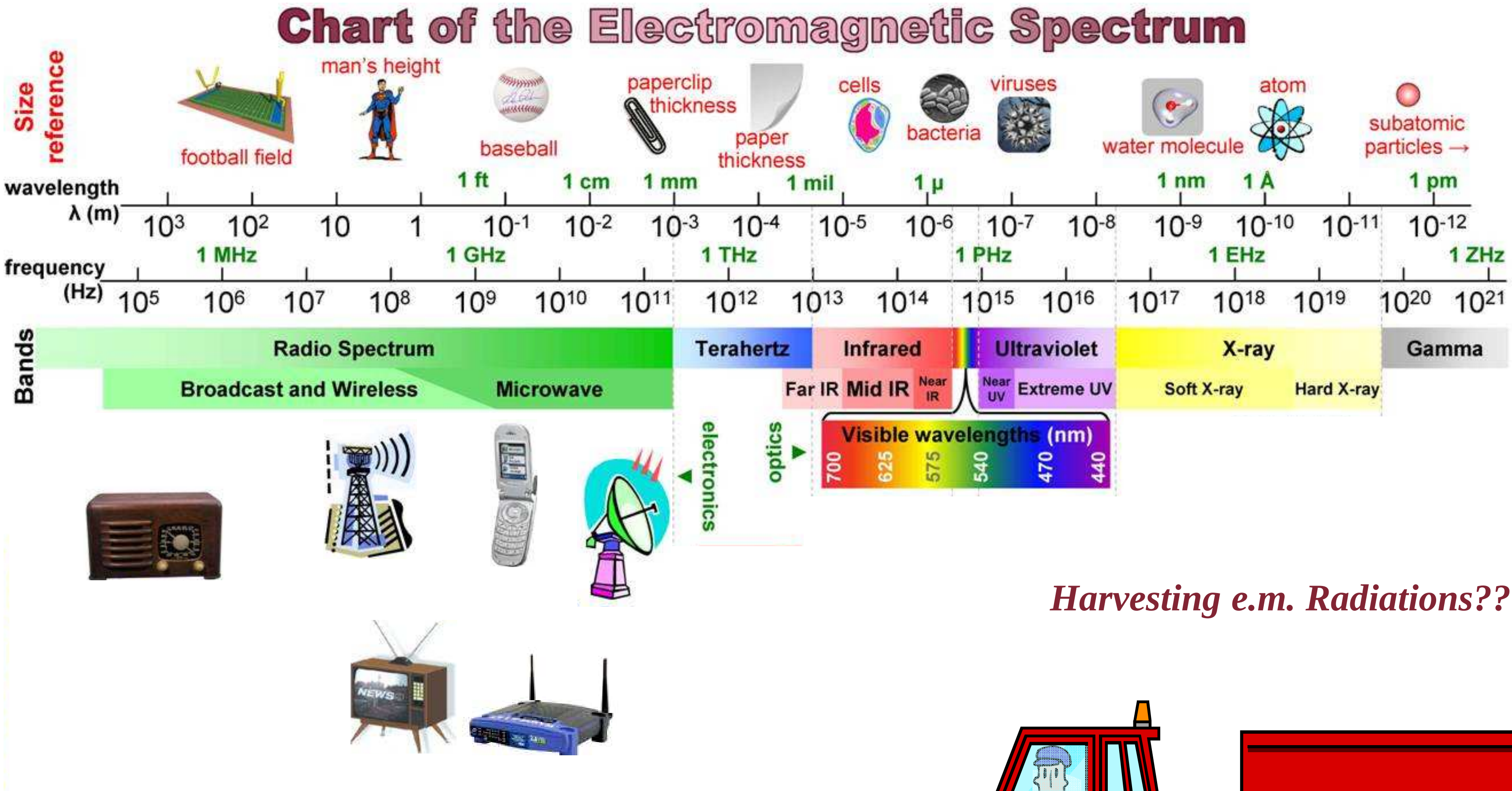
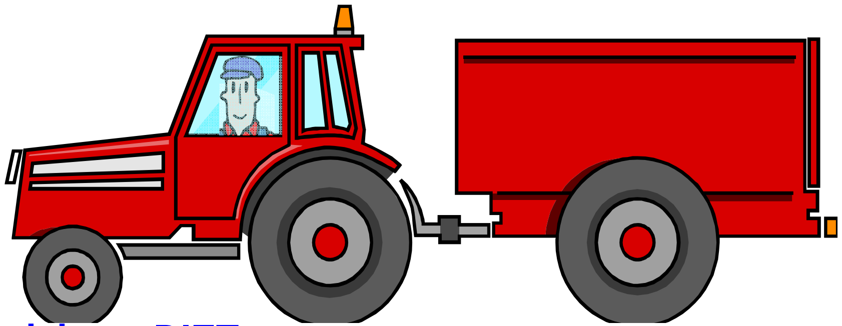
Passive Coherent Location (PCL):
Principles and ongoing activity at DIET

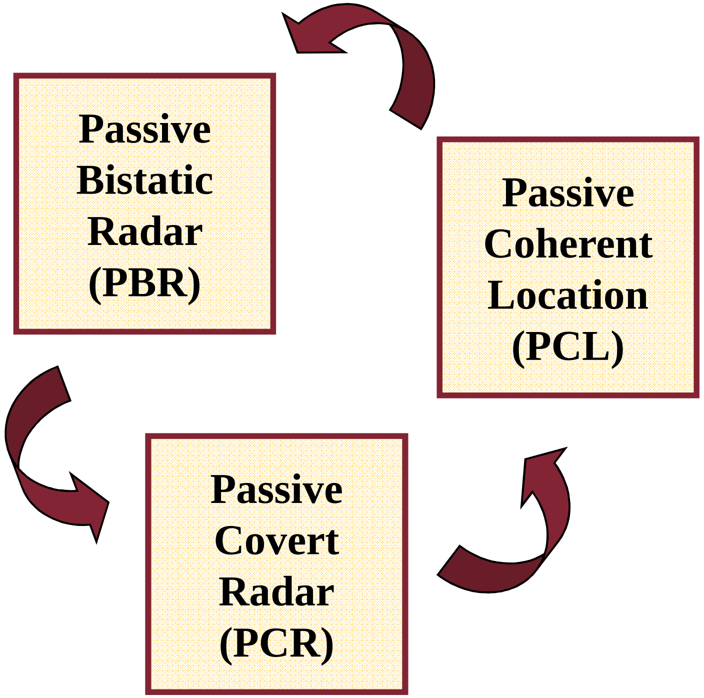
Passive radar operation (I)



Harvesting e.m. Radiations??

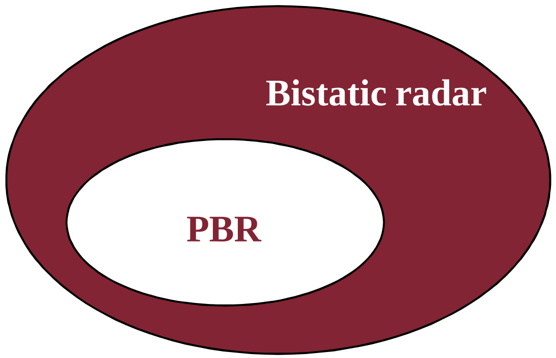


Passive radar operation (II)



All these definitions refer to the class of radar systems that exploit existing transmitters as illuminators of opportunity to perform target detection and localization.

Sub-class of bistatic radar systems exploiting non-cooperative transmitters



Passive radar operation (III)

Potential Transmitters of opportunity

- **Audio Broadcasting**
  - AM Radio
  - FM Radio
  - Digital Audio Broadcasting (DAB)

- **Video Broadcasting**
  - (Analogue TV)
  - Digital Video Broadcasting - Terrestrial (DVB-T)

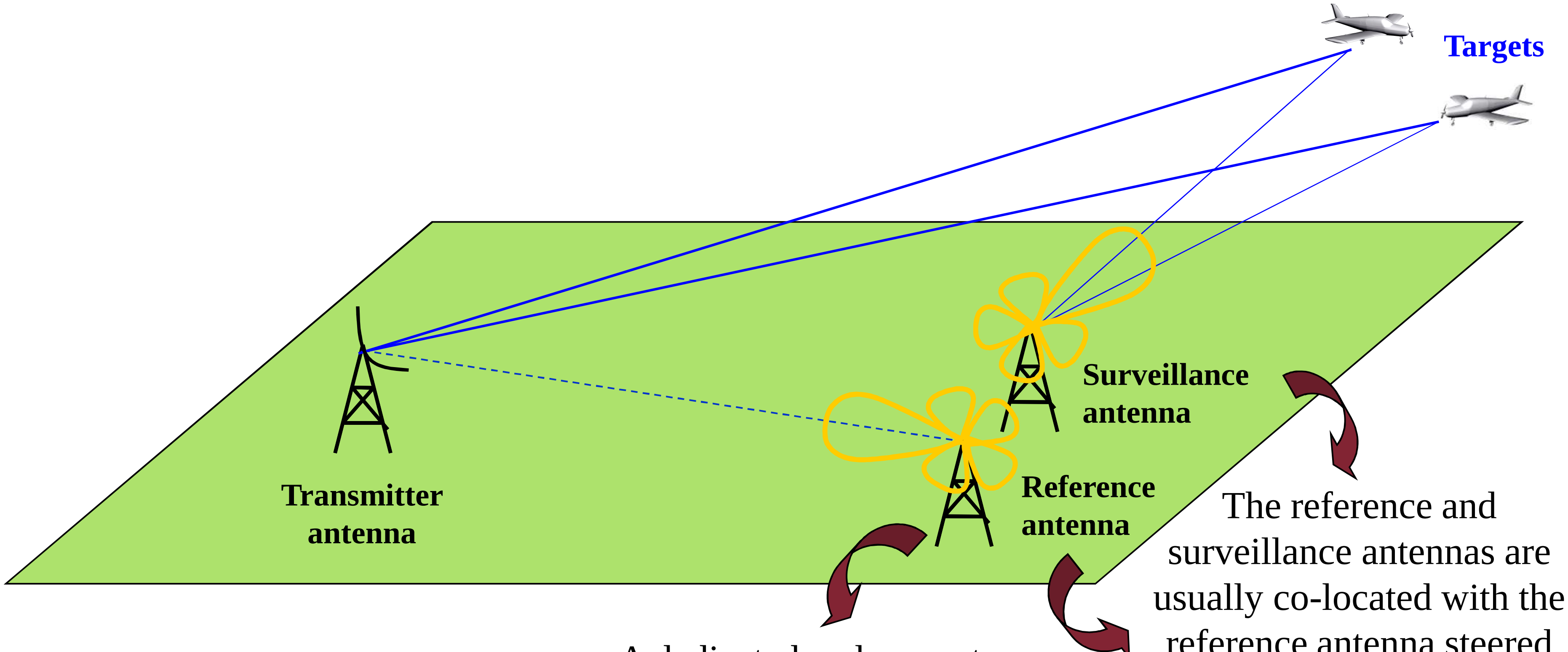
- **Mobile telephone networks**
  - GSM
  - UMTS

- **Satellite transmitters for telecommunication and navigation**
  - GNSS
  - Digital Video Broadcasting - Satellite (DVB-S)

- **Existing radar transmitters**

- **Local and Metropolitan Area Networks**
  - IEEE 802.11 - WiFi
  - IEEE 802.16 - WiMAX

PBR geometry



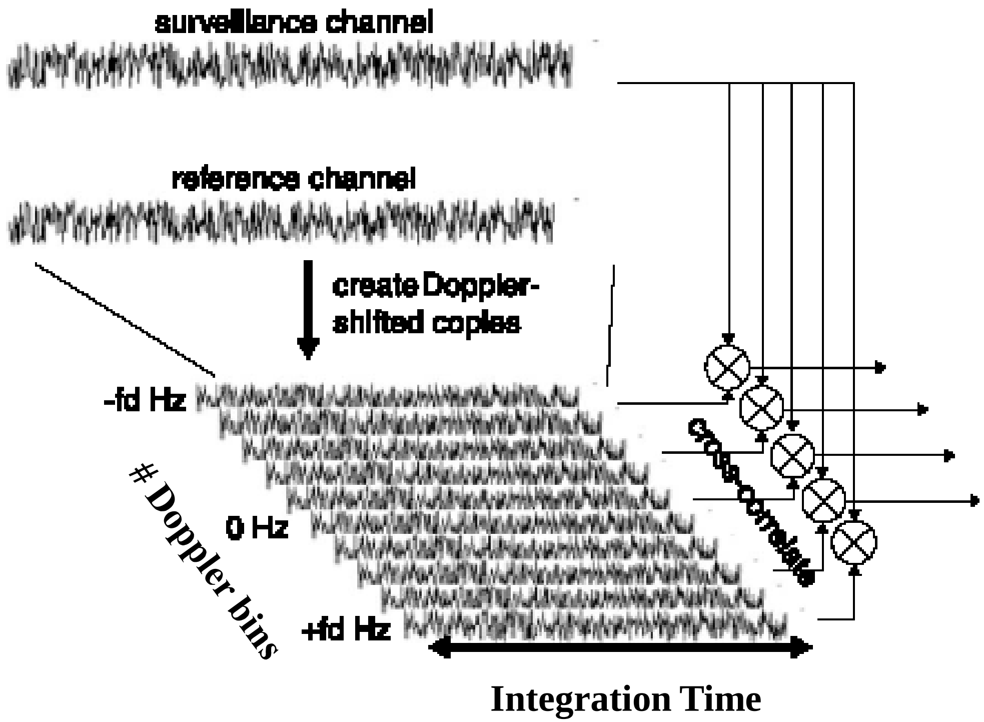
A dedicated and separate receiver channel is required to collect the directly transmitted signal

The reference and surveillance antennas are usually co-located with the reference antenna steered toward the transmitter and the surveillance antenna pointed in the direction to be surveyed

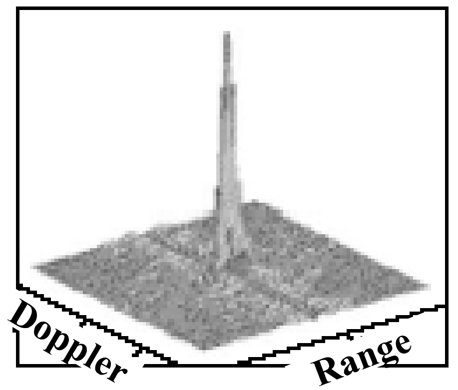
PBR target detection

Target detection is based on the cross-correlation of the surveillance signal with Doppler shifted replicas of the reference signal (matched filtering).

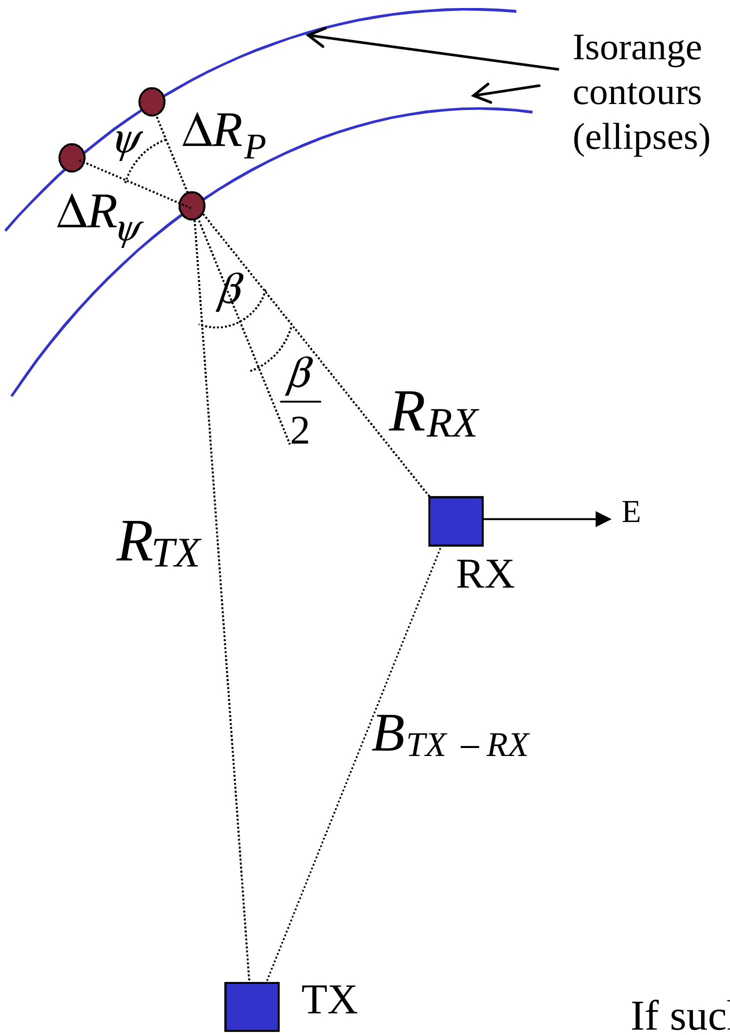
This also provides the estimates of the bistatic range and bistatic Doppler shift of each target echo.



Bank of Matched Filters (Cross-Ambiguity)



PBR measurements (I)



Relative Bistatic Range

The target echo delay is measured with respect to the reference signal:

$$R_B = c(\tau - \tau_{ref}) = R_{TX} + R_{RX} - B_{TX-RX}$$

The target lies on an ellipsoid having RX and TX as foci.

Bistatic range resolution: $\Delta r_B = \frac{c}{B}$ ← Exploited Signal Frequency Bandwidth

Target echoes can be discriminated if $\Delta\tau_2 - \Delta\tau_1 > 1/B$

or equivalently if $R_{B2} - R_{B1} > \Delta r_B = \frac{c}{B}$

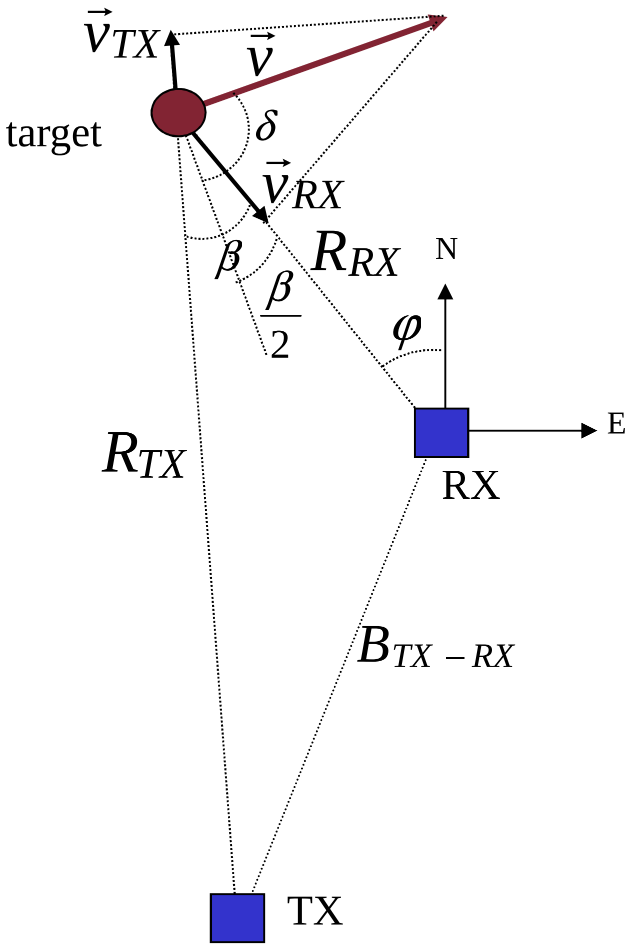
The corresponding distance between targets is a function of the bistatic angle:

$$\Delta R_P \cong \frac{c}{2B\cos(\beta/2)}$$ (Upper bound approximation)

If such distance is evaluated along the direction given by ψ , it is:

$$\Delta R_\psi \cong \frac{c}{2B\cos(\beta/2)\cos(\psi)}$$

PBR measurements (II)



Bistatic Doppler

$$f_D = \frac{v_{TX} + v_{RX}}{\lambda} = \frac{2v}{\lambda}\cos(\delta)\cos\left(\frac{\beta}{2}\right)$$

Targets on the baseline show zero Doppler.

Bistatic Doppler resolution:

$$\Delta f_D = \frac{1}{T_{\text{int}}}$$

← Coherent Processing Interval

Receiver Bearing

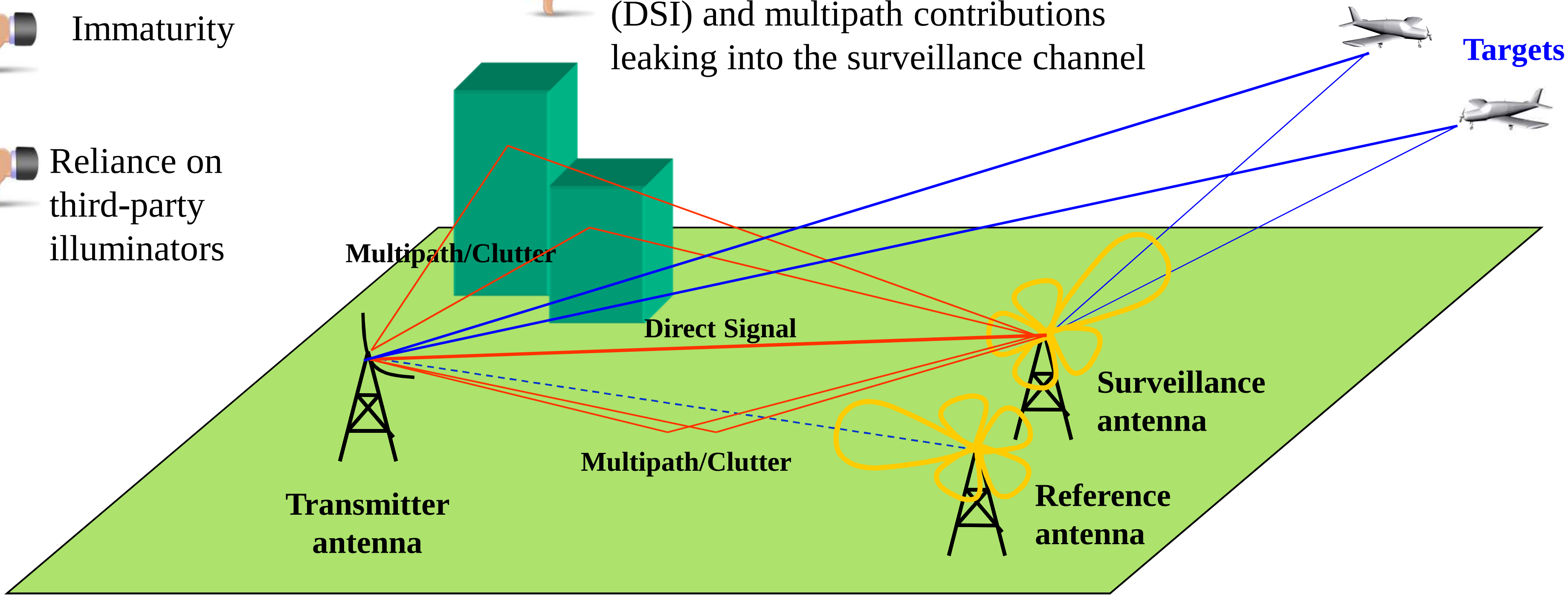
A pair of antenna elements allows to measure the phase-difference of arrival and hence the direction of arrival of the echoes. Alternatively, antenna arrays can be used with several elements and element-level digitization with standard or adaptive beam-forming techniques.

Passive Radar PRO's

- Lower costs of operation and maintenance, due to the lack of transmitter
- Covert operation, immunity to ECM threats
- No additional demand on spectrum resources
- Small size and hence easier deployment in places where conventional radars cannot be fielded
- Potentially higher target RCS, counter-stealth capability due not only to their inherently bistatic geometry, but also the lower frequency regimes often exploited
- Reduced impact on the environment and reduced Electro-Magnetic pollution

Passive Radar CON's

- Immaturity
- Reliance on third-party illuminators
- High power direct signal interference (DSI) and multipath contributions leaking into the surveillance channel



- The siting and radiative properties of the available emitters cannot be configured
- The transmitted waveform is not under control of the radar operator and has time-varying characteristics
- The need for a dedicated and separate RX channel to collect the transmitted signal (potentially affected by multipath)

PBR Radar Equation (I)

Target Signal to Noise Power Ratio:

Transmitted Power

TX and RX antenna gains for a target at (φ,θ)

Wavelength

Target RCS

$$SNR = \frac{P_{TX}\, G_{TX}(\varphi,\theta)\, G_{RX}(\varphi,\theta)\, \lambda^2 \sigma_B}{(4\pi)^3 R_{TX}^2 R_{RX}^2\; kT_0FB\, L_{loss}}\, G_{int}$$

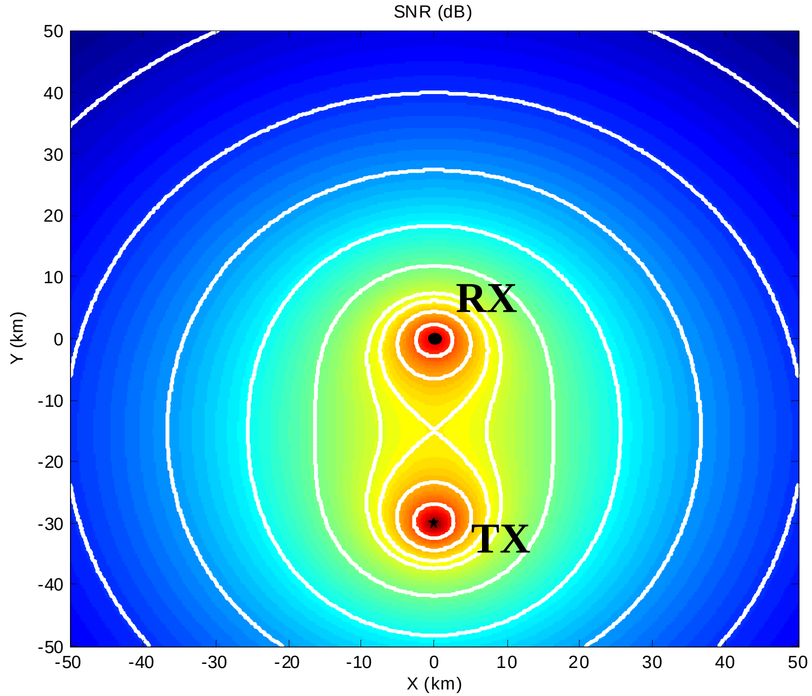
Noise Power

Coherent Integration Gain

Distances of the target from the TX and the RX

Cassini Ovals:

$$R_{TX} R_{RX} = K$$



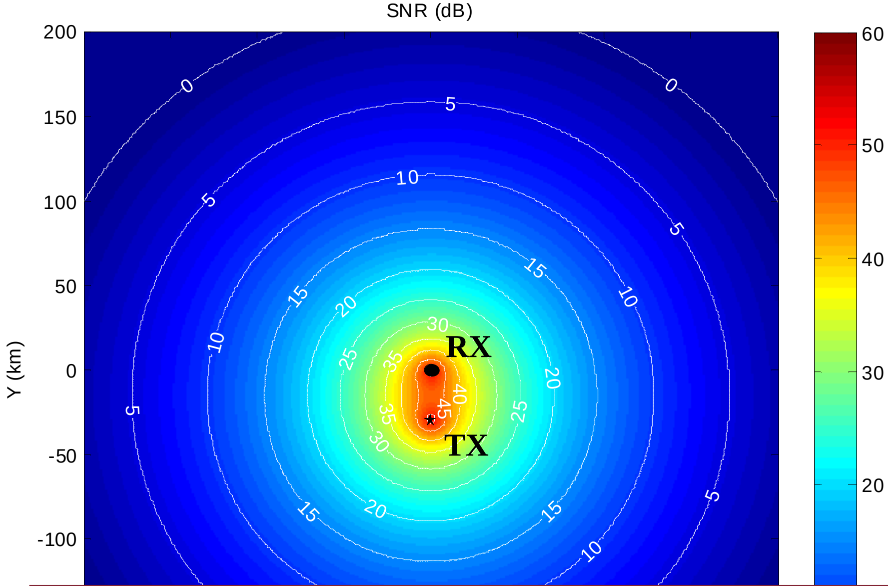
PBR Radar Equation (II)

Example:

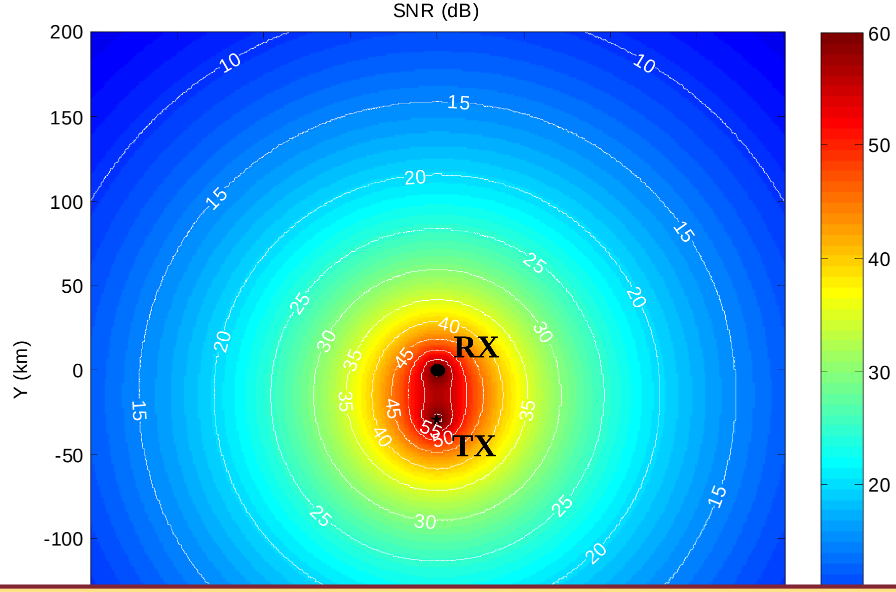
FM broadcast
(Isotropic antennas)

Transmitter Power (P_{TX})	10 kW	Bandwidth (B)	200 kHz
Transmitter antenna gain (G_{TX})	0 dB	Noise Figure (F)	3 dB
Receiver antenna power gain (G_{RX})	0 dB	System loss (L_{loss})	3 dB
FM carrier frequency	100 MHz	Target RCS (σ_B)	10 m^2
Wavelength (λ)	3 m	Target Height	5000 m

T_{int}=0.1 s



T_{int}=1 s



A long integration time is required to obtain an acceptable SNR; it needs to be traded off against the computational load and the expected target migration.

X (km)

X (km)

The problem of Direct Signal Interference (I)

Direct Signal to Noise Power Ratio:

TX antenna gain in the RX direction

RX antenna gain in the TX direction

$$DNR = \frac{P_{TX} G_{TX}(\varphi_{RX}, \theta_{RX}) G_{RX}(\varphi_{TX}, \theta_{TX}) \lambda^2}{(4\pi)^2 B_{TX-RX}^2 k T_0 F B L_{loss}} G_{int}$$

Baseline

Target Signal to Direct Signal Power Ratio:

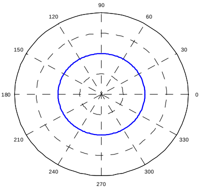
$$SDR = \frac{G_{TX}(\varphi, \theta) G_{RX}(\varphi, \theta)}{G_{TX}(\varphi_{RX}, \theta_{RX}) G_{RX}(\varphi_{TX}, \theta_{TX})} \left(\frac{B_{TX-RX}}{R_{TX} R_{RX}} \right)^2 \frac{\sigma_B}{4\pi}$$

The problem of Direct Signal Interference (II)

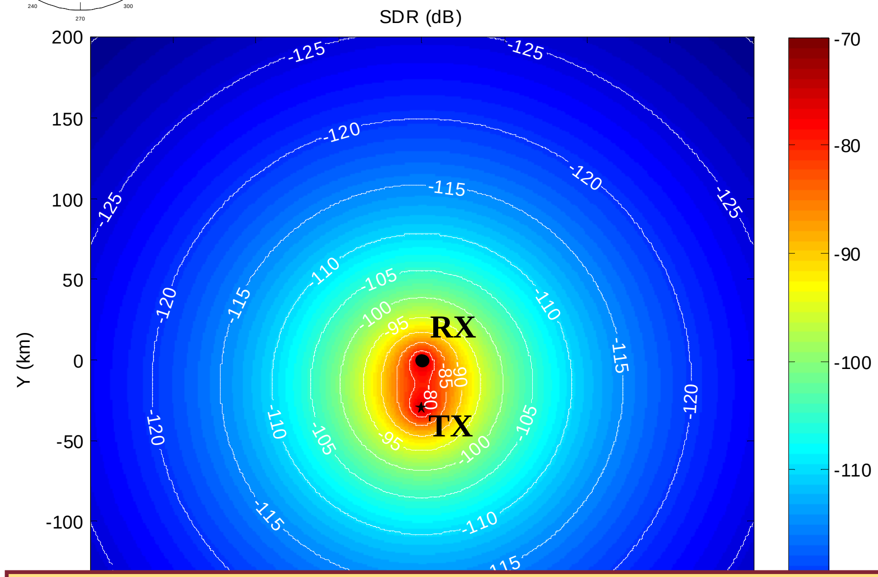
Example:

FM
broadcast

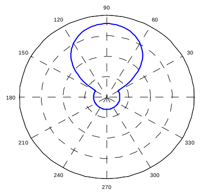
Transmitter Power (P_{TX})	10 kW	Bandwidth (B)	200 kHz
Transmitter antenna gain (G_{TX})	0 dB	Noise Figure (F)	3 dB
FM carrier frequency	100 MHz	System loss (L_{loss})	3 dB
Wavelength (λ)	3 m	Target RCS (σ_B)	10 m^2
Baseline (B_{TX-RX})	30 km	Target Height	5000 m

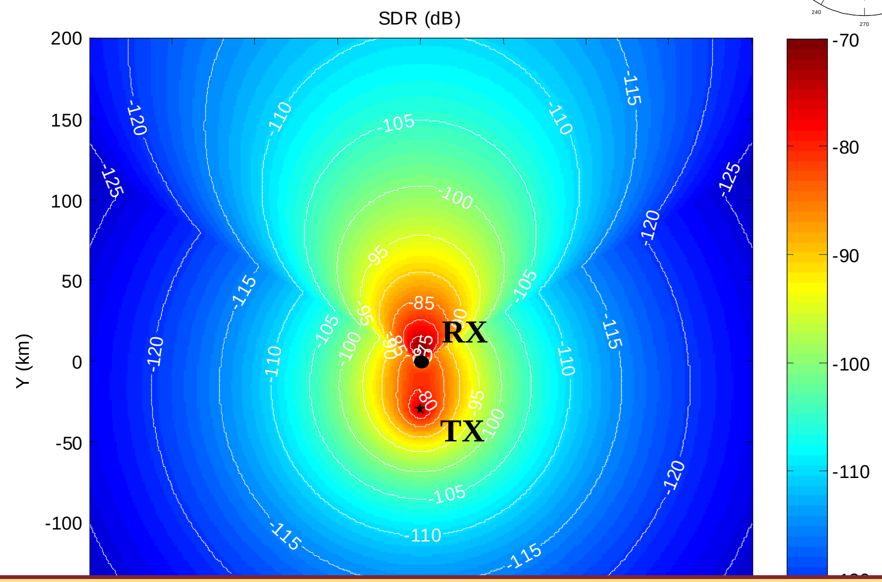


Isotropic RX antenna
G_{RX}=0dB



Directive RX antenna
G_{RX}=8dB, FB=-15 dB, BW=70 deg





Directive antennas allow to partially attenuate the DSI. However effective signal or data processing strategies are required to further reduce the DSI.

Coverage vs. waveform for PBR applications (I)

The choice of the best illuminator of opportunity for a designated application is based on factors mainly related to:

Coverage:

- Transmitted power
- TX-target-RX geometry
- Antenna radiation pattern (broadcast vs point-to-point transmissions)
- Frequency band (propagation issues), channels allocation
- Temporal coverage (stationary vs moving TX; 24 hour operation, etc.)
- Availability in the considered application scenario

Waveform:

- Bandwidth (range resolution, sampling frequency, computational burden)
- Modulation (analog vs digital)
- Ambiguity function (side-lobes and side-peaks due to periodic modulation features)
- Stability (time-varying characteristics)

Coverage vs. waveform for PBR applications (II)

Table 1: Signal parameters for typical passive radar illumination sources

Transmission	Frequency	Modulation, bandwidth	$P_t G_t$	Power density (Wm^{-2}) $\Phi = (P_t G_t)/4\pi r_1^2$
HF broadcast	10–30 MHz*	DSB AM, 9 kHz	50 MW	–67 to –53 dBW m^{-2} at r_1 = 1000 km
VHF FM (analogue)	~ 100 MHz	FM, 50 kHz	250 kW	–57 dBW m^{-2} at r_1 = 100 km
UHF TV (analogue)	~ 550 MHz	vestigial-sideband AM (vision); FM (sound), 5.5 MHz	1 MW	–51 dBW m^{-2} at r_1 = 100 km
Digital audio broadcast	~ 220 MHz	digital, OFDM 220 kHz	10 kW	–71 dBW m^{-2} at r_1 = 100 km
Digital TV	~750 MHz	digital, 6 MHz	8 kW	–72 dBW m^{-2} at r_1 = 100 km
Cellphone basestation (GSM)	900 MHz, 1.8 GHz	GMSK, FDM/TDMA/FDD 200 kHz	100 W	–81 dBW m^{-2} at r_1 = 10 km
Cellphone basestation (3G)	2 GHz	CDMA 5 MHz	100 W	–81 dBW m^{-2} at r_1 = 10 km

*Appropriate frequency will depend on time of day.

Moreover:

WiFi Access Point	2.4 GHz, 5 GHz	DSSS/OFDM, 11/20 MHz	<100mW	- 61 dBW m^{-2} at r_1 = 100 m

From: Griffiths, H. D., and Baker, C. J., "Passive coherent location radar systems. Part 1: Performance prediction.", IEE Proceedings on Radar, Sonar and Navigation, Vol. 152, Issue 3 (June 2005), pp. 153—159.

Waveforms of opportunity not optimized for radar (I)

The effect of the DSI and clutter/multipath contributions is exacerbated by the characteristics of the exploited waveforms of opportunity.

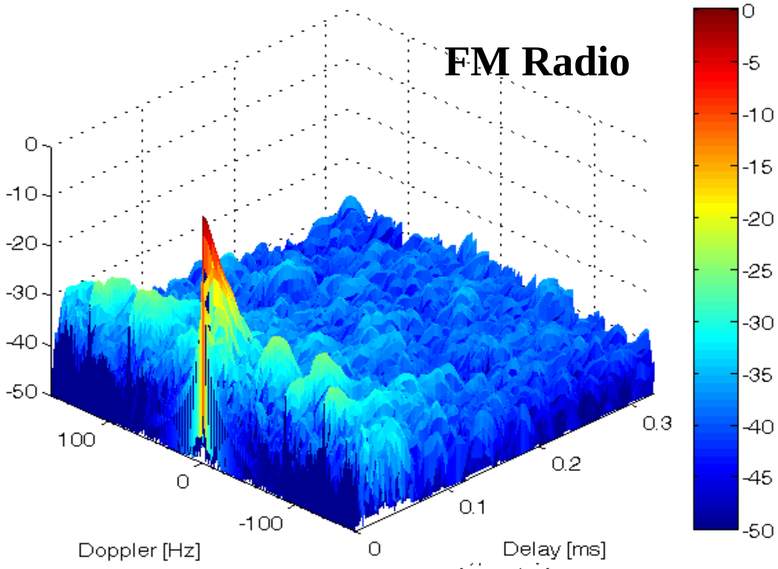
Conventional radar systems → the transmitted waveform is carefully designed to provide an ambiguity function with appropriate properties (e.g. narrow peak in both range and Doppler and low sidelobes).

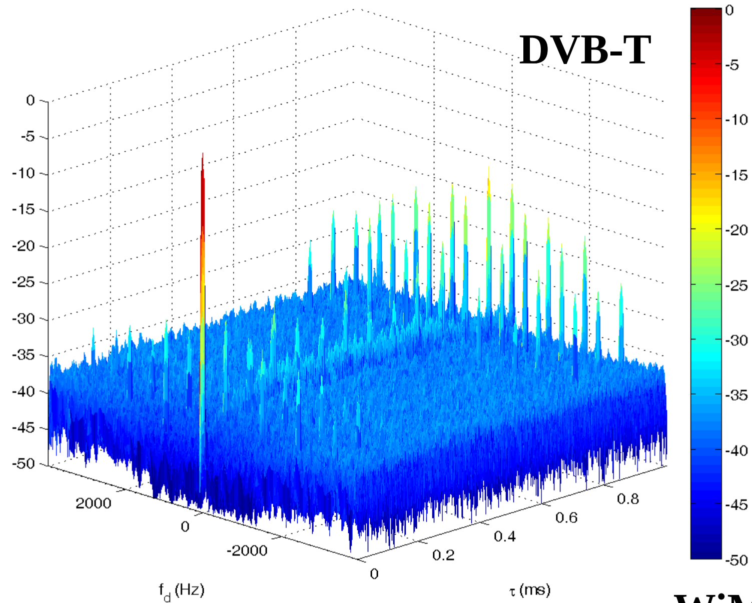
PBR operation → the transmitted waveform is not within the control of the radar designer and shows variable and unpredictable characteristics

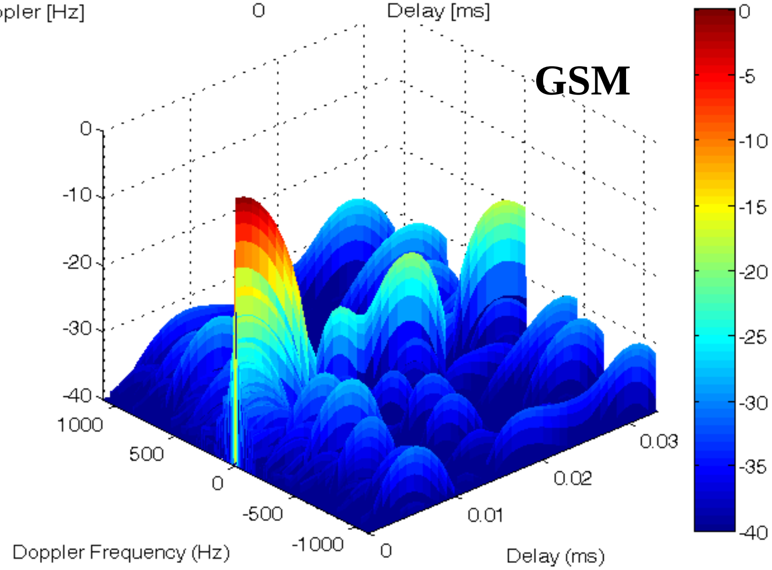
⇓

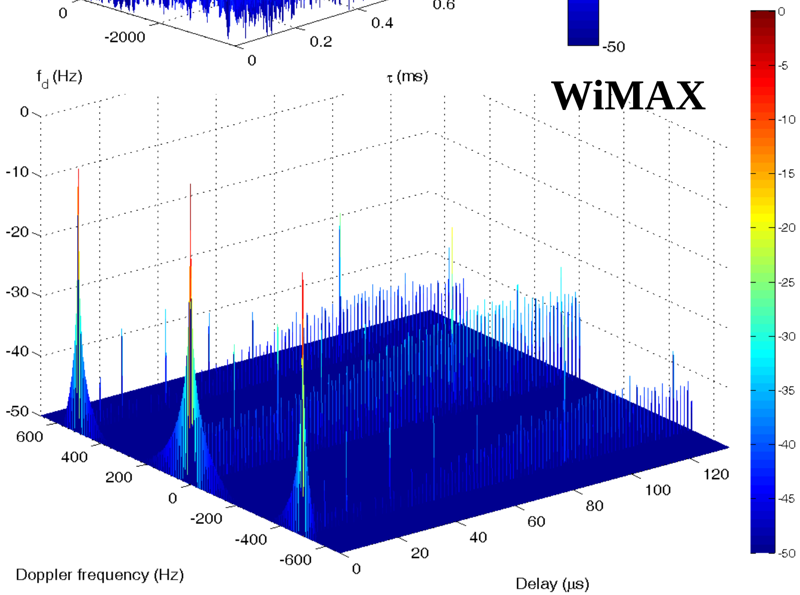
The sidelobes of the ambiguity function for PBR usually have a **time-varying** structure and exist at a level not greatly lower than that of the peak with the potential to **mask** even targets largely displaced in range and Doppler from the main clutter peak.

Waveforms of opportunity not optimized for radar (II)

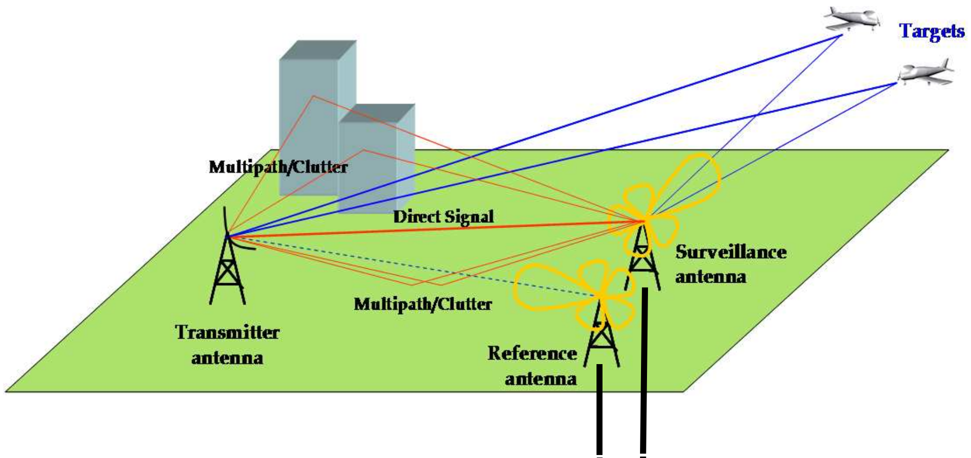






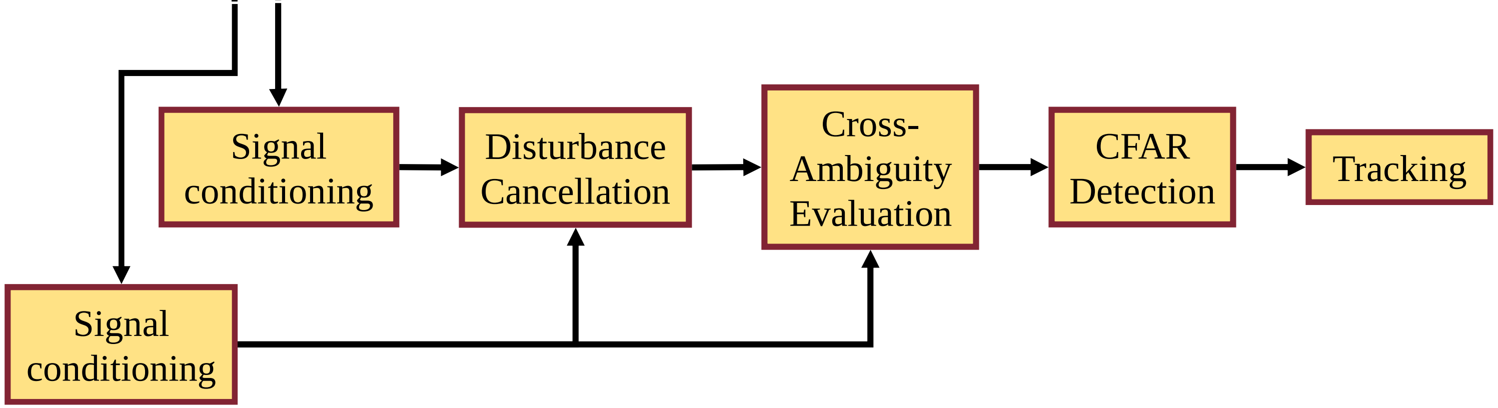


Schematic of PBR processing chain

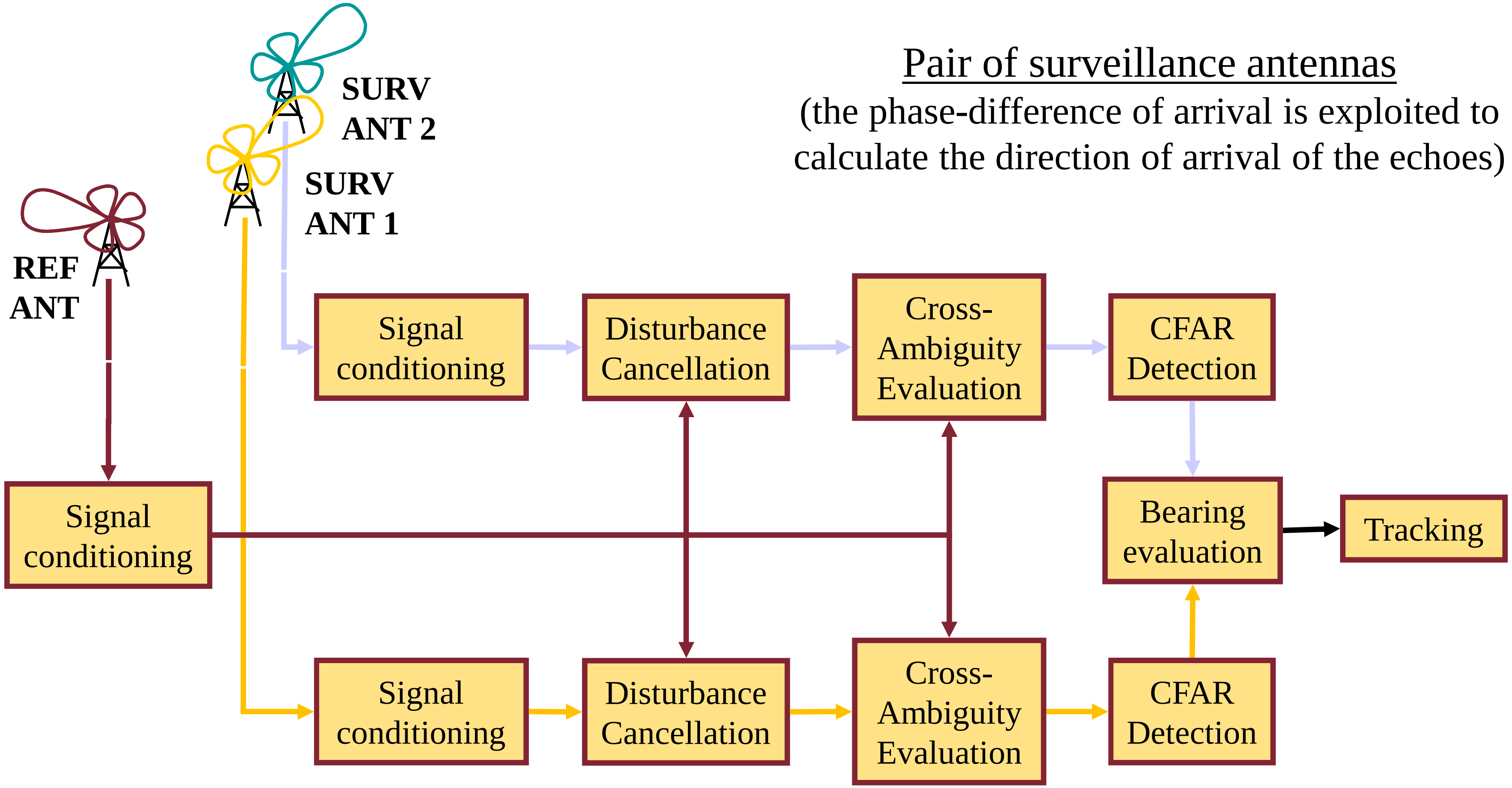


Single surveillance antenna

(no bearing info, target localization in the bistatic Range-Doppler plane only)

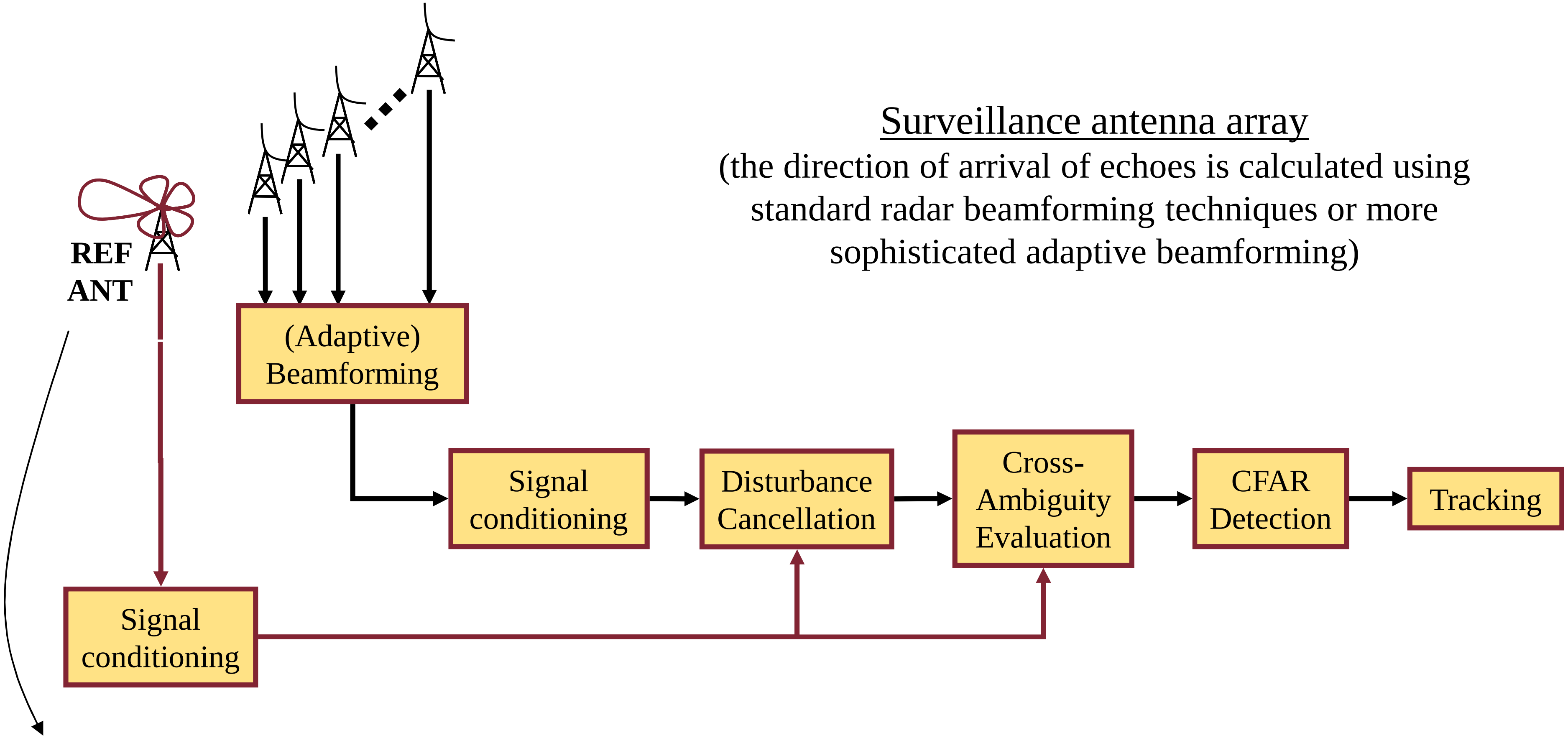


DOA estimation & localization (I)



Pair of surveillance antennas
(the phase-difference of arrival is exploited to calculate the direction of arrival of the echoes)

DOA estimation & localization (II)



Surveillance antenna array
(the direction of arrival of echoes is calculated using standard radar beamforming techniques or more sophisticated adaptive beamforming)

The same array of antennas might be exploited to collect the reference signal by forming a beam in the TX direction

PBR research activity at DIET

EU Projects

- **ARGUS-3D**: "AiR GUidance and Surveillance 3D“, FP7 (Security)
- **ATOM**: "Airport detection and Tracking Of dangerous Materials by passive and active sensors arrays”, FP7 (Transport)
- **SOS**: “Sensors system for detection and tracking of dangerous materials in order to increase the airport security in indoor landside area”, FP7 (Marie Curie Action)
- **DOLPHIN**: “Development of Pre-operational Services for Highly Innovative Maritime Surveillance Capabilities”, FP7
- **SpyGLASS**: “Galileo based passive radar system for maritime surveillance”, H2020

http://www.argus3d.eu

http://www.sos-project.eu

http://www.gmes-dolphin.eu/

http://www.spyglassproject.eu/

Projects funded by radar industries

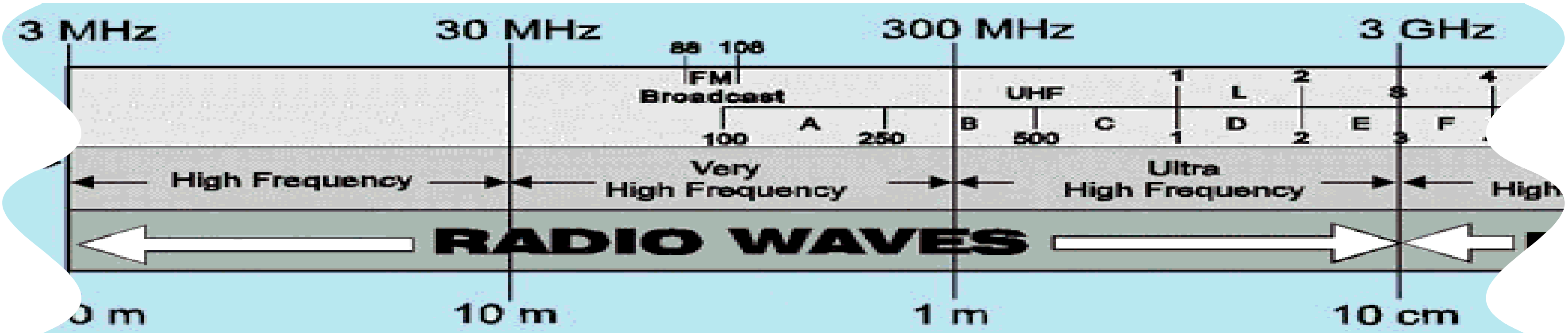
- DVB-T based passive radar for maritime and aerial surveillance
- FM-based passive radar for aerial surveillance
- Multistatic passive radar networks
- Passive Radar based on satellite transmissions

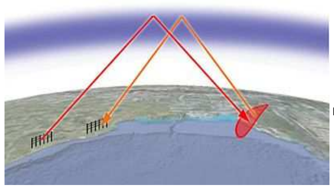
Illuminators of opportunity investigated

FM Radio Broadcast Transmitters

Satellite GNSS Transmitters

WiFi, WiMAX, Access Points





HF OTH Radar Transmitters

Digital Video Broadcast DVB-T Transmitters

Satellite Transmitters of DVB-SH

Performed research activity

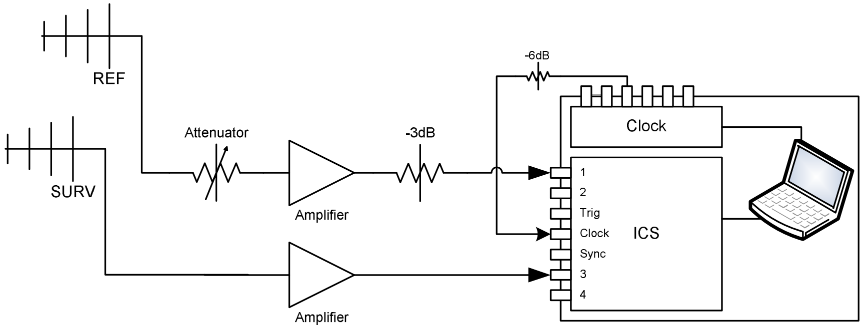
The applications of interest range from air traffic control, to maritime surveillance, vehicular traffic monitoring, up to indoor surveillance.

For each considered application and illuminator of opportunity, the performed activities typically included:

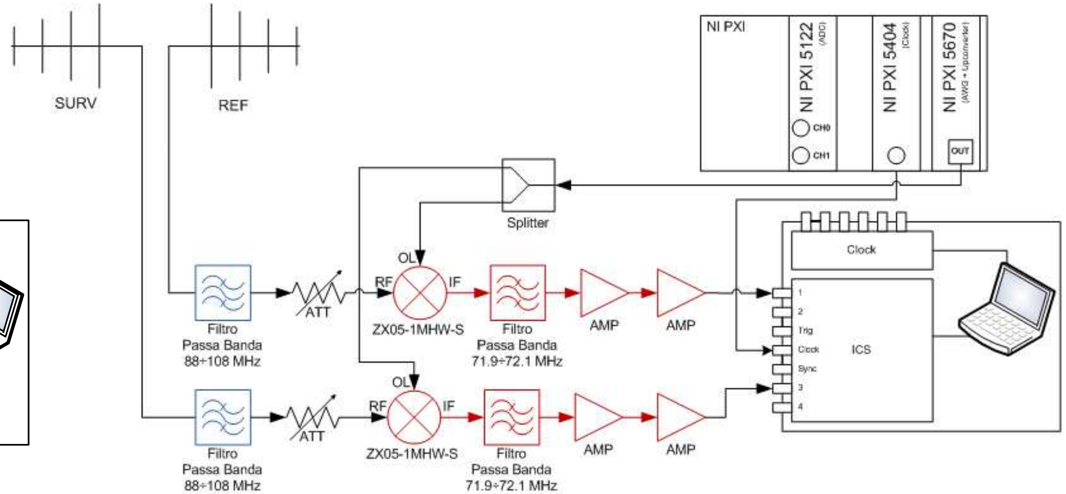
- Design of innovative **signal processing techniques** (e.g. for interference removal, target detection, localization, and tracking, passive cross-range profiling and imaging)
- Signal modeling and scenario **simulation**
- Design and development of **experimental receivers** for the practical demonstration of the conceived strategies
- **Experimental test campaigns** planning and implementation followed by the extensive analysis of the data collected.

FM radio-based passive radar for air traffic surveillance applications

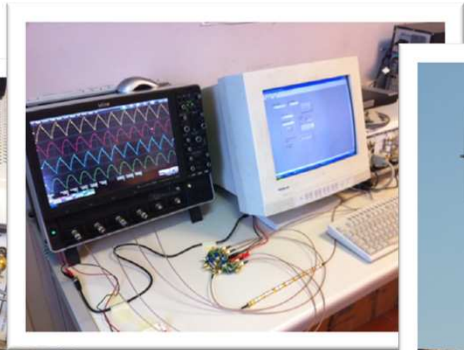
Prototypes development (I)



Direct RF sampling

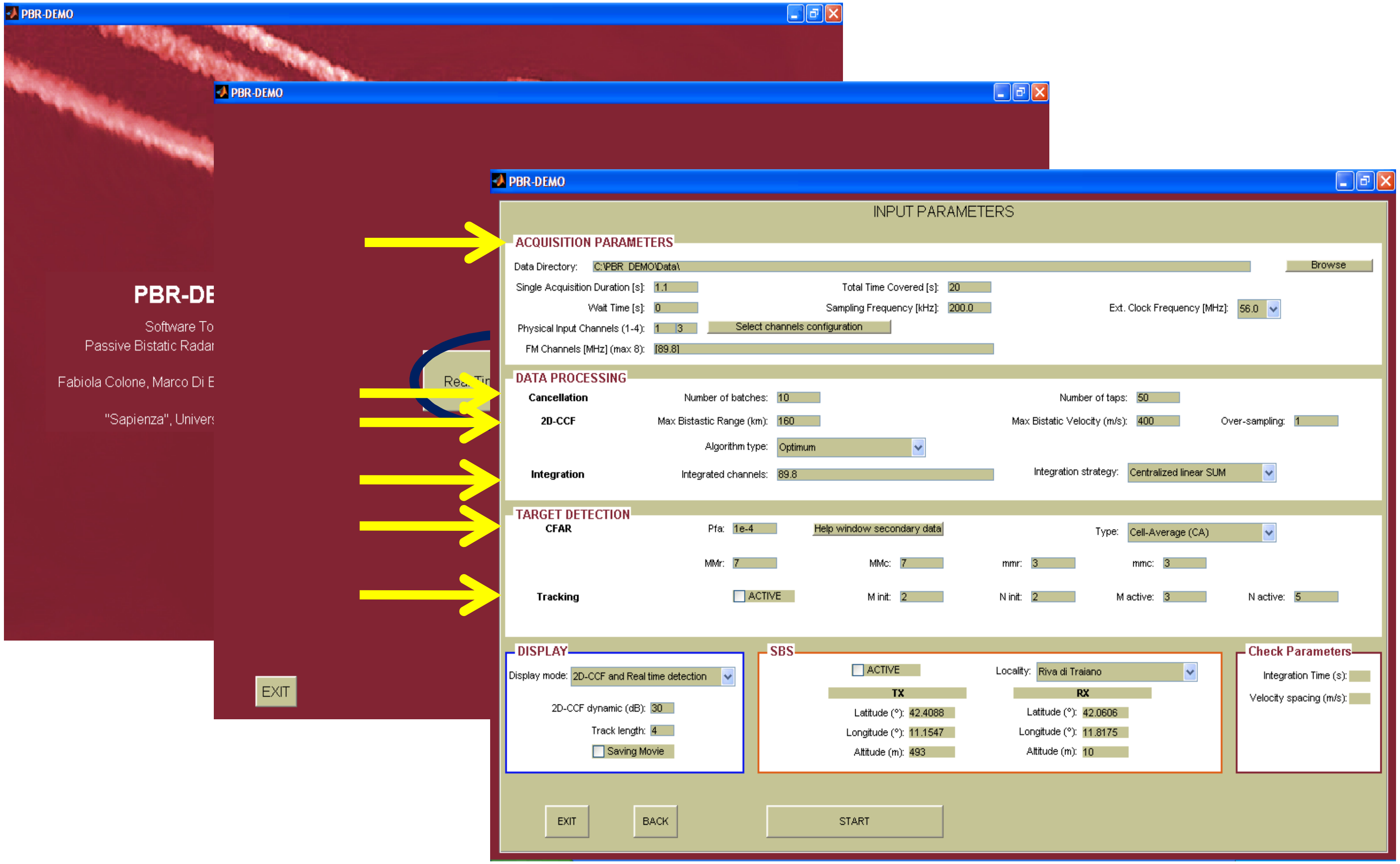


Signal down-conversion & IF sampling

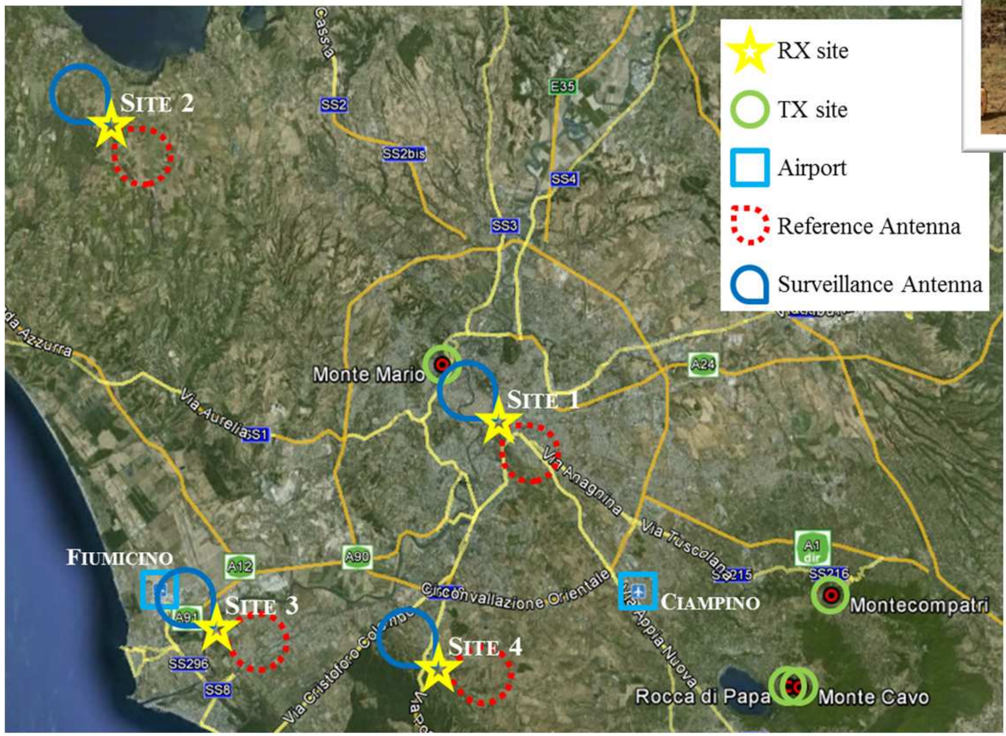


Prototypes development (II)

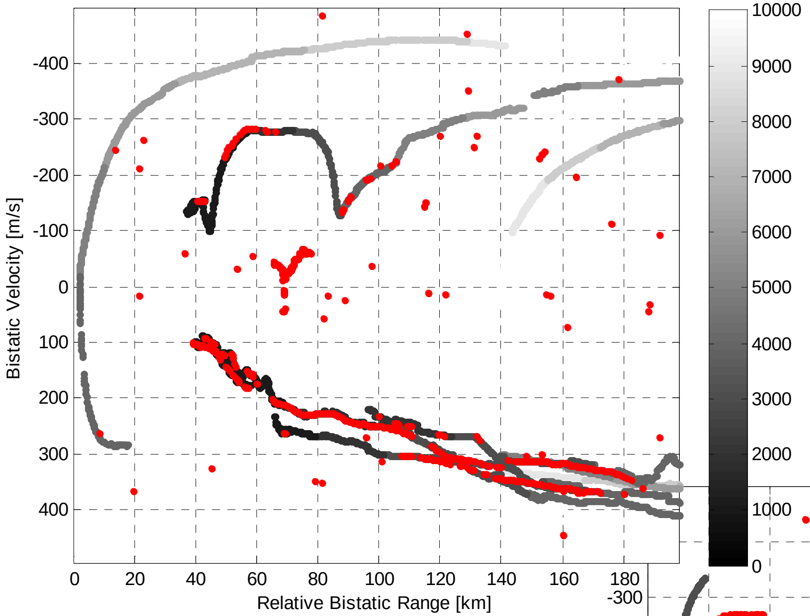
- GUI Software Demo



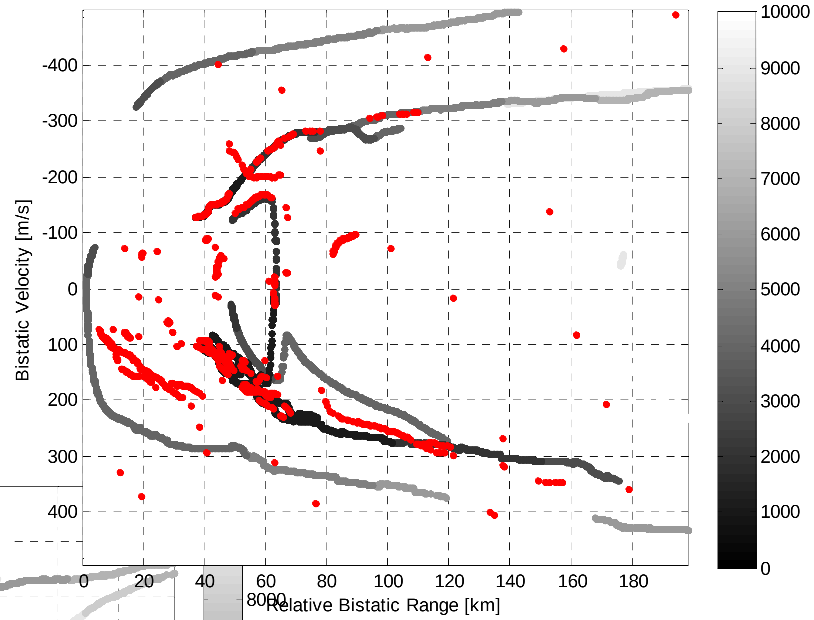
Acquisition Campaigns



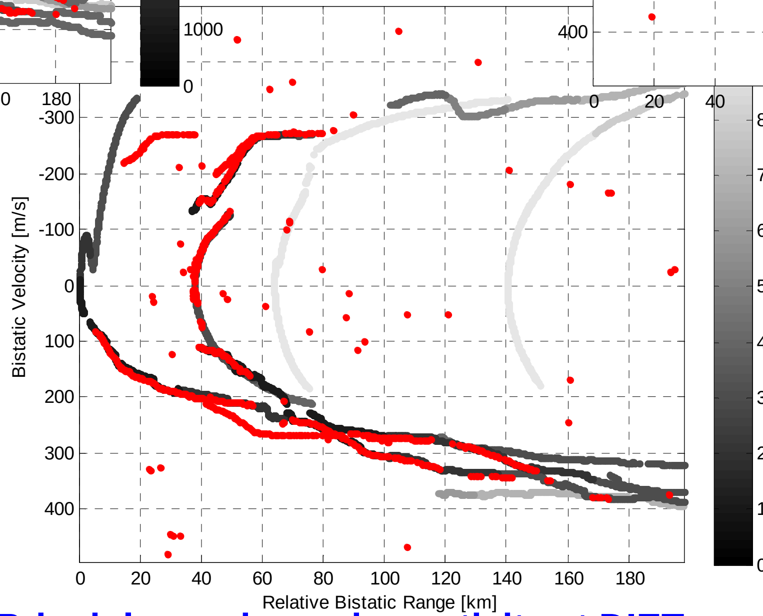
Target Detection Results



Site 4



- Single FM radio channel: **103.0** MHz
- Time interval: about 8 minutes

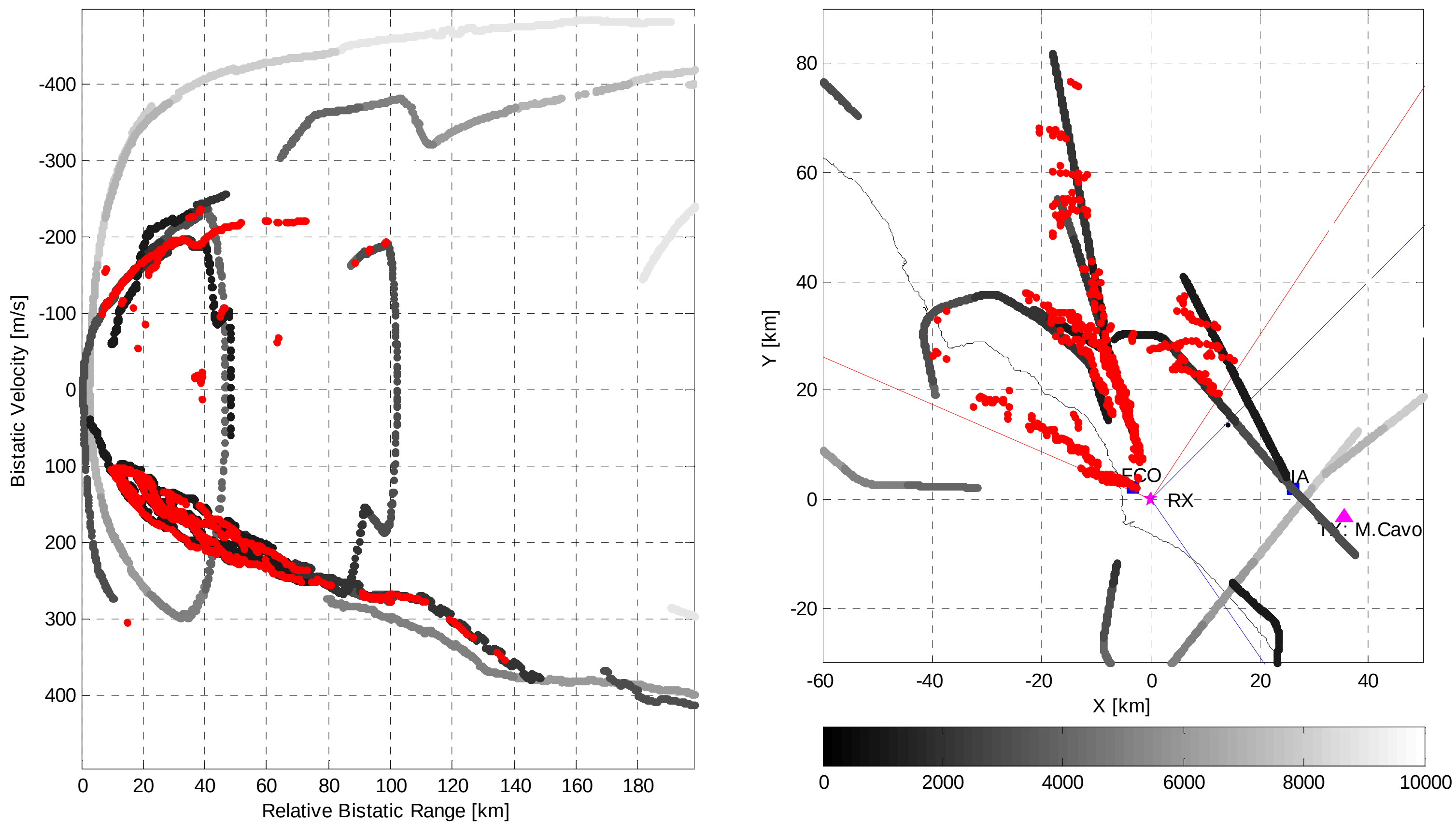


PBR detections

ATC data

Target Detection & Localization Results

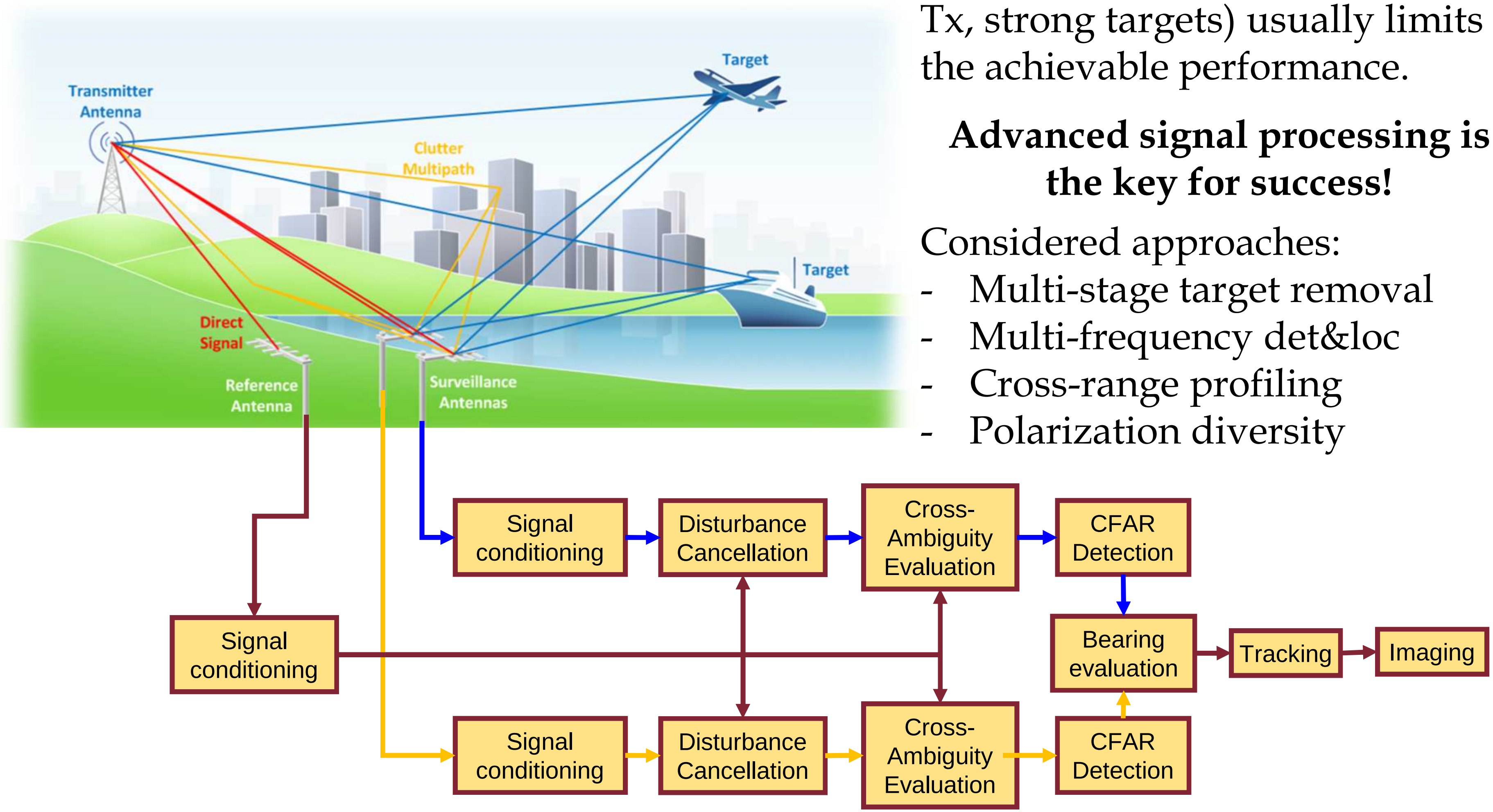
Site 3



- Single FM radio channel: **94,5** MHz
- Time interval: about 8 minutes

- PBR detections
- ATC data

Advanced signal processing techniques



Severe interference (clutter, other Tx, strong targets) usually limits the achievable performance.

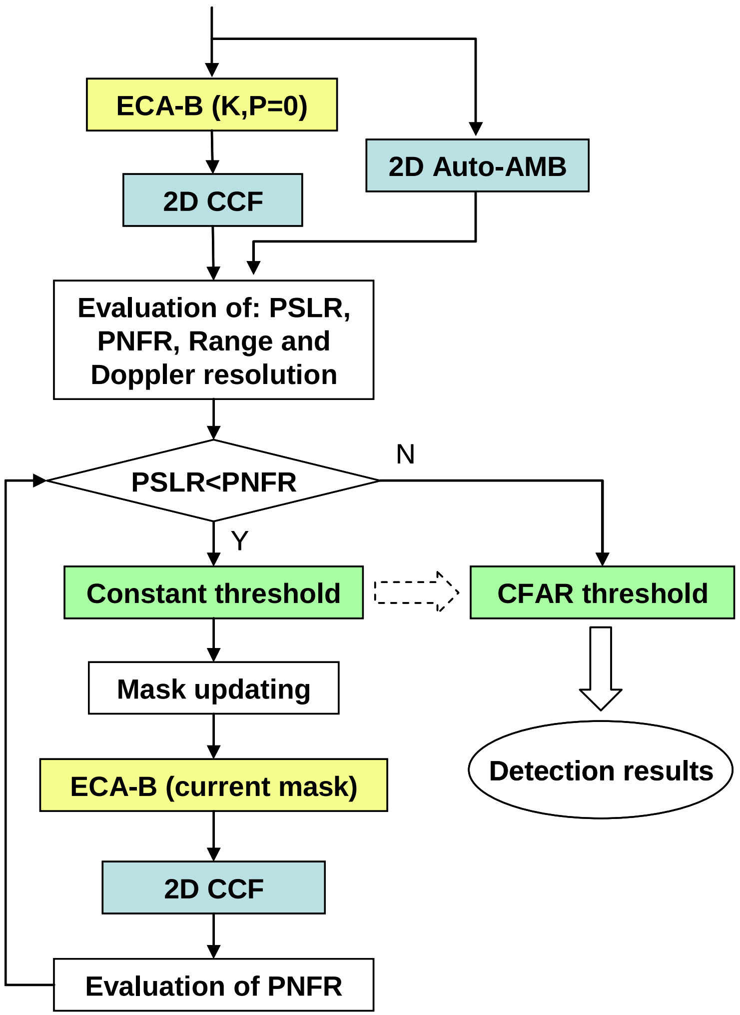
Advanced signal processing is the key for success!

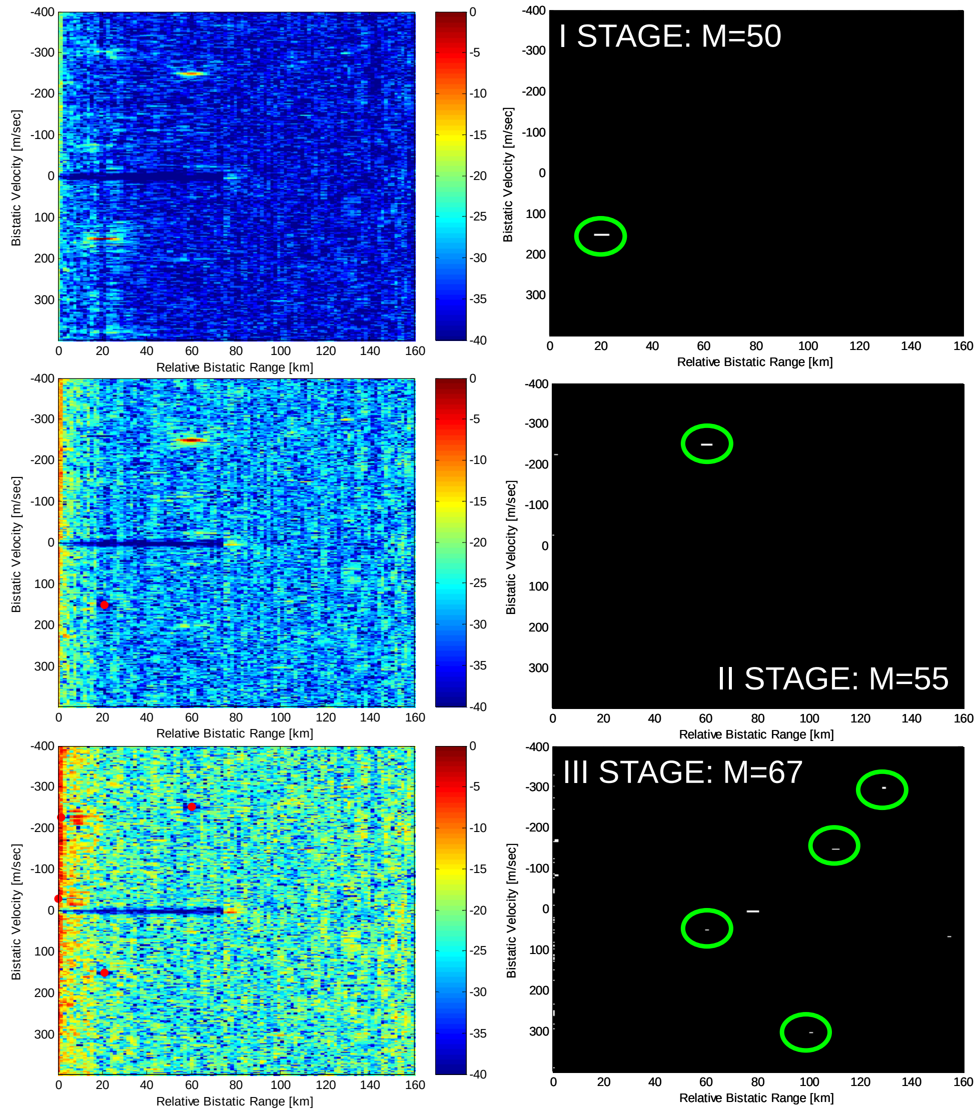
Considered approaches:

- Multi-stage target removal
- Multi-frequency det&loc
- Cross-range profiling
- Polarization diversity

Strong targets removal (I)

Multistage processing algorithm

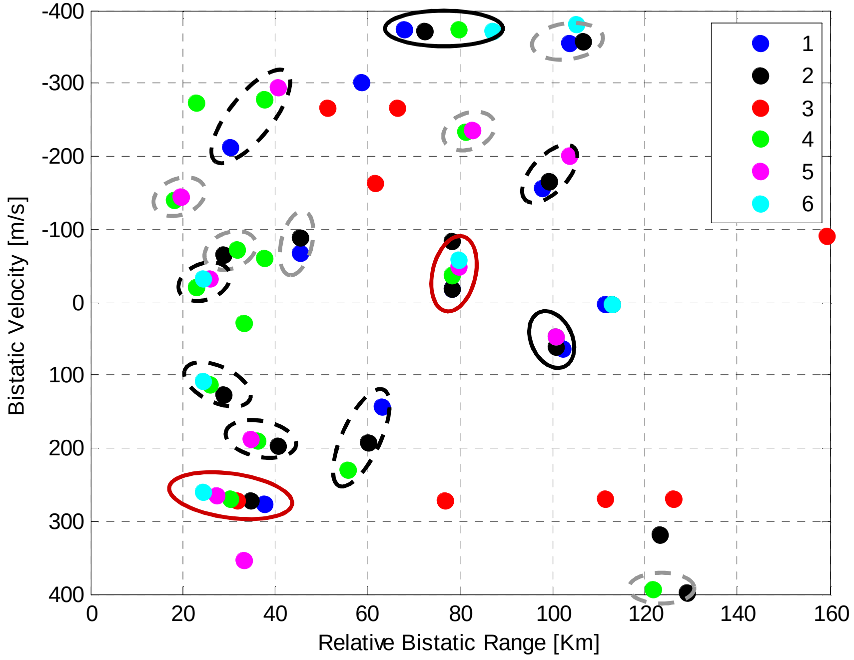




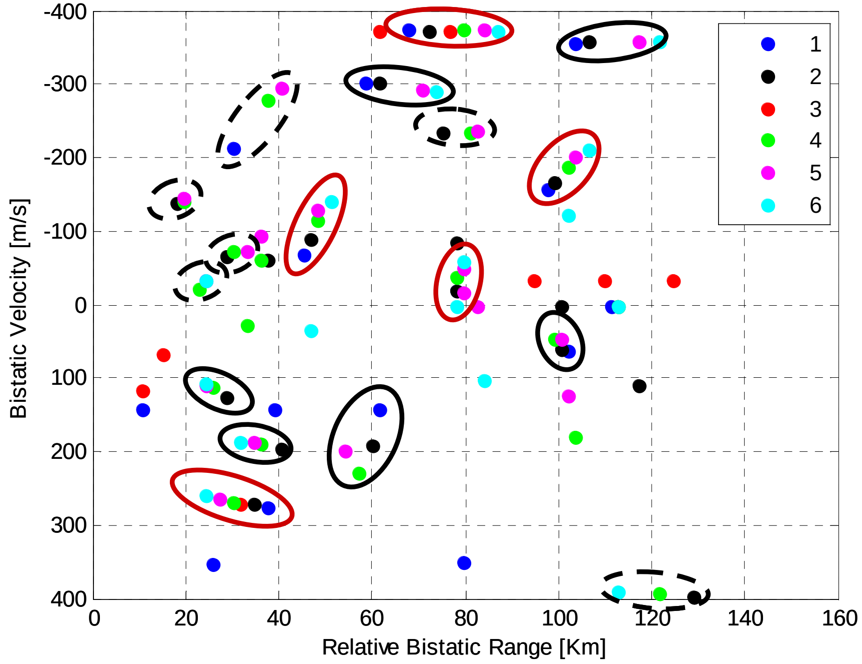
Strong targets removal (II)

Real data set collected by the PBR experimental prototype developed at UCL (London)

SINGLE STAGE



MULTI-STAGE

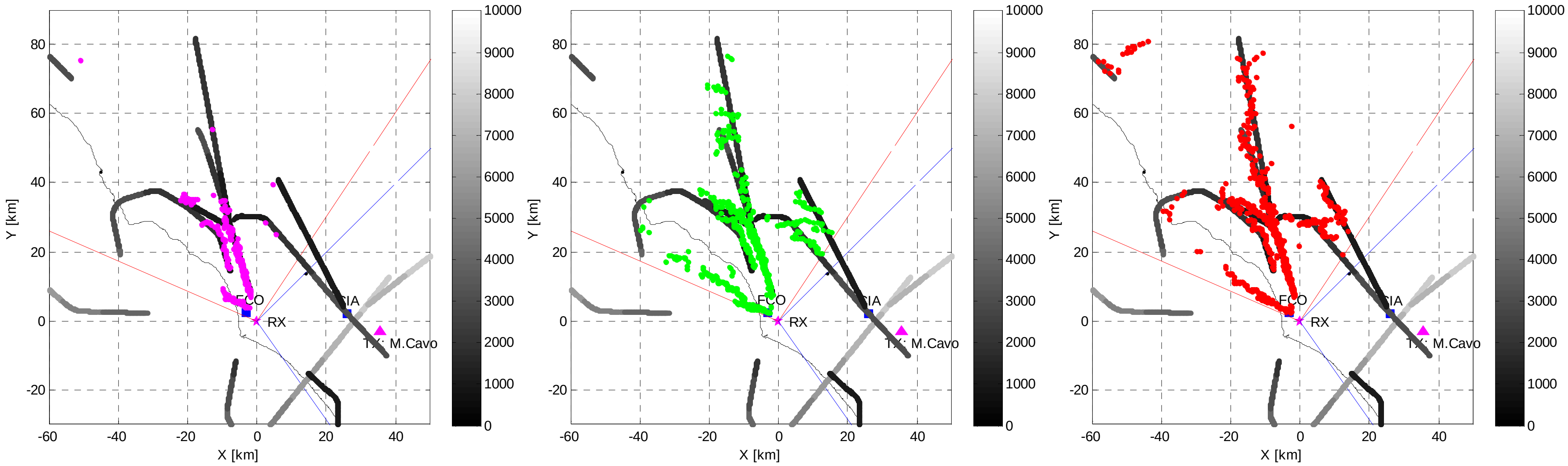


- With a Single-Stage Algorithm, many reasonably complete plot sequences are observed, while for the others only few plots are detected
- When using the Multi-Stage Algorithm, additional plots/tracks are detected

Multi-frequency operation (I)

Site 3

Joint exploitation of multiple FM radio channels
(for both target detection and DoA estimation)

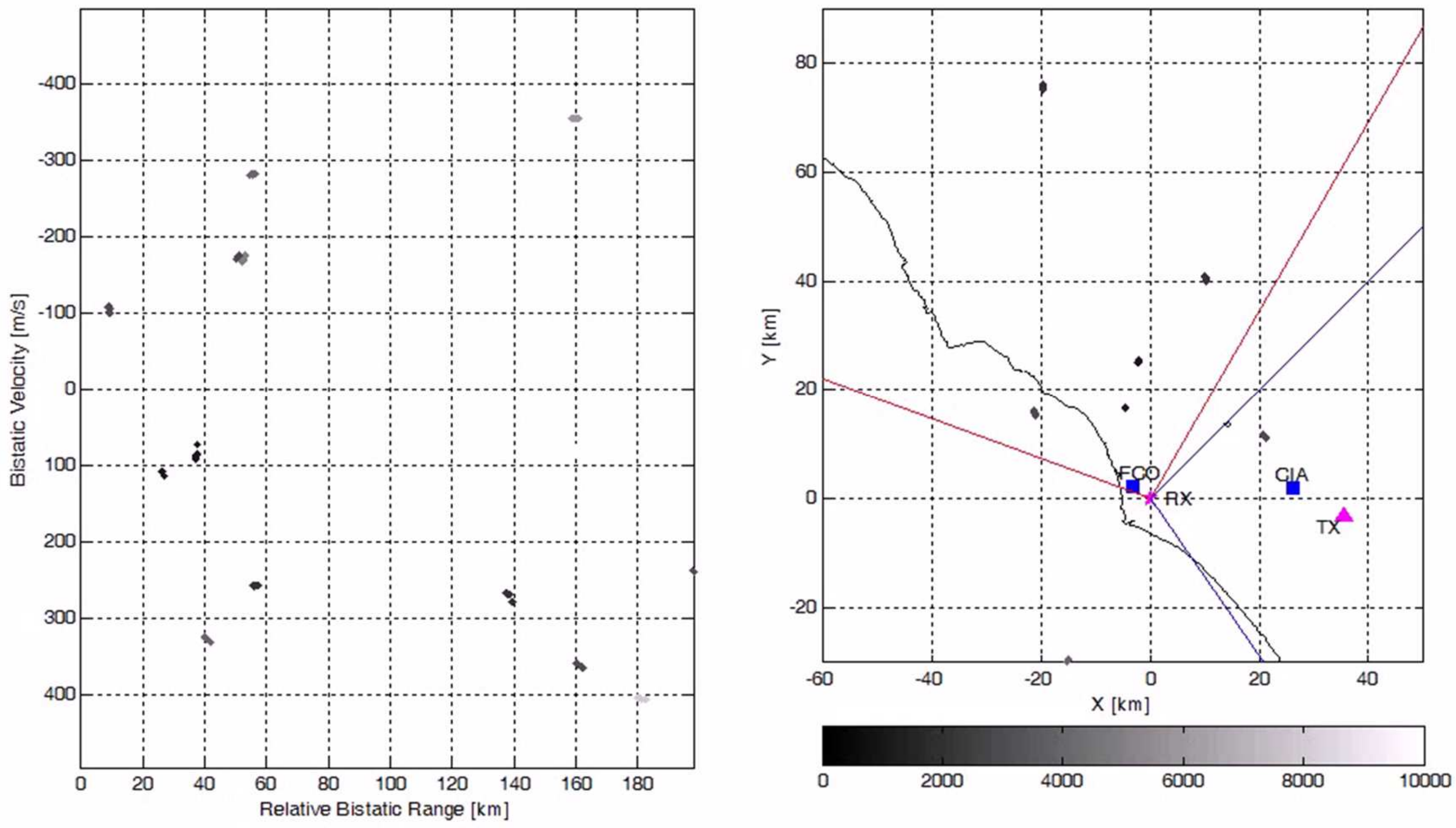


- Single FM radio channel: **106.6** – **94.5** MHz
- MF integration: **90.3 – 94.5 – 103.0 – 106.6** MHz
- Time interval: about 8 minutes

- 106.6 MHz
- 94.5 MHz
- MF Integration
- ATC data

Multi-frequency operation (II)

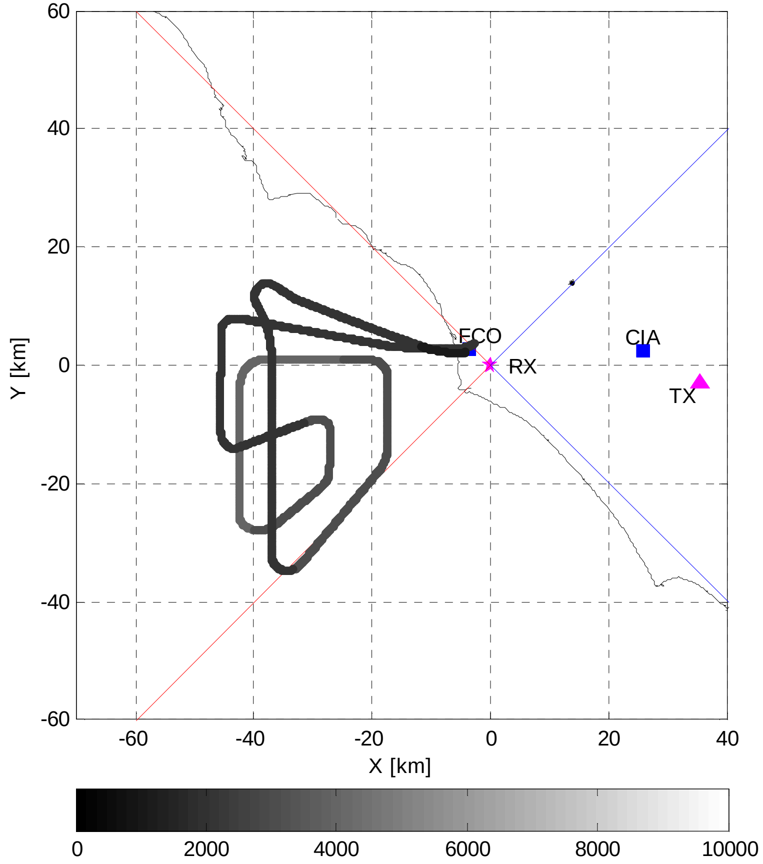
Site 3



- MF integration: **90.3 – 94.5 – 103.0** MHz
- Time interval: about 40 minutes

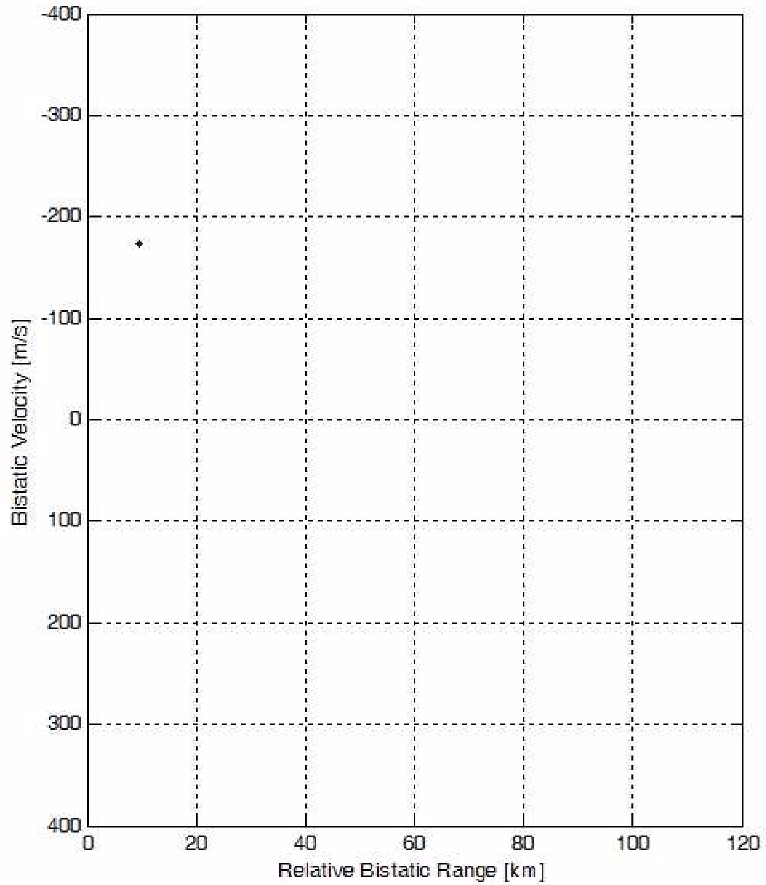
- PBR detections
- ATC data

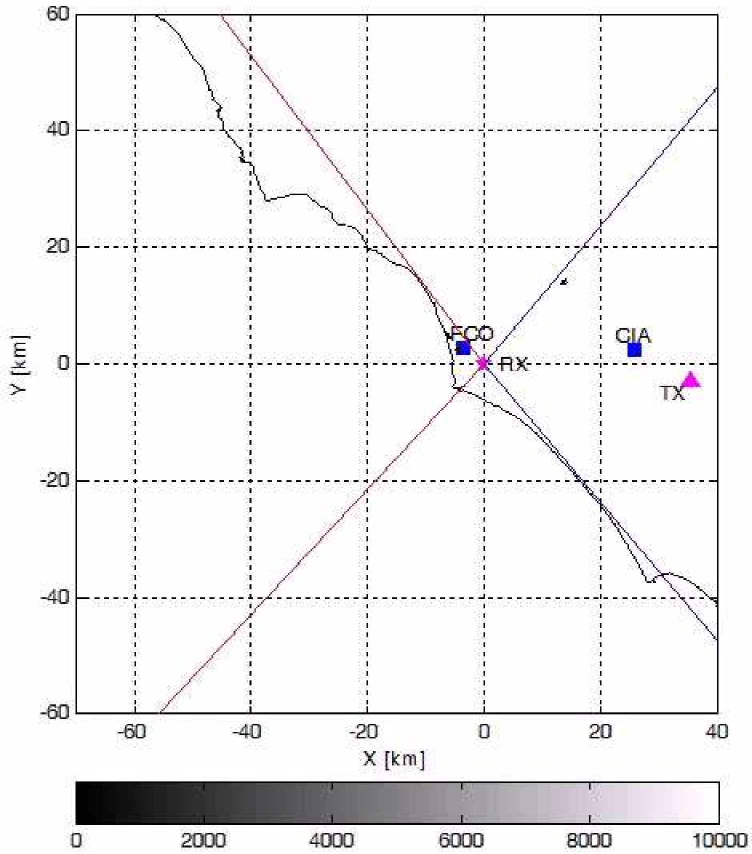
Results against cooperative targets (I)



- Acquisition campaign in cooperation with ENAV
- Time interval: about 56 minutes

Results against cooperative targets (II)





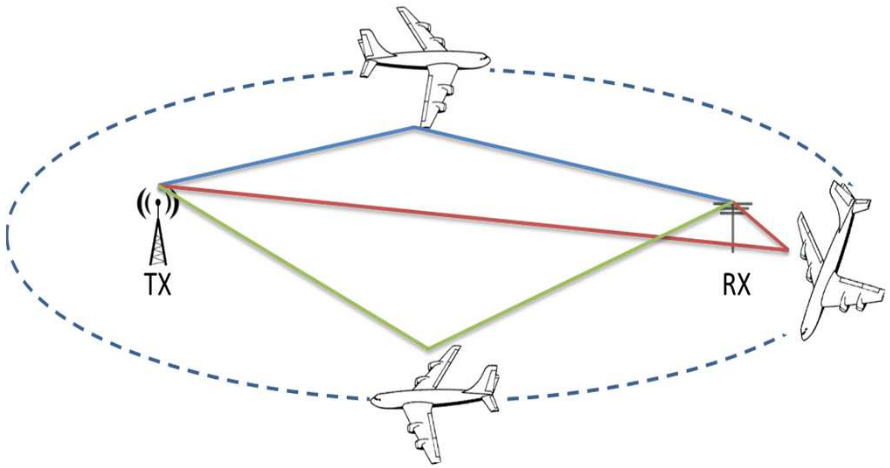
- Single FM radio channel: **94,4 – 106,6 - 107,1** MHz
- Time interval: about 56 minutes

- PBR detections
- ATC data

Steps toward target classification

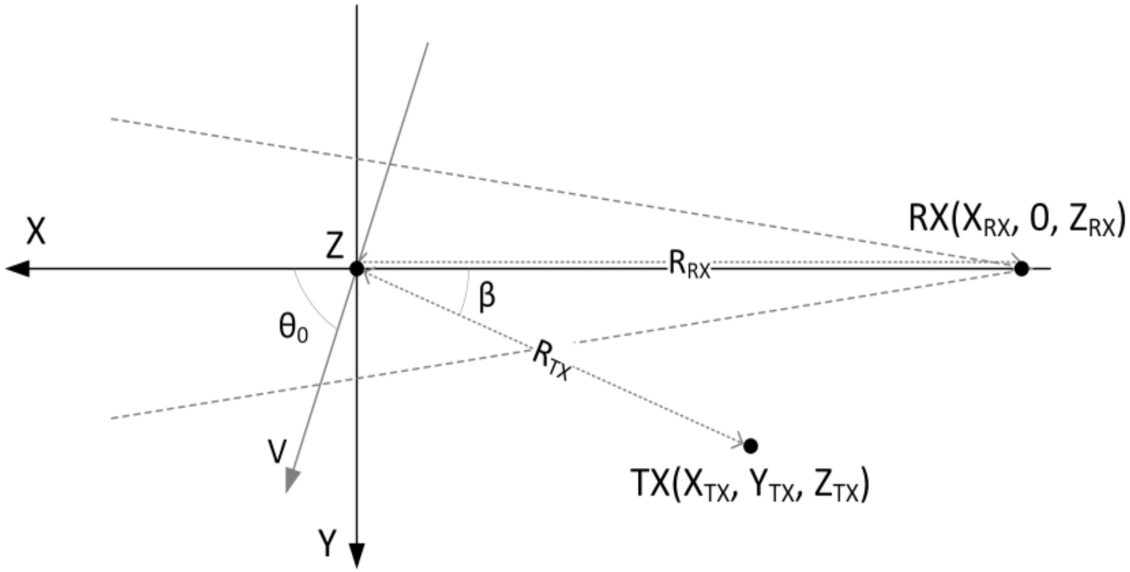
CROSS-RANGE PROFILING OF AERIAL TARGETS VIA PASSIVE ISAR PROCESSING

- Limited range resolution due to the narrow bandwidth (~1,5 km)
- Achievable good cross-range resolution thanks to passive ISAR techniques for targets with a motion component tangential to the bistatic radar ellipse



GOAL: IMPROVE TARGETS LOCALIZATION AND CLASSIFICATION CAPABILITY

System and target model description



The target is moving with a constant speed V following a straight path rotated of an angle θ_0 counter-clockwise from the X axis.

Bistatic range and Doppler frequency during the time t for scatterer n:

- $R_n(t) \equiv R_{TX,n}(t) + R_{RX,n}(t)$
- $f_n(t) \equiv -\frac{1}{\lambda}\dot{R}_n(t)$

By considering the target fulcrum as the $n = 0$ scatterer, the Doppler frequency at first order is:

$$f_0(t) \cong \frac{1}{\lambda}\left[\left(\frac{x_{TX}cos\theta_0+y_{TX}sin\theta_0}{R_{TX}}+\frac{x_{RX}cos\theta_0}{R_{RX}}\right)V-\left(\frac{1}{R_{TX}}-\frac{(x_{TX}cos\theta_0+y_{TX}sin\theta_0)^2}{R_{TX}^3}+\frac{1}{R_{RX}}-\frac{(x_{RX}cos\theta_0)^2}{R_{RX}^3}\right)V^2t\right]$$

Theoretical Doppler bandwidth and CPI

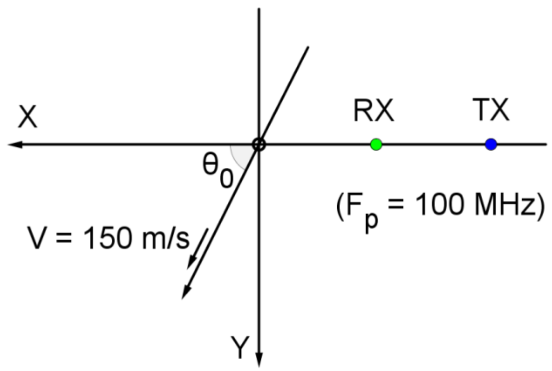
Thus, the total Doppler bandwidth is given by:

$$B_d = \frac{1}{\lambda}\left(\frac{1}{R_{TX}} - \frac{(x_{TX}cos\theta_0 + y_{TX}sin\theta_0)^2}{R_{TX}^3} + \frac{1}{R_{RX}} - \frac{(x_{RX}cos\theta_0)^2}{R_{RX}^3}\right)V^2T$$

Maximum theoretical achievable cross-range resolution:

$$r_{cr} \equiv \frac{V_{cr}}{B_d} = Vsin(\theta_0 - \beta/2)/B_d$$

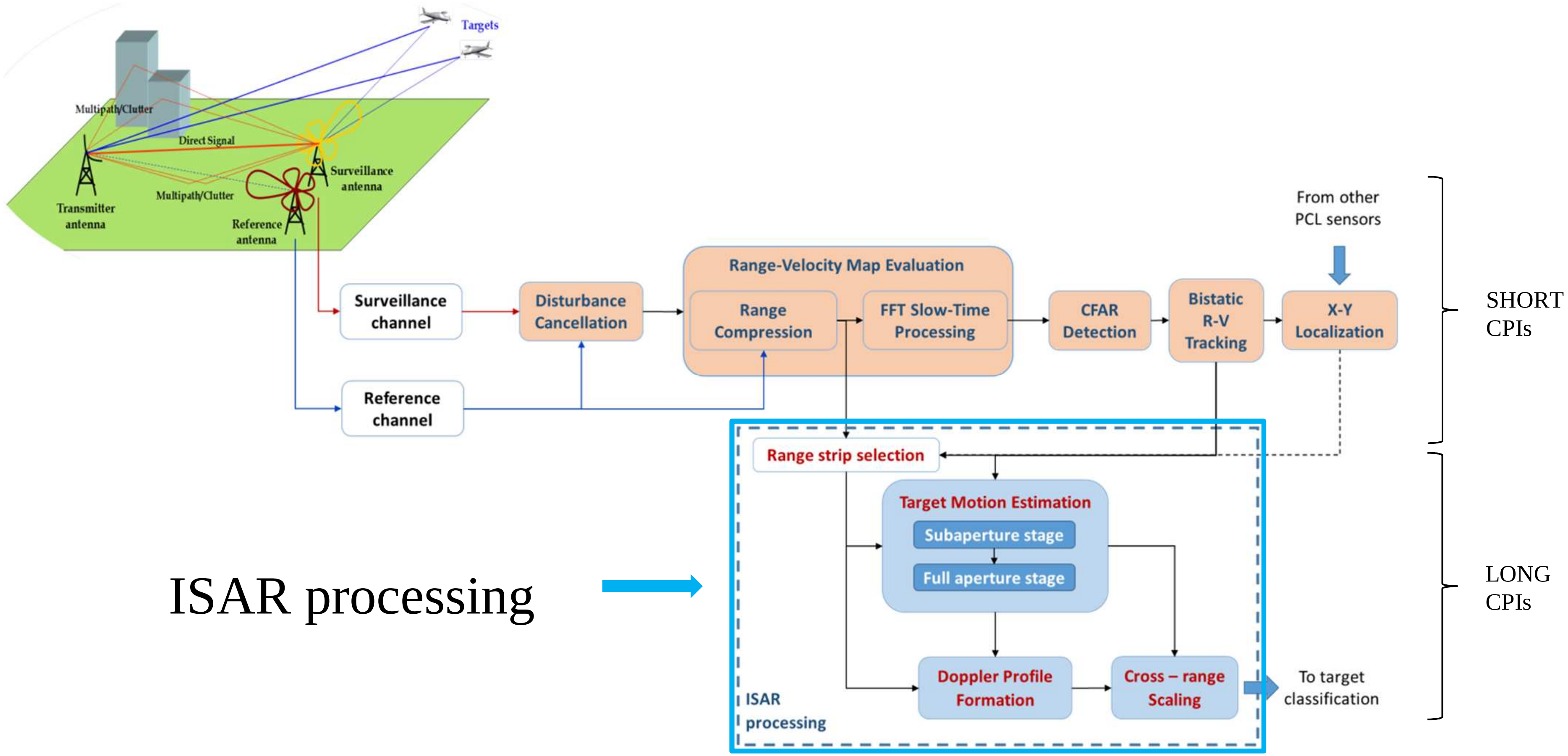
Example:



r_{cr} (m)	CPI T (s)	
	$\theta_0 = \pi/2$	$\theta_0 = \pi/4$
10	13.3	18.8
5	26.6	37.7
1	133.2	188.4

Long CPIs require an ISAR phase compensation of a rather high phase terms order

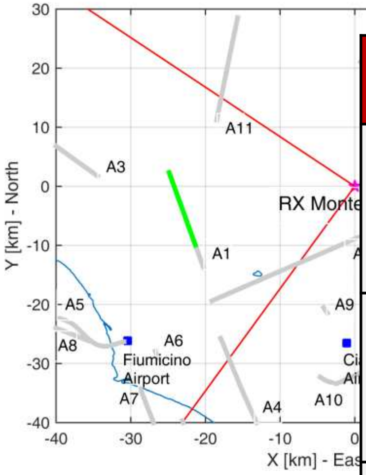
Advanced processing scheme for FM-ISAR systems



ISAR processing

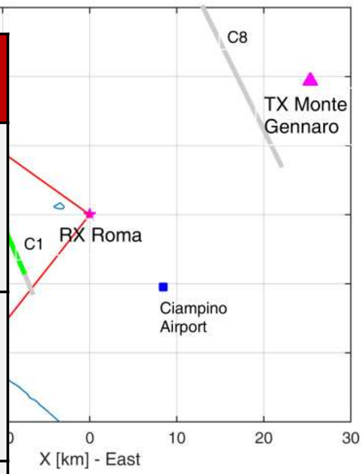
Experimental tests

Test A

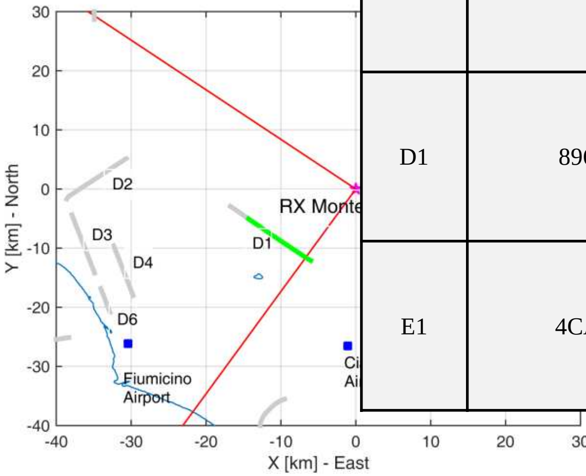


Test B

Test C



Test D

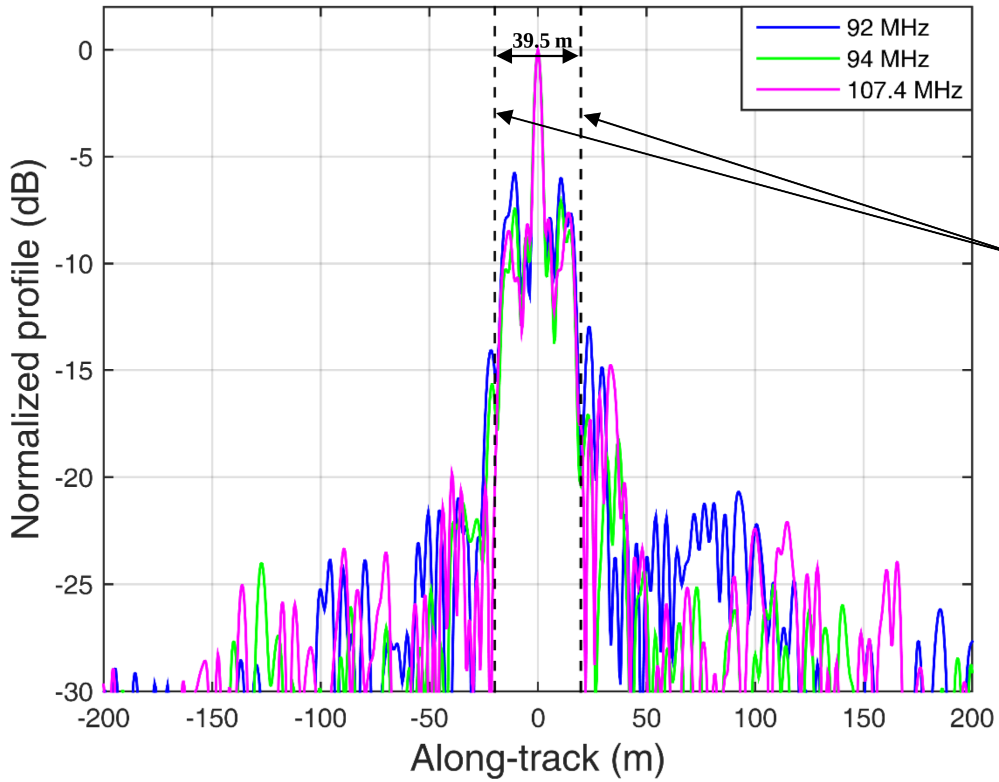


Target ID	Mode-S Address (Hex code)	Target type	Target size (Length x Wingspan)	Target photo
A1	47A721	Boeing 737-8JP (Norwegian)	39.5 m x 35.8 m	
B1	3C6606	Airbus 320-211 (Lufthansa)	37.57 m x 34.10 m	
C1	405638	Airbus A319-111 (EasyJet)	33.84 m x 34.10 m	
D1	8960F8	Airbus A380-861 (Emirates)	72.72 m x 79.75 m	
E1	4CA987	Boeing 777-243 (ER) (Alitalia)	63.7 m x 60.9 m	

s (A, B, C, D and E)
re days with different:
es
A1, B1, C1, D1 and E1)

Results for Test A

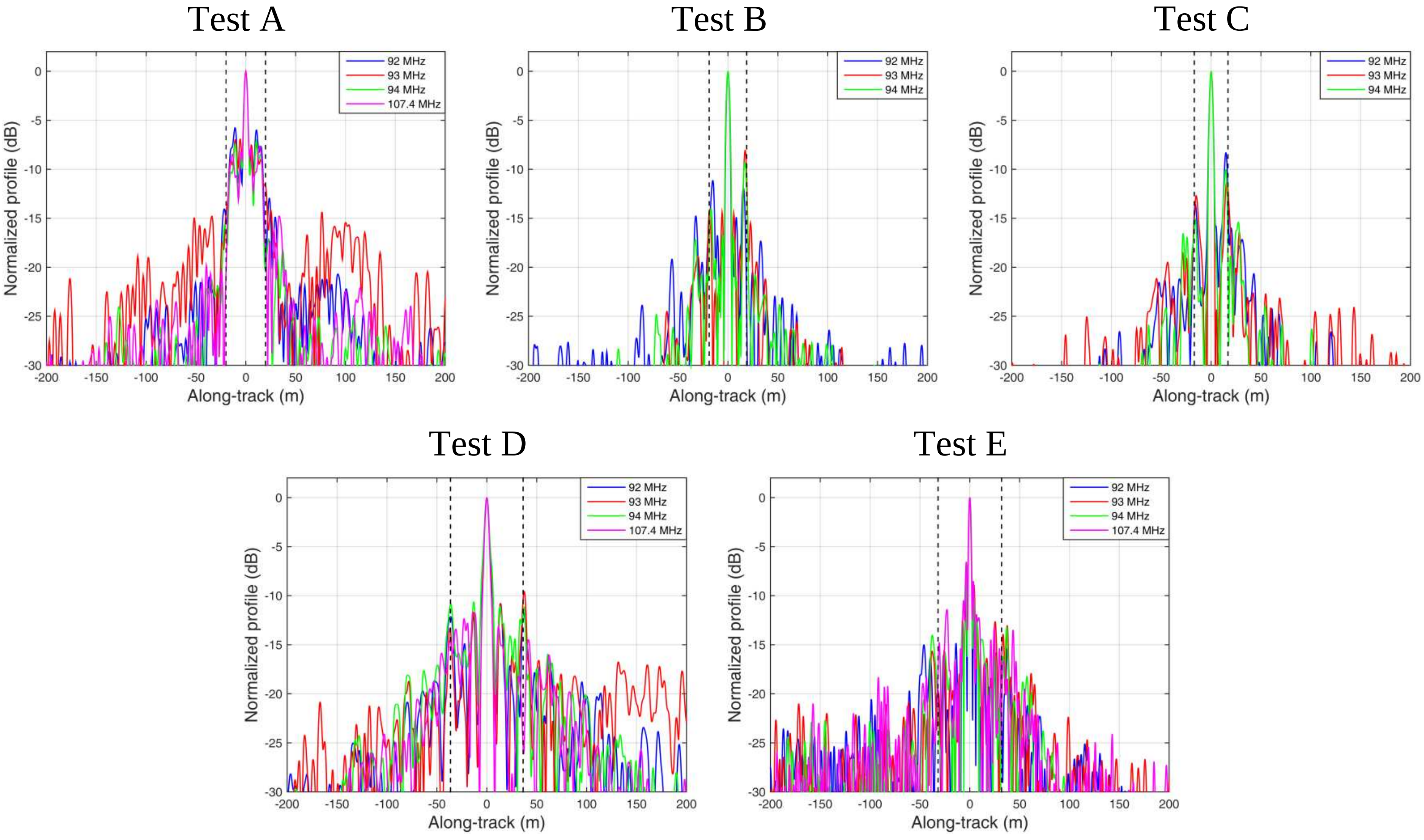
Along-track profiles for three different FM channels obtained using a CPI of 70 seconds.



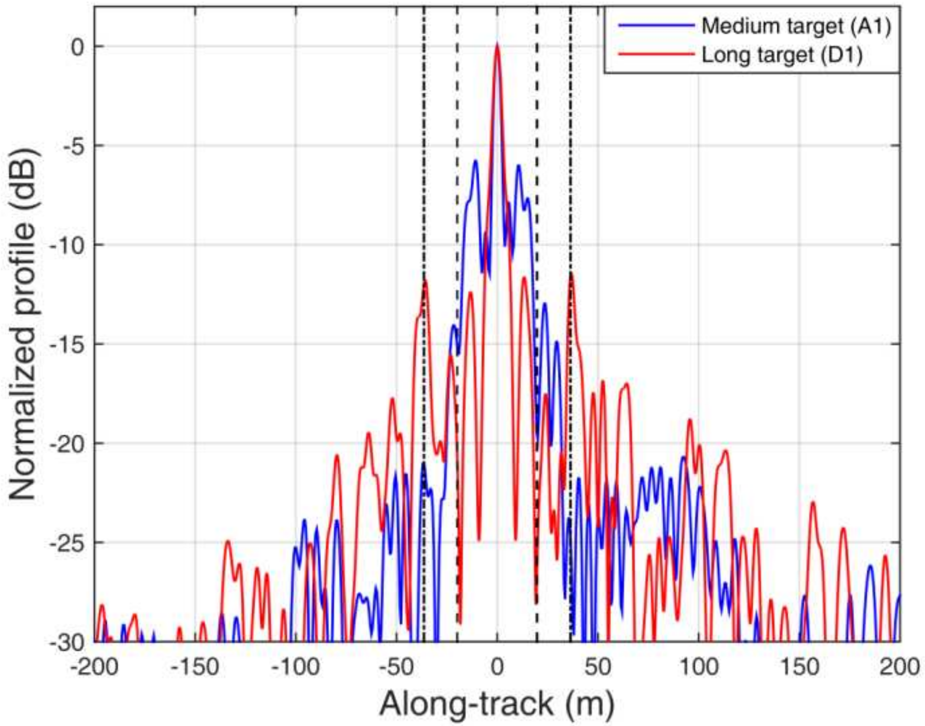
The dashed lines mark the target size of 39.5 m provided by the air truth (ADS-B)

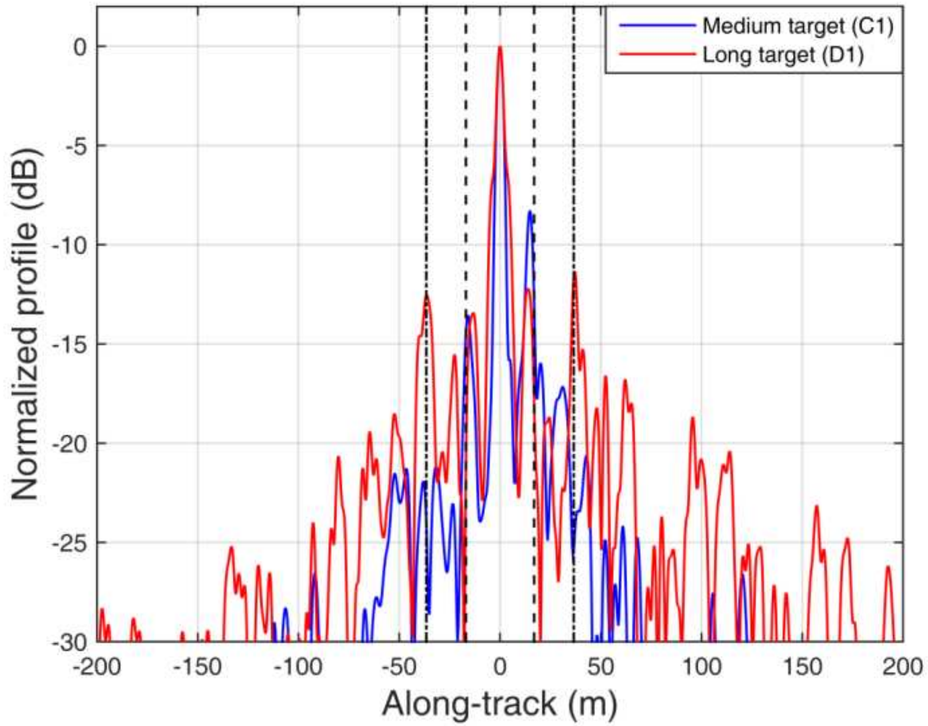
Good stability for target cross-range profiles achieved at different FM channels!

Results for all tests



Target classification capability

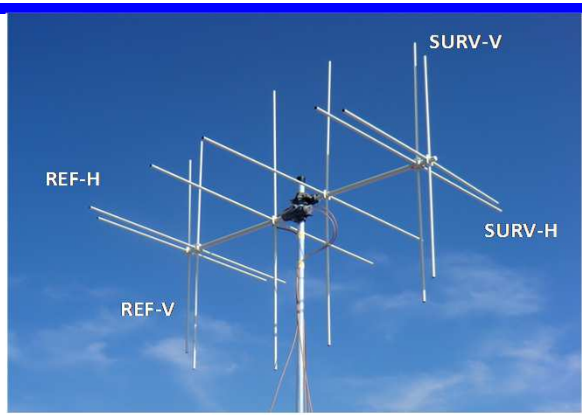




Conclusions: For target with a motion in the cross-range direction it is possible to identify the targets size class.

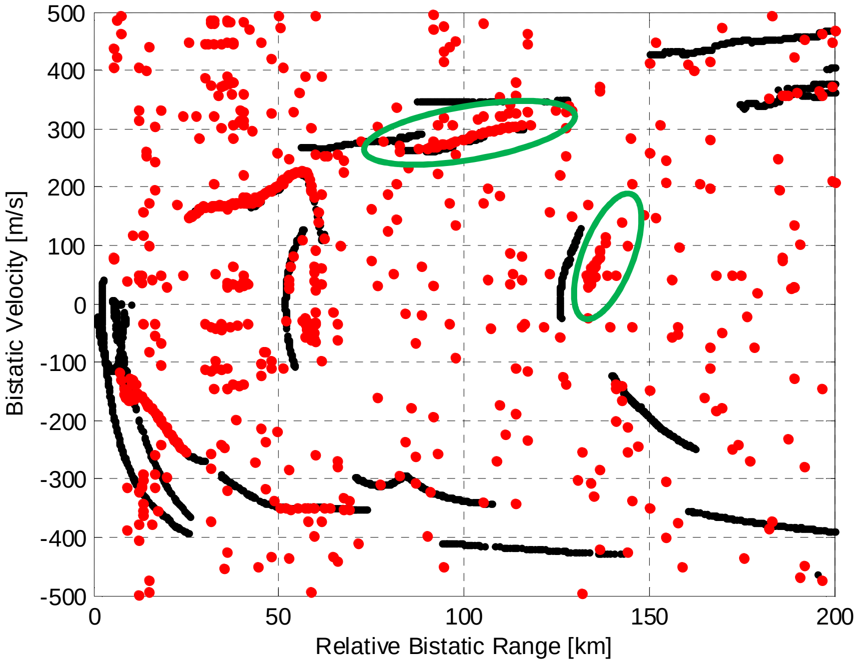
Exploitation of polarization diversity (I)

Use of different antenna polarizations

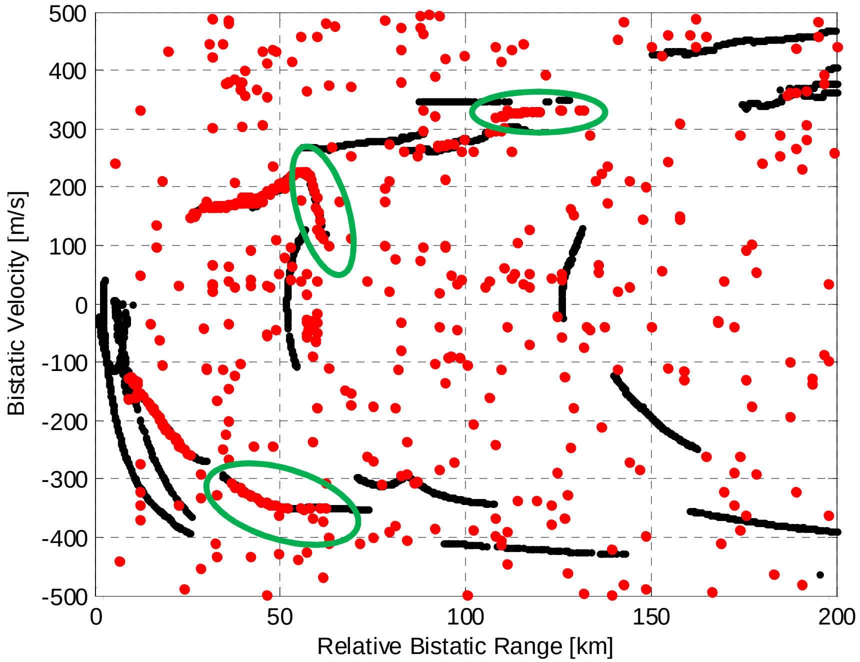


- Dual-polarized antennas (3 cross-elements Yagi, gain 7 dBi, front-to-back ratio >16 dB)
- 50 consecutive data files
- FM channel @ 94.5 MHz

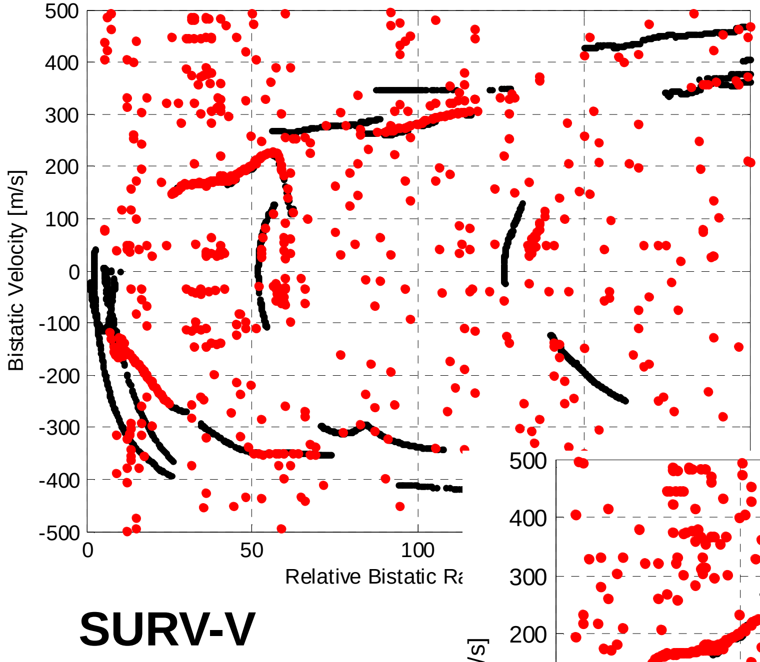
SURV-V

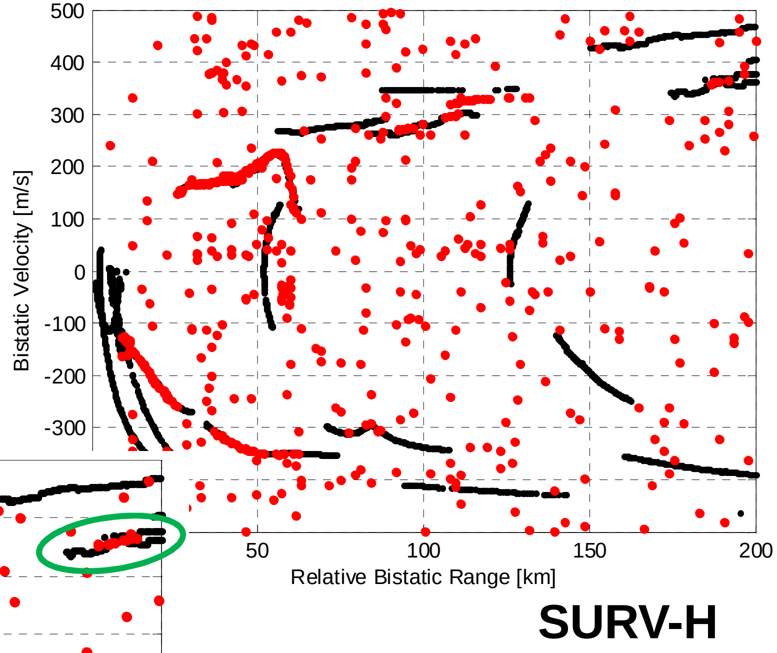


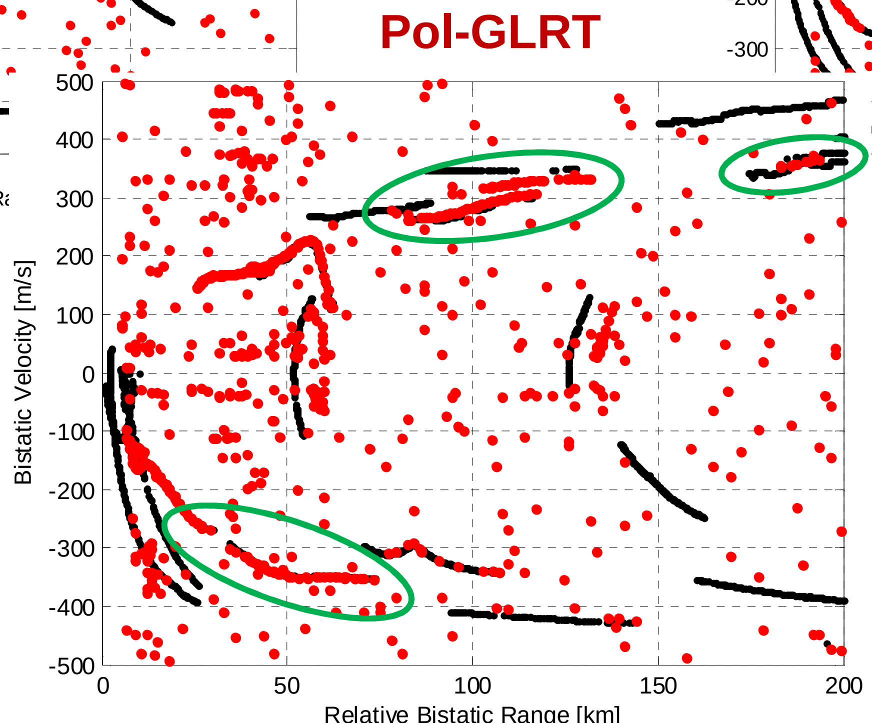
SURV-H



Exploitation of polarization diversity (II)

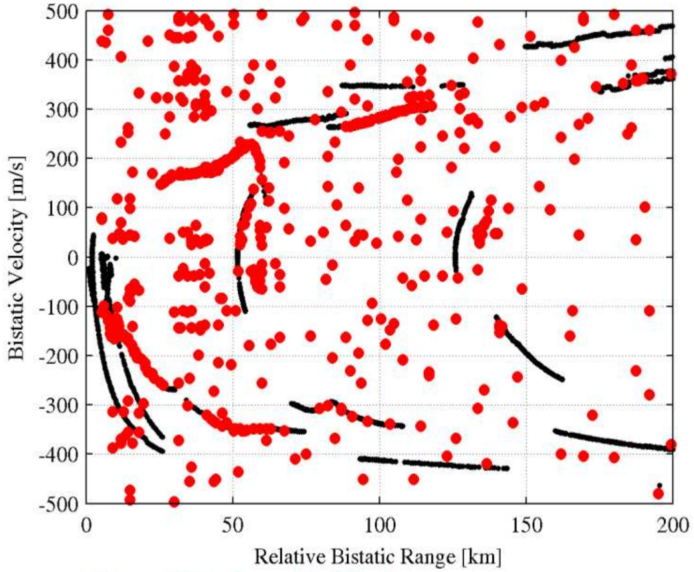




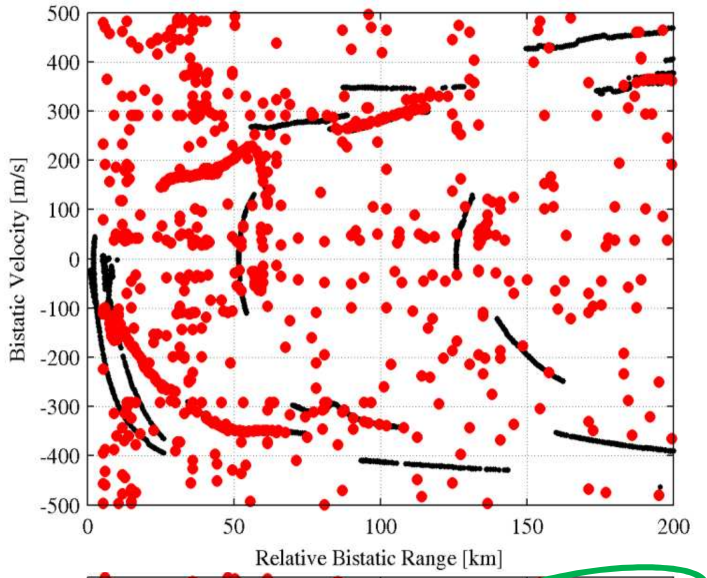


Joint exploitation of different antenna polarizations

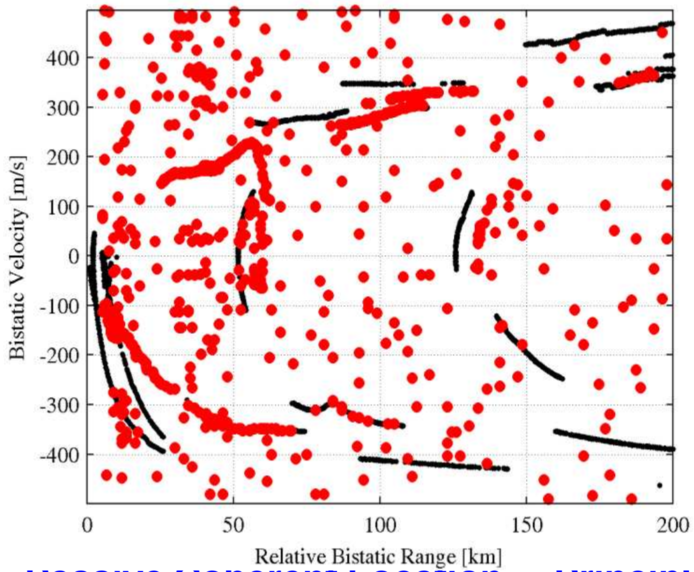
Exploitation of polarization & frequency diversity



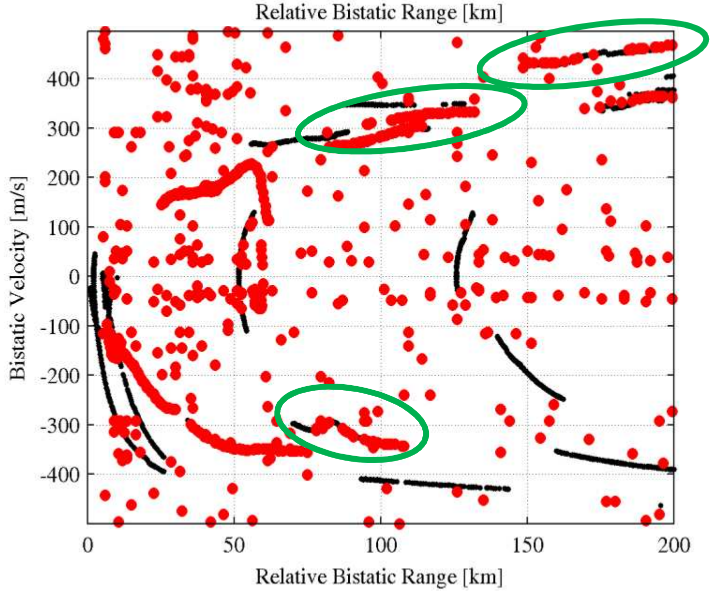
Single-Freq
Single-Pol



Multi-Freq
Single-Pol



SingleFreq
Dual-Pol



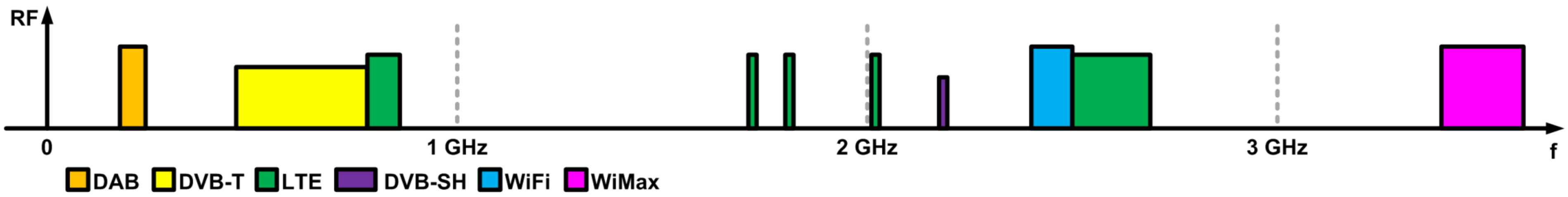
Multi-Freq
Dual-Pol

Joint exploitation of frequency and polarization diversity

DVB-T-based passive radar for air and ground traffic monitoring

OFDM waveforms of opportunity

Waveform	Bandwidth [MHz]	Channel Bandwidth [MHz]	Transmission type	Range Resolution	Velocity (Doppler) resolution	Surveillance application	Targets
DAB	174÷240	**1,537**	Continuous	**Good**	**Good**	**Medium**	**Aircrafts Boats**
DVB-T	460÷790	**8**	Continuous	**Very good**	**Good**	**Medium Short**	**Aircrafts Boats**
DVB-SH	2175÷2200	**5**	Continuous	**Good**	**Good**	**Very Short**	**Aircrafts Boats**
LTE	790÷862 1710÷1785 1805÷1880 2010÷2025 2500÷2690	**5 10 15 20**	Burst	**Good**	**Good**	**Short**	**Aircrafts Boats**
WiFi	2400÷2500 5150÷5350 5450÷5725	**20**	Burst	**Good**	**Good**	**Short**	**Humans Cars**
WiMAX	3400÷3600	**1,25 5 10 20**	Burst	**Good**	**Good**	**Medium Short**	**Boats Cars Humans**



DVB-T as IO : Advantages and drawbacks

In cooperation with Fraunhofer FHR

PRO's

✓ Wide Bandwidth → Good range resolution

✓ Constant bandwidth → close-to-ideal ambiguity function for target detection

✓ No need for a dedicated Reference Antenna

CON's

× Low-power → short range applications!

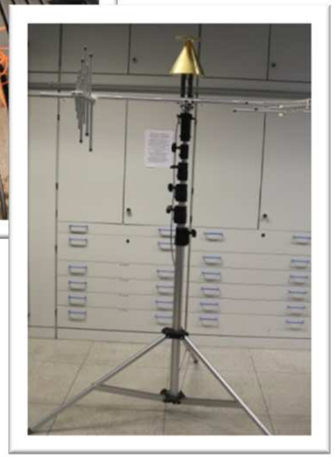
× Single Frequency Network

× Emissions towards the ground → not necessarily good coverage of higher altitude aircrafts

Acquisition Campaign (I)

In cooperation with Fraunhofer FHR

- In Eckernförde, Germany
- Passive radar system PARASOL developed at Fraunhofer FHR
- PARASOL was mounted on a moving boat
- Two parallel receiving channels, each one connected to a different log periodic antenna
- DVB-T signals as IO
- 3 Cooperative targets

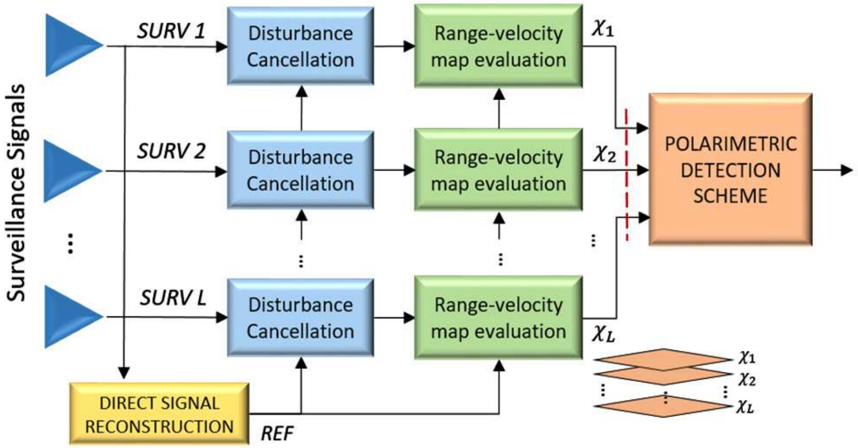


Ultra light aircraft: Delphin

Two identical speedboats

Acquisition Campaign and Processing

In cooperation with
Fraunhofer
FHR

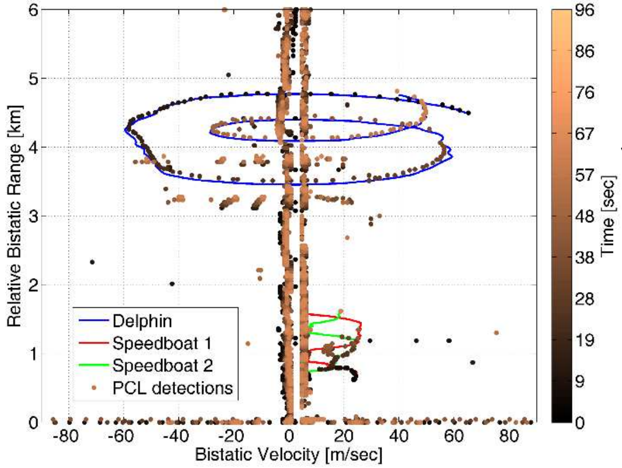


- Polarimetric Non Coherent Integration
- Polarimetric GLRT

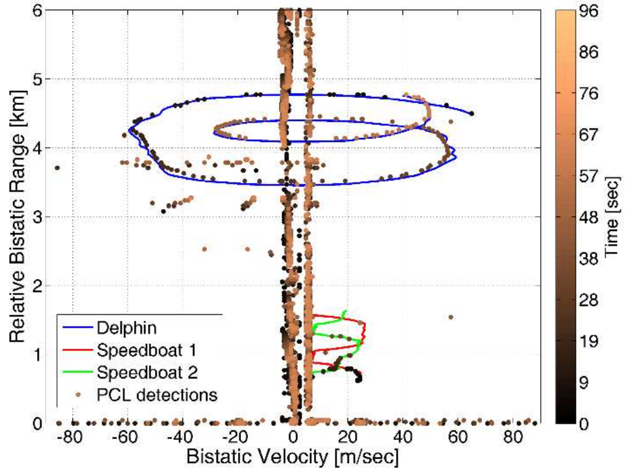
Experimental Results (I)

In cooperation with Fraunhofer FHR

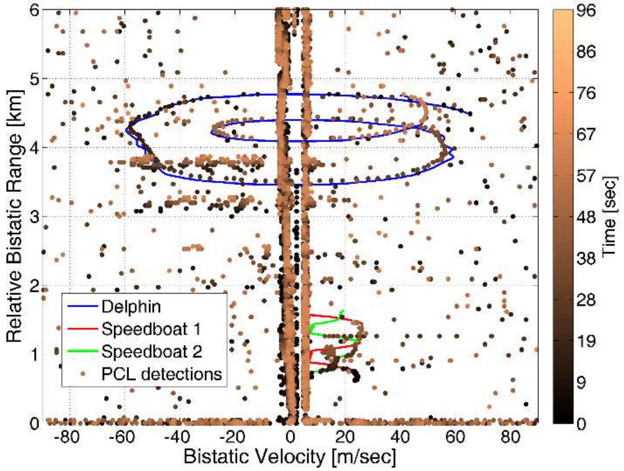
168 consecutive data files



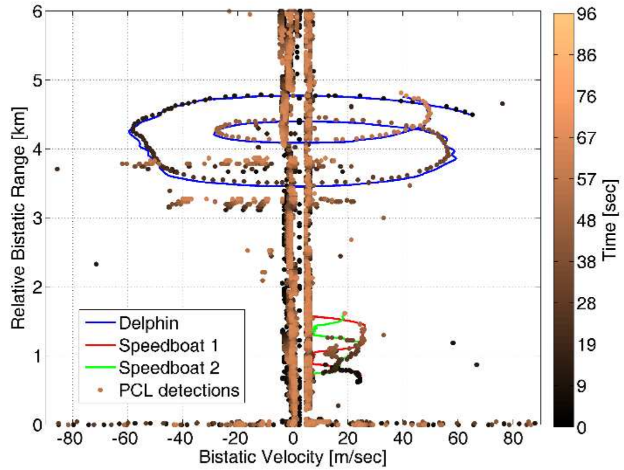
Single – Pol H



Single – Pol V



Polarimetric Non Coherent Integration

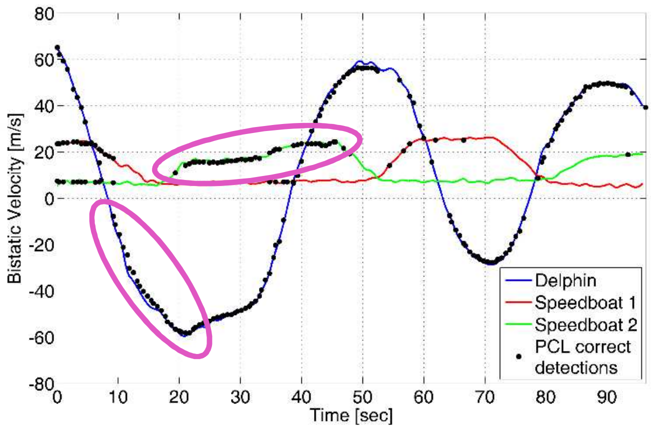


Pol - GLRT

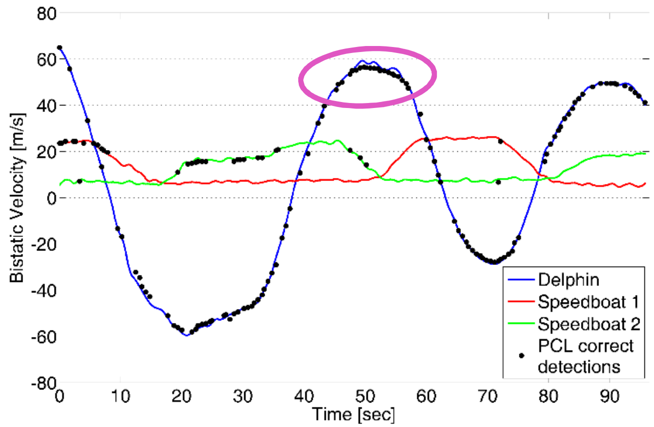
Experimental Results (II)

In cooperation with Fraunhofer FHR

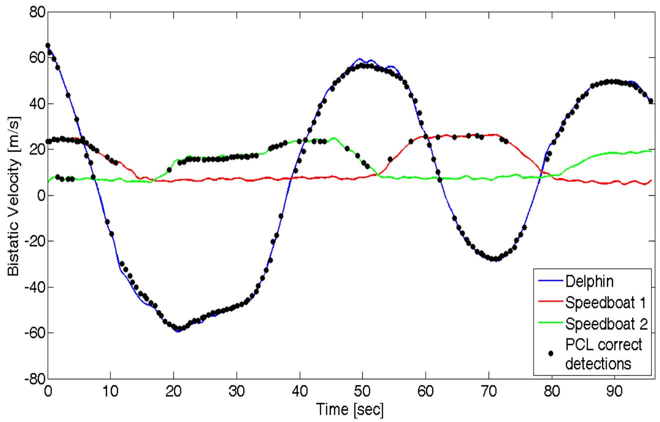
Single – Pol H



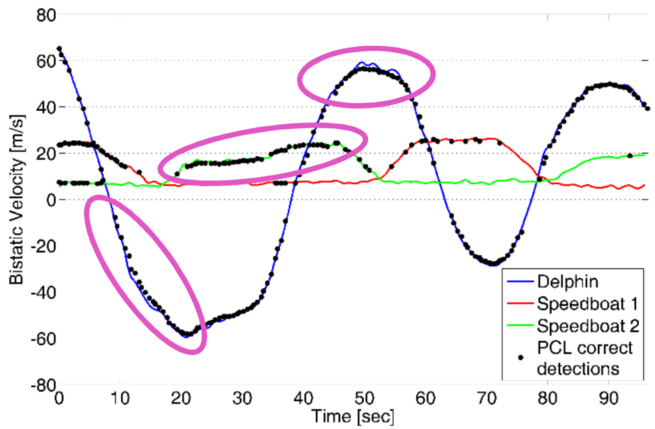
Single – Pol V



Polarimetric Non Coherent Integration



Pol - GLRT



Experimental Results (III)

Single Polarization

- × It is impossible to establish a priori the best performing polarimetric channel

Polarimetric NCI

- ✓ Slight improvement in target detection capability
- × False alarms increase

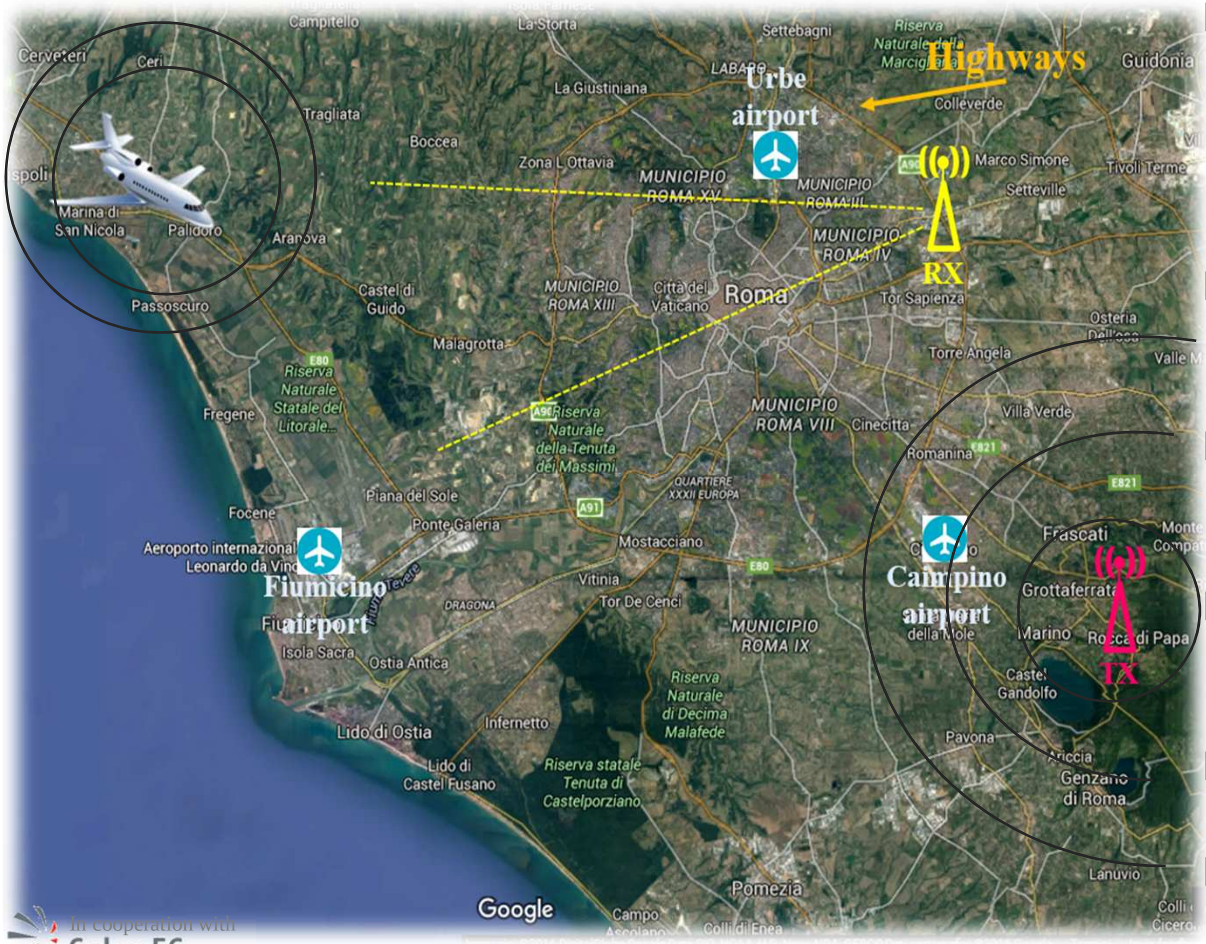
Polarimetric GLRT

- ✓ Strong improvement in target detection capability
- ✓ More continuity on the tracks
- ✓ Good false alarm control capability

In cooperation with Fraunhofer FHR

DVB-T based PBR for air traffic monitoring

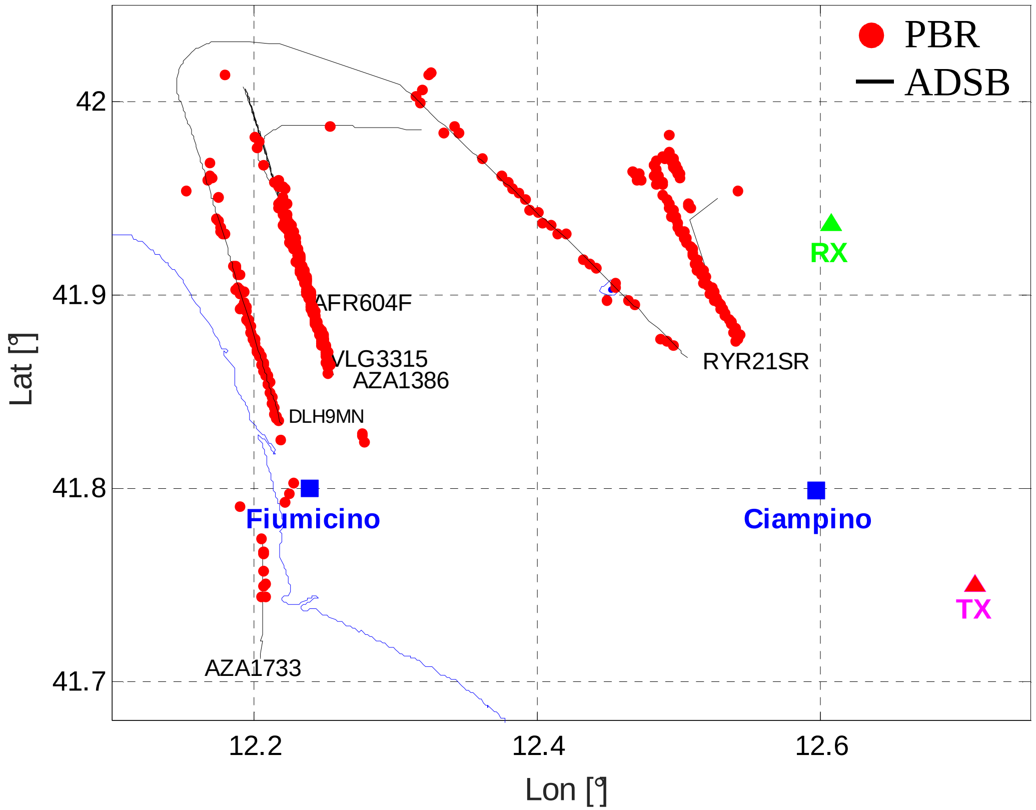
- Acquisition campaign of May 2016



- Surveillance antenna pointed according to standard arrival and departure routes to and from Fiumicino and Ciampino airports;
- Reference antenna steered toward Monte Cavo;
- Carrier frequencies: 586 MHz, 634 MHz, 714 MHz, 762 MHz;
- Continuous acquisition duration: about 0,45 sec;
- Live ATC registrations available;
- Highway near the receiver position;

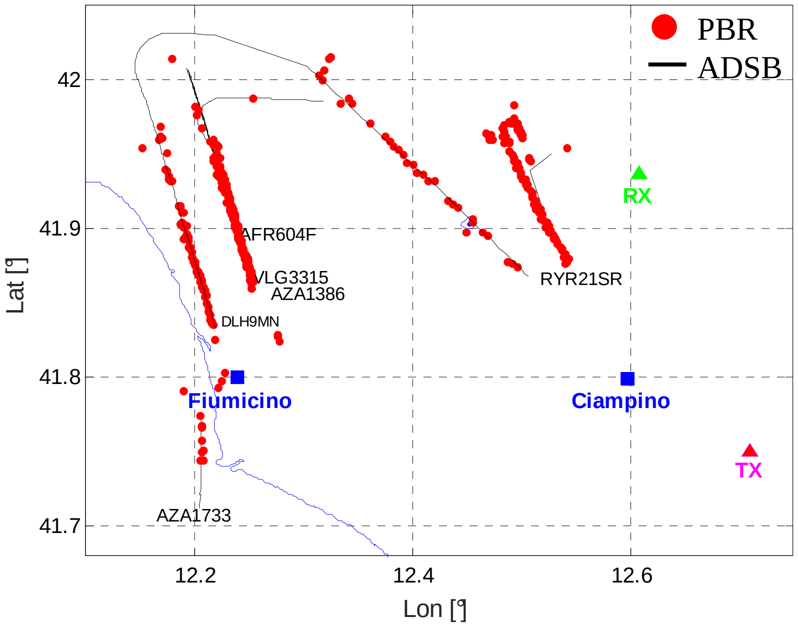
DVB-T based PBR for air traffic monitoring

- Acquisition campaign of May 2016

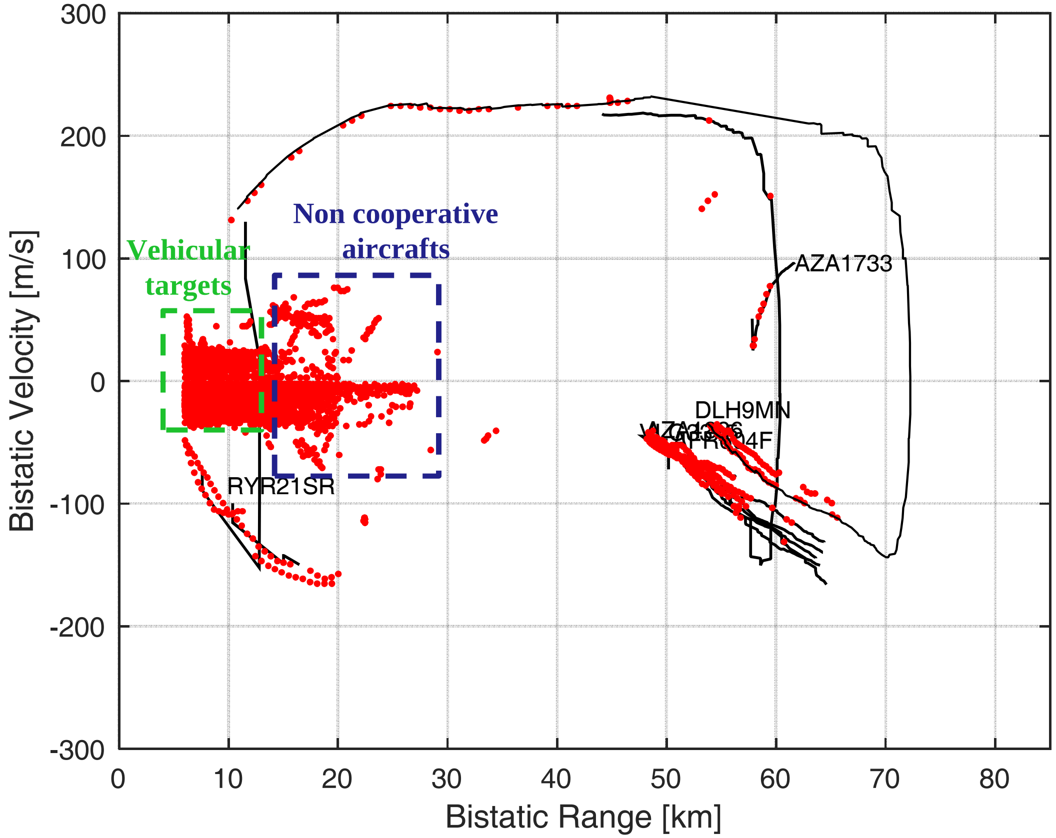


In cooperation with
Selex ES
A Finmeccanica Company

DVB-T based PBR for ground traffic monitoring

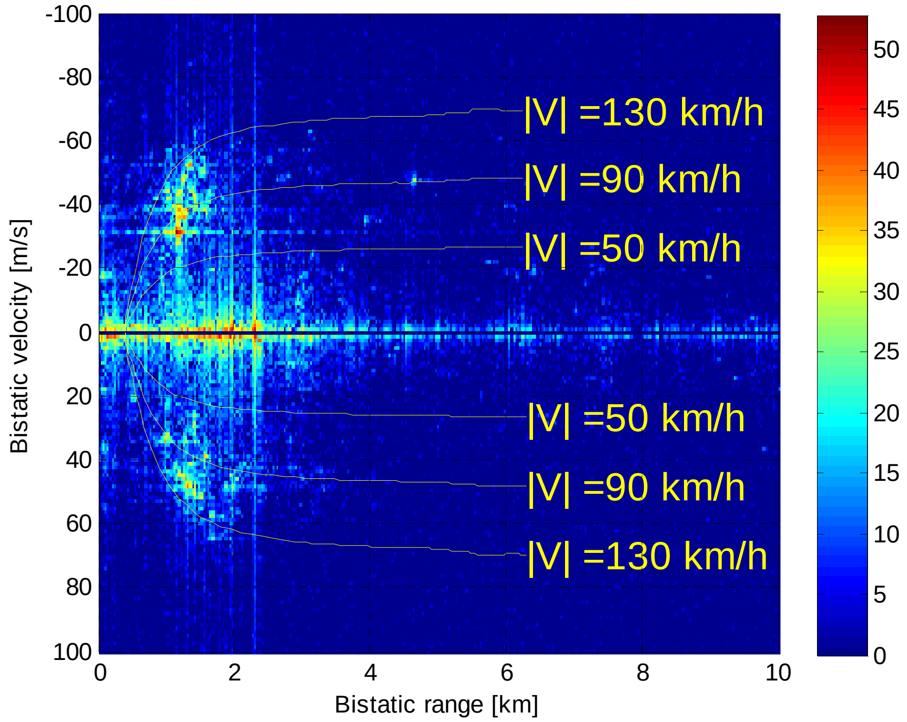


Local geographic coordinates
to Bistatic domain transformation



In cooperation with Selex ES
A Finmeccanica Company

DVB-T based PBR for ground traffic monitoring

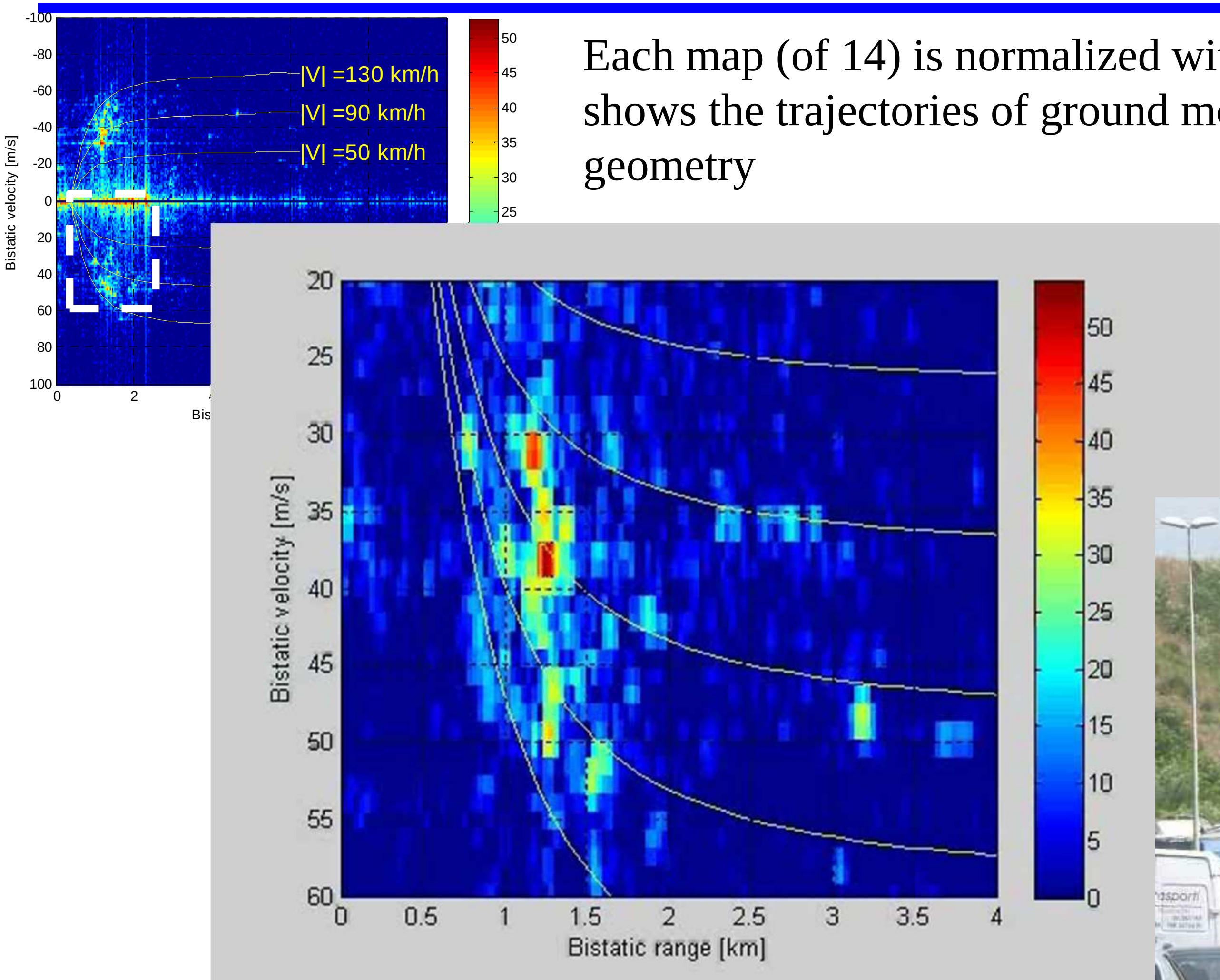


Local geographic coordinates
to Bistatic domain transformation

In cooperation with Selex ES
A Finmeccanica Company

DVB-T based PBR for ground traffic monitoring

Each map (of 14) is normalized with noise power estimation and shows the trajectories of ground moving target in the specific geometry

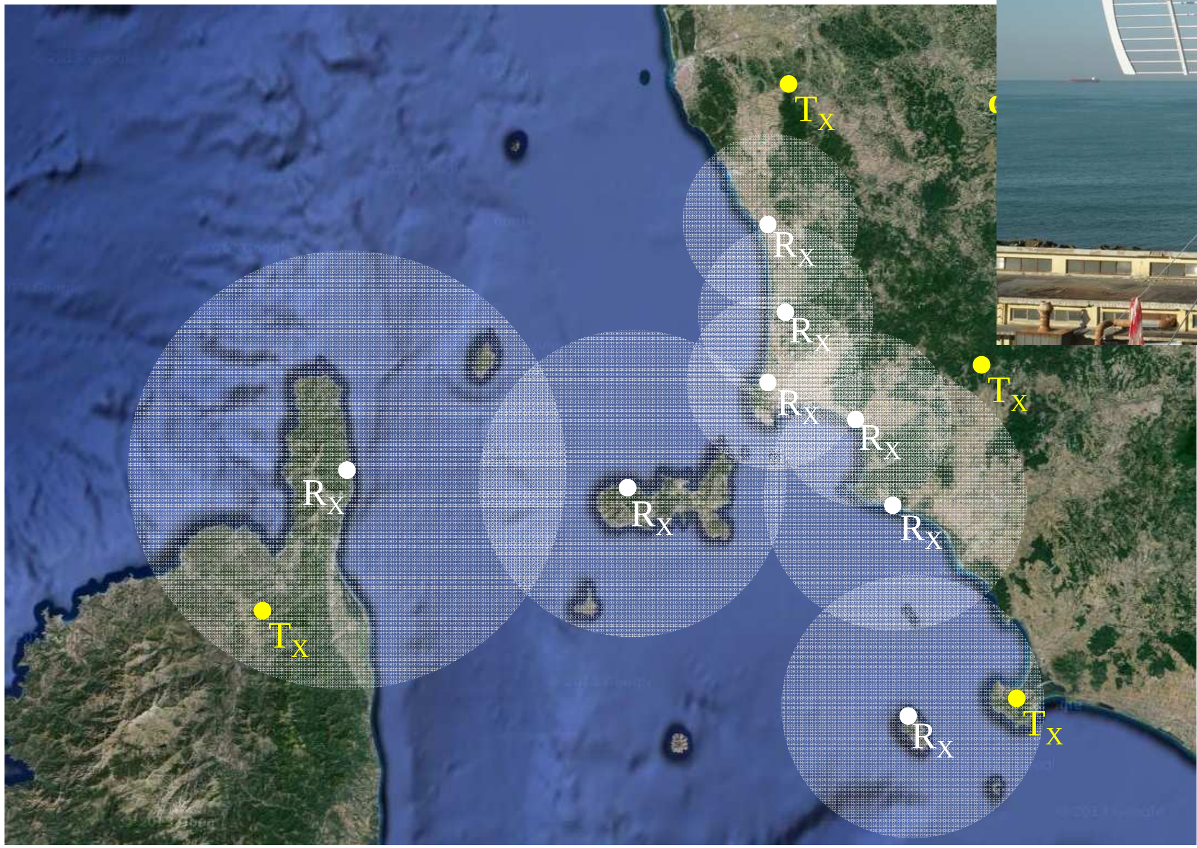


In cooperation with
Selex ES
A Finmeccanica Company

DVB-T based PBR for maritime traffic monitoring

Maritime surveillance application

In cooperation with Selex ES
A Finmeccanica Company



Could guarantee complete and continuous coverage (could be used as Gap filler)

Precise tracking is required at short range as well as the capability to detect small (low RCS) targets

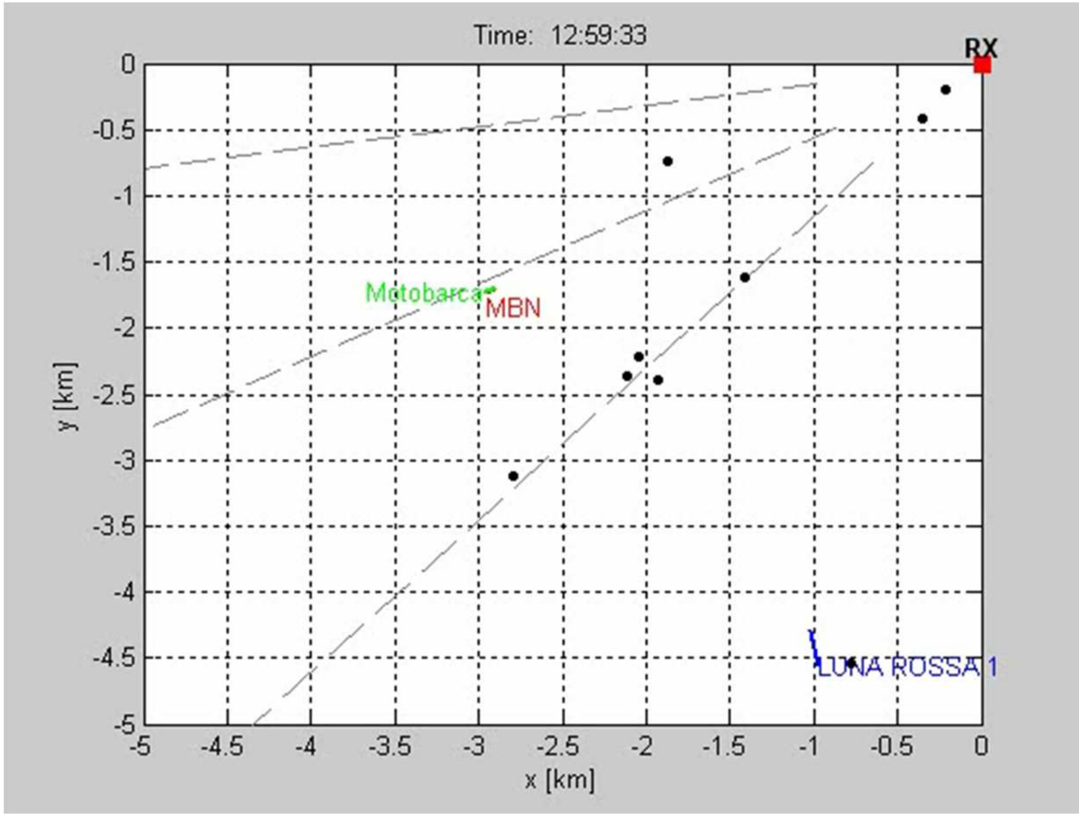
DVB-T based PBR for maritime traffic monitoring

Marina Militare tests at the Livorno harbour

In cooperation with Selex ES
A Finmeccanica Company

DVB-T based PBR for maritime traffic monitoring

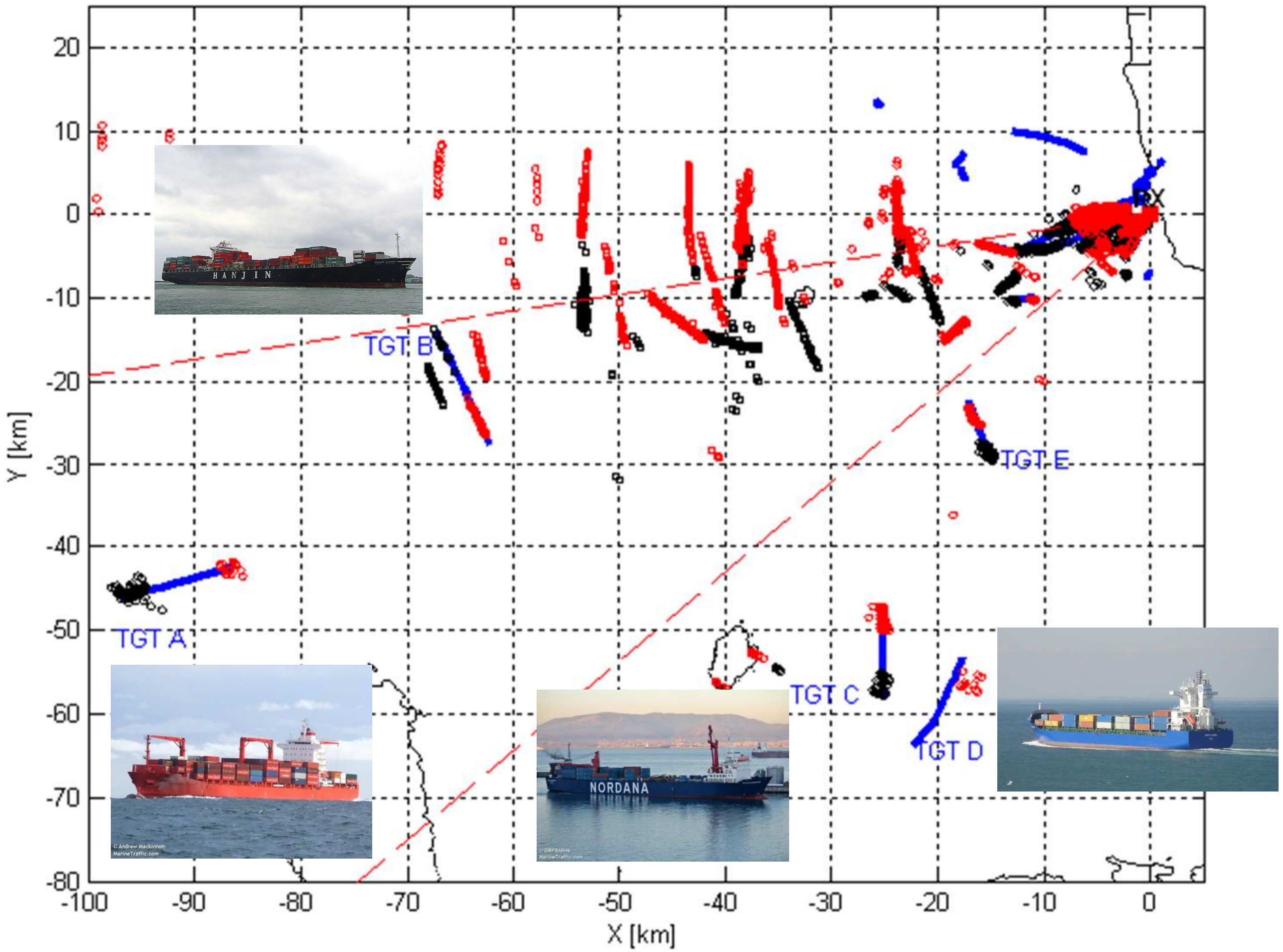
Marina Militare tests
at the Livorno harbour



In cooperation with Selex ES
A Finmeccanica Company

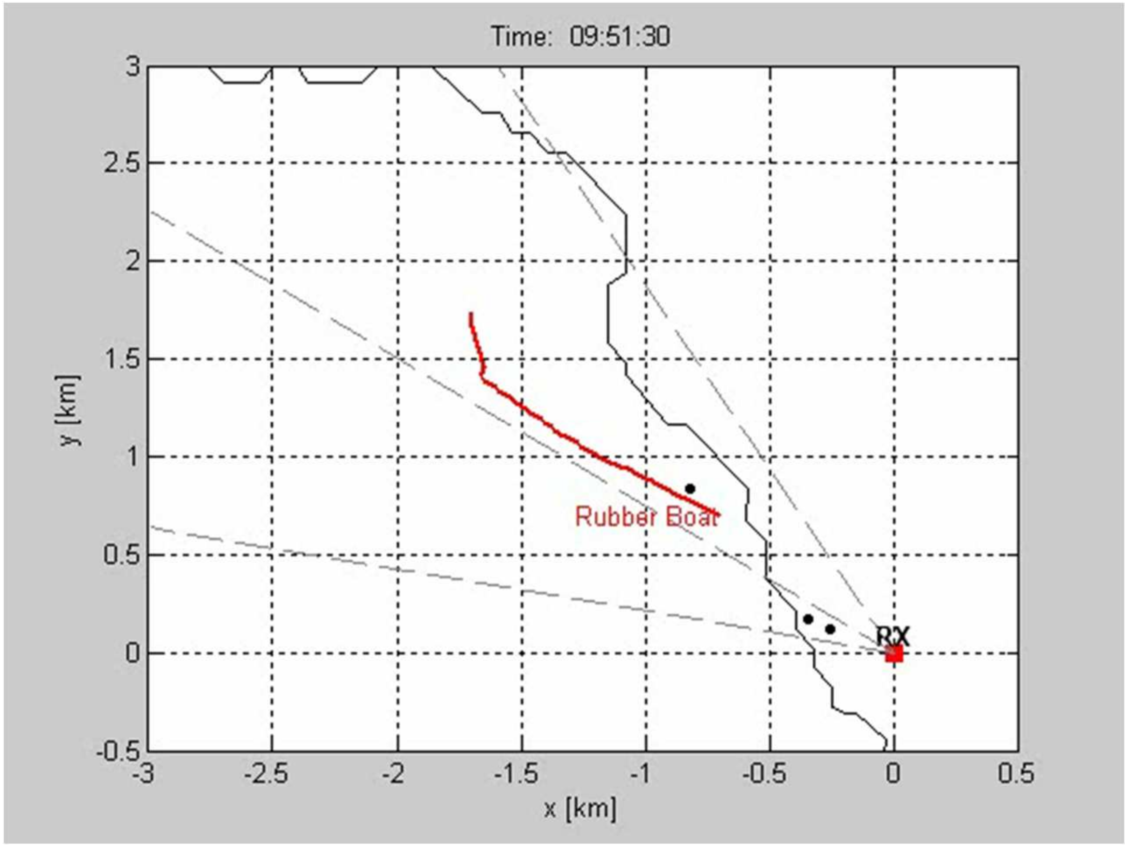
DVB-T based PBR for maritime traffic monitoring

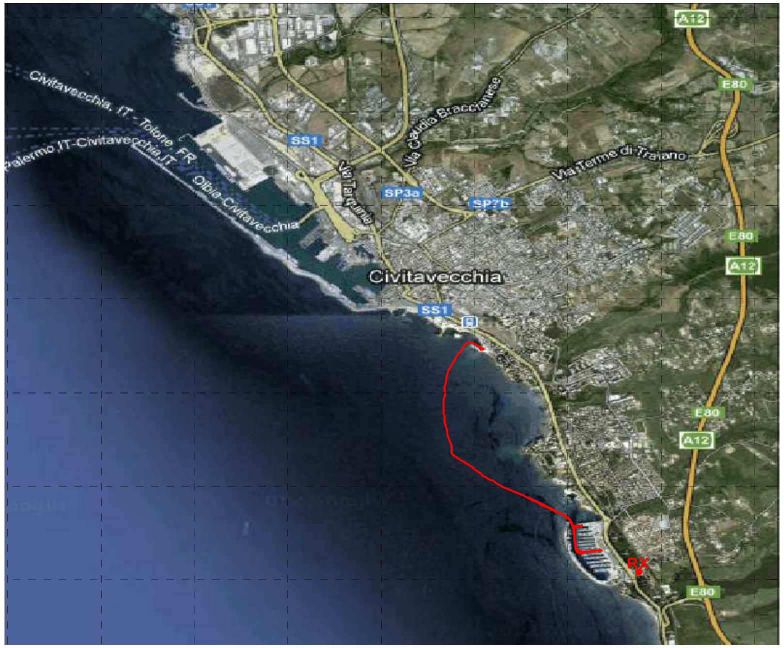
Over the horizon maritime surveillance capability



TGT ID	Max Dist. [km]	DoA [deg]	L [m]	W [m]
A	102	244	210	30
B	69	251	N/A	N/A
C	61	206	200	30
D	65	199	161	25

DVB-T based PBR for maritime traffic monitoring





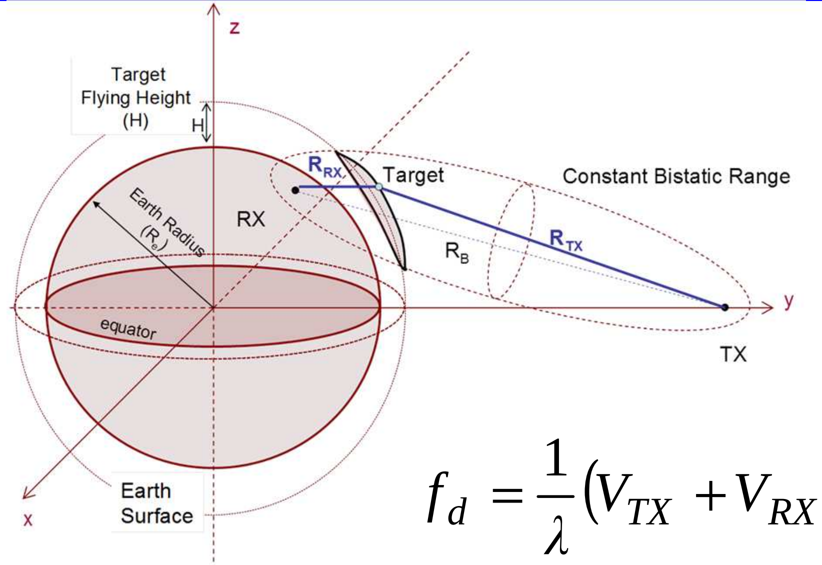
Test in Civitavecchia:
Very small inflatable boat

In cooperation with
Selex ES
A Finmeccanica Company

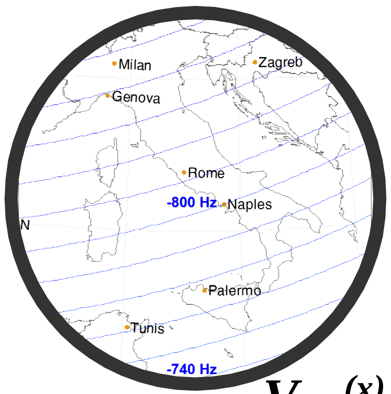
DVB-SH-based passive radar

DVB-SH-based PBR

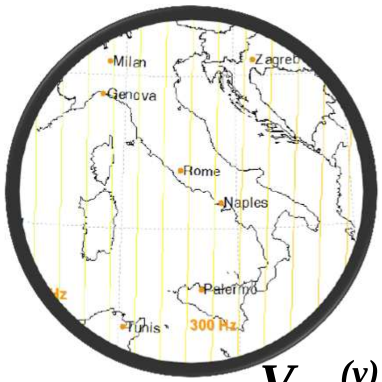
Eutelsat 10A (Ex W2A)	
Latitude Longitude	0.01° N 10.05 °E
Height	35840 Km
EIRP	72 dBW (nominal) (<59 dBW due to damage to the antenna during the launch)
Carrier frequency	2.185 GHz
Signal Bandwidth	5 MHz
Coverage	Europe



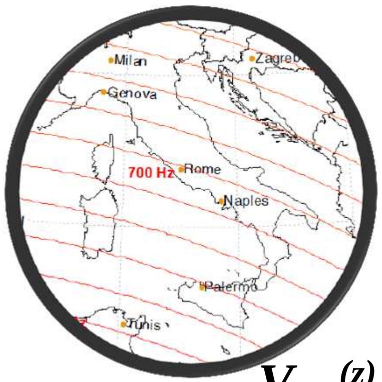
$$f_d = \frac{1}{\lambda}\left(V_{TX} + V_{RX}\right)$$



$V_{TX}^{(x)}$

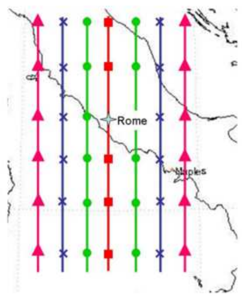


$V_{TX}^{(y)}$



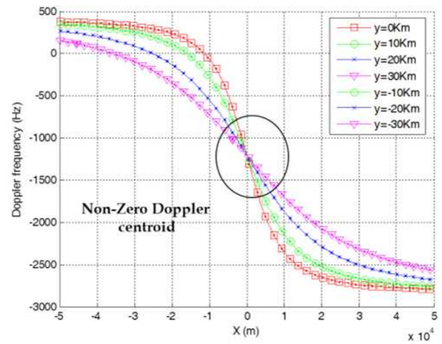
$V_{TX}^{(z)}$

V_{RX}



Target velocity: 220 m/s
Target flying heigth: 9000 m

HIGHLY VARIABLE → ANALYSIS OF SPECIFIC TRAJECTORIES



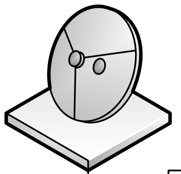
In cooperation with Selex ES – A Finmeccanica Company

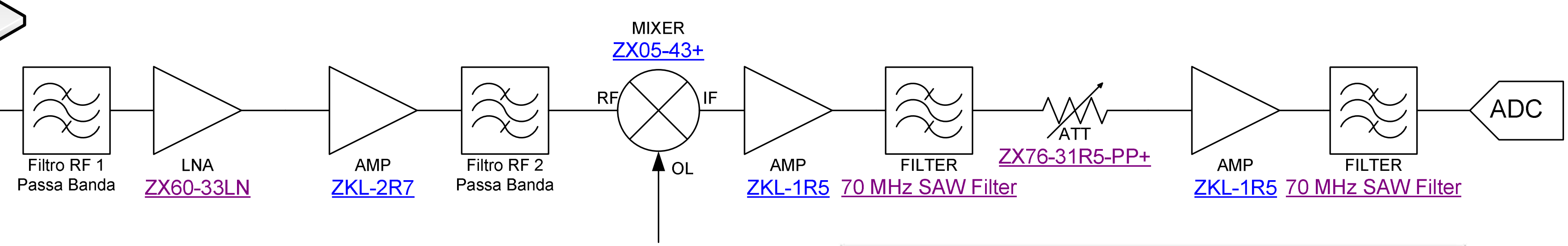
D. Cristallini#, M. Caruso#, P. Falcone#, D. Langellotti#, C. Bongioanni#, F. Colone#, S. Scafè*, P. Lombardo# "**Space-Based Passive Radar Enabled by the New Generation of Geostationary Broadcast Satellites**", #Dept. INFOCOM - University of Rome "La Sapienza", *Selex-Galileo

DVB-SH-based PBR

▶ Prototypes development & acquisition campaigns

- ❑ Super-heterodyne receiver architecture

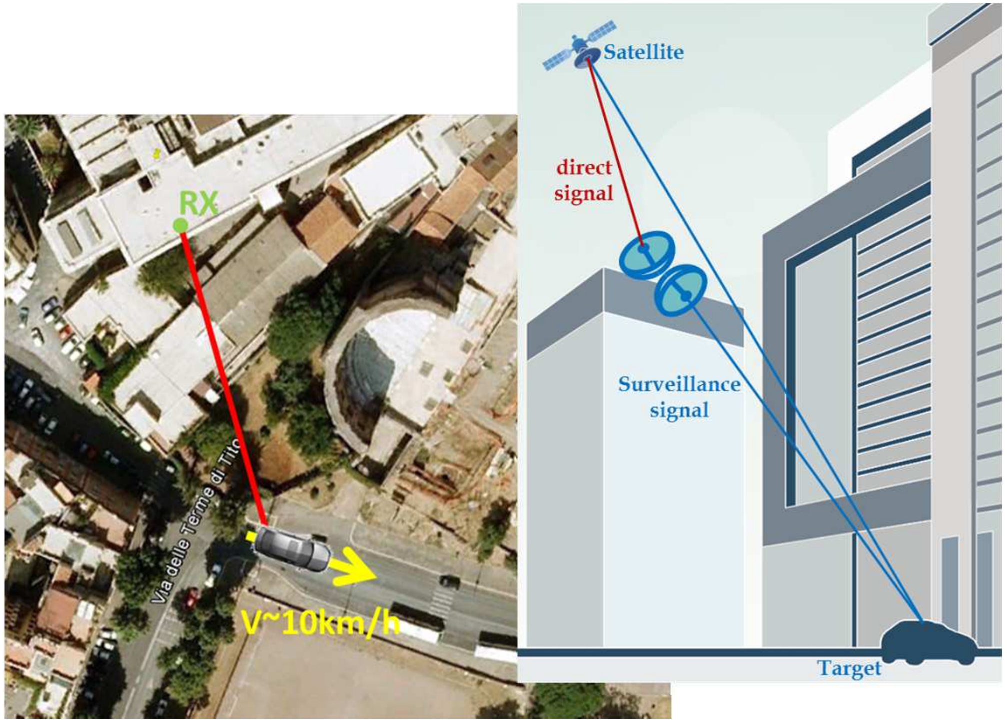


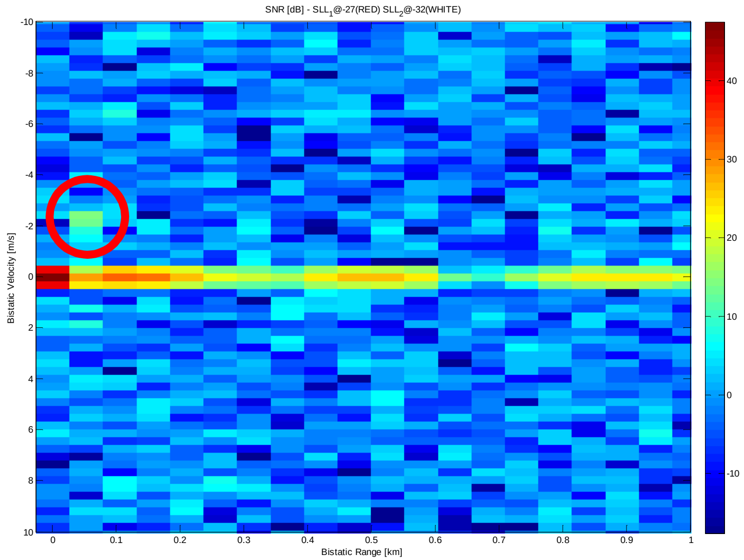


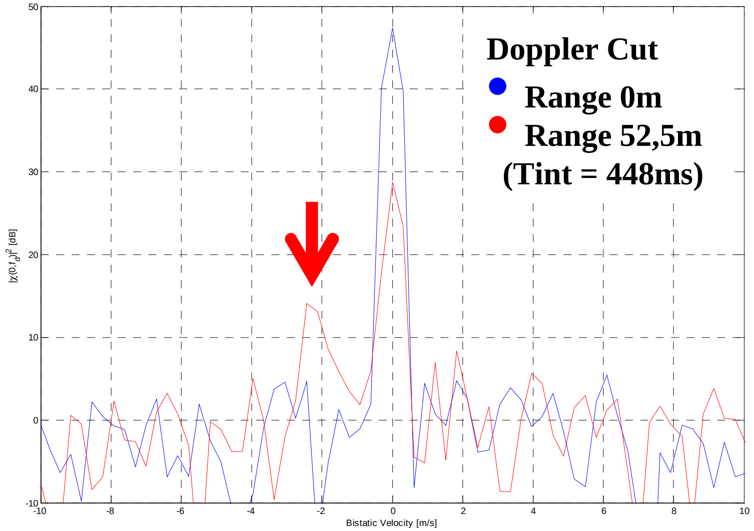
- ❑ Tests performed on the roof of our laboratory in Rome

In cooperation with
Selex ES
A Finmeccanica Company

DVB-SH-based PBR







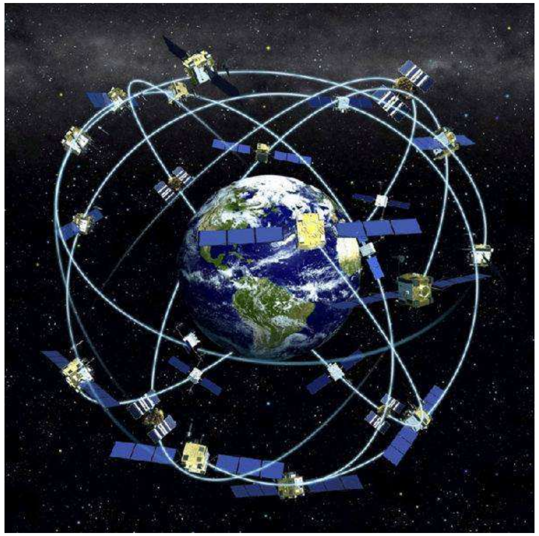
- A car moves along the path (velocity of about 10m/s)
- Acquisitions duration of 0,5s

In cooperation with Selex ES
A Finmeccanica Company

Passive radar system
based on navigation satellites

GNSS-based passive radar

Global Navigation Satellite Systems (GNSS) as opportunity transmitters for Passive Radar applications



GPS, GLONASS, Galileo, BeiDou

- Global coverage
- Multi-angle illumination
- Larger bandwidth than other opportunity transmitters
- Easy synchronization

- Very low power budget (power spectrum density ~-150 dBW)

GNSS-based PR - RRSN group activities

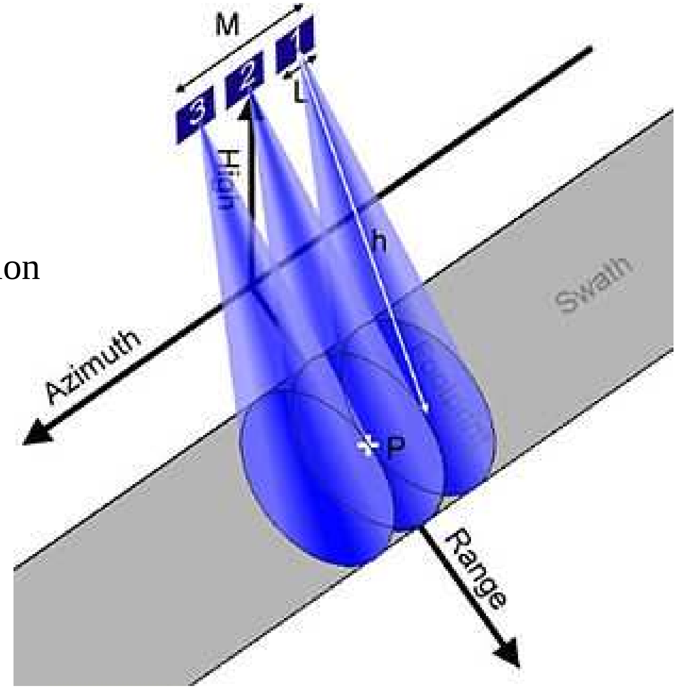
- GNSS-based passive SAR imaging
- GNSS-based passive radar for maritime surveillance

http://www.spyglassproject.eu

ASTER (Italy), UNIROMA1 (Italy), University of Birmingham (UK), ELT GmbH (Germany)

Passive bistatic Synthetic Aperture Radar

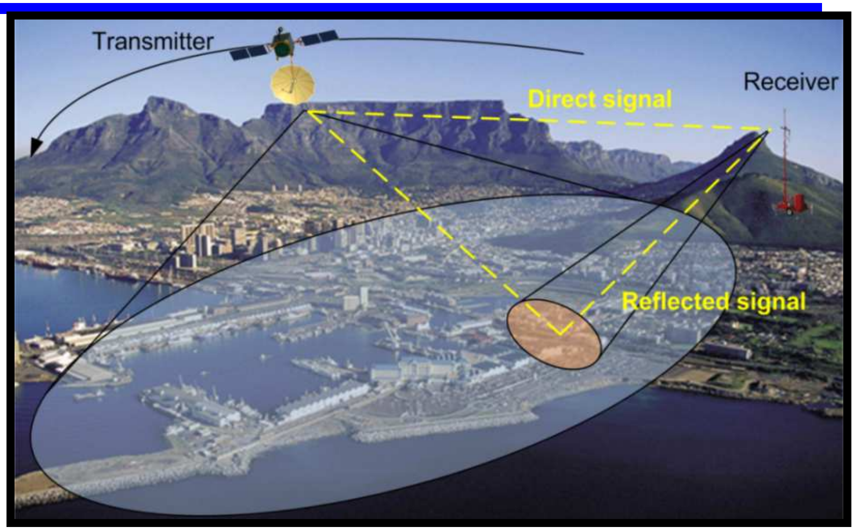
- **Synthetic Aperture Radar (SAR)**: a radar technique able to generate a 2D map of the reflectivity (**radar image**) of a stationary scene
- **Conventional SAR**: a spaceborne/airborne radar system transmits a number of successive radar pulses during its orbit
  - ❑ Range resolution→ high-res. achieved by transmitting wideband waveforms (e.g. chirp)
  - ❑ Azimuth resolution → high-res. achieved by processing the signal received from the scene during multiple transmitting antenna position

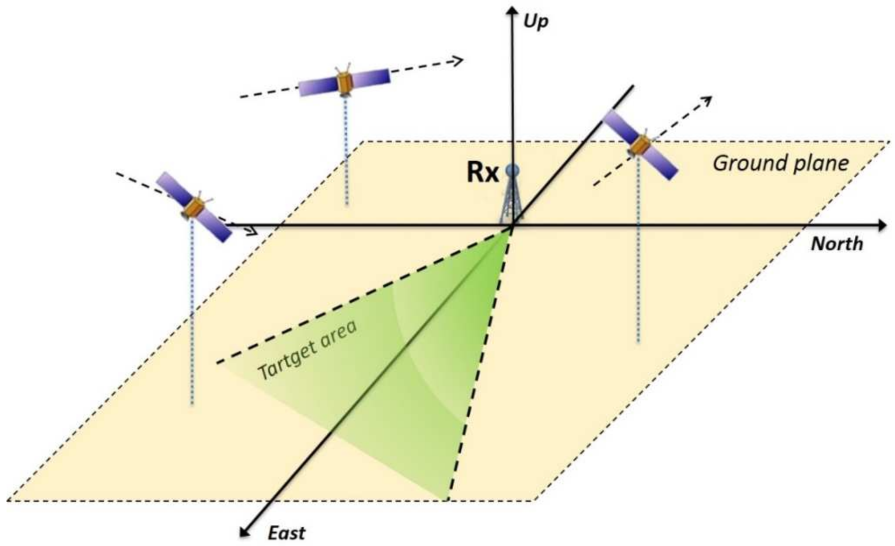


- A dedicated transmitter is needed
- Only the area illuminated by the transmitting antenna footprint can be imaged
- Interest in research alternative solutions making use of different illuminators → **Passive bistatic SAR**

GNSS-based passive SAR

- Ground-based stationary receiver collects the signals emitted by GNSS transmitter
- Radar Channel collects the reflected signals from a stationary scene for imaging
- Heterodyne Channel records the direct signal for synchronization



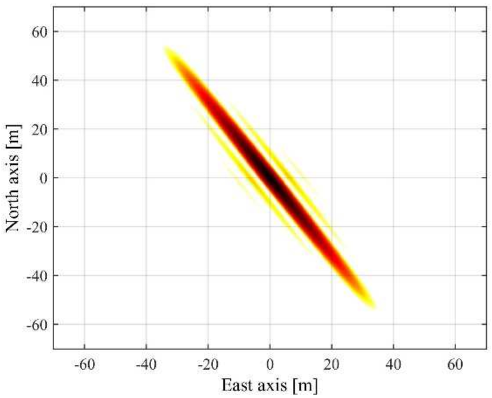


- 6-8 satellites simultaneously in visibility for a single constellation (24-32 when all 4 GNSS system fully operational)
- Multi-angle views of the same area

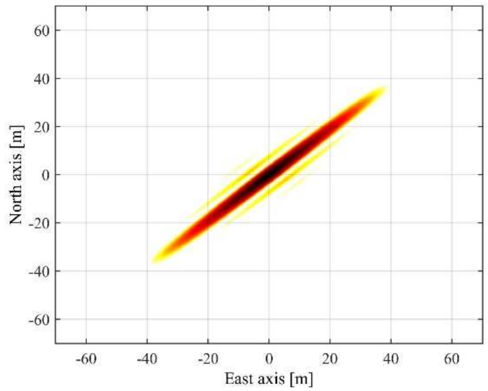
Bi/Multi-static image response

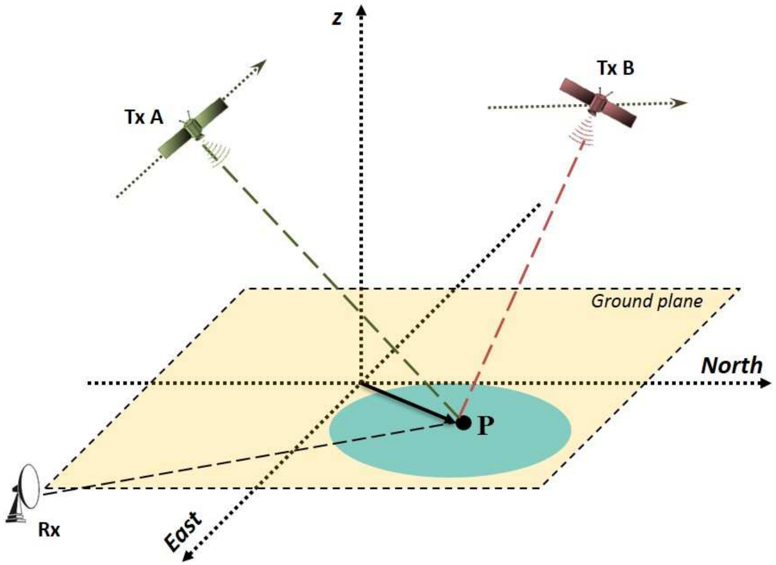
- Bistatic PSF is approximately an ellipse with resolution cell area around 100 m^2

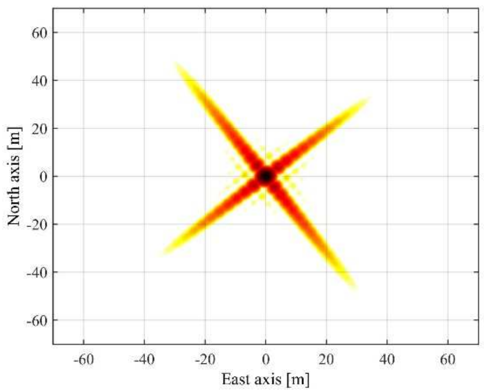
Tx A



Tx B







- A non-coherent combination of the individual images results in a multistatic image whose resolution cell area is the overlapping segment of the single bistatic PSFs, and therefore may be essentially reduced

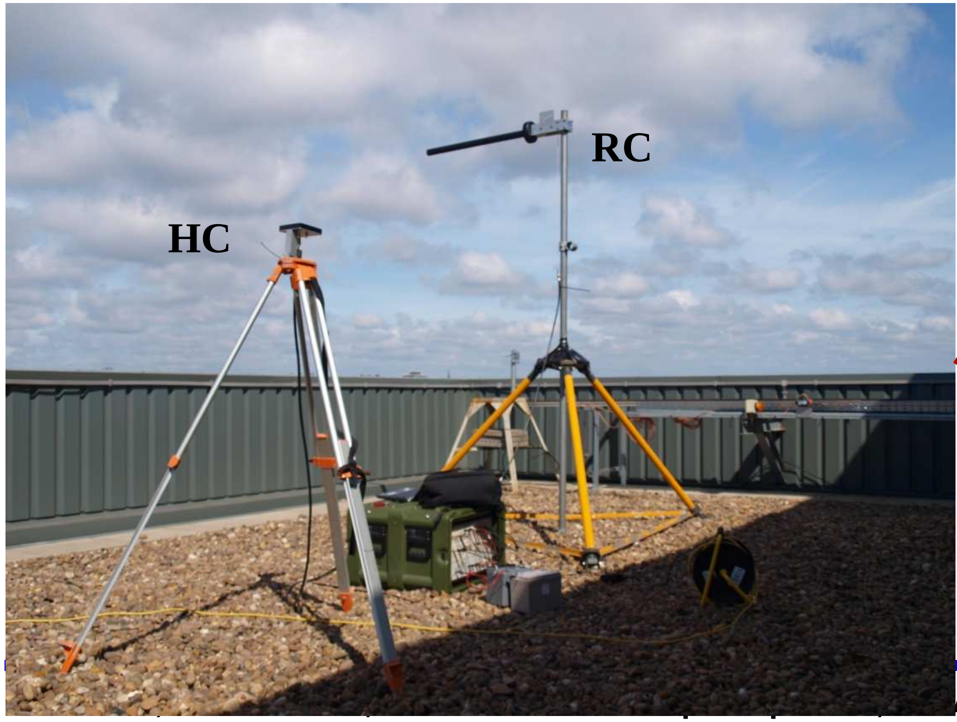
PSF AREA

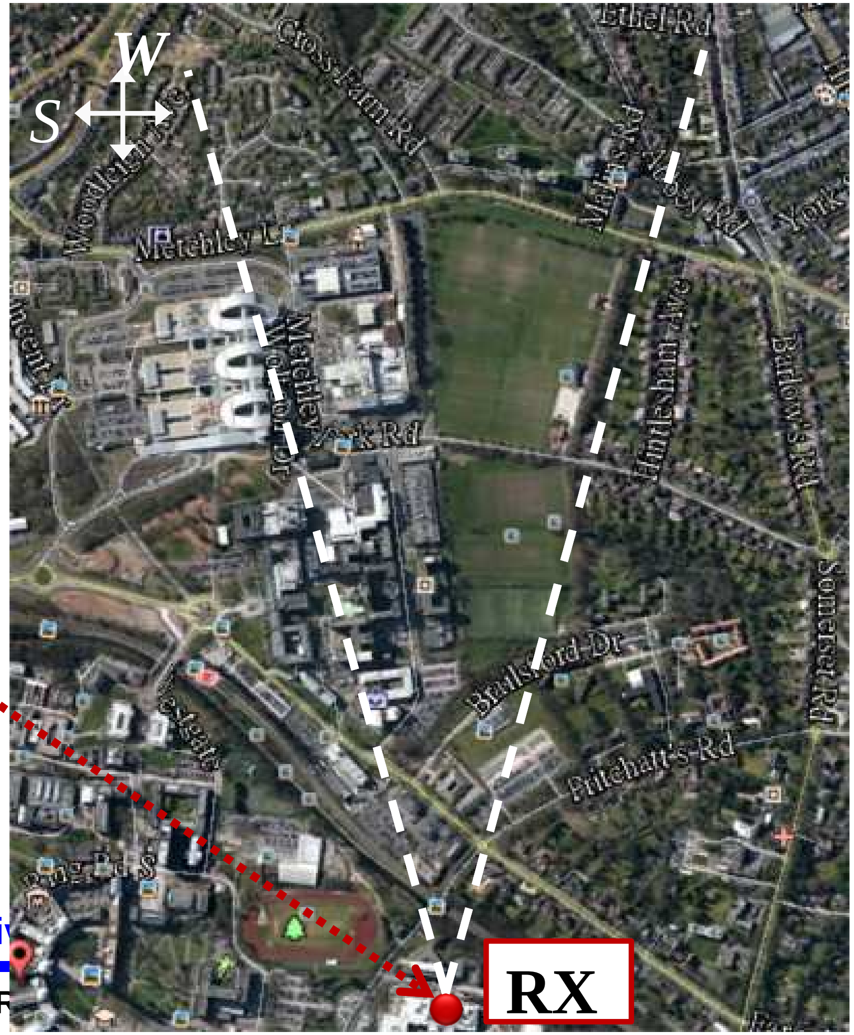
PSF A	PSF B	MPSF
98 m^2	80 m^2	17 m^2

*F. Santi, M. Antoniou, D. Pastina, "**Point Spread Function Analysis for GNSS-based Multistatic SAR,**" IEEE Geoscience and Remote Sensing Letters, Feb. 2015*

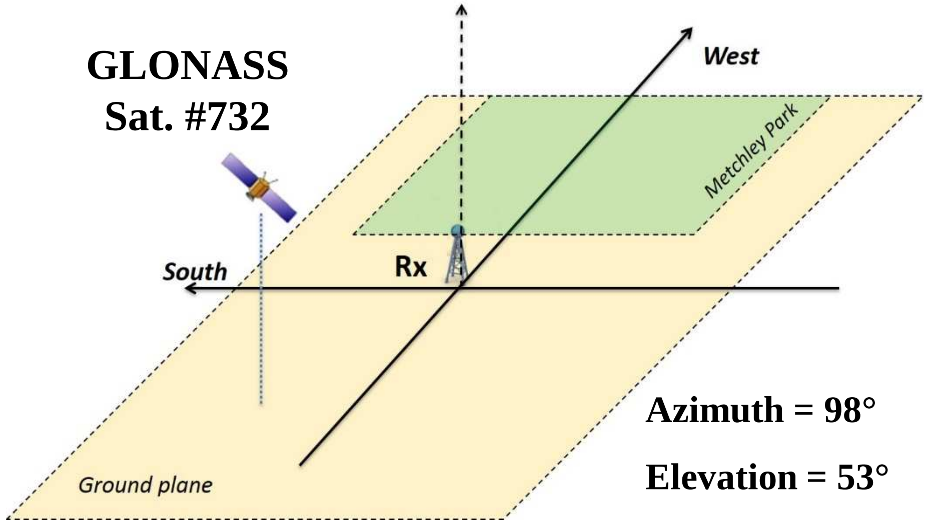
Experimental setup

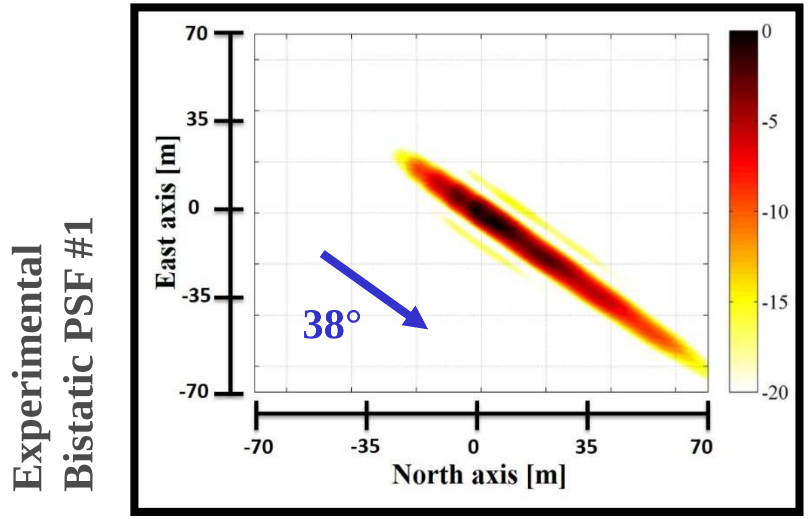
- Experimental hardware: superheterodyne receiver developed at the University of Birmingham
  - **Heterodyne channel** (HC) → direct signal for synchronization (low-gain antenna pointed toward the satellite)
  - **Radar channel** (RC) → signal reflections from the target area (high-gain antenna pointed toward the observed area)
- Target area: Metchley Park





Experimental bistatic image





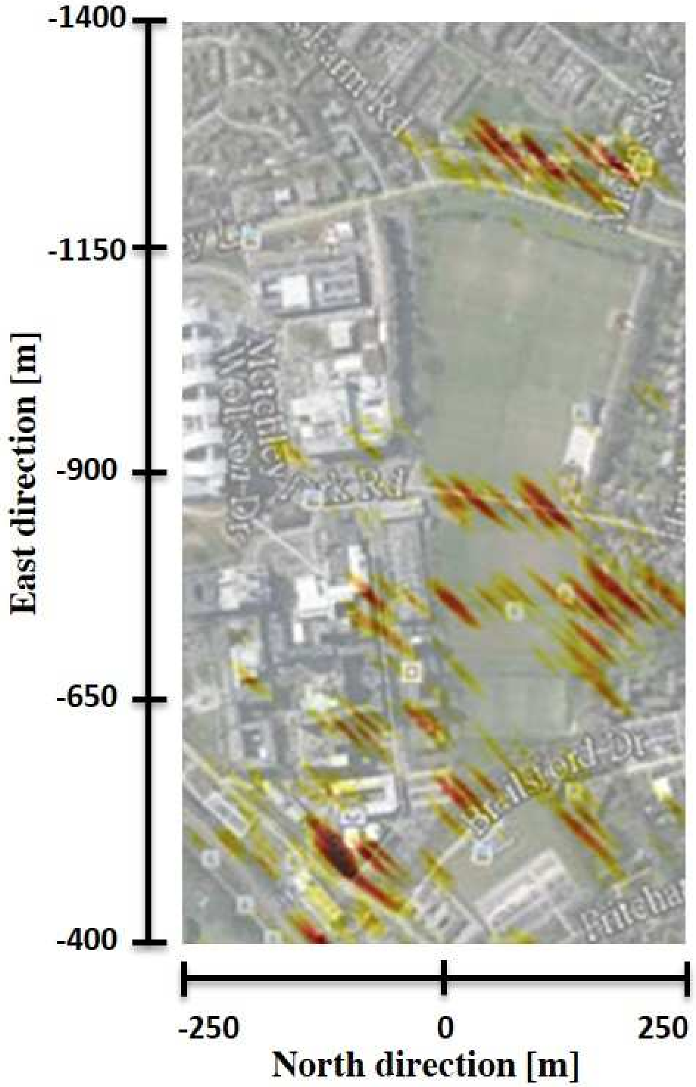
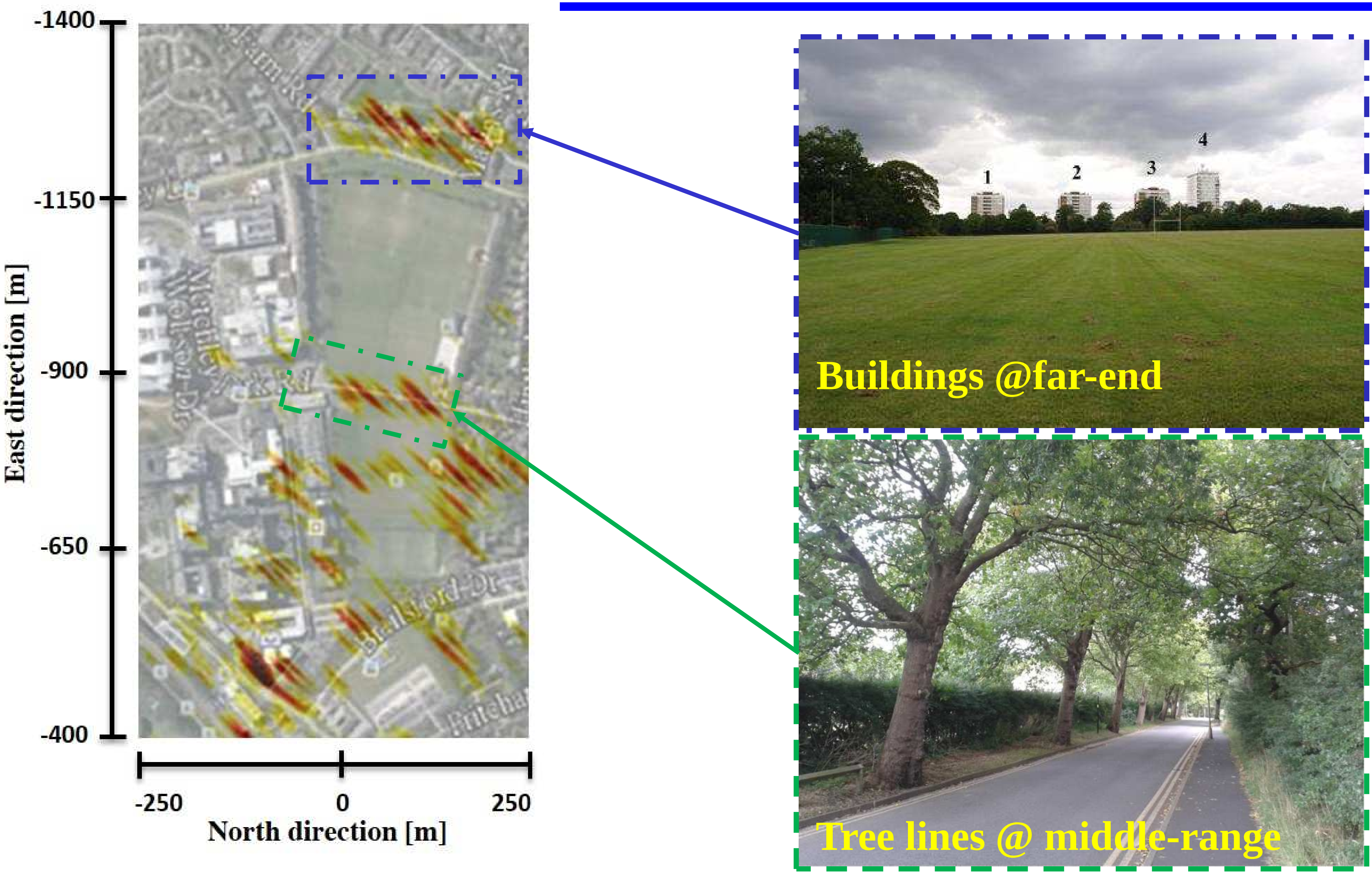
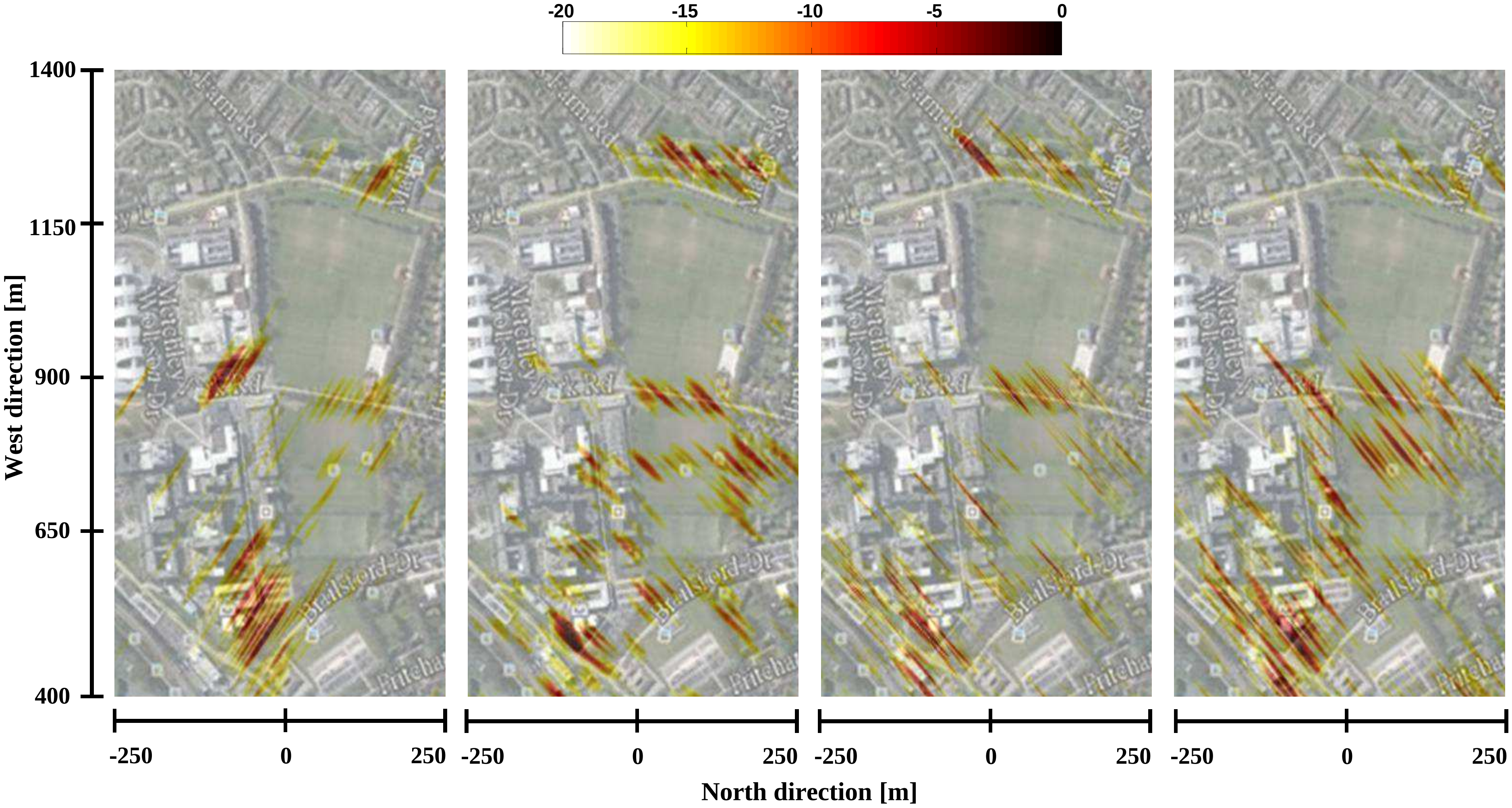


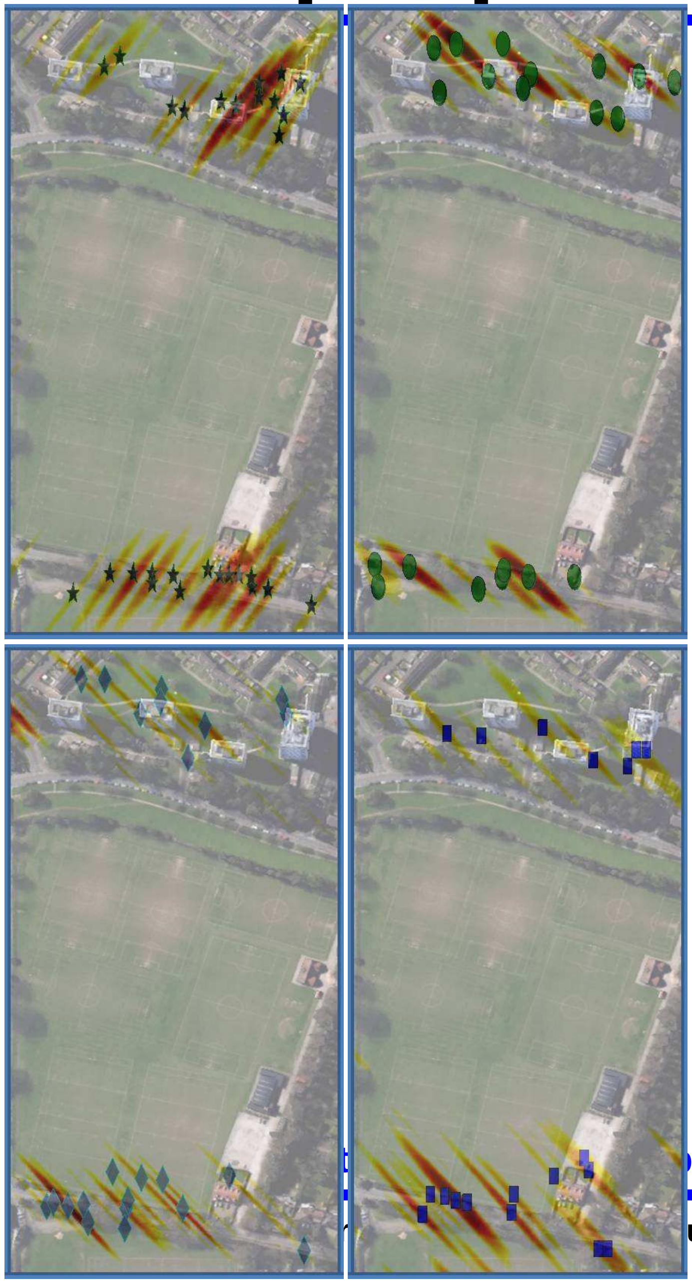
Image features



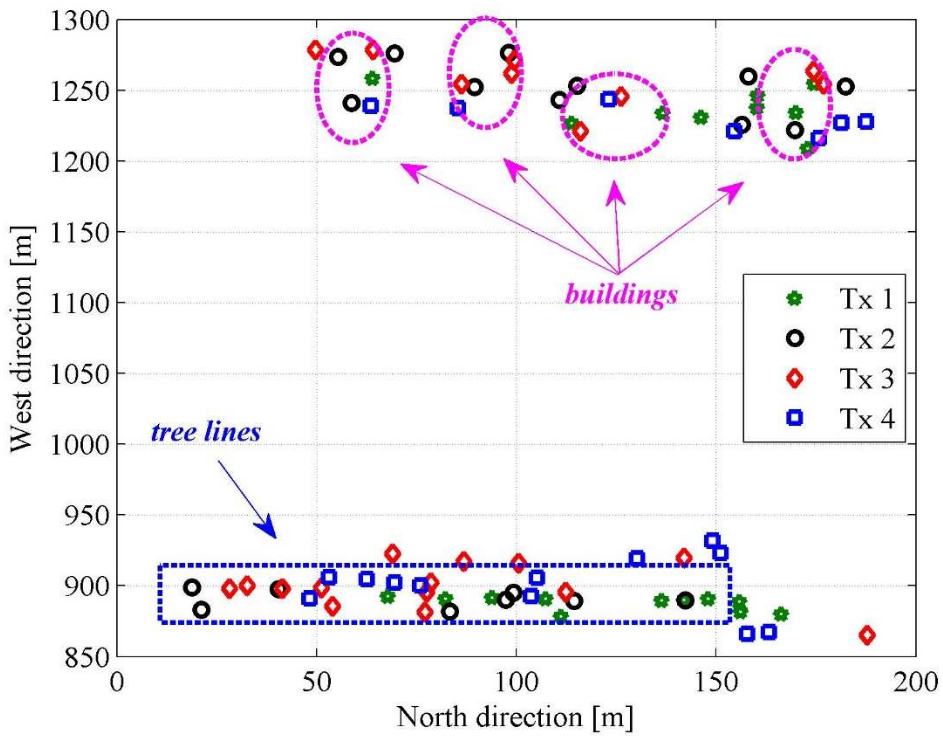
Multi-angle images



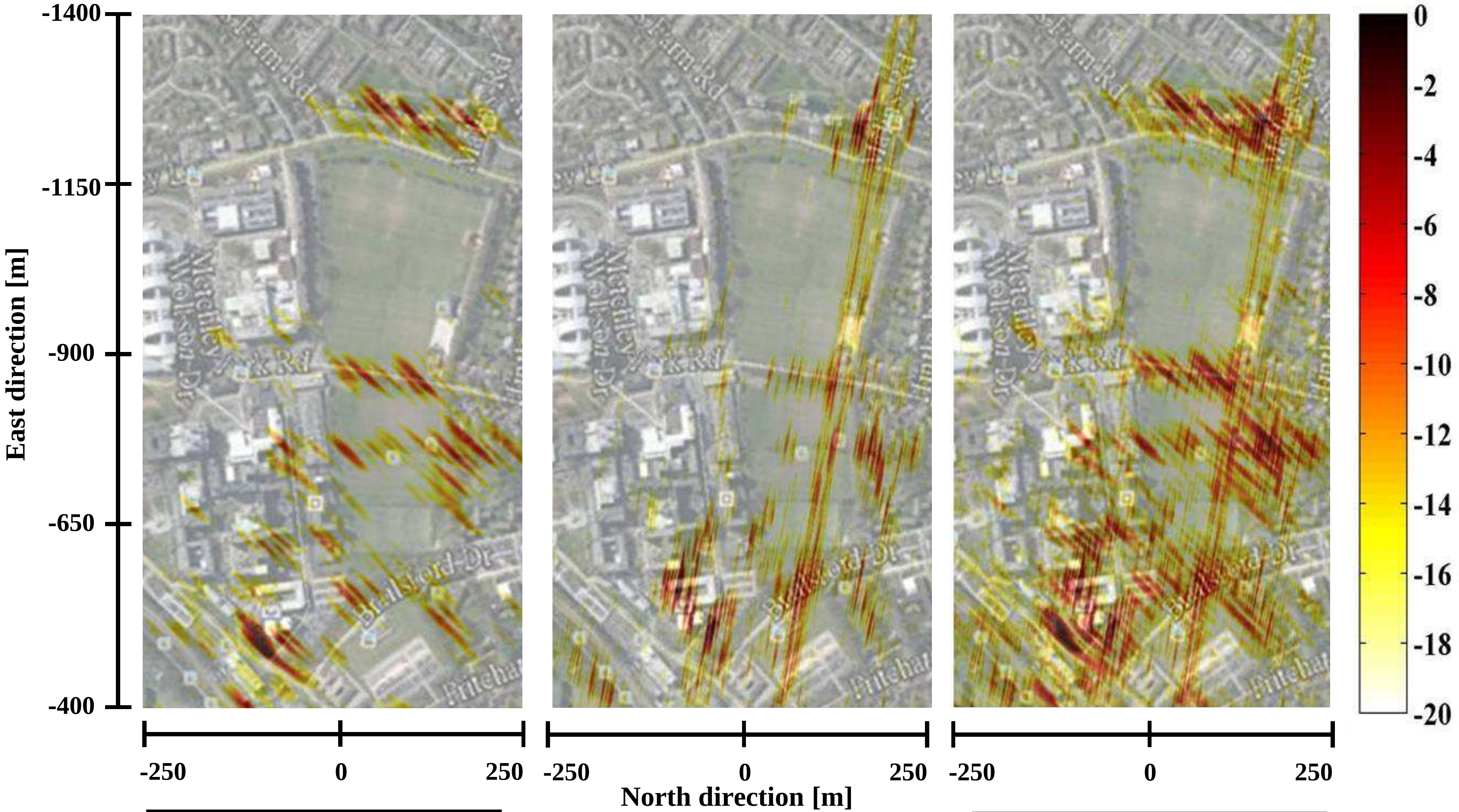
Multi-perspective analysis

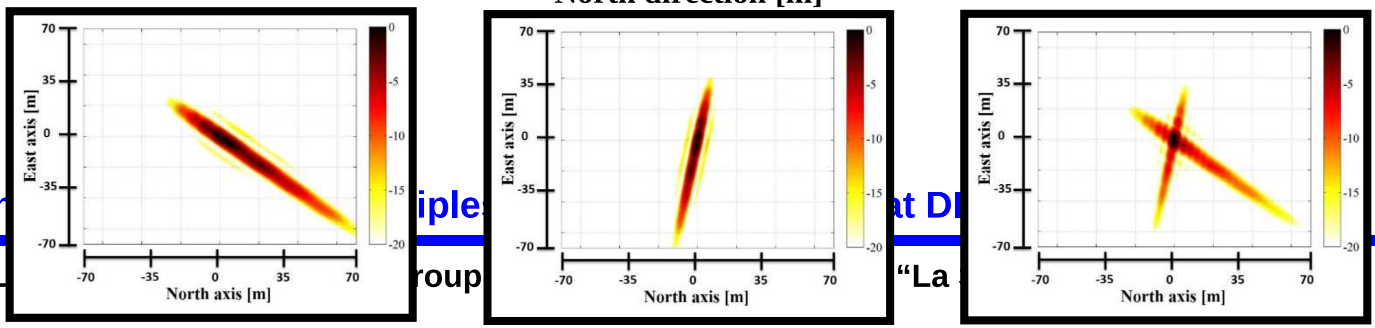


- Dominant scattering centers can be extracted from the individual images and then combined to form a scatterers map

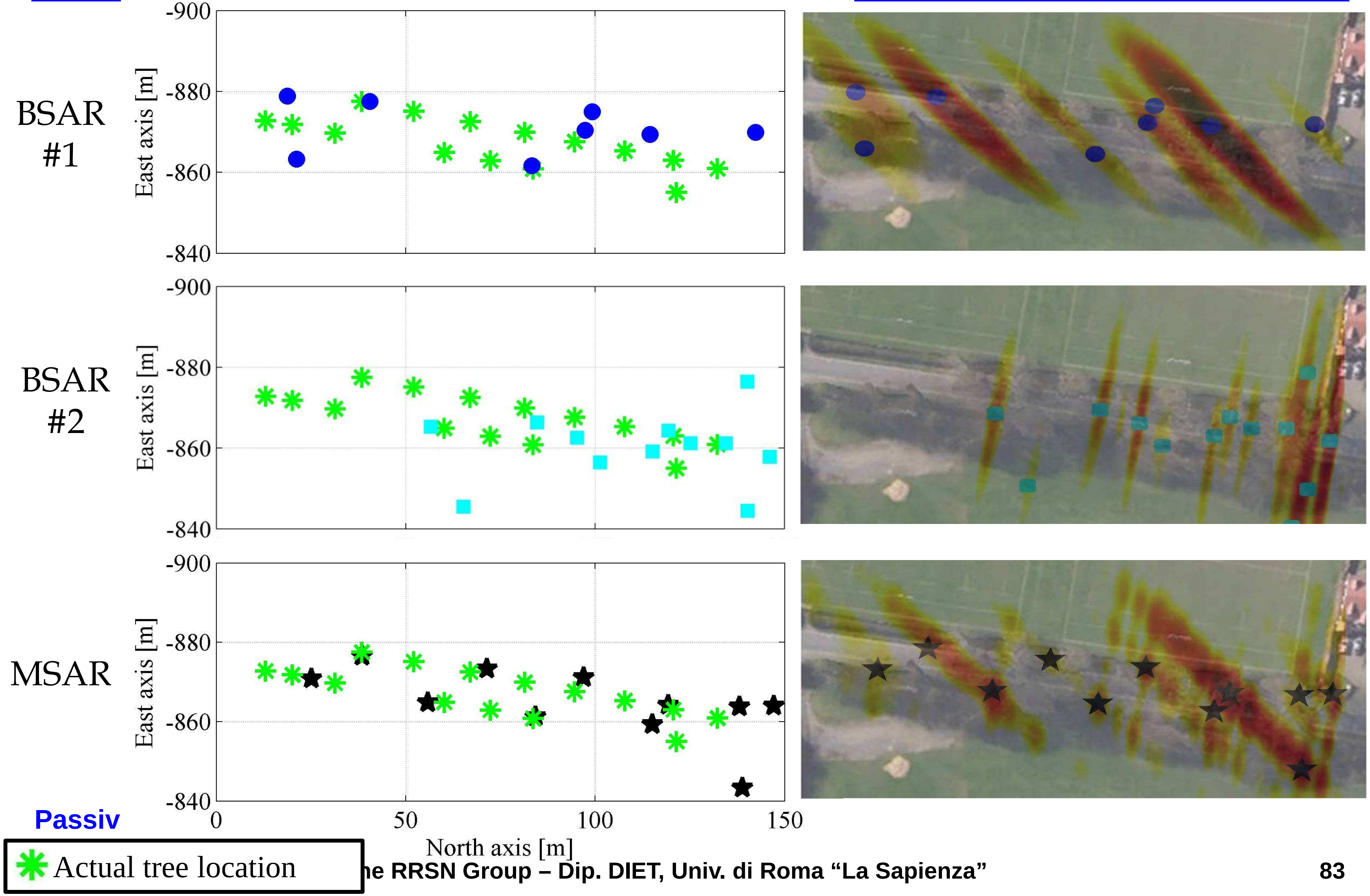


Multistatic image





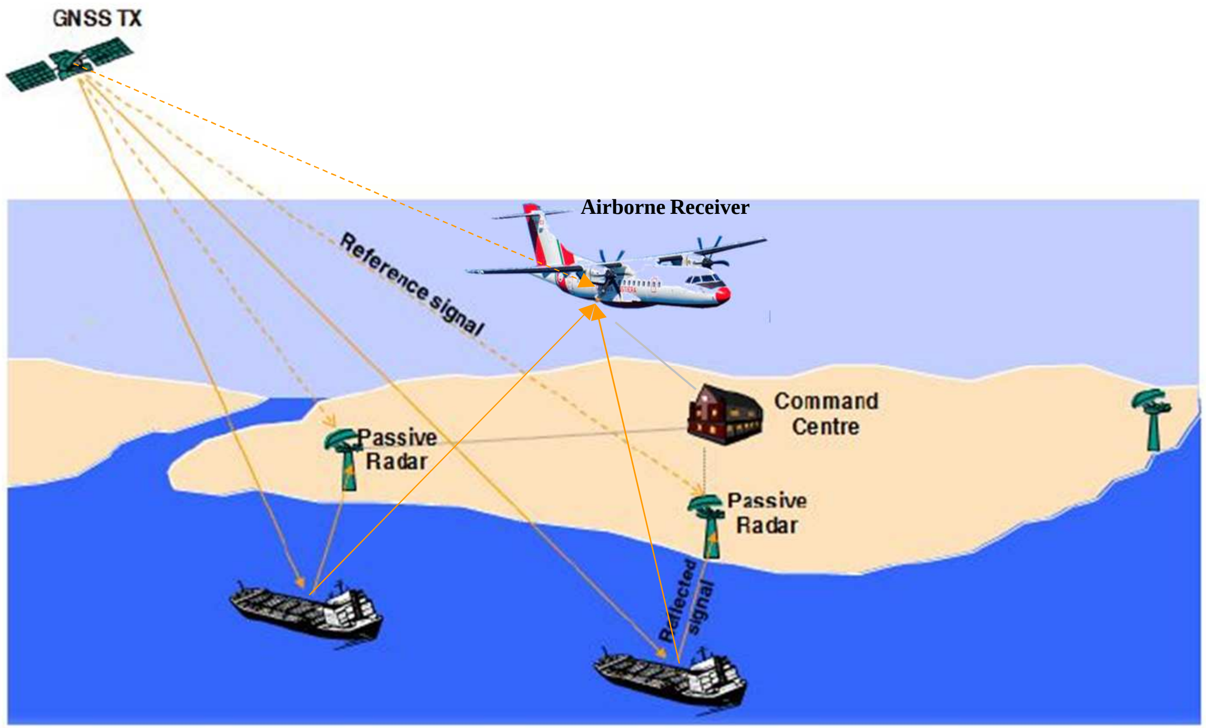
Tree-lines results



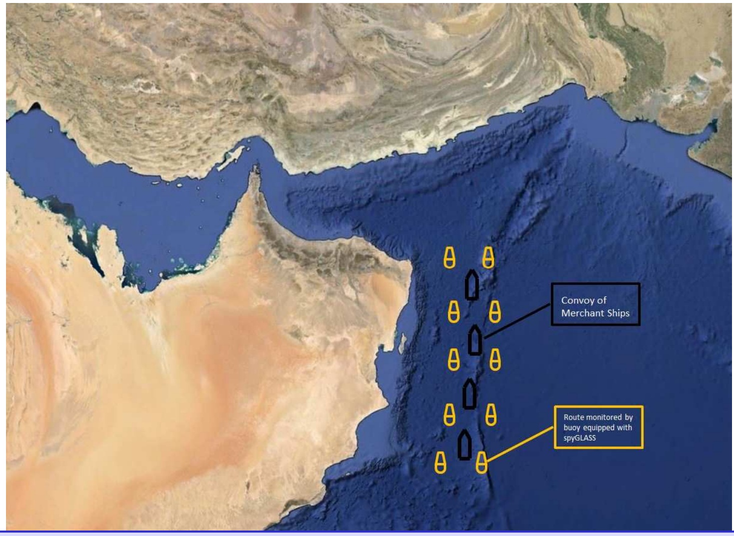
Passiv

Passive GNSS-based M-MTI

- GNSS Satellites used as transmitters
- Fixed Coastal receiver to monitor coastal areas
- Mobile receiver located on vehicle for hot spots surveillance or on aerial devices for open sea coverage
- Command Center for centralized analysis of data



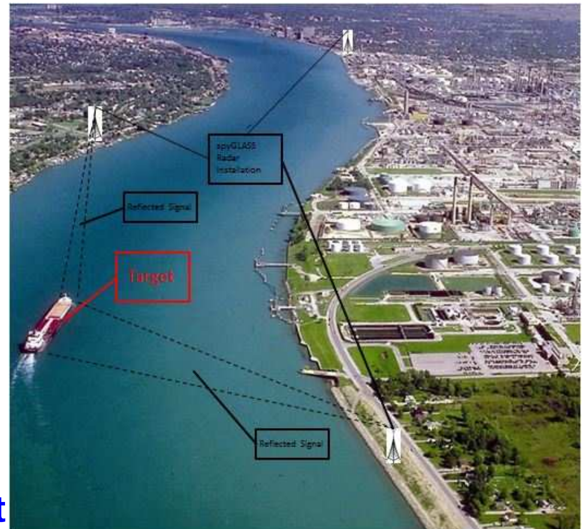
Possible application scenarios



Target Detection by means of buoys: anti-piracy operations

Target Detection by means of buoys: intrusion in marine protected areas

Port Operations Monitoring



River Navigation

Single channel M-MTI performance analysis (1/2)

SNR required to achieve a specific P_d given a desired P_{fa} when N_b batches are integrated non-coherently

$$(SNR)_{NCI} = I(N_B) \cdot SNR_B$$

non-coherent integration improvement factor

SNR on the single batch needed to achieve the desired performance

- SNR value to achieve the desired P_d and P_{fa} evaluated as

$$SNR = A + 0.12AB + 1.7B, \quad A = ln\frac{0.62}{P_{fa}}, B = ln\frac{P_D}{1-P_D}$$ Swerling 0 target

$$SNR = \frac{log(P_{fa}/P_D)}{log(P_D)}$$ Swerling I target

- Improvement factor for integration over N_B batches(square-law detector)

$$I(N_B)\Big|_{dB} = 6.79(1+0.253P_d)\left[1+\frac{log_{10}(1/P_{fa})}{46.6}\right](log_{10}N_B)(1-0.14log_{10}N_B+0.0183log_{10}^2N_B)$$

- SNR value at batch level

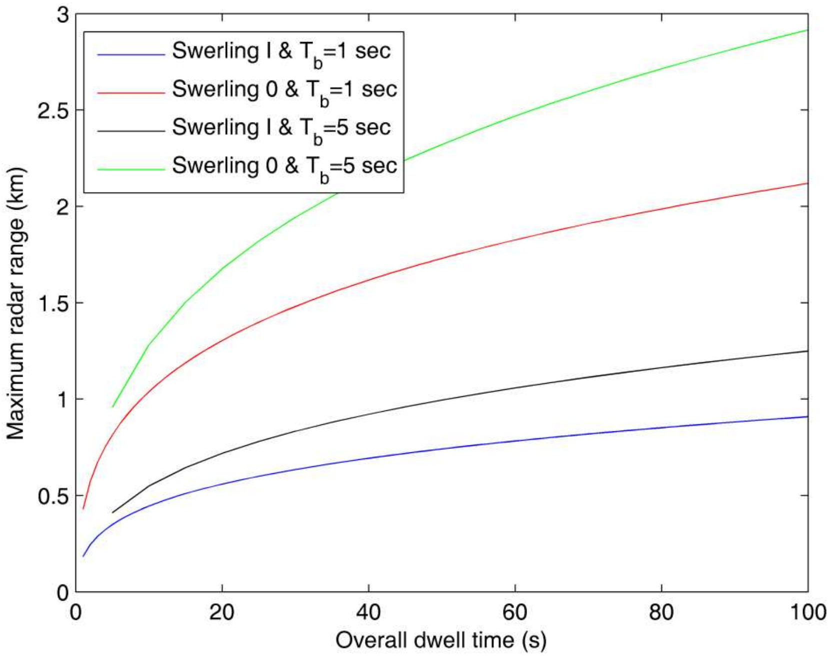
$$SNR_B = SNR_{input} \cdot T_b B$$

batch coherent integration gain

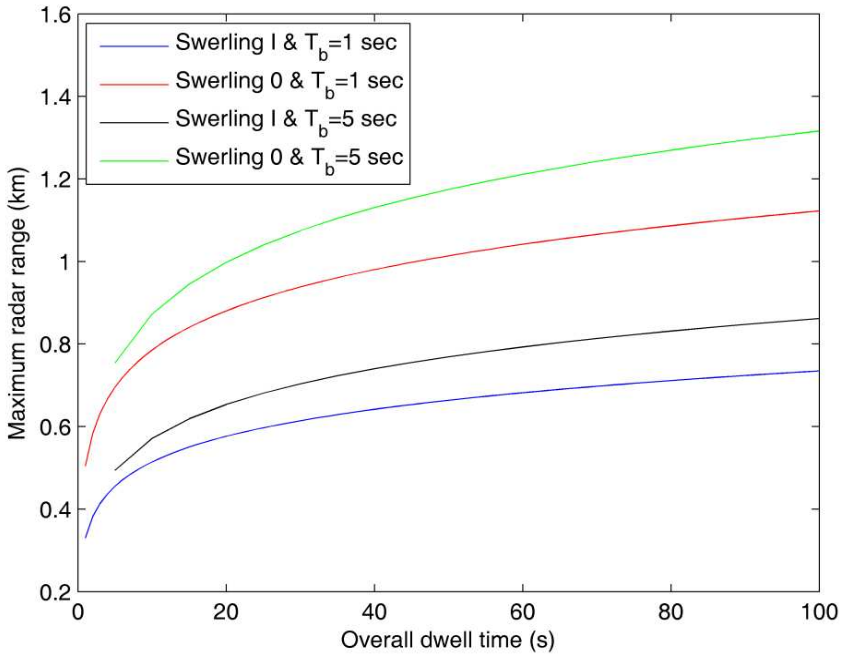
Single channel M-MTI performance analysis (2/2)

CASE STUDY: target RCS=100 m^2, $P_{fa}=10^{-3}$, $P_d=0.9$

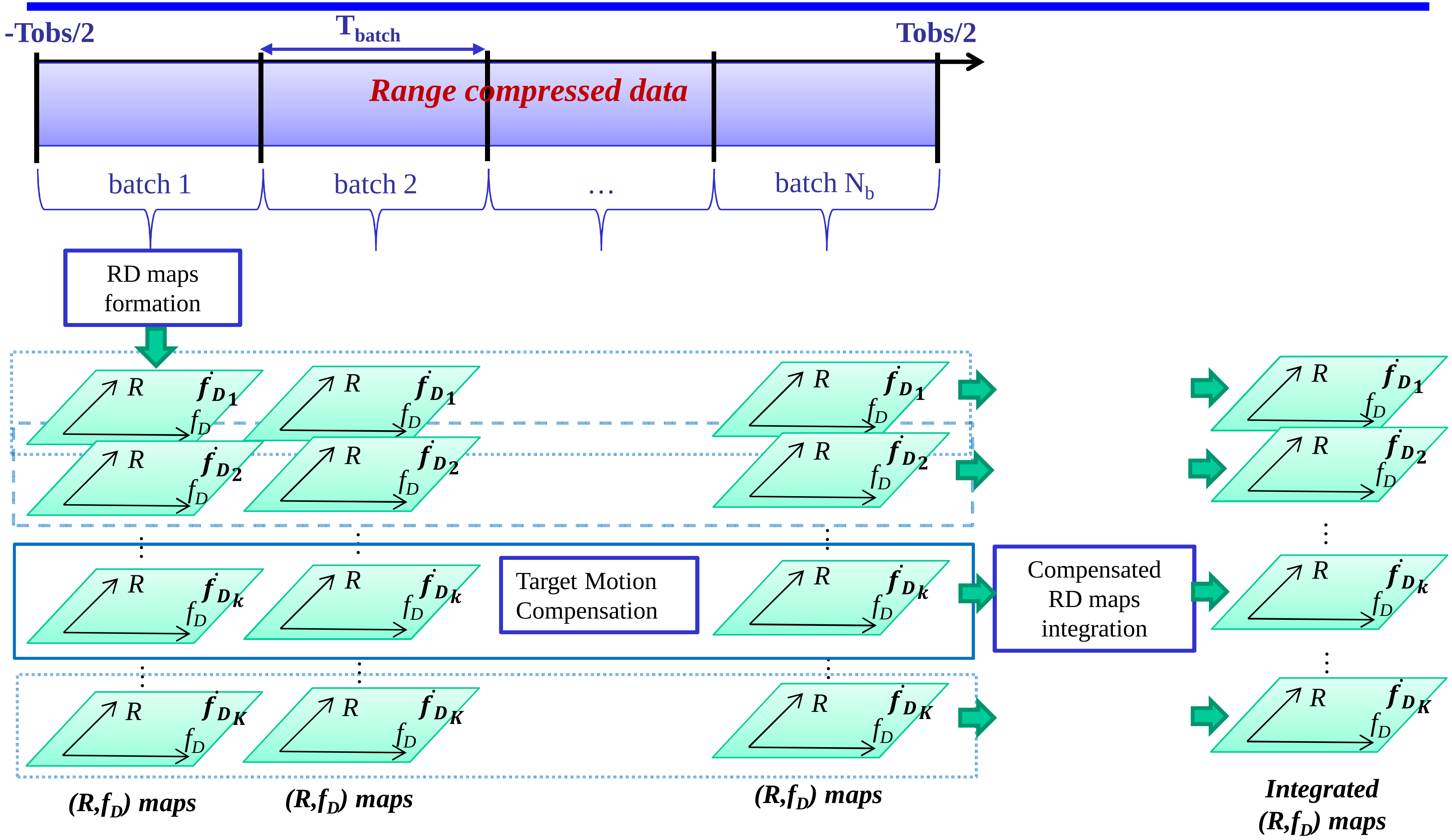
Free space model



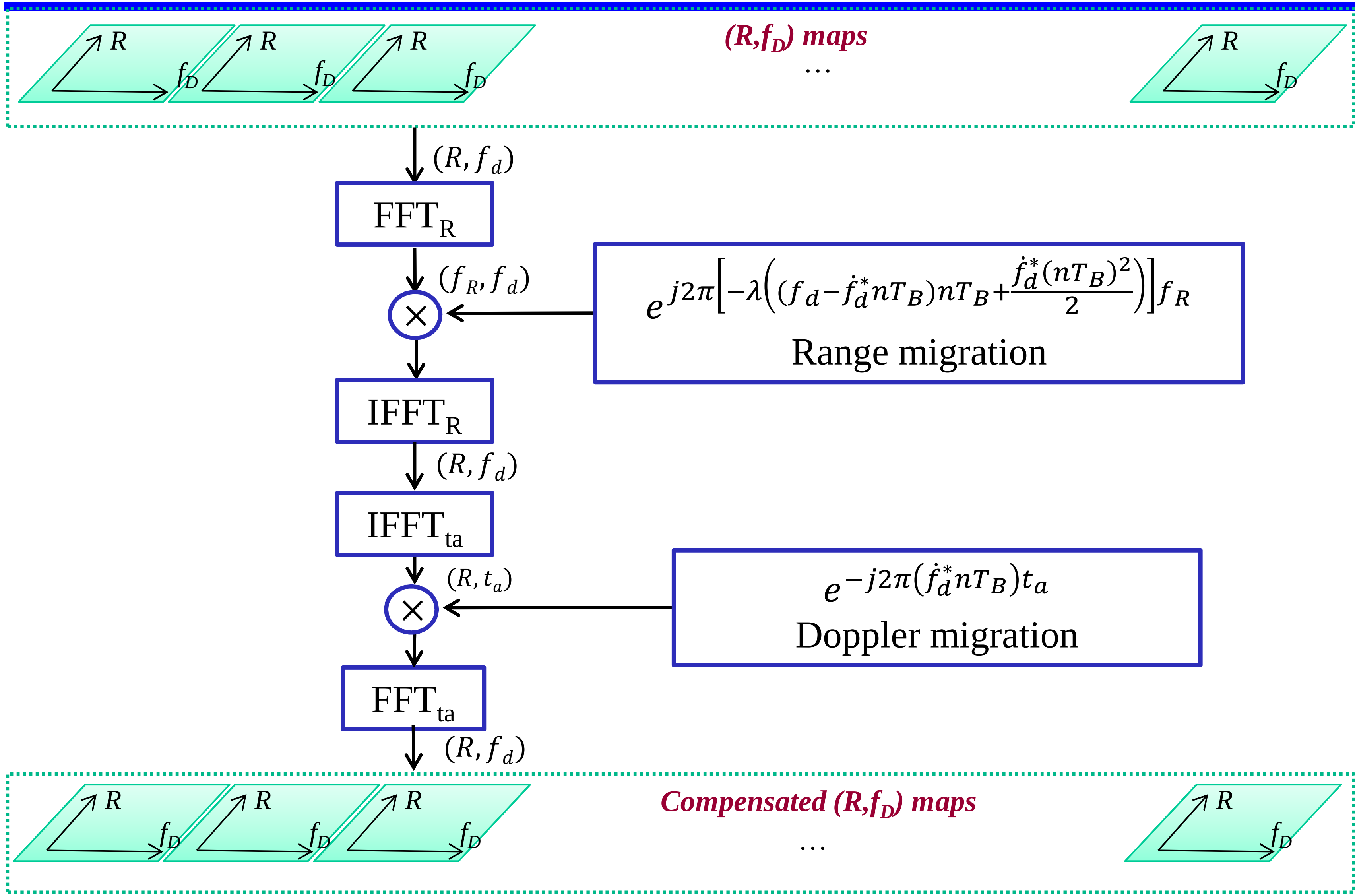
Two-rays model



Basic plane based M-MTI tecnique



Target Motion Compensation (TMC)

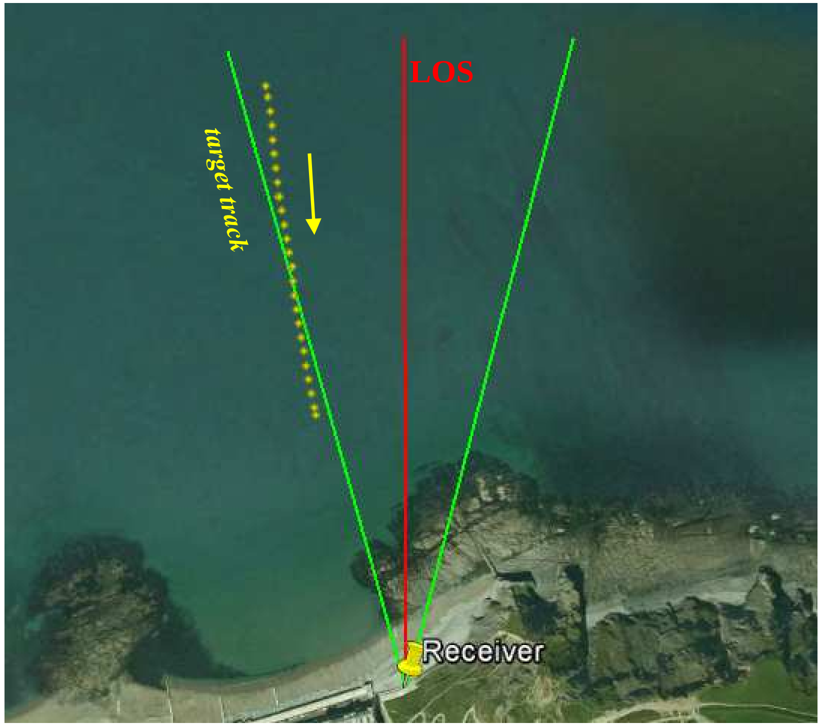


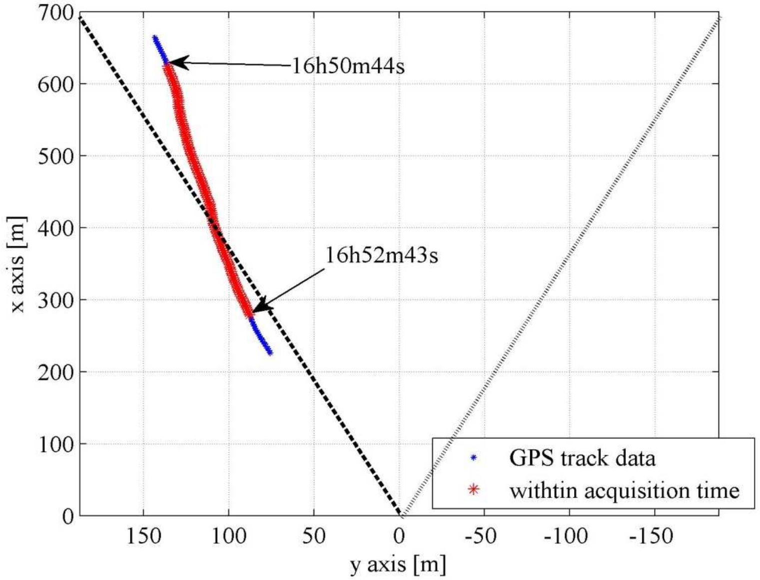
Dataset #1: target and receiver

Target

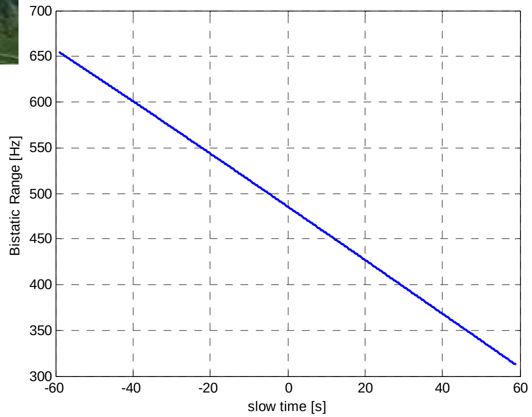
Ground receiver (Stationary)

Experimental dataset: GLONASS - Low RCS target

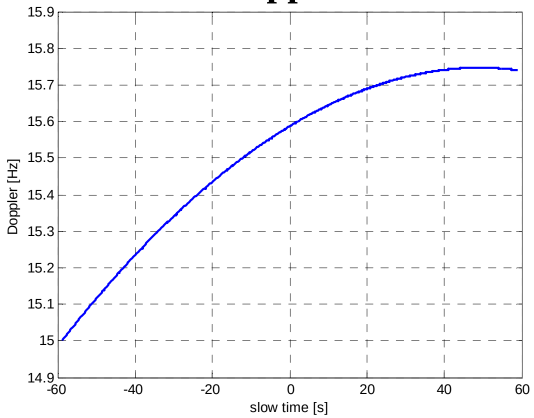




Bistatic range

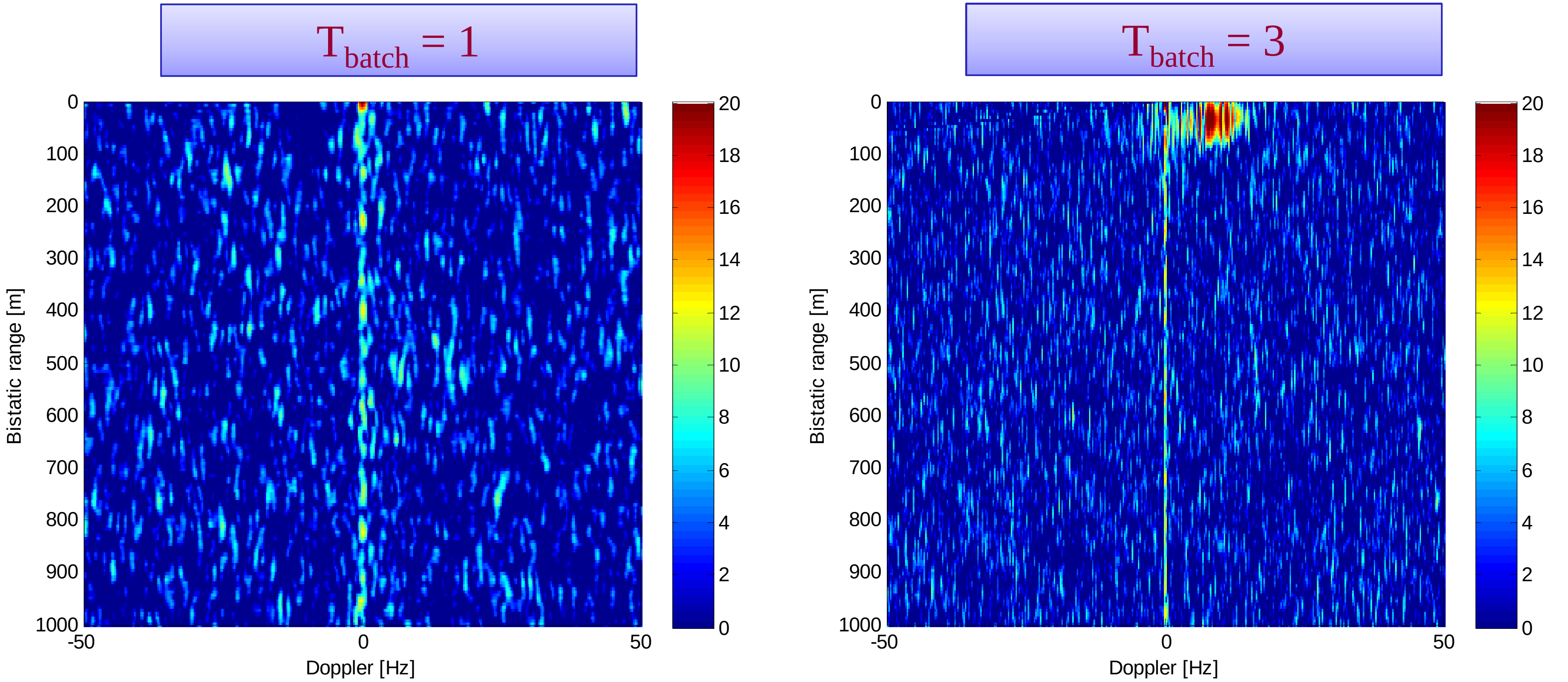


Doppler



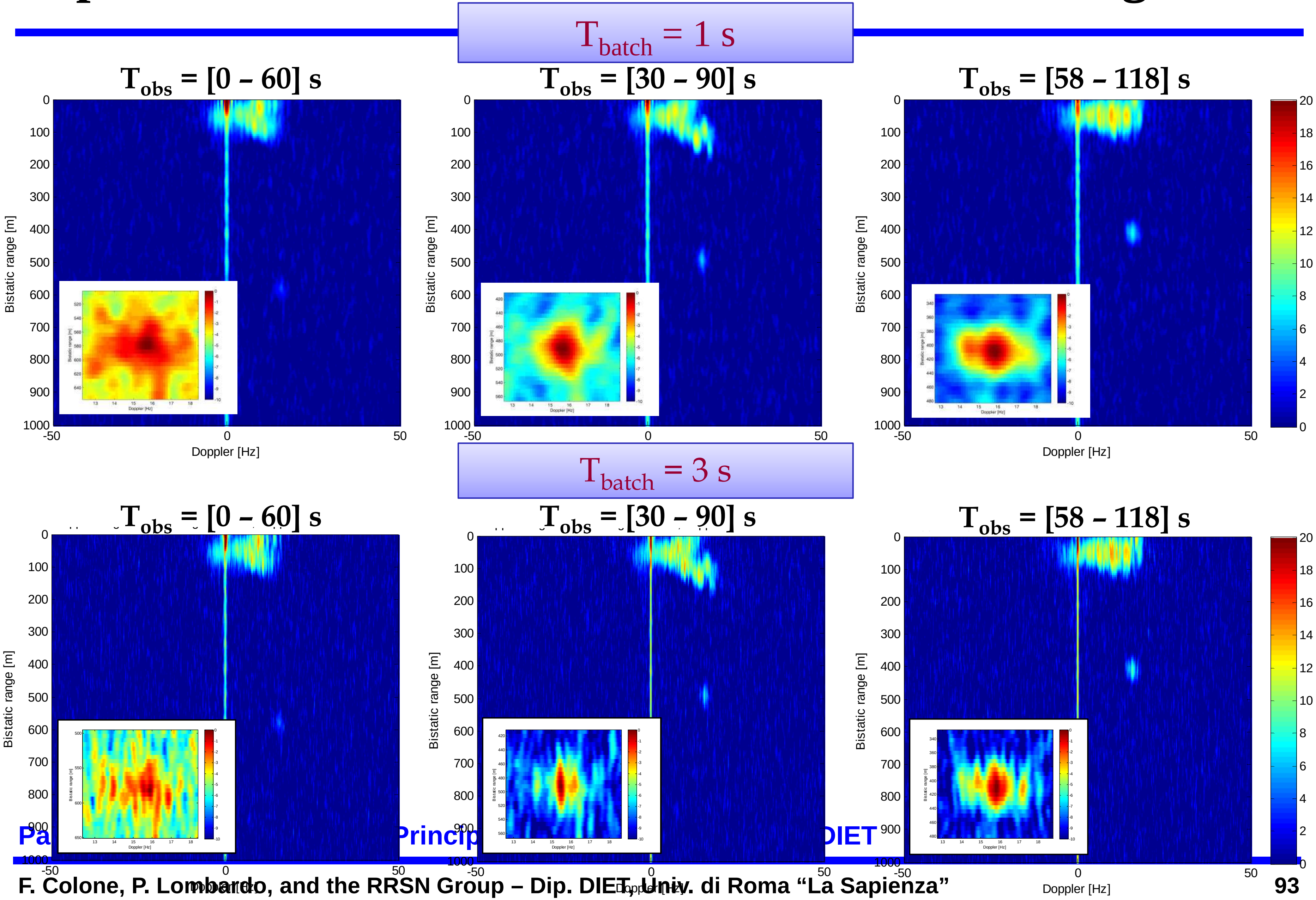
Experimental dataset: GLONASS - Low RCS target

Single batch RD maps



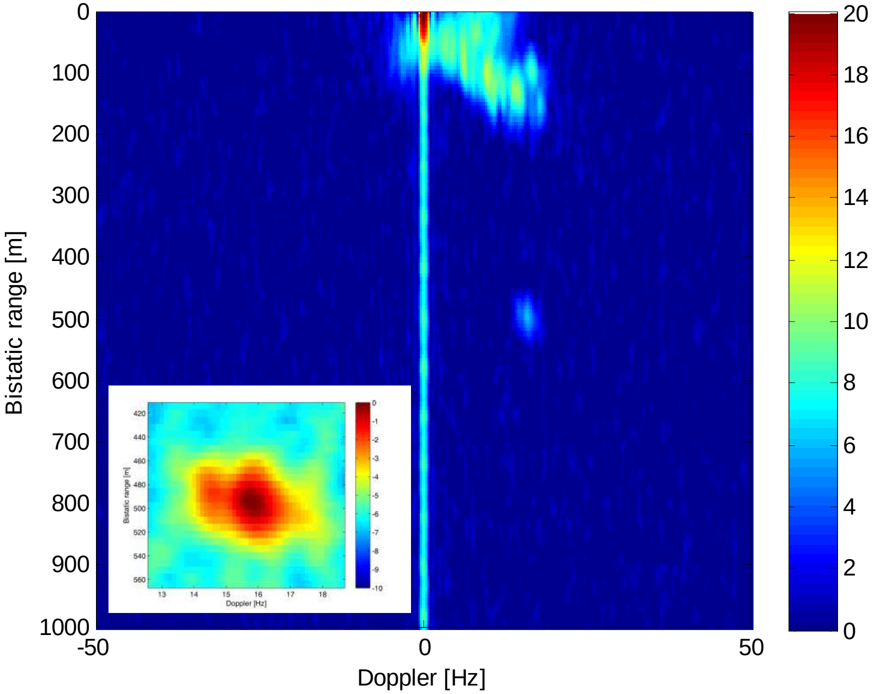
Integration over long time is mandatory to get the detection of target with low RCS

Experimental dataset: GLONASS - Low RCS target

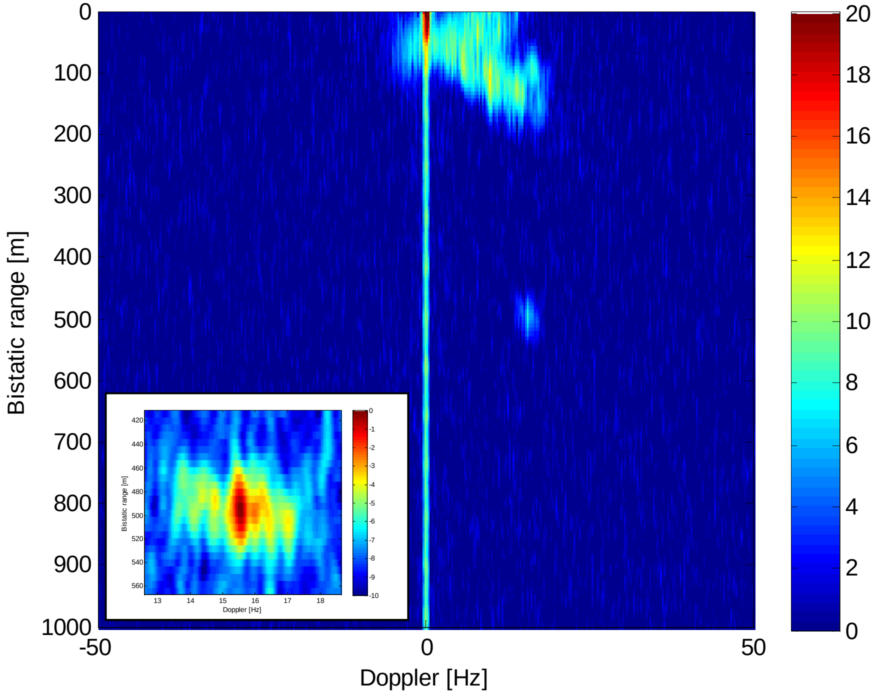


Experimental dataset: GLONASS - Low RCS target

T_{batch} = 1s, T_{obs}= [0-118] s

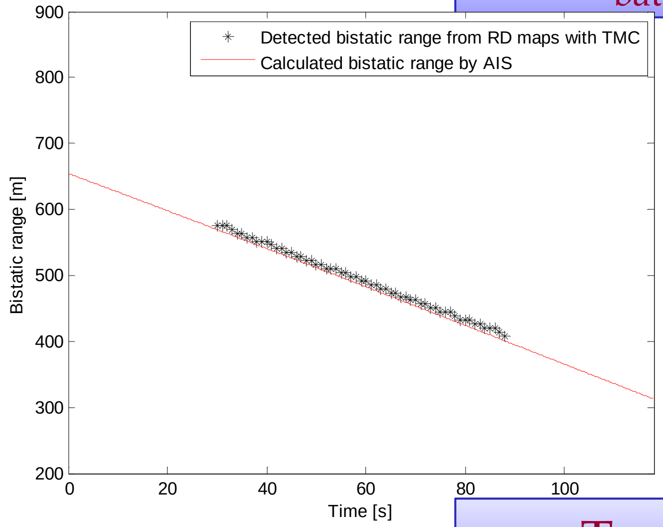


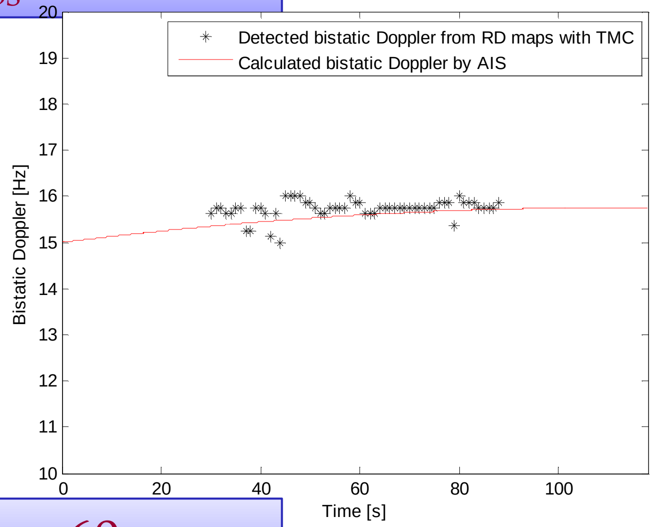
T_{batch} = 3s, T_{obs}= [0-118] s



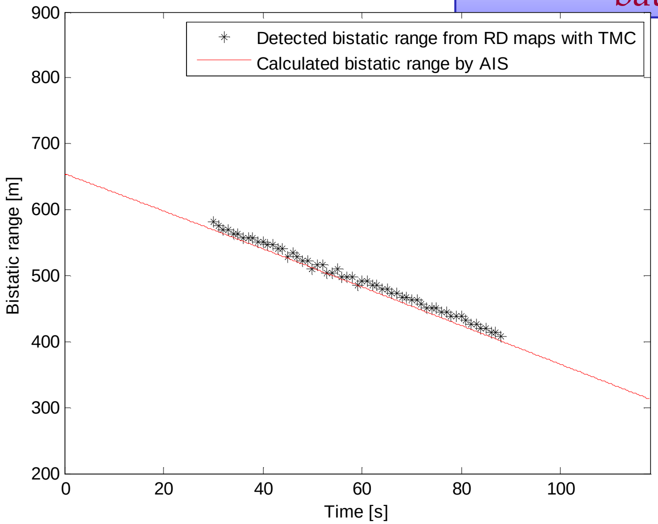
Experimental dataset: GLONASS - Low RCS target

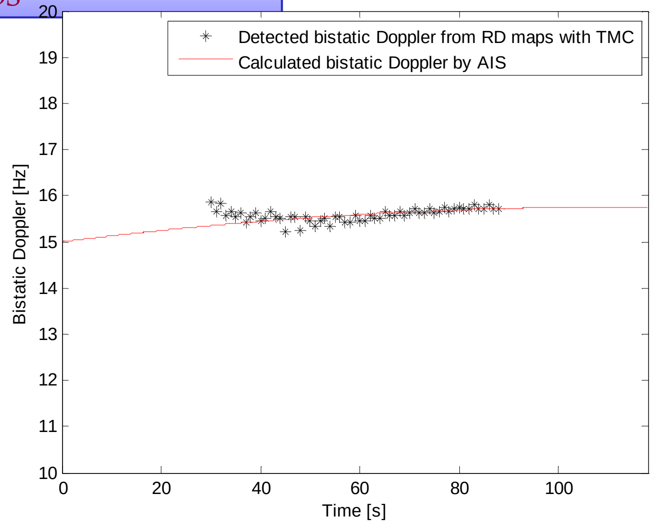
$T_{batch} = 1s, T_{obs} = 60\ s$





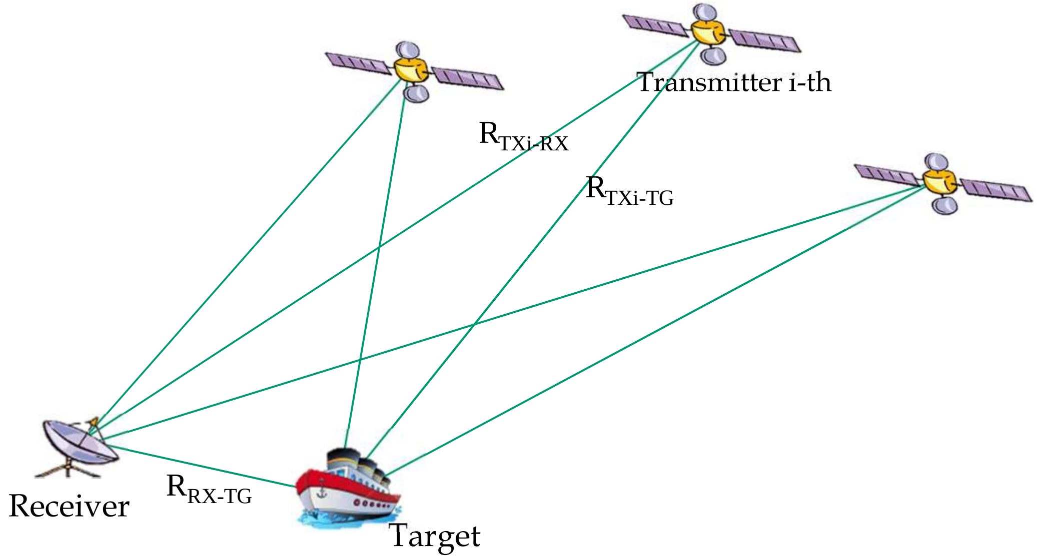
$T_{batch} = 3s, T_{obs} = 60\ s$





On going works and future activities

- Single transmitter: limited performance in detection
- Try to improve performance using the information of more transmitters
- Basic plane is dependent by the considered transmitter



Goal

Study of strategy to put together the contributions of different transmitters to improve performance

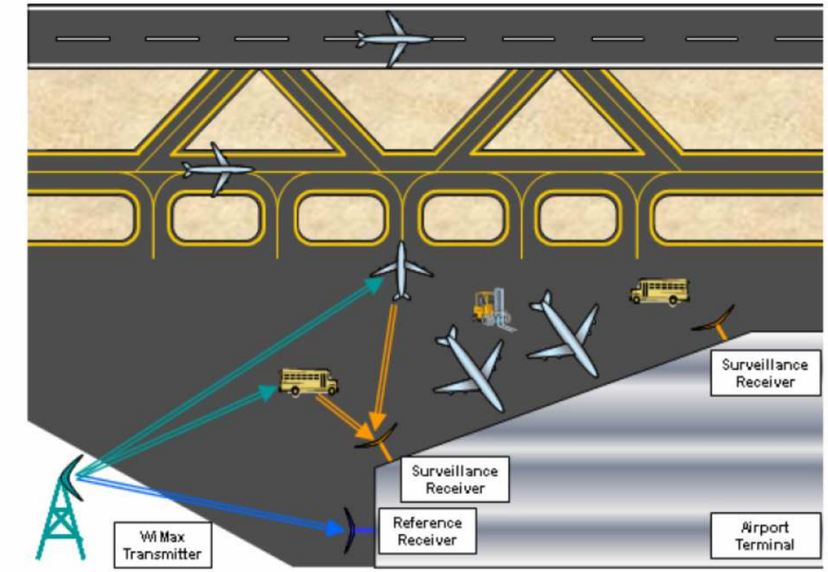
- ✓ Multiple transmitters could be exploited also:
  - localization
  - tracking
- ✓ Possibility to extract target features thought ISAR techniques.

WiFi-based PBR

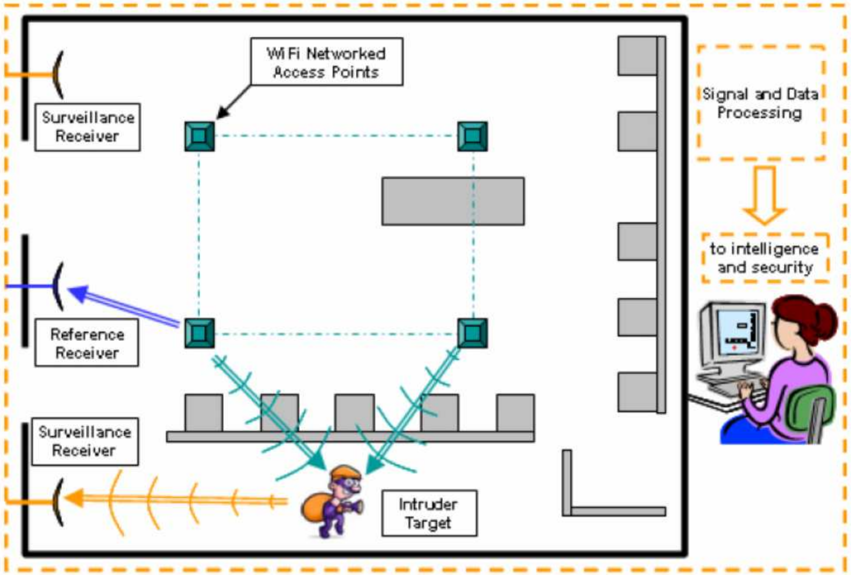
Short Range PBR potentialities

- Improve interior and exterior security for all types of building;
- Identify and track goods and people.

Outdoor



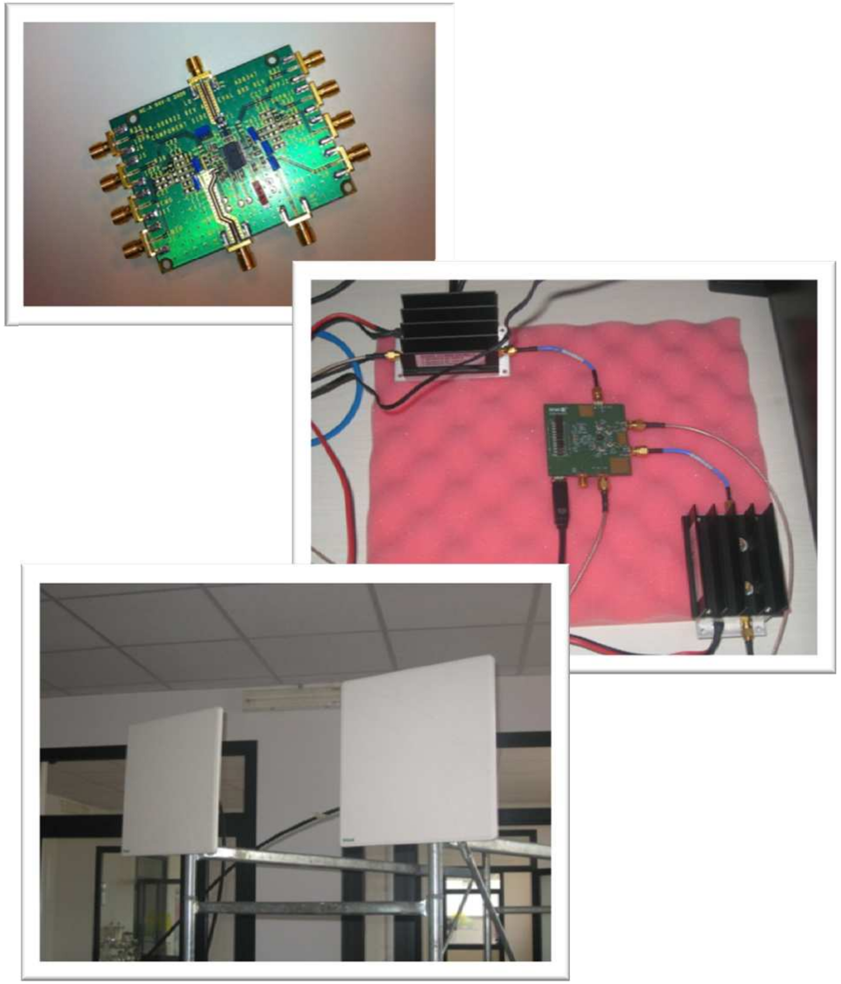
Indoor

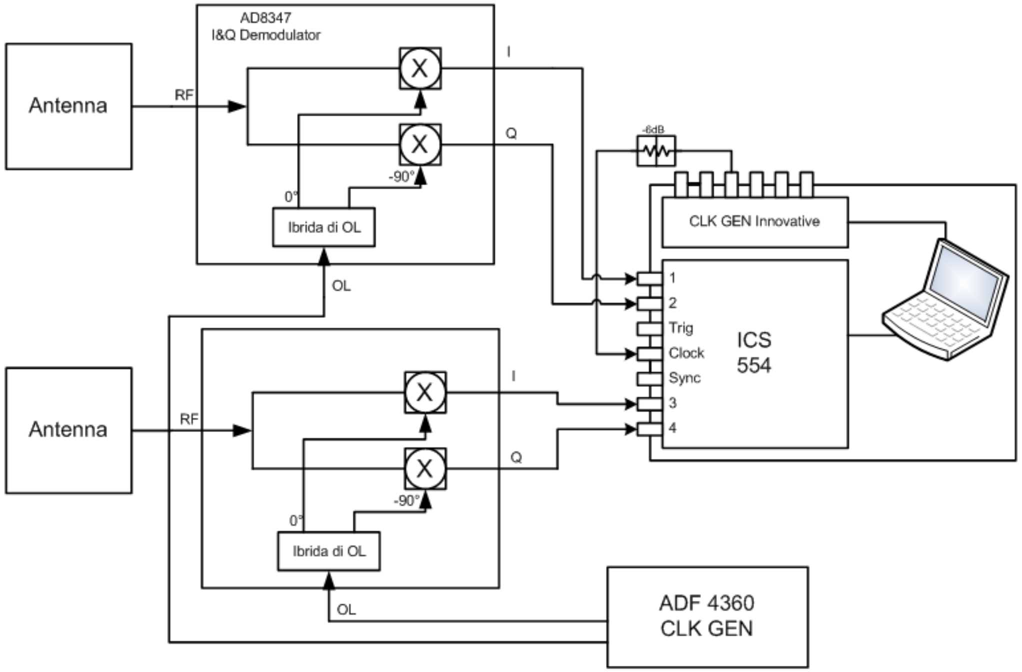


- Moving objects might potentially be detected and localized or classified.
- Security of public areas (railway stations, airport terminals) or private commercial premises.

Wireless LAN/MAN transmissions sources might potentially act as an ideal illuminator of opportunity for Short Range surveillance using the PBR principle. ⇨ **IEEE 802.11 - WiFi**

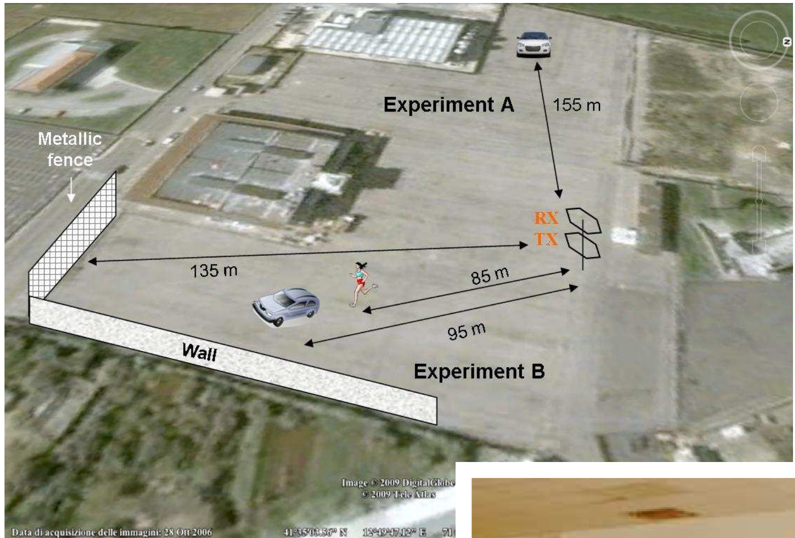
Prototypes development

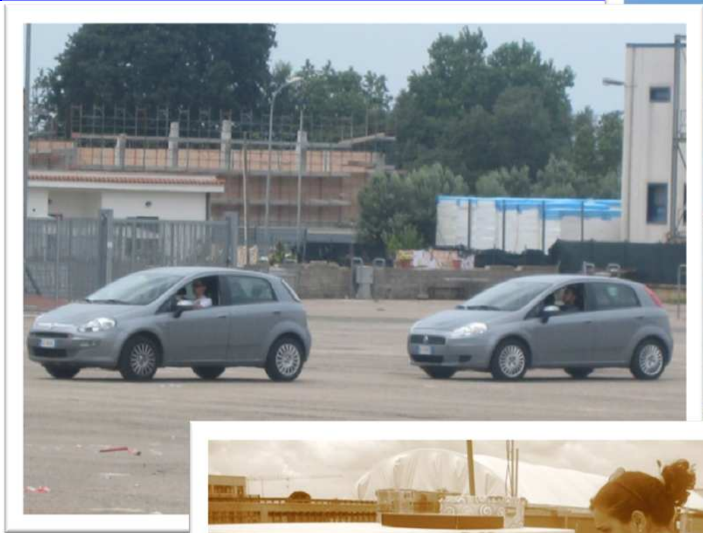




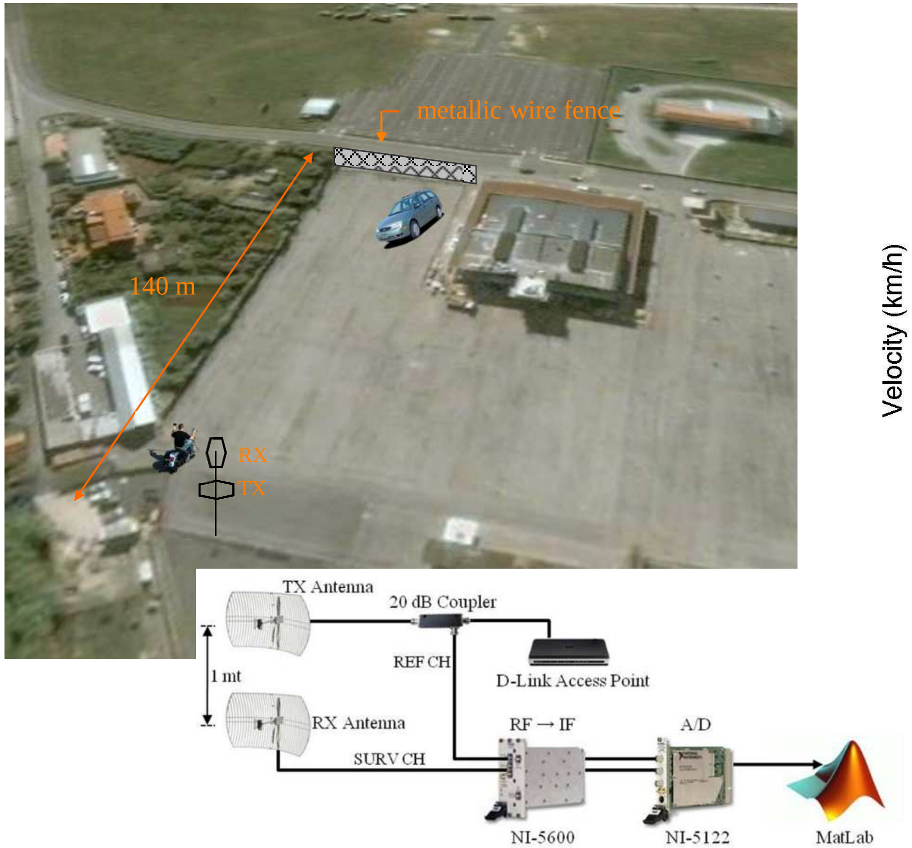
Signal down-conversion & base-band sampling

Acquisition Campaigns

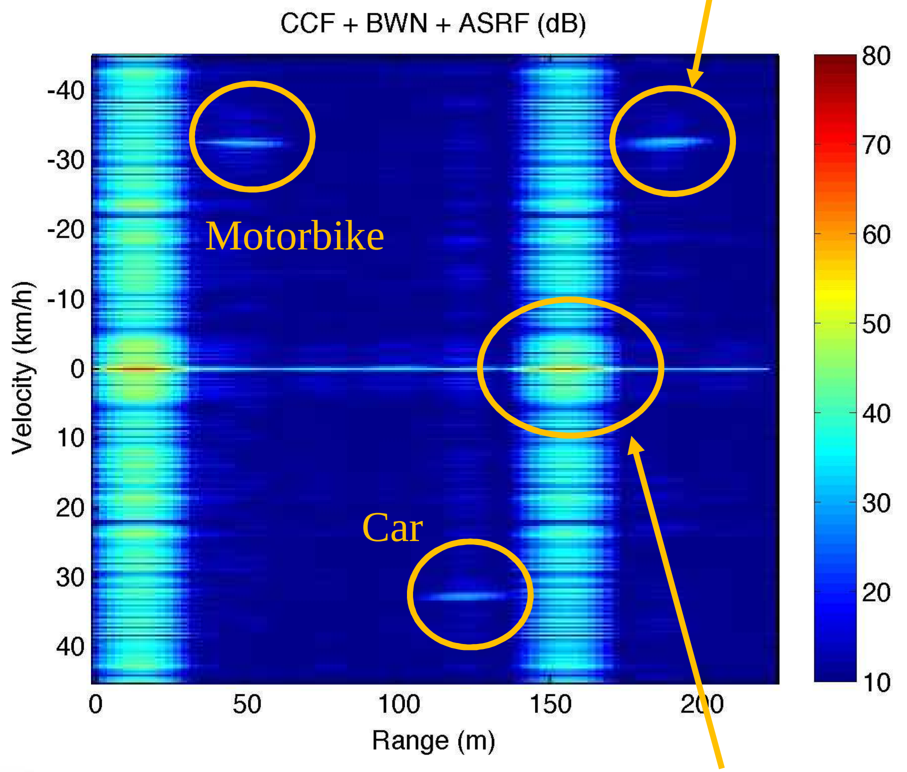




Vehicular target detection results

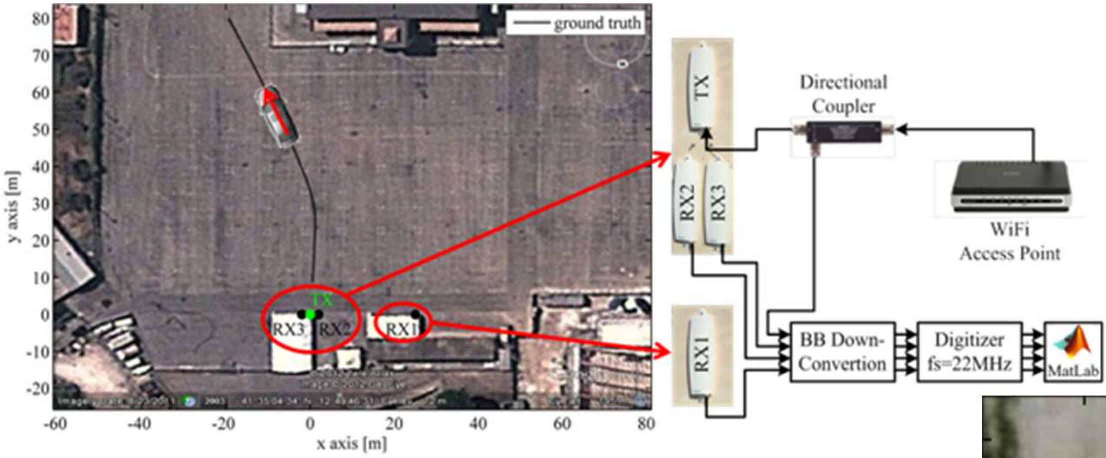


double bounce of the farther target on the metallic wire fence



metallic fence delimiting the parking area

Vehicular target localization results



▶ **Vehicles localization**

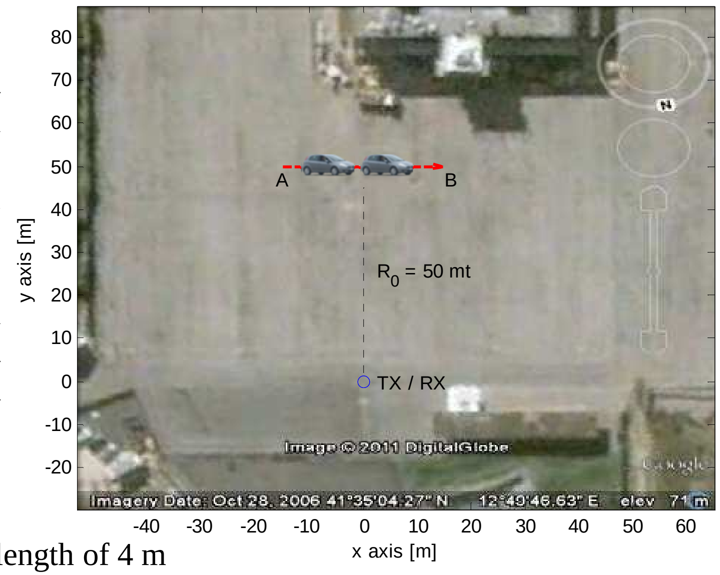
Target localization test: vehicular target

A GPS receiver was used to collect the ground truth.

PCL results exploiting pre-filtered Range (using Doppler) and DoA measurements from 2 PCL sensors

WiFi-based passive ISAR (I)

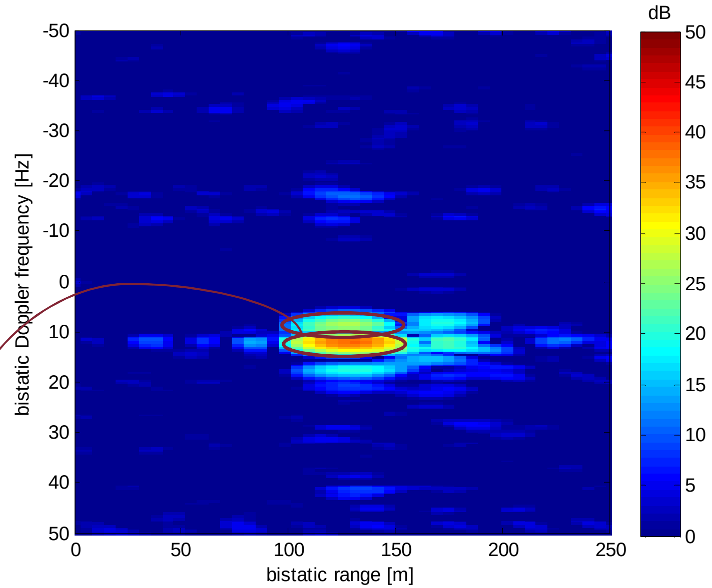
Vehicular target detection experiment. Two identical cars move in the cross-range direction with constant velocity (about 4m/s)



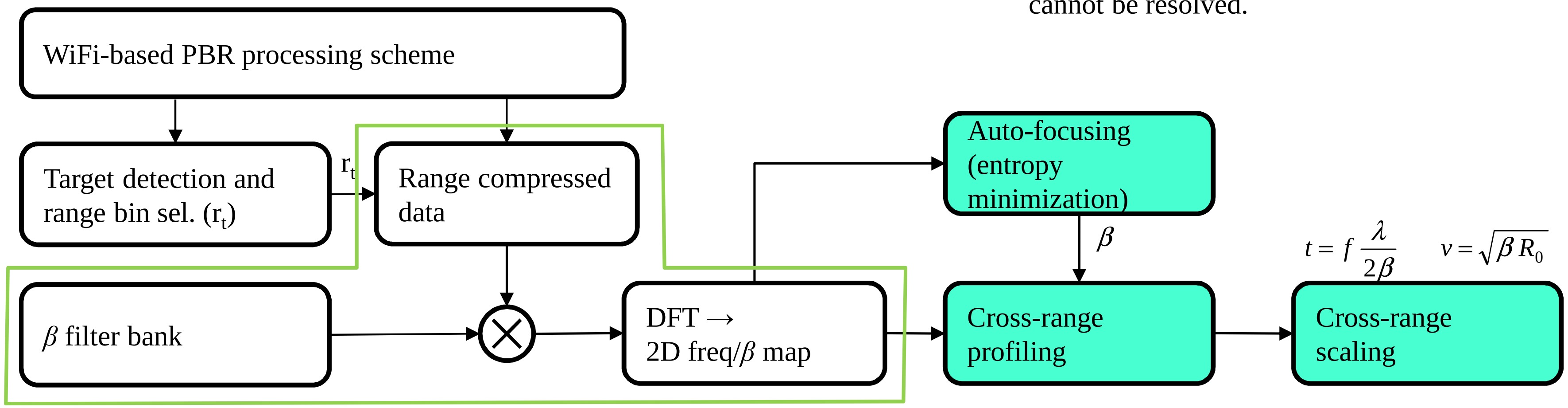
Each car has a length of 4 m

The cars have a fixed displacement of about 2 m

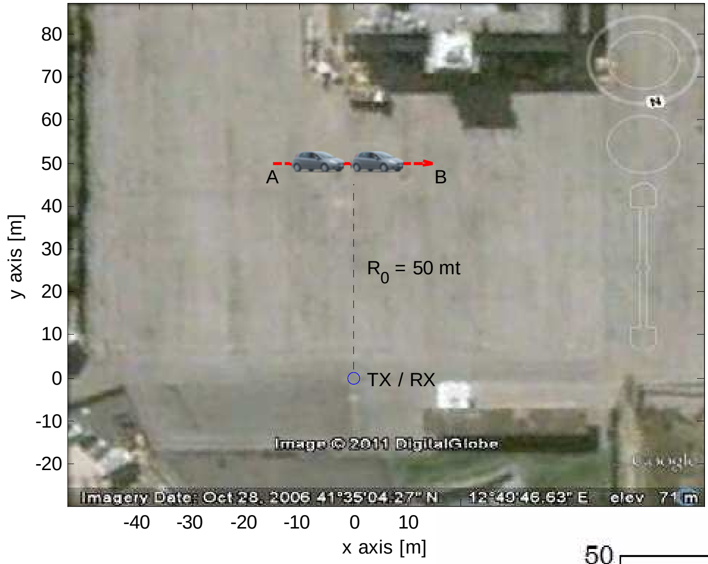
Two-dimensional range velocity map evaluated after sidelobes control and disturbance removal



The targets can be easily detected but they cannot be resolved.

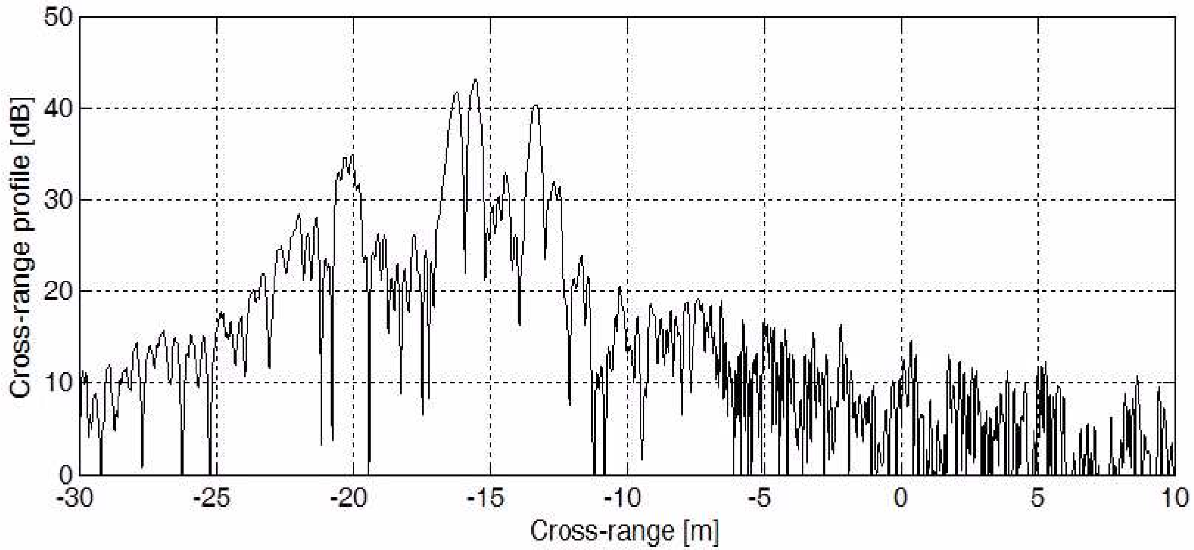


WiFi-based passive ISAR (II)



Vehicular target detection experiment.
Two identical cars move along the cross-range direction with constant velocity (about 4m/s).
Each car has a length of 4 m.
The car have a fixed displacement of about 2 m.

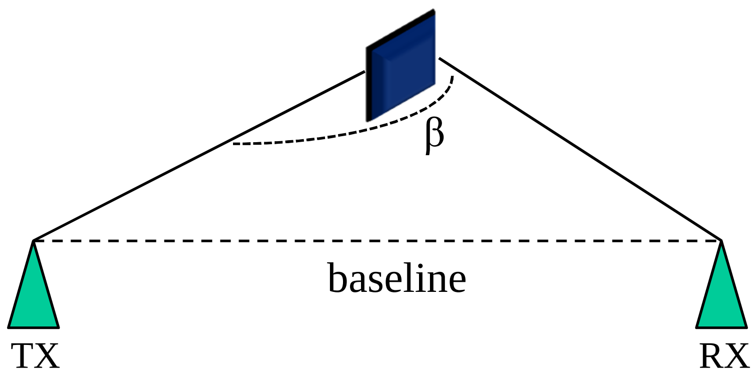
ISAR integration time 6 sec.
Separation among consecutive frames 0.1 sec.
Total acquisition 10 sec.

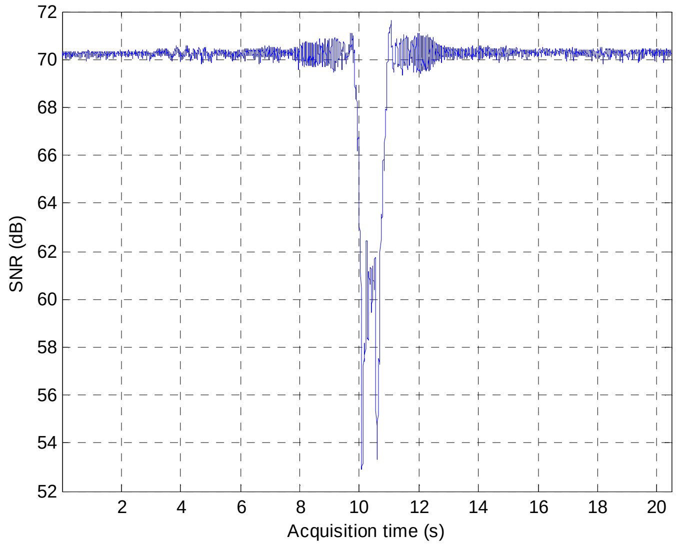


Passive Forward Scatter operation mode

What is Forward Scatter Radar?

- An extreme bistatic radar with a bistatic angle β ≈ 170-180°
- Signals received in FSR are presumed not to be reflections from the targets (such as in conventional radars) but the shadowing of the emitted electromagnetic (EM) energy.





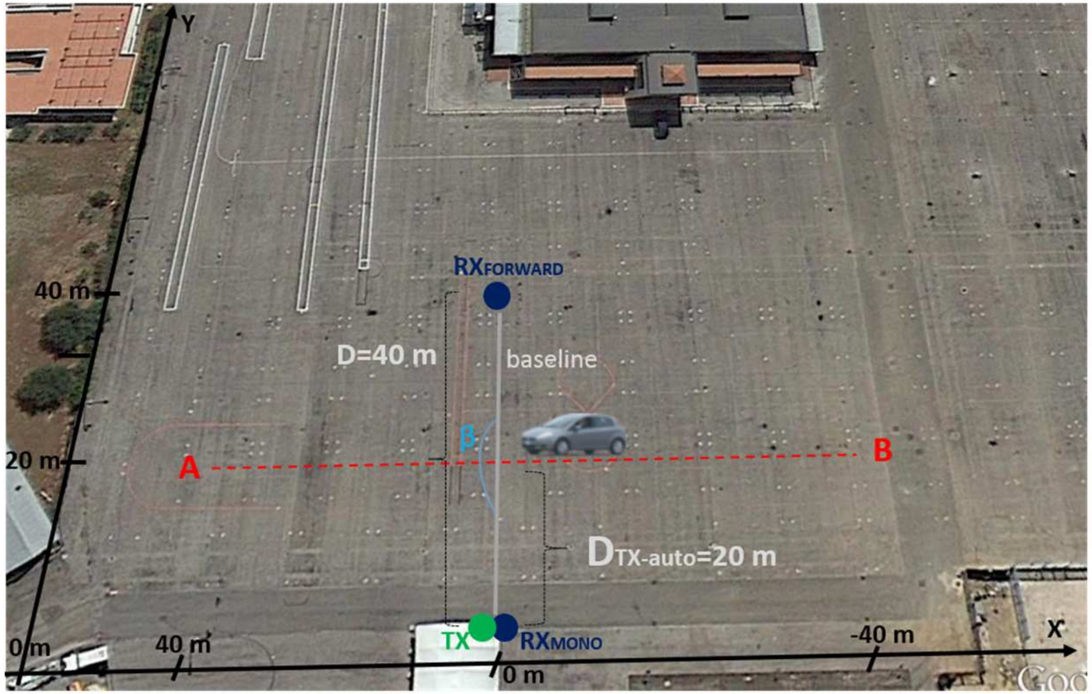
FSR Advantages:

- enhanced target radar cross-section
- simple processing
- robustness to stealth technology
- automatic target classification

The feasibility of a forward scattering passive radar using WiFi transmission has been investigated

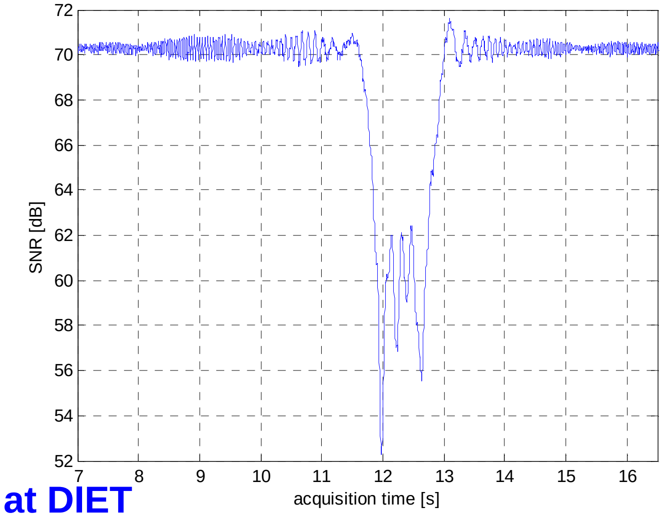
Passive Forward Scatter operation mode

In order to assess the impact of the FS geometry on WiFi passive radar, a new acquisition campaign has been performed.



- The test were performed in a parking area in Cisterna di Latina
- A single transmitter and two receivers:
  - ✓ RxMONO: in monostatic configuration
  - ✓ RxFORWARD: in forward configuration with β=180°
- Direction: B → A with BA≈80 m
- Velocity: between 3.5 – 5 m/s
- Vehicle- categories: Punto Evo, C3, Polo, Peugeot 107

Punto Evo vehicle signature

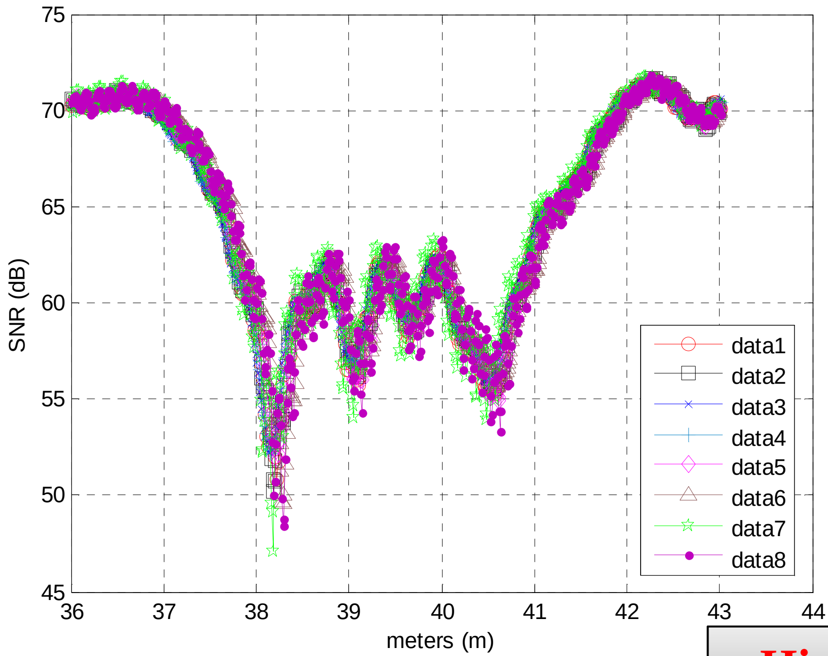


Passive Forward Scatter operation mode

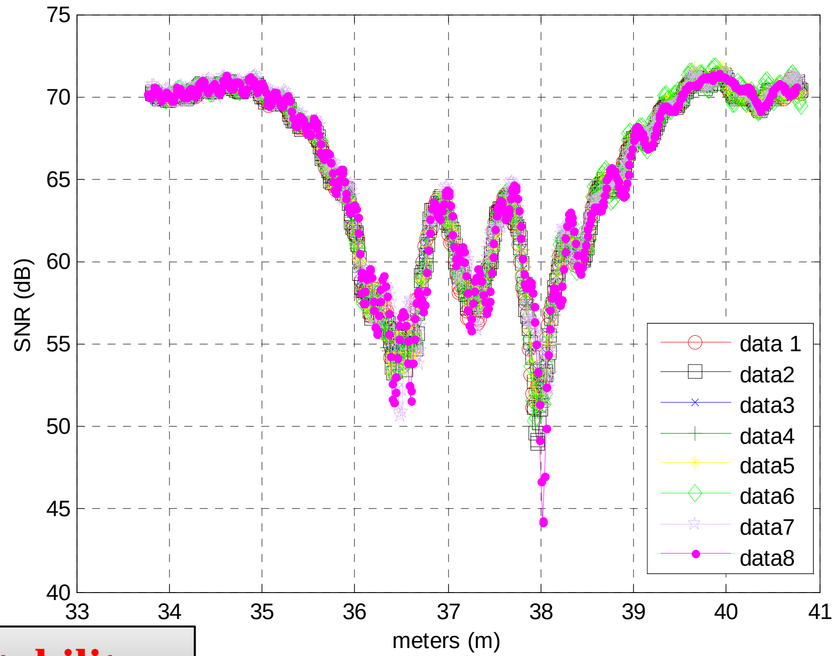
The vehicle signatures can be used in a classification system because:

- the same target along different tests has the same vehicle signatures.
- Each target has a particular shape.

PUNTO EVO



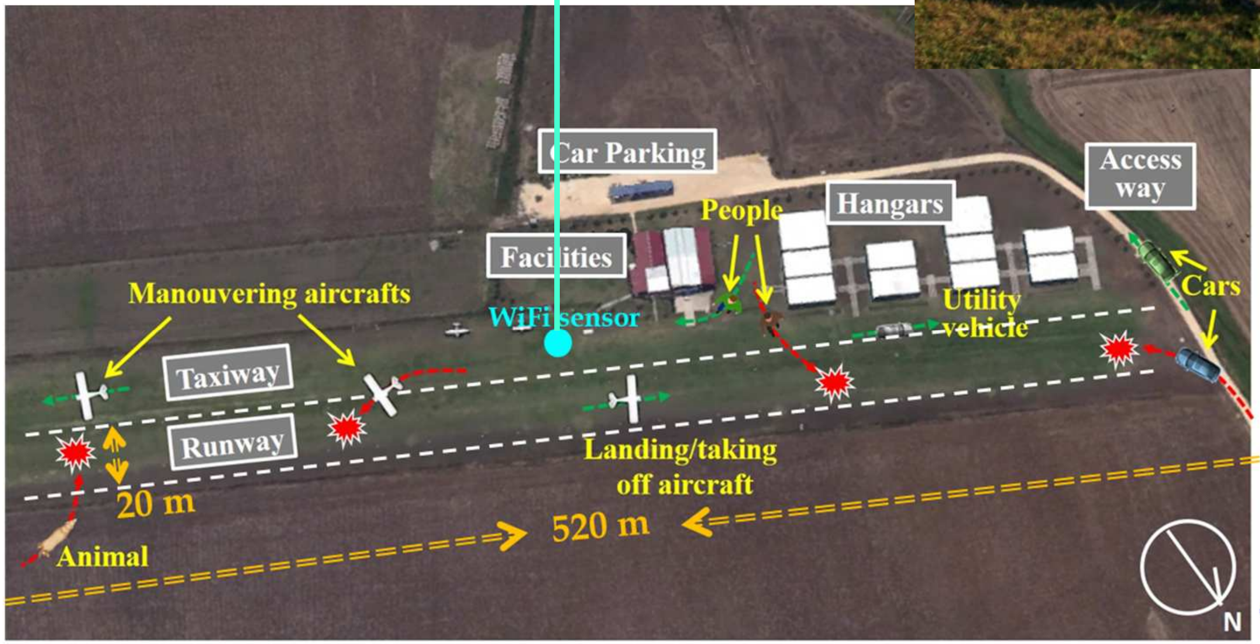
PEUGEOT 107



High stability

WiFi-based PBR for small aircrafts surveillance

Test campaigns performed in a small airfield named “Aviosuperficie Monti della Tolfa” located in Santa Severa

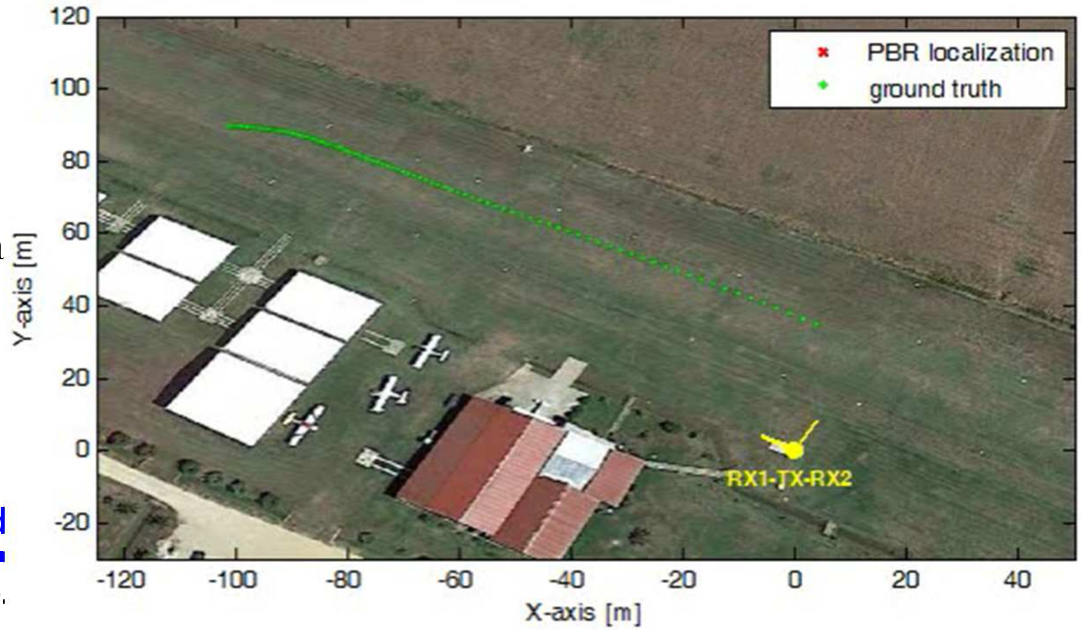


WiFi-based PBR for small aircrafts surveillance

TEST #1

A small aircraft moved on the runway just after landing

- The small aircraft is continuously detected along its trajectory
- A good agreement is observed between PBR results and available ground-truth

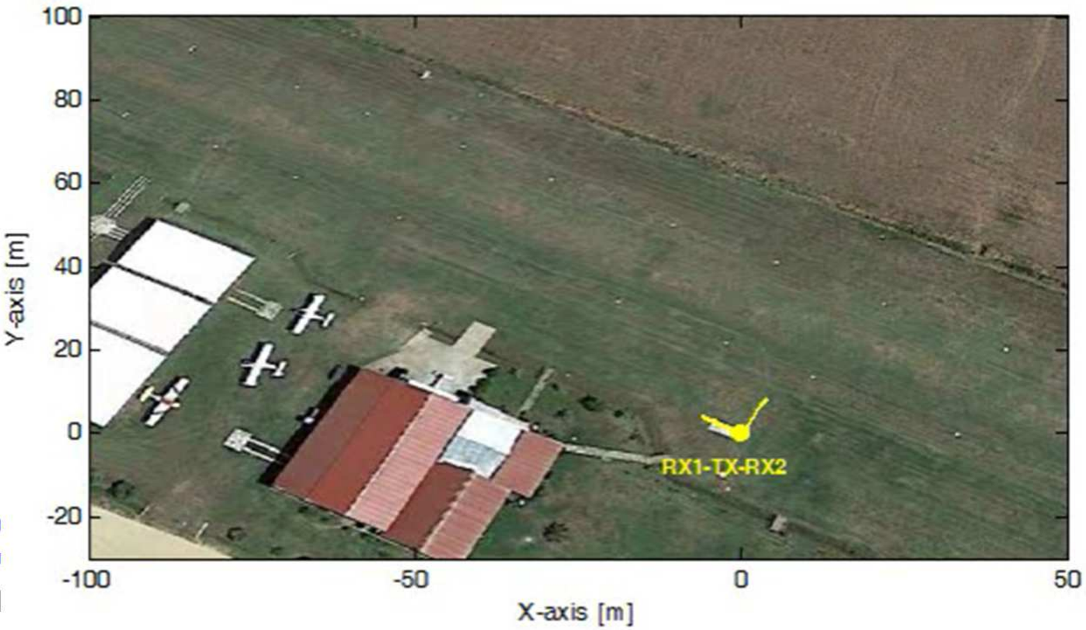


WiFi-based PBR for small aircrafts surveillance

TEST #2

A ultralight aircraft is moving in the proximities of the runway

The system is able to localize the very small aircraft

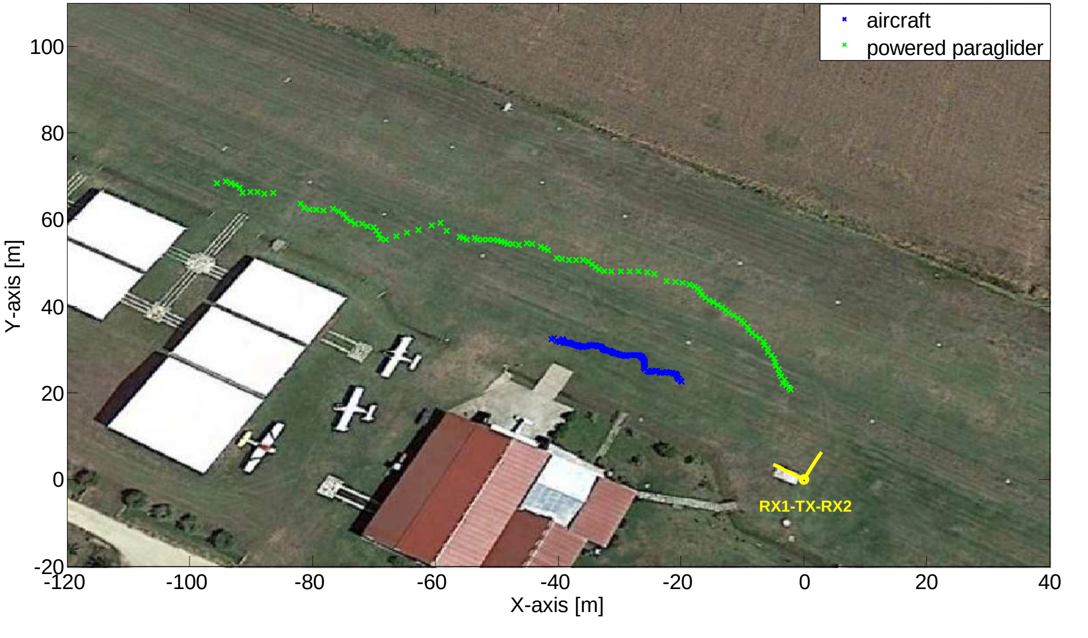


WiFi-based PBR for small aircrafts surveillance

TEST #3

A powered paraglider is flying over the runway involved in a ‘touch and go’ maneuver. Contemporaneously, a small aircraft is moving toward the passive sensor.

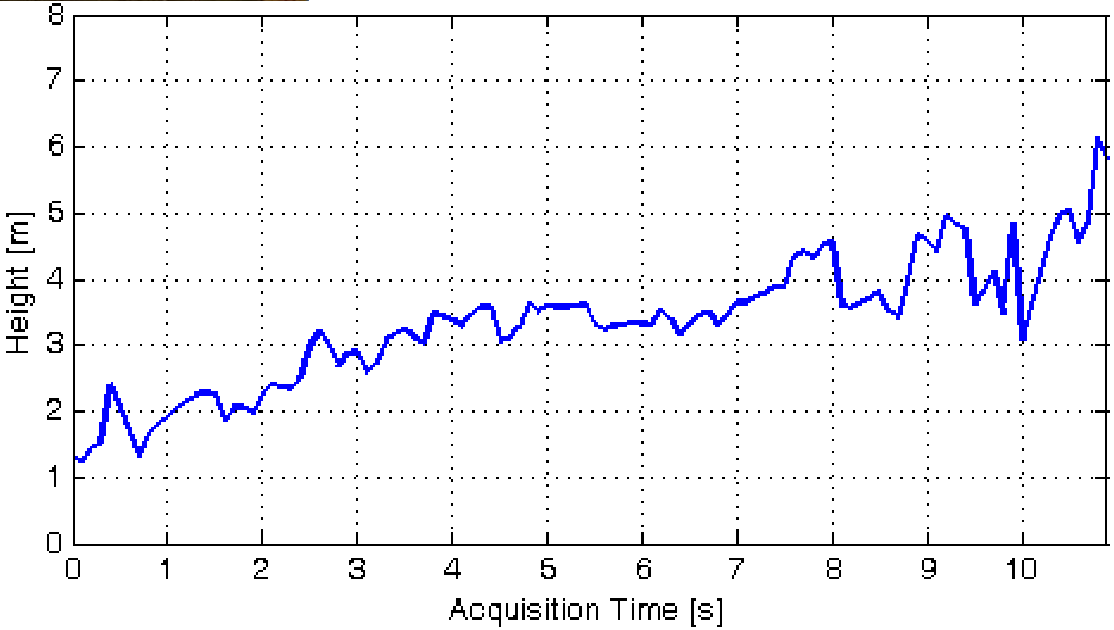
The two sequences of plots clearly reveal the presence of the observed targets



WiFi-based PBR for small aircrafts surveillance

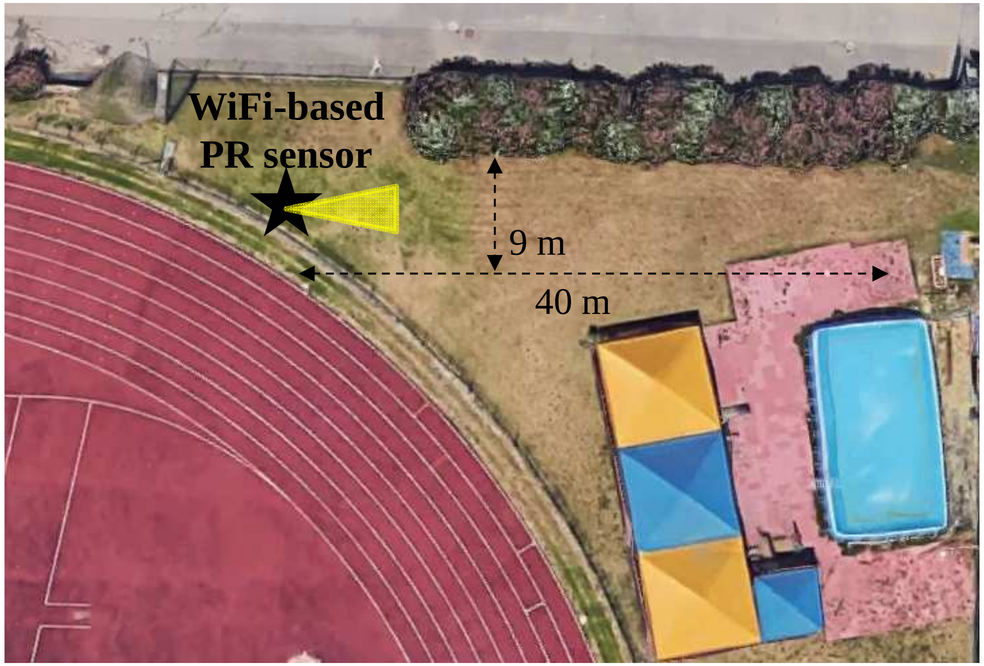
TEST #4

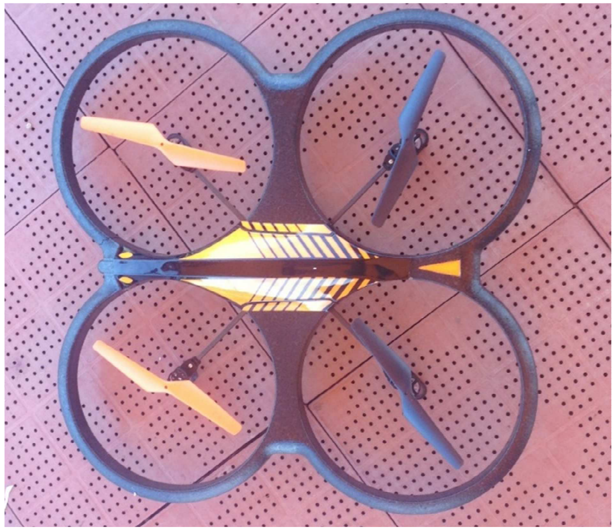
Ultralight aircraft during its phase of take-off



WiFi-based PBR for drone detection

Test campaigns performed in a University sport center (CUS)

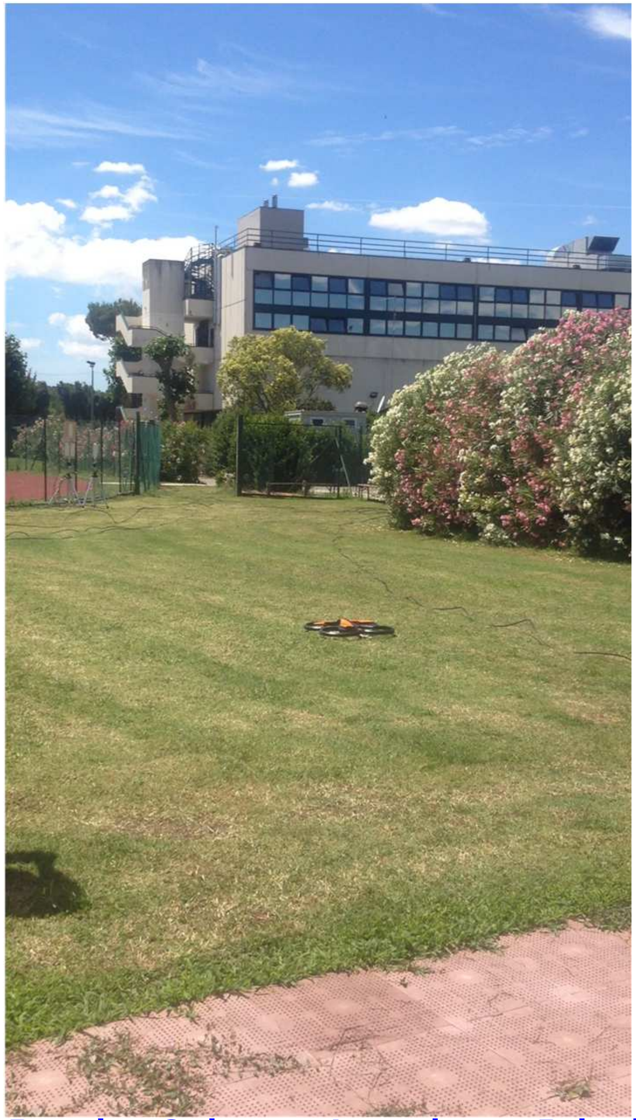


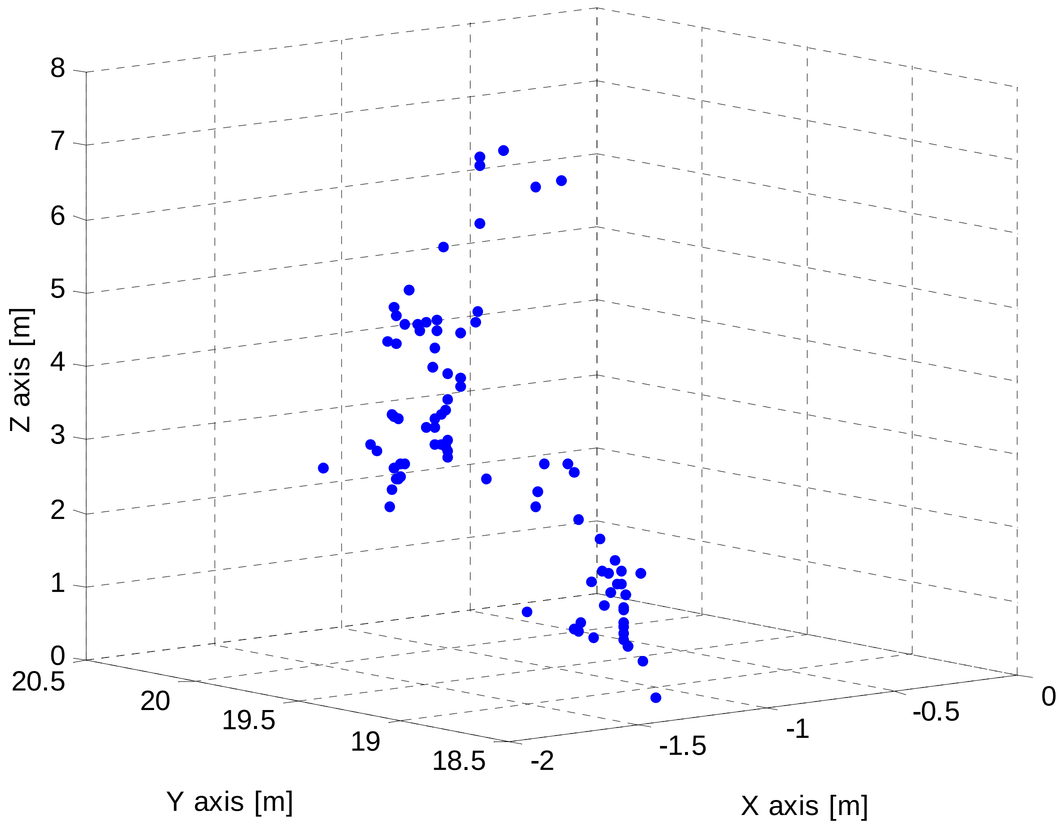


Size: 60 cm x 60 cm x 9 cm

Material: carbon fiber & expanded foam

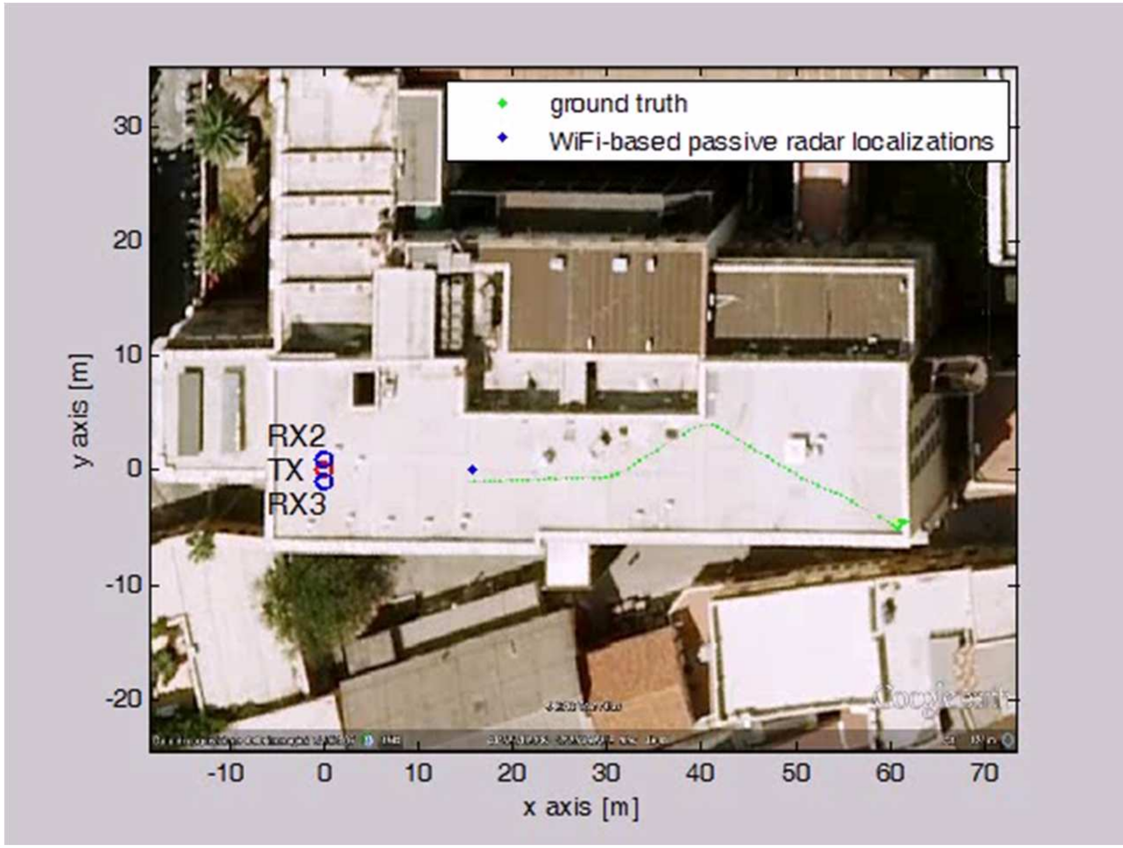
WiFi-based PBR for drone detection





Human targets detection and localization

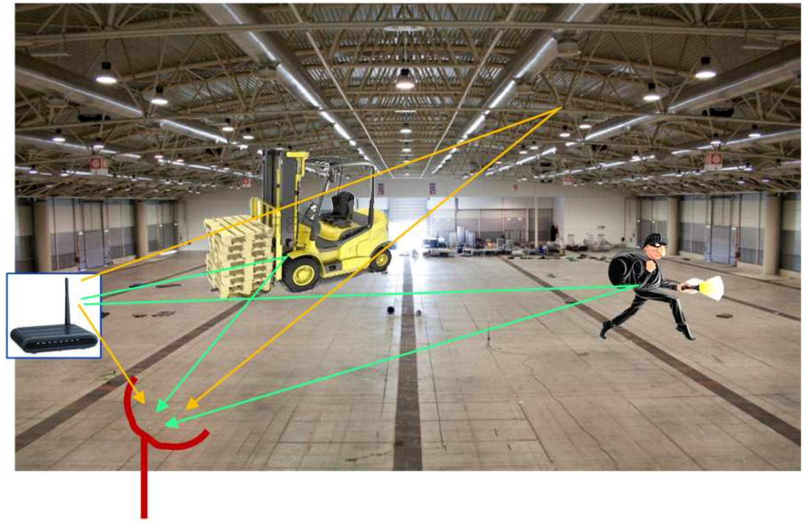
Human target walking on the roof of our faculty, equipped with a GPS receiver to collect the ground truth.



Target localization test: human target

Indoor surveillance applications (I)

Advantages of PCL for indoor localization and tracking (e.g. people location and navigation along buildings, automotive safety, vehicle navigation or asset tracking):

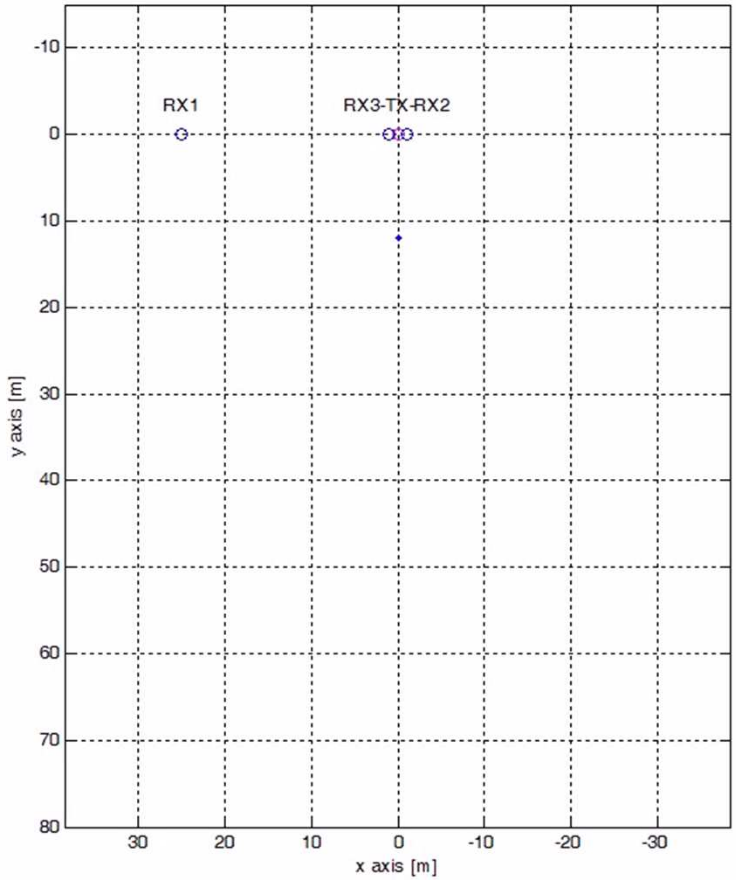


- o It complements existing technologies at low cost;
- o with respect to technologies such as RFID , IEEE 802.11 wireless LAN, and ultrasonic, it does not require the target objects to be equipped with a cooperative device → it is well suited for specific surveillance applications such as intruder location, detection, tracking and identification of unauthorized vehicles in a forbidden area, etc.;
- o with respect to technologies such as infrared, it does not require direct line-of-sight and is a “longer” range signal transmission → feasibility of uncooperatively and covertly detecting people moving behind walls ;
- o with respect to video surveillance, it is not subject to the blind spots and potentially intrusive equipment → it could be used in public areas or private commercial premises.
- o no extra signal is transmitted → this limits the energy consumption, prevents possible interferences with pre-existing systems, and makes the sensor free from any issue related to human health.

Indoor surveillance applications (II)

TEST #1

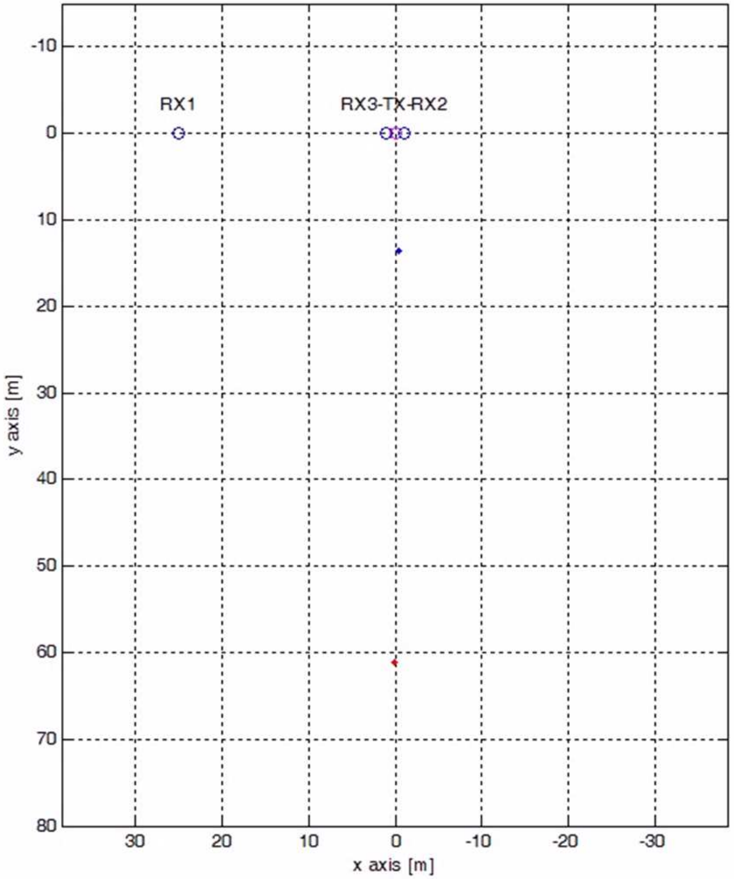
A single target walks forward the antennas location for a while and then changes its walking direction



Indoor surveillance applications (III)

TEST #2

Two targets move approaching each other for a while till both of them change their walking direction.

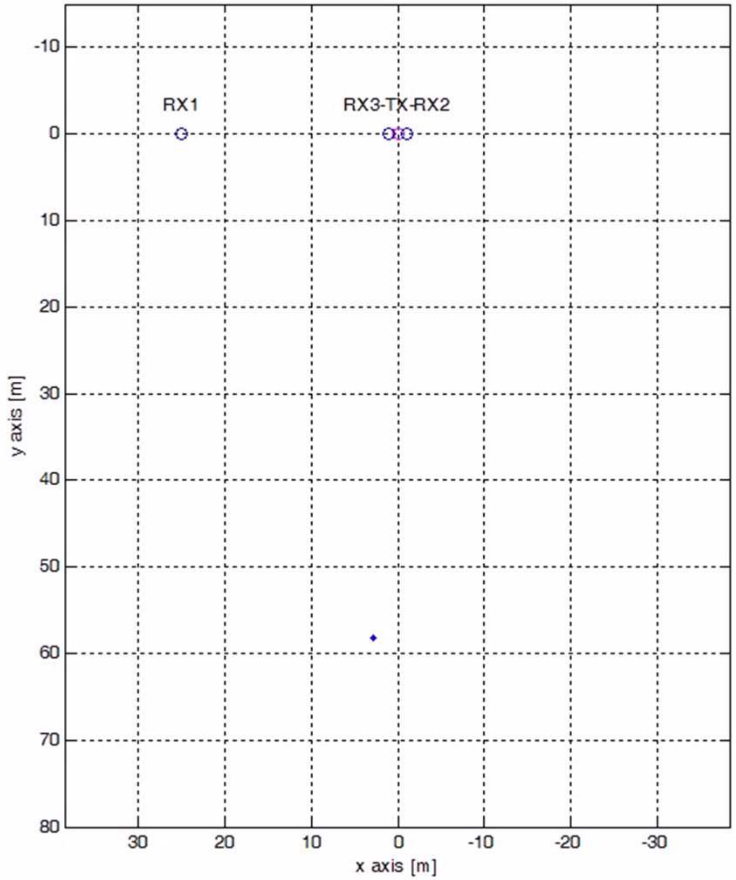


Indoor surveillance applications (IV)

TEST #3

Two targets move initially very close each other which results in the impossibility for the system to resolve between them.

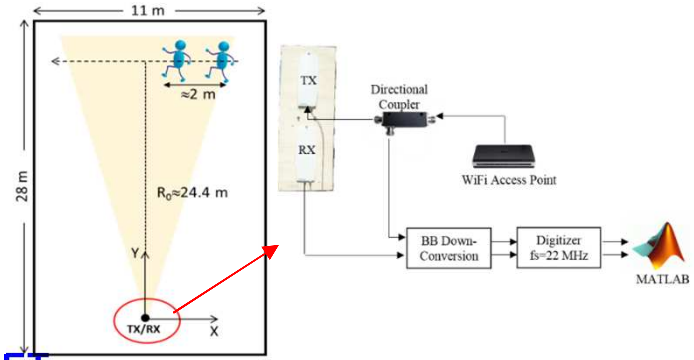
Only when a target changes his walking direction, the system is able to distinguish between them.



WiFi-based passive ISAR against human targets

Potential of ISAR techniques in resolving real human targets in a cluttered indoor scenario.

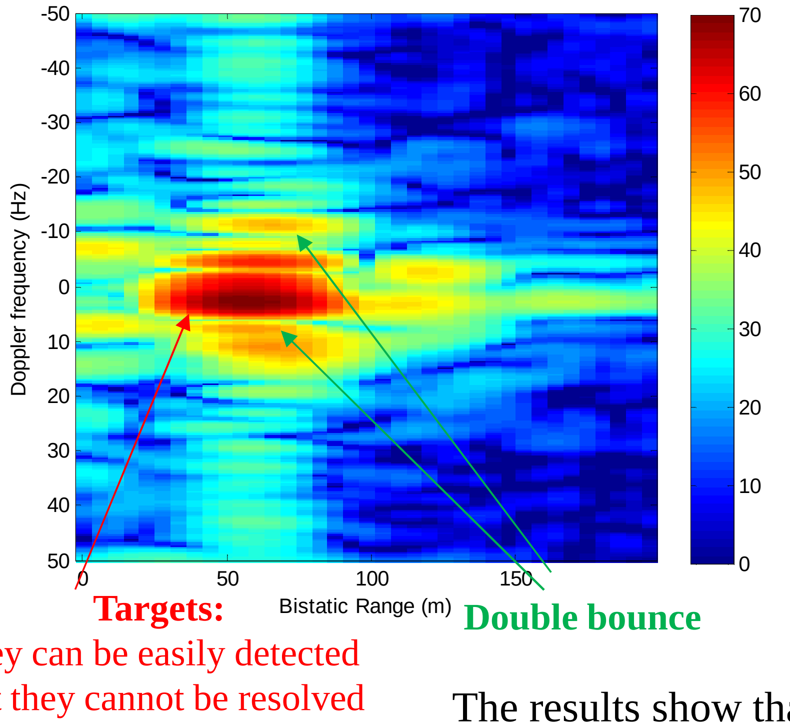
- The test were performed in the canteen of the school of Engineering at University of Rome "La Sapienza".
- A monostatic configuration has been employed.
- Two people move along cross-range direction with constant velocity (v ≈ 1.3 m/s).
- The human target have a fixed displacement of about 2 m.
- The total acquisition time is 10 s.

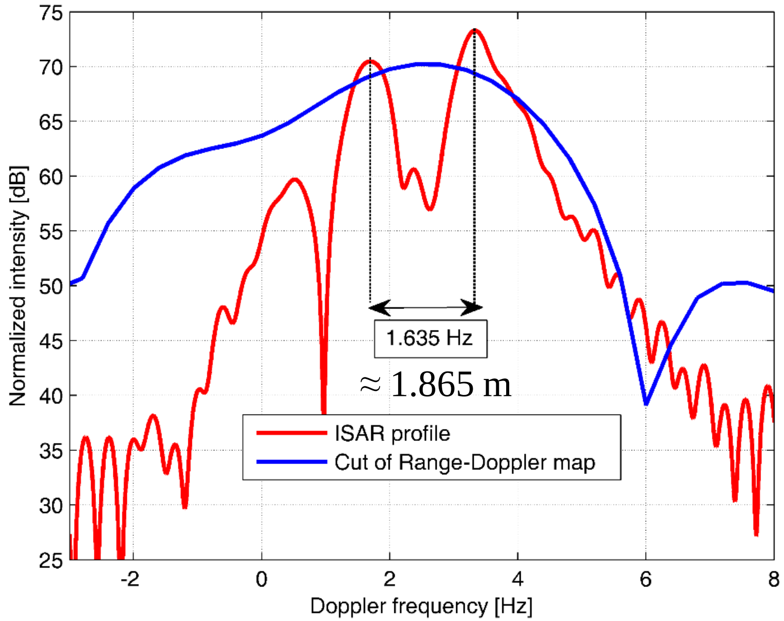


WiFi-based passive ISAR against human targets

The two targets give rise to the presence of:

- a single peak in the cut of range-Doppler map at the range bin interested by the targets (with integration time = 0.5 s)
- two peaks in the ISAR profile (with integration time = 3 s and compensation up to the third order)

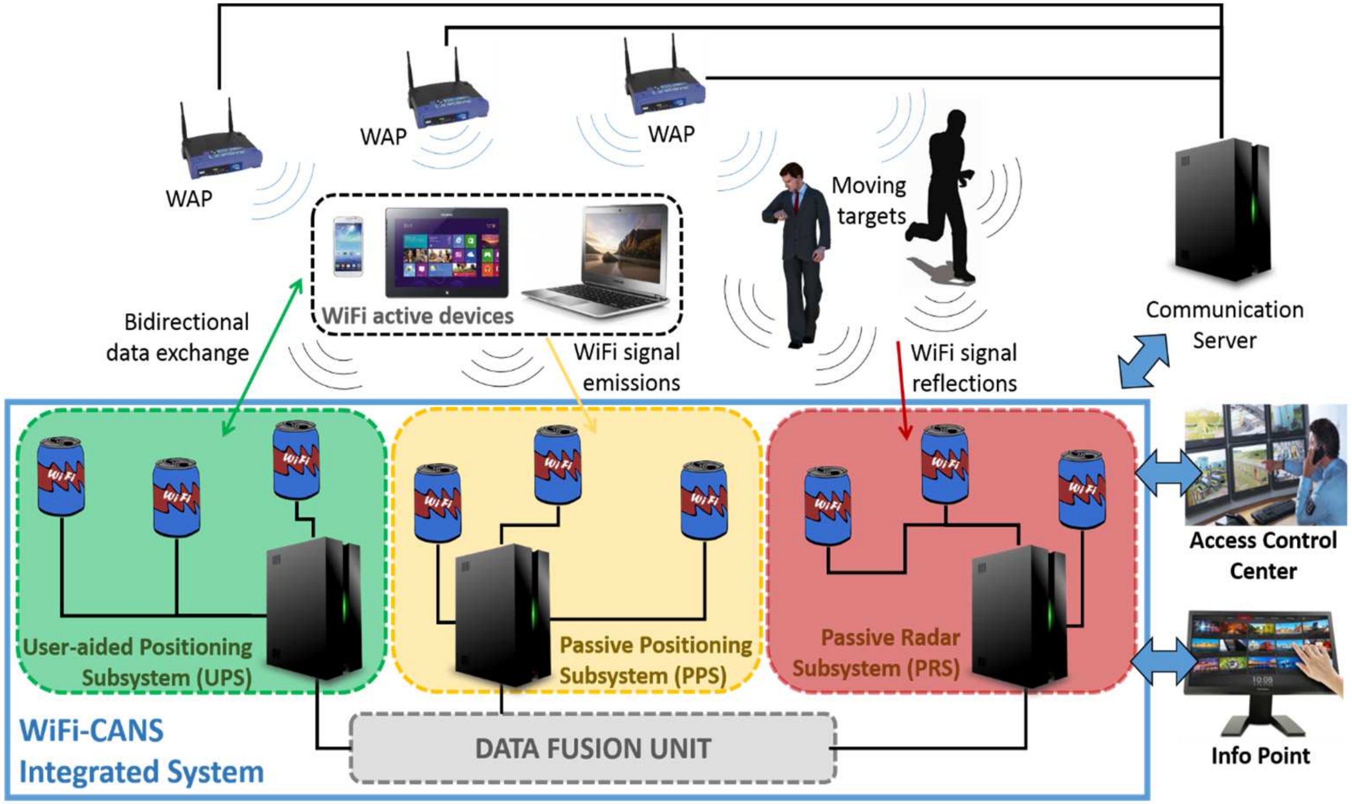




The results show that ISAR techniques can be exploited to improve cross-range resolution so that closely spaced targets can be discriminated.

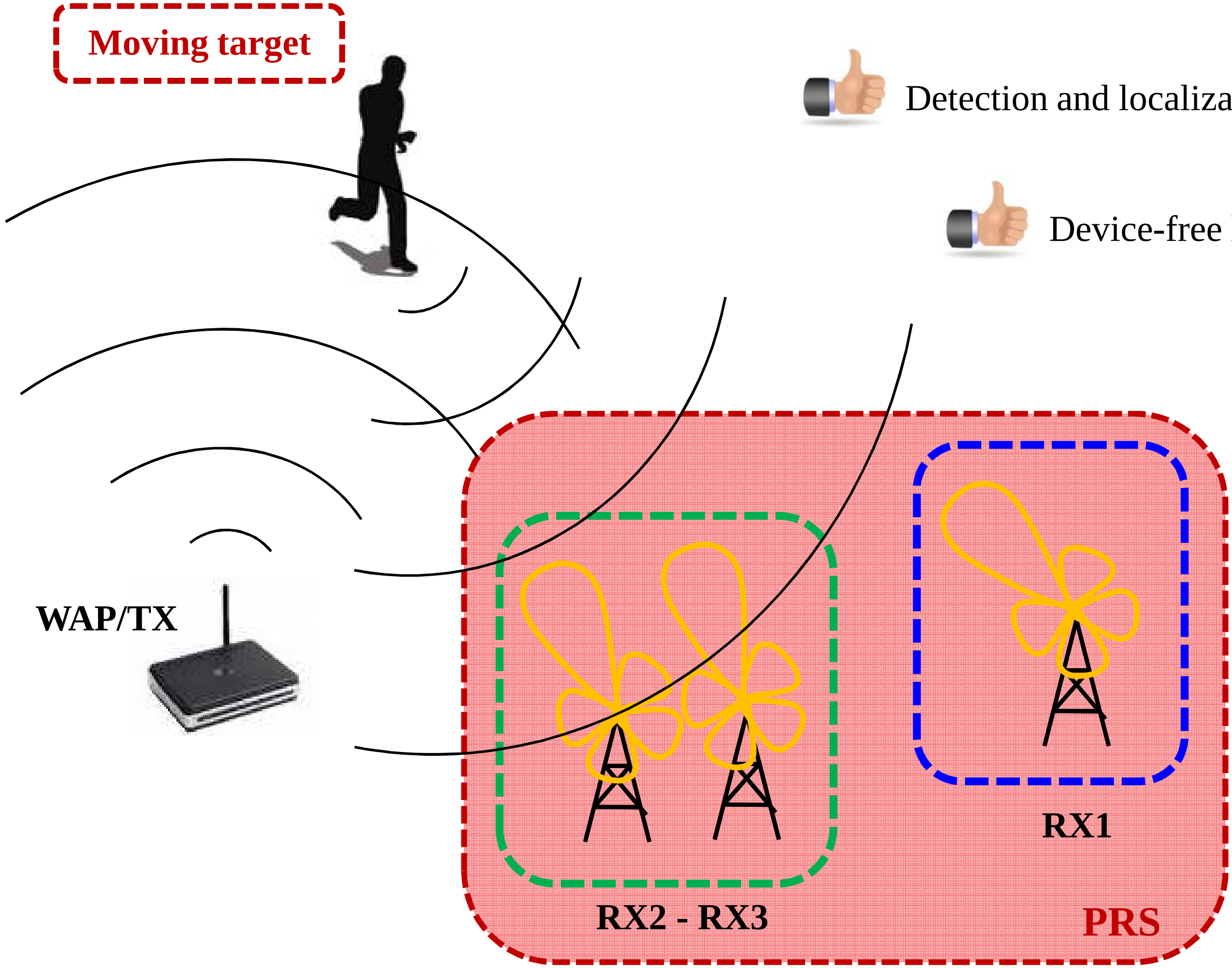
Integrated System for human targets localization

- Fusion of active and passive techniques for indoor/outdoor localization.
- This innovative system will be able to provide the position of both cooperative and non-cooperative targets.



Integrated System: PRS description

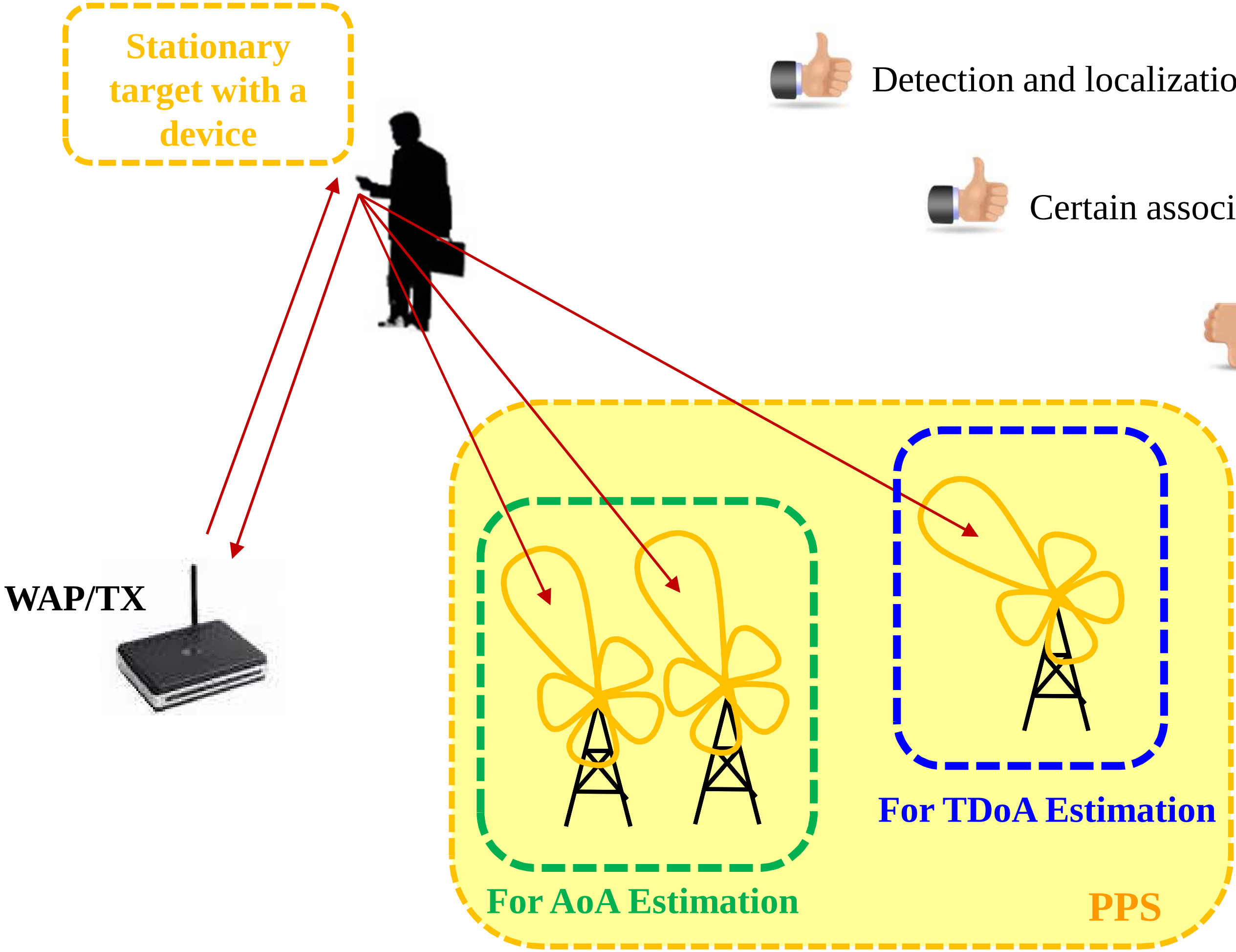
<u>Passive Radar Subsystem (PRS)</u>:



- 👍 Detection and localization of moving targets
- 👍 Device-free localization
- 👎 No detection of stationary targets
- 👎 Closely spaced targets cannot be discriminated

Integrated System: PPS description

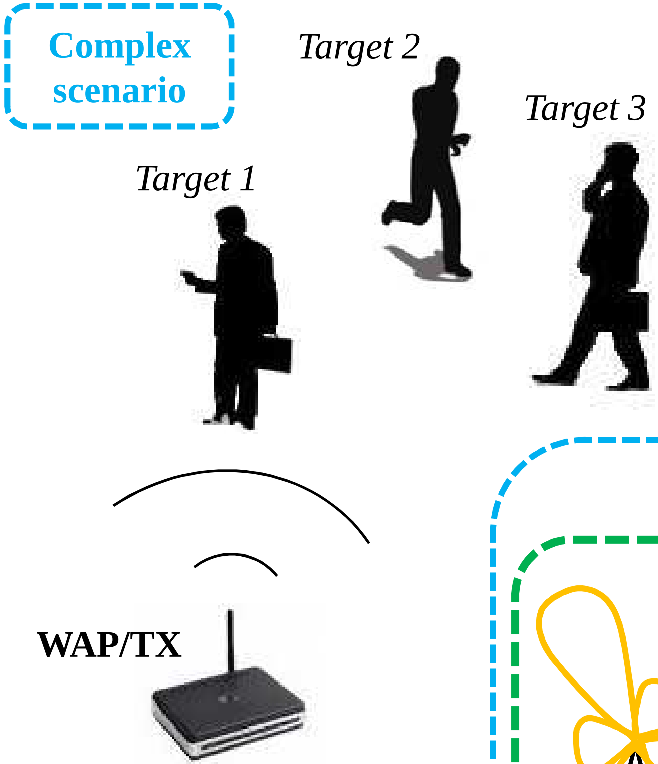
Passive Positioning Subsystem (PPS):



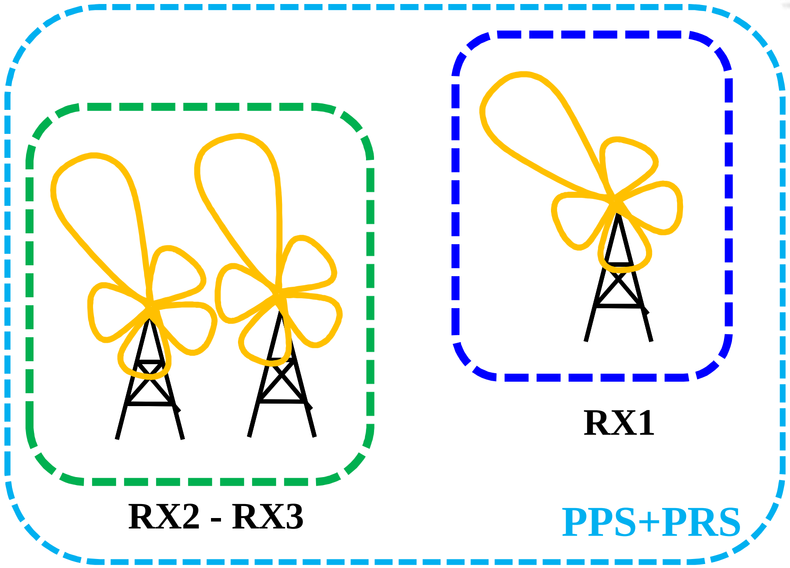
- Detection and localization of stationary targets
- Certain association transmission/target
- Potentially inaccurate for moving target (low integration)
- It is necessary the presence of a device

Integrated System: PPS + PRS

Fusion of PPS and PRS:



- Each target can be detected and localized (moving and stationary targets)
- Closely spaced targets can be discriminated if they have a device
- Integration of different estimates for moving targets with a device (for example *Target 3*)



Integrated System: Applications

- ❑ Surveillance and Security
- ❑ Coordination of rescue teams in emergency scenarios
- ❑ Supply of services:
  - Smart Museum
  - Smart Hospital
  - Smart University
  - …