S_X_MPL Signal Acquisition Modeling and Processing Lab

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Cognitive Sub-Nyquist Collocated MIMO Radar Prototype with Clutter Removal

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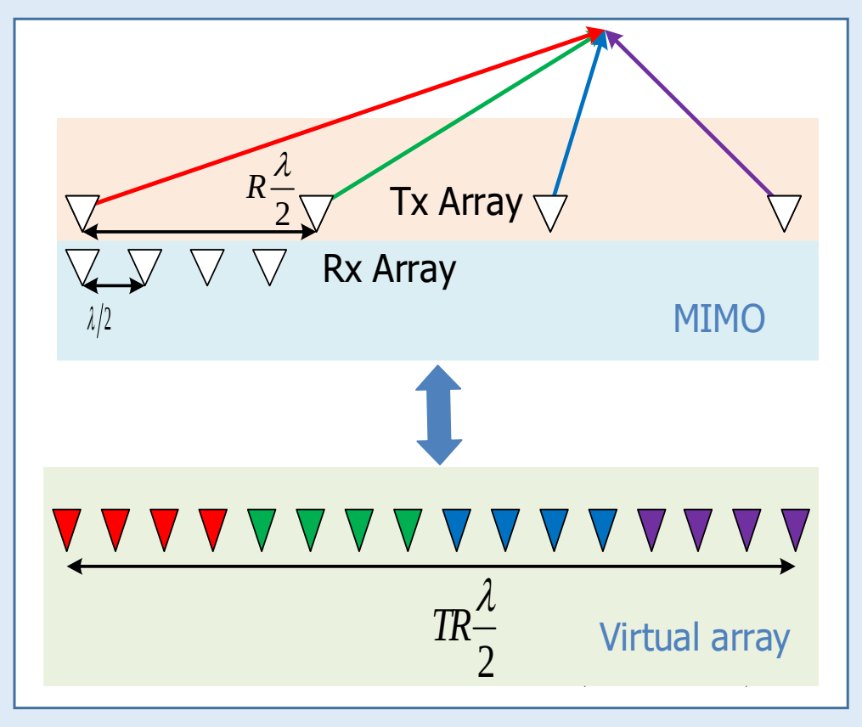
Main Contributions

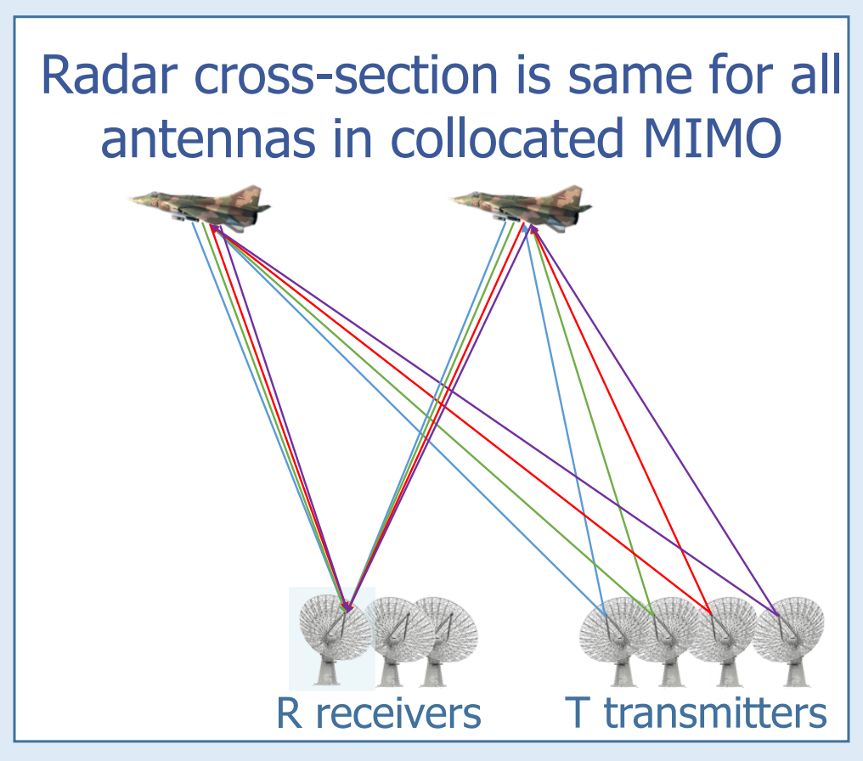
- Prototype realizes both spatial and temporal sub-Nyquist sampling in a MIMO radar without loss of angular and range resolution
- Sub-Nyquist 4x5 MIMO array shows same detection performance as Nyquist 8x10 ULA
- The Reduction rate is 75%
- Cognitive transmission is employed to further enhance SNR for sub-Nyquist arrays

Conventional Collocated MIMO

MIMO array with fewer elements has same spatial resolution as a virtual array with more elements



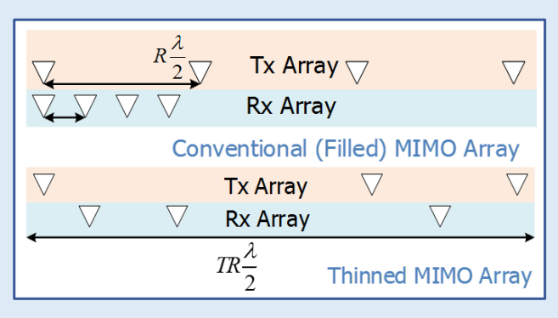
MIMO transmits orthogonal waveforms and processes linear combination of echoes received due to each waveform


Radar cross-section is same for all antennas in collocated MIMO

Sub-Nyquist MIMO

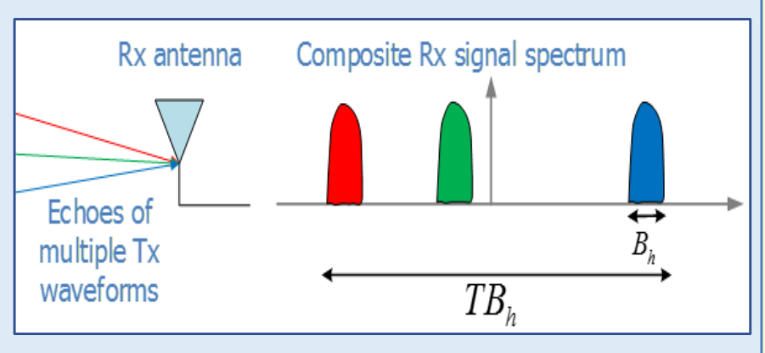
Spatial Sub-Nyquist

- Less antenna elements via randomly thinned arrays
- Same angular resolution as of virtual array



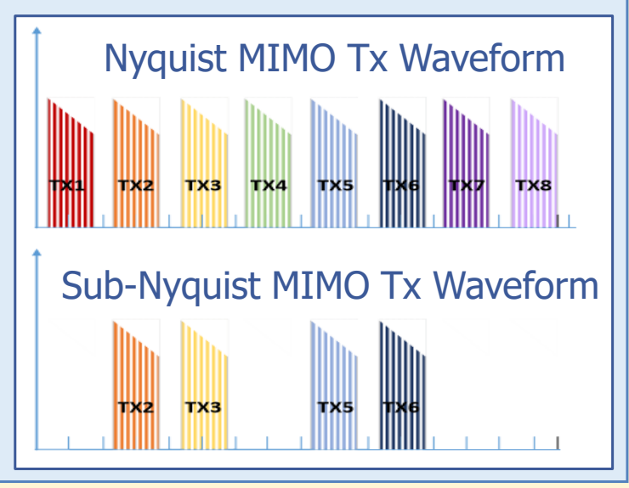
Temporal Sub-Nyquist

- Reduced sampling rate at each Rx
- Same range resolution as that of Nyquist bandwidth TB_h



Cognitive Transmission

- Entire power is focused in only few narrow subbands
- High SNR at receiver



Signal Model and Recovery

- Received signal for P pulses at the qth antenna after demodulation:

$$x_q(t)=\sum_{p=0}^{P-1}\sum_{m=0}^{M-1}\sum_{l=1}^{L}\alpha_l h_m(t-\tau_l-p\tau)e^{j2\pi\beta_{m,q}\theta_l}e^{j2\pi f_l^D p\tau}$$

Total number of Targets
Doppler Shift
Target time delay
Element location factor
Target Azimuth

- Fourier coefficients of the mth transmitter channel at the qth receiver:

$$y_{m,q}^p[k]=\sum_{l=1}^{L}\alpha_l e^{j2\pi\beta_{m,q}\theta_l}e^{-j\frac{2\pi}{\tau}k\tau_l}e^{-j2\pi f_m\tau_l}e^{j2\pi f_l^D p\tau}$$

Operating frequency
Target reflectivity

- Doppler focusing for a specific frequency v

$$\Phi_{m,q}^{\nu}[k]=\sum_{l=1}^{L}\alpha_l e^{j2\pi\beta_{m,q}\theta_l}e^{-j\frac{2\pi}{\tau}(k+f_m\tau)\tau_l}\times\begin{cases}P & |f_l^D-\nu|<1/2P\tau\\ 0 & else\end{cases}$$

- Use OMP for simultaneous sparse 3D recovery with focusing

Technical Specification

	Nyquist (Mode 1)	Sub-Nyquist (Mode 3)	Reduction
BW per Tx (incl. guard-bands)	15 MHz	3 MHz	80%
BW per Tx (excl. guard-bands)	12 MHz	3 MHz	75%
Temporal sampling rate	30 MHz	7.5 MHz	75%
Spatial sampling	8x10	4x5	50%
# Tx/Rx channels	80	20	75%
Total Bandwidth	120 MHz	12 MHz	90%

Clutter Model

The received signal $r_q(t)$ at the q^{th} antenna is $r_q(t)$=$x_q(t)$+$y_q(t)$+$n_q(t)$

The clutter amplitude in the angular range $[\theta-\epsilon,\theta+\epsilon)$ is

$$\alpha_c=\frac{1}{2\pi}\int_{\theta-\epsilon}^{\theta+\epsilon}S_c(\theta)d\theta$$

where $S_c(\theta)$ is the clutter amplitude density at angle θ. $a_c{\sim}N(a_c,\sigma_c^2)$

The delays $\tau_c\sim U(0,\tau)$,
DoA $\phi_c\sim U(-1,1)$ and
clutter Doppler spectrum $\nu_n{\sim}N(v_s,\sigma_d^2)$ are i.i.d.

Clutter Mitigation

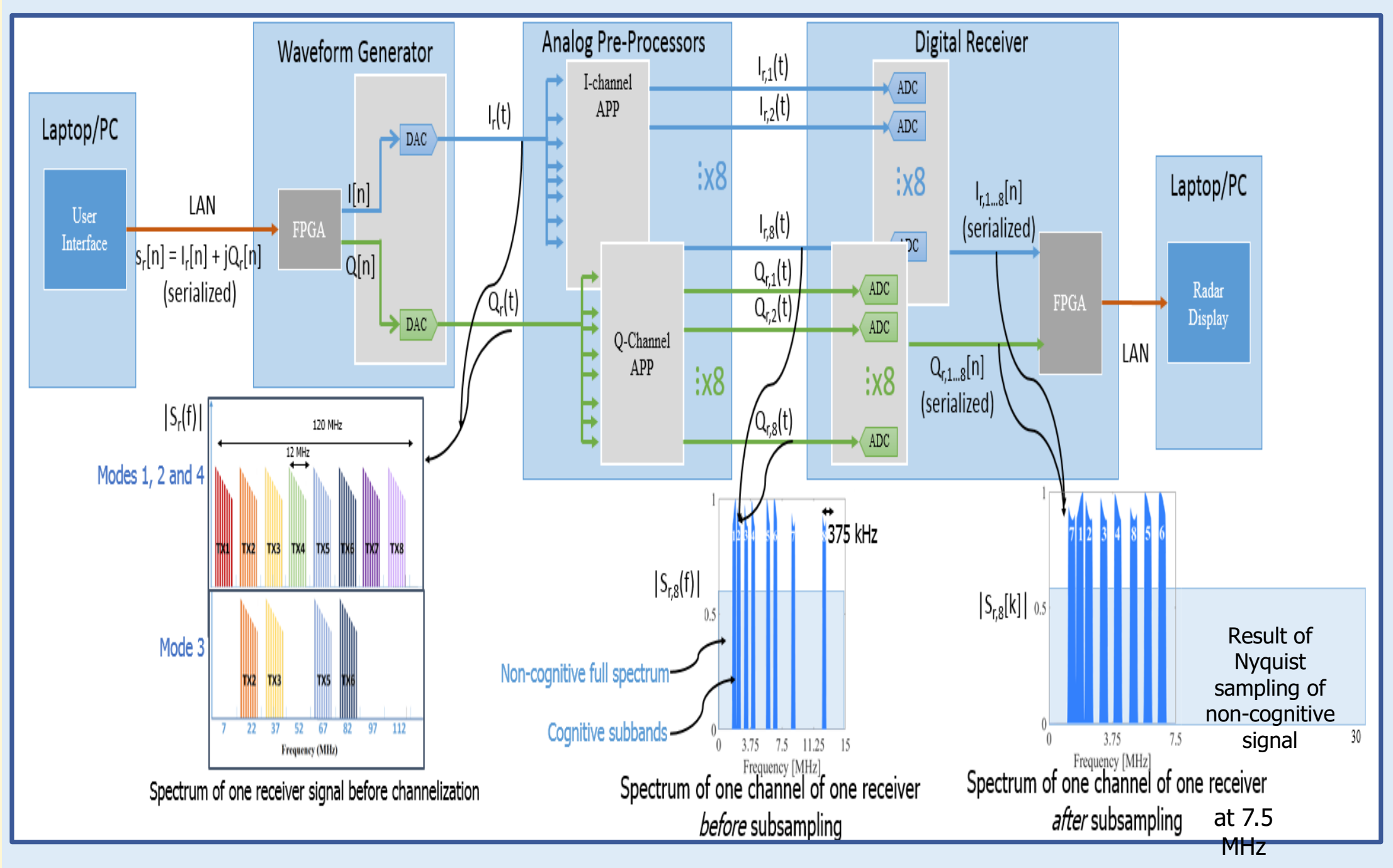
$Z_m{}^T$=P X KQ is the clutter plus noise matrix with columns $z_{m,1},z_{m,2},\ldots,z_{m,KQ}$

m is number of Transmitters
P is number of pulses
Q is number of receivers
K is randomly chosen group of coefficients

Four stages for clutter whitening

1. Subtracting the mean :
$R_m^T-E[Y_m^T+N_m^T]=X_m^T+Z_m^T-E[Y_m^T+N_m^T]$ or $\tilde{R}_m=X_m^T+\tilde{Z}_m$
2. Reshaping : $\tilde{Z}_m$ is reshaped from a $P{\times}KQ$ matrix to $PQ{\times}K$ matrix or $\hat{Z}_m$ is a $PO{\times}K$ clutter-plus-noise matrix. $\tilde{R}_m$ is reshaped to $\hat{R}_m$
3. Whitening : The covariance matrix of the q^{th} column $\hat{z}_{pq,k}$ of $\hat{Z}_m$ is a $PQ{\times}PQ$.
Toeplitz matrix: $D_m=E\left[\hat{z}_{pq,k}\overline{\hat{z}_{pq,k}}\right]$
Whitened measurements: $D_m^{-1/2}\hat{R}_m=D_m^{-1/2}X_m^T+W_m^T$
where W_m is white noise.
4. Signal recovery : Transpose the above equation to get the desired form and proceed with the Doppler focusing followed by the sub-Nyquist MIMO recovery algorithm.

Overview of Hardware Architecture



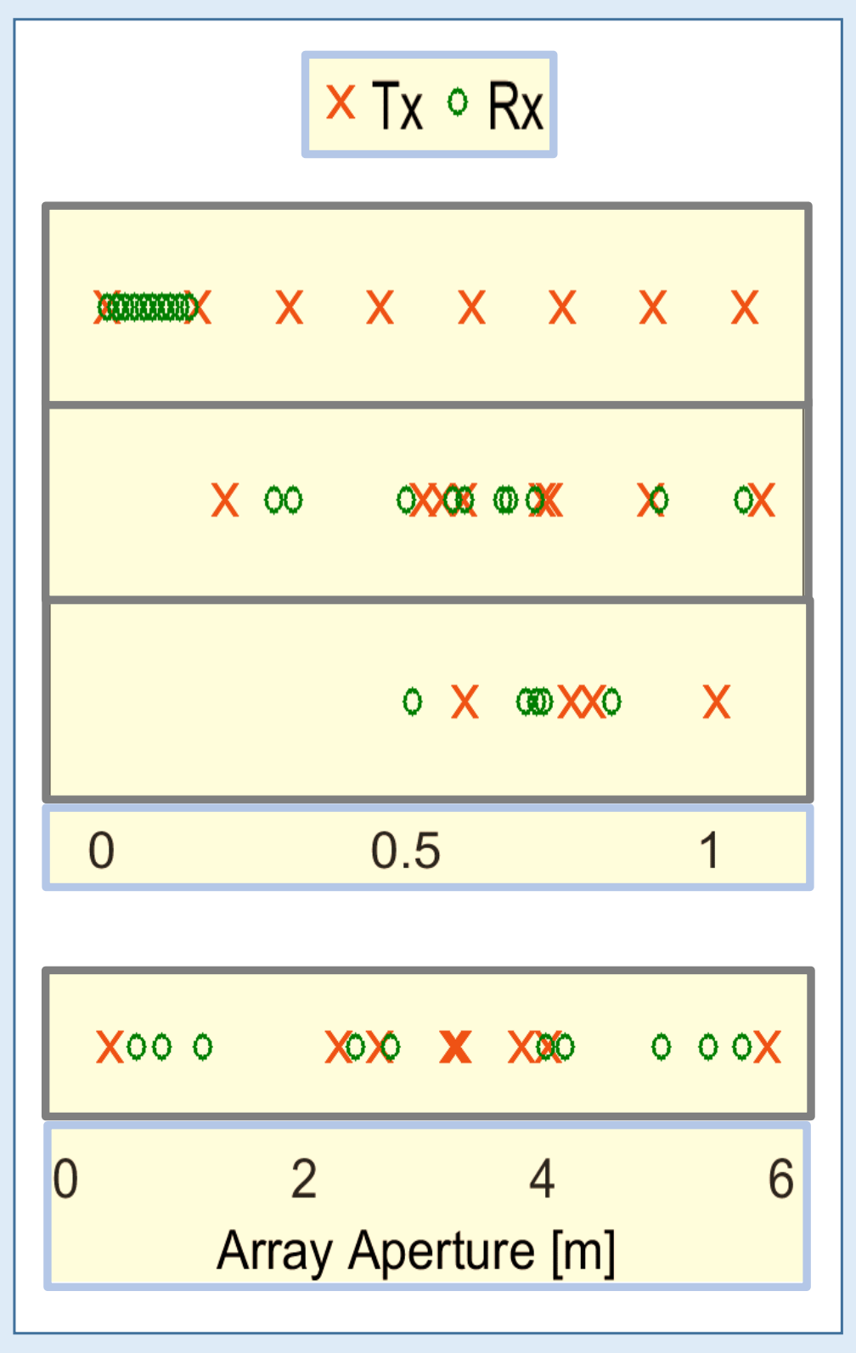
Array Modes

Mode 1: 8x10
Filled uniform array

Mode 2: 8x10
Filled random array

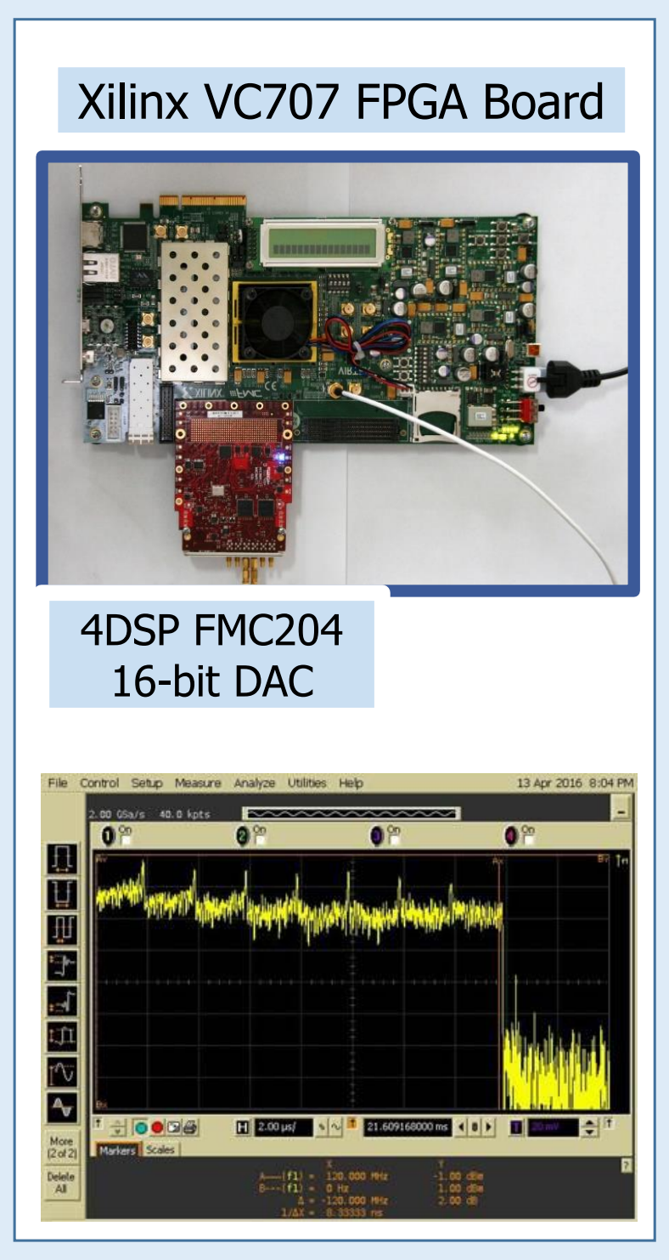
Mode 3: 4x5
Thinned random array
(~Virtual 8x10 ULA)
Spatial sub-Nyquist

Mode 4: 8x10
Thinned random array
(~Virtual 20x20 ULA)



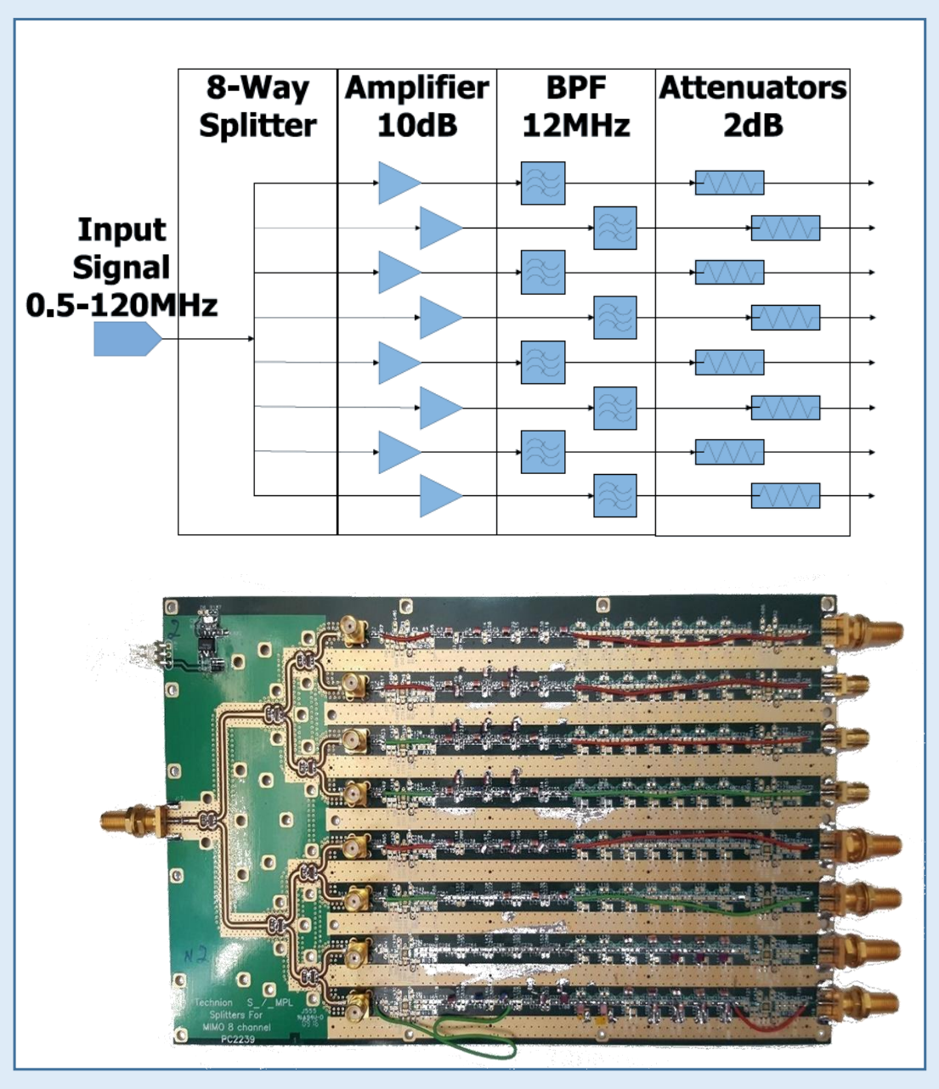
Waveform Generator

- Total BW, 8 Tx: 120 MHz
3 MHz guard-bands
- Eight 375 kHz cognitive slices per Tx
- Cognitive BW, 1 Tx:
3 MHz (= 8 x 375 kHz)
- BW reduction, 1 Tx (excl. guard-bands): 75% (3 of 12 Mhz)



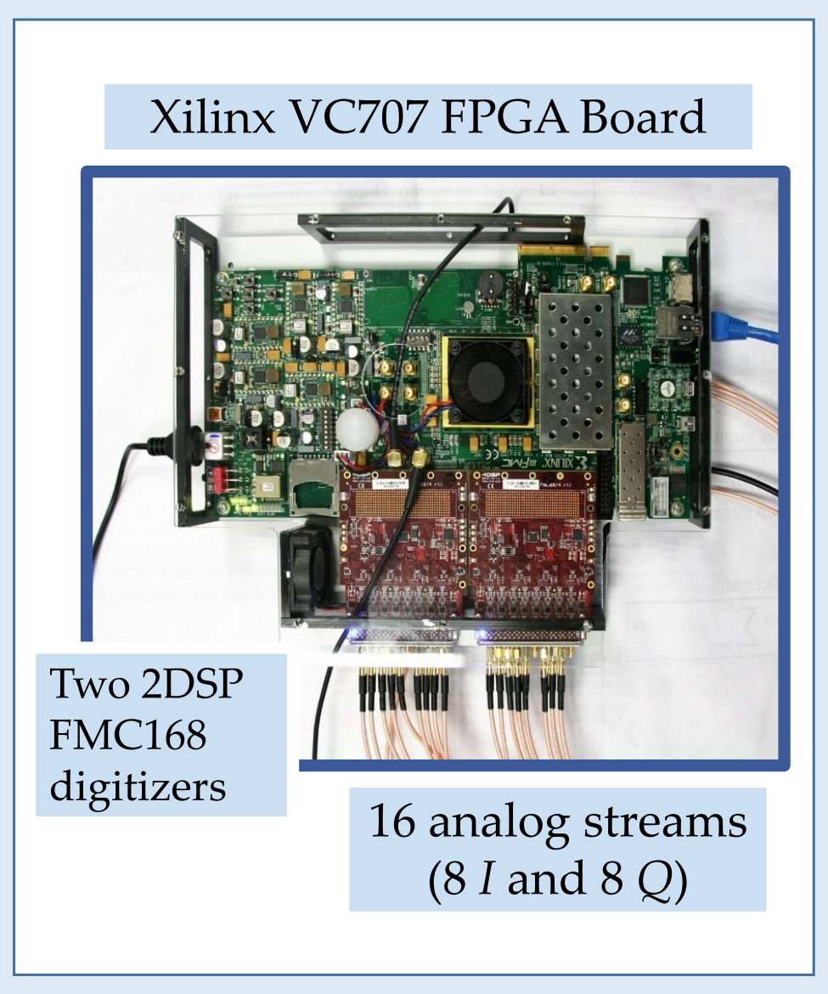
Analog Pre-Processor (APP)

- APP filters the receiver data into eight channels
- APP card in a single chassis
- BPFs have ~30 dB stopband attenuation to mitigate subsampling noise

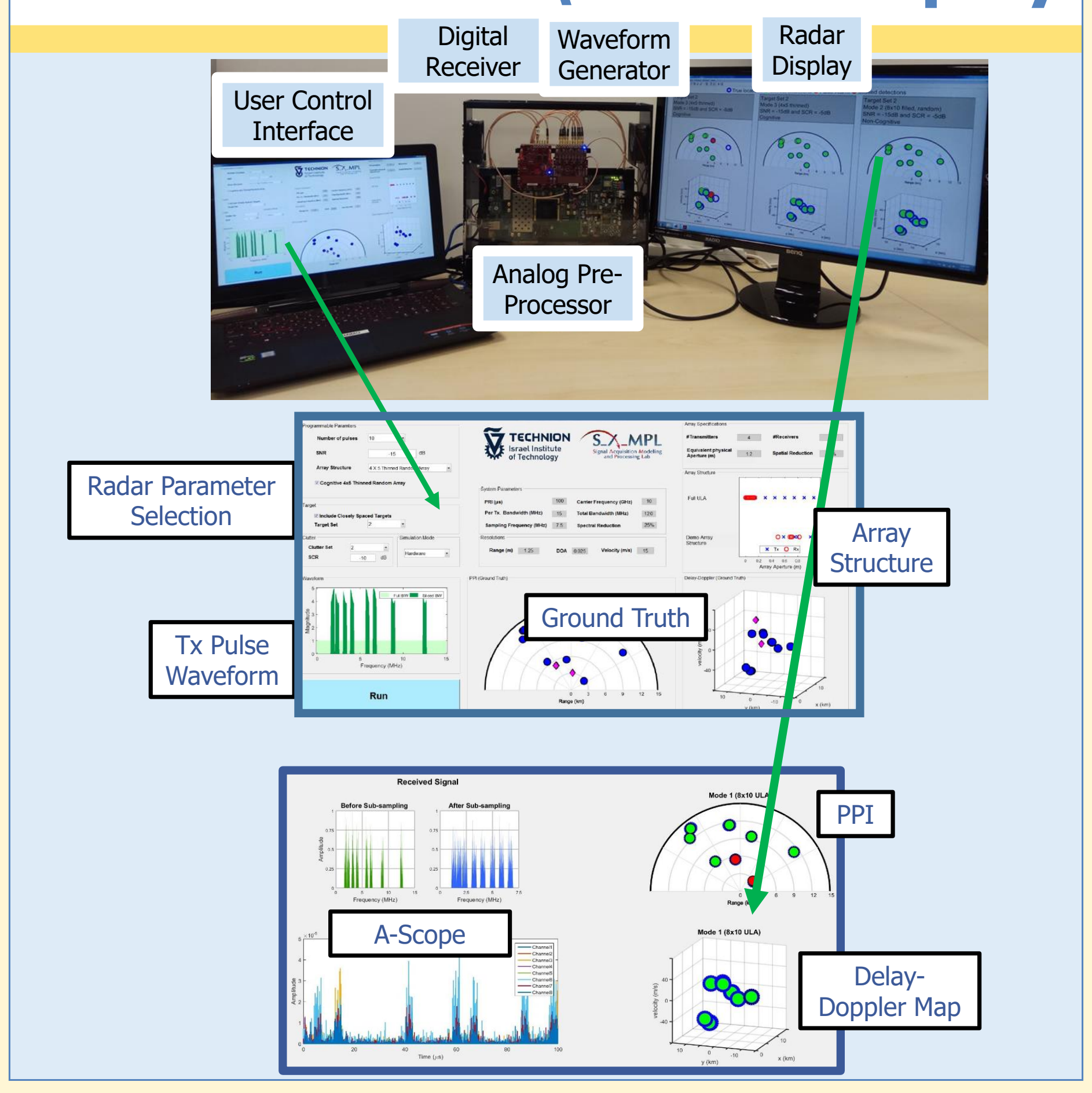


Digital Receiver

- Two 16-bit eight-channel digitizers for I and Q streams
- Sub-Nyquist sampling rate: 7.5 MHz/channel
- Signal BW with guard-bands: 30 MHz/channel

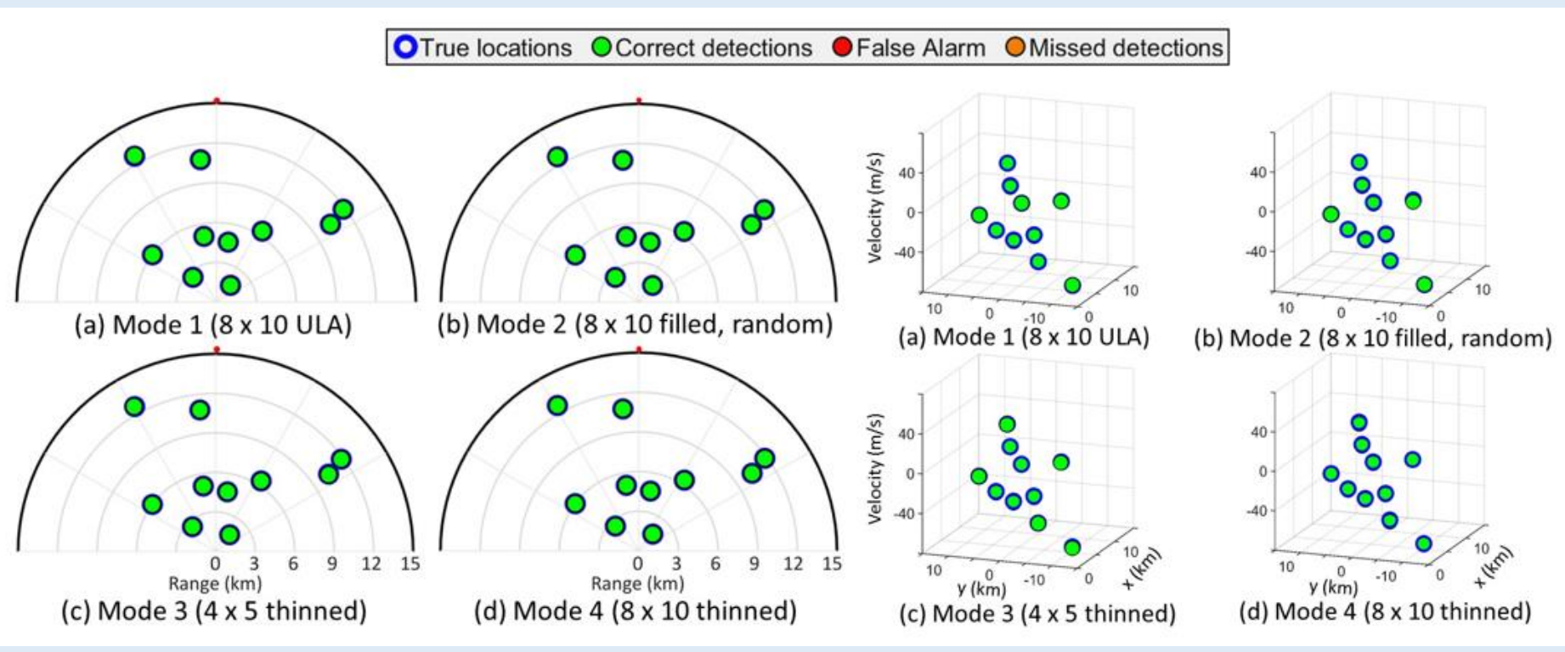


User Interface \ Radar Display



Sample Measurements Results

Randomly Placed Targets

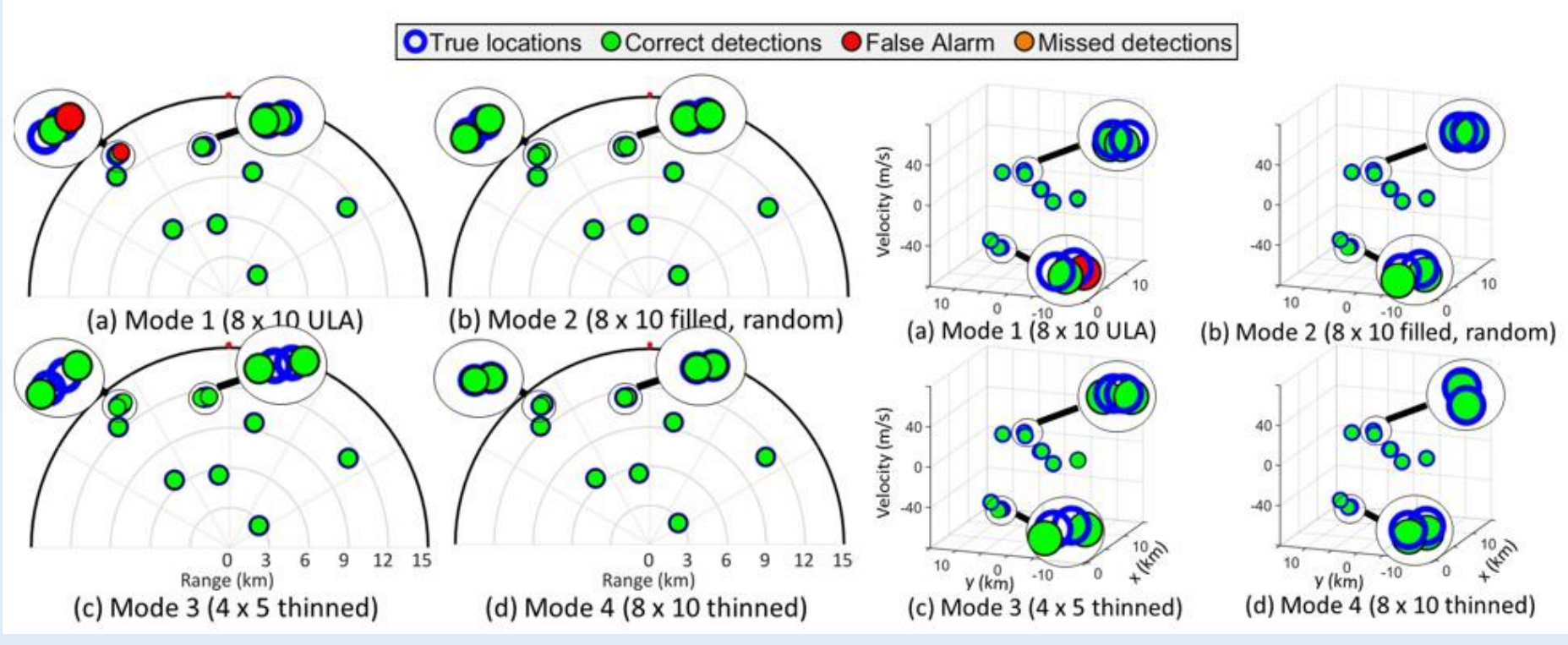


PPI Delay-Doppler Map

10 Targets	Min. angular spacing: 0.025	SNR = −15 dB

Mode 3 (sub-Nyquist) detection performance is same as that of Mode 1 (Nyquist)

Cognitive Sub-Nyquist Mode

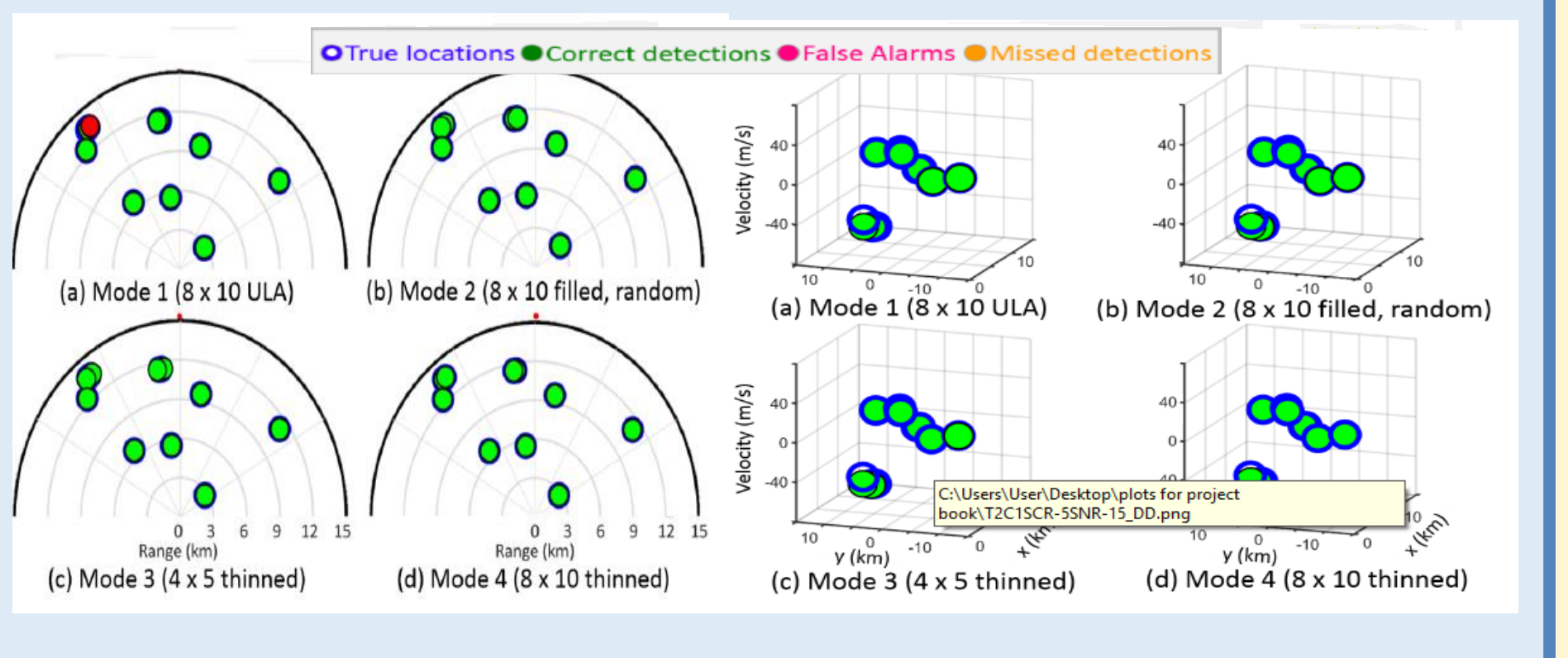


PPI Delay-Doppler Map

10 Targets	Min. angular spacing: 0.02	SNR = −15 dB

Cognitive mode 3 (sub-Nyquist 4x5) performs better than Nyquist in low SNR

Clutter removal with 1 clutter cloud



PPI Delay-Doppler Map

10 Targets	Min. angular spacing: 0.02	SNR = −15 dB

Cognitive mode 3 (sub-Nyquist 4x5) performs better than Nyquist in low SNR