05°
- Tilt angle (θ): $\pm$ 0.05°
- Roll/spin angle (ϕ): $\pm$ 0.05°

Systematic errors (e.g., mounting errors) in the order of 1° may exist

Spherical Trigonometry and Radial Velocity

$$V_r = u\sin(A_z)\cos(EL) + v\cos(A_z)\cos(EL) + (w + w_t)\sin(EL) - V_g - V_a$$



$$\cos A_z = \frac{\sin\theta - \sin EL \sin\beta}{\cos EL \cos\beta}$$

$$\sin EL = \sin\theta \sin\beta - \cos\theta\cos\beta\cos\phi$$

$$\cos\Psi = \cos\alpha\cos\beta\sin\theta - \cos\alpha\sin\beta\cos\theta\cos\phi - \sin\alpha\cos\theta\sin\phi$$

α: drift

β: pitch

ϕ: spin/rotation

θ: tilt

Ψ: $\pi/2$-track-relative tilt

A_z: azimuth

EL: elevation

Velocity Error Analysis

Estimated aircraft ground speed (V_{Ge}):

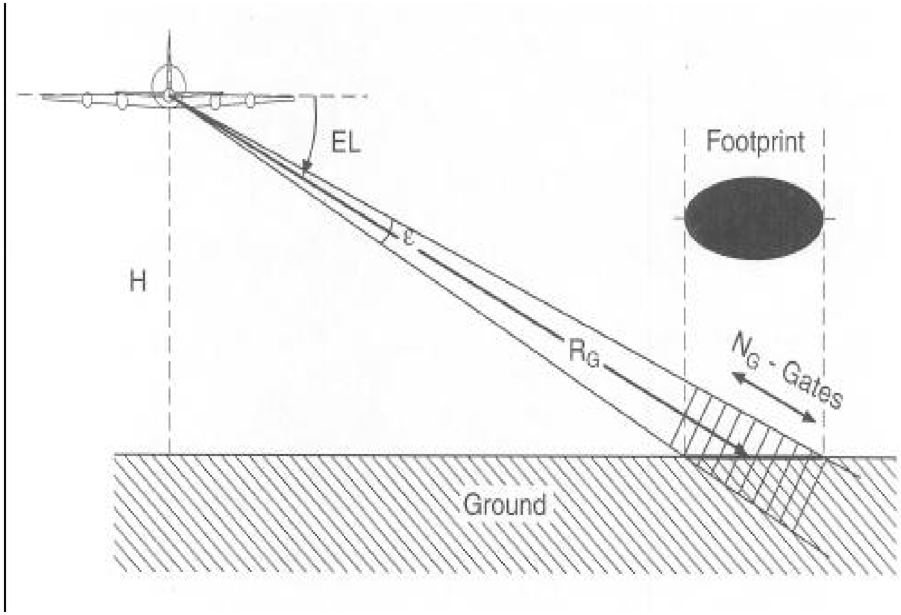
$$
\begin{aligned}
V_{Ge} &= V_H \cos\Psi - W \sin EL \\
&= (-V_H + V_o \cos\lambda_o)(\cos\alpha\cos\beta\sin\theta \\
&\quad + \cos\alpha\sin\beta\cos\theta\cos\phi - \sin\alpha\cos\theta\sin\phi) \\
&\quad - W(\sin\theta\sin\beta - \cos\theta\cos\beta\sin\phi)
\end{aligned}
$$

Measured aircraft ground speed by the radar (V_G):

δV_G: the velocity of the ground gate after removing ground speed

$$
\begin{aligned}
\delta V_G &= V_G - V_{Ge} \\
&= \delta(-V_H \cos\Psi - W \sin EL) \\
&= \delta W \cos\theta\cos\phi - V_H(\cos\alpha\cos\theta + \sin\alpha\sin\theta\sin\phi)\delta\theta \\
&\quad + \delta\theta V_H \sin\alpha\cos\theta\cos\phi - \delta\beta V_H \cos\alpha\cos\theta\cos\phi \\
&\quad + V_H(\sin\alpha\sin\theta + \cos\alpha\cos\theta\sin\phi) \\
&\quad - (\cos\alpha\sin\theta - \sin\alpha\cos\theta\sin\phi)\delta V_H \\
&= A + B_1 \sin\phi + B_2 \cos\phi
\end{aligned}
$$

Range Error Analysis



$$R_G = -\frac{H}{\sin EL}$$

$$N_G \approx \frac{R\varepsilon}{\delta R \tan EL}$$

δR: gate spacing
R_R: actual distance to the ground
ε: beam width

$$R_G = -\frac{H\cos\phi}{\sin EL} = -\frac{H}{\sin\theta\sin\beta - \cos\theta\cos\beta\cos\phi} = R_R + \Delta R$$

$$R_{Ge} = -\frac{H_e}{\sin\theta_e\sin\beta_e - \cos\theta_e\cos\beta_e\cos\phi_e}$$

Range Error Analysis (Continue)

δR_G: difference between the actual distance to the ground and estimates from aircraft altitude and elevation angles of a radar beam

$$\delta R_G = R_G - R_{Ge}$$

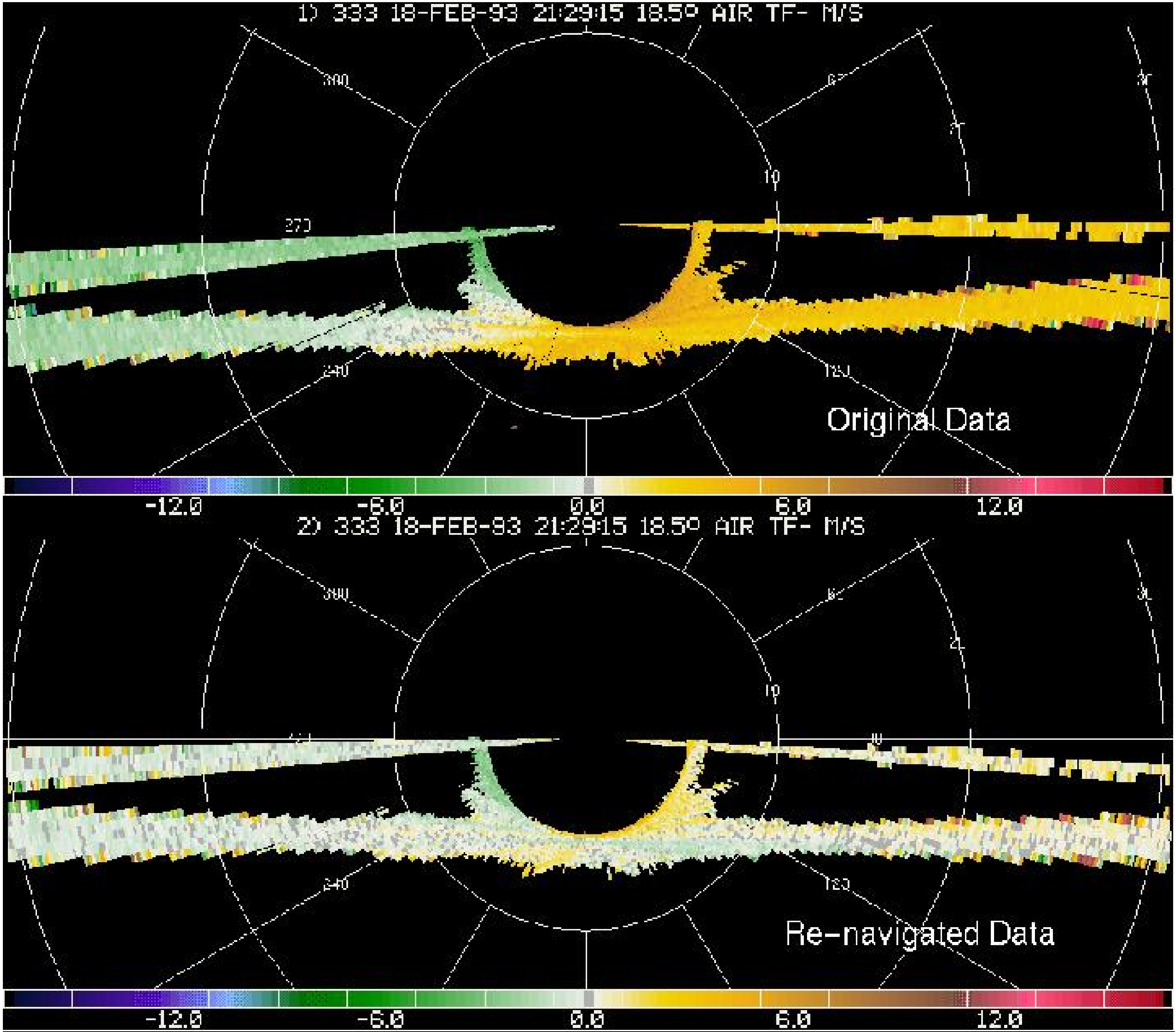
$$= R_G \left(\frac{\delta H}{H} + \frac{\tan\theta}{\cos\phi} \delta\beta + \tan\theta\delta\theta + \tan\theta\delta\phi \right)$$

$$R_R - R_{Ge} = \delta R_G - \Delta R$$

$$\cos^2\phi (R_R - R_{Ge}) = -\frac{\Delta R}{2} + \frac{H\tan\theta}{\cos\theta}\delta\beta + \left(\frac{H\delta\phi}{\cos\theta} \right) \sin\phi$$

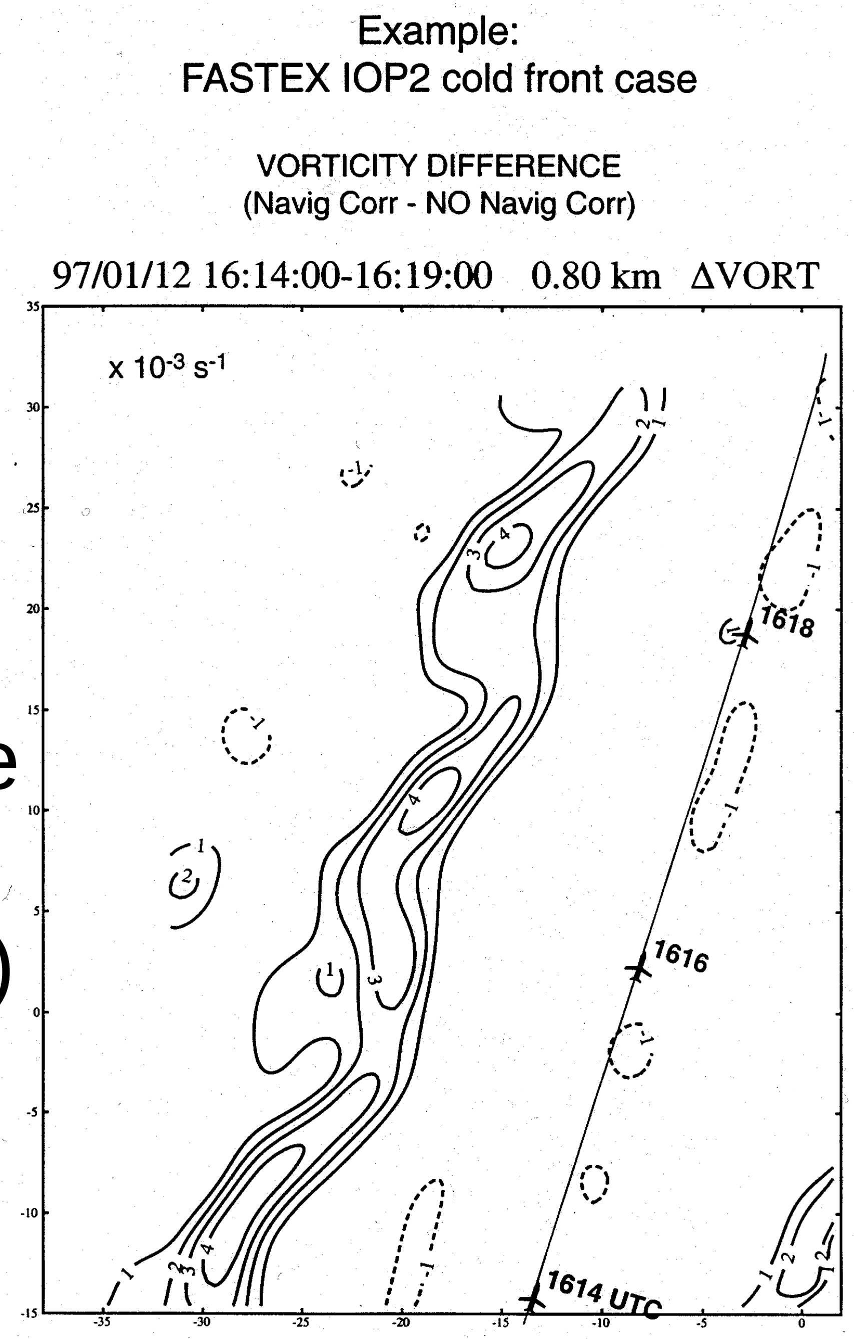
$$+ \left(\frac{\delta H + H\tan\theta\delta\theta}{\cos\theta} \right) \cos\phi - \frac{\Delta R}{2}\cos 2\phi$$

$$= C + D_1 \sin\phi + D_2 \cos\phi + E\cos 2\phi$$

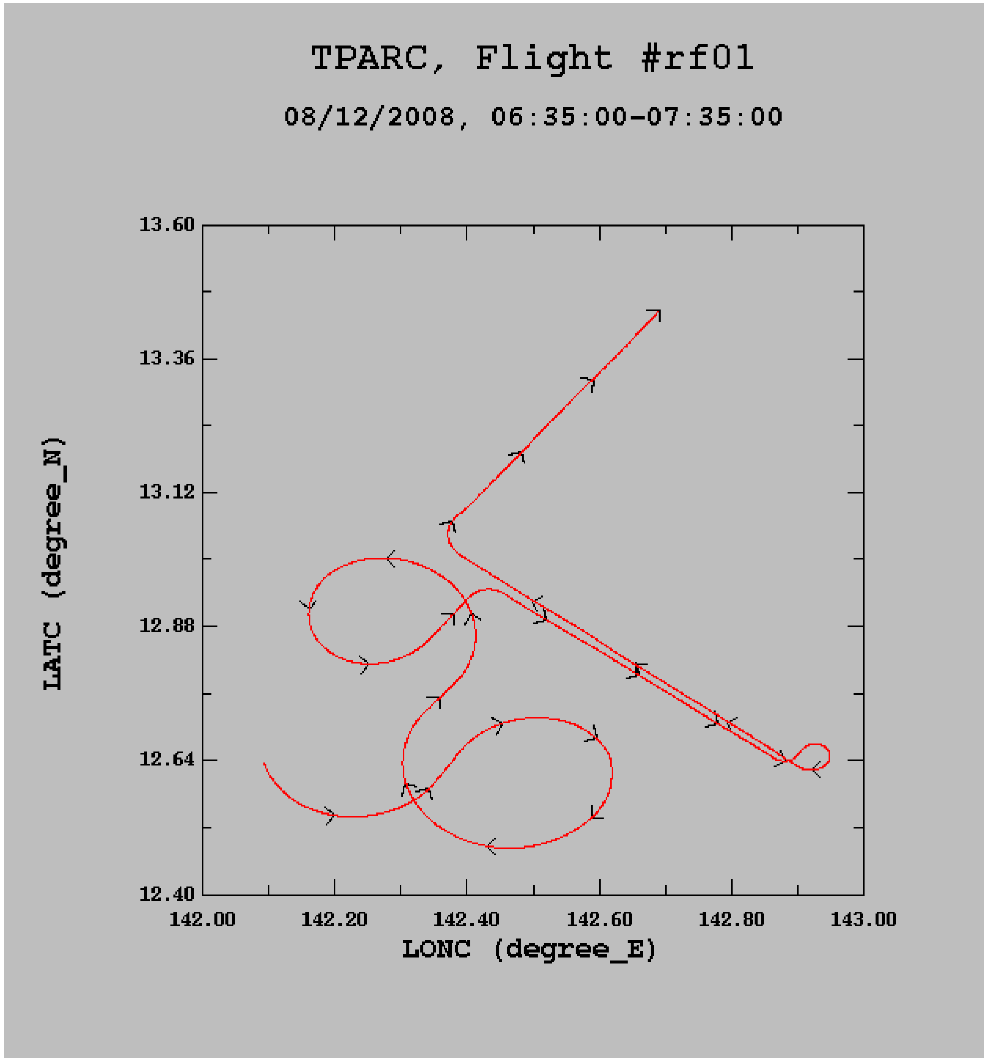

1) 333 18-FEB-93 21:29:15 18.5° AIR TF- M/S
300
270
240
120
10
Original Data
-12.0
-6.0
0.0
6.0
12.0
2) 333 18-FEB-93 21:29:15 18.5° AIR TF- M/S
300
240
120
10
Re-navigated Data
-12.0
-6.0
0.0
6.0
12.0

Moving Ocean Surface

- If the ground is not stationary, then we match in situ wind with near aircraft dual-Doppler wind if there are scatterers near the aircraft (BLW correction)
- Use to refine ground speed and drift



Reverse Headings



Research Flight	Date	Time	Range Fore	Range Aft	Altitude Corr	Pitch Corr	Rotation Aft	Rotation Fore
1	8/12/08	28:00.0	135.03	139	-0.036	-1.565	0.09	-0.17
2	8/16/08	08:00.0	122.28	120.38	-0.03	-1.575	0.03	-0.27
3	8/16/08	46:00.0	99.84	143.42	-0.053	-1.64	0.08	-0.22
4	8/18/08	49:00.0	84.26	175.26	-0.025	-1.605	0.02	-0.18
5	8/28/08	00:00.0	40	148.56	-0.013	-1.64	0.08	-0.11
6	8/29/08	43:00.0	41.29	156.29	-0.028	-1.585	0.05	-0.2
7	9/1/08	25:00.0	132.06	130.8	-0.039	-1.605	0.06	-0.18
8	9/8/08	12:00.0	125.63	202.43	-0.029	-1.625	0.09	-0.2
9	9/9/08	32:00.0	61.84	98.27	-0.031	-1.62	0.06	-0.23
10	9/11/08	00:00.0	165.28	151.09	-0.017	-1.63	-0.2	-0.47
11	9/13/08	20:00.0	126.73	146.37	-0.043	-1.645	-0.02	-0.34
12	9/14/08	20:00.0	88.62	84.66	-0.021	-1.63	-0.03	-0.32
13	9/17/08	40:00.0	38.15	171.38	-0.025	-1.635	-0.08	-0.33
14	9/18/08	10:00.0	134.1	163.38	-0.028	-1.645	-0.08	-0.38
15	9/19/08	30:00.0	159	145.24	-0.035	-1.61	-0.03	-0.37
16	9/20/08	16:00.0	66.5	196.3	-0.018	-1.64	-0.04	-0.33
17	9/22/08	15:00.0	168.96	156.46	-0.023	-1.645	-0.11	-0.39
18	9/23/08	06:00.0	79.65	209.02	-0.048	-1.615	-0.11	-0.32
19	9/24/08	15:00.0	89.18	120.33	-0.047	-1.625	-0.14	-0.33
20	9/25/08	27:00.0	94.17	90.62	-0.039	-1.58	-0.08	-0.36
21	9/27/08	12:00.0	46.47	192.2	-0.036	-1.62	-0.08	-0.33
22	10/2/08	27:00.0	164.69	184.85	-0.02	-1.63	-0.28	-0.51
23	10/4/08	35:00.0	94.07	205.96	-0.021	-1.66	-0.23	-0.53

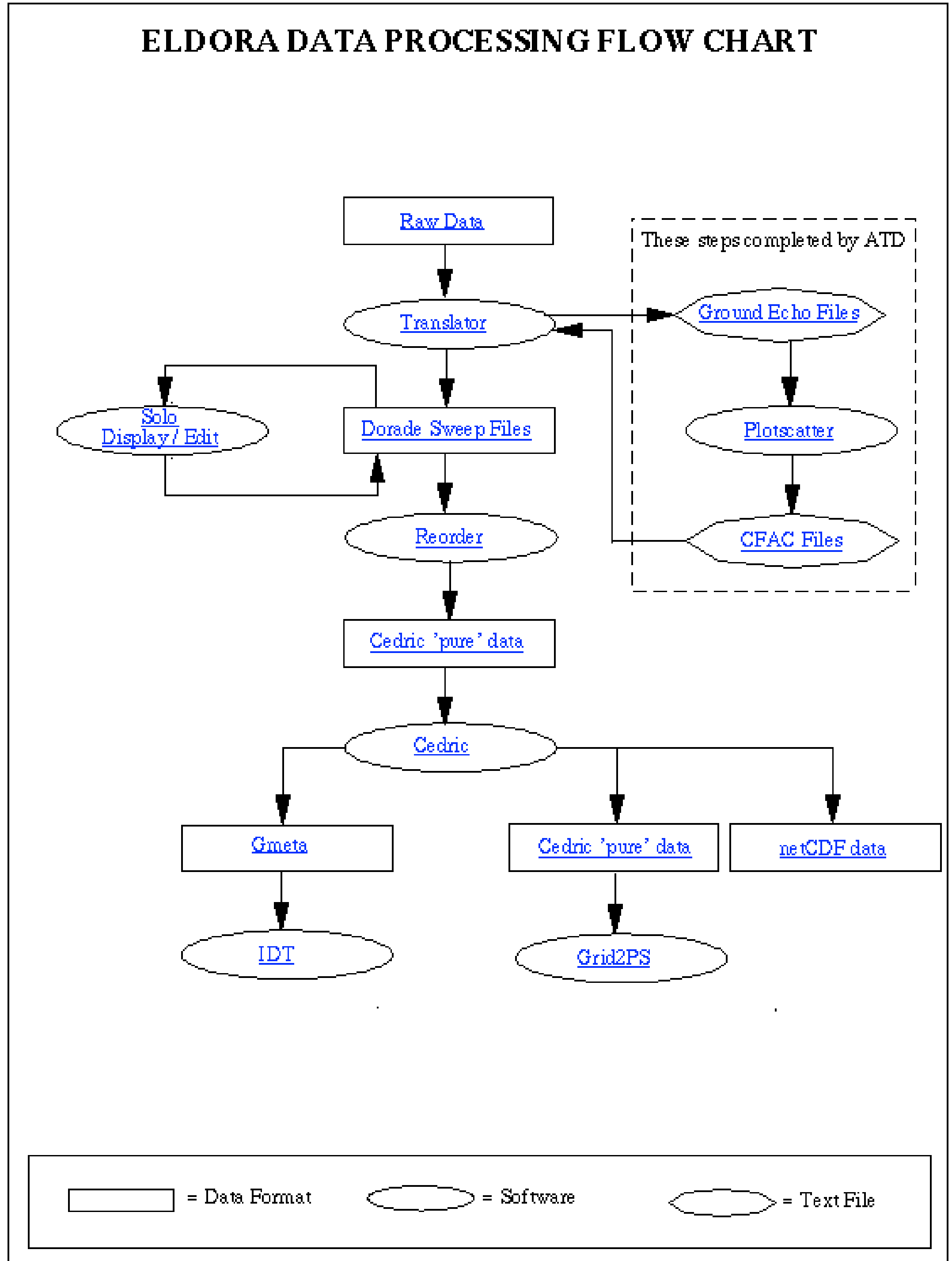
TPARC/TCS08 Corrections

	Drift Corr	Ground Speed Reverse Legs	Tilt Aft	Tilt Fore
Mean	0.019565	0.88563	0.30053	-0.13158
Median	0.055	0.9275	0.3	-0.15
Std Deviation	0.49641	0.15072	0.060044	0.070179

- Ground speed, Tilt error determined from reverse headings, drift from project average

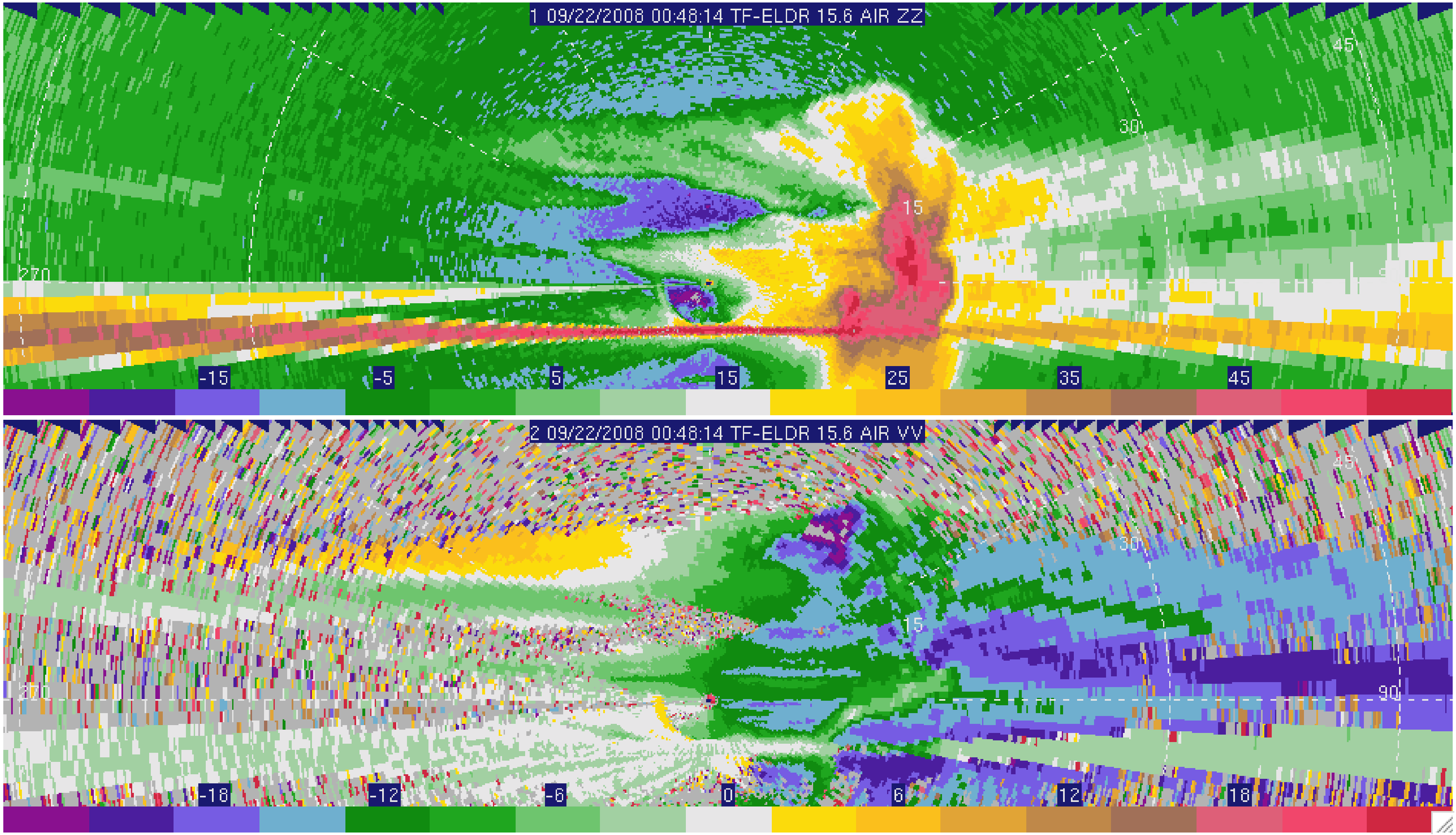
	Range Fore	Range Aft	Altitude Corr (km)	Pitch Corr	Rotation Aft	Rotation Fore
Mean	102.51	153.58	-0.030652	-1.6207	-0.041304	-0.30739
Median	94.17	151.09	-0.029	-1.625	-0.03	-0.33
Std Deviation	42.167	35.907	0.010731	0.024602	0.10559	0.1103

Basic Analysis Process

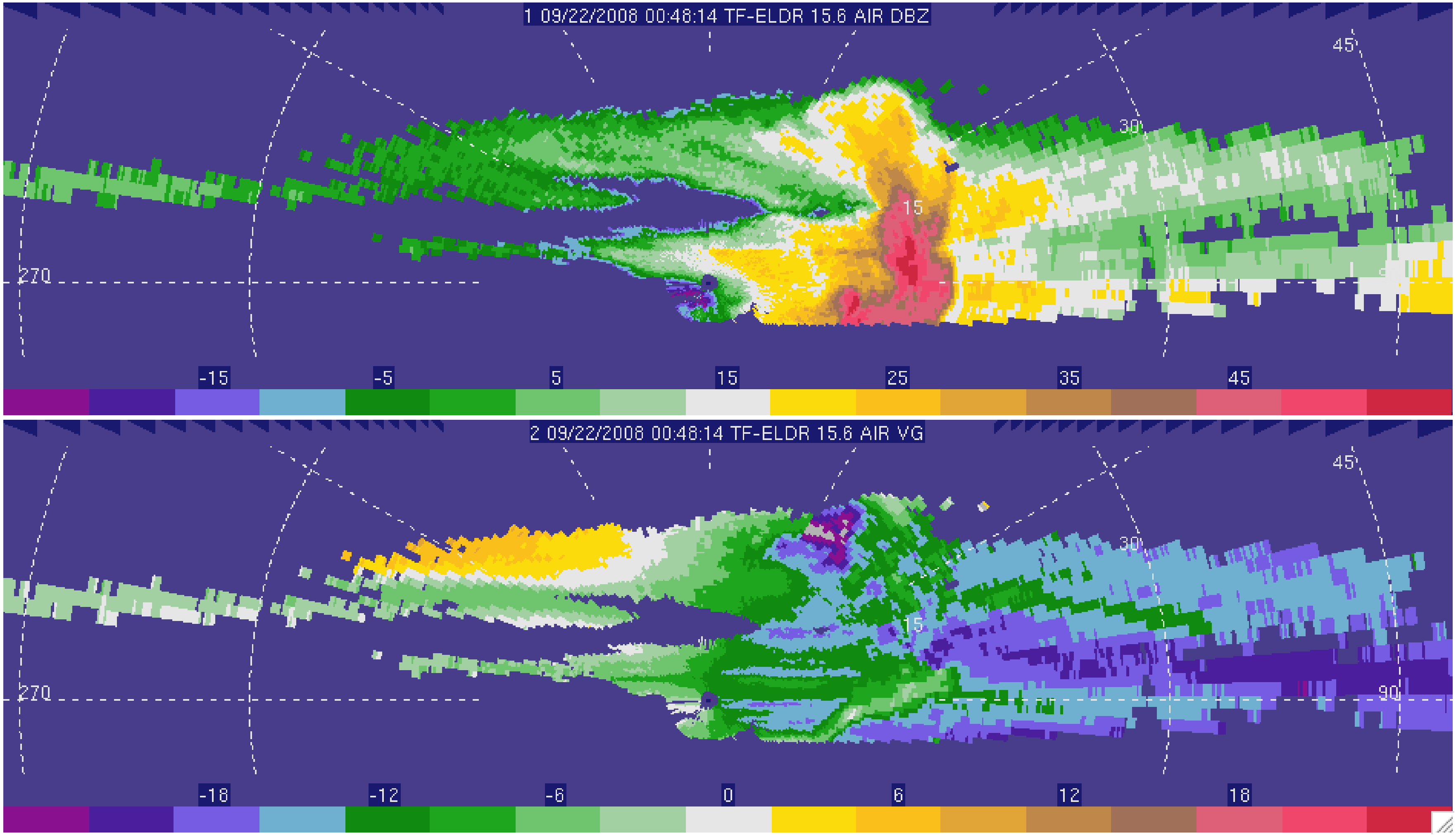


1. *Translate the raw ELDORA field format data into DORADE sweep files
2. *Calculate navigation correction factors (cfac files) for each flight
3. *Fine-tune navigation corrections for each leg of data*
4. **Edit the data to remove ground echo, noise, clutter, and radar side-lobes, as well as velocity unfolding.**
5. **Interpolate and/or Synthesize multiple data files to get 3-dimensional wind field and derived quantities.**

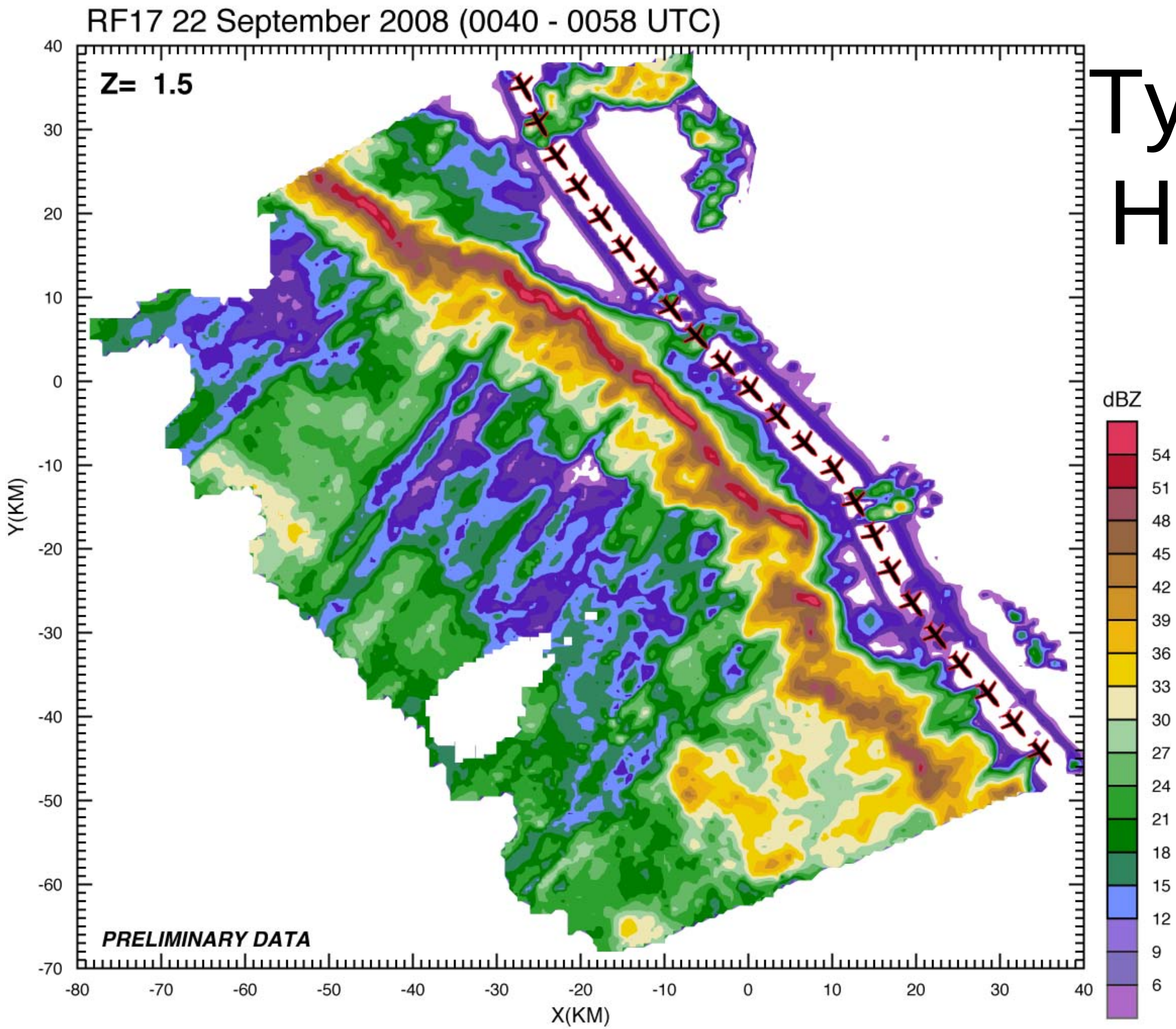
Raw Data

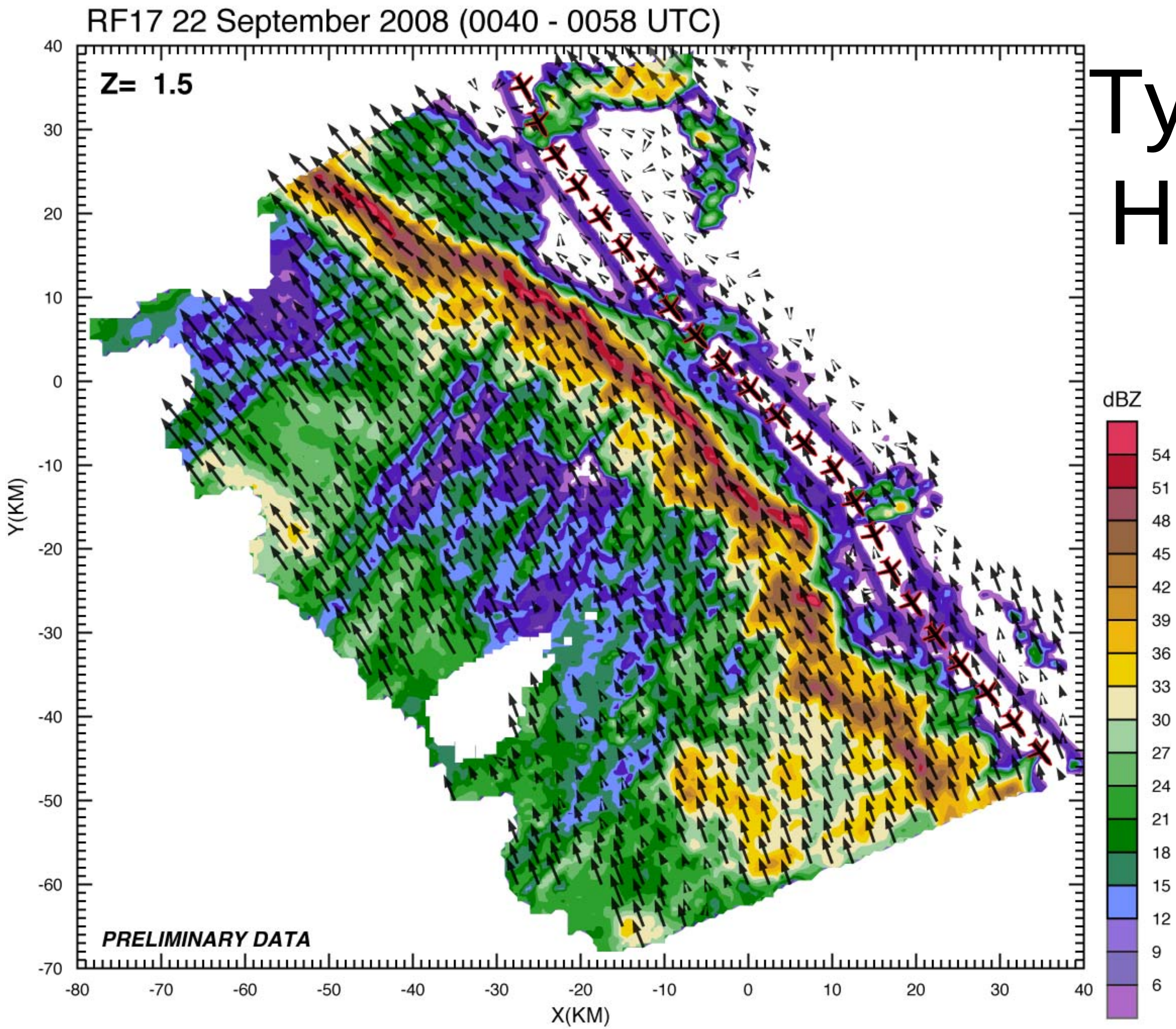

1 09/22/2008 00:48:14 TF-ELDR 15.6 AIR ZZ
-15
-5
5
15
25
35
45
2 09/22/2008 00:48:14 TF-ELDR 15.6 AIR VV
-18
-12
-6
0
6
12
18

Edited Data


1 09/22/2008 00:48:14 TF-ELDR 15.6 AIR DBZ
45
30
15
270
-15
-5
5
15
25
35
45
2 09/22/2008 00:48:14 TF-ELDR 15.6 AIR VG
45
30
15
270
90
-18
-12
-6
0
6
12
18

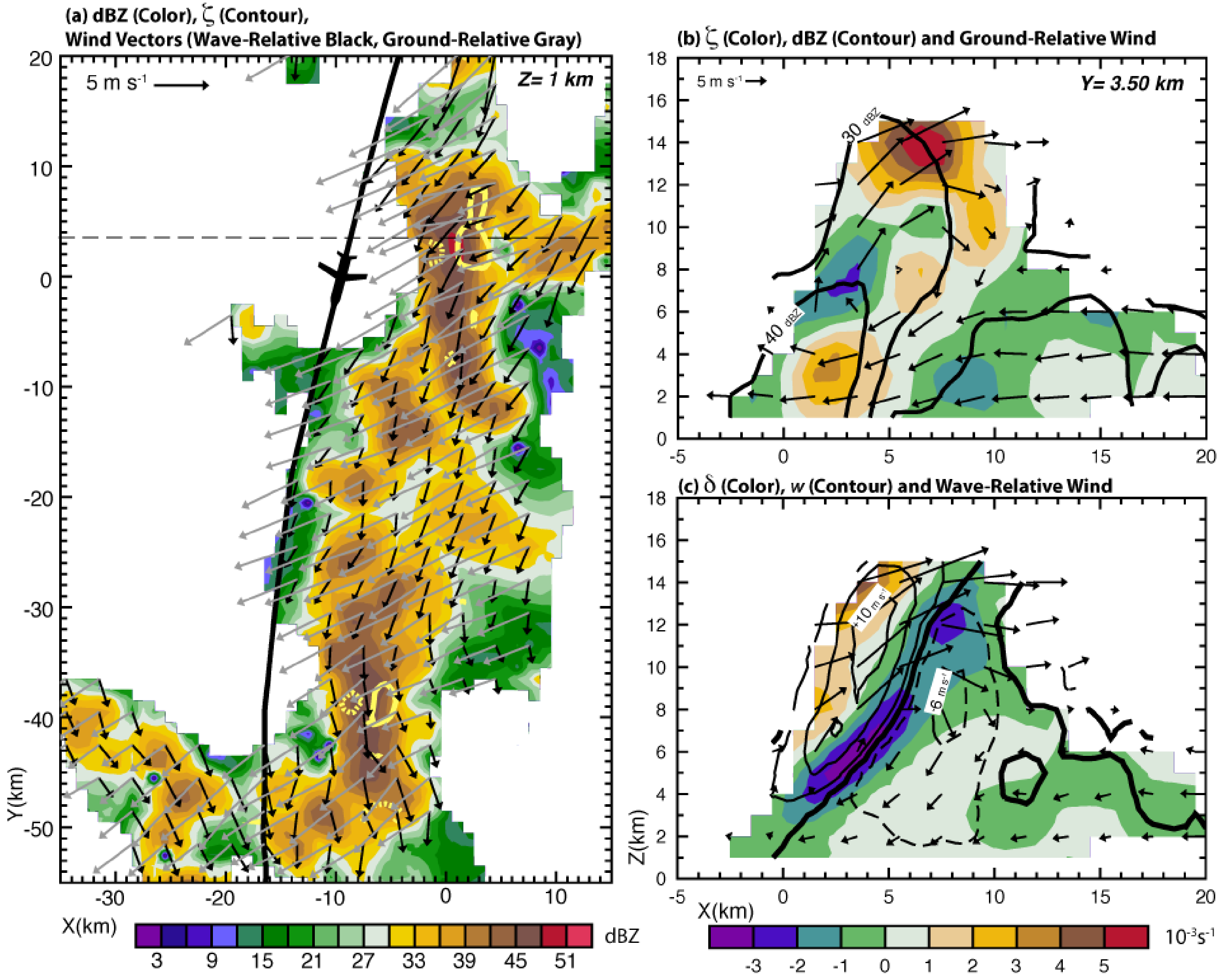
Typhoon Hagupit





Typhoon Hagupit

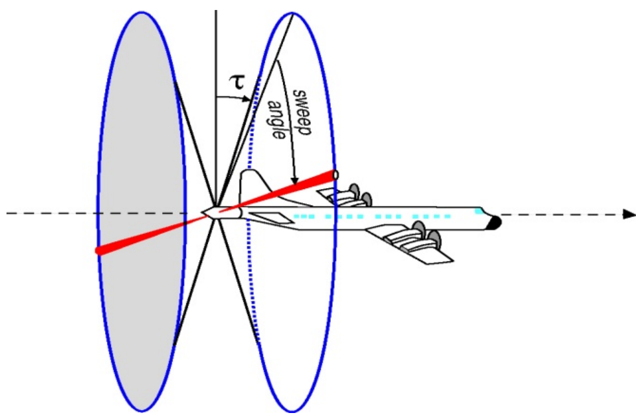
Hagupit Pre-genesis

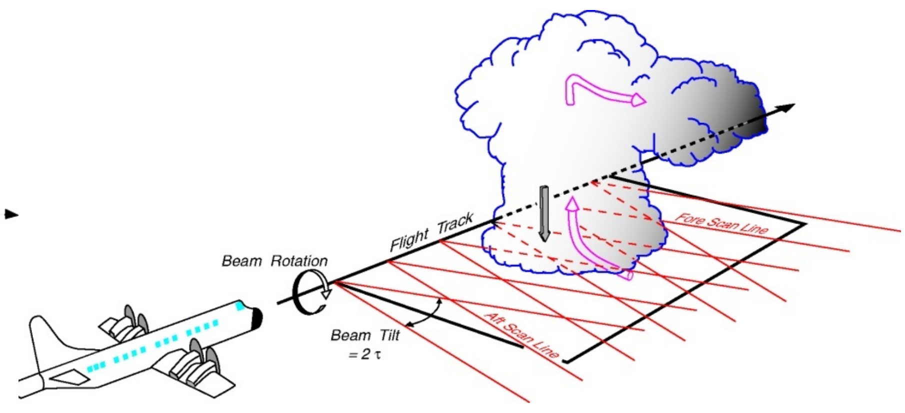


Multi-Doppler Synthesis

$$V_r = u\sin(a)\cos(e) + v\cos(a)\cos(e) + (w + w_t)\sin(e)$$

$$\begin{pmatrix} \sin^2 a\cos^2 e & \sin a\cos a\cos^2 e & \sin a\cos e\sin e \\ \sin a\cos a\cos^2 e & \cos^2 a\cos^2 e & \cos a\cos e\sin e \\ \sin a\cos e\sin e & \cos a\cos e\sin e & \sin^2 e \end{pmatrix} \begin{pmatrix} u \\ v \\ w + w_t \end{pmatrix} = \begin{pmatrix} V_r\sin a\cos e \\ V_r\cos a\cos e \\ V_r\sin e \end{pmatrix}$$





Hildebrand et al 1996

Doppler Synthesis Approaches

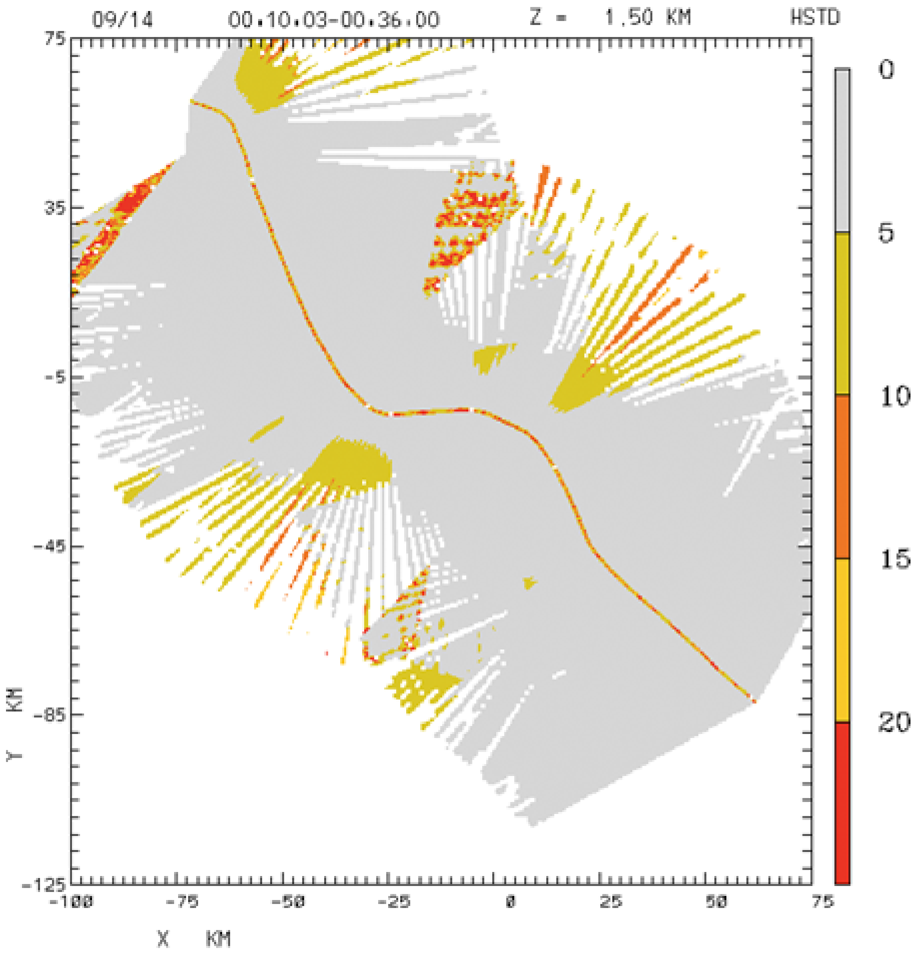
- **Forward Local** (Sprint/Reorder & Cedric)
  - Empirical Interpolation of V_r (Distance weighted averaging), then local synthesis
- **Forward Global** (Gamache, Raymond & Carrillo*)
  - Empirical Interpolation, then global synthesis
- **Reverse Global** (Gao et al. 1999/2004, Bell)
  - Interpolation from grid to radar space during cost function minimization

‘Forward Local’ synthesis

- ‘Conventional’ using reorder/cedric
- Quasi-horizontal assumption
- Resolve horizontal velocities then integrate continuity equation vertically to obtain vertical velocities
- Limited to elevation angle less than 45 deg
- Difficult to resolve storm top when storm is close to the radar

Problems with Radial Velocity Interpolation and Averaging

- Big issue for airborne synthesis and Reorder
- Also a problem for ground-based platforms near the radar
- Solutions:
  - Use more, small chunks
  - Include full az/elev info
  - Avoid it



3-D Variational Formulation (Gamache 1997, Reasor et al 2009): Solve two or more radial velocity equations and mass continuity equation simultaneously.

$$F = \lambda_1 J_1 + \lambda_2 J_2 + \cdots + \lambda_n J_n + \lambda_{n+1} J_{n+1} + \lambda_{n+2} J_{n+2} + \lambda_{n+3} J_{n+3}$$

$$J_m = \sum_{l=1}^{L} \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i=1}^{I} \rho_k (V_{rml} - u_{ijk} \cos\theta_{ml} \cos\phi_{ml} - v_{ijk} \sin\theta_{ml} \cos\phi_{ml} - w_{ijk} \sin\phi_{ml} - v_{Tml} \sin\phi_{ml})^2 \alpha_{ijkl}$$

$$J_{n+1} = \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i=1}^{I} (\nabla \cdot \rho_k \vec{V}_{ijk})^2$$

$$\begin{aligned} J_{n+2} = \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i=1}^{I} \Bigg\{ & \left(\frac{\partial^2 \rho u_{ijk_k}}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \rho u_{ijk_k}}{\partial y^2}\right)^2 + \left(\frac{\partial^2 \rho u_{ijk_k}}{\partial z^2}\right)^2 + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial y^2}\right)^2 + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial z^2}\right)^2 \\ & + \left(\frac{\partial^2 \rho w_{ijk_k}}{\partial x^2}\right)^2 + \left(\frac{\partial^2 \rho w_{ijk_k}}{\partial y^2}\right)^2 + \left(\frac{\partial^2 \rho w_{ijk_k}}{\partial z^2}\right)^2 + \left(\frac{\partial^2 \rho u_{ijk_k}}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2 \rho u_{ijk_k}}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial y \partial z}\right)^2 \\ & + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 \rho v_{ijk_k}}{\partial y \partial z}\right)^2 + \left(\frac{\partial^2 \rho w_{ijk_k}}{\partial x \partial y}\right)^2 + \left(\frac{\partial^2 \rho w_{ijk_k}}{\partial x \partial z}\right)^2 + \left(\frac{\partial^2 \rho w_{ijk_k}}{\partial y \partial z}\right)^2 \Bigg\} \end{aligned}$$

$$J_{n+3} = \sum_{k=1}^{K} \sum_{j=1}^{J} \sum_{i=1}^{I} \rho_k (w_{ijk} - w_B)^2 \delta_B$$

TCVAR (Bell 2009)

$$J(q) = \frac{1}{2}q^T q + \frac{1}{2}(\mathbf{HC}q - d)^T \mathbf{R}^{-1}(\mathbf{HC}q - d)$$

$$\nabla J(q) = (\mathbf{I} + \mathbf{C}^T\mathbf{H}^T\mathbf{R}^{-1}\mathbf{HC})q - \mathbf{C}^T\mathbf{H}^T\mathbf{R}^{-1}d$$

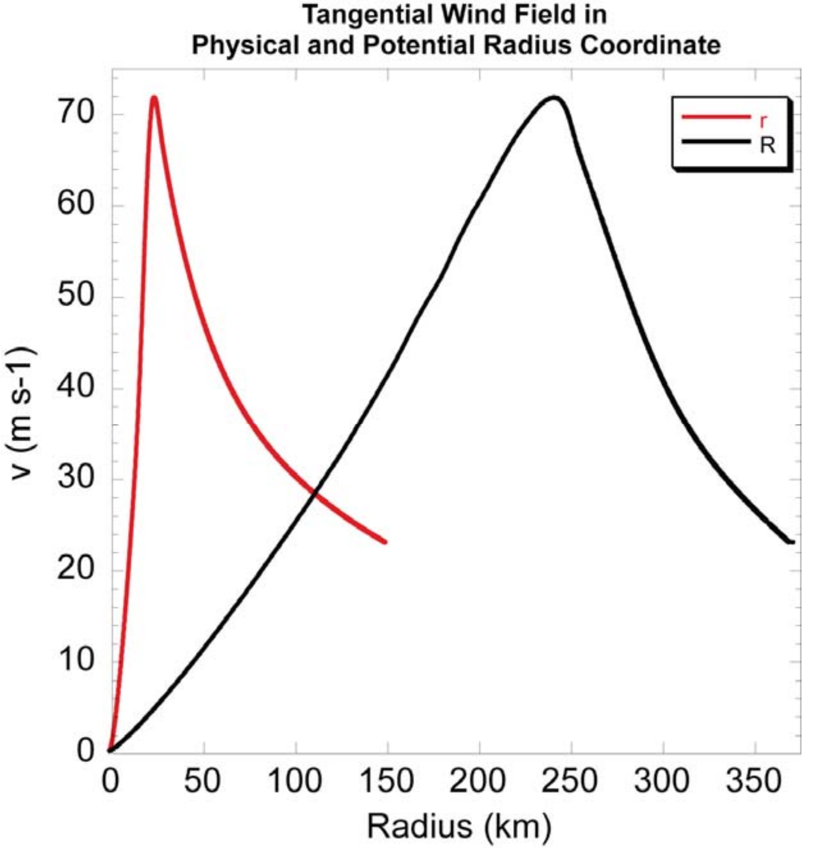
$$\mathbf{B} = \sqrt{\mathbf{B}}^T\sqrt{\mathbf{B}} = \mathbf{C}^T\mathbf{C}$$

$$q = \mathbf{C}^{-1}\delta x = \mathbf{C}^{-1}(x - x_b)$$

$$\mathbf{C} = \mathbf{PSDF}$$

P = Physical Coordinate Transform
S = Cubic Spline Transform
D = Diagonalized Background Error
F = Recursive Gaussian Filter

- Can combine radar, dropsonde, and flight level data
- Low noise via cubic interpolations and spectral derivatives
- Tunable error specifications and filtering



$$q(r,z) = \{\rho r v, \psi, h, q_v', \rho_a'\}$$

Raymond & Carrillo

Advantages / Disadvantages

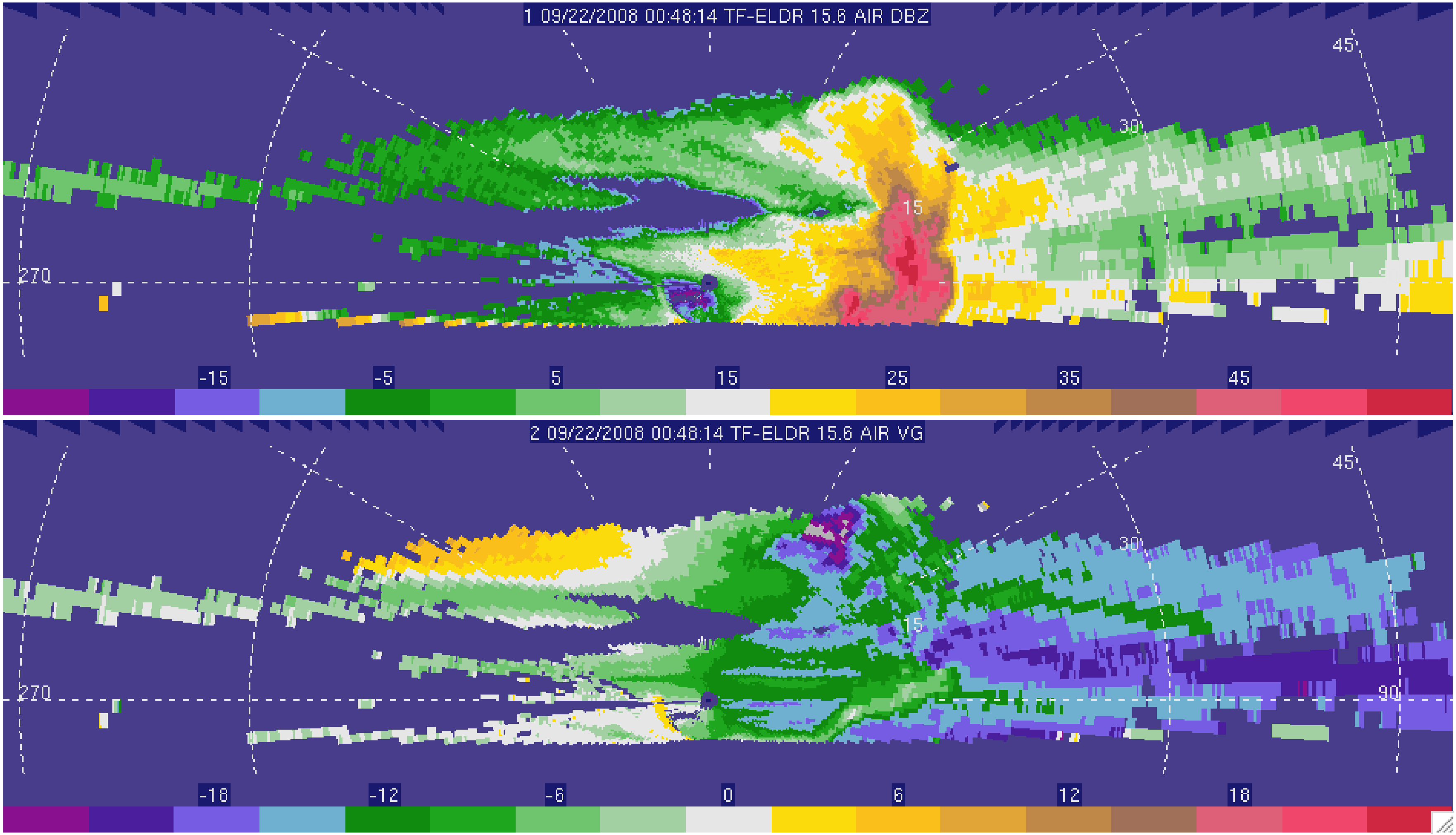
	Error Propagation	**Memory/CPU**	**Diagnostics**	**Multiple Data Sources**	**Anisotropic Filtering**	**Extra Balance Constraints**
Forward Local	Vertical	Low/Fast	Established	Difficult	Possible	Difficult
Forward Global	Horizontal & Vertical	High/Slow	Complex	Possible	Difficult	Possible
Reverse Global (Bell)	BG Error Covariance	Low/Slow	Moderate	Yes	Yes	Possible

Multiple analysis techniques are a good thing!

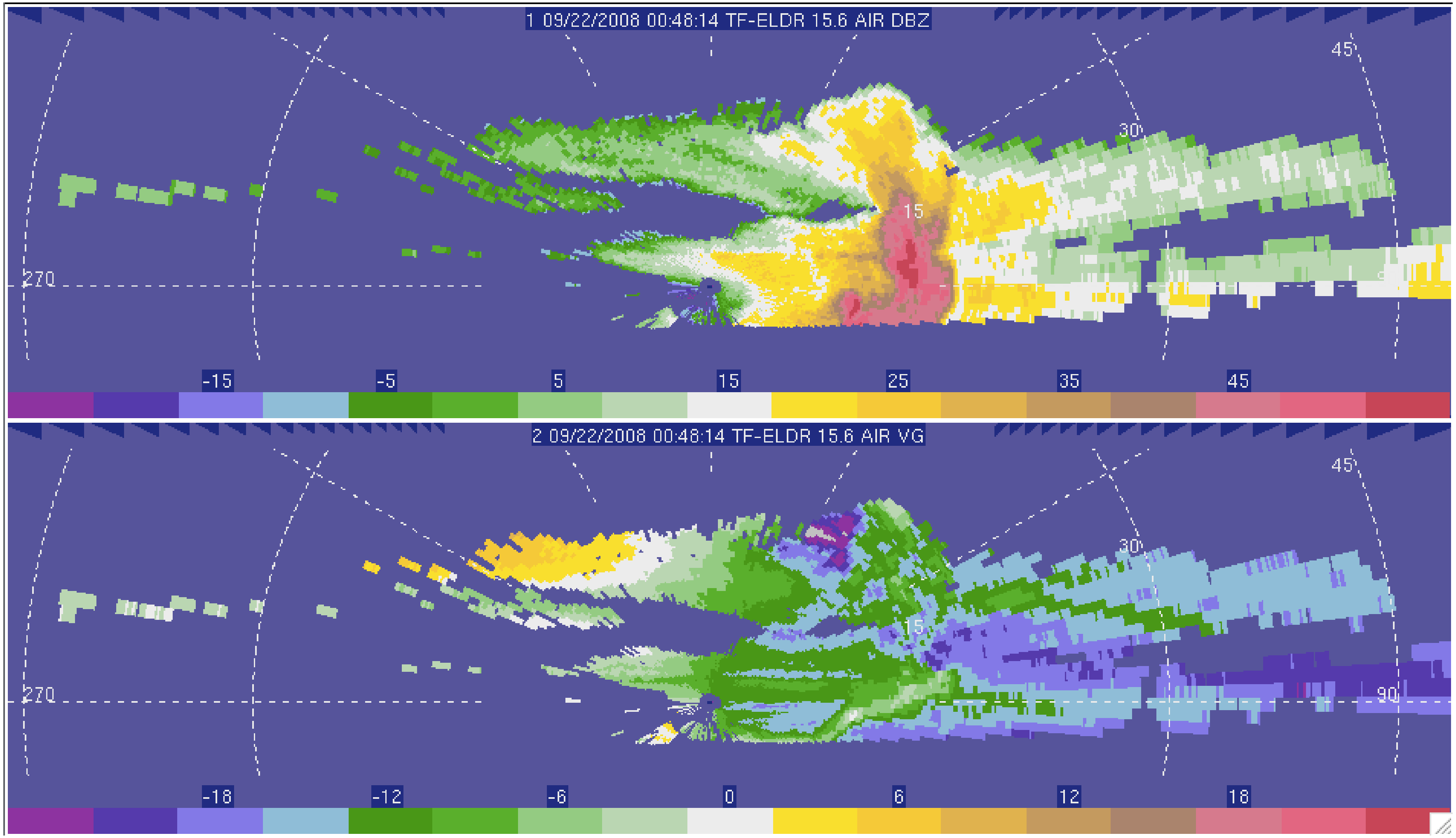
Automatic Editing for Data Assimilation and New Users

- Still work in progress
  - Fuzzy logic echo classification system under development
- Soloii scripts available now for light (80%) to heavy (99%) artifact removal
  - In between is most difficult

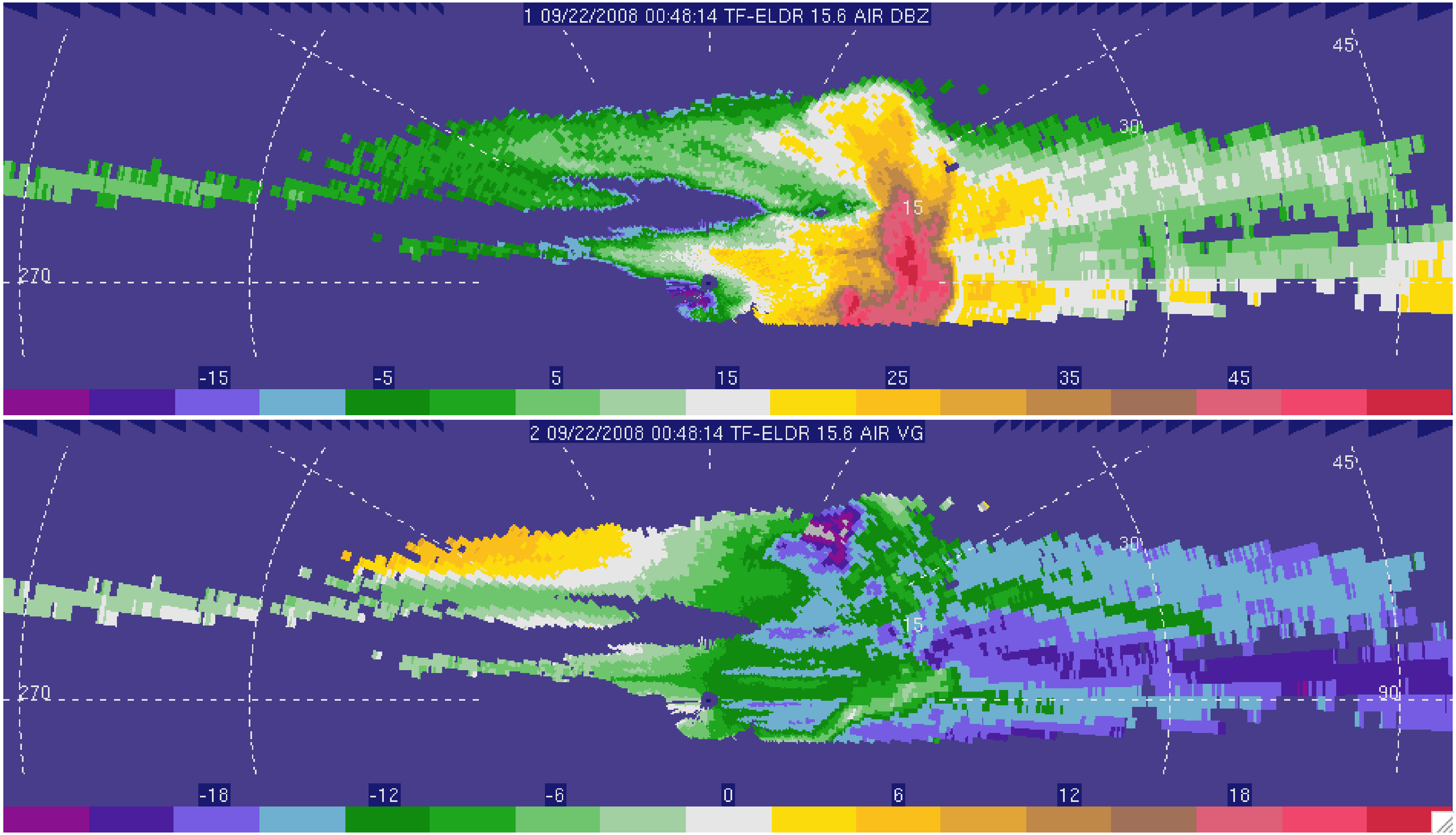
Automatically Edited (80%)



Automatically Edited (99%)



Manually Edited Data



Summary

- Data quality is good with exception of aft reflectivity later in project.
- Radar data is ready, on CODIAC soon
  - CAPPI movies will be available soon also
- A variety of software tools are available for viewing, editing, and processing
- New users welcome! Come talk to us about how you could use ELDORA data