Extended Space Doppler Processing for Non-Cooperative Ground Moving Target Imaging

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Introduction

Aim of the work

Define and test a technique for **imaging of moving targets in a SAR scene in presence of strong ground clutter**

Proposed solution

Joint E-SDAP - ISAR technique

E-SDAP: Extended Space Doppler Adaptive Processing
ISAR: Inverse Synthetic Aperture Radar

Outline

- **ISAR from SAR**:

  A solution based on ISAR processing for high resolution imaging of non-cooperative moving target in SAR images is introduced.

- **Detection Issues in Bistatic Configuration**:

  The problem of clutter non-stationarity along range dimension and clutter heterogeneity is addressed.

- **Extended Space Doppler Adaptive Processing**:

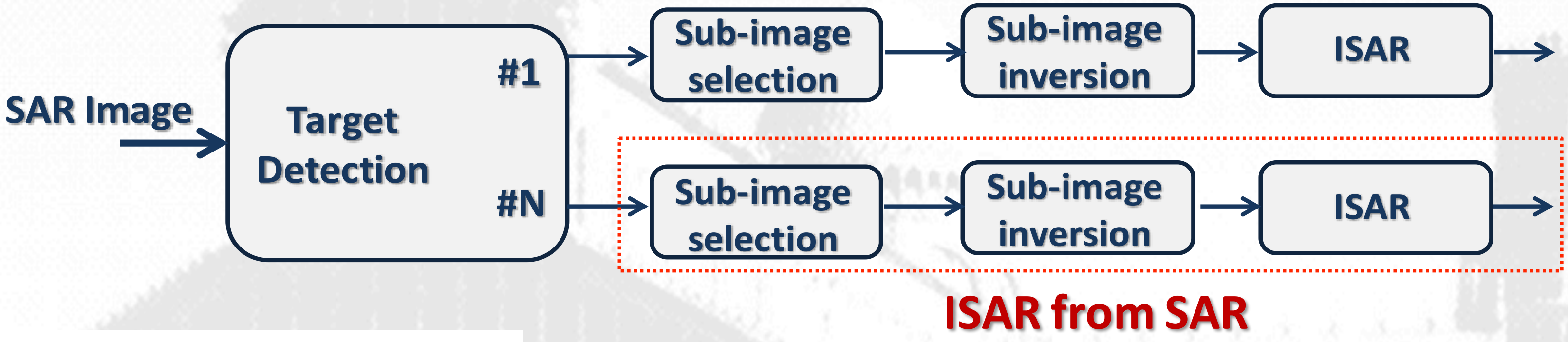
  Joint Extended-SDAP ISAR has been proposed for clutter suppression in strong non-stationary environment with high resolution imaging of non-cooperative moving target

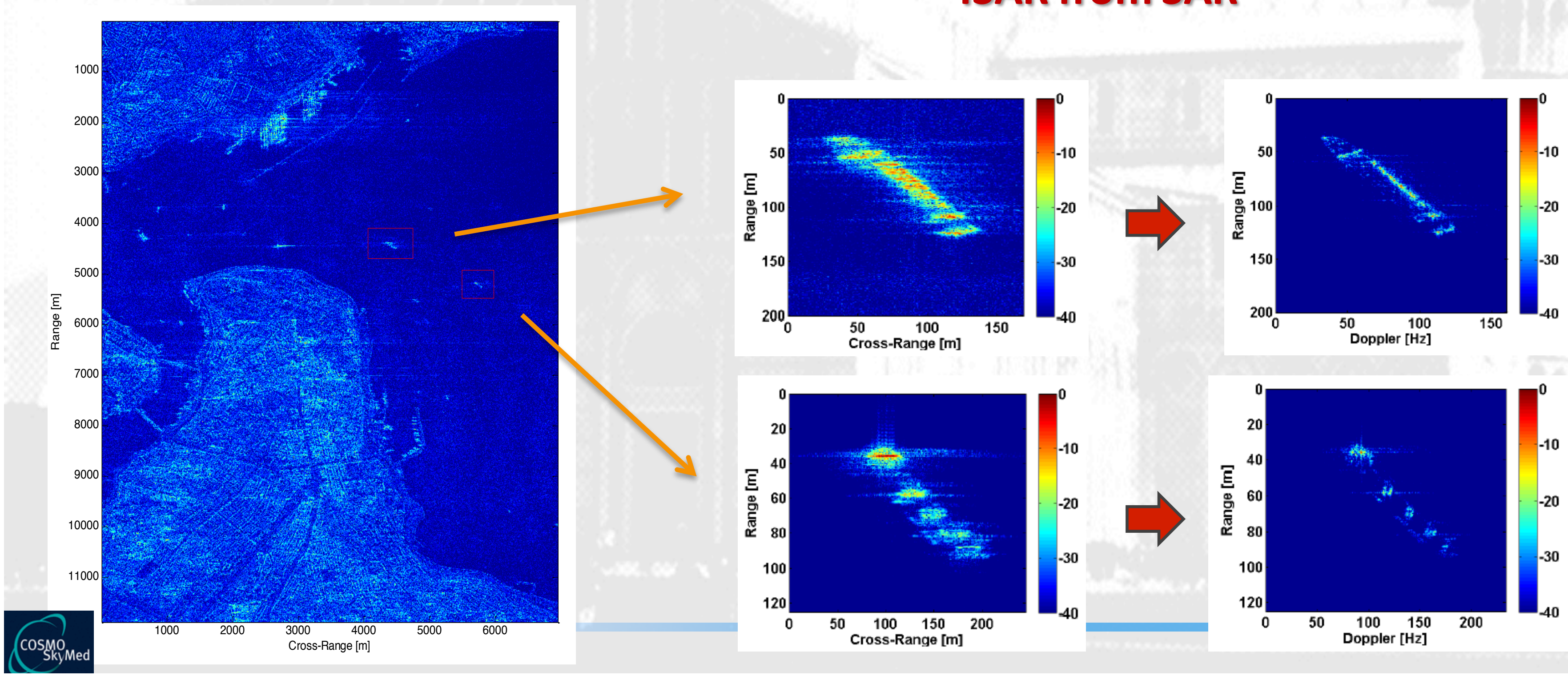
- **Results**:

  Results on simulated data are presented

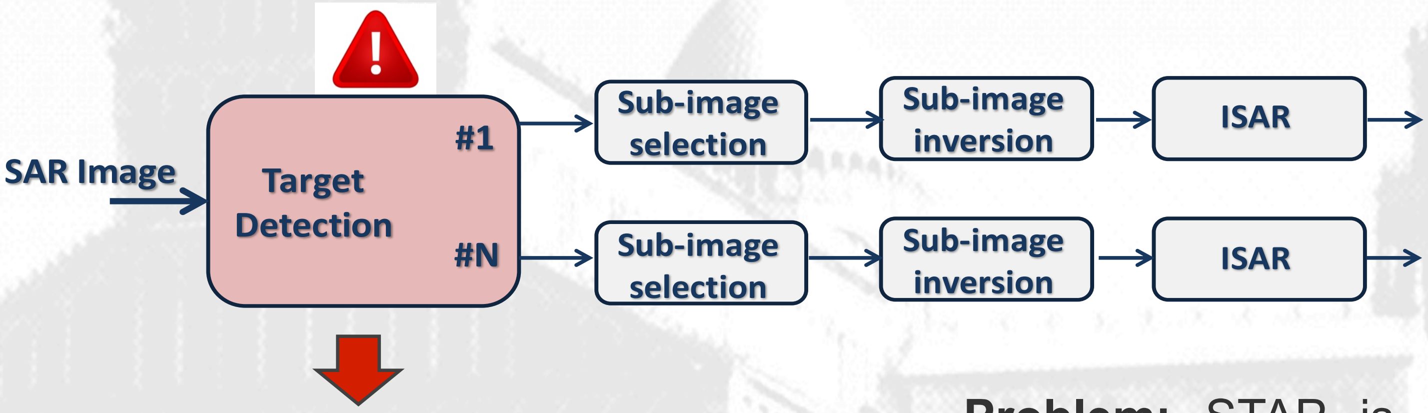
ISAR from SAR

- A solution based on ISAR processing to **compensate the unknown part of the relative motion between radar and non-cooperative target** is proposed





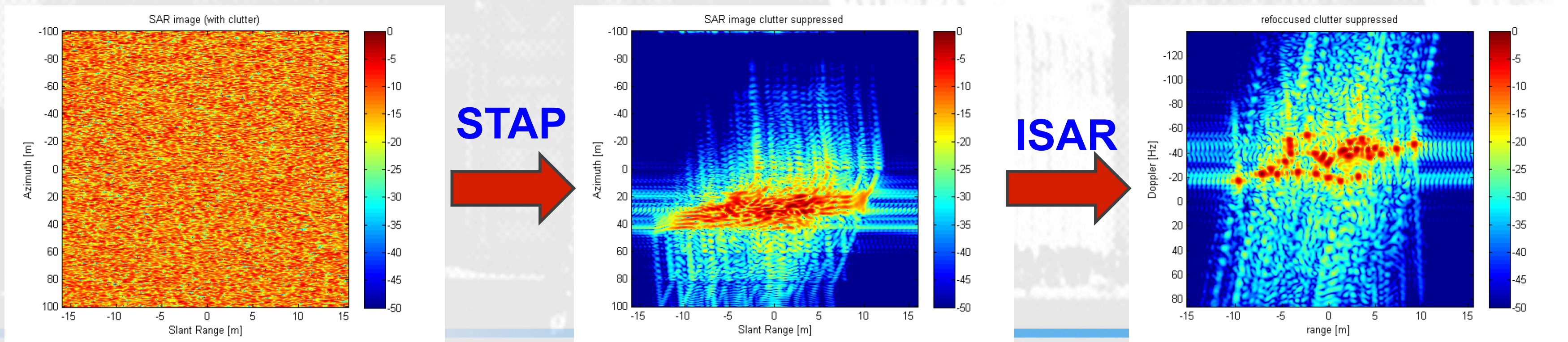
- ISAR processing can be applied after target detection
- **Detection of ground target embedded in strong ground clutter can be a critical issue**



Joint STAP-ISAR (monostatic)

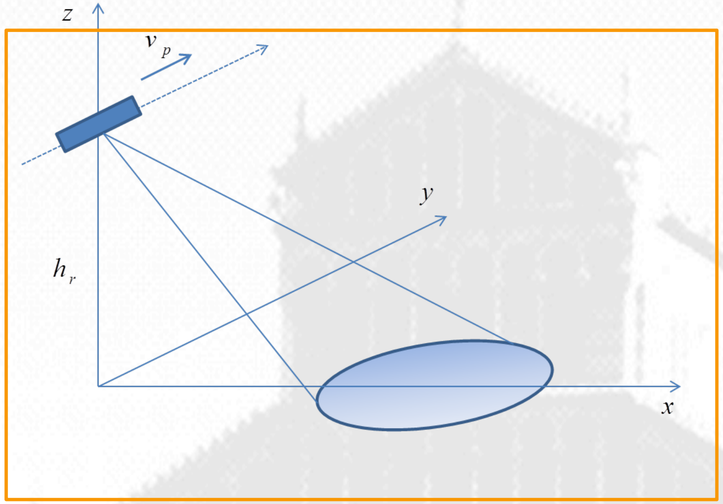
A. Bacci, M. Martorella, D. Gray, S.Gelli and F. Berizzi, "Virtual Multichannel SAR for ground target imaging " IET-RSN

Problem: STAP is conceived for stationary ground clutter

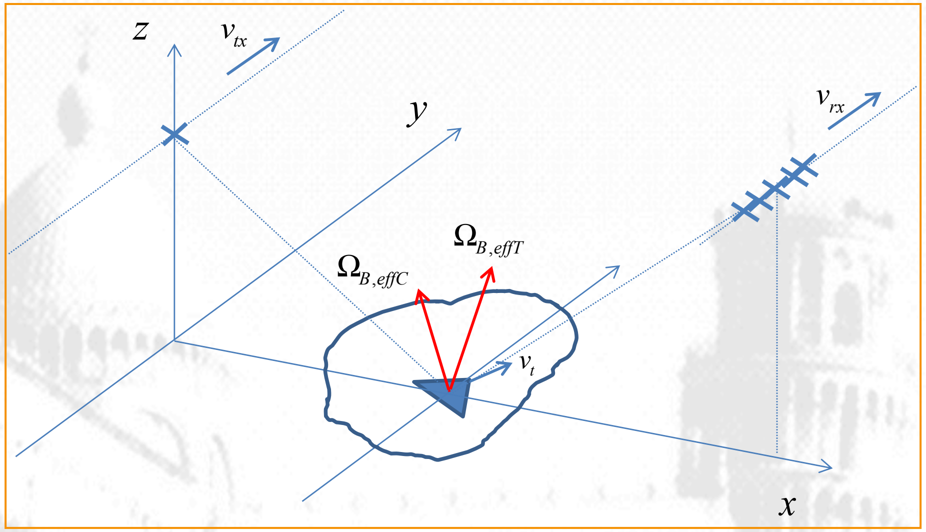


Detection issue: Multichannel SAR Signal

Acquisition geometry (monostatic)



Acquisition geometry (bistatic)



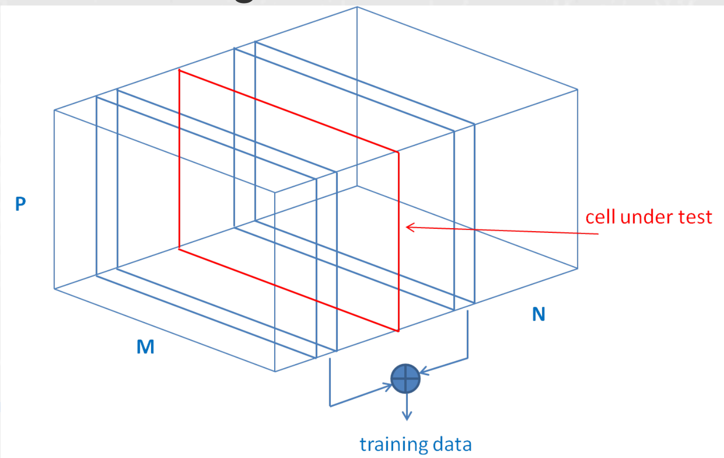
$$S_p(n,m) = S_{t,p}(n,m) + S_{c,p}(n,m) + N_p(n,m)$$

Target ↑ Clutter ↑ Noise ↑

$n = -\frac{N}{2},\ldots,\frac{N}{2}-1$ discrete sample in frequency domain

$m = -\frac{M}{2},\ldots,\frac{M}{2}-1$ discrete sample in slow-time domain

$p = -\frac{P}{2},\ldots,\frac{P}{2}-1$ Channel index



STACKING OPERATION

$$\mathbf{S}(n,m) = \left[S_1(n,m),\ldots,S_P(n,m)\right]^T \in C^{P\times 1}$$

$$\mathbf{S}(n) = \left[\mathbf{S}^T(n,0),\ldots,\mathbf{S}^T(n,M-1)\right]^T \in C^{MP\times 1}$$

Detection issue: Homogeneous Clutter Assumption

- Optimal STAP employ assumption **(restrictive)** of **statistically independent and identically distributed (IID) training data** in clutter covariance estimation

$$\mathbf{W}_{STAP}(n,m) = \delta \hat{\mathbf{R}}^{-1} \tilde{\mathbf{G}}(n,m) \in C^{MP\times 1}$$ **Weights**

$$\hat{\mathbf{R}} = \frac{1}{N_r} \sum_{n_r=1}^{N_r} \mathbf{Z}(n_r)\mathbf{Z}^H(n_r) \in C^{MP\times MP} \Rightarrow f(n,m) = \mathbf{W}_{STAP}^H(n,m)\mathbf{S}(n)$$ **STAP output**

$\tilde{\mathbf{G}}(n,m)$ Range-Time target matched filter (MF)

IID Hp

$$\mathbf{Z}(n_r) \sim N\left(0, \mathbf{R}_{n_r}\right)$$
$$\mathbf{R}_{n_r} \equiv \mathbf{R} \quad \forall n_r = 1 : N_r - 1$$

Homogeneous clutter assumption

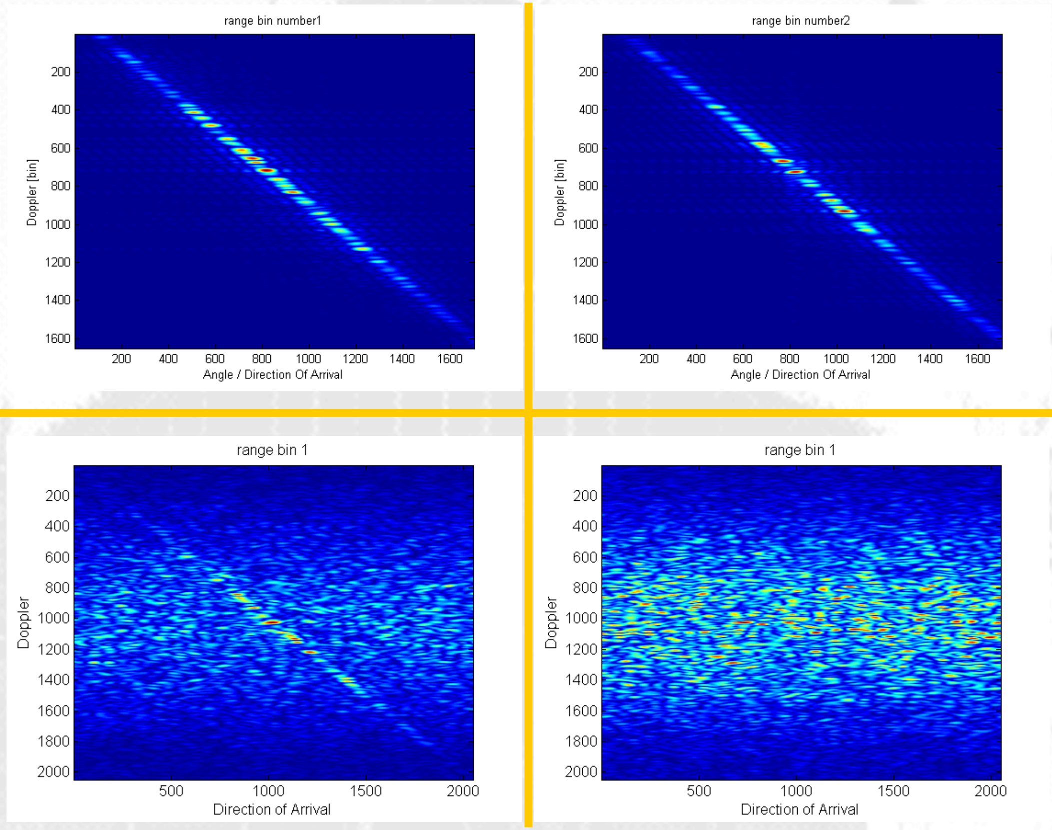
- $N_r = 2PM$ training data around the CUT is required for an average performance loss of 3dB

$$\left.\begin{matrix} T_{obs} = 1s \\ PRF = 1KHz \end{matrix}\right\} \Rightarrow \begin{matrix} M = 1000 \\ P = 3 \end{matrix} \Rightarrow \begin{matrix} 2MP = 6000 \\ \delta_r = 0.5m \end{matrix} \Rightarrow$$ **Homogeneous Area of 3 Km**

- In general **temporally and spatial clutter variation** cause an alteration in clutter covariance estimation leading to **degradation of STAP performance**

Detection issue: Internal Clutter Motion

- The **Doppler shift of the stationary clutter seen by the moving platform varies with the look angle** results in the clutter ridge in the angle/Doppler plane



Homogeneous scenario
(IID assumption)

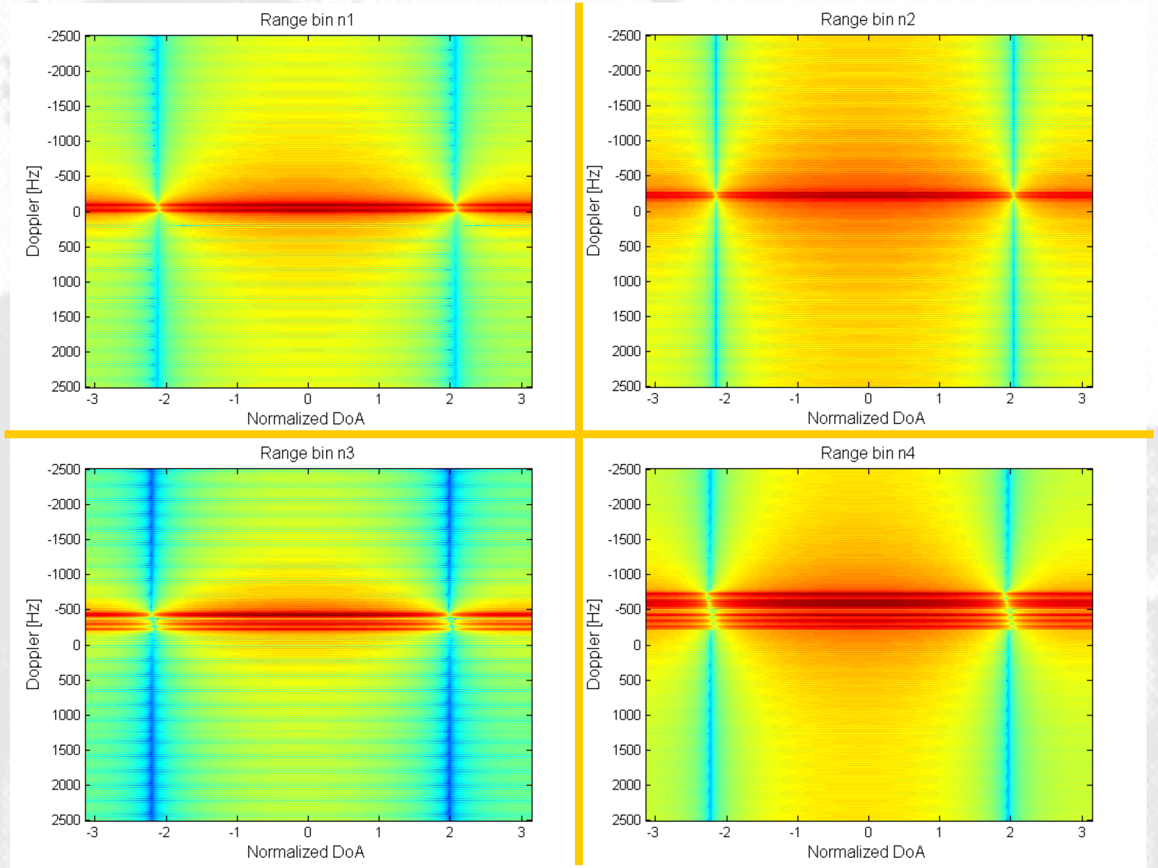
Heterogeneous scenario
(Degradation of STAP performance)

- The motion of objects (like tree leaves motion)cause a **pulse to pulse decorrelation** of the received clutter.
- In general **temporal and spatial variation in clutter** reflectivity produce a degradation of STAP performance. Sub-optimum approach can mitigate the effect of heterogeneity

Melvin, W. "Space-time radar performance in heterogeneous clutter", 2000, IEEE Transactions on Aerospace and Electronic Systems

Detection issue: Clutter Angle/Doppler behavior in bistatic geometry

- Clutter return exhibits a **range dependent Doppler shift that varies with platform velocity as well as the direction and the width of the antenna beam**



- **Bistatic Collection geometry influence clutter angle/Doppler response for a given range cell** and in general clutter behavior shows some degrees of variation along range n

E-SDAP: solution proposal

- **Range dependence breaks the IID assumption** degrading STAP performance

$$E\left[\hat{\mathbf{R}}\right] = \frac{1}{N_r}\sum_{n_r=1}^{N_r}\mathbf{Z}(n_r)\mathbf{Z}^H(n_r) = \frac{1}{N_r}\sum_{n_r=1}^{N_r}\mathbf{R}_{n_r}$$

$$\mathbf{Z}(n_r):\ CN(0,\mathbf{R}_{n_r})$$
$$\mathbf{R}_{n_{r1}} \neq \mathbf{R}_{n_{r2}}$$

- A possible way to take into account clutter range and Doppler frequency variation consist in **exploiting power series expansion of the instantaneous weight vector**

Extended Space Doppler Adaptive Processing (E-SDAP)

- **E-SDAP is derived** from multichannel **Space Doppler adaptive algorithm (SDAP)** and is structurally and algorithmically different from conventional bistatic STAP

- **E-SDAP perform space-time varying clutter suppression and platform motion compensation** leading to a defocused image of moving target

Joint E-SDAP ISAR

E-SDAP: SDAP description

In absence of ground stationary clutter…

$$S_p\left(n,m_D\right) = DFT_m\left\{S_p\left(n,m\right)\right\}$$

STACKING OPERATION

$$\mathbf{S}(n,m_D) = \left[S_1(n,m_D),\ldots,S_P(n,m_D)\right]^T \in C^{P\times 1}$$

$$\mathbf{S}(n) = \left[\mathbf{S}^T(n,0),\ldots,\mathbf{S}^T(n,M-1)\right]^T \in C^{MP\times 1}$$

RD processing

$$f_D\left(n,m_D\right) = \mathbf{G}^H\left(n,m_D\right)\mathbf{S}\left(n\right)$$

$\mathbf{G}\left(n,m_D\right)$ RD target matched filter (MF)

In presence of ground stationary clutter…

SDAP

$$f_D(n,m_D) = \mathbf{W}^H(n,m_D)\mathbf{S}(n)$$

$\mathbf{W}^H(n,m_D)$ Clutter whitening + RD-MF

$$\mathbf{W}(n,m_D) = \delta\hat{\mathbf{R}}_D^{-1}\mathbf{G}(n,m_D) \in C^{MP\times 1}$$

$$\hat{\mathbf{R}}_D = \frac{1}{N_r}\sum_{n_r=1}^{N_r}\mathbf{Z}(n_r)\mathbf{Z}^H(n_r) \in C^{MP\times MP}$$

SDAP **perform clutter suppression and platform motion compensation leading to a detect but unfocussed target**

Bacci, A. Gray,D. Martorella,M. Berizzi, F. "Joint STAP-ISAR for non-cooperative target imaging in strong clutter", 2013, IEEE RadCon

E-SDAP Processing

$$\tilde{\mathbf{W}}(n_r,m)=\tilde{\mathbf{W}}_0(n_r,m)+n_r\Delta\tilde{\mathbf{W}}(n_r,m)$$

Fixed and linearly time variable component model

$$\tilde{\mathbf{W}}(n,m)=DFT_{n_r}\{\tilde{\mathbf{W}}(n_r,m)\}$$

$$\tilde{\mathbf{W}}(n,m_D)=DFT_m\{\tilde{\mathbf{W}}(n,m)\}$$

- Filtering operation to avoid range cell migration
- **SDAP weights in the frequency Doppler domain**

Optimal Extended SDAP

$$F_{ESDAP}(n,m_D)=\tilde{\mathbf{W}}'^{H}(n,m_D)\tilde{\mathbf{S}}'(n)$$

$$\tilde{\mathbf{W}}'(n,m_D)=\begin{bmatrix}\tilde{\mathbf{W}}_0(n,m_D)\\ \Delta\tilde{\mathbf{W}}(n,m_D)\end{bmatrix}\in C^{2MP\times 1}$$

$$\tilde{\mathbf{S}}'(n,m_D)=\begin{bmatrix}\tilde{\mathbf{S}}(n,m_D)\\ n_r\tilde{\mathbf{S}}(n,m_D)\end{bmatrix}\in C^{2MP\times 1}$$

$$\tilde{\mathbf{W}}'(n,m_D)=\gamma'\tilde{\mathbf{R}}'^{-1}_{esdap}\tilde{\mathbf{G}}'(n,m_D)$$

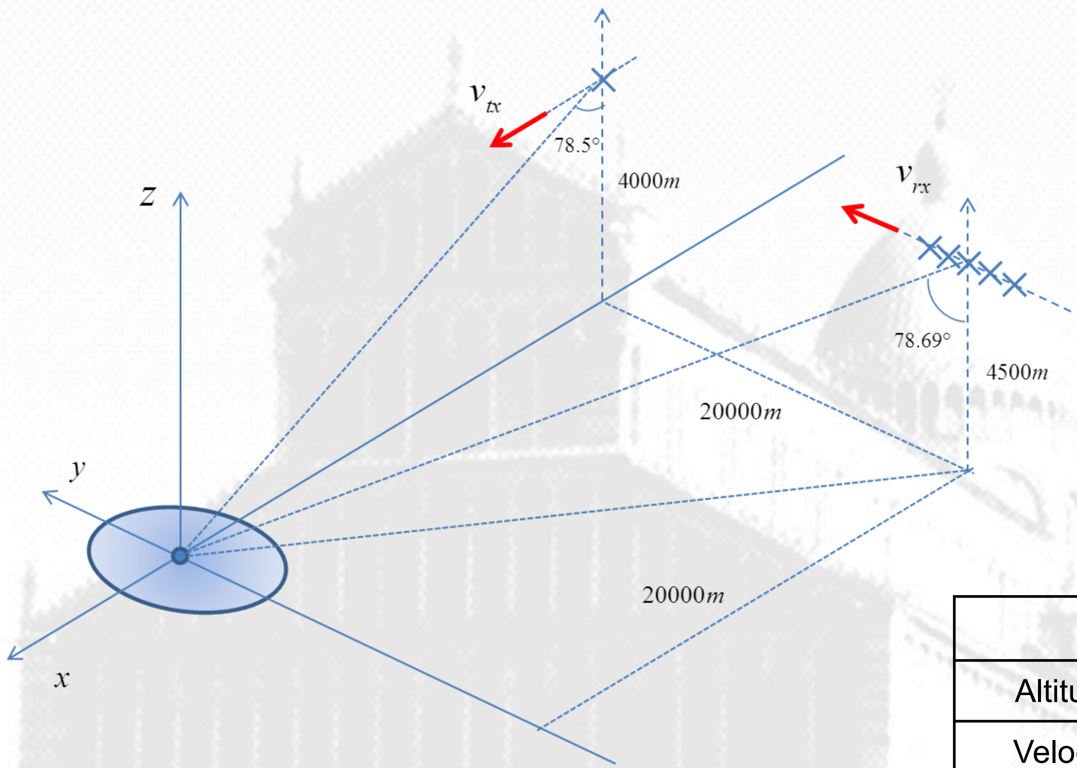
$$\tilde{\mathbf{G}}'(n,m_D)=\begin{bmatrix}\tilde{\mathbf{G}}(n,m_D)\\ 0\end{bmatrix}$$

$$\tilde{\mathbf{R}}'_{esdap}=\frac{1}{N_t}\sum_{n_t=1}^{N_t-1}\tilde{\mathbf{Z}}'(n_r)\tilde{\mathbf{Z}}^H(n_r)$$

$$\tilde{\mathbf{R}}'_{esdap}=\begin{bmatrix}\tilde{\mathbf{R}}_D^{(0)} & \tilde{\mathbf{R}}_D^{(1)}\\ \tilde{\mathbf{R}}_D^{(1)} & \tilde{\mathbf{R}}_D^{(2)}\end{bmatrix}$$

$$\tilde{\mathbf{R}}_D^{(k)}=\frac{1}{N_t}\sum_{n_t=1}^{N_t-1}n_r^k\tilde{\mathbf{Z}}(n_r)\tilde{\mathbf{Z}}^H(n_r)\in C^{MP\times MP}$$

Results: Simulated Scenario

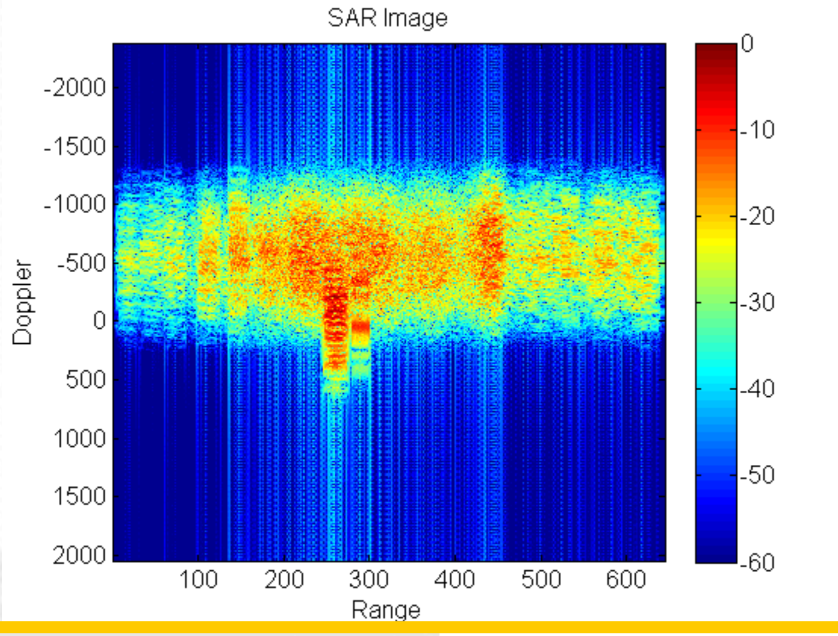


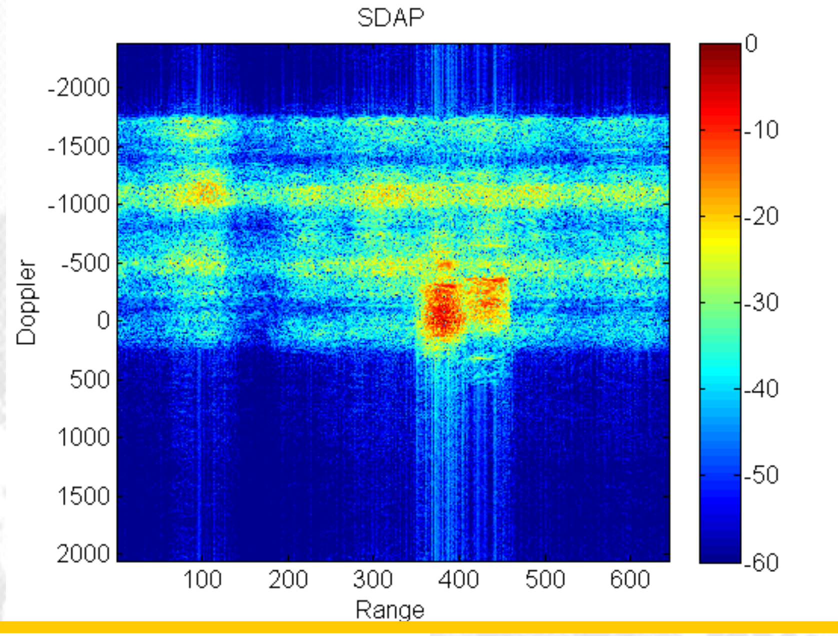
Center Frequency	9.6 GHz
Tx Bandwidth	500 MHz
Observation Time	0.2 sec
Channel Distance	0.015m
PRF	500 KHZ
Receiver Channels	3
Bistatic Angle	110°

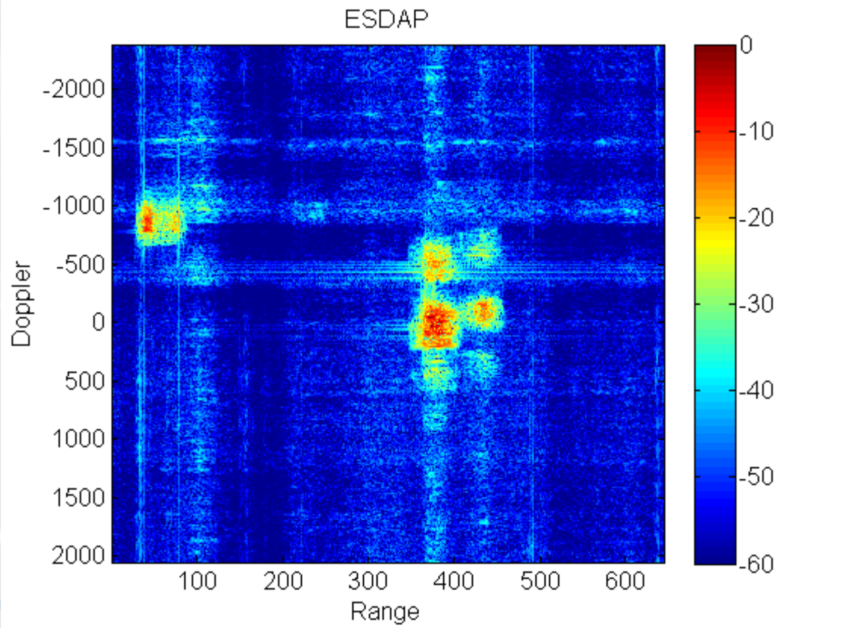
	Tx parameters	Rx parameters
Altitude	4000 m	4500 m
Velocity	50 m/s	60 m/s
Look Angle	78.6°	78.5°

- Dataset simulated by **Warsaw Institute of Technology** has been used
- Two slow moving targets are present: large truck (10m/s) and military truck (8m/s). A point-like target (3m/s) has also been added

Results: SDAP & E-SDAP applications

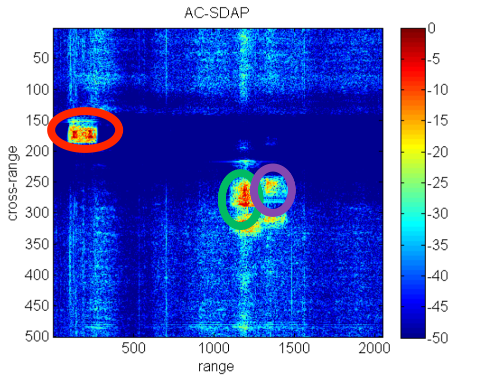






Cancellation of slow motion target

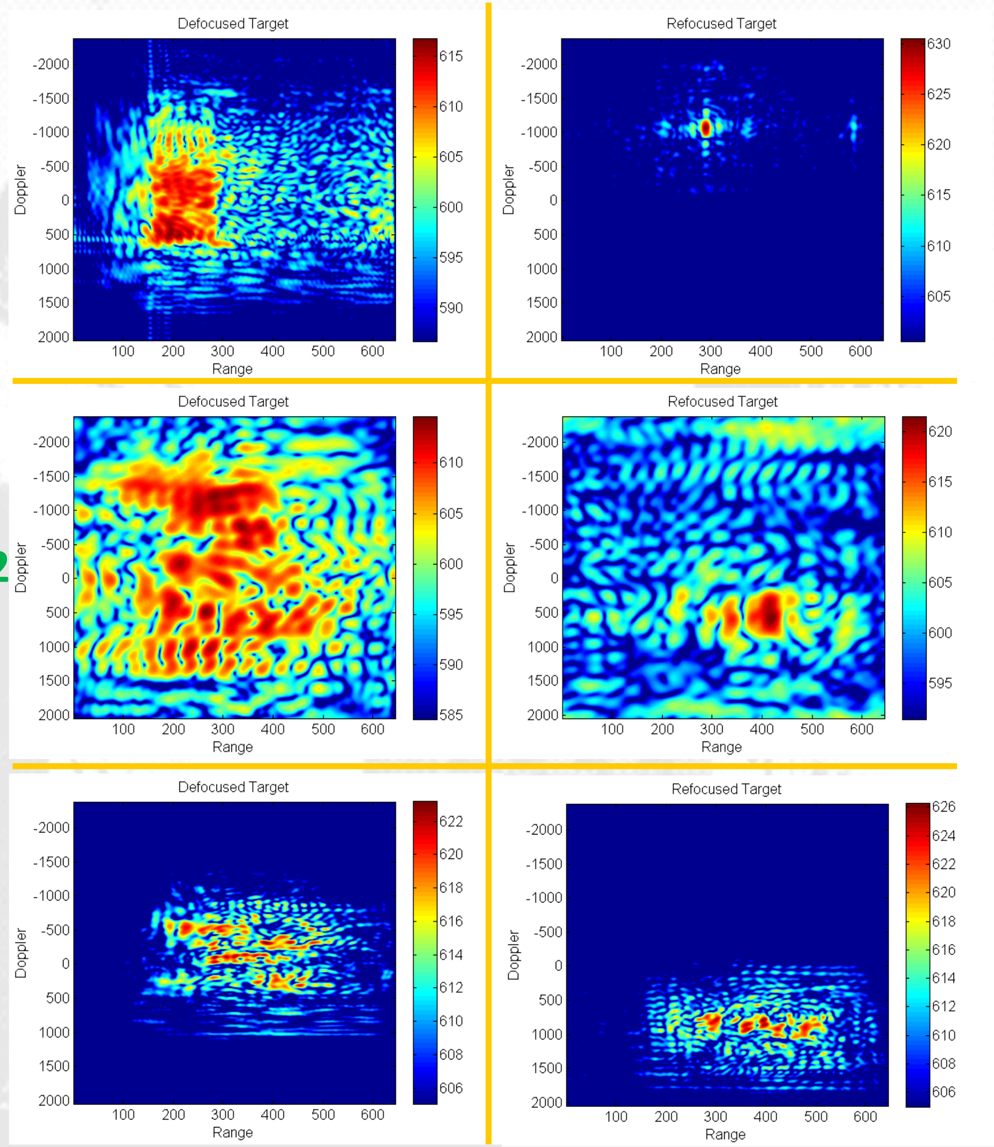
Results: ISAR Refocusing



TARGET 1

TARGET 2

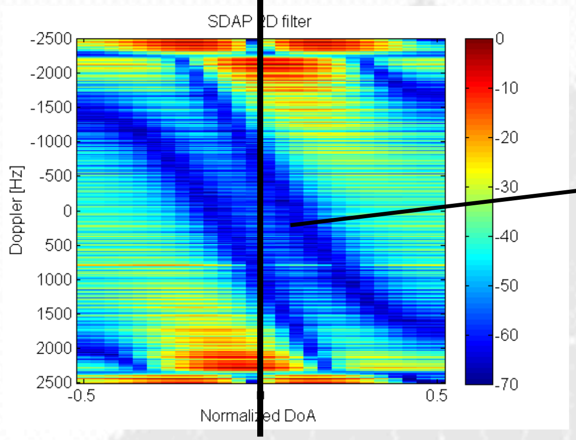
TARGET 3

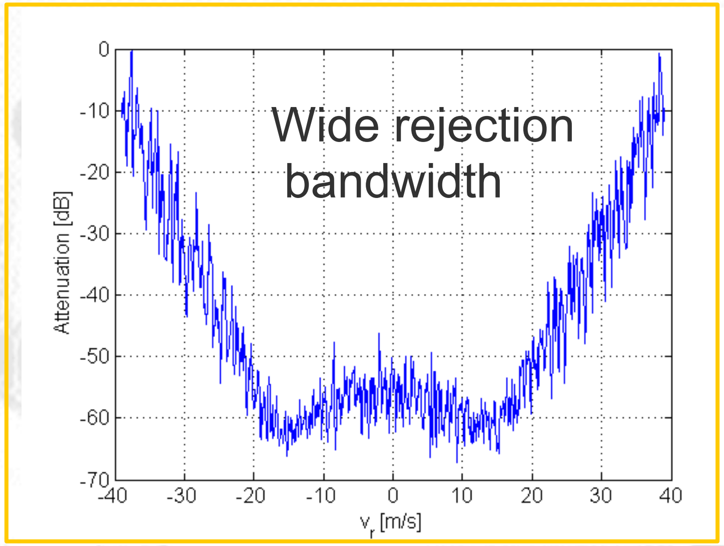


	SAR IC	ISAR IC
Crop1	2.55	19.28
Crop2	0.58	2.62
Crop3	1.81	2.79

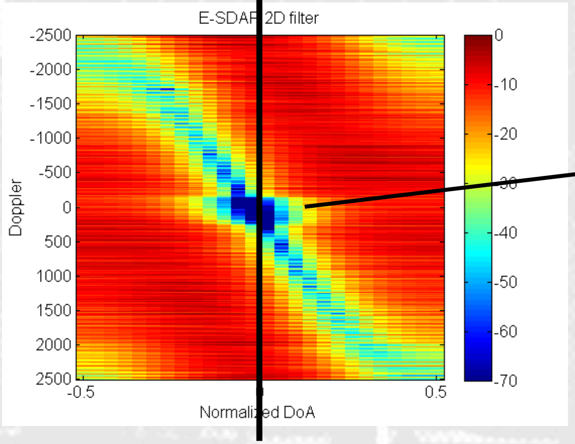
Results: Comparison between 2D null filters

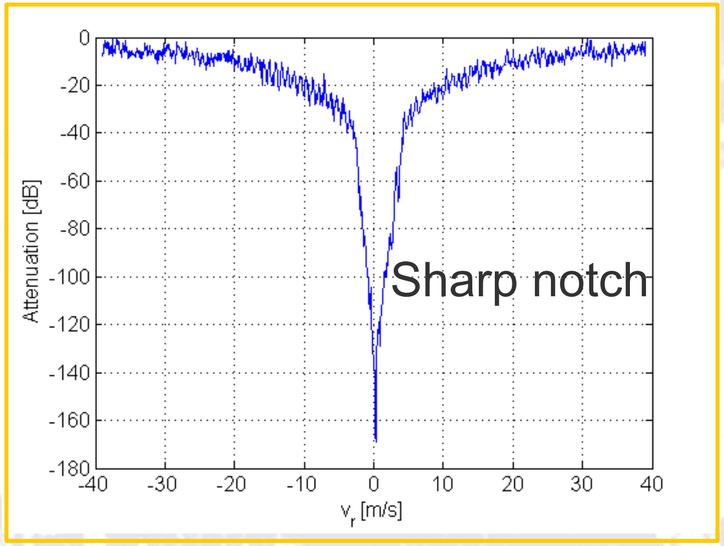
SDAP





E-SDAP





Results: Remarks

- The **improvement in the image refocus** is quite evident as it is possible to see from a visual point of view and from Image Contrast value
- Both the filters SDAP and E-SDAPare centered along the clutter angle/Doppler ridge but **only E-SDAP filter have a narrow bandwidth and allows detection of for slow moving targets**
- **The mismatch between the estimated and exact clutter covariance matrix** leads to a **undernulling** effect that increased the interference residual in the SDAP image **, or overnulling** effect where both target and clutter are cancelled
- The **sub-optimal E-SDAP** approach has been used in order to **reduce the number of required training data**. Less training data correspond to a small range area where is more reasonable to approximate clutter range variation as linear

Conclusions

- **A different version of STAP algorithm for Multichannel SAR** system called **SDAP** in **bistatic configuration** has been introduced

- Joint use of **bistatic STAP and ISAR technique for both clutter suppression and imaging has been developed**

Future developments

- Apply **joint bistatic STAP-ISAR processing to real a data set**

- The development of **Knowledge-Aided bistatic STAP** processing based on the concept of **Virtual STAP**

Thank You!

IN SUPREMÆ DIGNITATIS

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