Proposal for Dissertation

Networked Radar System: Waveforms, Signal Processing and Retrievals for Volume Targets

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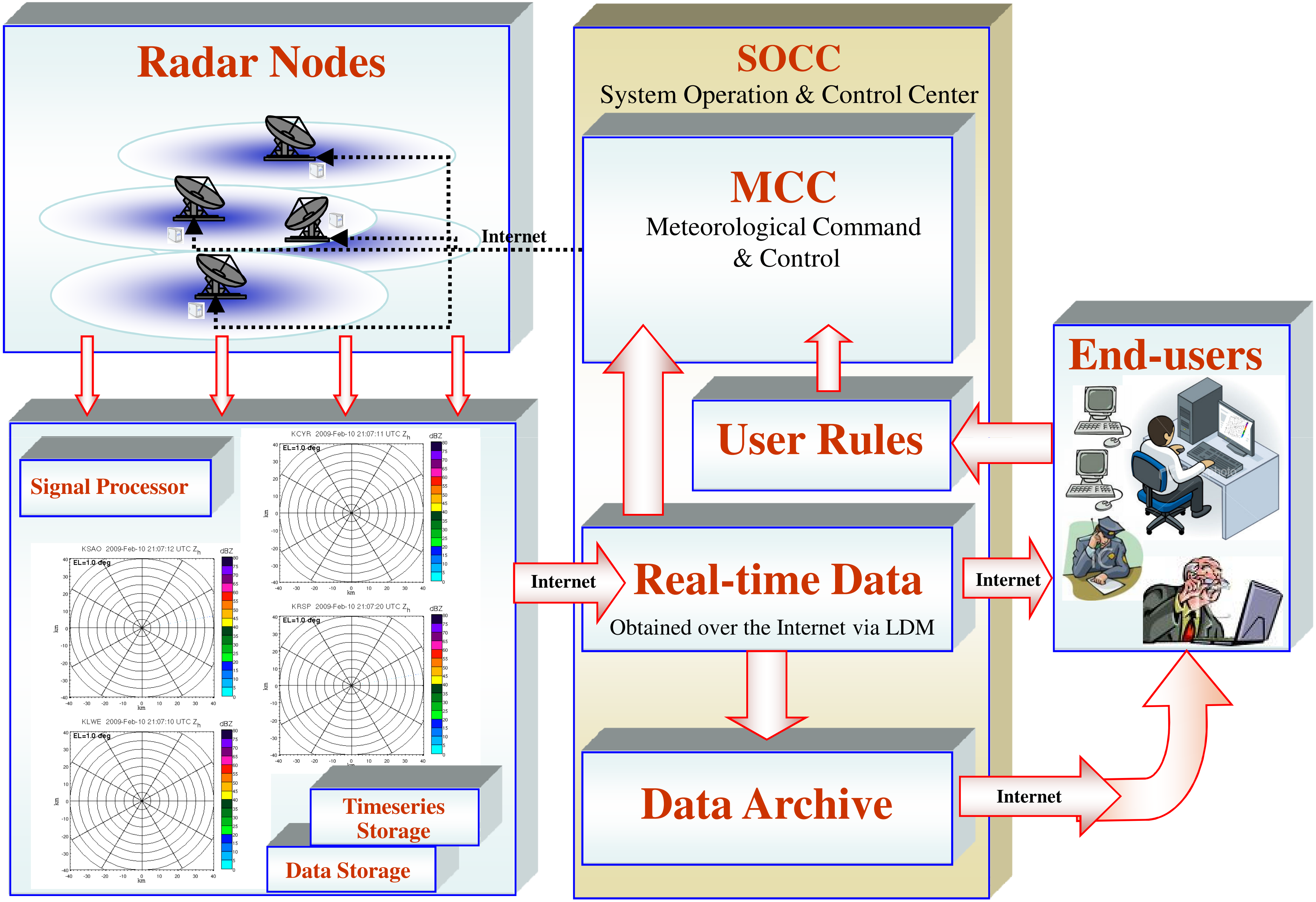
Networked Radar System



Radar Nodes

Internet

Signal Processor

Timeseries Storage

Data Storage

SOCC

System Operation & Control Center

MCC

Meteorological Command & Control

User Rules

Real-time Data

Obtained over the Internet via LDM

Data Archive

End-users

Internet

Internet

Internet

Colorado State University

RESEARCH QUESTION:

The goal of this research is

1. *To develop waveform systems which will enable operation of the radar nodes in the networked radar system*
2. *To provide networked retrieval algorithms to enhance the radar observations*
3. *To provide both qualitative and quantitative inferences about the waveforms and retrieval algorithms.*

OBJECTIVES OF THE RESEARCH:

Waveforms and signal processing

- Pulsing scheme & processing
  - *Study the performance of spectral processing in estimating the Doppler spectral moments and polarimetric variables*
  - *Evaluate spectral filtering methodology for polarimetric radars*
  - *Design the waveform for a single node to minimize the impact of range-velocity ambiguity and ground clutter*
  - *Evaluate the performance of the waveform with the CASA's first generation radar network*

- Waveforms for solid-state transmitters
  - *Design and evaluate wideband pulse compression waveform for meteorological radar*
  - *Design and evaluate the performance of frequency diversity pulse compression waveform*

OUTLINE

- Spectral processing for polarimetric radars
- Spectral ground clutter filtering
- Waveform design for X-band radars
- Waveforms for solid state radars

OUTLINE

v **Spectral processing for polarimetric radars**

v Spectral ground clutter filtering

v Waveform design for X-band radars

v Waveforms for solid state radars

Estimates of Spectral Moment and Polarimetric Variables

Time domain

$\mathbf{v}_h, \mathbf{v}_v$: *Received signal in horizontal and vertical polarization channel*

$$\hat{R}(n) = \frac{1}{N}\sum_{k=0}^{N-2} v_h(k+n) v_h^*(k)$$

$$power : \hat{P}_h = \frac{1}{N}\|\mathbf{v}_h\|^2,\ \hat{P}_v = \frac{1}{N}\|\mathbf{v}_v\|^2$$

$$velocity : \hat{\upsilon} = -\frac{\lambda}{4\pi T_s}\arctan\{\hat{R}(1)\}$$

$$spectral\ \ width : \hat{\sigma}_v = \frac{\lambda}{2\pi T_s\sqrt{2}}\sqrt{\ln\left|\frac{R(0)}{R(1)}\right|}$$

$$differential\ reflectivity : \hat{Z}_{dr} = 10\log_{10}\left(\frac{\hat{P}_h}{\hat{P}_v}\right)$$

$$differenti\ al\ \ phase : \hat{\psi}_{dp} = \arctan\{\mathbf{v}_h^H \mathbf{v}_v\}$$

$$co\text{-}polar\,correlation : |\hat{\rho}_{hv}(0)| = \frac{\mathbf{v}_h^H \mathbf{v}_v}{\|\mathbf{v}_h\|\|\mathbf{v}_v\|}$$

Spectral domain

$\mathbf{\Phi}$: *Normalized DFT matrix*

$\mathbf{w}$: *Normalized processing window function*

$\mathbf{\Phi}_m = \mathbf{\Phi}\,\mathrm{diag}\{\mathbf{w}\}$

$\mathbf{s}_h = \mathbf{\Phi}_m \mathbf{v}_h$: *Spectral coefficients in H - channel*

$\mathbf{s}_v = \mathbf{\Phi}_m \mathbf{v}_v$: *Spectral coefficients in V - channel*

$$power : \hat{P}_h = \frac{1}{N}\|\mathbf{s}_h\|^2,\ \hat{P}_v = \frac{1}{N}\|\mathbf{s}_v\|^2$$

$$velocity : \hat{\upsilon} = \frac{\sum_{k=0}^{N-1} \upsilon_k |s_k|^2}{\sum_{k=0}^{N-1} |s_k|^2}$$

$$spectral\ \ width : \hat{\sigma}_v = \sqrt{\frac{\sum_{k=0}^{N-1} (\upsilon_k - \hat{\upsilon})^2 |s_k|^2}{\sum_{k=0}^{N-1} |s_k|^2}}$$

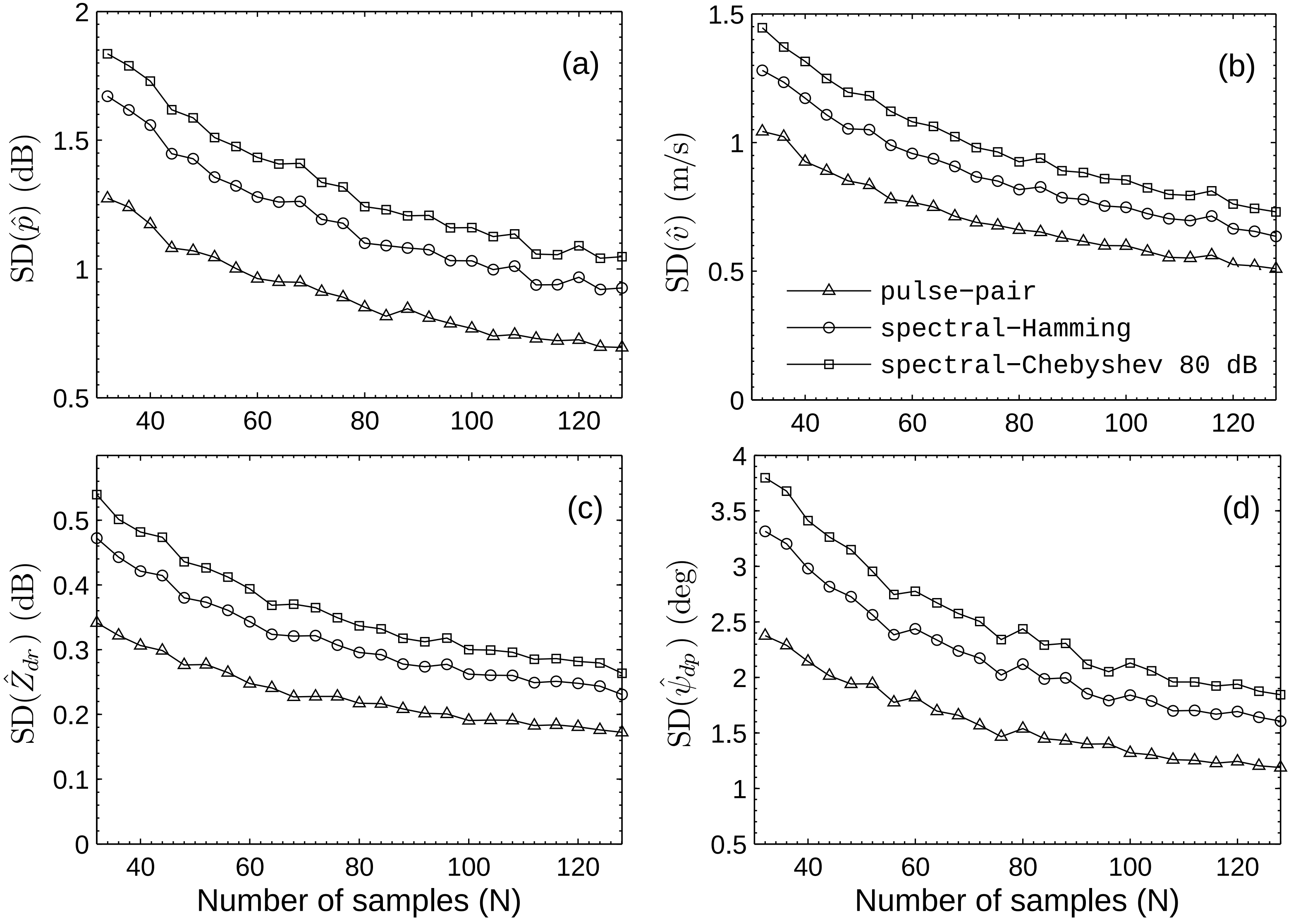
$$differential\ reflectivity : \hat{Z}_{dr} = 10\log_{10}\left(\frac{\hat{P}_h}{\hat{P}_v}\right)$$

$$differenti\ al\ \ phase : \hat{\psi}_{dp} = \arctan\{\mathbf{s}_h^H \mathbf{s}_v\}$$

$$co\text{-}polar\,correlation : |\hat{\rho}_{hv}(0)| = \frac{\mathbf{s}_h^H \mathbf{s}_v}{\|\mathbf{s}_h\|\|\mathbf{s}_v\|}$$

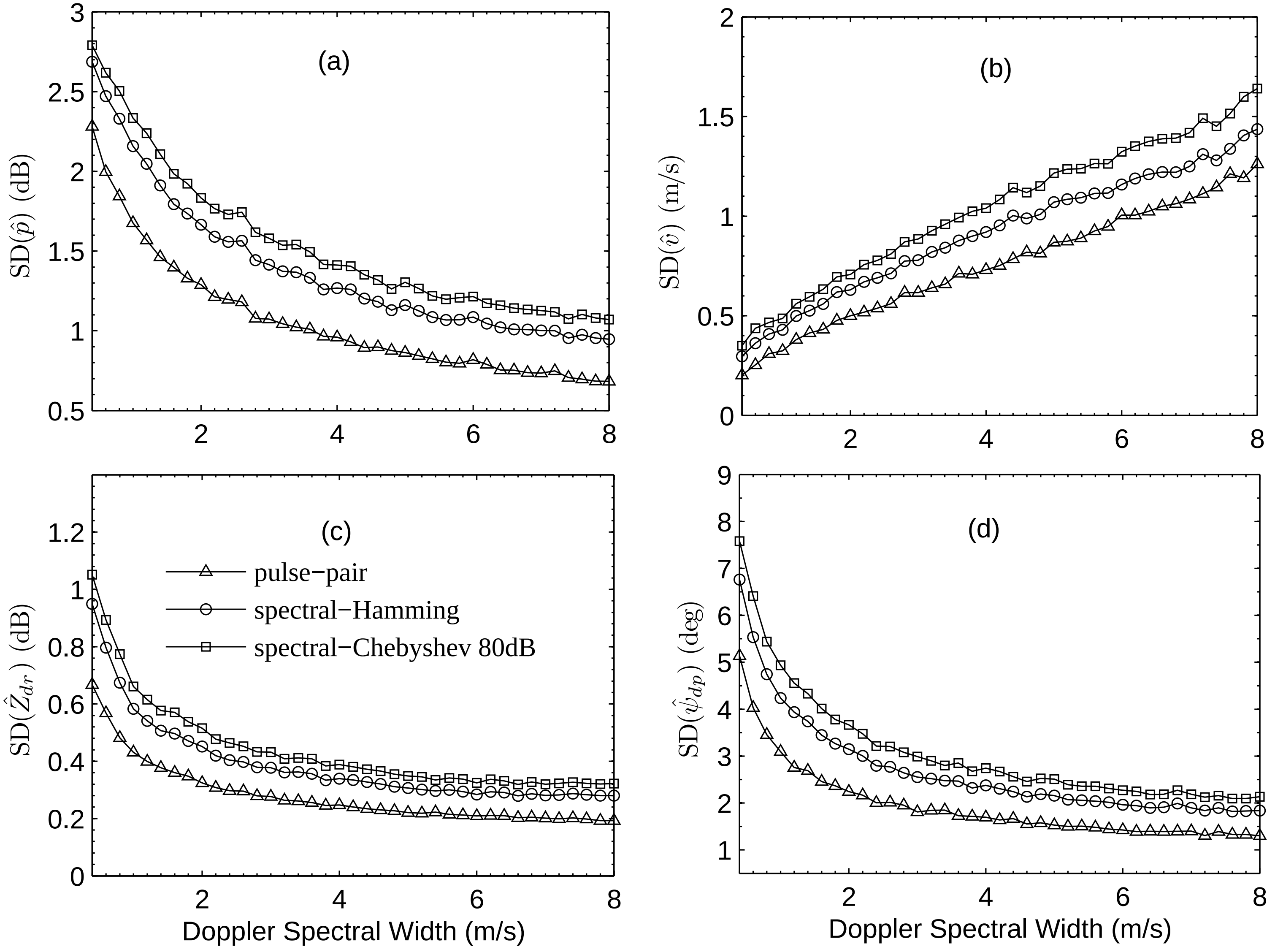
Standard Deviations Vs No. Pulses

$\lambda = 11$ cm, $\sigma_v = 4$ m/s, SNR=20 dB, PRT=1.0 ms, $|\rho_{hv}(0)| = 0.99$



Standard Deviations Vs Spectral width

$\lambda = 11$ cm, $N = 64$, $SNR = 20$ dB, PRT$= 1.0$ ms, $|\rho_{hv}(0)| = 0.99$



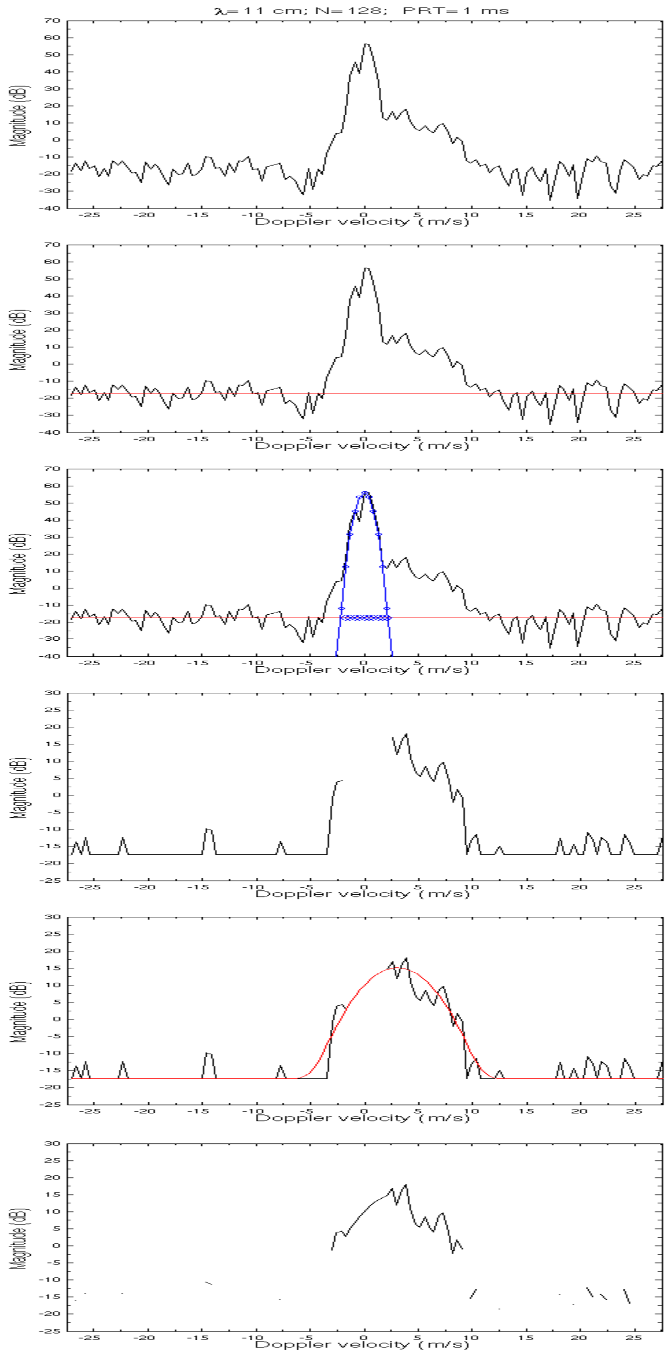
OUTLINE

- Spectral processing for polarimetric radars
- **Spectral ground clutter filtering**
- Waveform design for X-band radars
- Waveforms for solid state radars

Ground Clutter Filtering

- Ground clutter is the radar return from non-meteorological targets that bias radar parameters.
- Clutter filtering is performed by applying a notch filter centered at zero Doppler velocity
- Ground clutter filtering techniques
    - IIR notch filter centered at zero Doppler velocity
    - Advanced spectral filter
    - Advanced time domain filters

Spectral Clutter Filtering



- Obtain spectral coefficients and power spectral density of received signal

$$\mathbf{S}(\mathbf{v},\theta) = \frac{p_c}{\sqrt{2\pi\sigma_c^2}}\exp\left\{-\frac{\mathbf{v}^2}{2\sigma_c^2}\right\} + \frac{p}{\sqrt{2\pi w^2}}\exp\left\{-\frac{(\mathbf{v}-v)^2}{2w^2}\right\} + \frac{2T_s}{\lambda}p_n$$

- Obtain adaptive noise floor by sorting spectral coefficients by power

- Design notch filter in spectral domain

  Estimate clutter model based on Gaussian model fit to zero Doppler region

  Estimate notch width based on clutter model and noise

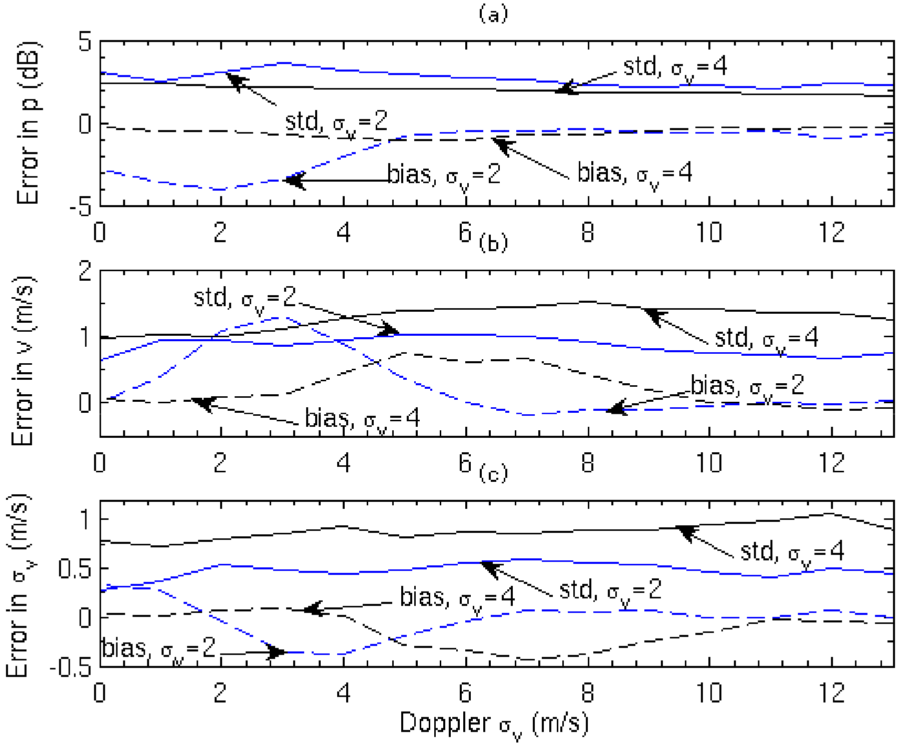
$$n = \left\lfloor \frac{4\sigma_c T_s}{\lambda}\sqrt{2\ln\left[\sqrt{2\pi}\sigma_c\left(\frac{p_c}{\tilde{p}_n}\right)\right]}\right\rfloor$$

- Notch the clutter signal with a spectral clipper

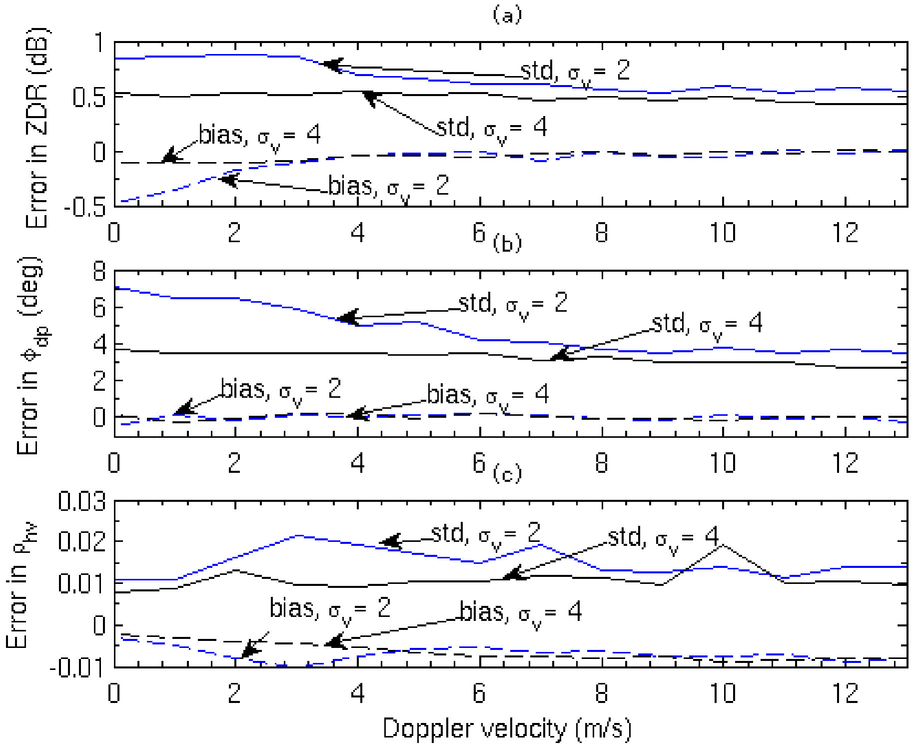
- Interpolate the notch filtered region by iteratively fitting a Gaussian model to the weather signal

- Replace the clutter region with model and subtract noise power

Spectral Clutter Filtering



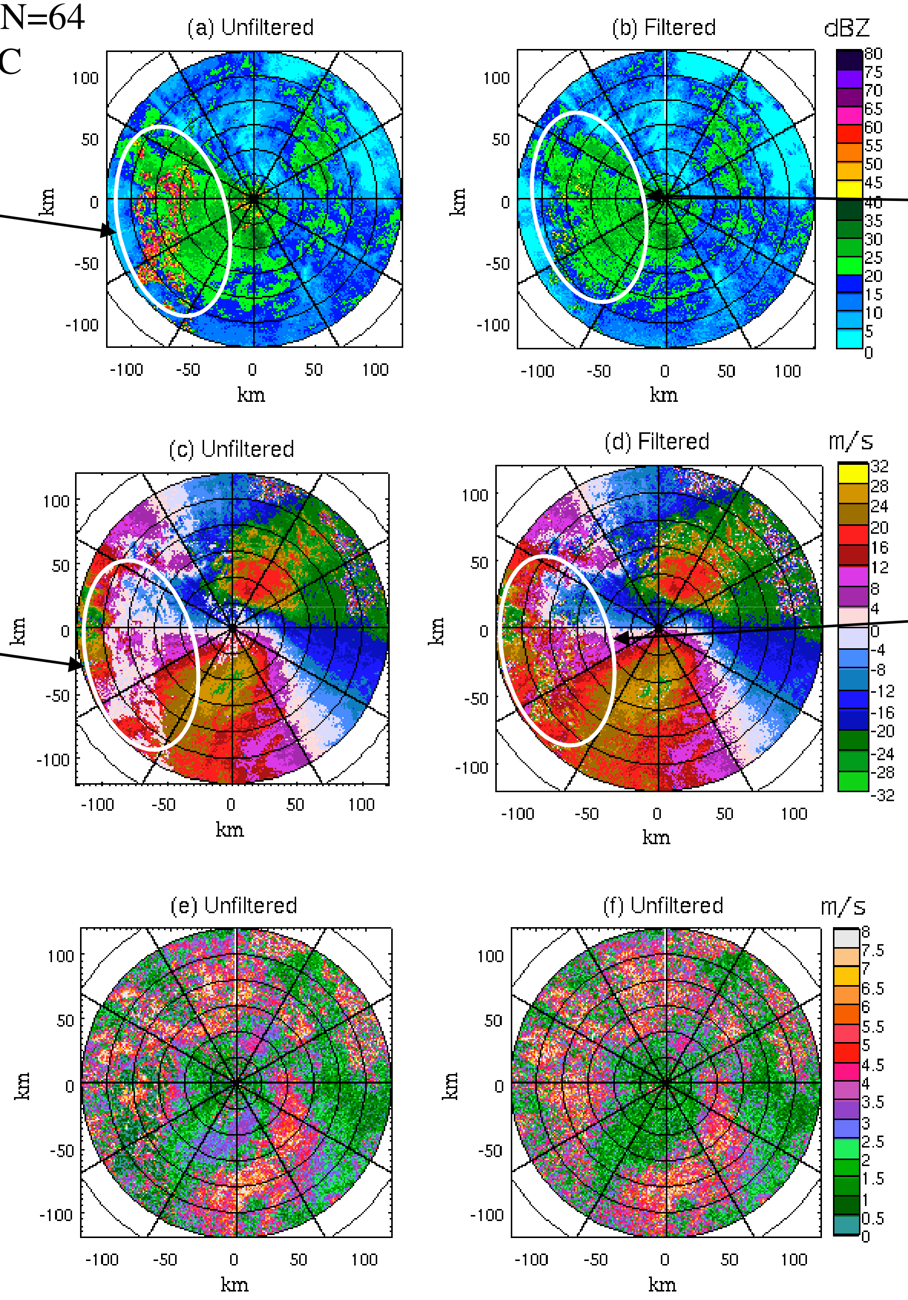
Error in estimated spectral moments as a function mean Doppler velocity



Error in estimated polarimetric variables as a function mean Doppler velocity

Spectral Clutter Filtering: Implementation with CSU-CHILL

Data collected with PRT =1 ms; N=64
on Dec 20, 2006 at 23:58:19 UTC



Severe clutter from
Rocky mountains

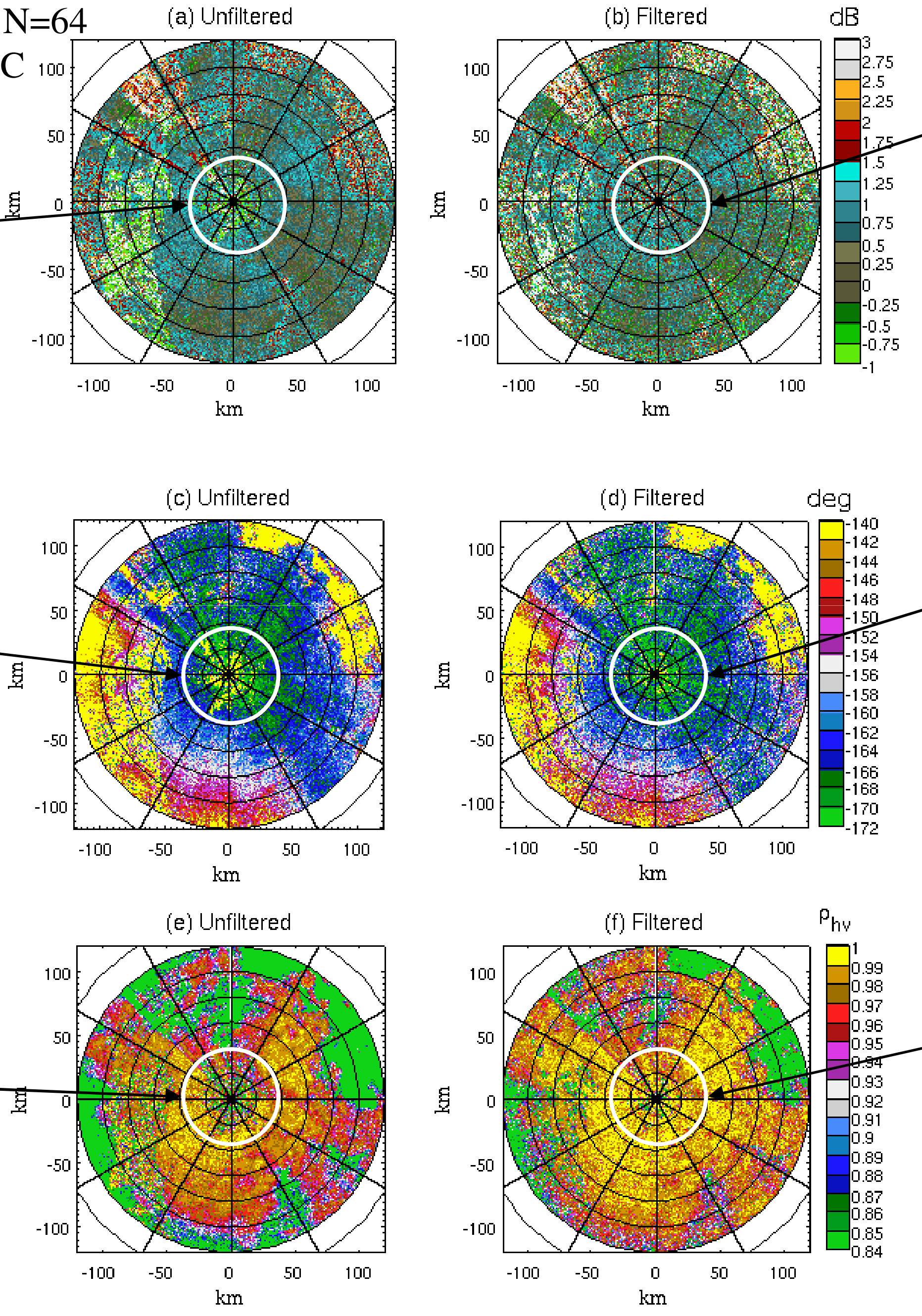
Reflectivity after
spectral clutter
filtering

Velocities biased due
to clutter

Velocities after
clutter filtering

Spectral Clutter Filtering: Implementation with CSU-CHILL

Data collected with PRT =1 ms; N=64
on Dec 20, 2006 at 23:58:19 UTC



Clutter contaminated differential reflectivity

Filtered differential reflectivity

Biased differential phase due to clutter

Filtered differential phase

Clutter contaminated co-polar correlation coefficient

Filtered co-polar correlation coefficient

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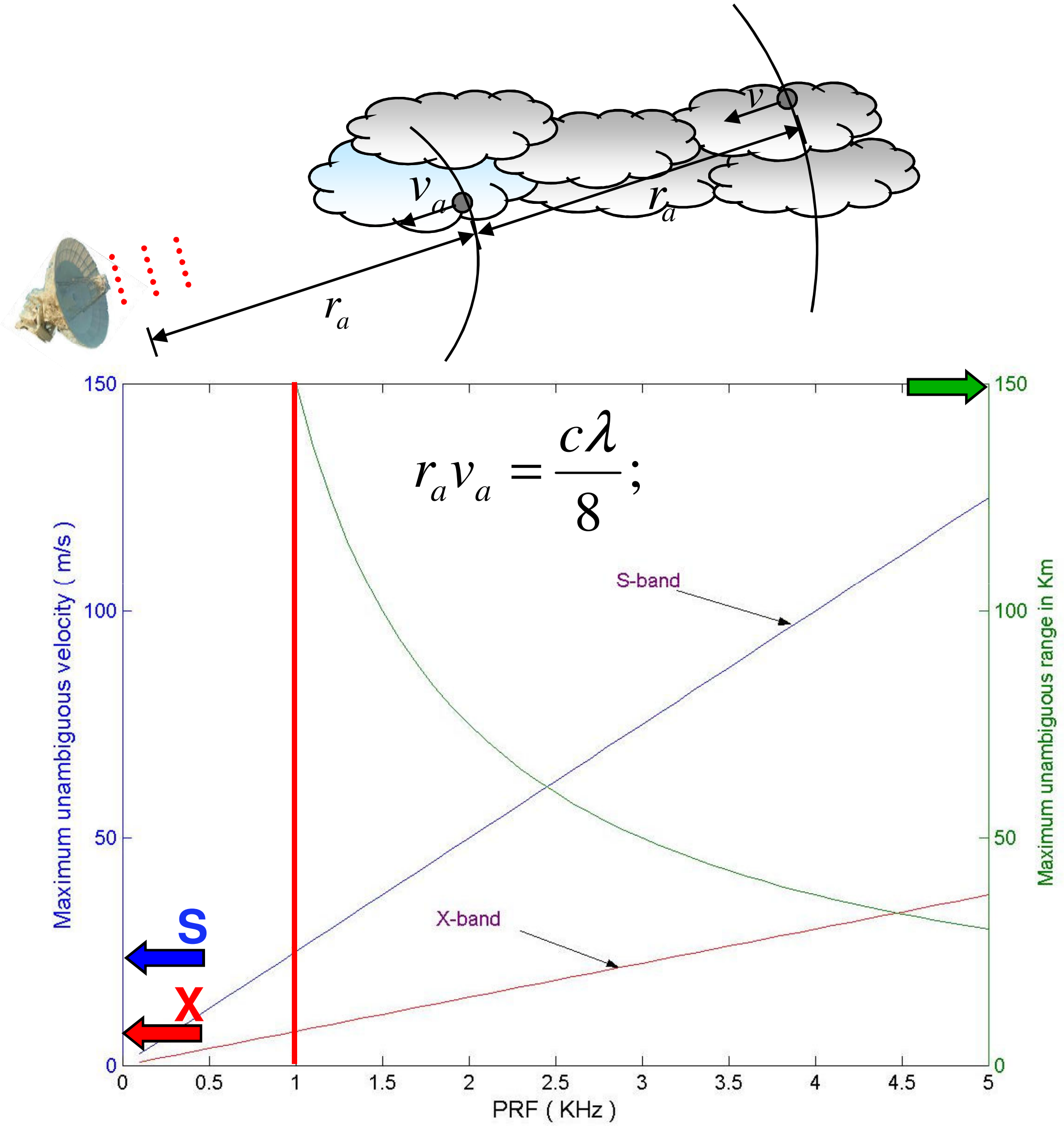
- **Waveform design for X-band radars**
- Waveforms for solid state radars

Range-Velocity Ambiguity

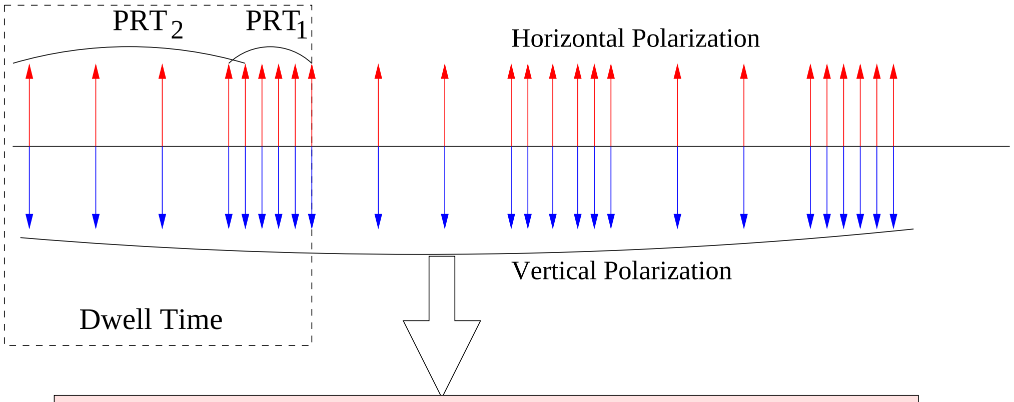


$$r_a v_a = \frac{c\lambda}{8};$$

- In a pulsed Doppler weather radar scattering is due to precipitation particles that spatially extend over a large area
- Fundamental limitation of pulsed Doppler radar transmitting uniformly spaced pulses
- If v_a is increased, r_a decreases correspondingly (Range-velocity ambiguity)
- The trade off between maximum range and maximum velocity is more stringent for X-band radar

Dual-PRF Waveform

- A dual-PRF waveform with is recommended for operational use
- Phase coding of the transmitted pulse is used to suppress overlaid echoes
- Staggered PRF unfolding to measure high velocities
- A waveform look-up table provides the necessary tool to adaptively select the waveform



Random Phase Processing with Dual−PRF

Scan Speed (deg/s)	PRF_1 (kHz)	PRF_2 (kHz)	~Velocity (m/s)	N_1	N_2
10~20	1.6 ~ 2.0	2.4 ~ 3.0	35 ~ 47	40 ~	54 ~
21	1.60	2.40	35.00	40	54
	1.70	2.55	40.00	42	58
	1.80	2.70	43.00	44	62
	1.90	2.85	45.00	46	66
	2.00	3.00	47.00	48	70

Dual-PRF with phase coding

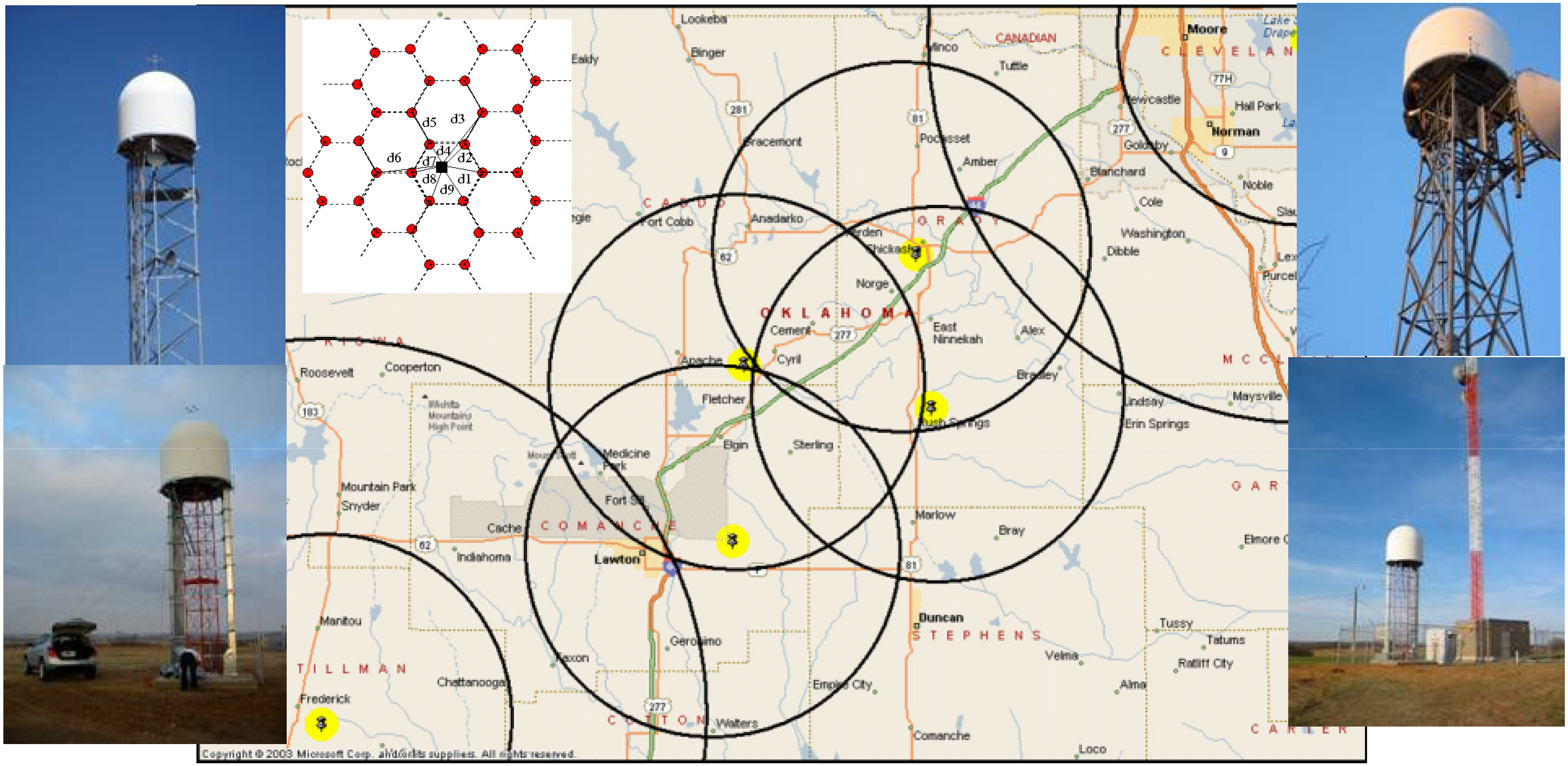
Scan Speed (deg/s)	PRF_1 (kHz)	PRF_2 (kHz)	~Velocity (m/s)	N_1	N_2
22.00	3.20	~	25.40	145	~
25.00	3.20	~	25.40	128	~
28.00	3.20	~	25.40	114	~
31.00	3.20	~	25.40	103	~
34.00	3.20	~	25.40	94	~
37.00	3.20	~	25.40	86	~
40.00	3.20	~	25.40	80	~
43.00	3.20	~	25.40	74	~
46.00	3.20	~	25.40	69	~
49.00	3.20	~	25.40	65	~
52.00	3.20	~	25.40	61	~
55.00	3.20	~	25.40	58	~
58.00	3.20	~	25.40	55	~

Single PRF with phase coding

Scan Speed (deg/s)	PRF_1 (kHz)	PRF_2 (kHz)	~Velocity (m/s)	N_1	N_2
61.00	3.20	~	25.40	52	~
64.00	3.20	~	25.40	50	~
67.00	3.20	~	25.40	47	~
70.00	3.20	~	25.40	45	~
73.00	3.20	~	25.40	43	~

Single PRF without phase coding

Results from IP1 Radar Network



- Covers an area of 7000 square km
- The deployment of this four-node network represents a unit-cell of a larger deployment

Design Considerations : Hardware Requirements (First Generation)

v The first generation CASA radar systems are magnetron based systems with limited agility on duty cycle and supported waveforms. The transmitter can deliver a maximum peak power of 25 kW at a duty cycle of 0.1 %.

v The transmitter can be tuned below its maximum peak power allowing one to increase the duty cycle, which is used to accommodate higher PRF.

v Random phase coding is the only scheme that can be implemented because a magnetron based system has a random start-up phase.

Design Considerations : Hardware Requirements (First Generation)

- Sensitivity better than 10 dBZ at 30 km and with an accuracy on the order of a 1dB

- The Nyquist velocity should be no less than 25 m/s with an accuracy of 1m/s

- Increase in PRF beyond 1.5 kHz has to compensated by reducing the peak power.

- Increasing PRF will lead to range overlay. Minimize impact of range overlay on the first 30 km

Design Considerations : Operational Requirements (First Generation)

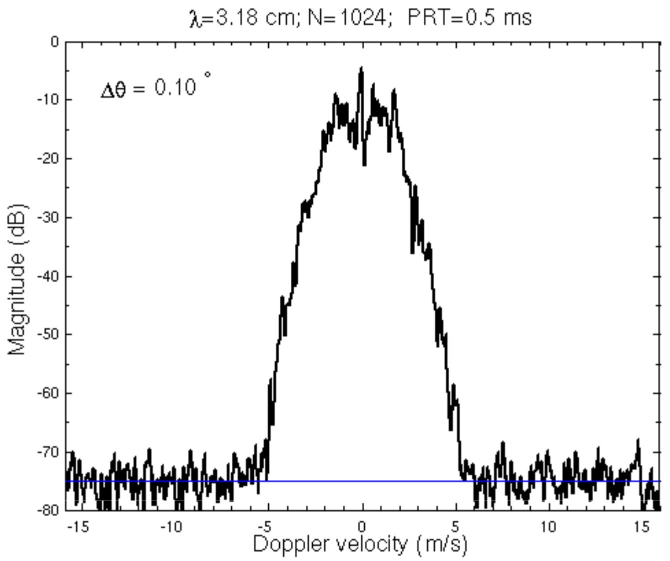
- Minimum clutter suppression capability of 30 dB

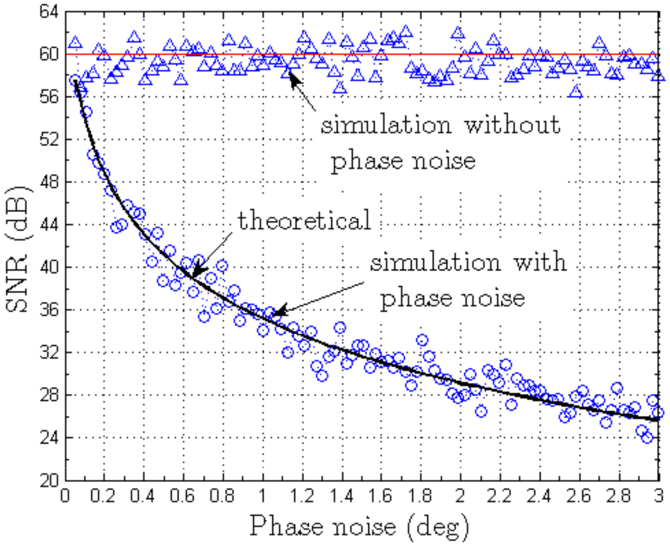
- The bias and standard deviation of velocity after clutter filtering will be no greater than 2 m/s for an SNR of 20 dB

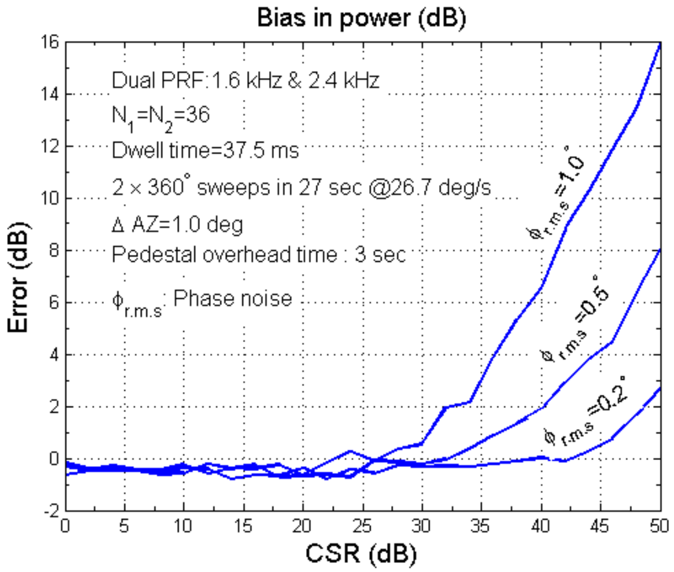
- Maximum allowable bias in reflectivity after clutter filtering 1 dB

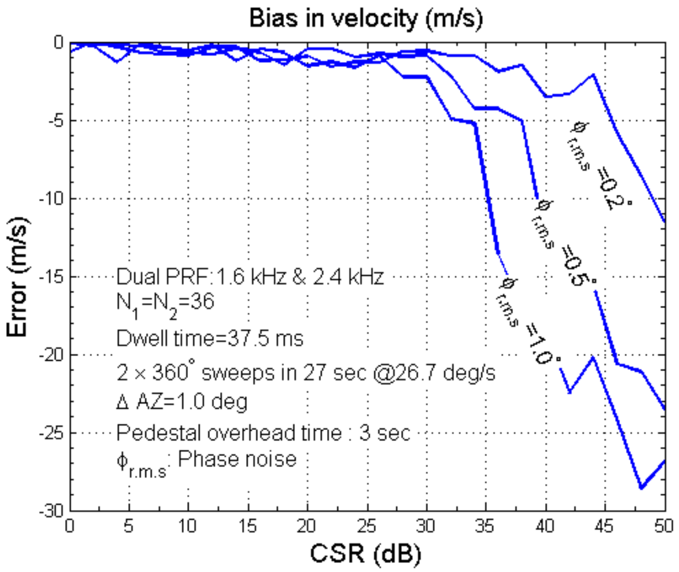
Ground Clutter Filtering

Impact of Phase Noise

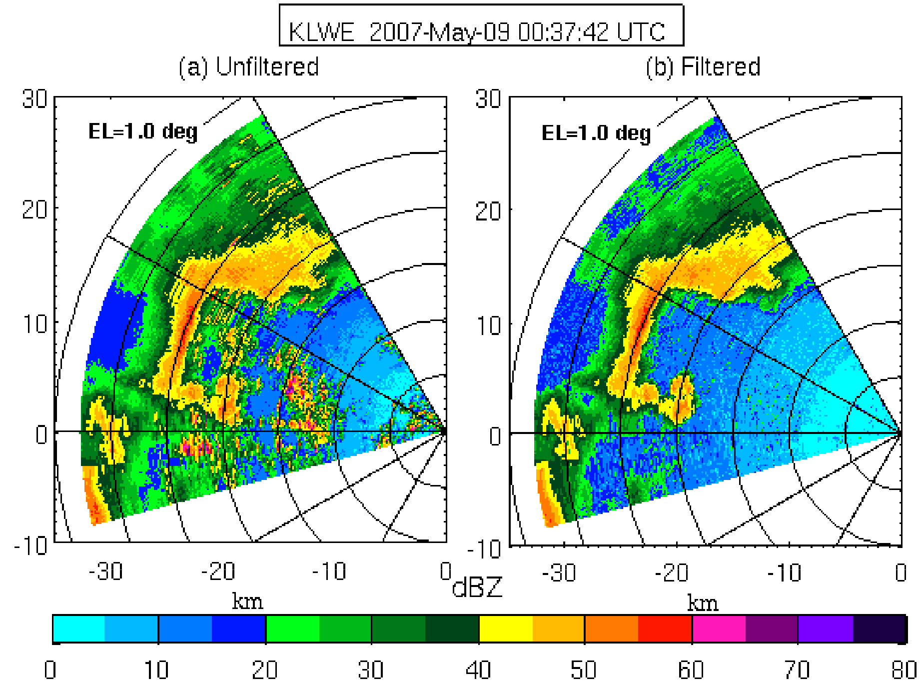








Ground Clutter Filtering



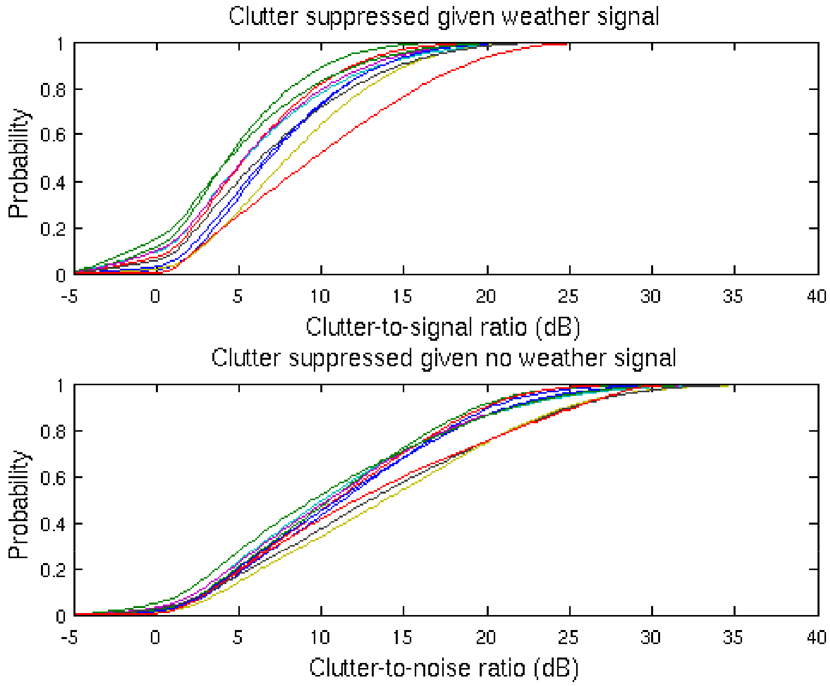
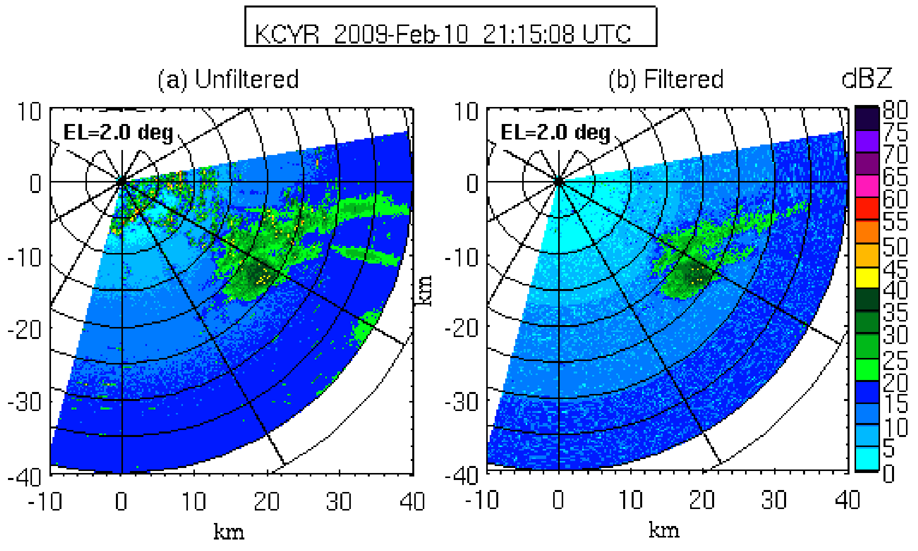


Table 4.2: Ground clutter suppression

Date	Radars	CSR with no weather (dB)	CSR with weather (dB)
May 06, 2007	KCYR, KLWE	27.50	19.25
May 07, 2007	KCYR, KLWE	26.25	15.25
May 09, 2007	KCYR, KLWE	26.00	17.50
Jun 14, 2007	KCYR, KSAO, KRSP, KLWE	31.25	21.00
Jun 20, 2007	KCYR, KSAO, KRSP, KLWE	30.50	19.50
Mar 31, 2008	KSAO	33.50	21.00
Apr 09, 2008	KSAO	33.00	21.25
May 02, 2008	KCYR, KSAO	29.50	19.50
May 07, 2008	KCYR, KSAO, KRSP, KLWE	30.25	19.00
Jun 17, 2008	KCYR, KRSP	30.00	24.25

Overlaid Echo Suppression



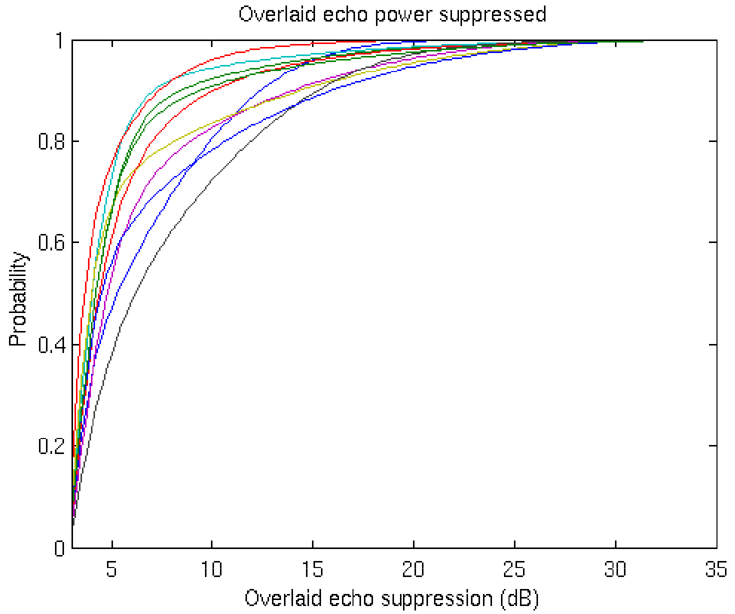
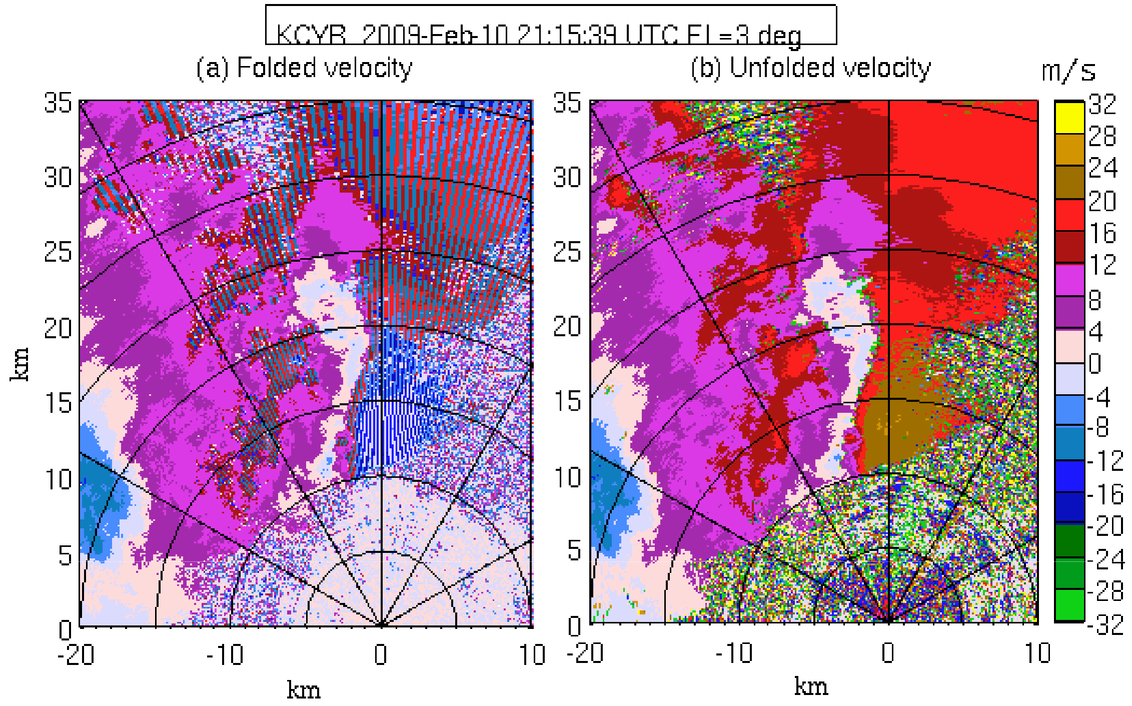


Table 4.3: Overlaid echo suppression

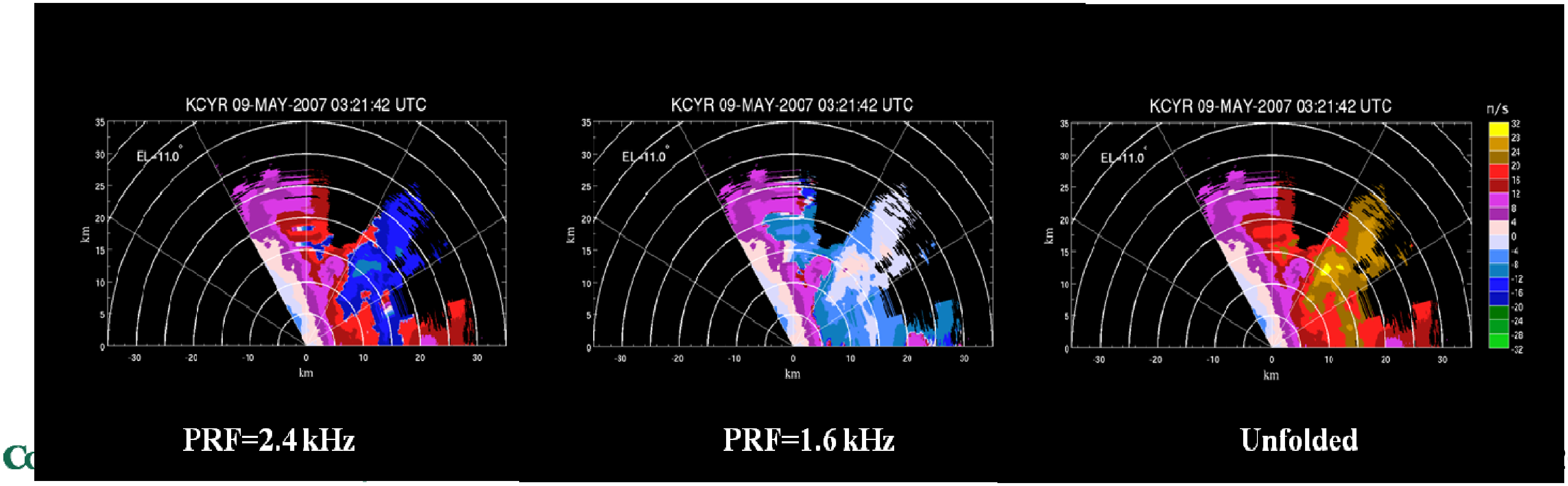
Date	Radars	Overlaid echo suppressed (dB)
May 06, 2007	KCYR, KLWE	18.00
May 07, 2007	KCYR, KLWE	22.75
May 09, 2007	KCYR, KLWE	23.75
Jun 14, 2007	KCYR, KSAO, KRSP, KLWE	22.25
Jun 20, 2007	KCYR, KSAO, KRSP, KLWE	25.00
Mar 31, 2008	KSAO	27.00
Apr 09, 2008	KSAO	23.50
May 02, 2008	KCYR, KSAO	27.50
May 07, 2008	KCYR, KSAO, KRSP, KLWE	25.25
Jun 17, 2008	KCYR, KRSP	14.25

Velocity Unfolding

Velocity measurements on a radial-by-radial basis with dual-PRF →



← Unfolded velocity with dual-PRF



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Sensitivity of Weather Radar

- The received signal at the antenna reference port is used to measure reflectivity

$$Z_e = C' \bar{P}_{ref} R^2$$

$$Z_e\,[dBZ] = \bar{P}_{ref}\,[dBm] + C\,[dB] + 20\log\left(R\,[km]\right)$$

where the radar constant C is given by

$$C = 10\log\left\{\frac{1}{\pi^5|K_w|^2}\left(\frac{2}{c\tau}\right)\left[\frac{(4\pi^3 l_{wg}^2)}{P_t G_0^2}\right]\left(\frac{8\ln 2}{\pi\theta_B\phi_B}\right)\lambda^2 10^{21}\right\}$$

- The minimum detectable reflectivity is a function of pulse width for a fixed transmitter and antenna
- The sensitivity can be mapped to the transmit pulse length
- Long pulses are transmitted to achieve sensitivity

Pulse compression Waveform

- Pulse Compression – a mature technology for hard-target radar
  - Improved range resolution
  - Reduced peak-power requirement
- Weather radar use has been limited
  - Range sidelobe impact for volume targets
  - Not operationally proven
- Offers several benefits
  - Increased sensitivity
  - Improved range resolution
  - Improved accuracy of estimates through range averaging
  - Enables low-power solid-state transmitter technology
  - Dynamic range beyond RF hardware limitations

Nonlinear FM Pulse Compression

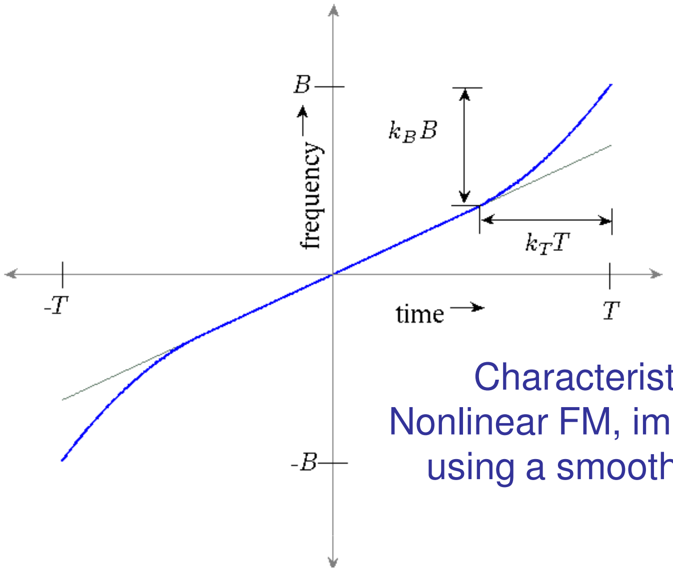
- The complex envelope of the transmitted pulse is

$$u(t) = g(t)\exp\left\{ j2\pi \int_{-T/2}^{t} f(\tau)d\tau \right\}$$

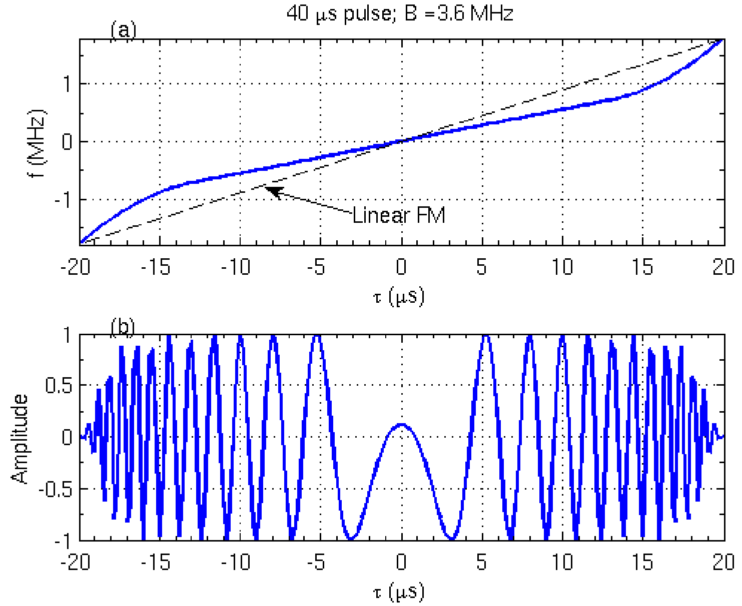
- The FM characteristic, f(t), is decomposed into linear and nonlinear components, as

$$f(t) = \begin{cases} \dfrac{B}{T}\left(\dfrac{1-k_B}{1-k_T}\right) & |t| \le T(1-k_T) \\ \varphi(t) & |t| > T(1-k_T) \end{cases}$$

- B is the total bandwidth of the chirp, $0<k_T<1$ and $0<k_B<1$ are parameters that control the nonlinearity



Characteristics of Nonlinear FM, implemented using a smooth FM law



Sidelobe Suppression

- Low range sidelobe levels are essential for weather radar applications
    - Strong reflectivity gradients (40 dBZ/km) can result in contamination of adjacent range gates
- Integrated Sidelobe Level (ISL) are important for volume targets
- ISL is controlled by
    - Adjusting the nonlinearity parameters, k_T and k_B
    - Applying amplitude weighting functions on transmit
    - Using suitable compression filters
- Compression filters
    - Window functions
    - Minimum ISL filter

Sidelobe Suppression: Min ISL Filter

- Let **G** be the transmit convolution matrix based on the discrete transmit complex envelope **g** and **h** be the FIR filter
- Output of the filter is when transmit pulse is used as input is

$$y = G^T h$$

- Let $\mathbf{G}_m$ be the modified transmit convolution matrix obtained by deleting the columns that corresponds to mainlobe
- The ISL is given by

$$ISL = f(h) = h^H G_m^* G_m^T h$$

- The ISL is minimized with a constraint on the peak of the output as

$$g^T h = \alpha$$

Sidelobe Suppression: Min ISL Filter

- The filter is obtained by solving the Lagrangian

$$\frac{\partial f\left(\boldsymbol{h}\right)}{\partial \boldsymbol{h}^*} + \lambda \frac{\partial \Re e\left(\boldsymbol{g}^T \boldsymbol{h} - \alpha\right)}{\partial \boldsymbol{h}^*} = 0$$

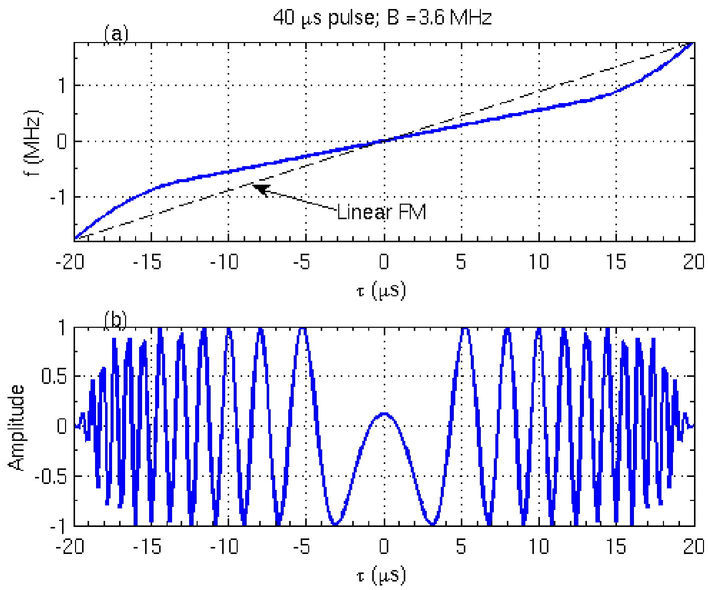
- The min ISL filter is given by

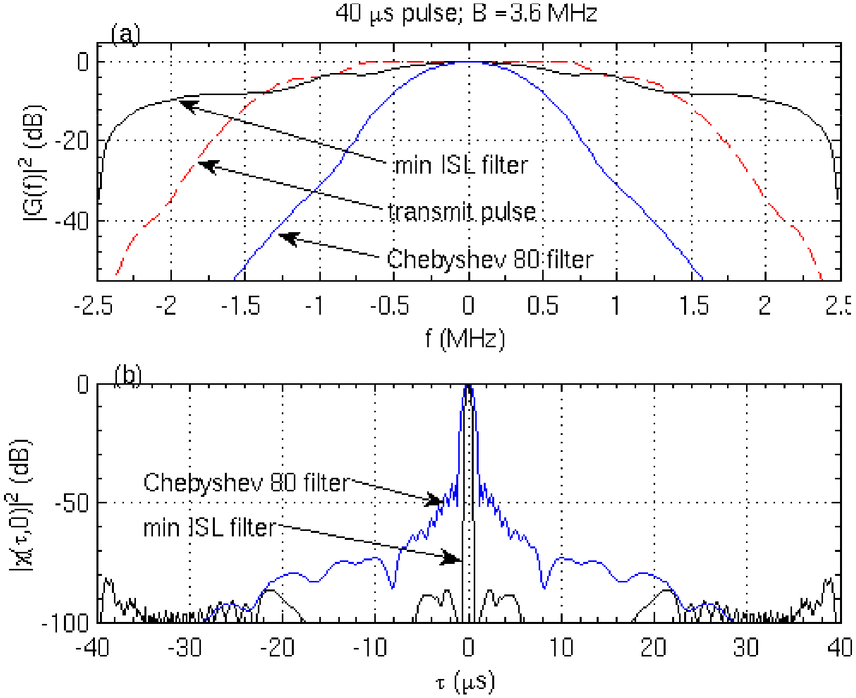
$$\boldsymbol{h} = \frac{\alpha \left(\boldsymbol{G}_m^* \boldsymbol{G}_m^T\right)^{-1} \boldsymbol{g}^H}{\boldsymbol{g} \left(\boldsymbol{G}_m^* \boldsymbol{G}_m^T\right)^{-1} \boldsymbol{g}^H}$$

- The filter is obtained by normalizing it to have zero DC gain

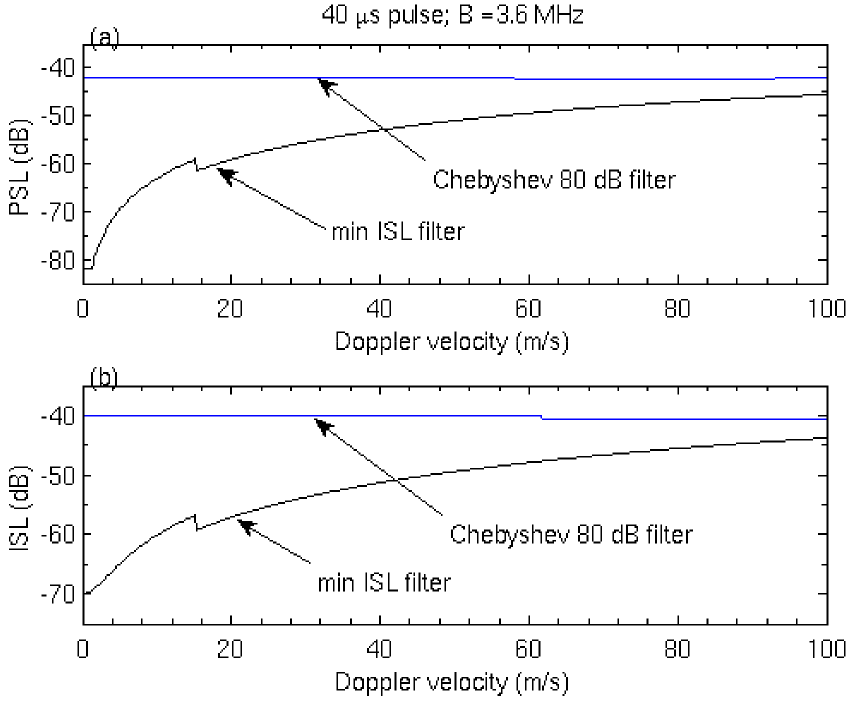
$$\boldsymbol{b} = \frac{\boldsymbol{h}}{\left|\left\langle 1, \boldsymbol{h} \right\rangle\right|}$$

Compression Filter Performance





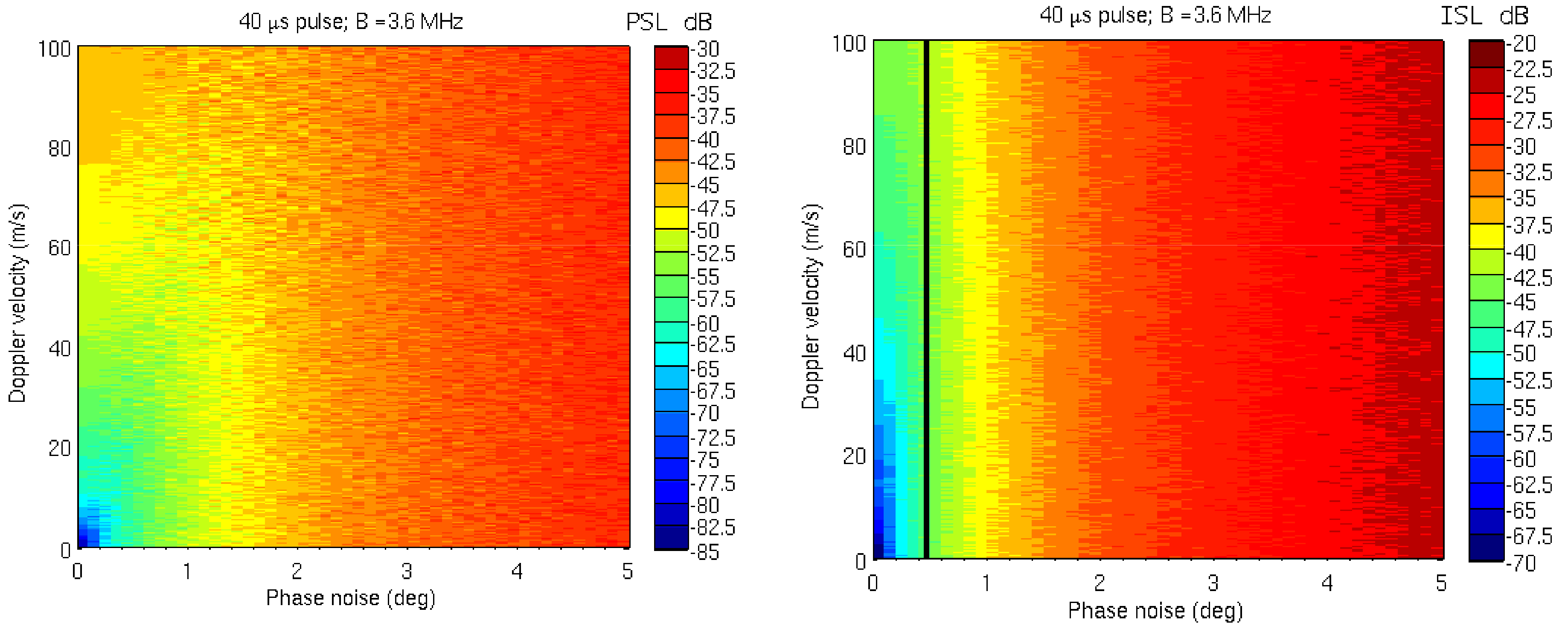
Frequency response of the transmit pulse and compression filter along with the ambiguity function



Sidelobe level as a function of Doppler velocity for a Chebyshev and minimum ISL compression filter

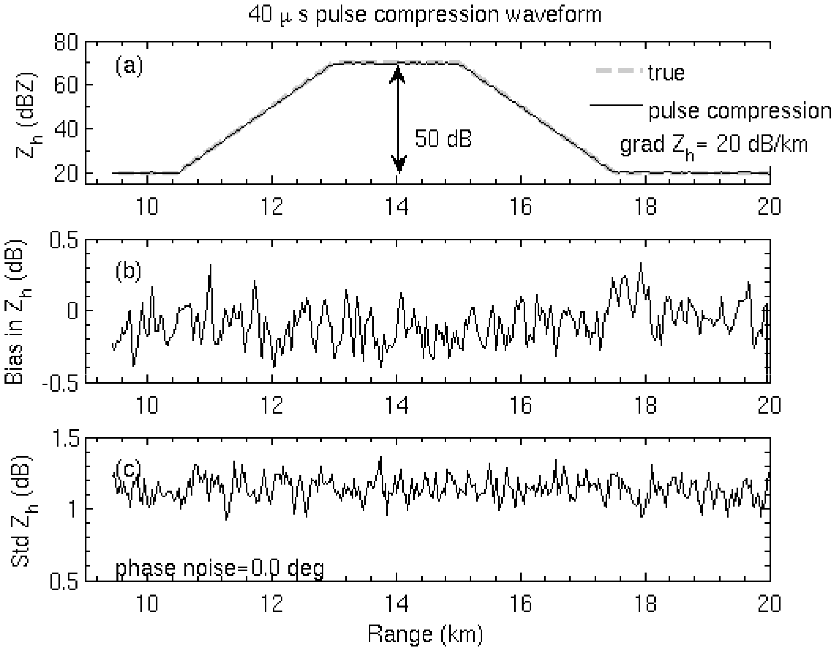
Compression Filter Performance

Impact of Phase Noise

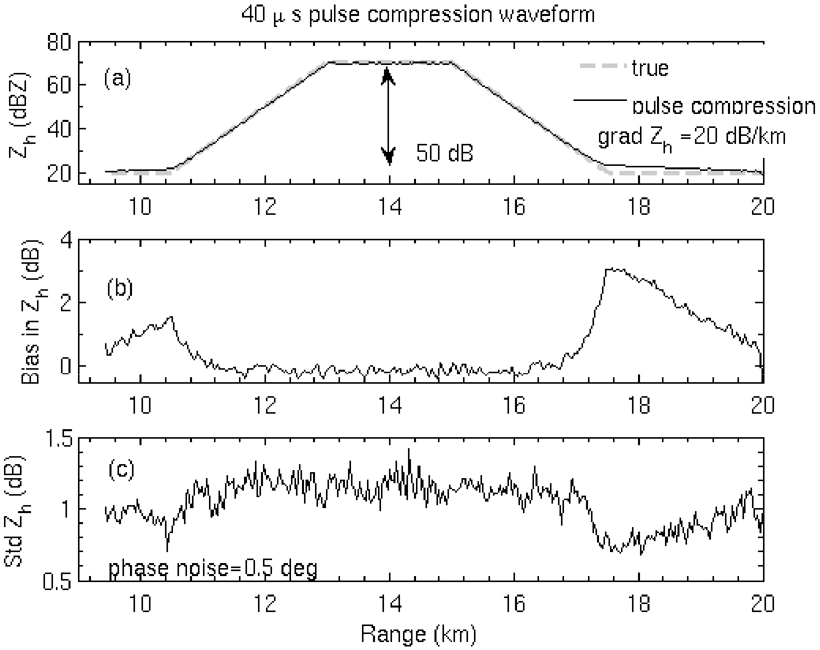


Sidelobe level as a function of Doppler velocity and system phase noise obtained using a minimum ISL compression filter

Impact of Sidelobe Level on Reflectivity

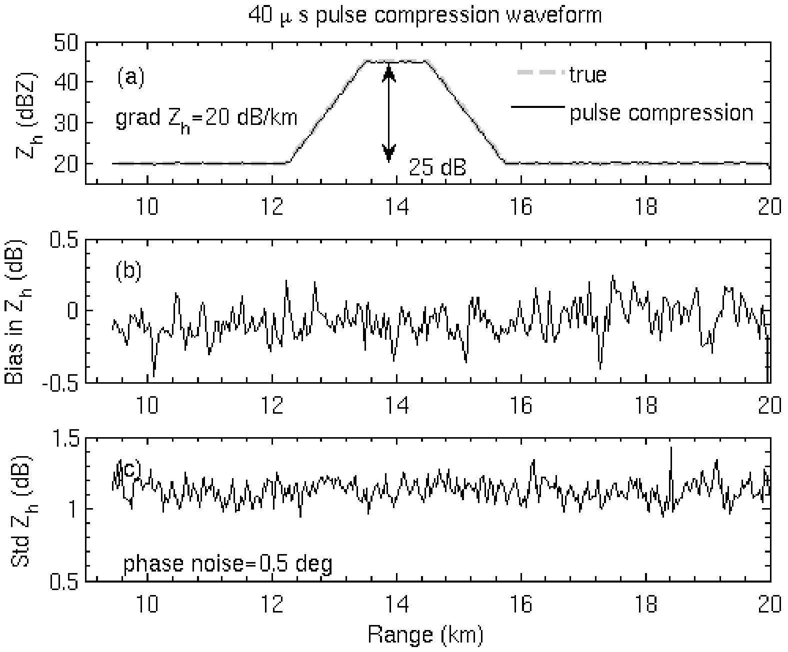


Error in reflectivity with a 50 dB rise with 20 db/km gradient using a 40 microsecond pulse compression waveform with phase noise = 0.0 deg

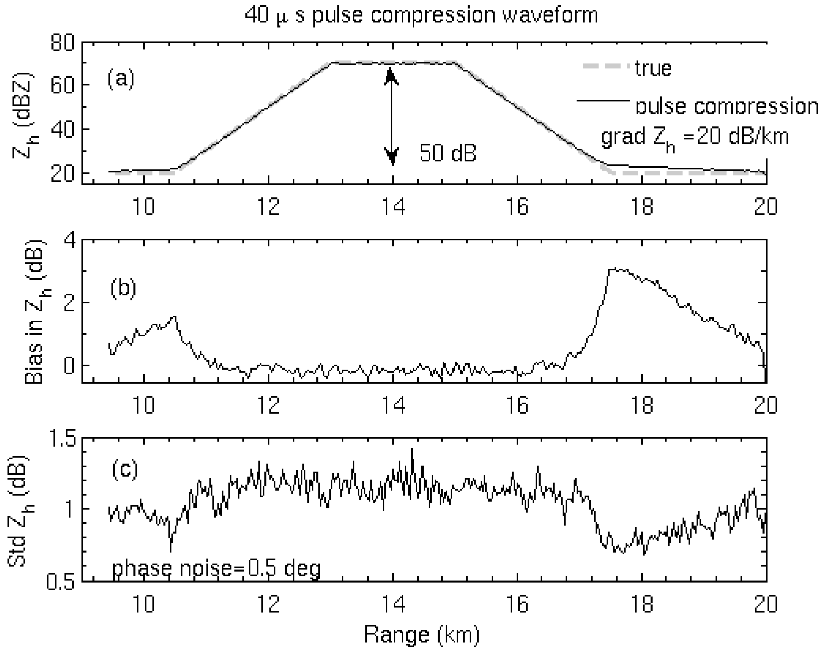


Error in reflectivity with a 50 dB rise with 20 db/km gradient using a 40 microsecond pulse compression waveform with phase noise = 0.5 deg. Phase noise of 0.5 deg results in ~ -45 dB ISL

Impact of Sidelobe Level on Reflectivity

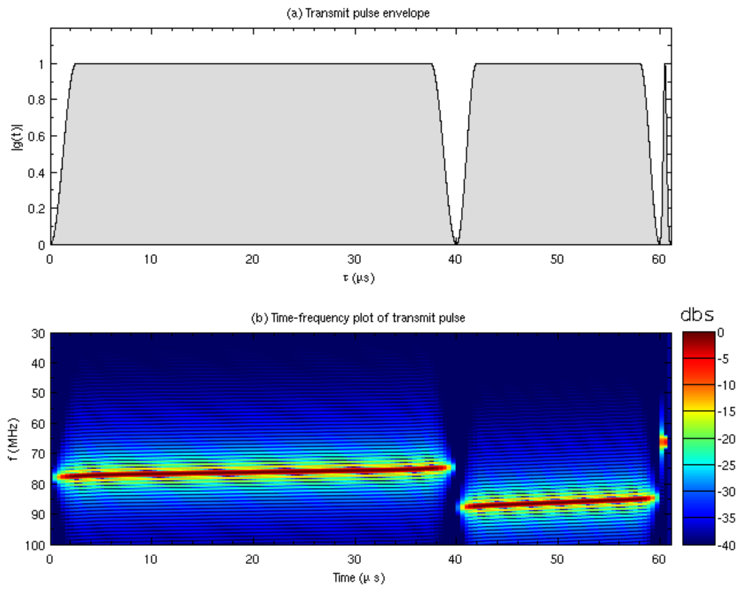


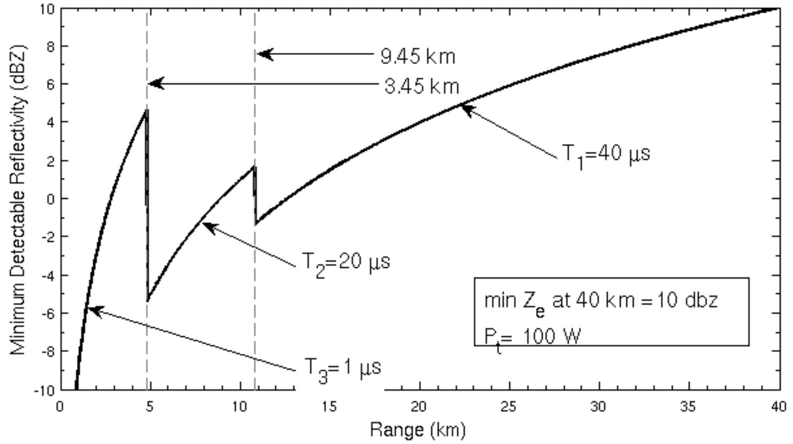
Error in reflectivity with a 25 dB rise with 20 db/km gradient using a 40 microsecond pulse compression waveform with phase noise = 0.5 deg. Phase noise of 0.5 deg results in ~ -45 dB ISL



Error in reflectivity with a 50 dB rise with 20 db/km gradient using a 40 microsecond pulse compression waveform with phase noise = 0.5 deg. Phase noise of 0.5 deg results in ~ -45 dB ISL

Frequency Diversity Pulse Compression





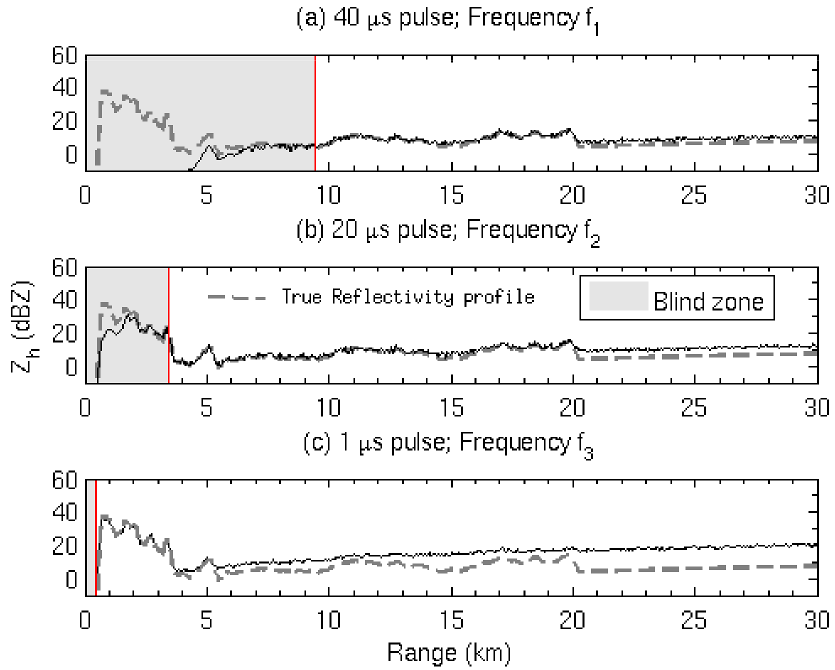
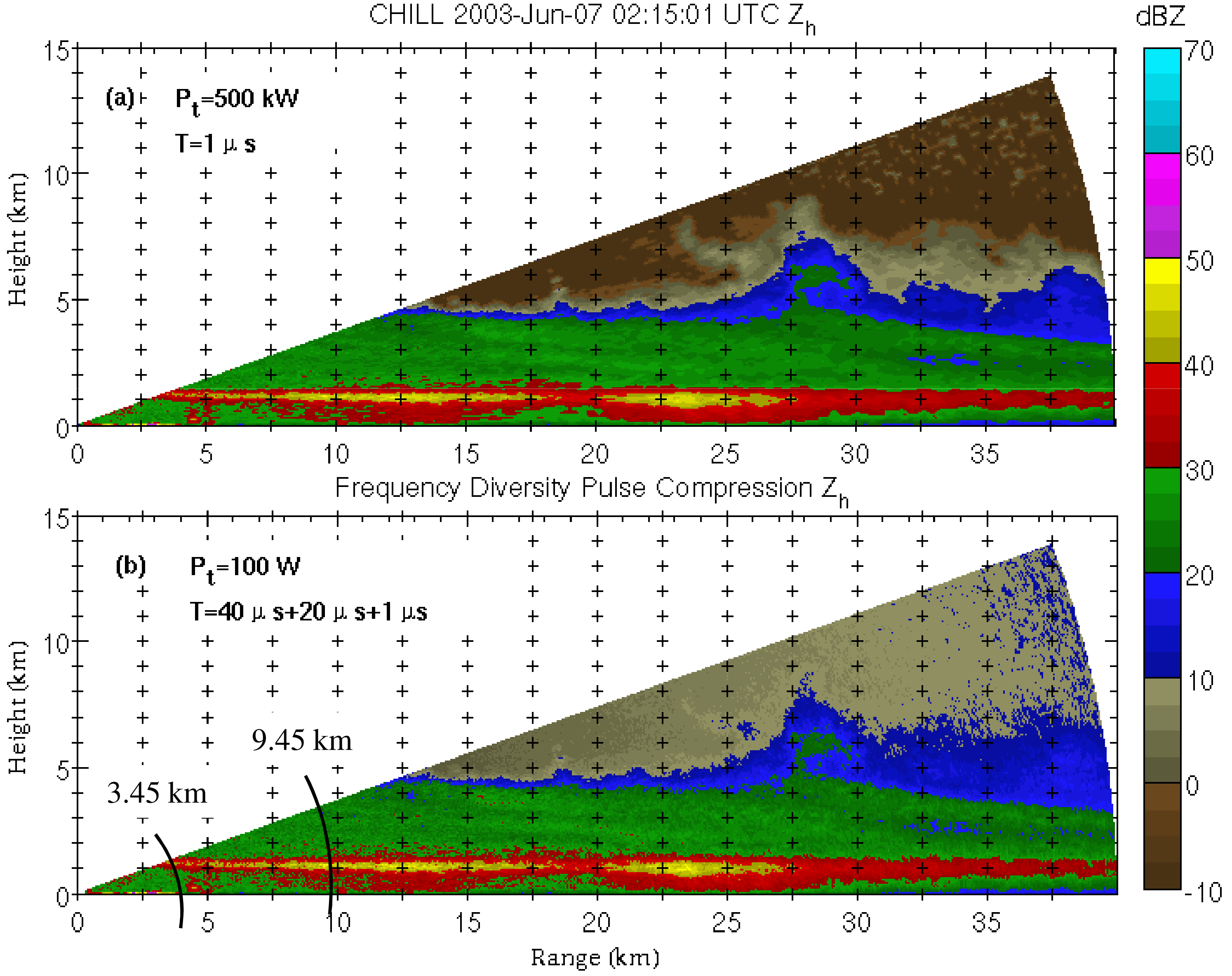


Table 7.1: Frequency diversity pulse compression waveform

Parameter	$i = 1$	$i = 2$	$i = 3$
Frequency	f_1	f_2	f_3
Pulse width, μs	40	20	1
Chirp bandwidth, MHz	3.6	3.6	-
Tukey window tuning	0.1268	0.1944	-
k_T	0.0543	0.3274	-
k_B	0.5	0.4920	-

Frequency Diversity Pulse Compression

Simulations (phase noise 0.25 deg) based on CSU-CHILL data



Summary(1/3)

- The primary motivation was the development of waveforms and retrieval algorithms for X-band system

- The performance of spectral processing in terms of standard deviations were presented
  - The standard deviation of the estimated spectral moments and polarimetric variables increase due to the application of processing widow
  - It is recommended to use time-domain methods where applicable

- Spectral clutter filtering for polarimetric radars was presented
  - Clutter suppression is improved by using spectral processing
  - The errors in estimated polarimetric variables is within acceptable level in the presence of spectral clutter filtering
  - Implementation with CSU-CHILL radar shows good performance in suppressing high clutter levels

Summary(2/3)

- A dual-PRF waveform is suggested for use on a X-band radar system
  - The dual-PRF waveform is used to measure high velocities
  - Spectral clutter filtering is performed on each PRF block and satisfactory results are obtained if more than 40 pulses are used
  - Phase coding the transmit pulses along with spectral processing is suggested to suppress overlaid echoes
  - A waveform table is provided to change the waveform based on scan speed
- The dual-PRF waveform was implemented with CASA's IP1 radars
  - The statistics of clutter suppression were presented from data collected during 2007 and 2008.
  - A clutter suppression of 30 dB was achieved with the IP1 radars and the limiting factor is the phase noise of the system
  - Statistics of overlaid echoes suppressed with random phase coding were presented. About 22 dB SNR of overlaid echoes were suppressed
  - The dual-PRF waveform provided unambiguous velocities in excess of 25 m/s

Summary(3/3)

v A frequency diversity pulse compression waveform was presented to mitigate the low sensitivity and blind range problems associated with solid-state radars

  v A non-linear pulse compression waveform was presented

  v Minimum ISL Compression filter provided low sidelobe level

  v The phase noise performance of pulse compression waveform was presented for a waveform

  v Frequency diversity is recommended to mitigate blind range

  v A simulation based on CSU-CHILL observation indicates good performance of the frequency diversity pulse compression waveform