Single-Doppler Velocity Retrieval

presented by

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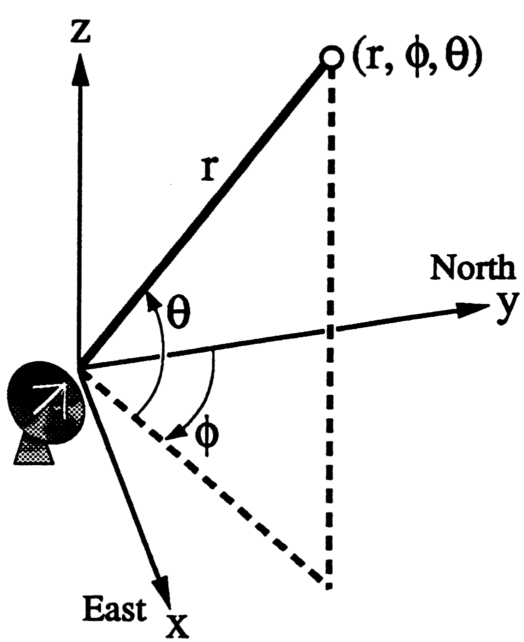
Outline of Presentation

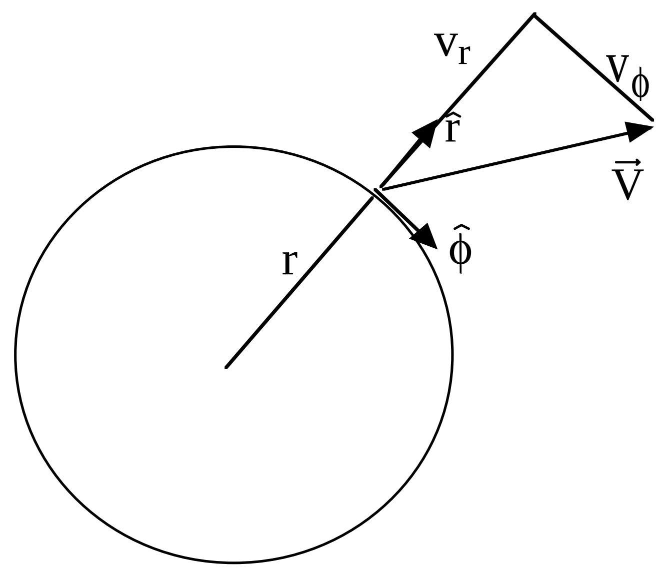
1. Problem statement
2. Constraints in wind retrieval
3. Milestones in wind retrieval:
   - Synthetic dual-Doppler analysis
   - Linear spatial model: VAD and its extensions
   - Tracking Radar Echoes by Correlation (TREC)
   - Moving reference frames (a building block)
   - Adjoint methodology
4. Summary/future work

Single-Doppler Velocity Retrieval (SDVR)

Dual-Doppler radar coverage is generally limited.

Single-Doppler velocity retrievals (SDVR) estimate cross-beam wind information from single-Doppler data and other constraints.





Potential Applications of SDVR

* Nowcasting/hazard warning (e.g., detecting and predicting motion of microbursts, colliding boundaries, mesocyclones).

* Guidance for aviation operations, field experiments, agricultural interests, fire-fighting, emergency managers, etc.

* Numerical Weather Prediction (NWP) model initialization/data assimilation (including thermodynamic and microphysical retrievals).

* Diagnostic studies.

Strong Versus Weak Formulations

Data and dynamical constraints can be incorporated in analysis and retrieval systems as **strong** or **weak** constraints.

Strong constraint: constraint is imposed exactly. Use it when you really trust it. Since the retrieval will enforce it, the retrieved fields may be contorted if the constraint is inappropriate.

Weak constraint: constraint is imposed approximately, i.e., in a least-squares error sense. Use it if you don't completely trust it. Must quantify the uncertainty by specifying weighting factors.

Notes on "Strong Versus Weak Formulations" slide

The basic formalisms of strong and weak constraints are discussed in a series of papers by Sasaki (1970a,b,c). Wahba and Wendelberger (1980) discuss extensions, including splines and smoothness constraints.

Constraints in SDVR

Data constraints

Set analyzed fields equal to (or nearly equal to) observed data.

Dynamical constraints

Prognostic equations such as radial wind conservation, reflectivity conservation, or full equations of motion.

Mass conservation

Incompressibility condition ($\nabla \cdot \vec{V} = 0$) or anelastic mass conservation equation ($\nabla \cdot \rho_0 \vec{V} = 0$)

Background constraint

Background obtained from NWP model, larger-scale analysis, linear wind model, or retrieval at previous time level.

Spatial constraints

Explicit low-order spatial model: linear wind model (VAD), vortex model (GBVTD), spectral or spline representation.

Weak smoothness constraints: horizontal non-divergence, zero vertical vorticity, gradient or second derivative constraints.

Temporal constraints

Temporal model: velocity stationarity, Taylor frozen turbulence (stationarity in a moving reference frame), linear variation.

Retrieved field at previous time used as background field at current time or as first guess to start minimization procedure.

Boundary Conditions (B.C.)

Lateral b.c. from larger-scale analysis.
Impermeability b.c. at ground level.

Notes on Constraints in SDVR slides

- If other wind data are available (e.g., from soundings, tower, etc), one can constrain retrieval to agree with them as well, through a weak constraint.

- Incompressibility condition or anelastic mass conservation can be used in 3D retrievals to simultaneously retrieve u, v, w. Can be used in 2D retrievals to get w from u, v.

- Vortex models include Velocity Track Display (VTD; Lee et al. 1994), Extended VTD (EVTD; Roux & Marks 1996), Ground-Based VTD (GBVTD; Lee et al. 1999)

- For an example of spectral representation in SDVR, see Xu & Qiu 1994. For an example of spline representation in SDVR see Xu et al. 2001b.

- For an example of a temporal constraint in which velocity field varies linearly with t, see Xu et al. 2001b. [Numerous examples of velocity stationarity given later in talk]

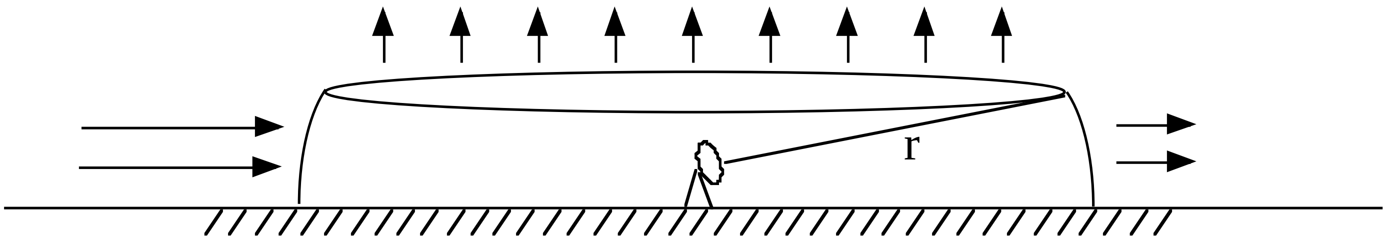
- If data extend down to ground (or are extrapolated down to ground), can impose the impermeability condition (lower b.c.):

$$w = u \, \partial(\text{terrain height})/\partial x + v \, \partial(\text{terrain height})/\partial y.$$

If ground is flat, this latter equation becomes $w = 0$.

Simple Example: Retrieving Average w

Consider surface composed of: (i) ground (ii) strip of sphere of radius r centered on radar and (iii) circular area on top:



Assuming flow is incompressibile ($\nabla \cdot \vec{V} = 0$) and the ground impermeable, the Divergence Theorem yields average w through the top as:

$$\overline{w} = \frac{1}{\pi r^2 \cos^2\theta} \iint v_r \, r^2 \cos\theta \, d\theta \, d\phi$$

Notes on "Simple Example: Retrieving Average w" slide

- For an example of this method see Rabin and Zawadzki 1984.

- A similar method that uses anelastic mass conservation instead of the incompressibility condition is discussed in section 9.4 of Doviak and Zrnic 1984.

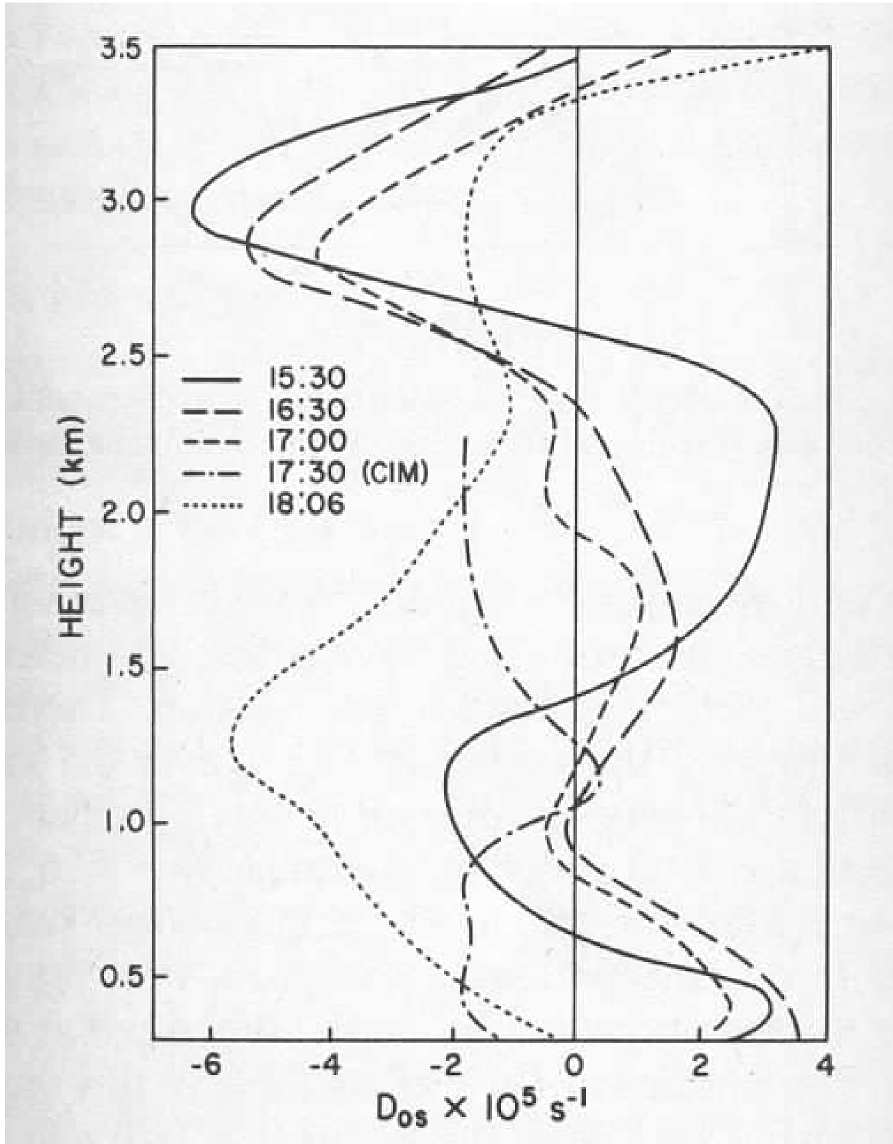
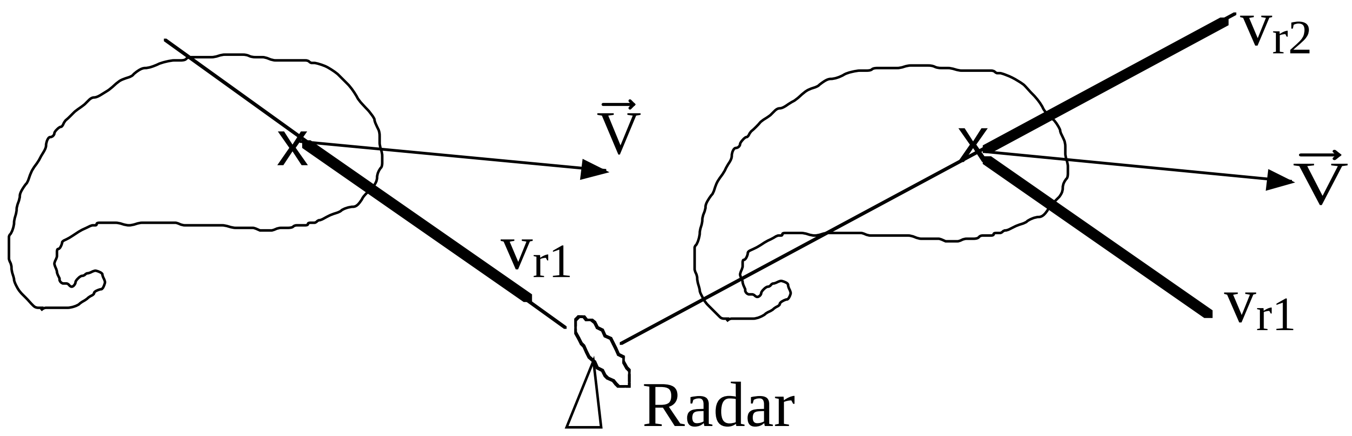


Fig. 8 from Rabin & Zawadzki 1984: Divergence versus height at 5 different times.

Notes on "Fig. 8 from Rabin & Zawadzki 1984" slide

The figure displays the horizontal divergence of the velocity field (its integral yields vertical velocity) over central Oklahoma as a function of height at 5 different times. At the earlier times the divergence is largely positive (indicating subsidence), but at the final time, the divergence below 2 km has become negative (indicating ascent). Severe thunderstorms developed within 2 hours of the final measurement.

Synthetic Dual-Doppler Analysis



From Taylor hypothesis, 1 radar observing a storm at 2 different times sees same features from 2 different look angles.

Equivalent to 2 radars seeing same feature at 1 time (dual-Doppler)

Notes on "Synthetic Dual-Doppler Analysis" slide

One of the earliest descriptions is in Peace et al. 1969. A notable application (hurricane) is in Bluestein & Hazen 1989. See also Klimowski & Marwitz 1992.

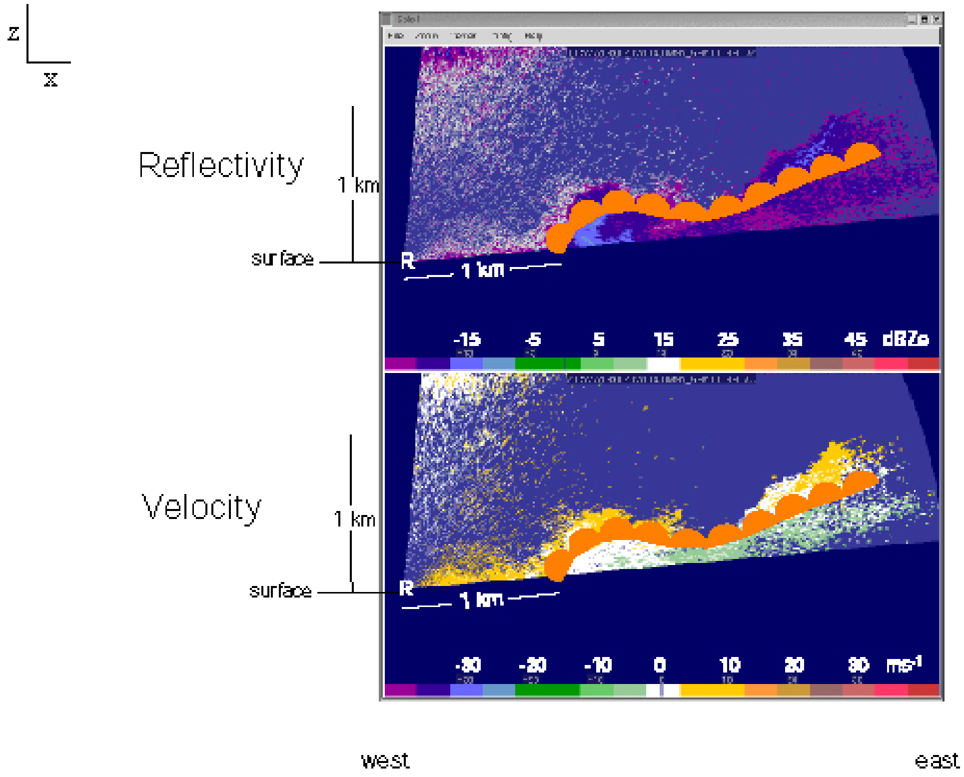
Airborne/Truckbed Synthetic Dual-Doppler Analysis

Problem: patterns must be (nearly) steady during the time it takes look angles of features to change appreciably. Trouble if pattern evolves quickly or translates slowly, especially at large r.

Solution: have radar move quickly! Put it on plane or truck. Look angles then change quickly over a short period of time.

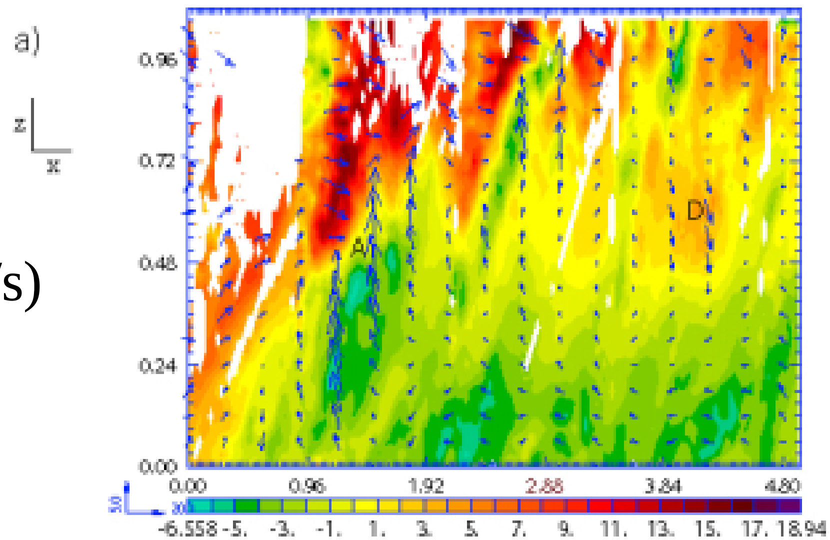
Example: truckbed-pseudo-dual-Doppler analysis of an IHOP dryline (Weiss et al., MWR, 2005).

Vertical cross-section through IHOP dryline (Weiss et al, MWR, 2005)

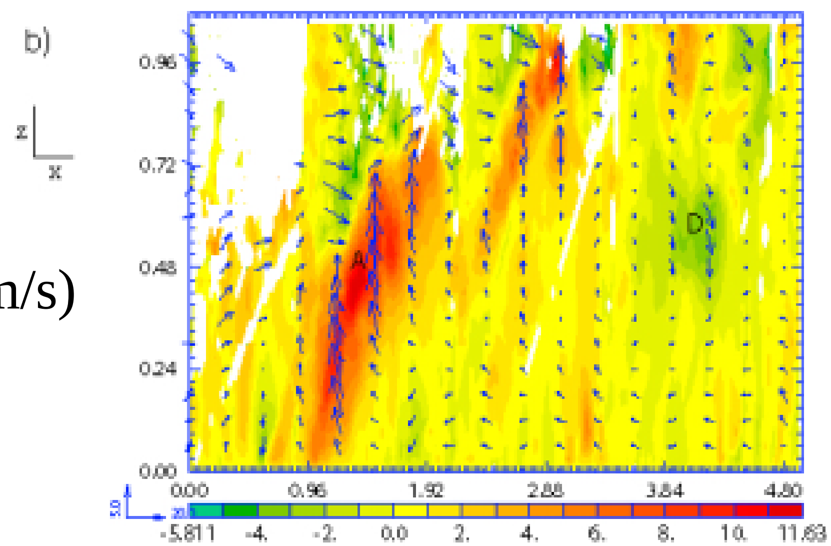


Vertical cross-section through IHOP dryline (Weiss et al, MWR, 2005)

Vertical cross section of u (m/s)



Vertical cross section of w (m/s)



Linear Spatial Models

Assume wind varies linearly with x, y, z:

$$u(x,y,z) = u_0 + u_x\,(x - x_0) + u_y\,(y - y_0) + u_z\,(z - z_0),$$

$$v(x,y,z) = v_0 + v_x\,(x - x_0) + v_y\,(y - y_0) + v_z\,(z - z_0).$$

Get u_0, u_x, etc from regression analysis -- fit model to v_r data:

- on edge of circle in Velocity Azimuth Display (VAD),
- in sector of fixed θ in Velocity Area Display (VARD),
- in volume in Volume Velocity Processing (VVP).

Good features of linear spatial models

- Conceptually simple
- Well-explored error sensitivity
- Relatively easy to code up.
- Small computational overhead.

Not good features

- Relatively coarse resolution.
- Large biases when linear wind model is violated.
- Vertical vorticity cannot be recovered.

Attempts have been made to circumvent these limitations by:

- Constructing nonlinear VADs
- Using additional constraints to get vorticity

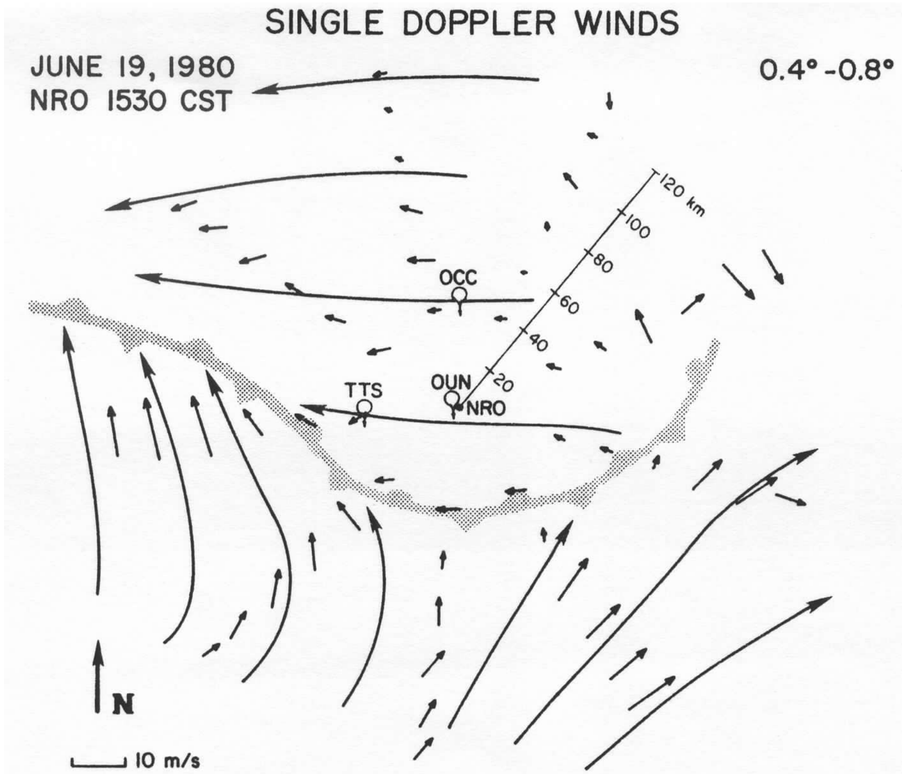


Figure 5. Wind pattern as estimated with a single Doppler radar. Length of arrows are scaled to wind speed.

VVP analysis of stationary front/convergence zone prior to deep convection (Doviak et al. 1981)

Notes on Linear Wind Model slides

- Key papers in the development of Velocity Azimuth Display (VAD) and its extensions are by Probert-Jones 1960; Lhermitte & Atlas 1961; Caton 1963; Browning & Wexler 1968; Easterbrook 1975; Waldteufel & Corbin 1979; Koscielny et al. 1982.

- Sensitivity of VAD/VVP winds to observational errors has been studied by Boccippio 1995, and Koscielny et al. 1982.

- Nonlinear VAD constructed by Caya & Zawadzki 1992.

- Caya et al. 2002 retrieved vorticity in a VAD framework by imposing the additional constraints of velocity stationarity and mass conservation.

Tracking Radar Echoes by Correlation (TREC)

Winds obtained by tracking small-scale reflectivity blobs on PPIs.

Reflectivity conservation is an implicit constraint.

Z field should have trackable features, and echo motion should represent air motion. Possible trouble:

- Z field flat or linear
- sedimentation/fallout of scatterers in vertical shear
- strong vertical motions
- growth/decay of precip
- ground clutter contamination

TREC has been successfully applied to winds in optically clear boundary layer and in hurricanes.

Notes on "Tracking Radar Echoes by Correlation (TREC)" slide

- Original algorithm described in Rinehart & Garvey (1978) and Rinehart (1979). Refined by Tuttle & Foote (1990), and extended for hurricane wind retrieval by Tuttle & Gall (1999).

- Smythe & Zrnic (1983) applied a TREC-like technique to radial velocity data.

- Strong vertical shear is known to cause difficulties for TREC (e.g., convective storms in the Great Plains). The success of TREC in hurricanes may be due, in part, to the fact that the large shear in the near-surface boundary layer is often beneath the lower beam of ground-based (coastal) radars. Above this boundary layer, the shear is relatively weak.

How TREC Works

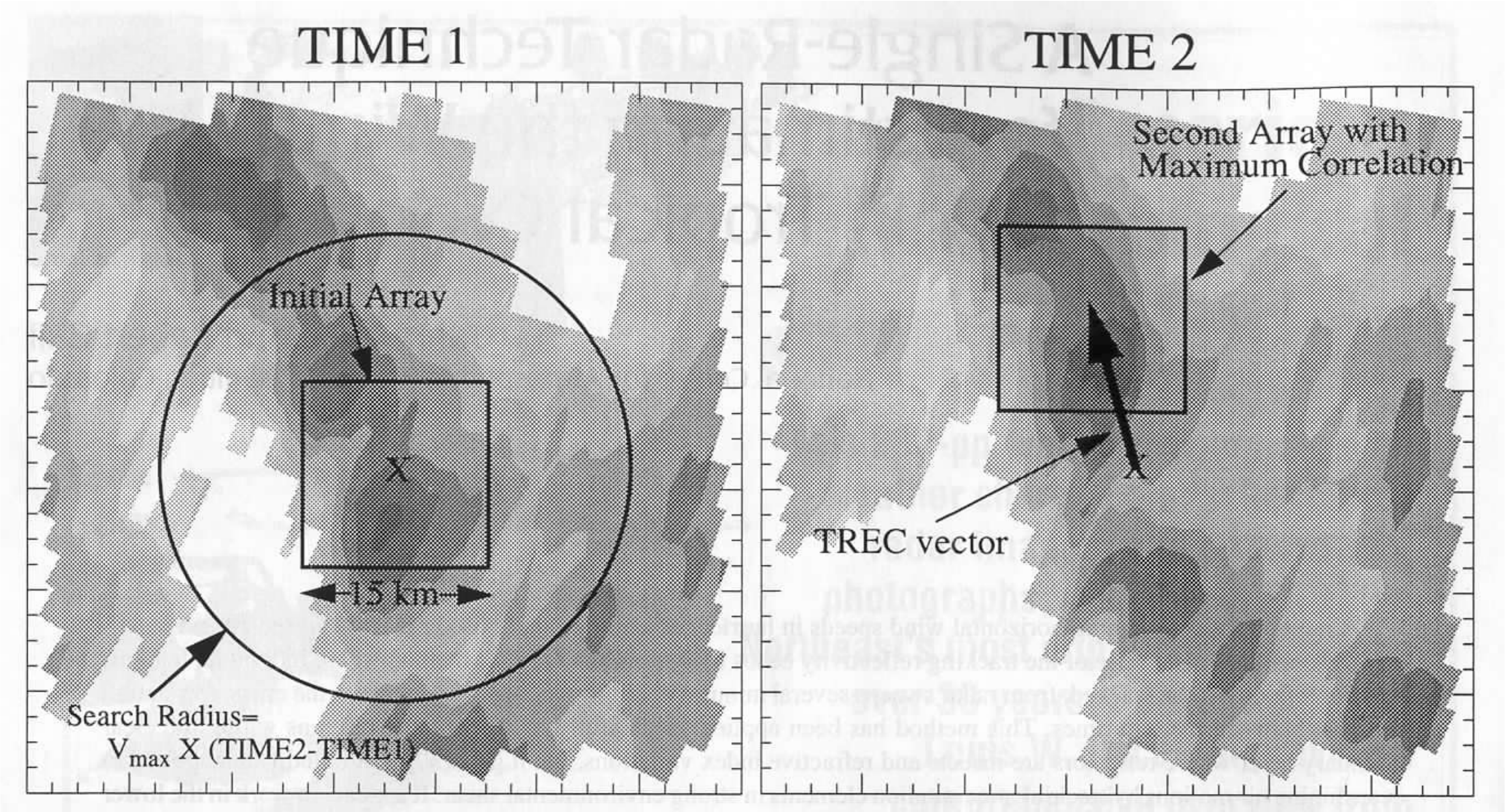


Fig. 1 from Tuttle & Gall 1999

Notes on "How TREC Works" slide

Here's a brief summary of the algorithm:

1. Take two PPI scans of reflectivity at same elevation angle measured a few minutes apart.

2. Divide the PPI at the first time level into a collection of equal-sized analysis sub-domains (boxes).

3. For each box at the 1st time level, find the box at the 2nd time level that it is most similar to (in terms of reflectivity pattern). Do this by identifying, from all possible 2nd time level boxes, the box that is the most highly correlated with the 1st box.

4. Calculate the velocity by dividing vector distance between a 1st time level box and its highest-correlated 2nd time level box by the time between the two time levels.

Danger! Ground Clutter!

TREC velocity vectors | Reflectivity field + tiny blob of artificial ground clutter

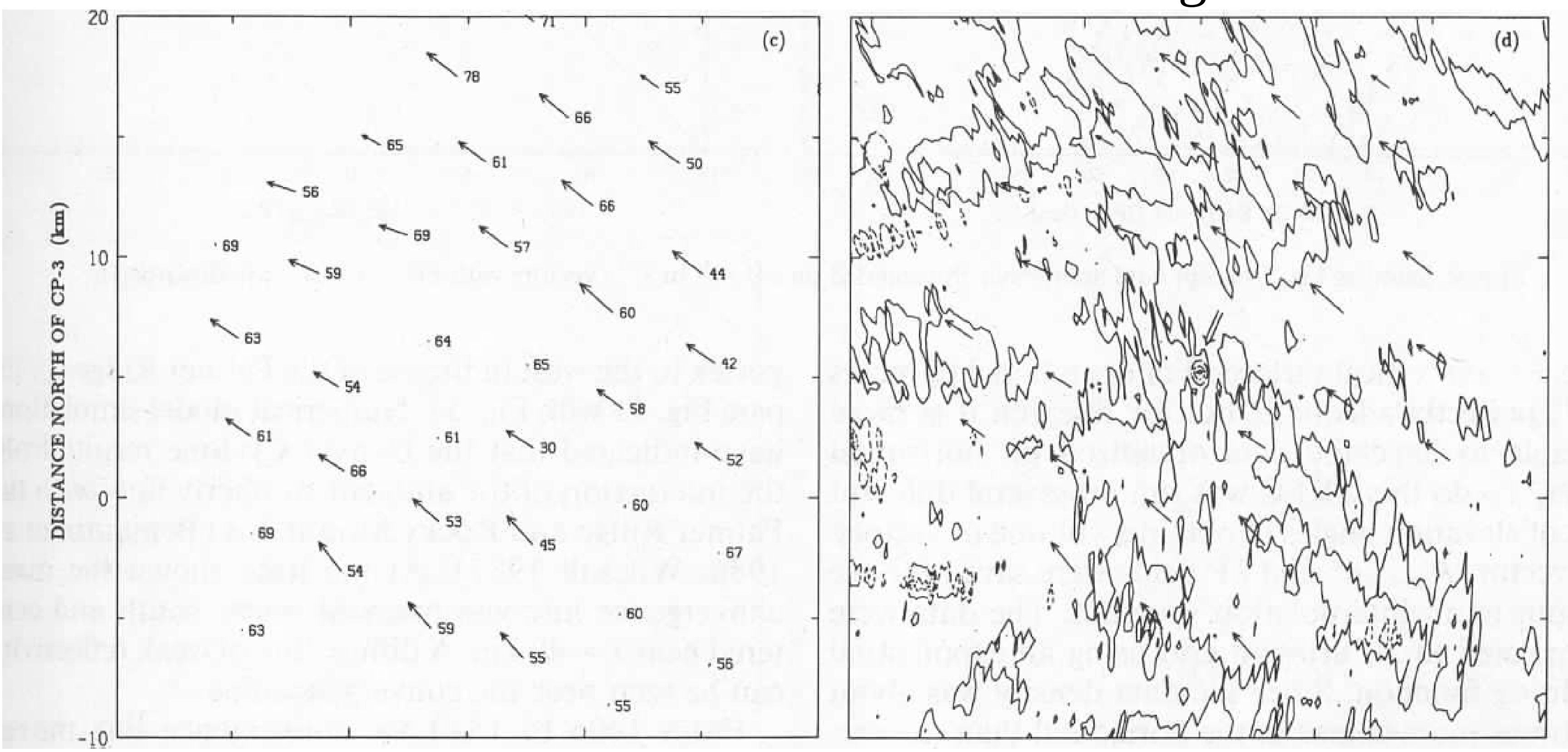


Fig. 8c,d from Tuttle & Foote 1990

Notes on "Danger! Ground Clutter!" slide

Fig. 8c,d illustrates the deleterious effect of ground clutter. A tiny blob of ground clutter has been added to the reflectivity data (small open arrow near middle of right panel points to the blob). The resulting TREC winds have a spurious "lull" in the vicinity of the blob (3 zero-magnitude wind vectors in middle of left panel).

TREC Hurricane Winds Versus Aircraft Observations

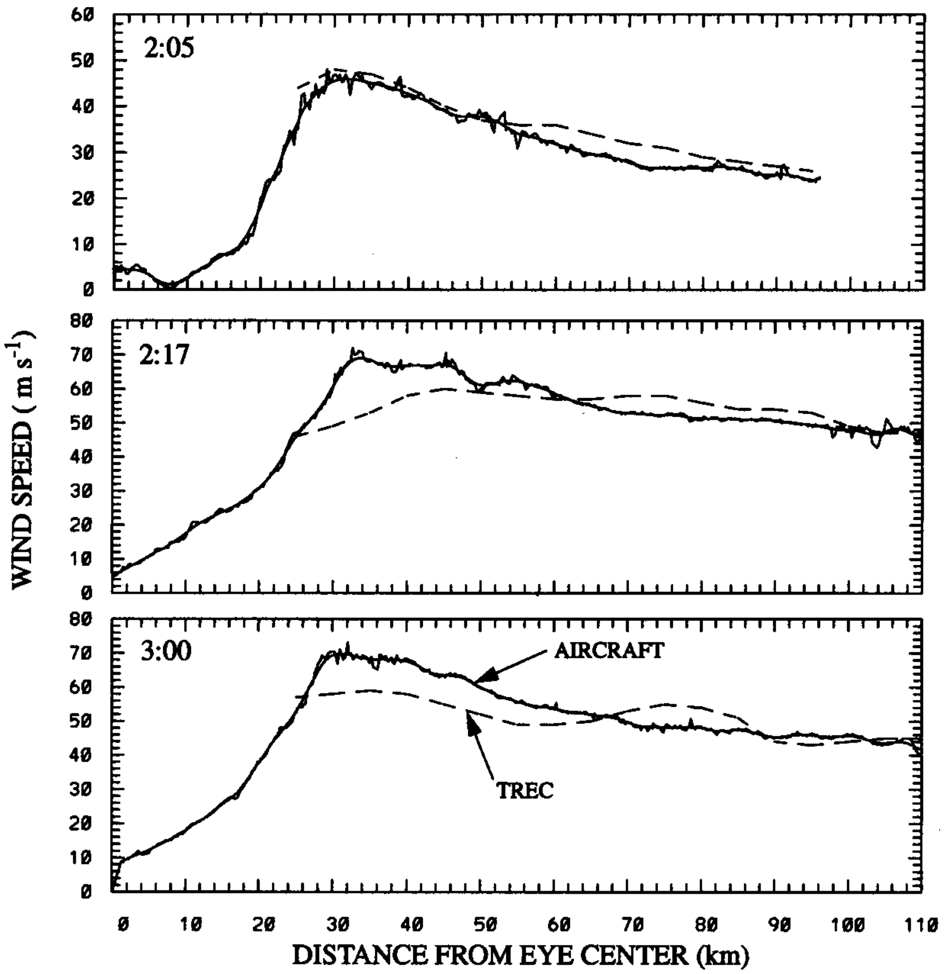


Fig. 5 from Tuttle & Gall 1999

Isotach Analysis of Hurricane Hugo

TREC Isotach Analysis

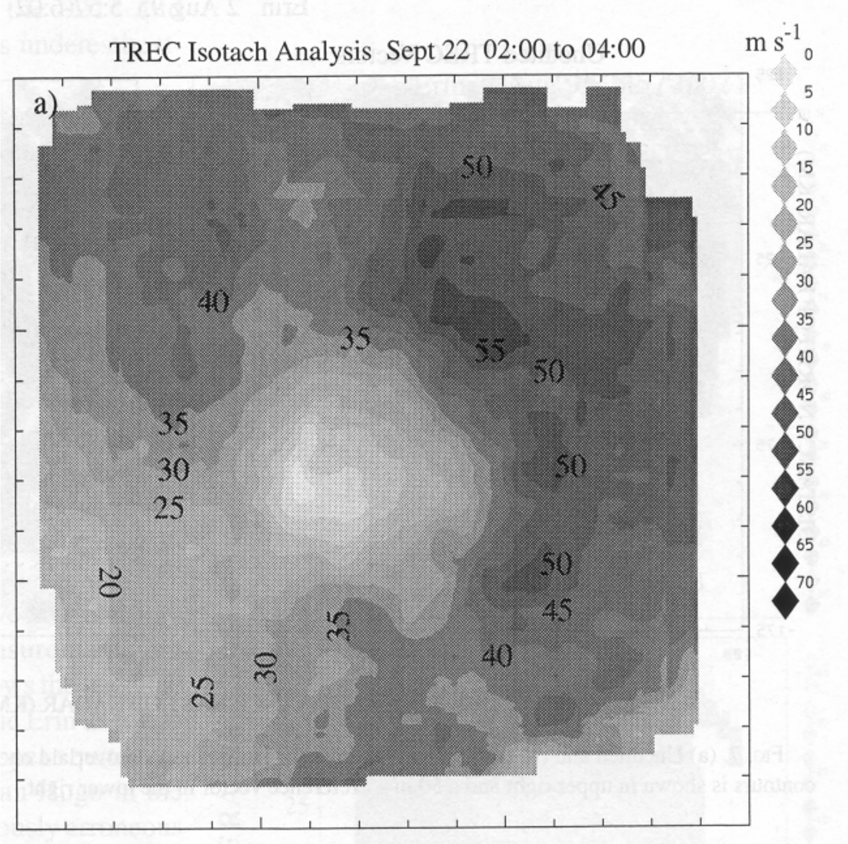
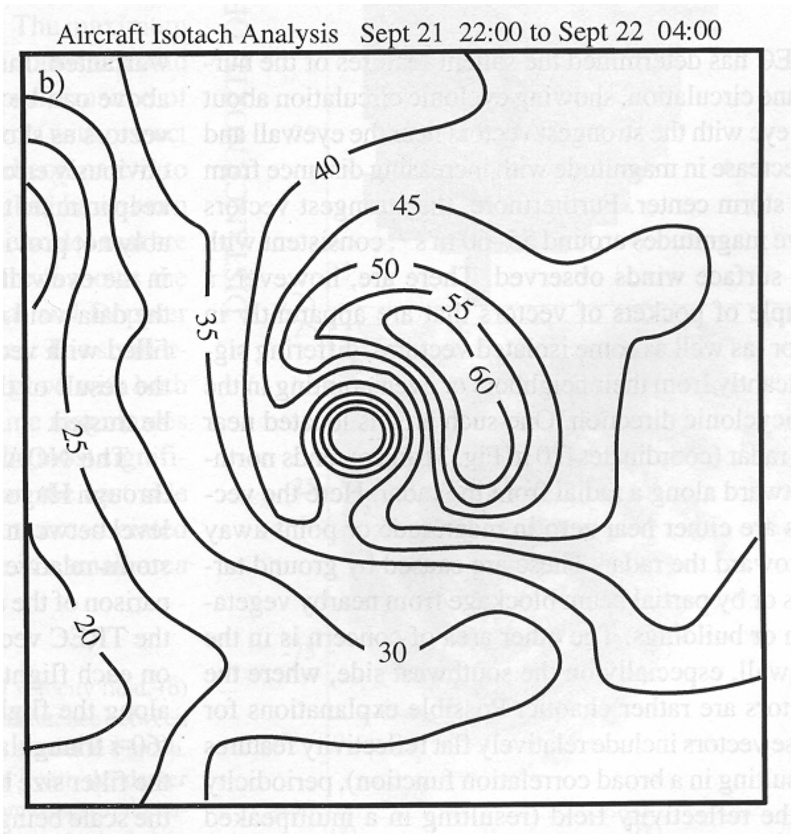
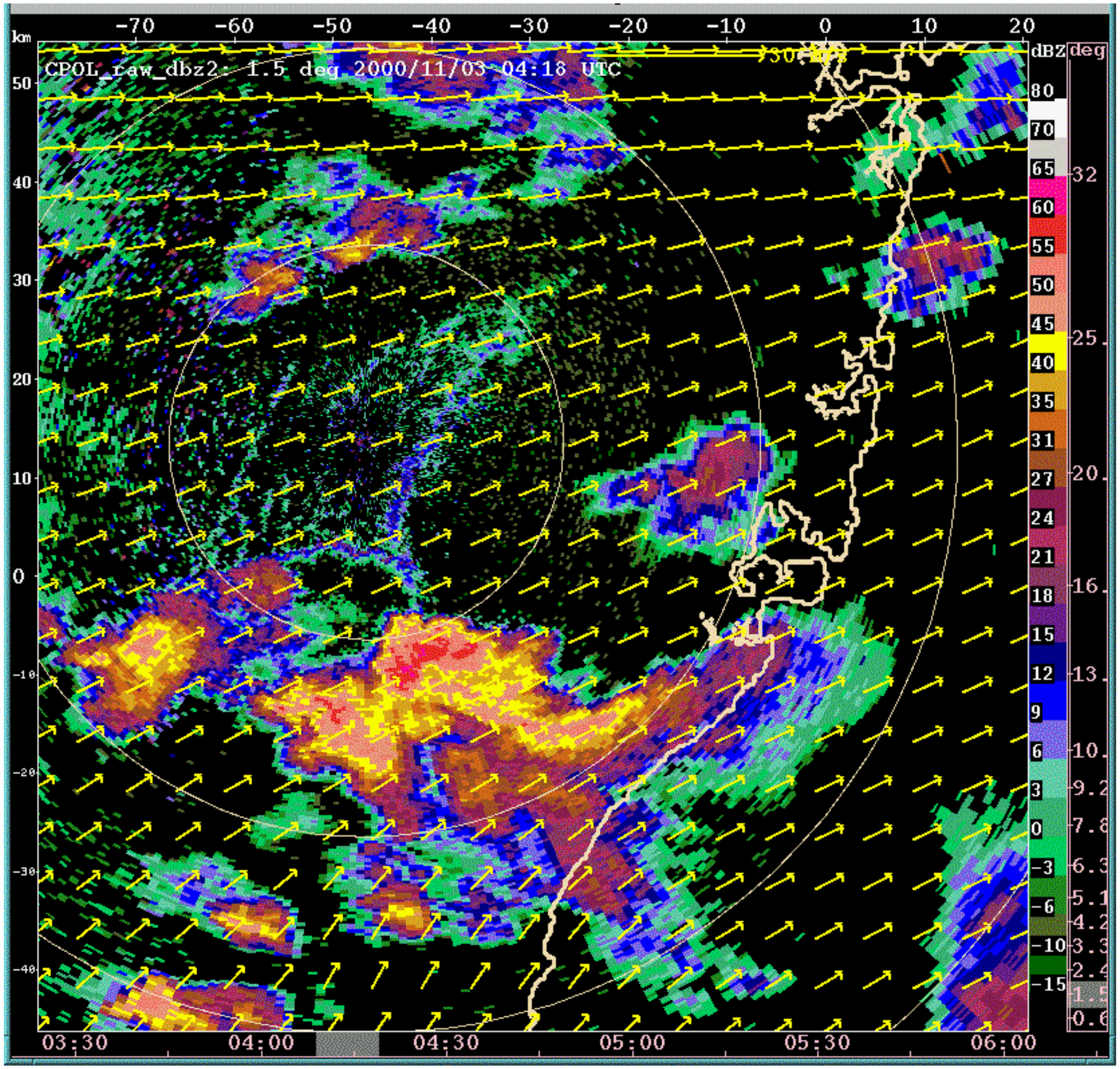


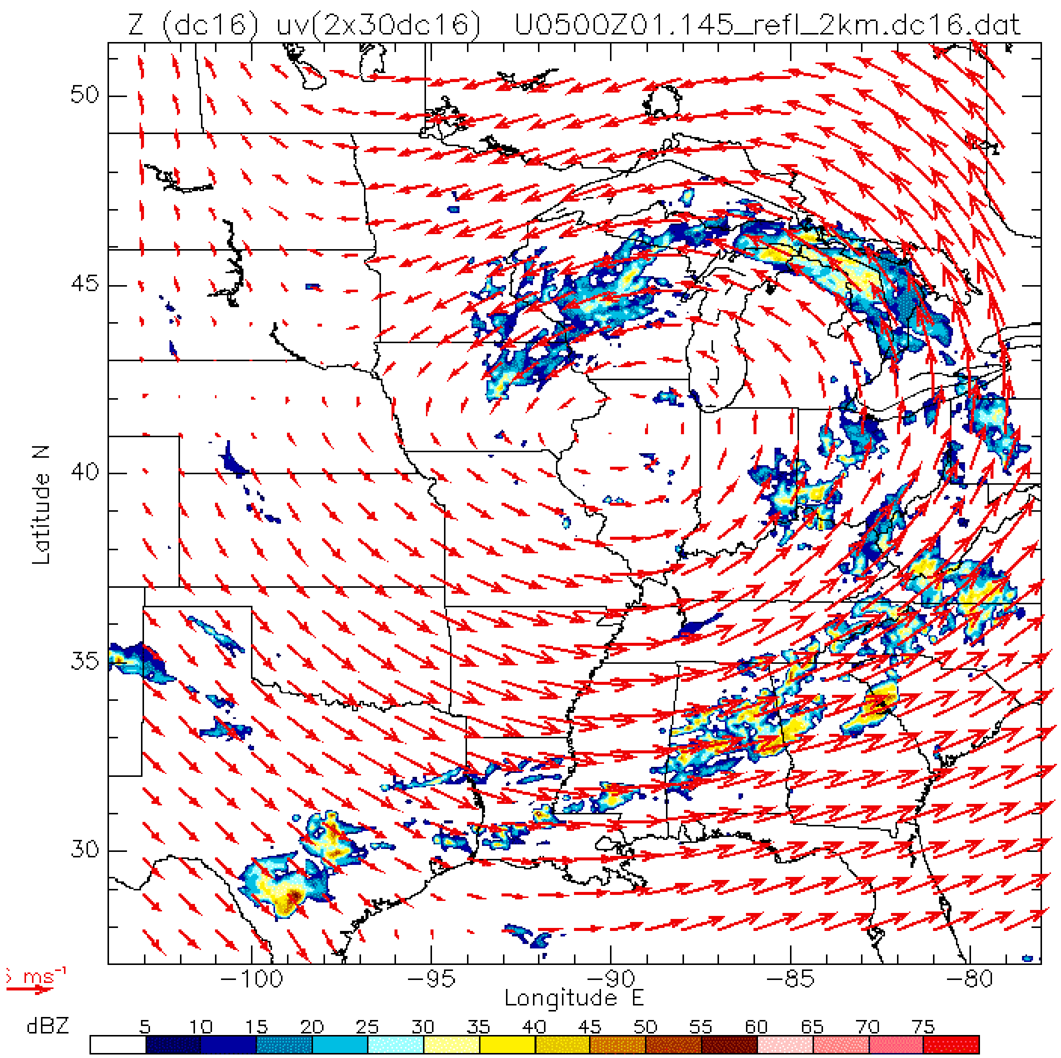
Fig. 6 from Tuttle & Gall 1999

Aircraft Isotach Analysis





TREC vectors from Sydney 2000 Forecast Demonstration Project (NCAR)



An application of Variational Echo Tracking (VET), Germann & Zawadzki MWR 2002

Note on the Germann & Zawadzki figure slide

- The wind vectors are obtained from the Variational Echo Tracking (VET) technique. VET is not exactly TREC, but it's pretty close in spirit. The VET technique and its relation to TREC is discussed in Laroche & Zawadzki (1995).

Weak-Constraint Reflectivity-Conservation Based Retrievals

Many retrieval techniques use reflectivity conservation (2D/3D) as a weak constraint with precipitation fallout as the only source term:

$$\frac{\partial Z}{\partial t} + u\frac{\partial Z}{\partial x} + v\frac{\partial Z}{\partial y} + (w + w_t)\frac{\partial Z}{\partial z} = 0$$

Most of these methods assume a temporal constraint: velocity stationary or Taylor's frozen turbulence hypothesis (velocity stationarity in moving reference frame). In the latter case, must estimate the U, V components of moving reference frame!

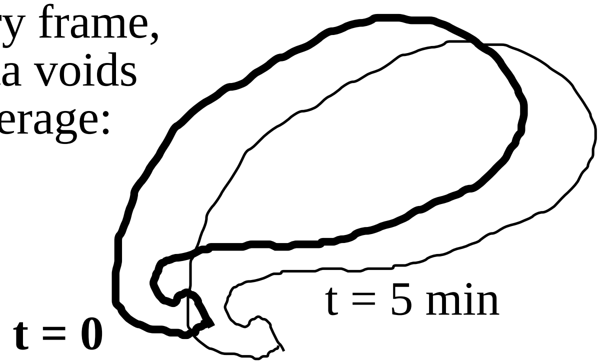
Let's digress and discuss moving reference frames.

Notes on "Weak-constraint reflectivity-conservation based retrievals" slide

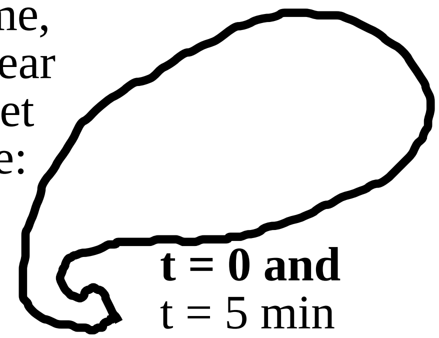
- 2D or 3D weak-constraint reflectivity conservation has been imposed in the retrievals of Laroche & Zawadzki (1994, 1995), Shapiro et al. (1995), Zhang & Gal-Chen (1996), Liou (1999), Liou & Luo (1999), Lazarus et al. (2001), and Weygandt et al. (2002).

Moving Reference Frames

In stationary frame,
moving data voids
reduce coverage:



In moving frame,
data voids appear
stationary so get
better coverage:



Why are moving reference frames useful in wind retrieval?

- Some retrievals assume stationarity (in moving reference frame)
- Minimize discretization errors in temporal derivative terms
- Maximize data coverage
- Moving frame may already contain most of the velocity vector (if reference frame motion is close to mean wind).

Z-based Moving Reference Frame (Gal-Chen 1982)

Find reference frame in which Z is most stationary ($\partial Z/\partial t' = 0$).

Equivalent to finding pattern-translation components U, V such that $DZ/Dt = 0$ where $D/Dt = \partial/\partial t + U\,\partial/\partial x + V\,\partial/\partial y$. Introduce

$$J(U, V) \equiv \iiiint \left(\frac{\partial Z}{\partial t} + U \frac{\partial Z}{\partial x} + V \frac{\partial Z}{\partial y} \right)^2 dx\,dy\,dz\,dt$$

Obtain U, V as solution of least-square error: set $\partial J/\partial U = 0$ and $\partial J/\partial V = 0$, and solve the resulting 2 linear equations for U, V.

v_r-Based Moving Reference Frame (Gal-Chen 1982)

Find reference frame in which u, v are most stationary. Equivalent to finding pattern-translation comps U, V such that

$$Du/Dt = 0 \quad \text{and} \quad Dv/Dt = 0. \tag{1}$$

It can be shown that (1) leads to

$$\frac{D^2}{Dt^2}(r\, v_r) = 0. \tag{2}$$

Expand (2) out as $A + 2UB + 2VC + U^2D + V^2E + 2UVF = 0$, where A - F involve space and time derivatives of v_r. Seek U, V as solution of least squares error.

Notes on "v_r-Based Moving Reference Frame (Gal-Chen 1982)" slide

- For a detailed derivation of this technique see Gal-Chen (1982) or Shapiro et al. (1995).

- Equation (2) is deceptively simple. Since $D/Dt = \partial/\partial t + U\,\partial/\partial x + V\,\partial/\partial y$, the left hand side of (2) (second derivative) expands out to $A + 2UB + 2VC + U^2D + V^2E + 2UVF = 0$, a nonlinear equation for U, V with A - F being known coefficients (integrals of the space and time derivatives of v_r). A cost functional quantifying the error in that equation is

$$J(U, V) \equiv \iiiint \left(A + 2UB + 2VC + U^2D + V^2E + 2UVF\right)^2 dx\,dy\,dz\,dt$$

To obtain the solution of least-square error, set $\partial J/\partial U = 0$, $\partial J/\partial V = 0$, and solve the resulting 2 nonlinear equations for U, V (e.g., with Newton's method, steepest-descent or other minimization algorithm). Multiple solutions may be possible.

- In both Z- and v_r-estimated reference frames, errors in discretized local derivative terms may contaminate some of A - F. To mitigate this problem, one can iterate between data remapping and recalculations of J (and U, V).

- An improved v_r-based method is discussed by Matejka (2002)

Examples of Weak-Constraint Reflectivity-Based Retrievals

Zhang & Gal-Chen (1996), Lazarus et al. (1999, 2001) minimized:

$$J(u', v', w') \equiv \iiiint \alpha_1 \left[\frac{\partial Z}{\partial t'} + u' \frac{\partial Z}{\partial x'} + v' \frac{\partial Z}{\partial y'} + (w' + w_t) \frac{\partial Z}{\partial z'} \right]^2 +$$

$$\alpha_2 \left[v_r' - u' \frac{x' - x_0(t)}{r'} - v' \frac{y' - y_0(t)}{r'} - w' \frac{z' - z_0(t)}{r'} \right]^2 dx'dy'dz'dt'$$

where primed quantities are in Z-based moving reference frame, and x_0, y_0, z_0 are radar coordinates in this moving reference frame.

To minimize J, set $\partial J/\partial u' = 0$, $\partial J/\partial v' = 0$, $\partial J/\partial w' = 0$. Get 3 linear equations for u', v', w'.

Application: Microburst Wind Retrieval

"True" v_ϕ Retrieved v_ϕ:

Fixed Frame Moving Frame

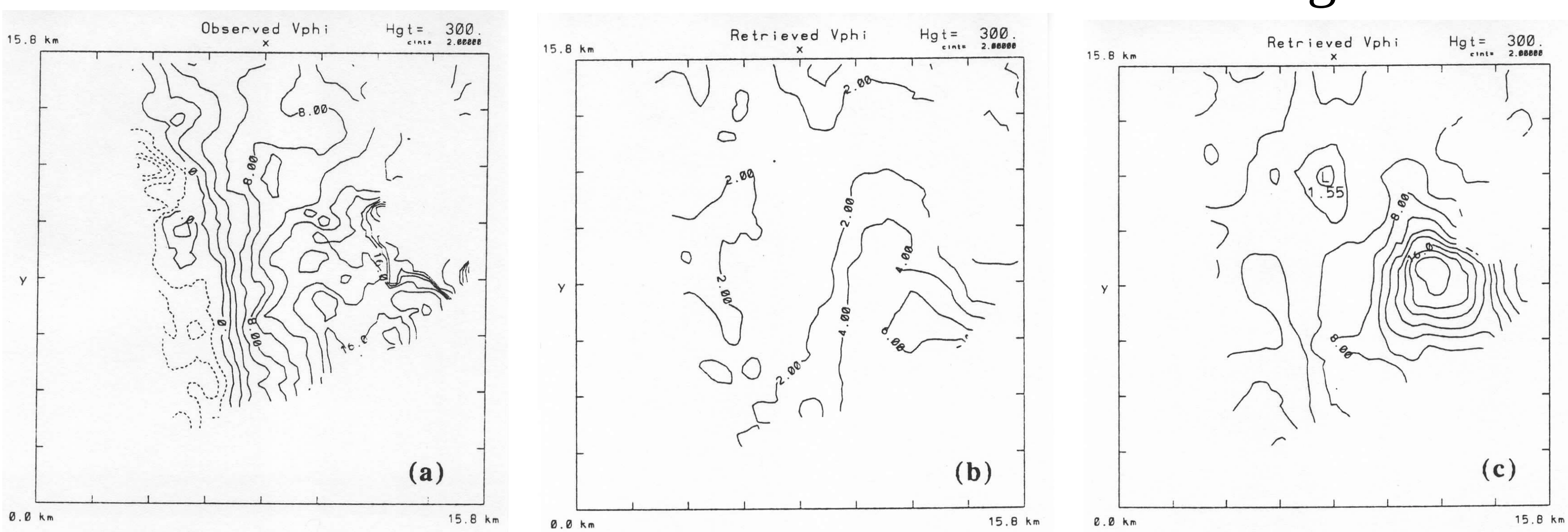


Fig. 8 from Lazarus et al. 2001

Notes on "Application: Microburst Wind Retrieval" slide

- This test case was of a multicell storm complex and microburst observed by three radars near the Orlando, Florida airport on 9 August 1991. Very high spatial resolution (200 m) multiple Doppler wind analyses were available for ground truth.

- The determination of a single "best" moving reference frame was problematic in this case because of relatively large wind shear.

- In Fig. 8, the fixed-frame retrieval yields cross-beam winds that are far too weak. In contrast, the peak cross-beam winds in the moving-frame retrieval are of nearly the same intensity (~ 18 m/s) as the "true" cross-beam winds.

Liou (1999) and Liou & Luo (2001) minimized:

$$J(u', v', w') \equiv \iiiint \alpha_1 \left[\frac{\partial Z}{\partial t'} + u' \frac{\partial Z}{\partial x'} + v' \frac{\partial Z}{\partial y'} + (w' + w_t) \frac{\partial Z}{\partial z'} \right]^2 +$$

$$\alpha_2 \left[v_r' - u' \frac{x' - x_0(t)}{r'} - v' \frac{y' - y_0(t)}{r'} - w' \frac{z' - z_0(t)}{r'} \right]^2 +$$

$$\boxed{\alpha_3 \left(\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} + \frac{\partial w'}{\partial z'} \right)^2 + \alpha_4 \left(\frac{\partial u'}{\partial x'} + \frac{\partial v'}{\partial y'} \right)^2} +$$

$$\boxed{\alpha_5 \left\| \nabla \times \vec{V}' \right\|^2 + \alpha_6 \left\| \nabla^2 \vec{V}' \right\|^2} \; dx' \, dy' \, dz' \, dt'$$

Use ∂J/∂u', ∂J/∂v', ∂J/∂w' to find minimum J.

Notes on the slide of a modified costfunction of Liou (1999) and Liou & Luo (2001)

- Compared to the Zhang/Gal-Chen/Lazarus formulation, the modified costfunction J includes 4 new terms accounting for: weak incompressibility, weak horizontal non-divergence, weak zero vorticity and smoothness.

- The modifications are found to significantly improve the accuracy of the retrieval.

- The location of minimum J (in parameter space) was obtained with a quasi-Newton conjugate-gradient iterative technique.

Application: TAMEX Squall Line

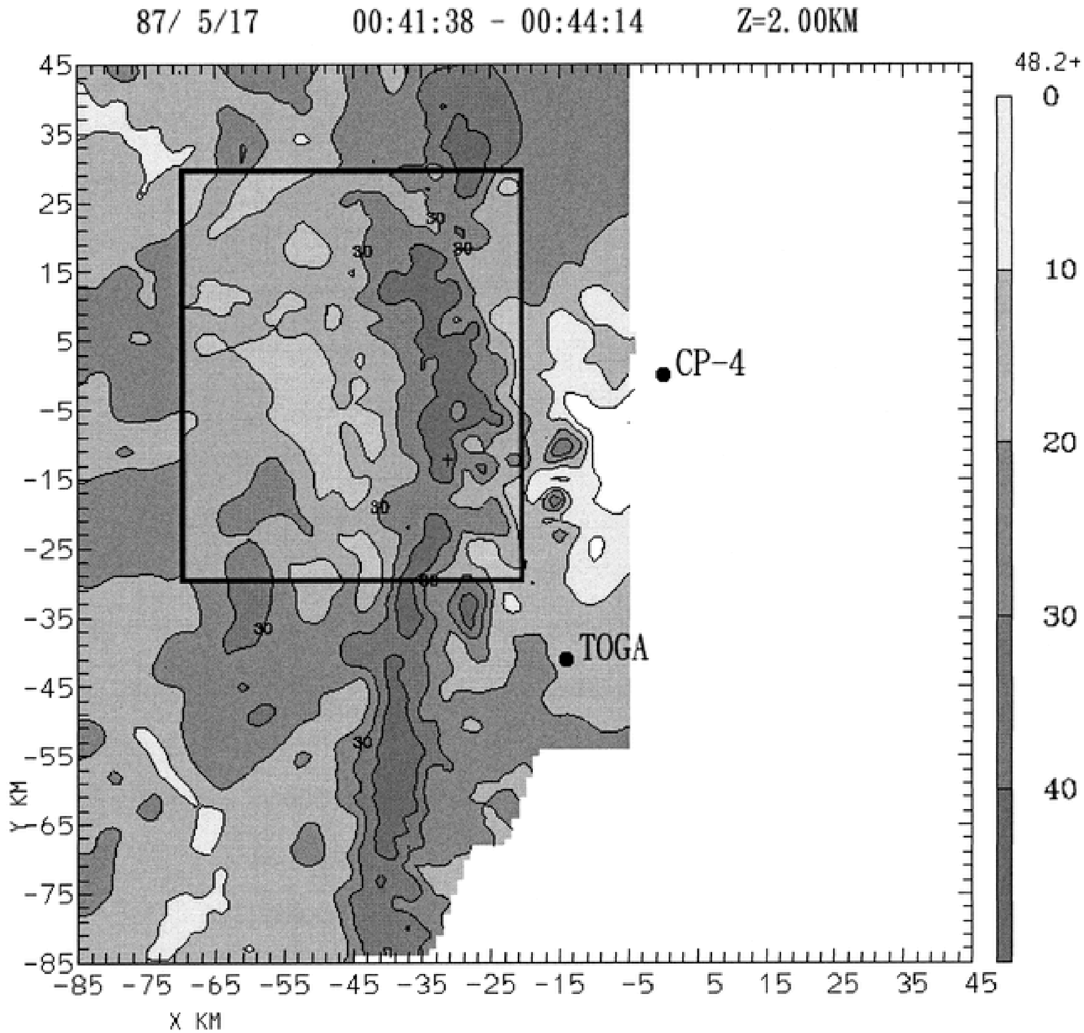
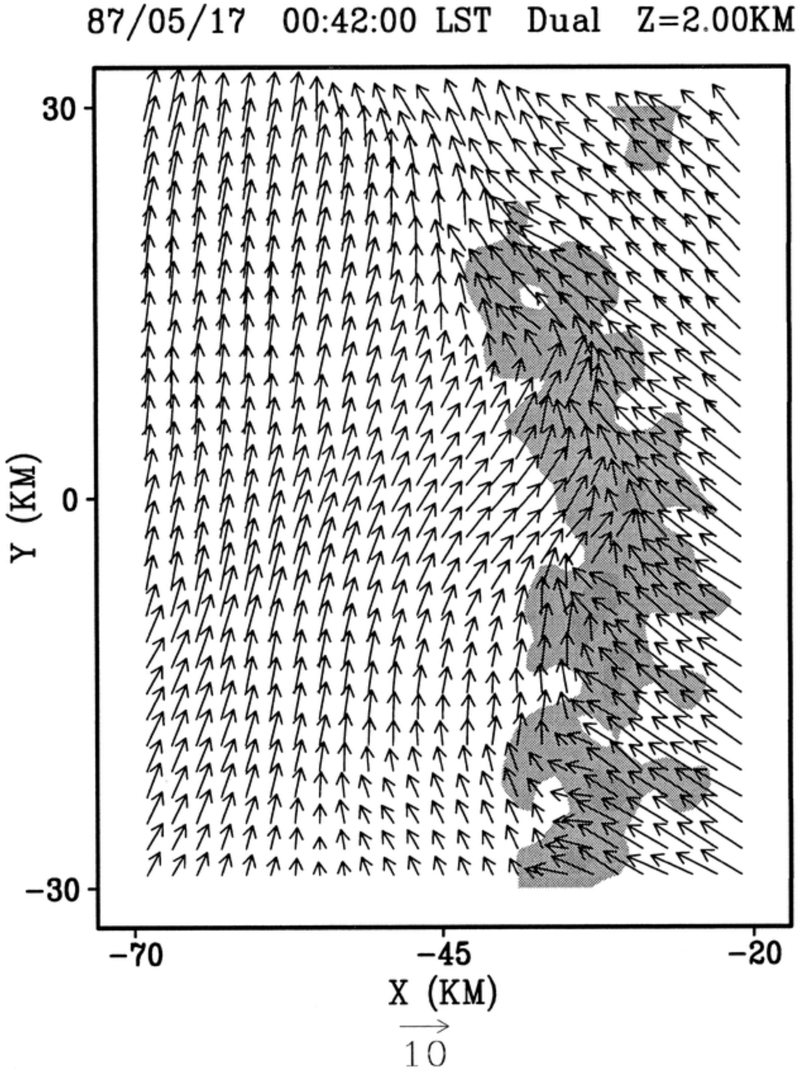
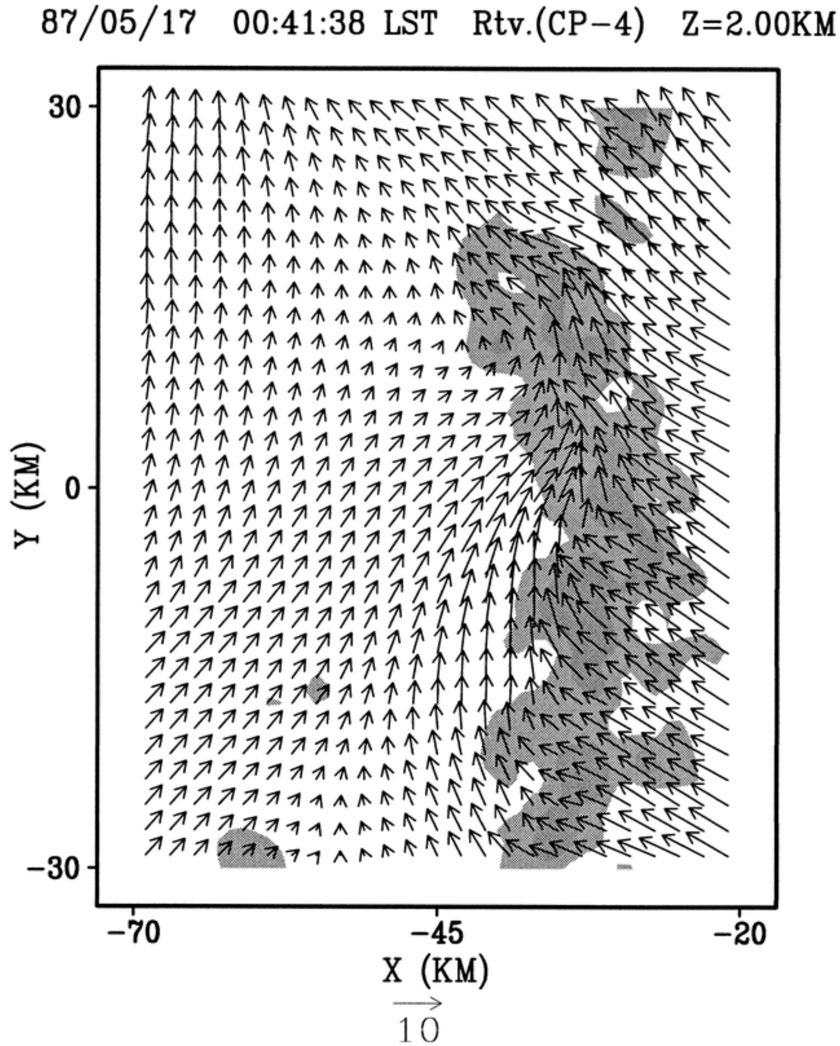


Fig. 1 from Liou & Luo, 2001

Storm-relative dual-Doppler winds

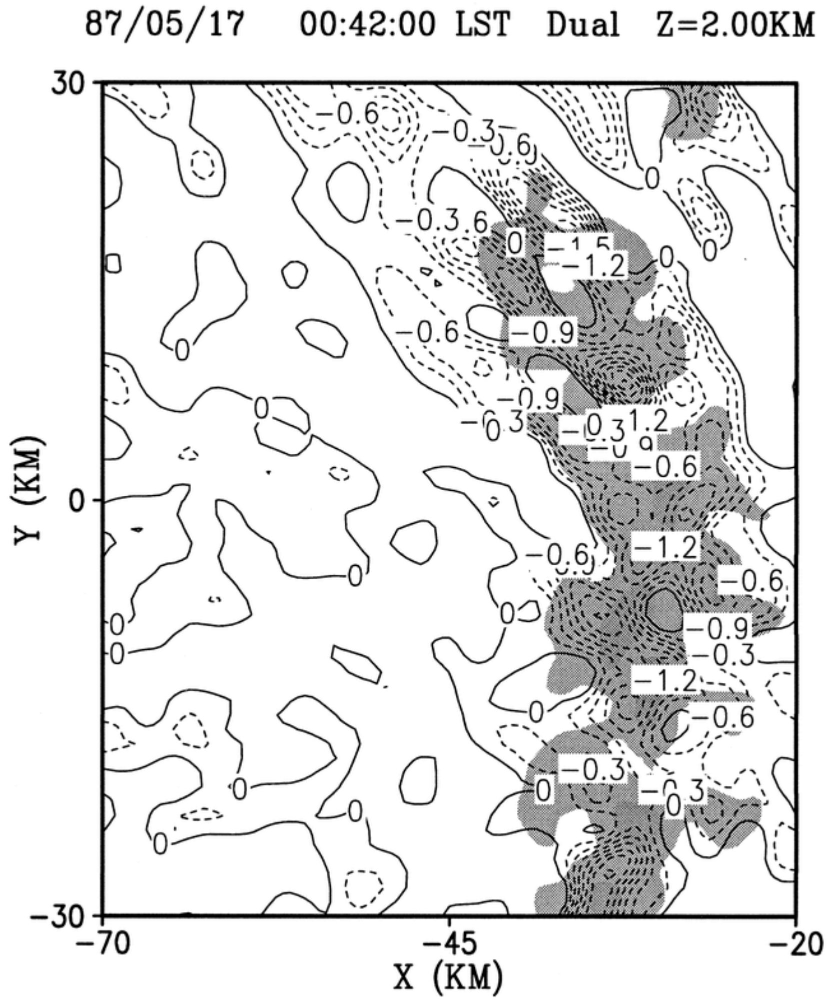


Storm-relative retrieved winds

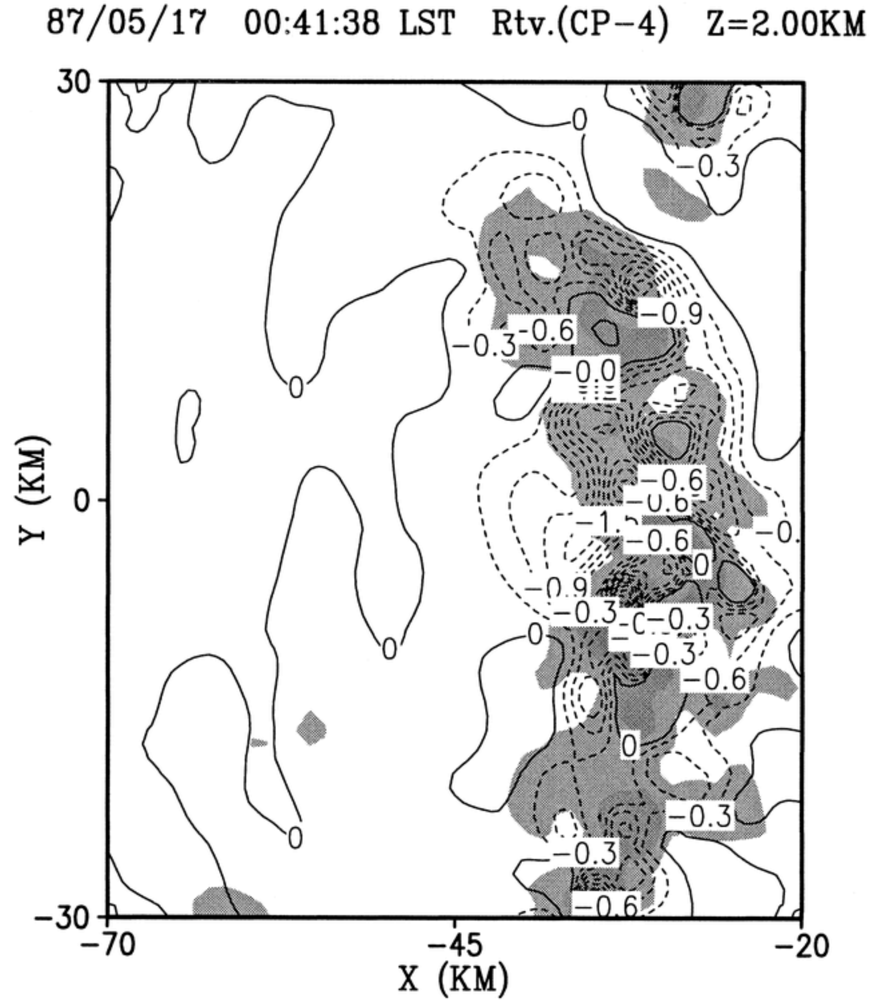


Figs. 3 and 6 from Liou & Luo, 2001

Dual-Doppler analysed horizontal divergence



Single-Doppler retrieved horizontal divergence



Figs. 4 and 7 from Liou & Luo, 2001

Problem: Weak Gradients

SDVRs based on conservation equations may run into trouble if the gradient of the tracer is weak. If retrieval is to work well, other aspects of the algorithm must "pick up the slack", for example:

- spatial, background, mass conservation, or smoothness constraints may help bridge the gap in area of weak gradient.

- temporal constraint or 4DVAR formulation may help bridge the gap by bringing in information from times when gap doesn't exist, or exists in a different location.

Full Model Adjoint Retrieval

Full adjoint applied to SDVR by Sun et al. 1991, Sun & Crook 1994, 2001. See Jenny Sun's presentation -- coming up next!

Seeks <u>initial state</u> of an NWP model that minimizes discrepancy J between observed- and model-predicted v_r over a time window.

Prognostic equations of NWP model are imposed as strong constraints. Corresponding to each prognostic equation is an adjoint equation whose solution -- running backward in time -- is used to locate the minimum of J.

Can also be used for dual-Doppler analysis and data assimilation.

Simple Adjoint Retrieval

Seeks time-mean u, v (and maybe w) that minimize difference between observed Z, v_r and simple-model predicted Z, v_r.

Simple prognostic equation for Z or v_r imposed as strong constraint (not full equation set of NWP model). Boundary condition and initial condition are known (data).

Can be 2D or 3D. Mass conservation can be included (in 3D), or applied afterward (in 2D) to get w from u, v.

Simple adjoint introduced as computationally cheap alternative to full adjoint.

Notes on "Simple Adjoint Retrieval" slide

- Simple adjoint single-Doppler velocity retrievals developed by Qiu & Xu (1992), Xu & Qiu (1994), Xu et al. (1994a,b, 1995), Gao et al. (2001), Xu et al. (2001a,b)

2D Simple Adjoint Retrieval (Xu et al. 1995)

Consider radial wind conservation equation,

$$\frac{\partial v_r}{\partial t} + u\frac{\partial v_r}{\partial x} + v\frac{\partial v_r}{\partial y} + w\frac{\partial v_r}{\partial z} - \frac{v_\phi^2}{r} = -\frac{1}{\rho}\frac{\partial p}{\partial r} + \kappa_h \nabla_h^2 v_r + \kappa_{vert}\frac{\partial^2 v_r}{\partial z^2}$$

Break u, v into time-mean and fluctuations, $u = u_m + u'$, $v = v_m + v'$ and put troublesome terms onto right hand side:

- Fluctuating terms (can't retrieve them: more unknowns than discretized equations + data points. Underdetermined problem)
- Pressure gradient force (underdetermined)
- Vertical advection and vertical diffusion (cannot treat in 2D)

So now we have

$$\frac{\partial v_r}{\partial t} + u_m \frac{\partial v_r}{\partial x} + v_m \frac{\partial v_r}{\partial y} - \frac{v_{\phi m}^2}{r} - \kappa_h \nabla_h^2 v_r =$$

$$- w \frac{\partial v_r}{\partial z} - \frac{1}{\rho}\frac{\partial p}{\partial r} + \kappa_{vert}\frac{\partial^2 v_r}{\partial z^2} - u' \frac{\partial v_r}{\partial x} - v' \frac{\partial v_r}{\partial y} + \frac{1}{r}\left(2 v_\phi' v_{\phi m} + v_\phi'^2\right)$$

Approximate right hand side with a single lumped time-mean residual forcing F_m term,

$$\frac{\partial v_r}{\partial t} + u_m \frac{\partial v_r}{\partial x} + v_m \frac{\partial v_r}{\partial y} - \frac{v_{\phi m}^2}{r} - \kappa_h \nabla_h^2 v_r = F_m$$

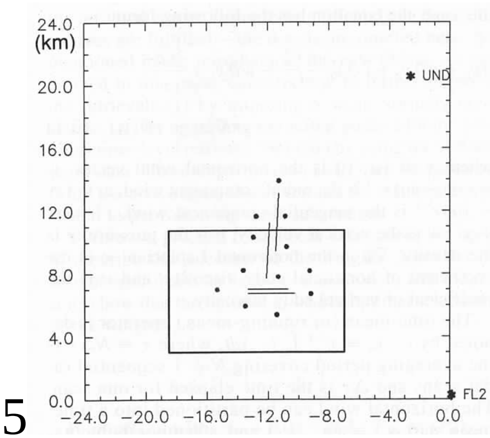
Unknown parameters are treated as temporally constant. v_r is a tracer in flow that is considered stationary -- valid only if retrieval time window is short (rapid scans).

$$J \equiv \iiint \left[\alpha_1 \left(v_{r\,predicted} - v_{r\,obs} \right)^2 + \alpha_2 \left(v_{r\,predicted_m} - v_{r\,obs\,m} \right)^2 + \alpha_3 \left(\frac{\partial u}{\partial x} + \frac{\partial v}{\partial y} \right)^2 + \alpha_4 \left(\frac{\partial v}{\partial x} - \frac{\partial u}{\partial y} \right)^2 \right] dx\, dy\, dt$$

$\alpha_1 \downarrow$ with t since validity of stationarity hypothesis $\downarrow$ with t.

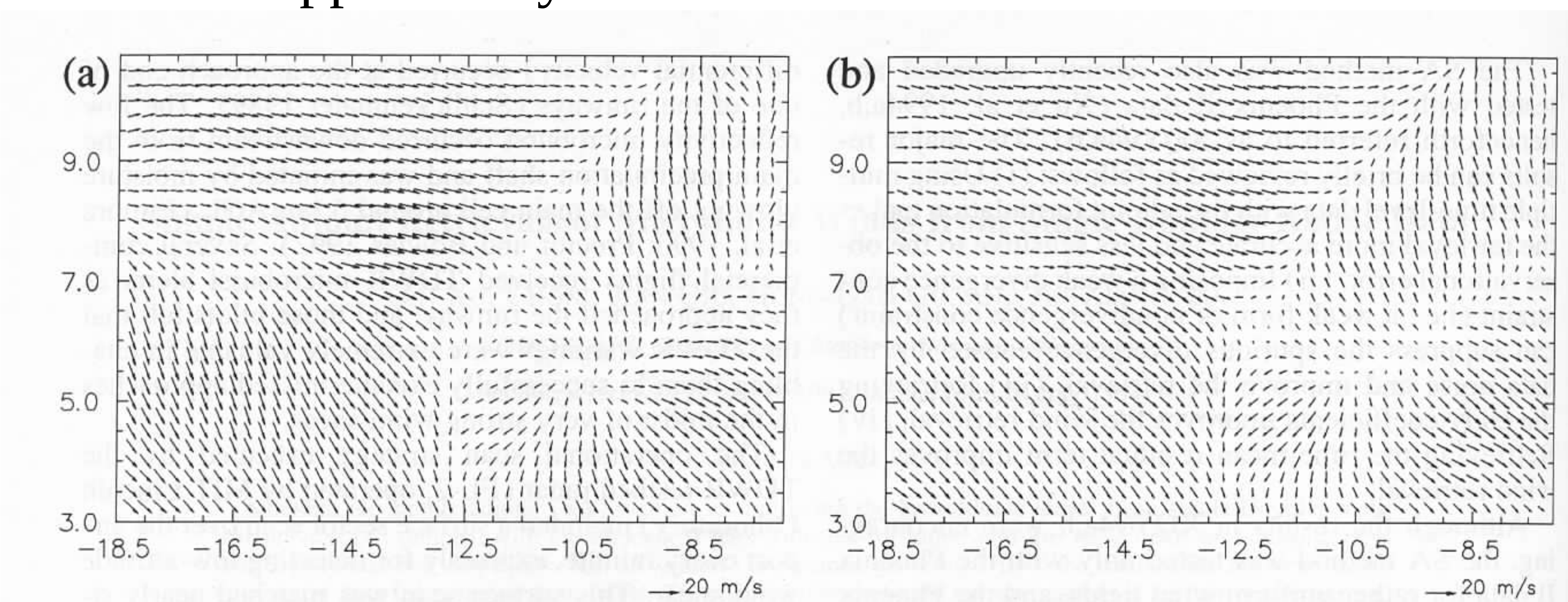
To minimize J, solve the adjoint equations (not shown) to find ∇J in parameter space (derivative of J with respect to u_m, v_m, F_m, κ_h) - this yields direction of steepest descent.

An example: microburst wind retrieval



Figs. 1 and 2a,b from Xu et al. 1995

Dual-Doppler analyzed winds SDVR retrieved winds

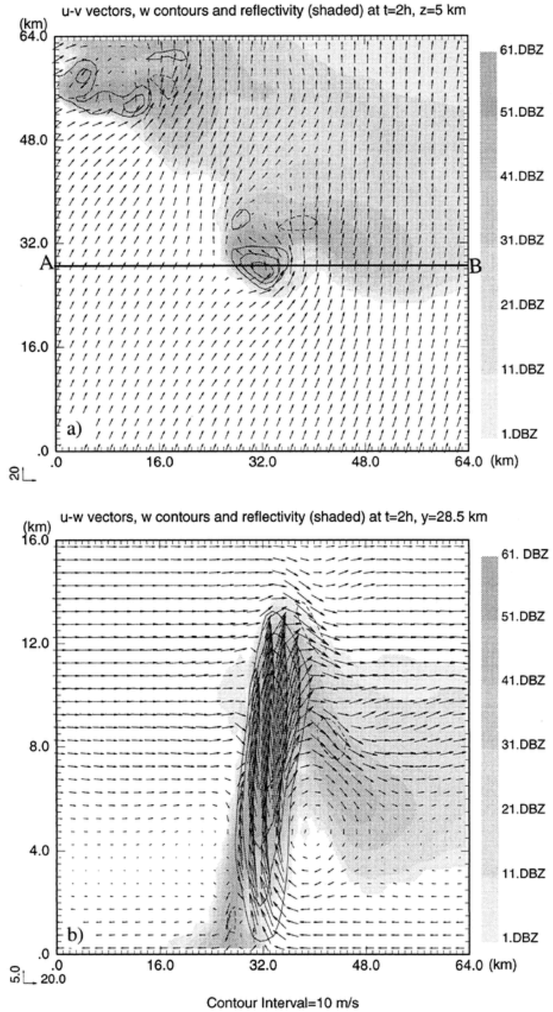


Notes on "Figs 1, 2 from Xu et al 1995" slide

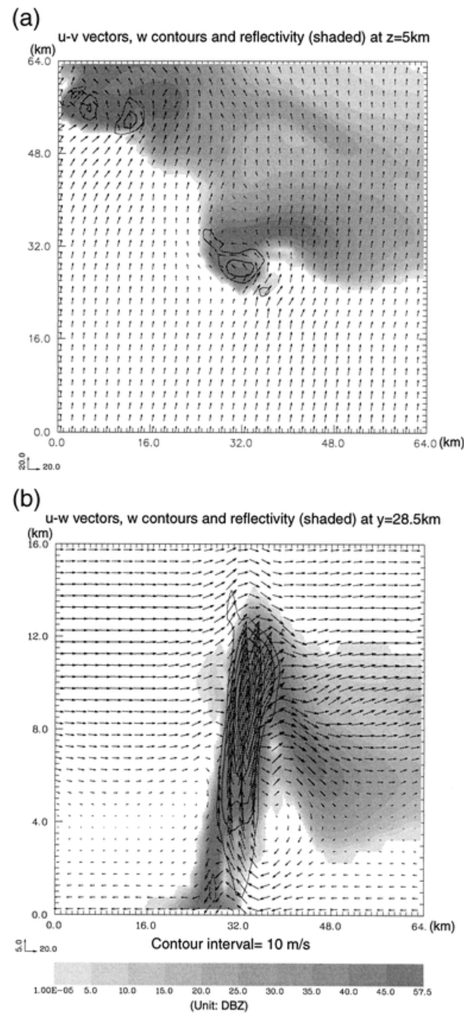
- Dual-Doppler data (used for ground truth) were collected by MIT Lincoln Lab on 11 July 1988. The microburst occurred over the Denver airport. Peak winds were on the order of 20 m/s.

Results From a 3D Simple Adjoint Retrieval

ARPS-simulated winds



Retrieved winds



From Gao et al 2001

Notes on "Results From a 3D Simple Adjoint Retrieval" slide

- The main extension of this 3D retrieval formulation over the 2D Simple Adjoint of Xu et al. (1995) is its provision for mass conservation.

- This retrieval was tested with numerically-simulated data of a supercell storm obtained from a run of the Advanced Regional Prediction System (ARPS). Cross-beam winds in the right-mover (center of the grid) were well-retrieved. The left-mover proved to be problematic.

Summary Comments on SDVRs

For the most part, wind retrievals are still experimental.

Many retrievals suffer from similar deficiencies (e.g., trouble with weak gradients, need for rapid scans if stationarity is assumed).

Much research needs to be done, especially in determining the weighting factors, and in characterizing retrieval sensitivities.

Framework of modern data assimilation (weak/strong constraints in 3D or 4D frameworks, quantifying uncertainty) is a flexible and logical way of bringing together many aspects of previous "stand alone" retrievals.

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