Passive Forward Scatter Radar

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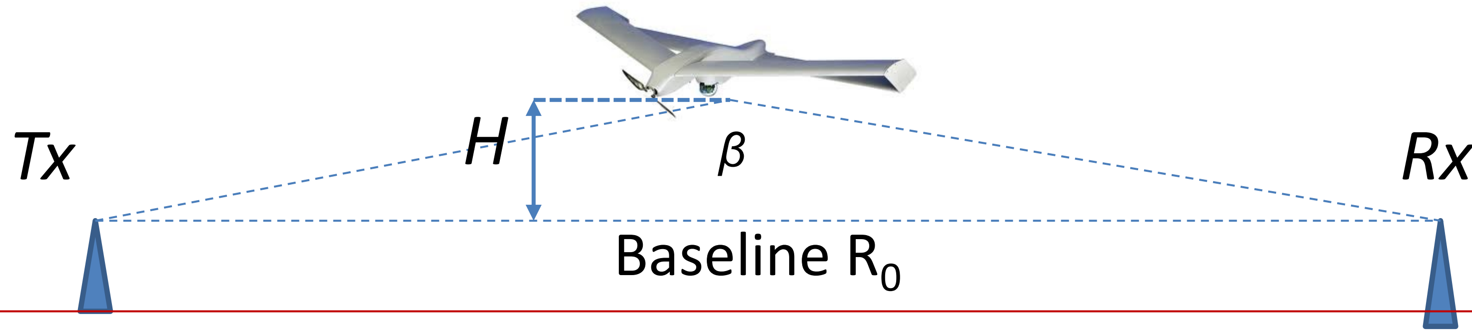
What is Forward Scatter Radar?



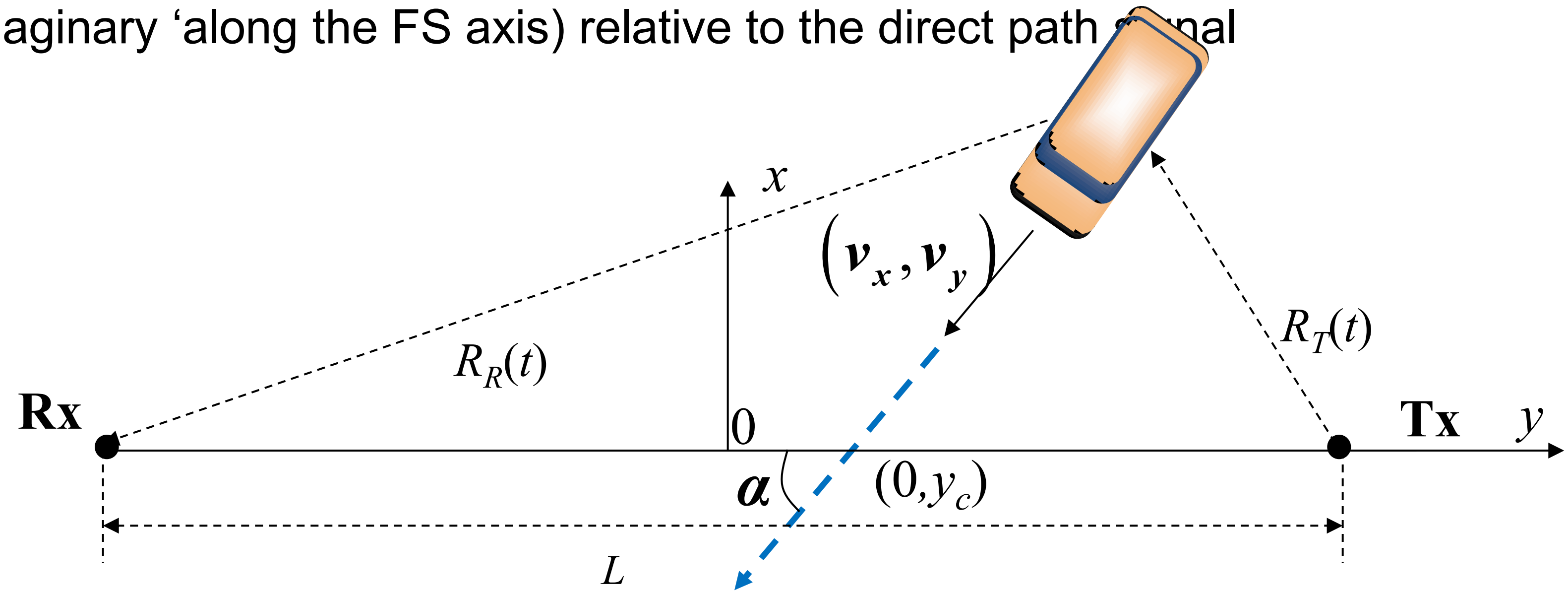
λ-1 m, R_0=40 km, H=5 km, β~165, it is FSR

- A bistatic radar
  - which operates when the bistatic angle is $\beta \sim 180^0$ (TBD)
  - its received signal strength and modulation has a negligible dependence on the target's 3-D shape and material

but depends on the target shadow contour, scattering region and cross section with respect to Tx and Rx.

FSR – how it works: Doppler phase signature

- Being 'shadow' the forward scatter signal is $\pi/2$ phase shifted (‘imaginary ‘along the FS axis) relative to the direct path signal

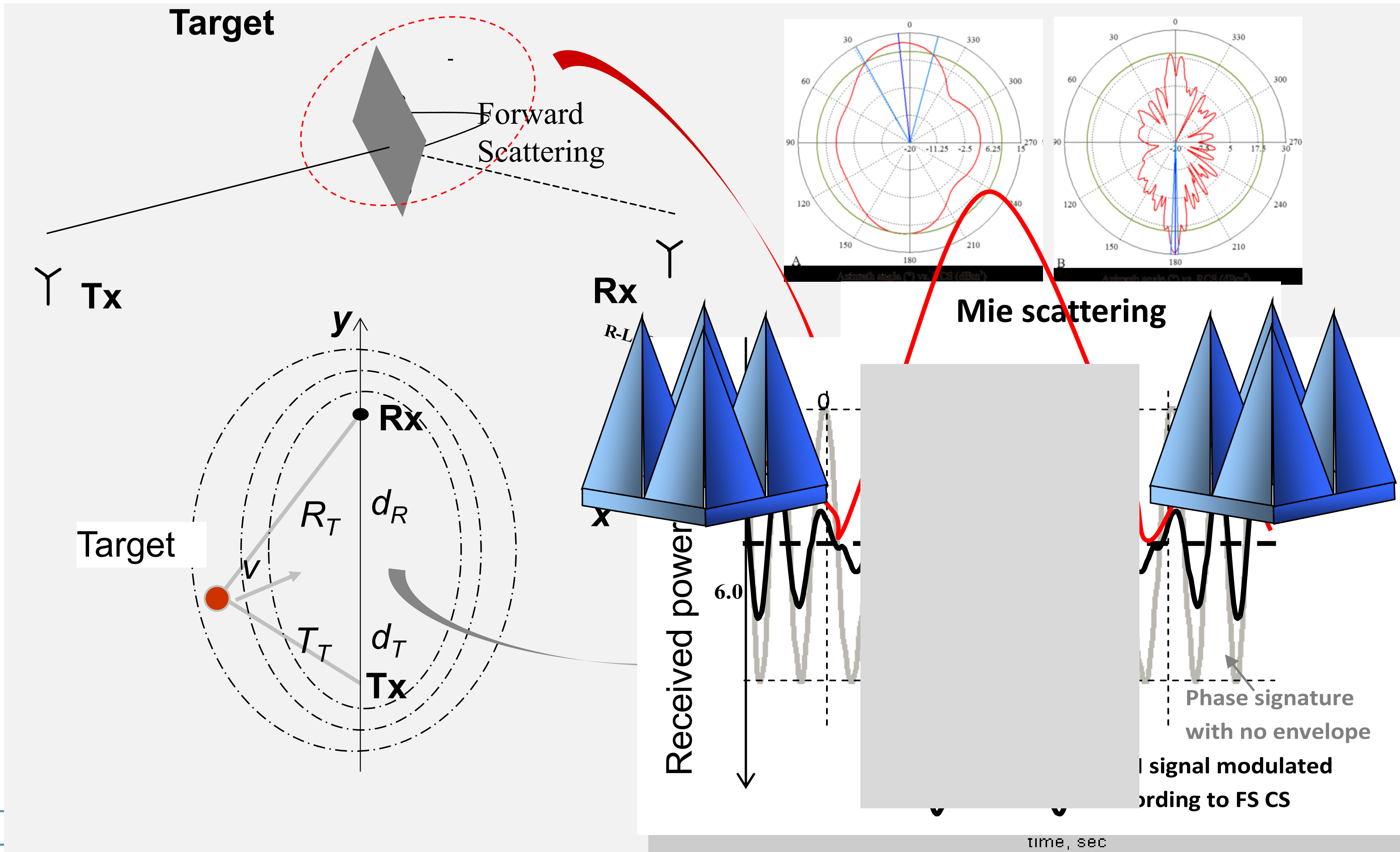


$$S_{RO}^{FS} \overset{SLD}{\approx} \left(A_{DP}\cos(\omega_0 t) + A_{Tg}\sin\left(\omega_0\left(t - t_{shift}\right)\right)\right)^2 \overset{HPF\&LPF}{=}$$

$$\rightleftarrows \qquad)\sin\left(-\frac{2\pi}{\lambda}\left(R_R(t) + R_T(t) - L\right)\right)$$

FSCS&Prop.loss   Freq `   target velocity and topology

Doppler ‘chirp’ and ‘modulation’



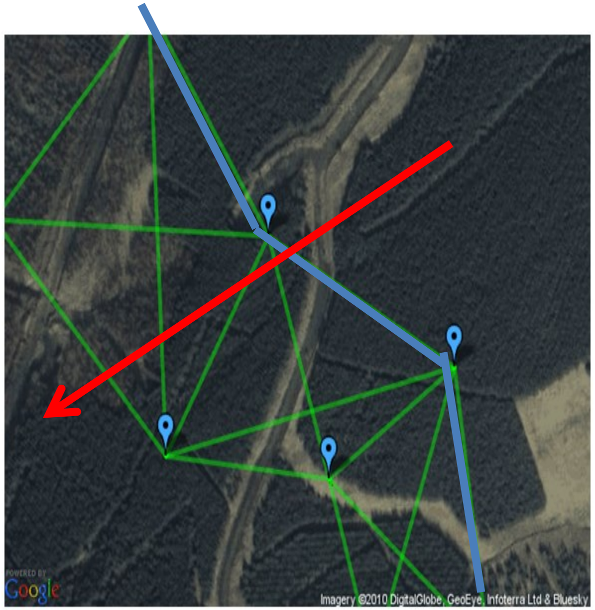
Motivation

Traditionally Research on Forward Scatter Radar has been focused on its ability to serve as an **electronic fence due to spatially separated transmitter and receiver with permanently "attentive" direct path link between them.**

Recently a wave of interest has emerged in FSR;

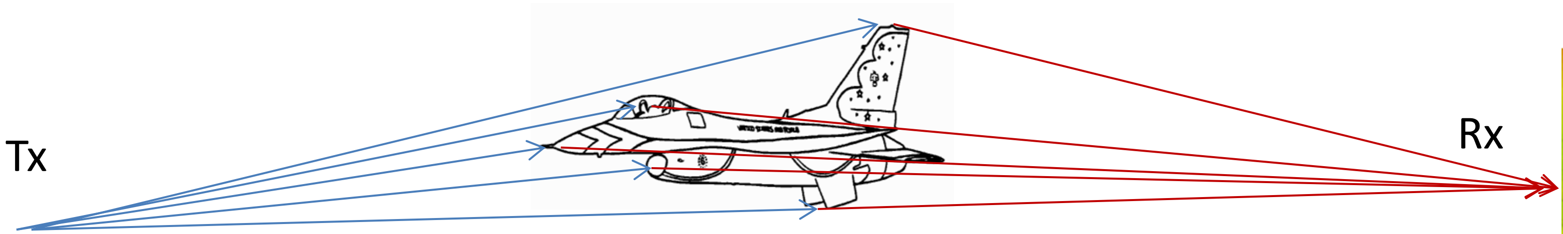
Firstly, this is a consequence of the introduction of **'stealth' targets**. These targets have a significantly reduced radar cross-section (RCS) because of their specific shapes and/or coatings which may greatly suppress backscattering, yet their shadows will still render them perfectly 'visible' to FSR. S

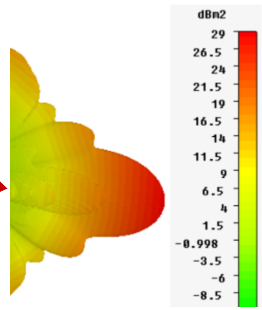
secondly, interest in FSR has appeared because of the establishment of passive coherent location concepts where illuminators of opportunity are used to form a multi-static radar network.



Multi-tier network structure composed by single FSR nodes

FSR EM peculiarities ?





1. FS region – the **mainlobe** of FS pattern, or main lobe of the Forward Scatter Cross Section is formed in the area where all the scattered EMW are coming in phase. Diffraction on the aperture edge results in co-phasal secondary radiation which is actually – **shadow radiation**
2. Thus the received signal is a result of interference of secondary (scattered) electromagnetic (EM) waves generated by the target aperture with the direct path wave which is coherent to the scattered wave.

This highlights the FSR advantage – ability to detect stealth target through observing perturbations in the direct path signal (leakage signal)

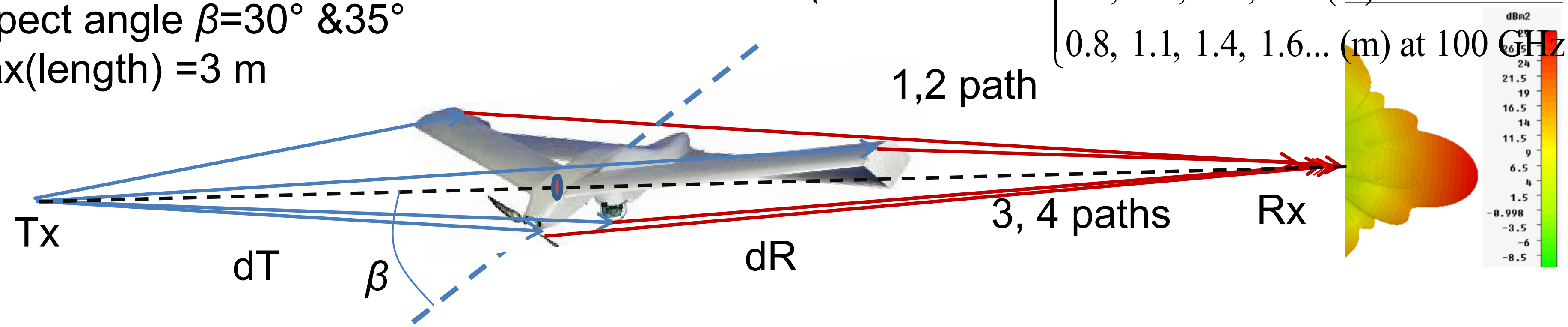
Assuming that the distribution of secondary surface sources of waves on the opaque screen is known EM field may be found by surface integration, which corresponds to the close form problem of diffraction of EM wave on a screen with known boundary conditions.

FSR coherent scattering

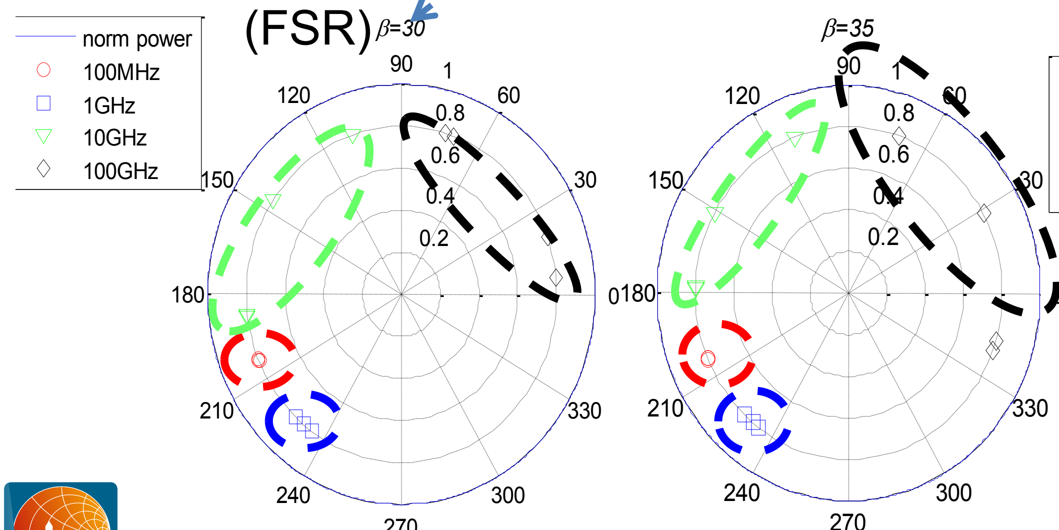
BL=1000m
dT=300m, dR=700m
Wing span – 4m
Aspect angle β=30° &35°
Max(length) =3 m

Fresnel zones

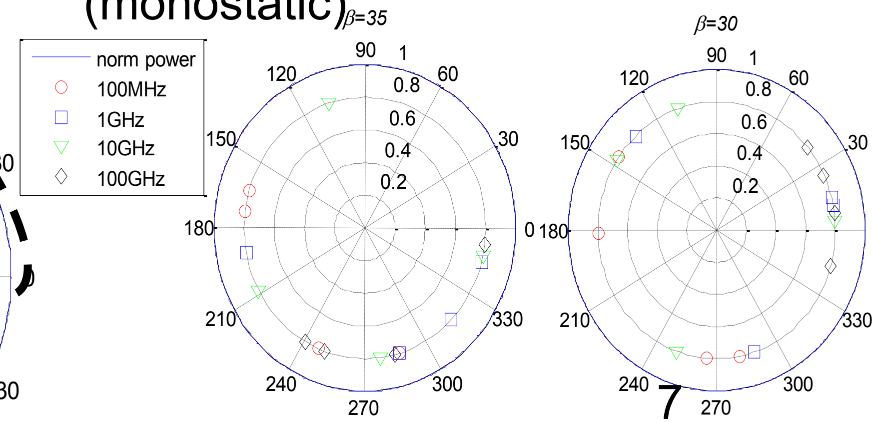
$$R_{FZ}(k)=\sqrt{\frac{k\cdot\lambda\cdot dT\cdot dR}{dT+dR}}\approx\begin{cases}25,\ 35,\ 43,\ 50...\text{ (m) at 100MHz}\\ 8,\ 11,\ 14,\ 16...\text{ (m) at 1 GHz}\\ 2.5,\ 3.5,\ 4.4,\ 5...\text{ (m) at 10 GHz}\\ 0.8,\ 1.1,\ 1.4,\ 1.6...\text{ (m) at 100 GHz}\end{cases}$$



Phases of scattered wave, deg (FSR)



Phases of reflected wave (monostatic)



Physical mechanism of scattering

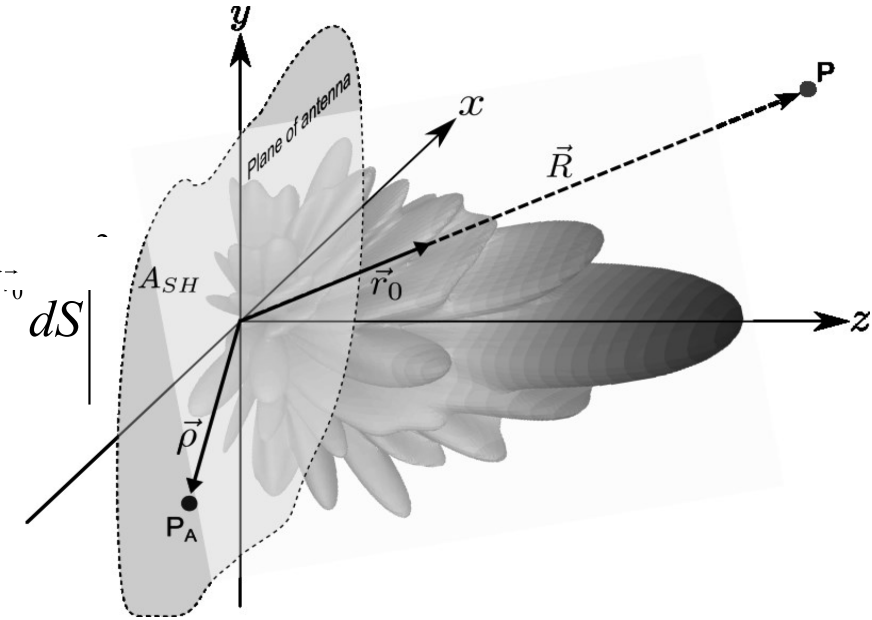
FSR could be viewed as subclass of BR where the bistatic angle is close to 180^0 .
However physical operation principle of FSR is essentially different from that of BR

	Monostatic Doppler radar	Forward Scatter Doppler Radar
Scattering mechanism	Bistatic reflections (Backscattering)	**Shadow radiation (Forward Scattering)**
Signature	result of correlation of the received waveform and locally generated heterodyne reference	**result of interference between the direct path (or leakage) signal and shadow radiation – self-mixing**
Scattering regions	Rayleigh (target dimensions << λ) Mie (target dimensions ~ λ) advantage of FSR **Optical (target dimensions >> λ) advantage of FSR**	
Radar cross section (optical region)	Targets shape, material, polarization	**Target silhouette**
Signature	Fluctuating	**Non-fluctuating**
Range resolution	Yes	**No**

Forward Scatter Cross Section

The full FSCS pattern (as opposed to just the main lobe) can be viewed and analysed as the radiation pattern of the secondary planar antenna.

$$\sigma_{fs}(\vec{r}_0) = \lim_{R\to\infty} 4\pi R^2 \left(|E_{sh}|^2 / |E_{inc}|^2\right) = \frac{4\pi}{\lambda^2}\left|\int_{A_{SH}} e^{j\left(\frac{2\pi}{\lambda}\right)\vec{\rho}\cdot\vec{r}_0} dS\right|$$



This mathematically describes directional pattern of a shadow aperture of the target, which can be seen as 'black body' radiation, i.e. radiation of an object which absorbs the incident EM wave.

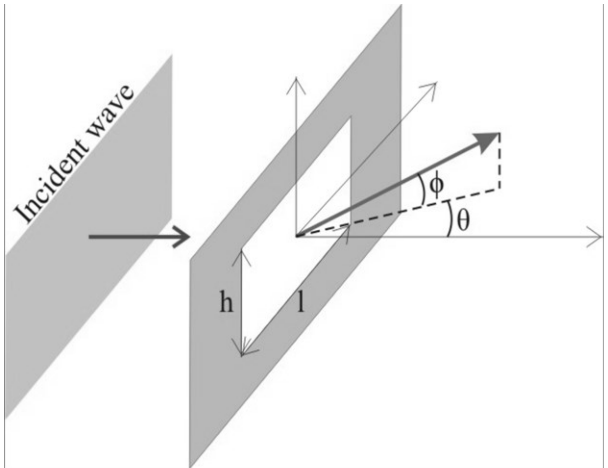
The fundamental analogy to this is ideal 'stealth' target and therefore the only way to detect such a target is to use FSR: **any detectable scattering on the target shall be attributed to shadowing components even if target is well outside the baseline**.

P_A Point on an aperture with position vector ρ

P – observation point

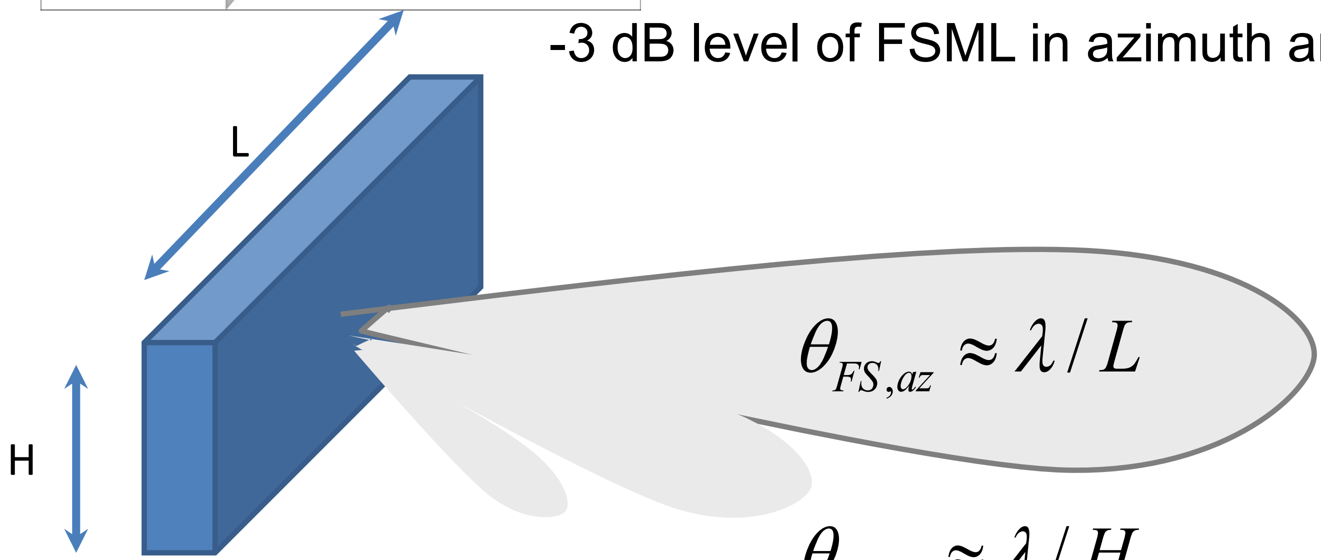
A_{SH} – shadow aperture

RCS of the rectangular plate or rectangular aperture



$$\sigma_{fs}(\theta,\phi)=4\pi\frac{\boldsymbol{A}_{eff}{}^{2}}{\lambda^{2}}\left(\frac{\sin(\frac{\pi \boldsymbol{l}_{eff}}{\lambda}\sin\theta)}{\frac{\pi \boldsymbol{l}_{eff}}{\lambda}\sin\theta}\right)^{2}\left(\frac{\sin(\frac{\pi \boldsymbol{h}_{eff}}{\lambda}\sin\phi)}{\frac{\pi \boldsymbol{h}_{eff}}{\lambda}\sin\phi}\right)^{2}$$

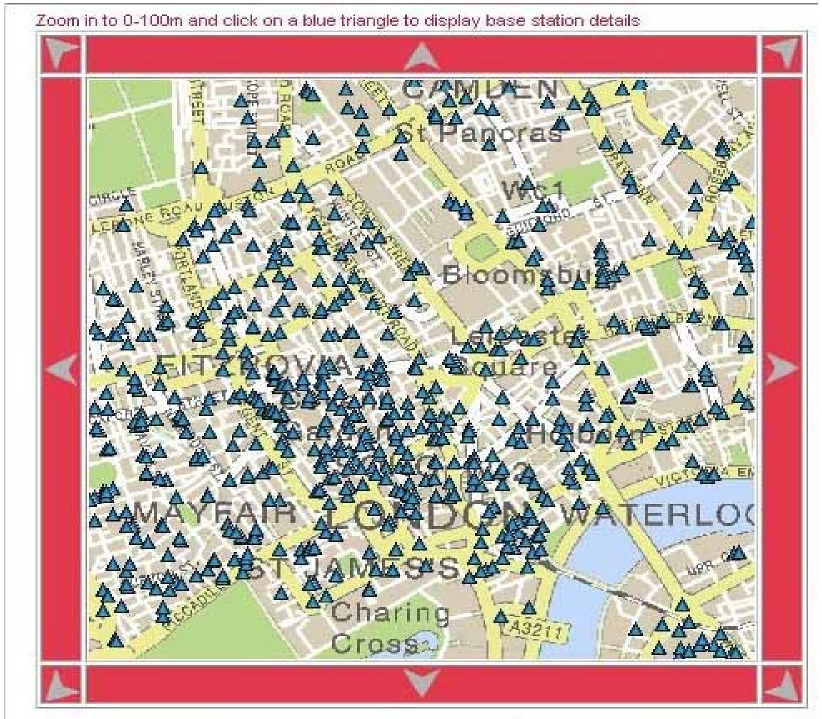
-3 dB level of FSML in azimuth and elevation planes



$$\theta_{FS,az}\approx\lambda/L$$

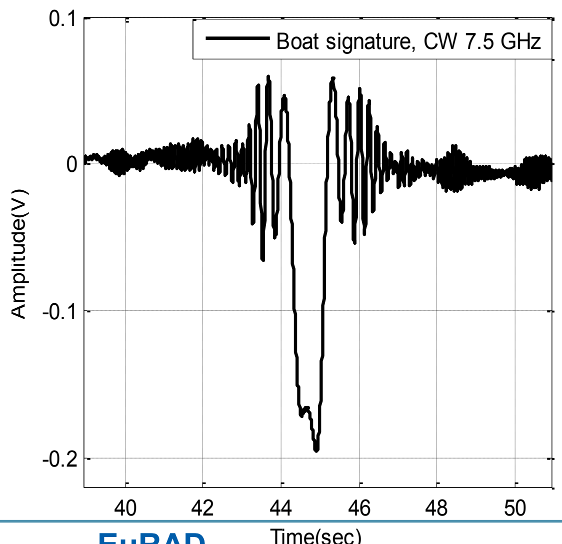
$$\theta_{FS,el}\approx\lambda/H$$

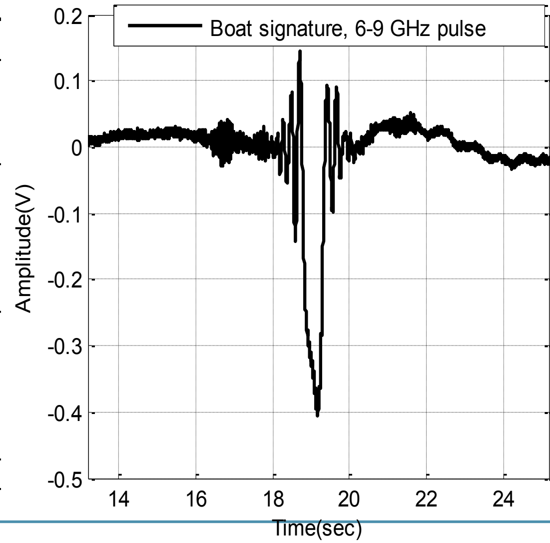
Why Passive FSR is attractive?



- The major disadvantage of FSR is a narrow area of observation.
- Having a big number of transmitters surrounding the receiver a vast territory could be covered by one receiving station
- self-mixing procedure removes any modulation of the transmitting signal, making signal processing in PCL **independent of the specific modulation of the transmitter.**

Example: FS signature of a boat obtained by non-modulated signals CW signal and modulated UWB - 3 GHz bandwidth signal.





Passive FSR

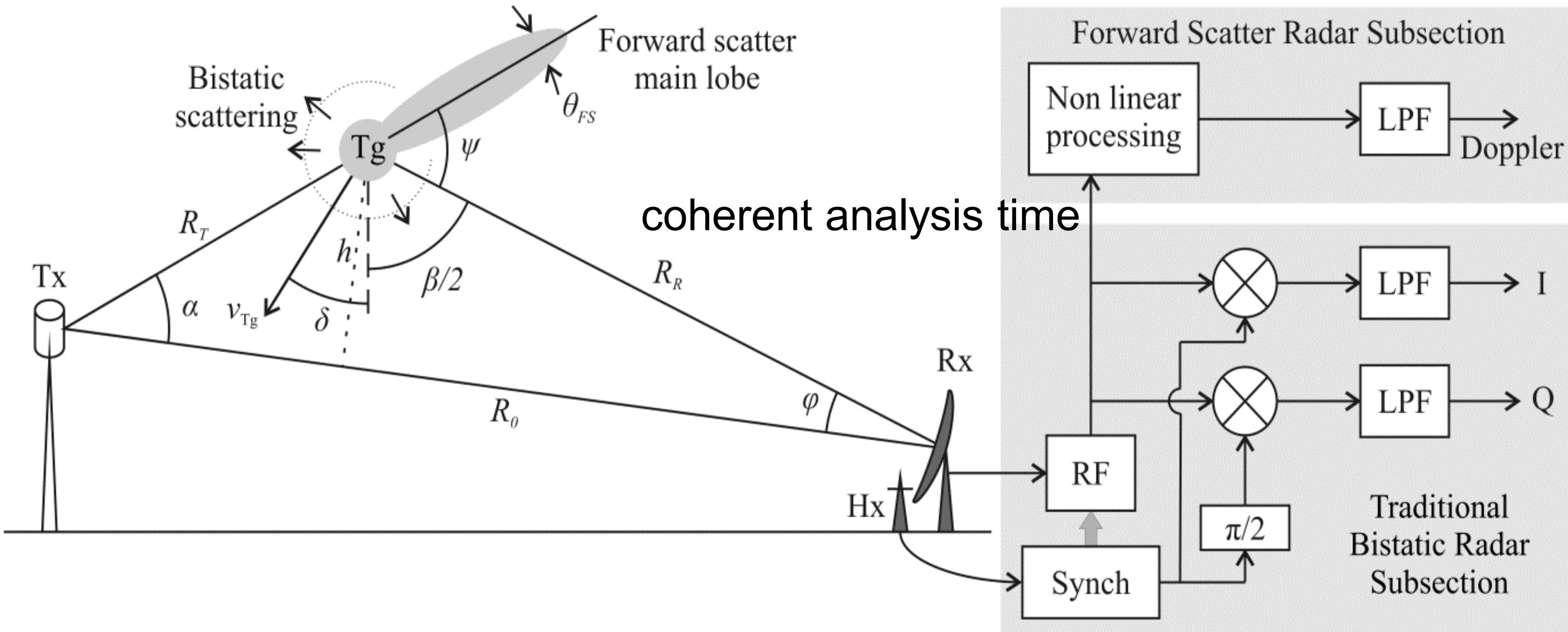
The transfer of the forward scatter (FS) concept to passive coherent location (FS PCL) systems provides a new emerging area of research.

FSR when integrated into PCL systems will have the same capabilities as in the case of dedicated FSR, will add extra benefits to the existing bistatic mode of operation of PCL and can practically be implemented on both hardware and software levels without requiring significant restructuring.

Emitter	Frequency, GHz	Wavelength, m	Functionality as PCL
FM Radio	0.1	3	Medium to long range air target detection and tracking.
Digital Audio Broadcasting (DAB) .	0.2	1.5	
Digital Video Broadcasting – Terrestrial (DVB-T)	0.4 0.6	0.75 0.50	
LEO satellite communication	1.5	0.2	
Mobile Cellular Radio (MCR)	0.9 1.8	0.33 0.16	Short to medium range air targets and local vicinity surface target observations.
Local Area wireless Network (LAN)	2.4	0.13	Indoor and close range security applications intended for human and vehicle detection.

Passive bistatic radar -traditional hardware signal processing

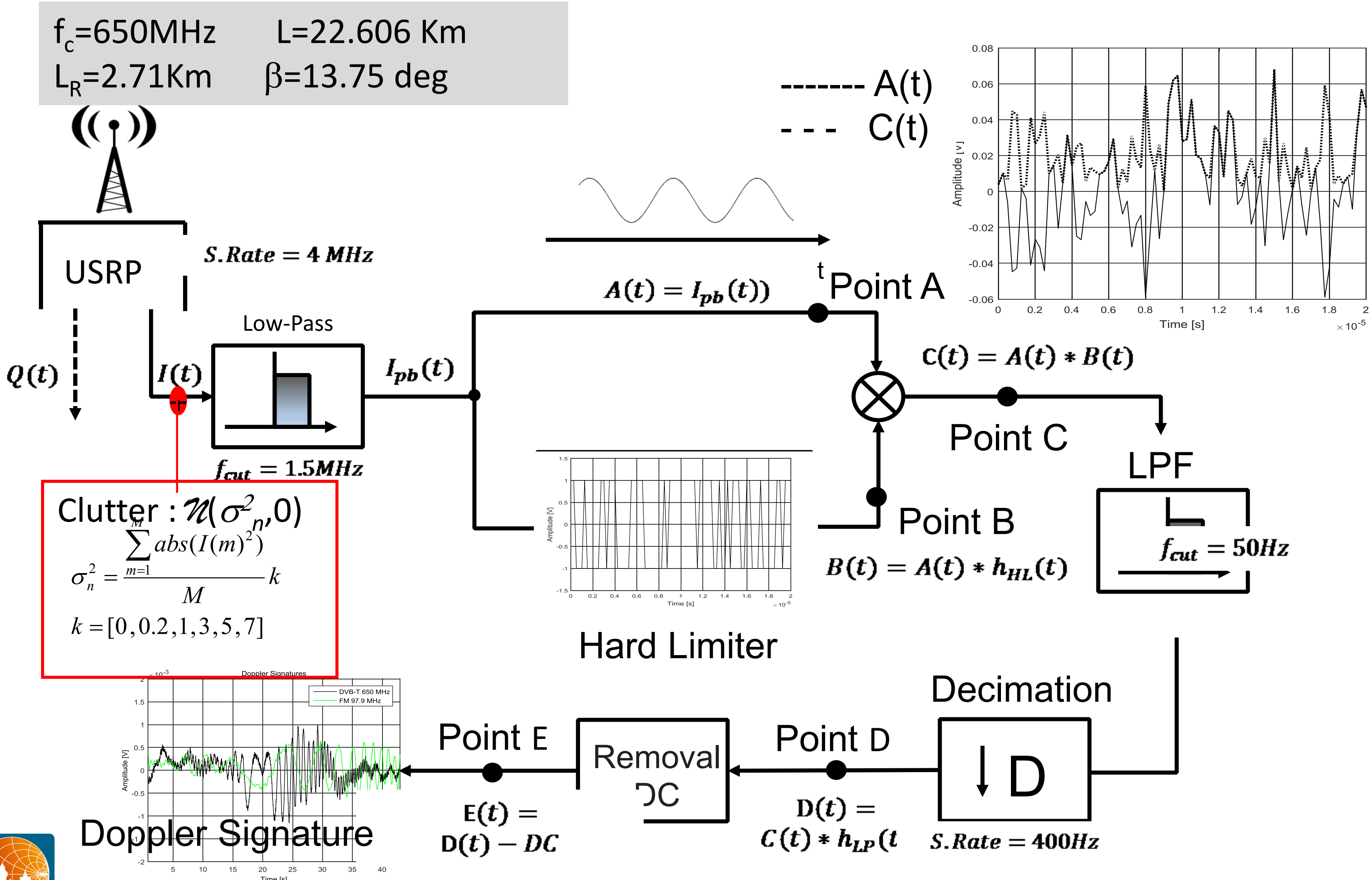
As the bistatic angle increases, the forward scatter main lobe becomes more aligned with the baseline, indicating the transition to the FS regime and, therefore, to the utilisation of the additional FSR subsection non linear processing block*.



Traditional bistatic processing scheme uses the heterodyne channel, Hx, intended for synchronisation (Synch) of the transmitted and received signals at the receiver

* M. Gashinova, L. Daniel, E. Hoare, V. Sizov, K. Kabakchiev, and M. Cherniakov, “Signal characterisation and processing in the forward scatter mode of bistatic passive coherent location systems”, EURASIP Journal on Advances in Signal Processing, vol 2013, no. 1, pp. 1-13, 2013.

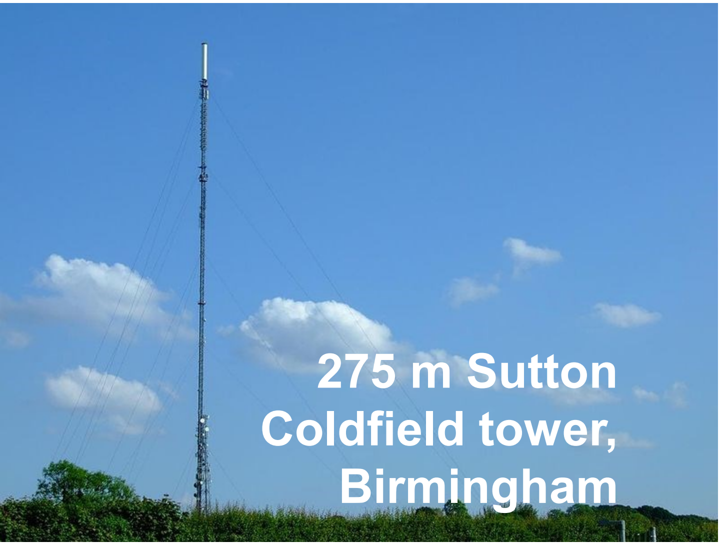
The block diagram of the processing chain used to extract the Doppler signature. (DVB-T example)



Aircrafts detection: Multi-mode transmitter – FM, DVB-T, DAB in Sutton Coldfield, UK

In many cases each tower transmit various independent signals which may be used for the detection reinforcement, targets parameters estimations, etc. In FSR with self mixing receiver the modulation does not affect the targets signature.

So that detection of aircrafts can be made “multi-frequency/digital/analogue” using a range of signals of opportunity



FM - 0.15MHz bandwidth

FreqMHz	P_t, kW
100.1	125
100.7	11
105.2	11
105.7	11
88.3	250
90.5	250
92.7	250
95.6	11
96.4	10
97.9	250

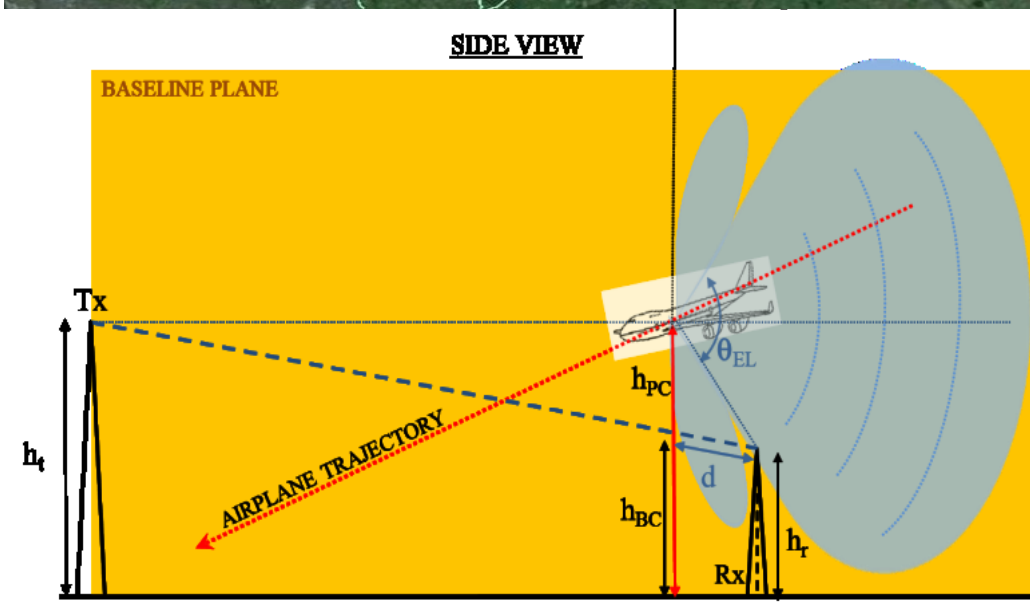
DVB-T - 8 MHz

Freq, MHz	**UHF**	P_t, **kW**
618.166 MHz	39+	200
626.166 MHz	40+	200
642.000 MHz	42	200
650.000 MHz	43	200
666.000 MHz	45	200
674.000 MHz	46	200

DAB (12B) – 1.536 MHz

Freq MHz	P_t, **kW**
222.064 MHz	8.7
223.936 MHz	3
225.648 MHz	10

Aircrafts detection. I. Commercial airliners



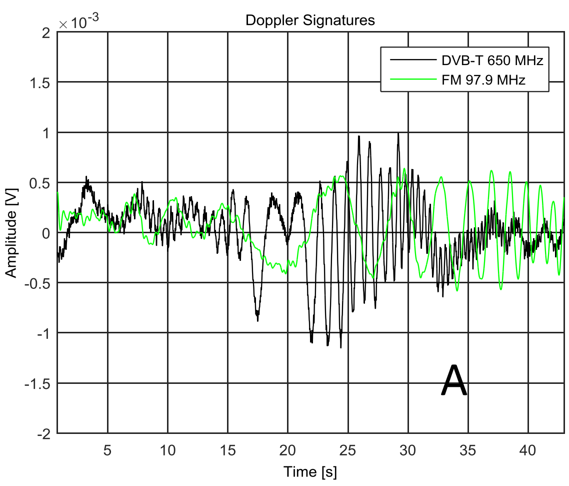
UoB experimental receiver

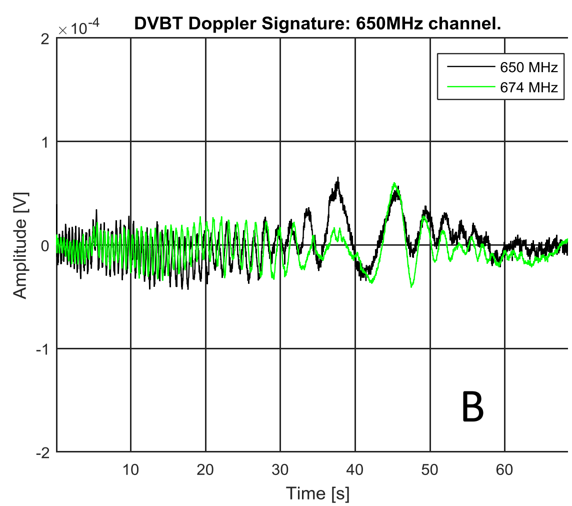
Table 4 – Parameters of the UoB experimental receiver

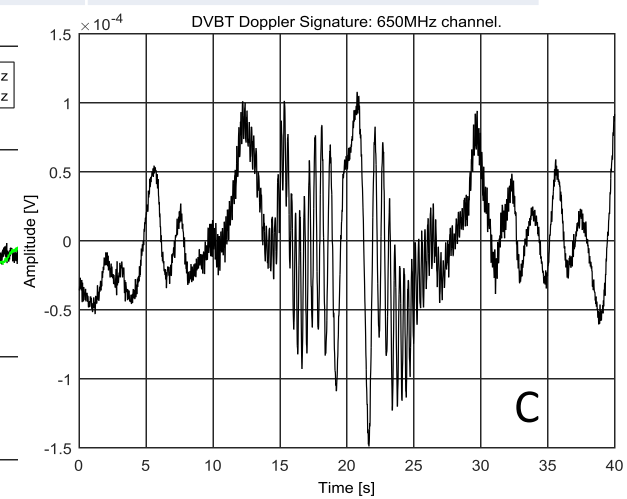
Tunable frequency range	50 MHz-2.2 GHz.
Antennas	DVB-T – Yagi, gain 8 dBi DAB – three element commercial antenna Gain – 6.2 dBi FM – Yagi FM antenna Gain – 5dBi
Number of channels	2
USRP channel bandwidth	10 MHz
Azimuth coverage	DVB-T – 20˚, DAB – 60° FM – 110˚
Elevation coverage	DVB-T – 20˚ DAB – 60° FM –70˚

Example targets

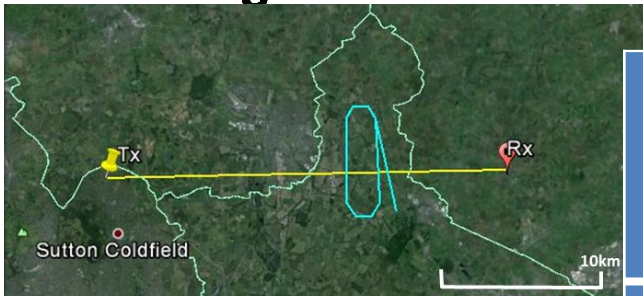
Aircraft	Dimensions Length x Height x Wingspan, m	Attitude at the Baseline crossing, m	Speed, km/h Ground truth/Processing
A. Airbus A320	33.8 x 11.7 x 34.1	180	Takeoff -240-285/ 250
B. Bombardier Dash8 Q-400	32.8 x 8.3 x 28.4	236	Landing - 263
C. Cessna 172	7.3 x 2.3 x 11	483, (788, 947)	Flight - 167/174
D. Delphin	6.5 x 2.2 x 9.4		



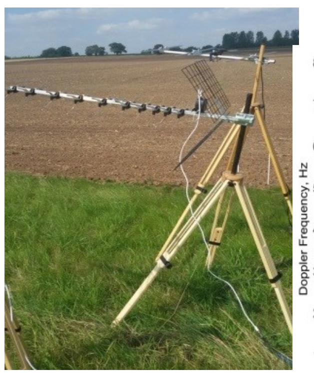


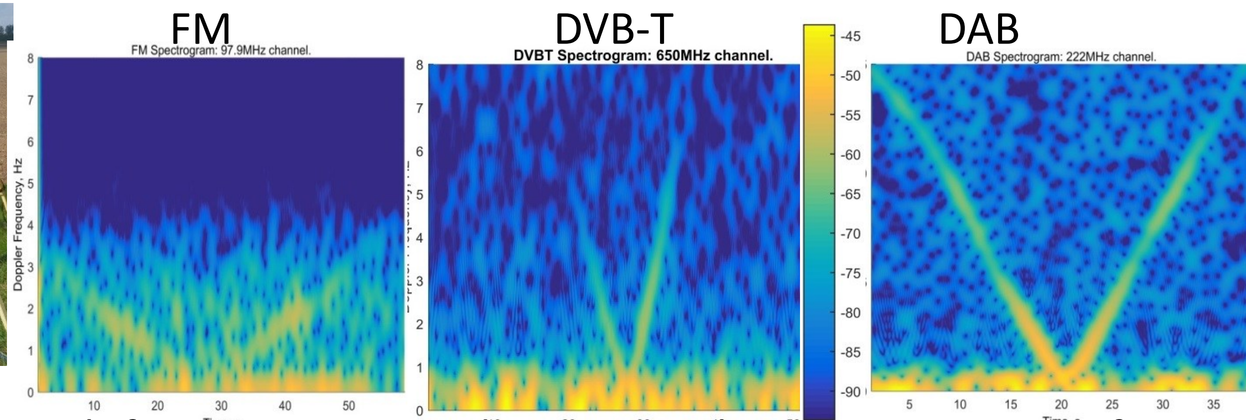


Ultralight aircraft – detection at different altitudes



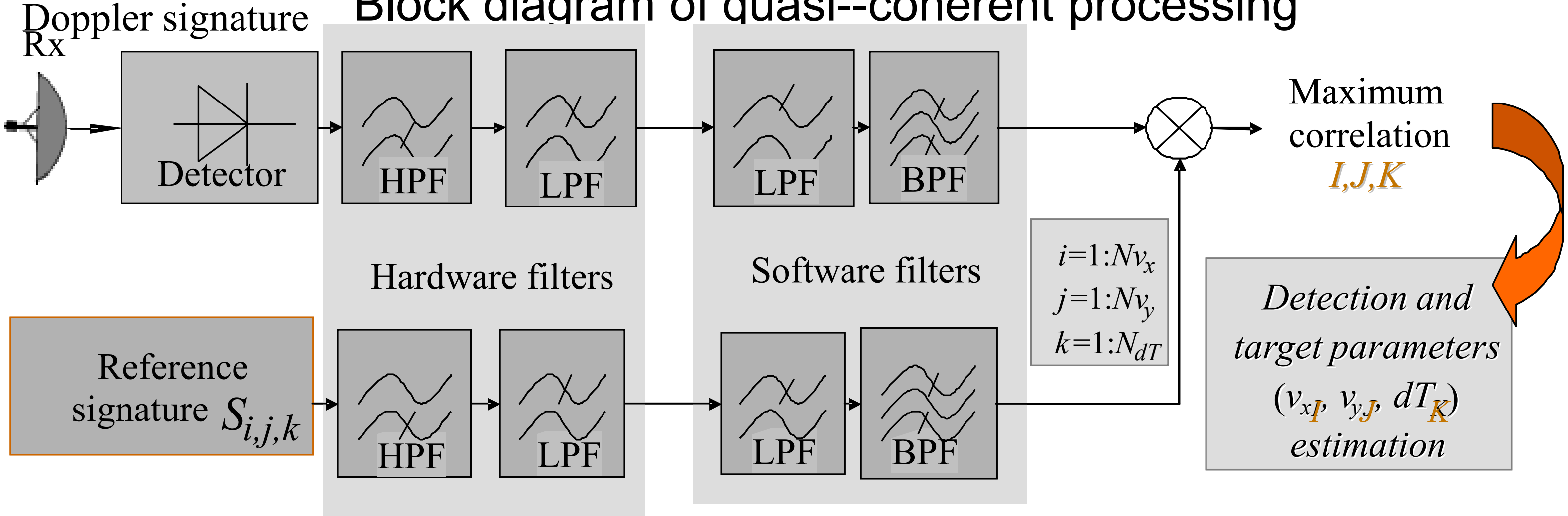
Data Cessna 172	Crossing distance from Rx[km]	Crossing Angle [deg]	Crossing Height a.s.l. and above baseline)[m]	Recorded Signals
1	9.1	86	483 (354)	DVB-T + DAB
2	9.0	87	788 (659)	DVB-T + FM
3	7.9	85	947 (833)	DVB-T + FM



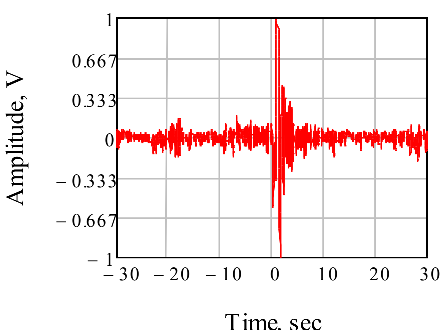


M. Contu *et al.*, "Passive Multifrequency Forward-Scatter Radar Measurements of Airborne Targets Using Broadcasting Signals," in *IEEE Transactions on Aerospace and Electronic Systems*, vol. 53, no. 3, pp. 1067-1087, June 2017

Kinematic parameters estimation
Block diagram of quasi--coherent processing

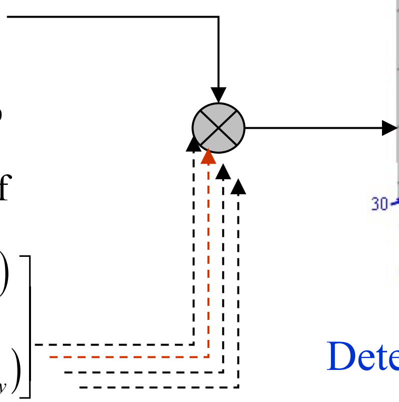


The total number of reference functions is *I·J·K*

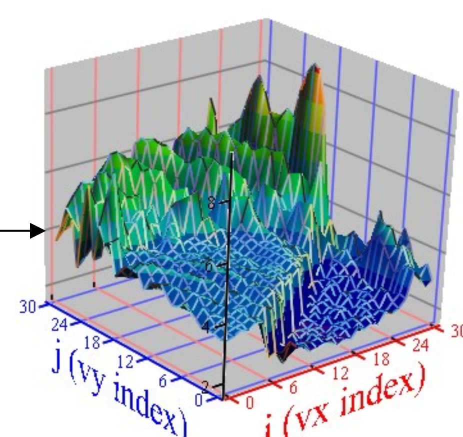


Two-dimensional array of signatures by v_x and v_y

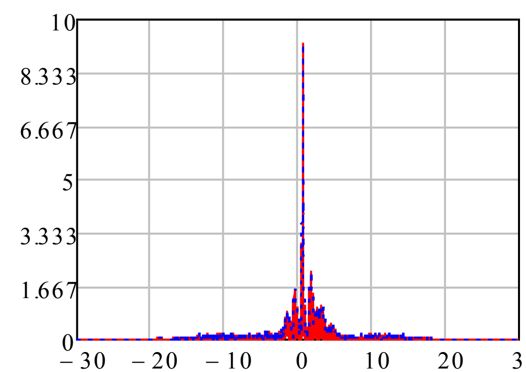
$$\begin{bmatrix} S(v_{x,1}, v_{y,1}) & .. & S(v_{x,1}, v_{y,Nvy}) \\ : & : & : \\ S(v_{x,Nx}, v_{y,1}) & .. & S(v_{x,Nvx}, v_{y,Nvy}) \end{bmatrix}$$



Surface of max correlations



Compressed signal

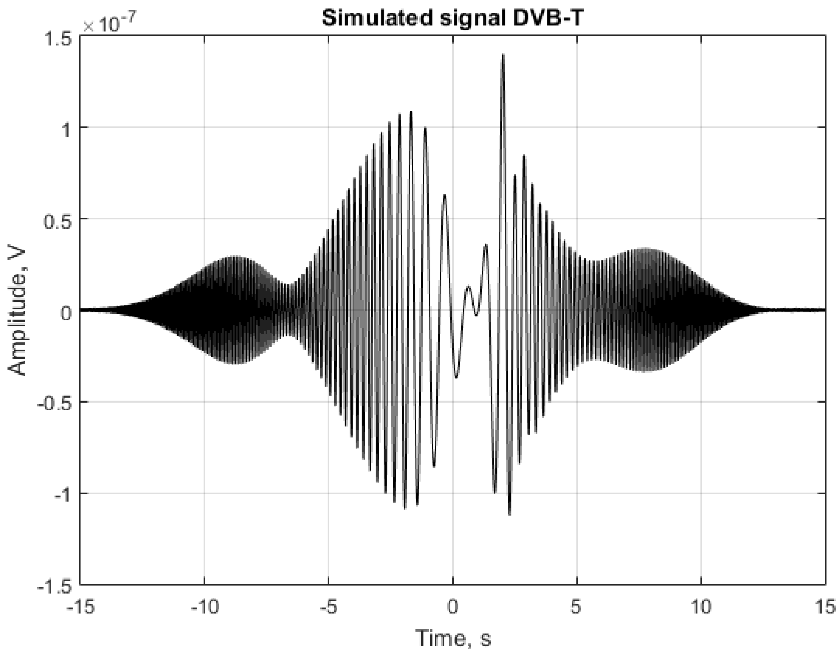


Detection criterion – signal compression

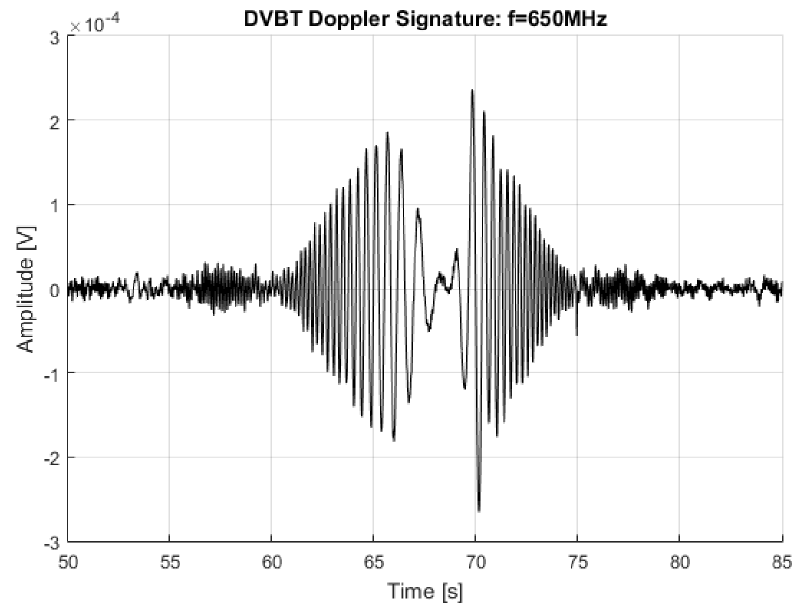
Hu Cheng, V. Sizov, M. Antoniou, M. Gashinova, M. Cherniakov, “Optimal signal processing in ground-based forward scatter micro radars”, IEEE Trans. Aerospace Electr. Syst., 2012, vol. 48, (4), pp. 3006–3026.

Data	Signals	Frequency MHz	Estimated speed km/h	Ground truth km/h
Airbus 320	DVB-T	650	248.4	263 by Flightradar24
	DVB-T	674	216.0	
Sessna, 800 m flight altitude	DAB	222	176.4	167 by GPS
		225	176	
	DVB-T	650	188.1	

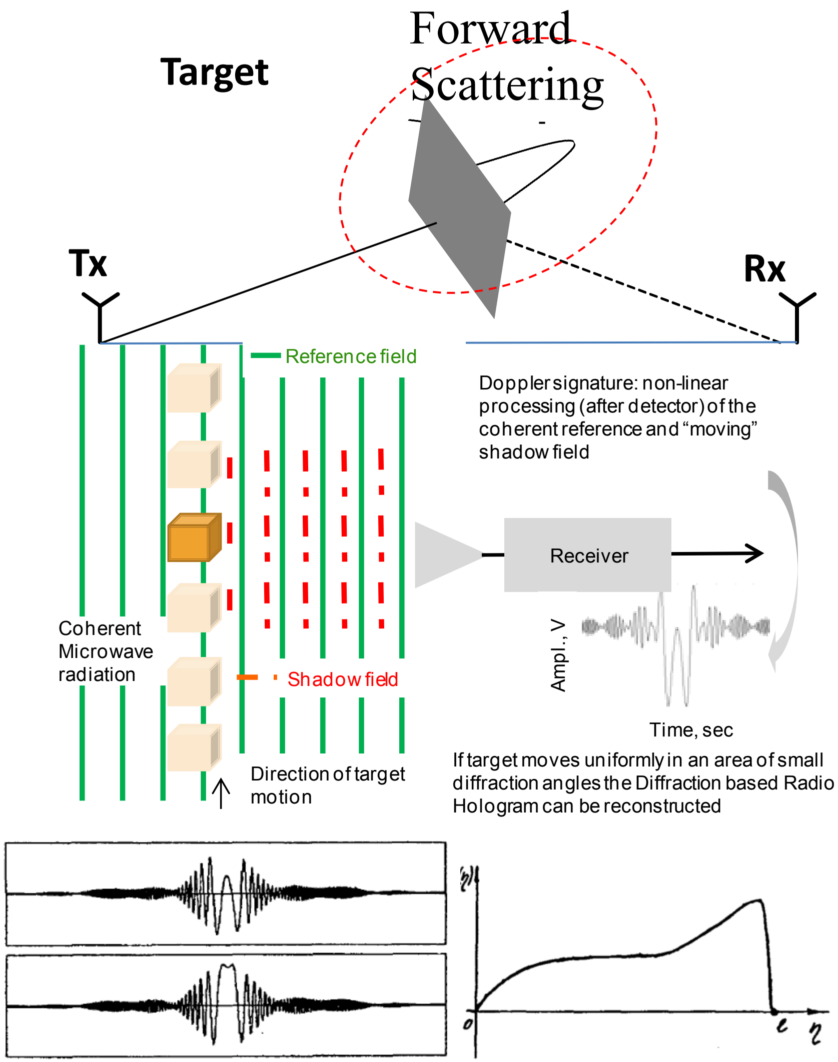
Simulated



- After 1 Hz HPF



Target shadow profile reconstruction
Physical principle of Forward scatter radar (FSR) imaging



In FSR the received signal is a result of interference of the scattered wave (secondary electromagnetic waves generated by the target aperture – Shadow Radiation), with the direct path wave which is strictly coherent to the scattered wave.

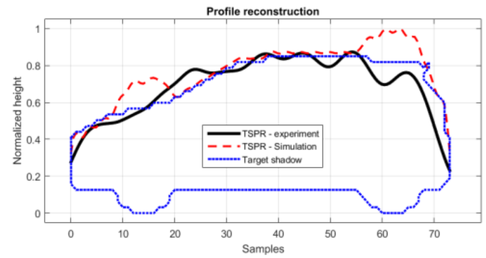
Thus both amplitude and phase of the scattered field can be extracted providing information on the target and, therefore, this method refers as the RF hologram (RFH) similar to optical image reconstruction used in holography

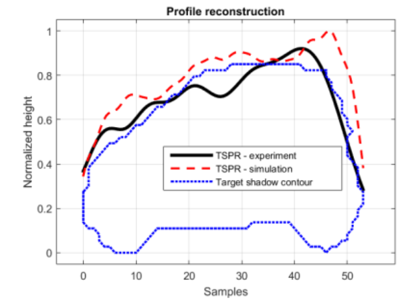
RFH synthesis is possible if target and transceivers have relative motion, so the Shadow synthetic inverse aperture algorithm (SISAR) is used to reconstruct shadow profile of the target Prerequisites are exact knowledge of target motion parameters and radar topology and availability of both quadrature channels

*Chapurskiy, V.V.; Sablin, V.N., "SISAR: **shadow inverse synthetic aperture radiolocation**," *Radar Conference, 2000. The Record of the IEEE 2000 International* , vol., no., pp.322,328, 2000

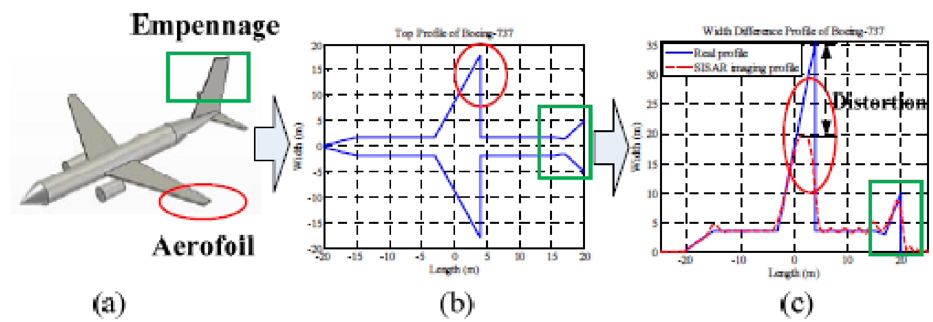
Target profile reconstruction in Forward Scatter Radar

S. Hristov, L. Daniel, E. Hoare, M. Cherniakov, M. Gashinova, “Target Shadow Profile Reconstruction in ground-based forward scatter radar”, in Radar Conference (RadarCon), 2015 IEEE, pp.0846-0851, 10-15 May 2015.





Cheng Hu; C. Liu; R. Wang; L. Chen; L. Wang,
"Detection and SISAR Imaging of Aircrafts Using GNSS Forward Scatter Radar: Signal Modeling and Experimental Validation,"
in *IEEE Transactions on Aerospace and Electronic Systems* , vol.PP, no.99, pp.1-1



Conclusions

- Using broadcasting transmitters as illuminators for passive radars meanings, which have not been designed for radar use, mean that the ambiguity function is not under the system designers control.
- However this is not an issue in the forward-scatter case because of the ‘explosion’ of the ambiguity function in the forward-scatter case to cover all the range-velocity space. This distinctive feature defines FSR’s strengths and limitations at the same time.
- The physical principle and topology of FSR implies that the target can only be detected when it is moving within the proximity of the baseline. Although the radar has no ‘classical’ resolution in this configuration, the physical principle on which these systems rely allows the detection performance to be completely independent on both the target material and shape. This makes this type of radar a good counter-stealth system, which naturally makes it capable to serve as an electronic fence . As well as giving a return which is independent of the target material, the target FS Cross Section (FSCS) in the optical scattering region is usually significantly bigger than its monostatic and bistatic counterparts.
- FSR mode can add considerable extra benefits to the existing bistatic radar and can in practice be integrated in those systems without requiring significant changes to the hardware while offering simple and elegant processing procedure to extract Doppler signature and estimate target kinematic and topological parameters.
- The independence of the FSR signature from the modulation of the transmit signal has been demonstrated both analytically and experimentally. This shows the universality and wide applicability of the FSR approach for target detection in passive coherent location systems.