Passive Imaging Using SAR and ISAR Technology

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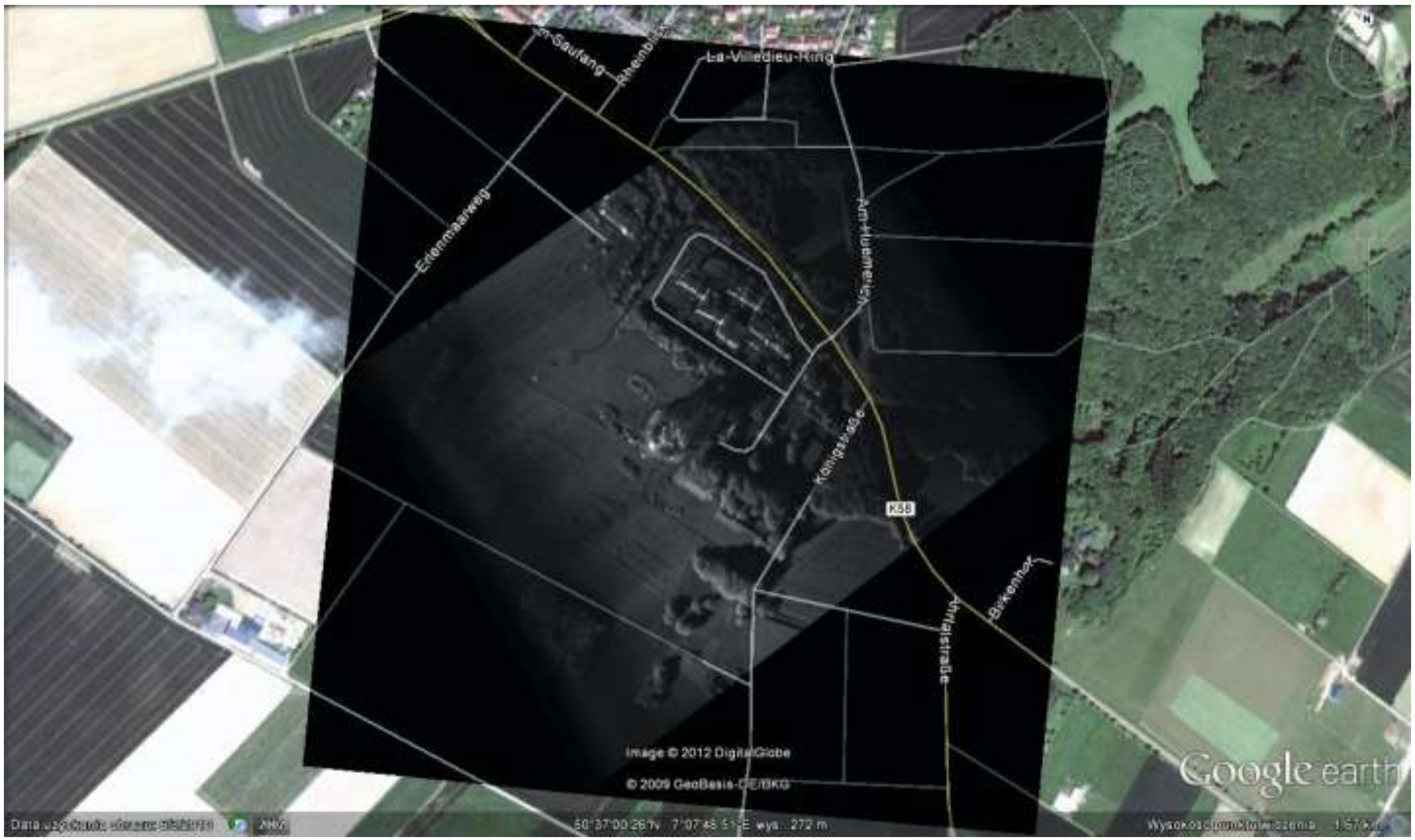
EuRAD 2017
The 14th European Radar Conference

Present and Future Perspectives of Passive Radar, 13 October 2017, Nuremberg, Germany

WUT

ise

Research Group on Radar Techniques



EuRAD 2017
The 14th European Radar Conference

WUT is the largest of 18 Polish technical universities

Public state school

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Research Group on Radar Techniques

ise

- Radar signal processing
- Signal sampling (ADCs)
- Telecommunication signal processing
- DSP platforms
- Simulation and modeling
- Target tracking
- Image processing

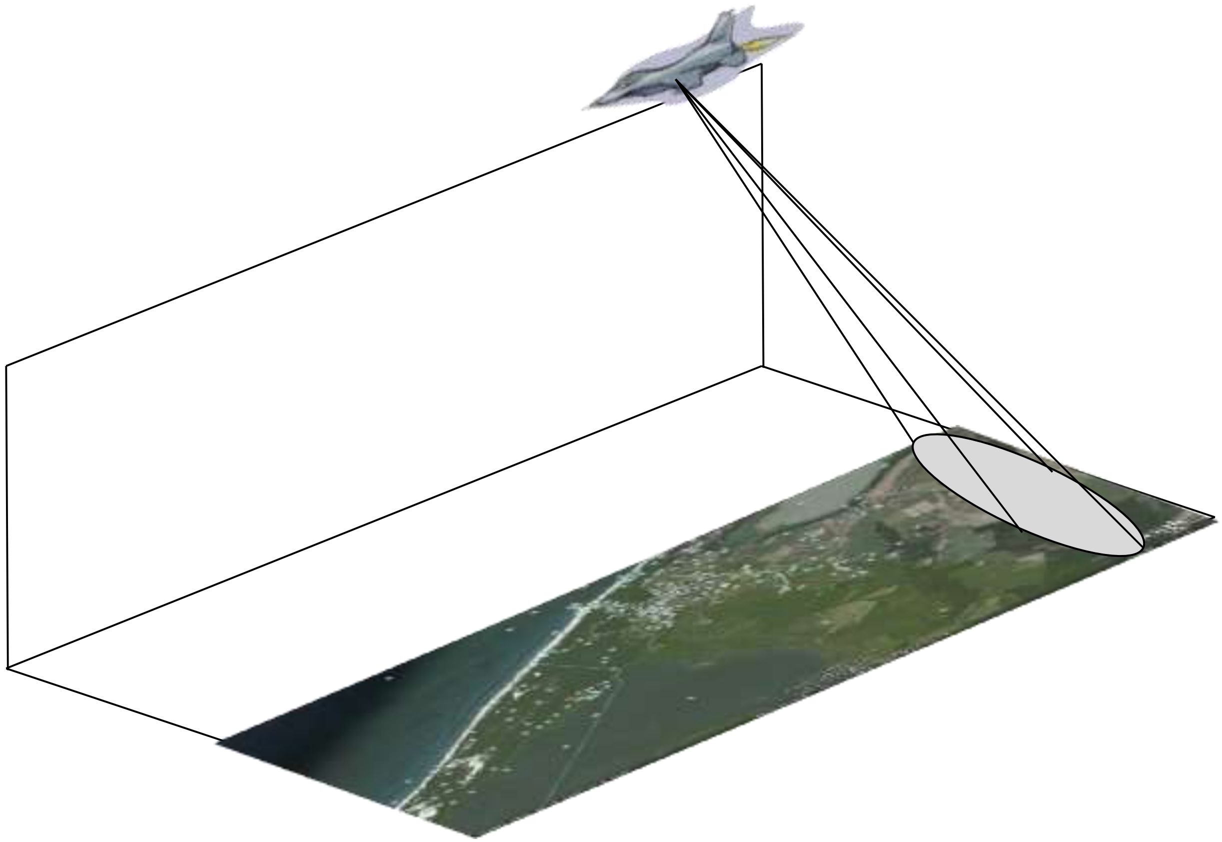
Tutorial Agenda

- Short intro to SAR/ISAR imaging (a monostatic case)
- Introduction to passive bistatic radar imaging

- Passive SAR imaging using non-cooperative satellite-based illumination
- Passive SAR imaging using commercial ground based illuminators
- Passive ISAR imaging

- Summary

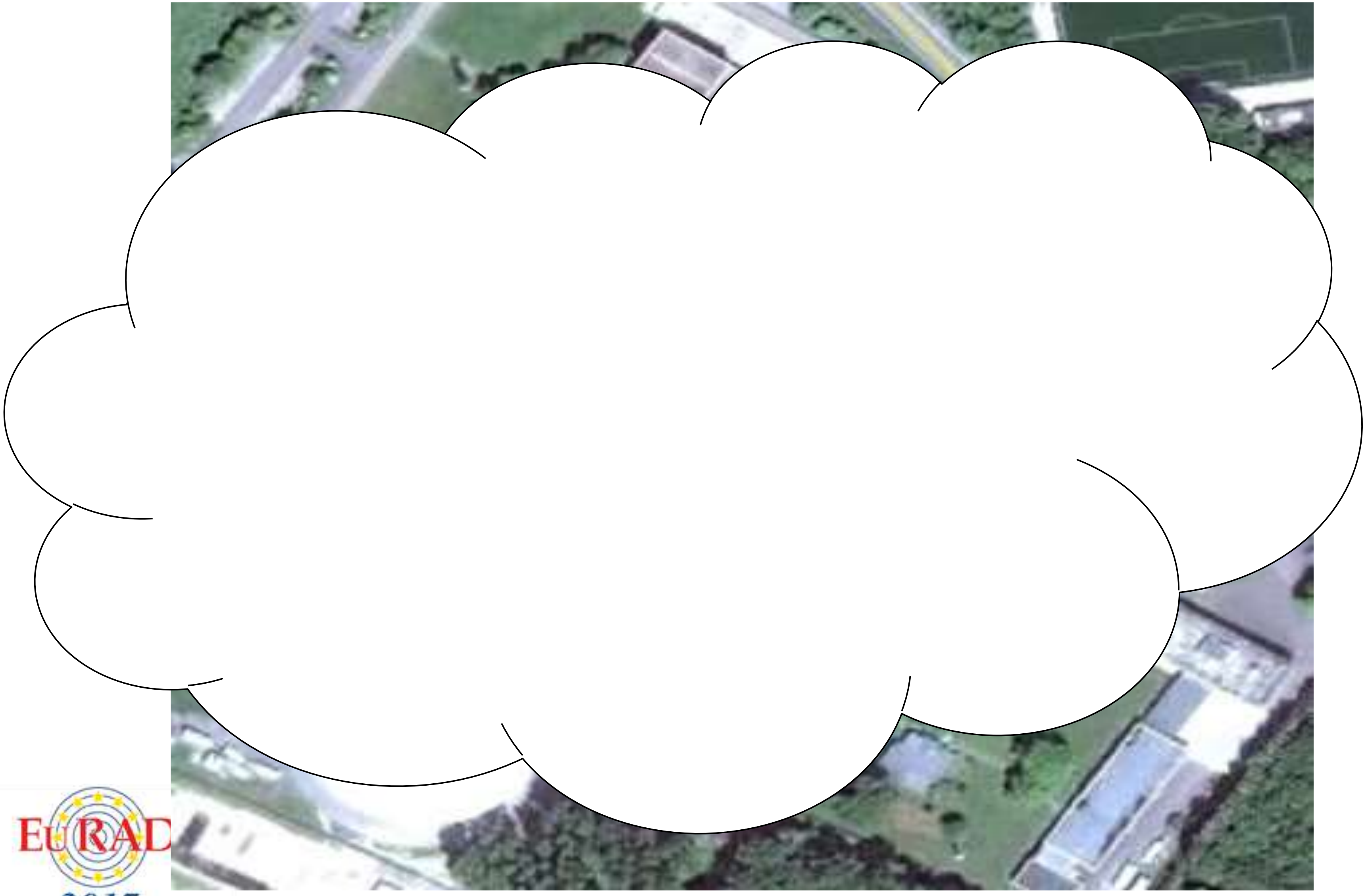
SAR – Synthetic Aperture Radar



Radar mounted on the moving platform
(UAV, aircraft, missile, satellite, etc.)

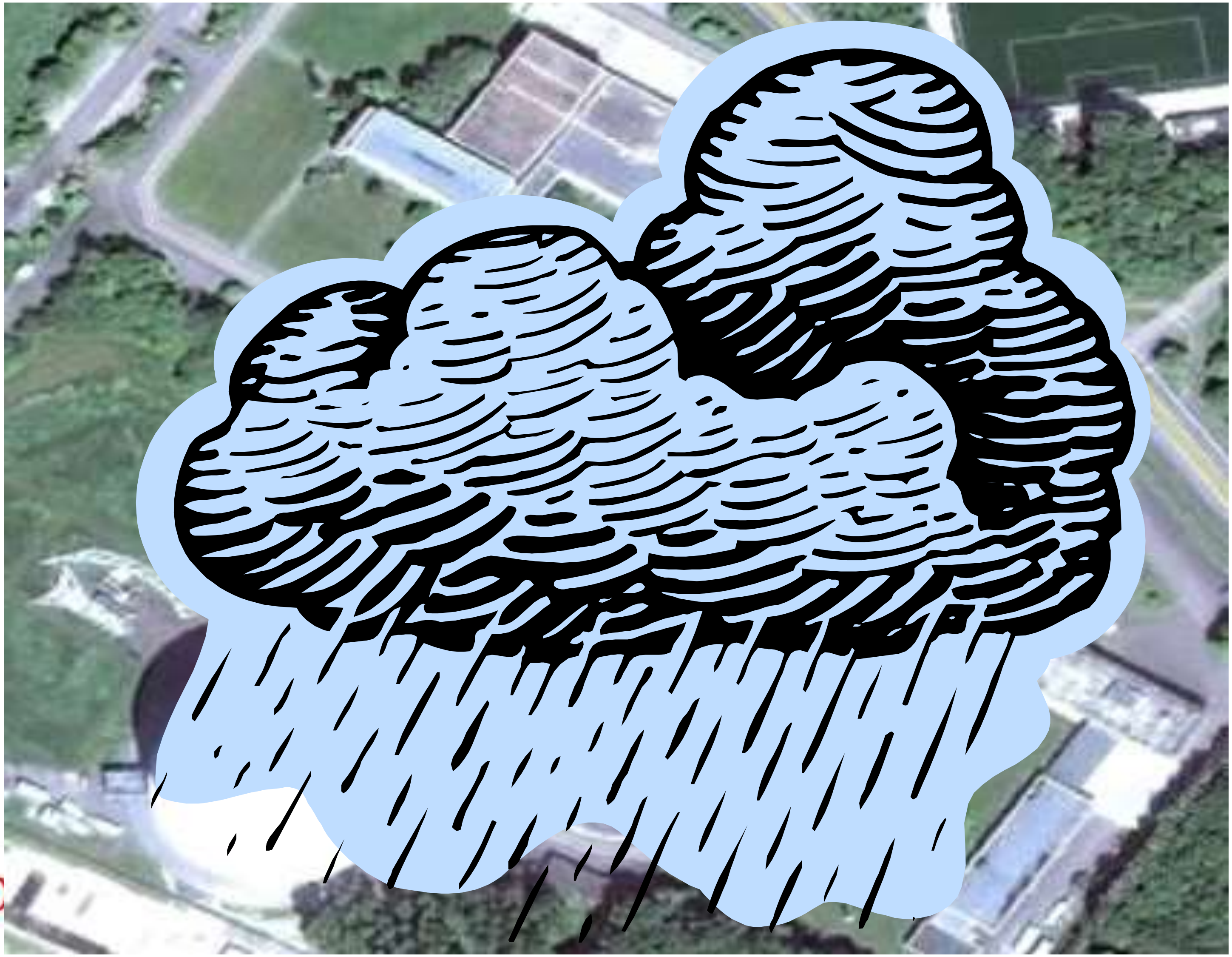
Optical Image

Optical Image



The 14th European Radar Conference

Optical Image



Optical Image

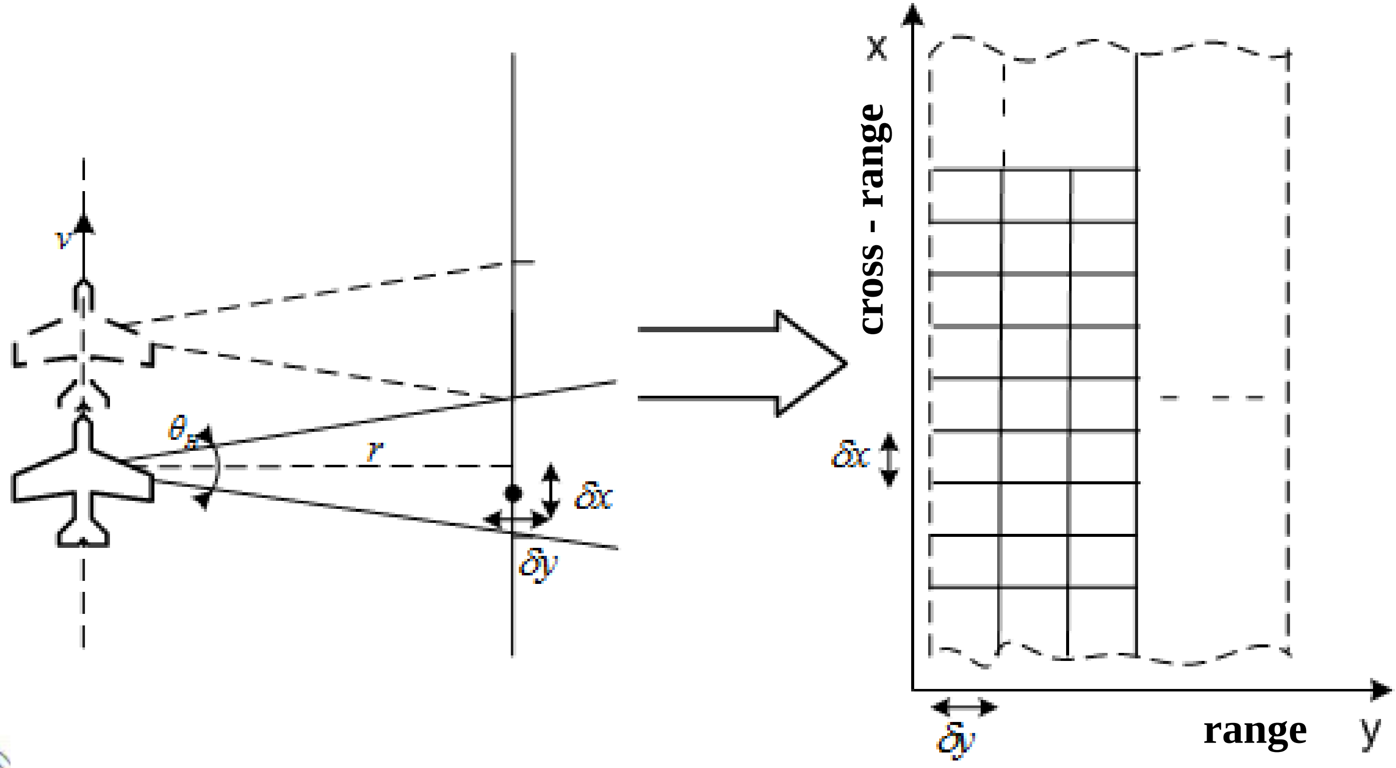
SAR Image

(*) M. Caris, S. Stanko, A. Leuther, A. Tessmann, M. Malanowski, P. Samczynski, K. Kulpa, M. Cohen, P. Kovacs, A. C. Papanastasiou, C. Topping, G. E. Georgiou, R. Guraly: "SARape – Synthetic Aperture Radar for all weather penetrating UAV Application", in Proc.of IRS 2013, vol.1, pp. 41-46, 19-21 June 2013, Dresden, Germany16.
(**) M. Caris, S. Stanko, M. Malanowski, P. Samczyński, K. Kulpa, A. Leuther, A. Tessmann, mm-Wave SAR demonstrator as a test bed for advanced solutions in microwave Imaging, Aerospace and Electronic Systems Magazine, IEEE, vol.29, no.7, July 2014, pp.8,15

Optical Image

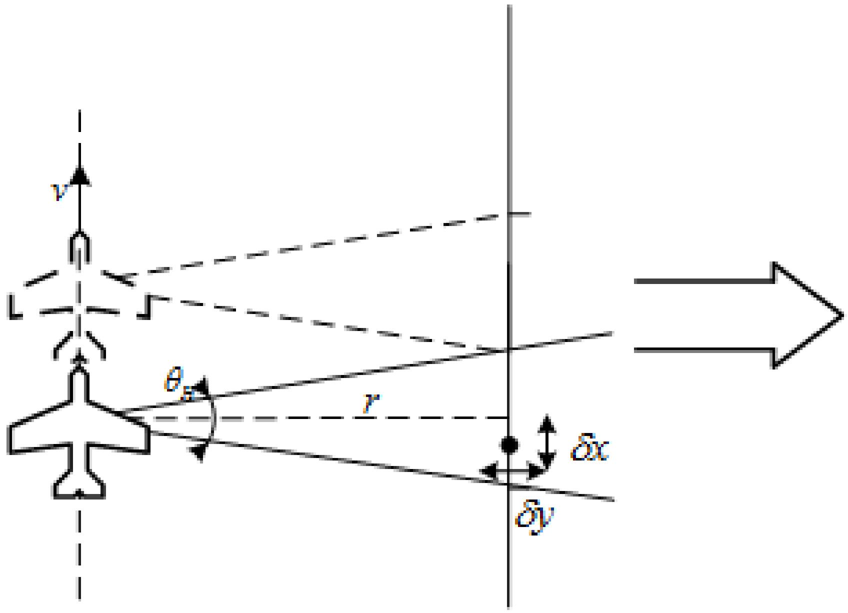
SAR - How Does It Work?

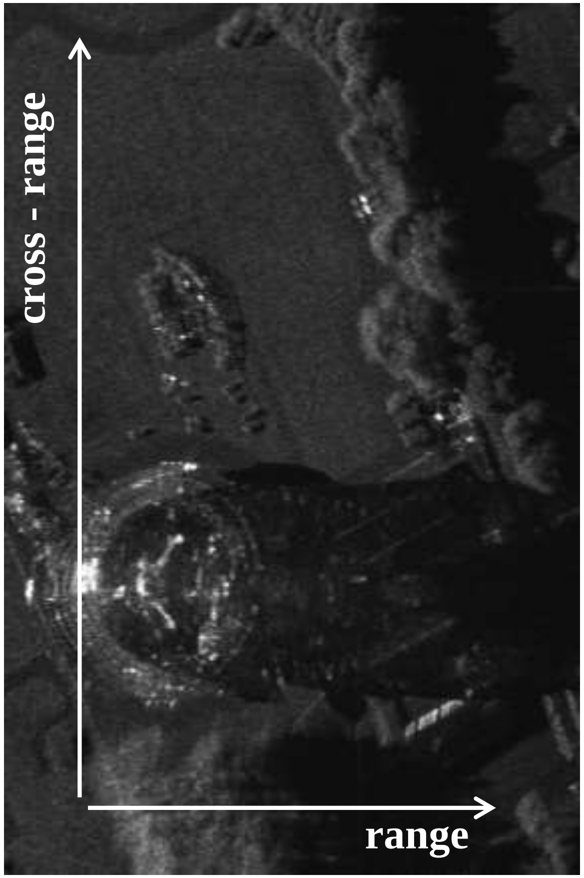
Azimuth + Range compression = 2D SAR image



SAR - How Does It Work?

Azimuth + Range compression = 2D SAR image





SAR - How Does It Work?

Range compression

Slant range resolution:

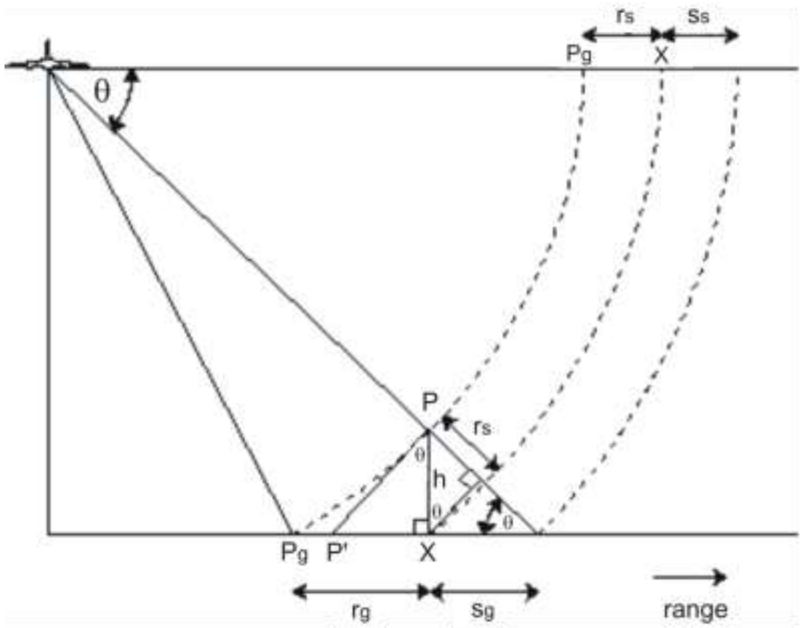
$$r_s = \frac{c}{2\beta}$$

Relief displacement in slant-range representation:

$$r_s \cong h \cdot \sin\theta$$

Relief displacement in slant-range representation:

$$r_g \cong h \cdot \tan\theta$$



Ground range resolution: $r_g = \frac{c}{2\beta \cdot \cos\theta}$

$\beta = 1GHz$

$\theta = 30°$

$r_g \approx 17{,}5cm$

SAR - How Does It Work?

Cross-range compression

Received signal phase:

$$\varphi(t) = \varphi_o - 2 \cdot \frac{2\pi \cdot r(t)}{\lambda}$$

Distance to target:

$$r(t) = \sqrt{R^2 + (v \cdot t)^2}$$

Taylor extension:

$$r(t) = R + \frac{(v \cdot t)^2}{2R} + \dots$$

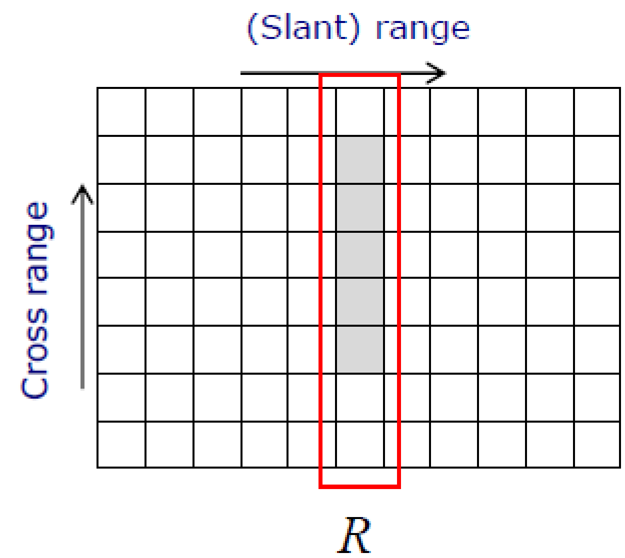
Received phase:

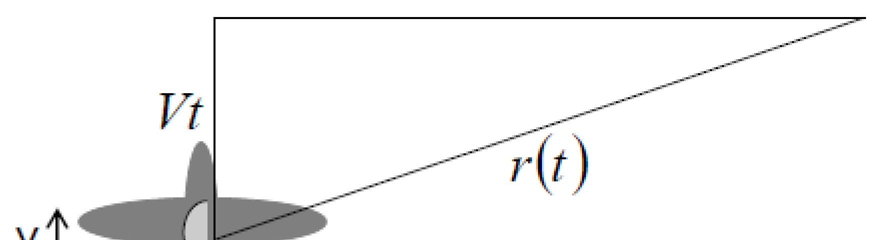
$$\varphi(t) = \varphi_o - \frac{4\pi}{\lambda}\left[R + \frac{(v \cdot t)^2}{2R} + \dots\right]$$

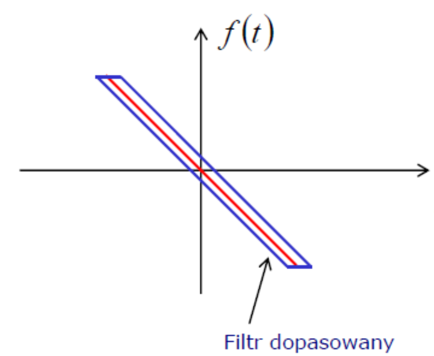
Received frequency:

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \approx -\frac{2v^2}{\lambda R}t$$

LFM signal





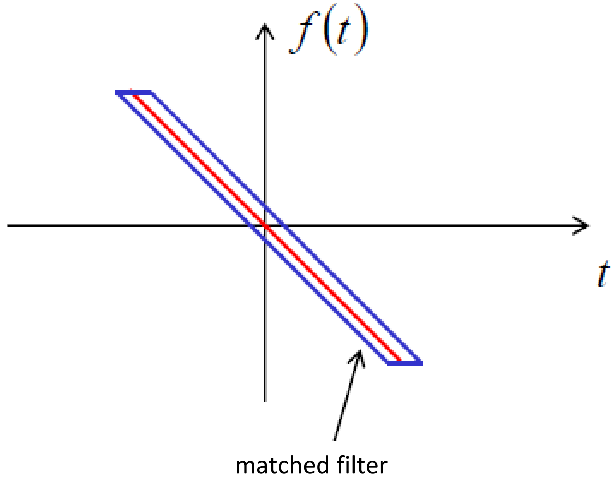


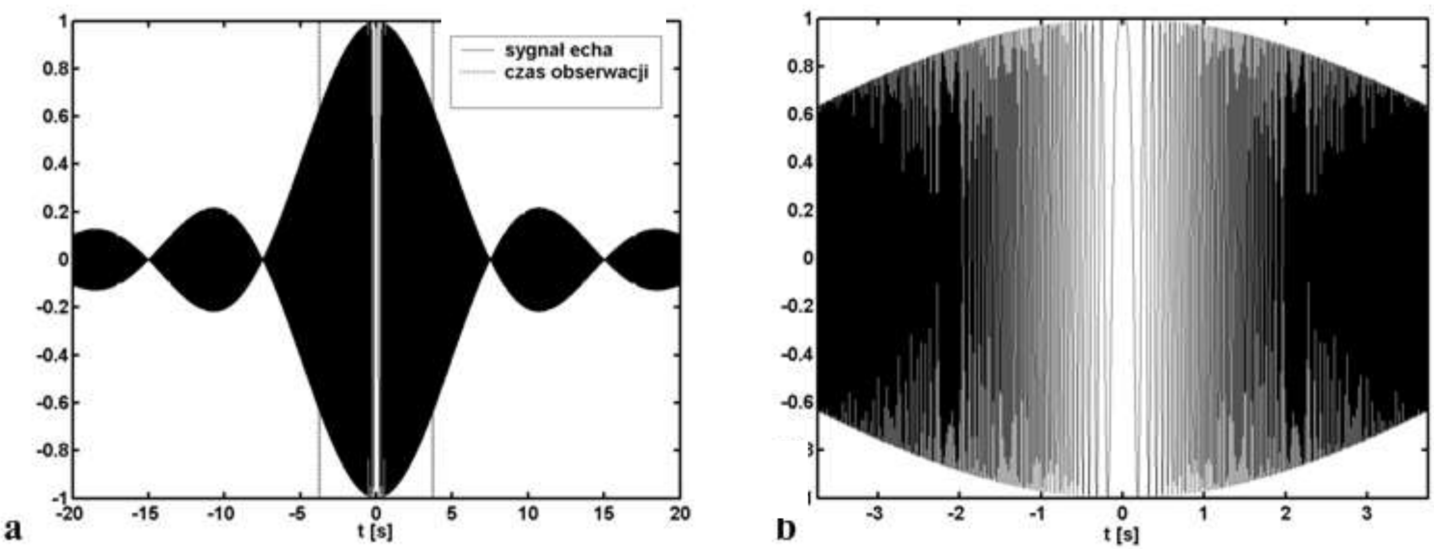
SAR - How Does It Work?

Received frequency:

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \approx -\frac{2v^2}{\lambda R}t$$

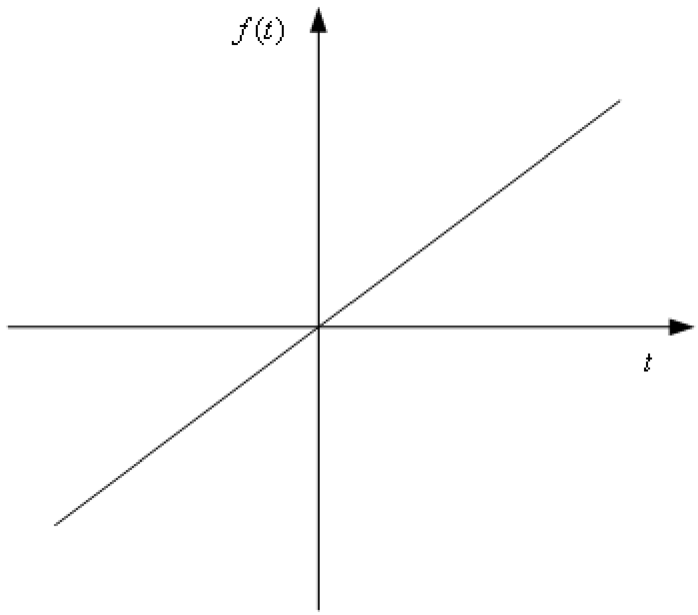
LFM signal

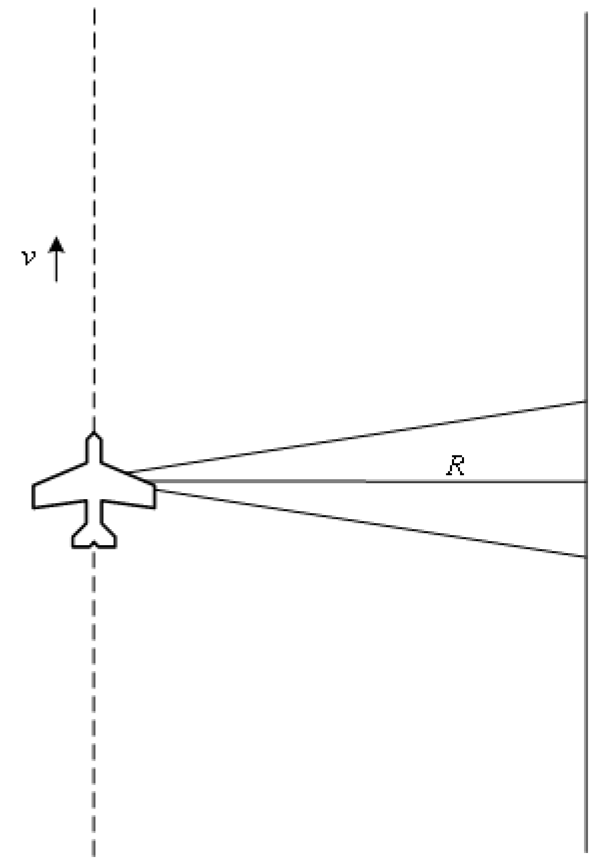




SAR Processing – Limitations and Practical Difficulties:

Ideal case

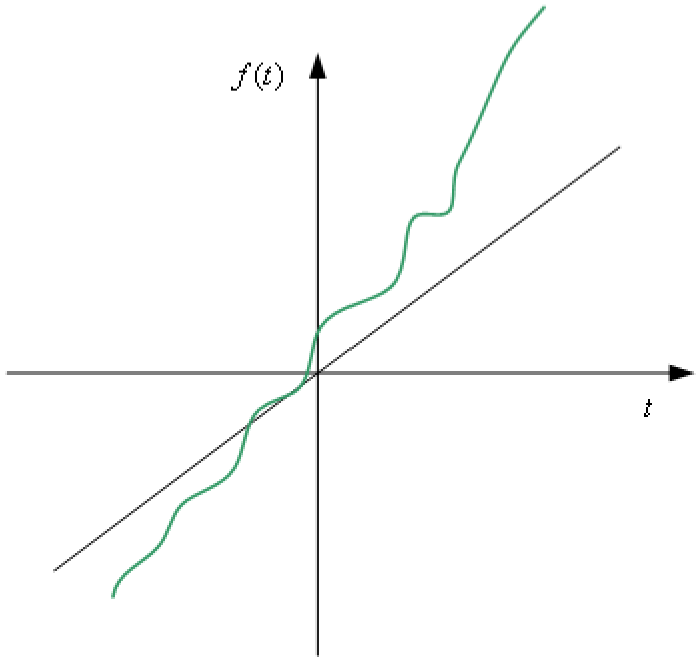


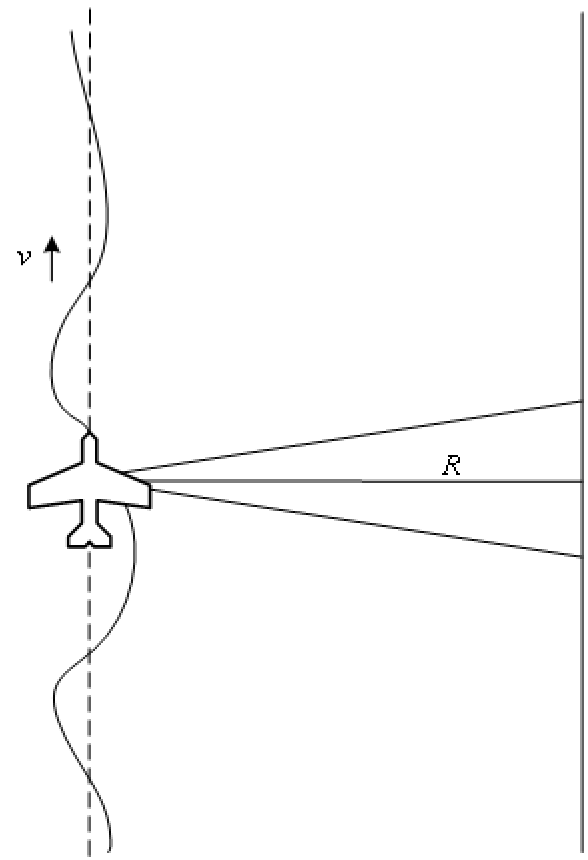


$$\varphi(t) = \varphi_o - \frac{4\pi}{\lambda}\left[R + \frac{(v \cdot t)^2}{2R}\right]$$

SAR Processing – Limitations and Practical Difficulties:

Reality



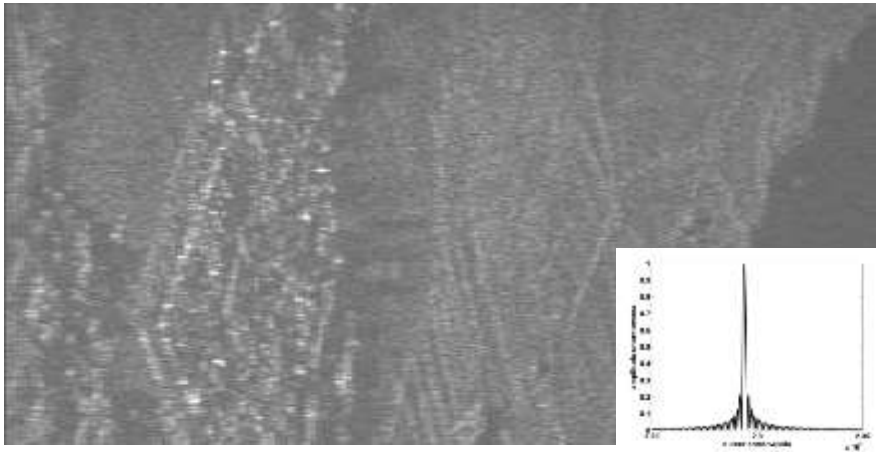


$$\varphi(t) = \varphi_o - \frac{4\pi}{\lambda}\left[R + v_r \cdot t + \frac{(v \cdot t)^2}{2R} + \dots\right] = \varphi_o - \left[\xi + \chi t + \gamma t^2 + \dots\right]$$

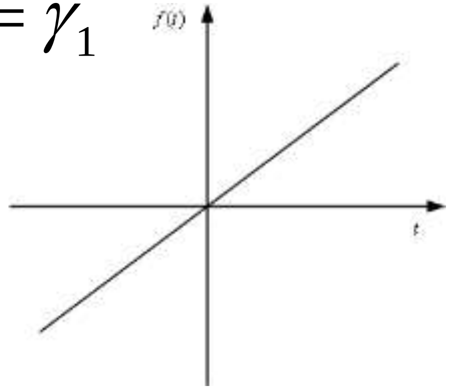
SAR Processing – Limitations and Practical Difficulties:

$$\varphi(t) = \varphi_o - \left[\xi + \chi t + \gamma t^2 + \ldots\right]$$

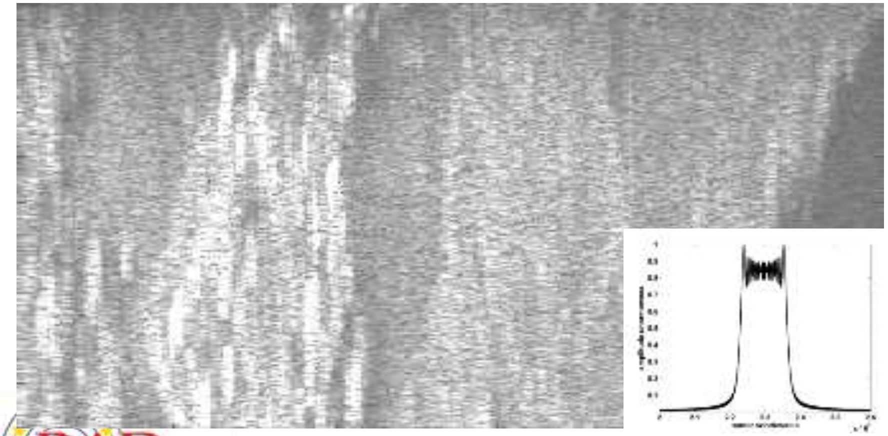
Fully focus image



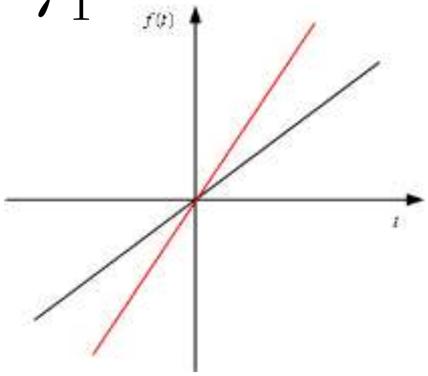
$$\gamma_2 = \gamma_1$$



Blurred image (velocity error)



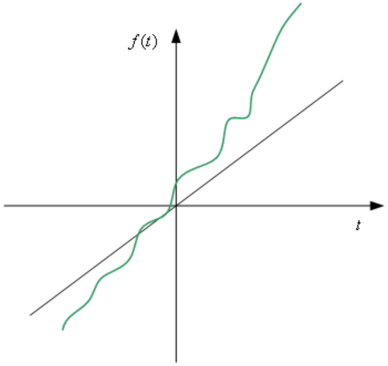
$$\gamma_2 \neq \gamma_1$$



Autofocus techniques are required!

SAR Processing – Limitations and Practical Difficulties:

Autofocus techniques – an overview



Non-parametric:

- Prominent Point Processing (PPP),
- Phase Gradient (PG),

Parametric:

Non-coherent:

- Contrast Optimization (CO)
- MapDrift (MD)

Coherent:

- Phase Difference (PD)
- Shift And Correlate (SAC)
- Coherent MapDrift (CMD)

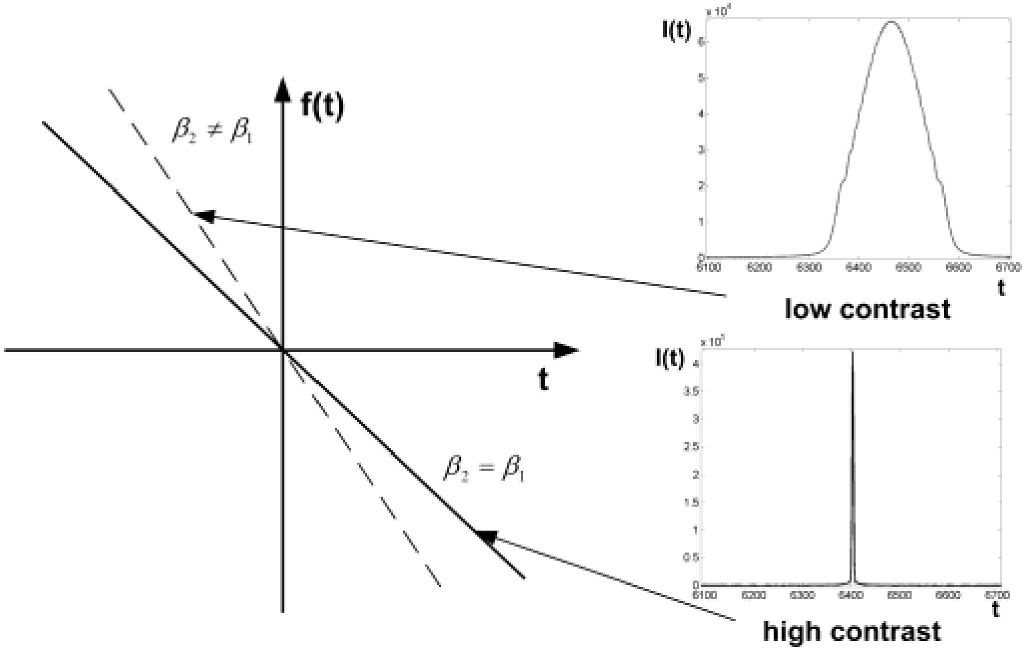
$$\varphi(t) = \varphi_o - \frac{4\pi}{\lambda}\left[R + v_r \cdot t + \frac{(v \cdot t)^2}{2R} + \dots\right]$$

$$\varphi(t) = \varphi_o - \left[\xi + \chi t + \gamma t^2 + \dots\right]$$

SAR Processing – Limitations and Practical Difficulties:

CO Autofocus Technique

$$C = \frac{E\left[\left(I(x,y)^2 - E\left[I(x,y)^2\right]\right)^2\right]}{E\left[I(x,y)^2\right]}$$



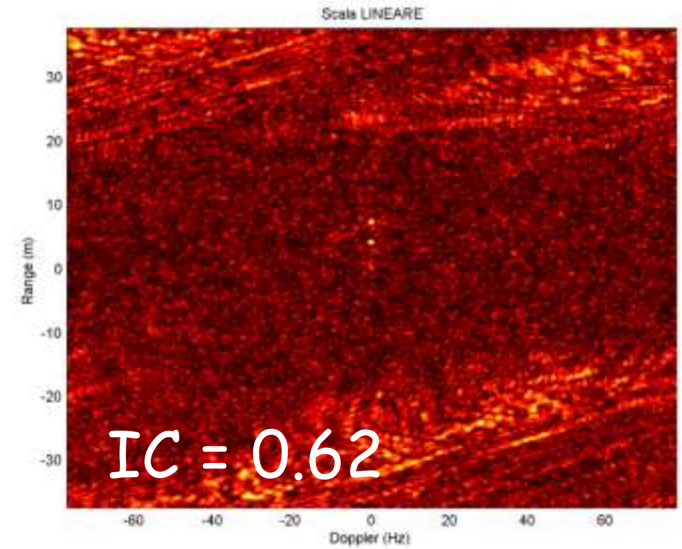
SAR Processing – Limitations and Practical Difficulties:

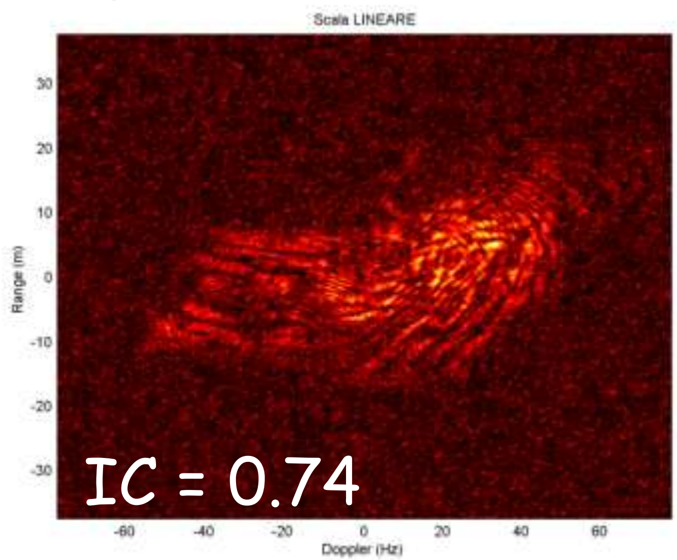
CO Autofocus Technique

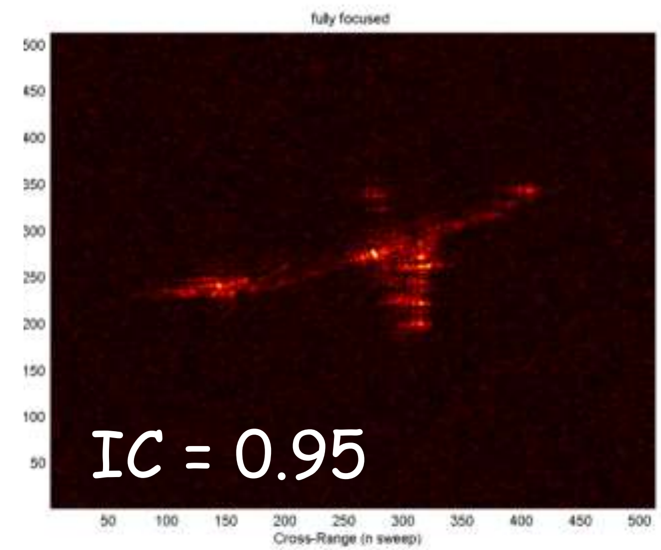
Example:

On courtesy of
Professor Marco Martorella - University of Pisa

The higher the Image Contrast the better the image focus







SAR Processing – Limitations and Practical Difficulties:

MD Autofocus Technique

MD cross-correlation function:

$$r(\tau) = \int_{t=-\infty}^{\infty} |I_1(t)| \cdot |I_2(t-\tau)| dt$$

Estimated velocity is determined as:

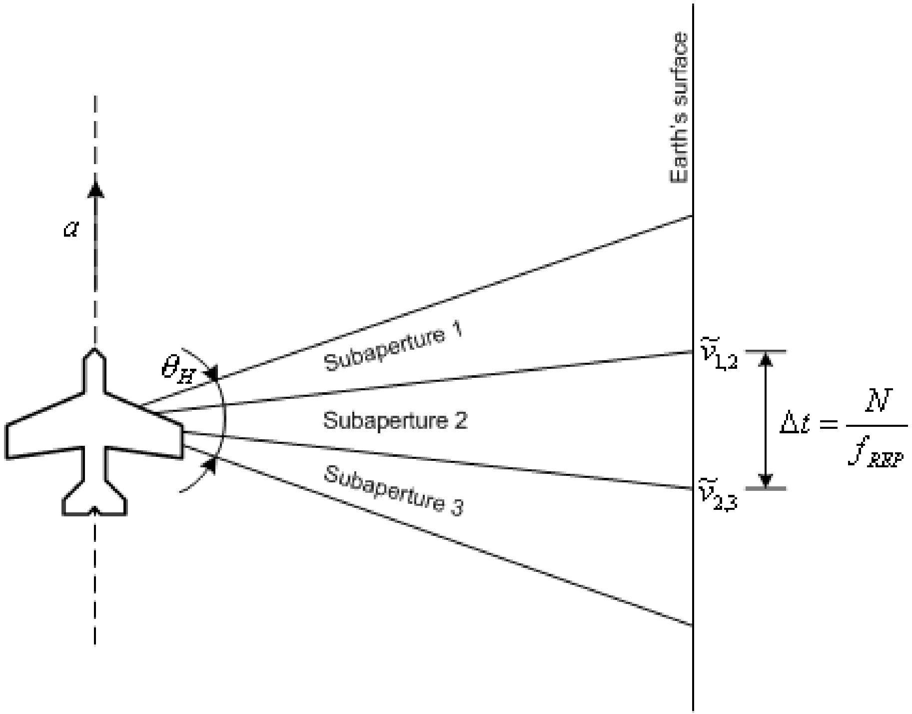
$$\tilde{v}_{k+1} = \Delta\tilde{v}_k + \tilde{v}_k$$

where:

$$\Delta\tilde{v}_k = \frac{\tilde{v}_k^{\,2}}{\theta \cdot R \cdot f_{PRF}} \cdot \Delta x$$

Estimated acceleration:

$$\tilde{a} = \frac{\Delta\tilde{v}}{\Delta t} = \frac{(\tilde{v}_{1,2} - \tilde{v}_{2,3})}{N} \cdot f_{REP}$$



(*) P. Samczyński, G. Pietrzyk, K. Kulpa, Simple Method for Estimating Along Track Acceleration Using Autofocus Map Drift Algorithm, Proc. of the International Radar Symposium – IRS 2005, 06-08 September, Berlin, Germany, pp.43-47

SAR Processing – Limitations and Practical Difficulties:

CMD Autofocus Technique

CMD cross-correlation function:

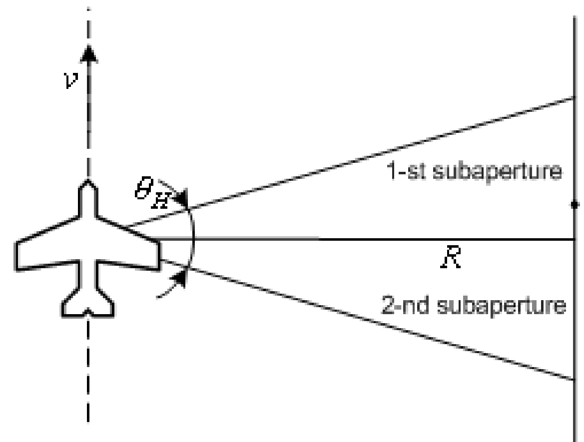
$$r_C(\tau) = \int_{t=-\infty}^{\infty} I_1(t) \cdot I_2^*(t-\tau) e^{-j\cdot\pi\cdot\frac{\Delta f}{2}\cdot t} dt$$

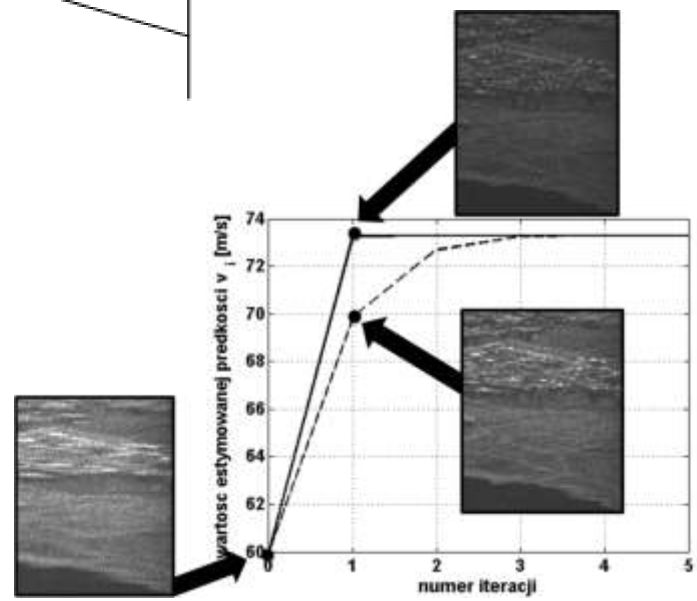
where:

$$\Delta f = 2k\beta_2 T_{ob} / \pi$$

Estimated velocity (**):

$$\hat{v}_2 = \sqrt{\frac{R\cdot\theta\cdot v_1}{2\frac{\Delta x}{f_{PRF}} + \frac{R\cdot\theta}{v_1}}}$$

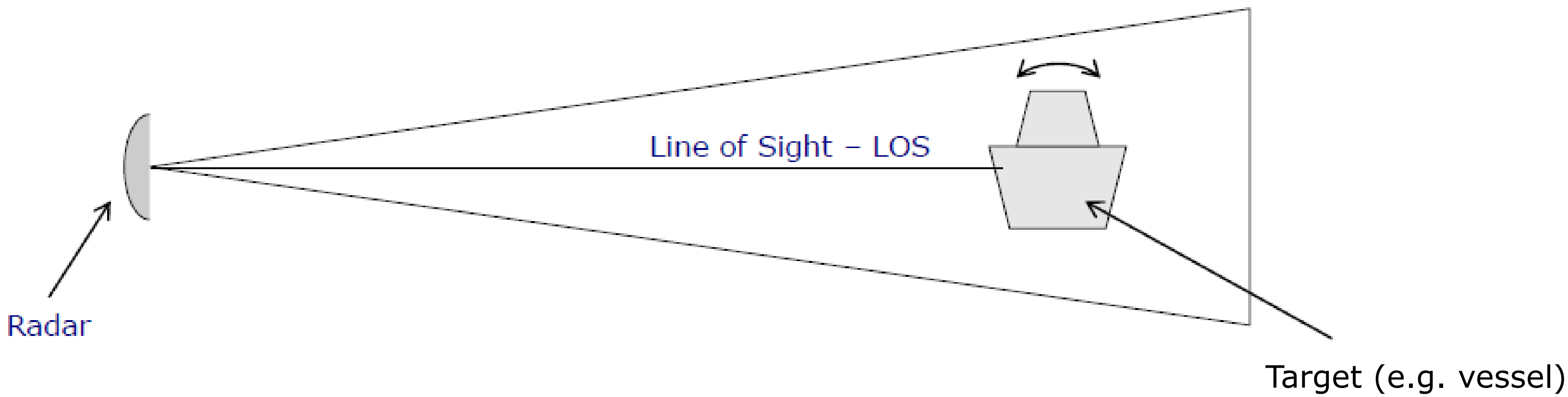




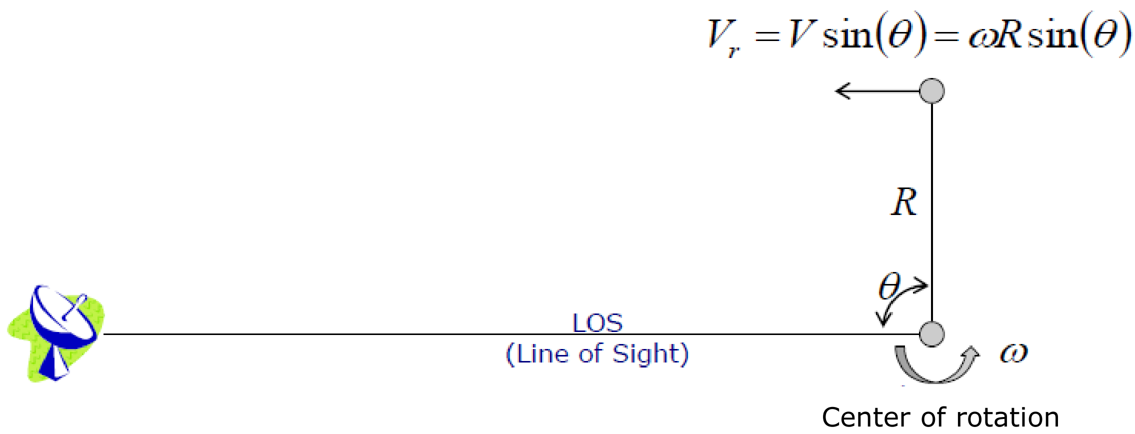
(*) P. Samczyński, K. Kulpa, Concept of the Coherent Autofocus Map-Drift Technique, Proc. of the International Radar Symposium (IRS 2006), 23-25 May 2006, Cracow, Poland, pp.63-66
(**) P. Samczynski: "Super-Convergent Velocity Estimator for an Autofocus Coherent MapDrift Technique", in IEEE Geoscience and Remote Sensing Letters, Vol. 9, Issue 2, March 2012, pp. 204-208

Short intro to SAR/**ISAR** imaging
(a monostatic case)

ISAR – Inverse SAR



ISAR – Inverse SAR



Doppler frequency

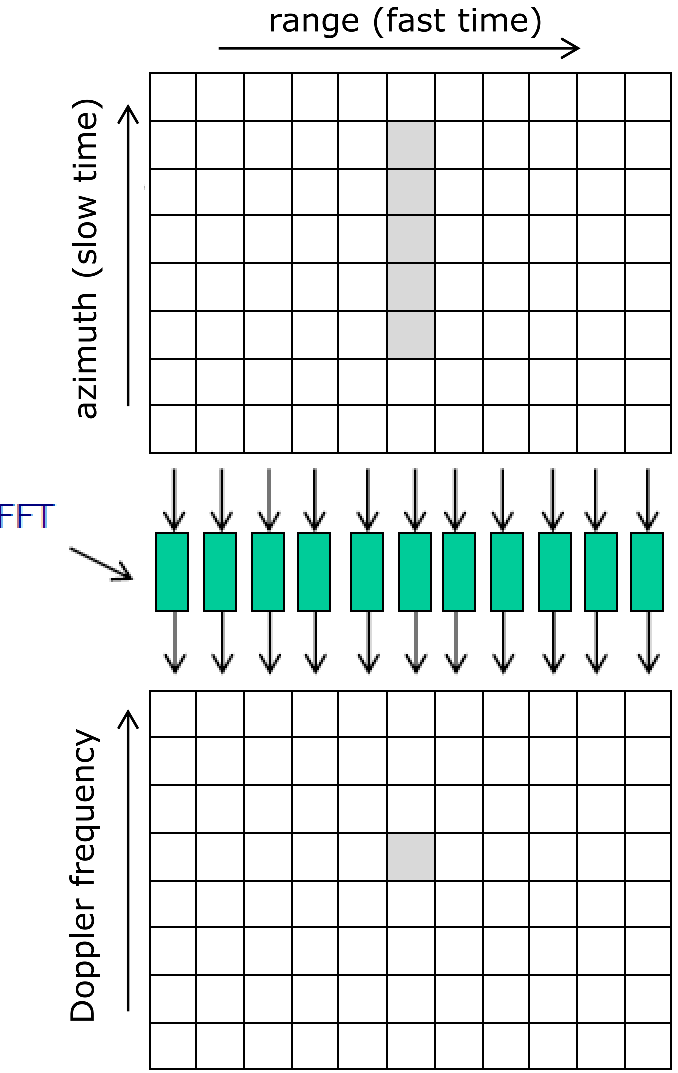
$$f_d = \frac{2V_r}{\lambda} = \frac{2\omega R\sin(\theta)}{\lambda}$$

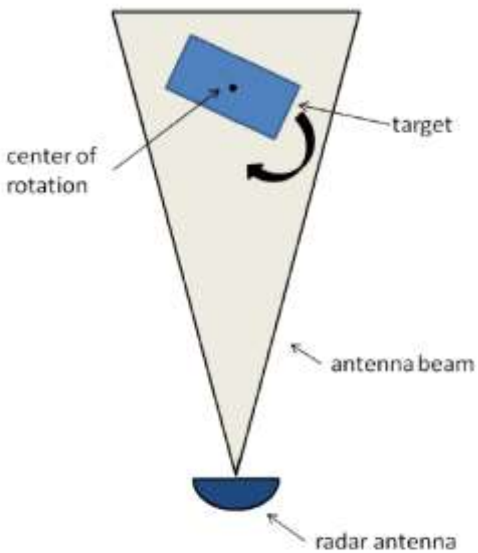
Frequency resolution

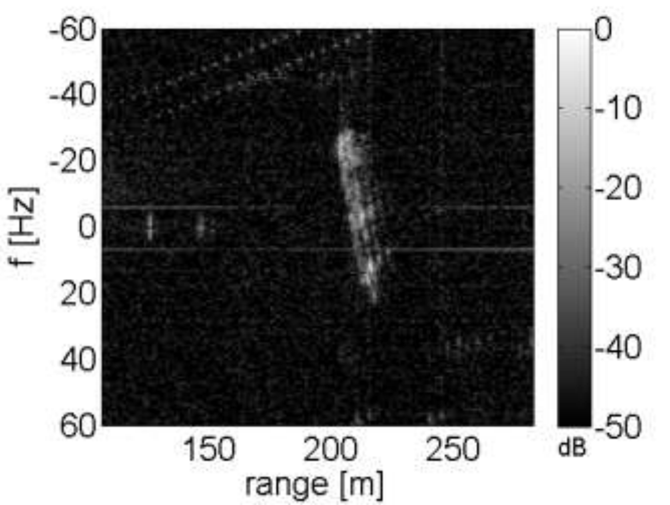
$$\Delta f_d = \frac{1}{T}$$

ISAR – Inverse SAR

Simple ISAR Processing



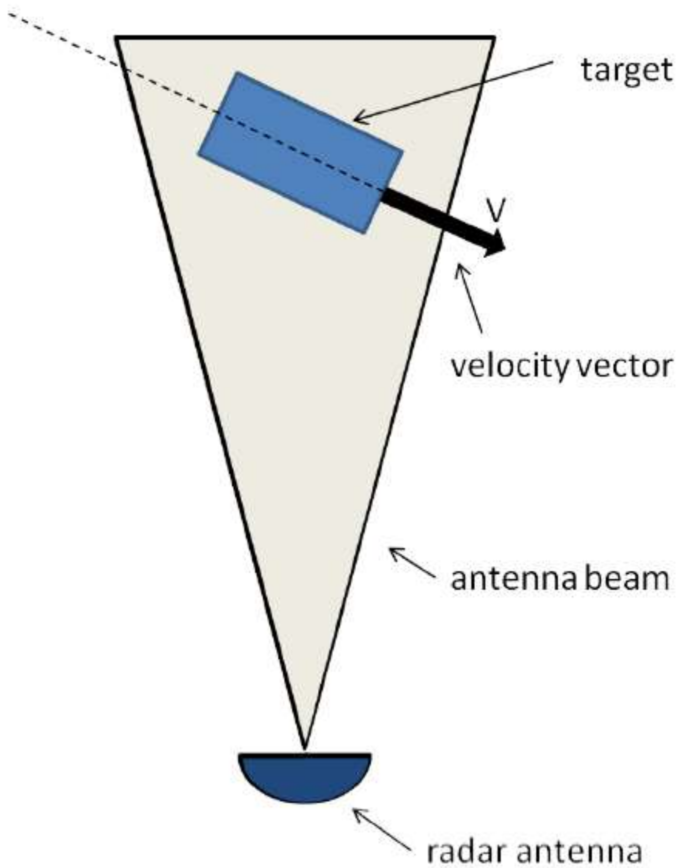


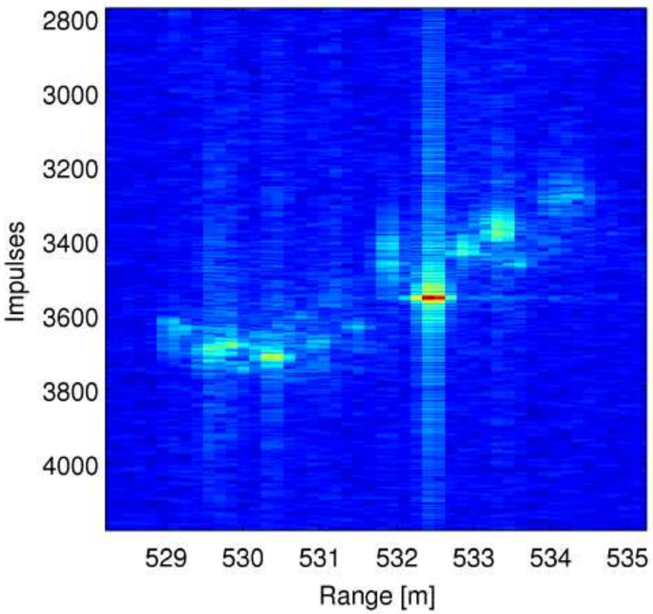


(*) M. Wielgo, P. Samczyński, M. Malanowski, K. Ndini, K. Kulpa, P. Baranowski, The SARENKA SAR system – Experimental results of ISAR imaging, in Proc. of 15th International Radar Symposium (IRS), 2014, pp.1,4, 16-18 June 2014

ISAR – Inverse SAR

Geometry No. 2





(*) J. S. Kulpa, M. Malanowski, D. Gromek, P. Samczyński, K. Kulpa, and A. Gromek, „Experimental Results of High-Resolution ISAR Imaging of Ground-Moving Vehicles with a Stationary FMCW Radar" in INTL – International Journal of Electronics and Telecommunications, PAN, vol. 59, nr 3, 2013, ss. 293-299

Introduction to passive bistatic radar imaging

Introduction to passive radar imaging

Passive radars:

- ground based PCL system for air surveillance
- technology entering to the maturity stage

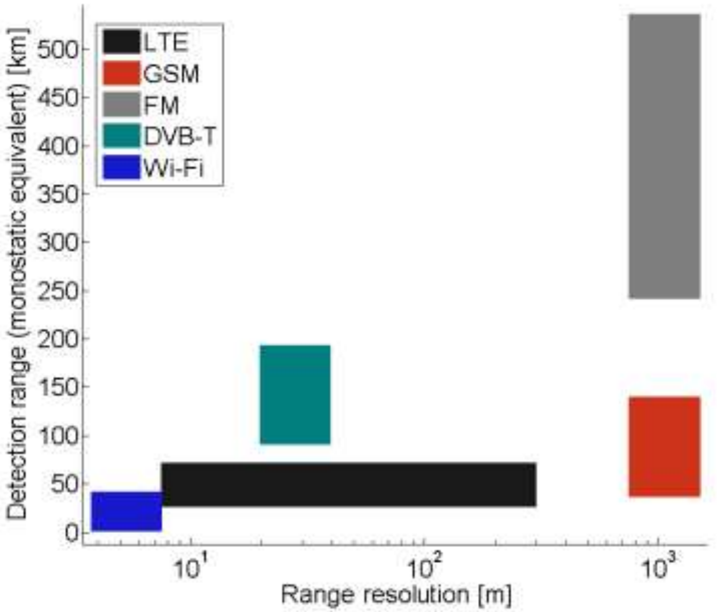
New trends in passive radars:

- airborne passive radar applications
- **SAR/ISAR mapping**
  – both for ground based and moving systems

Illuminators of Opportunity

- Analogue TV (long range, poor signal characteristics)
- FM radio (long range, relatively low resolution, content-dependent)
- **DVB-T** (medium range, good range resolution, signal conditioning)
- DAB (medium range, good range resolution, not widespread)
- GSM (short range, relatively low resolution)
- **DVB-S** (very short range, very good range resolution)
- Others (WiFi, WiMAX, GNSS)

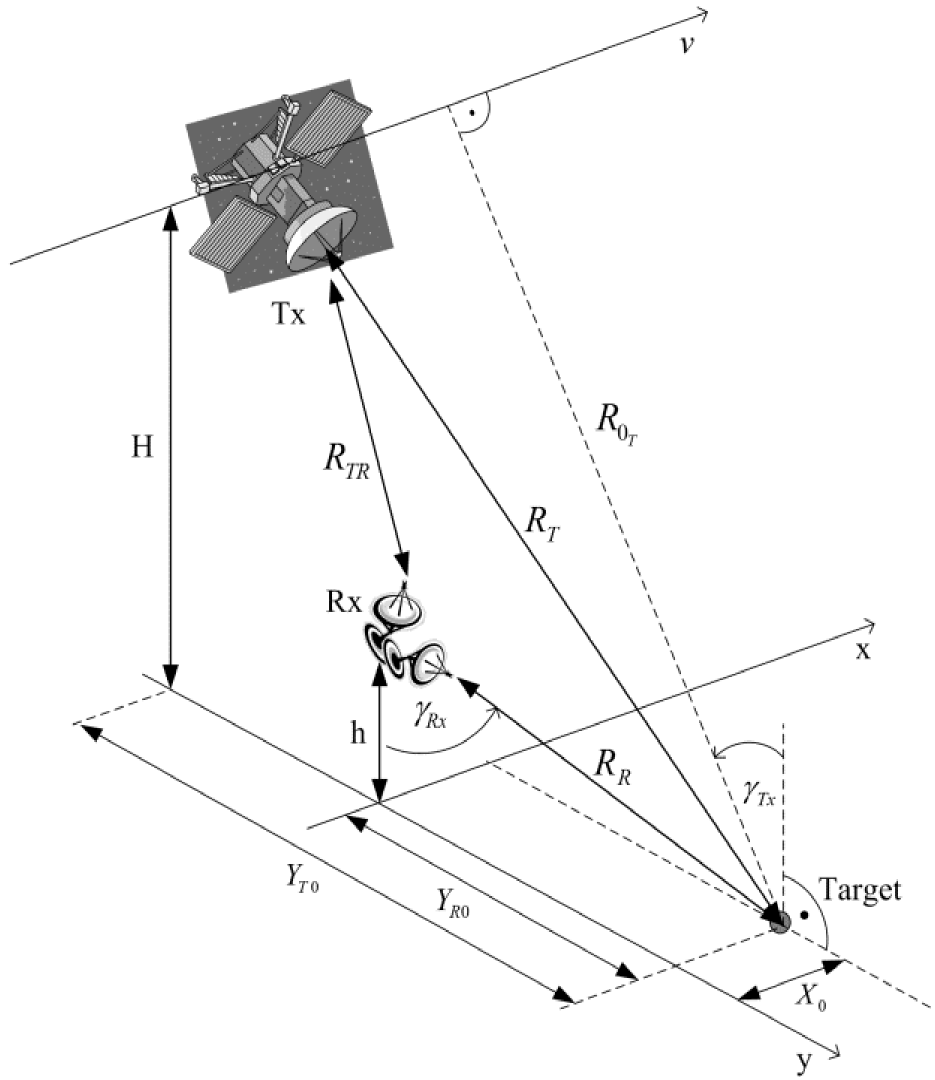
- **Other radars (ATC, EW, SAR, ...)**



Passive SAR Imaging

- **Passive SAR Imaging using non-cooperative sattelite-based illumination**
- Passive SAR Imaging using commercial ground based illuminators

System Geometry



System Geometry

For such geometry the **SAR image** can be obtained using **FFT in cross-range!**

For the observation time T, the FFT resolution equals:

$$\Delta f_d = \frac{1}{T} = \frac{v \cdot \delta_a}{\lambda \cdot R_o}$$

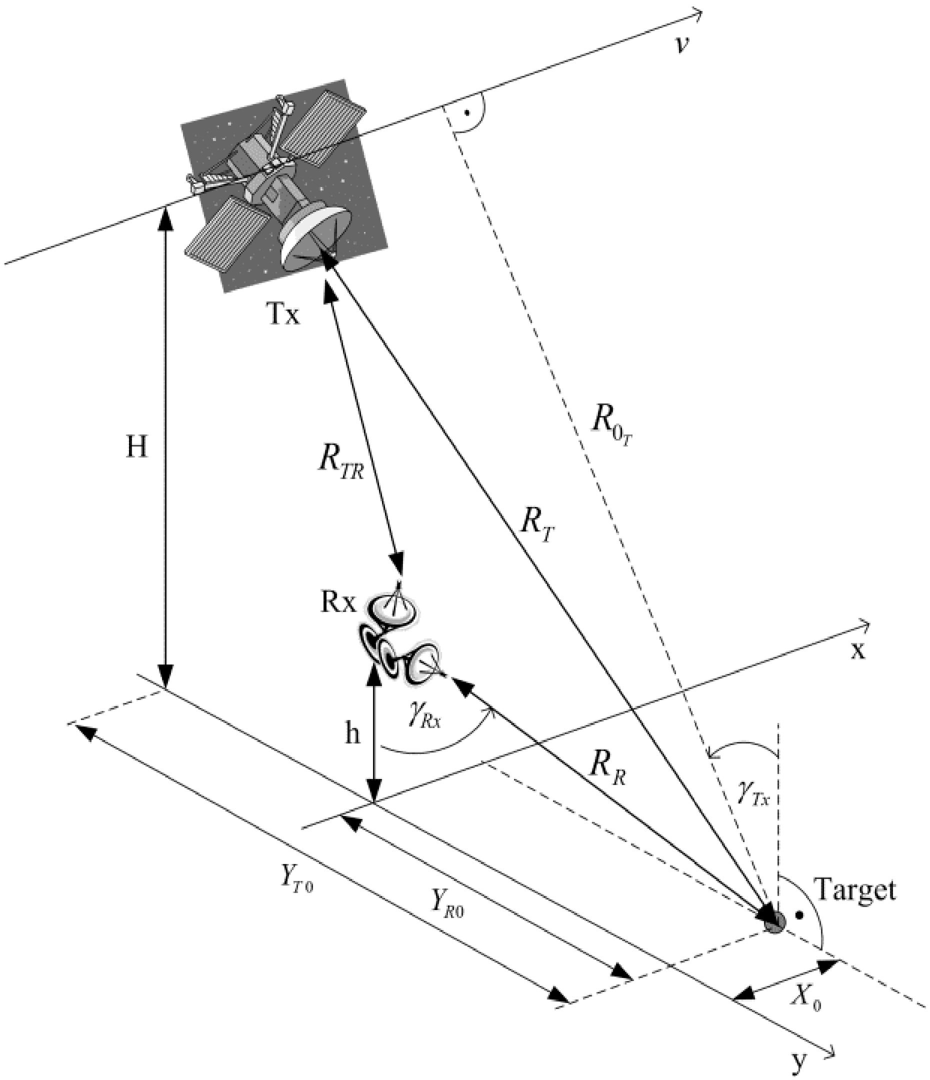
This gives cross-range resolution:

$$\delta_a = \frac{\lambda \cdot R_o}{v \cdot T}$$

This gives maximum cross-range resolution equals **L**, Where **L** is antenna length.

$$\delta_a = L_a$$

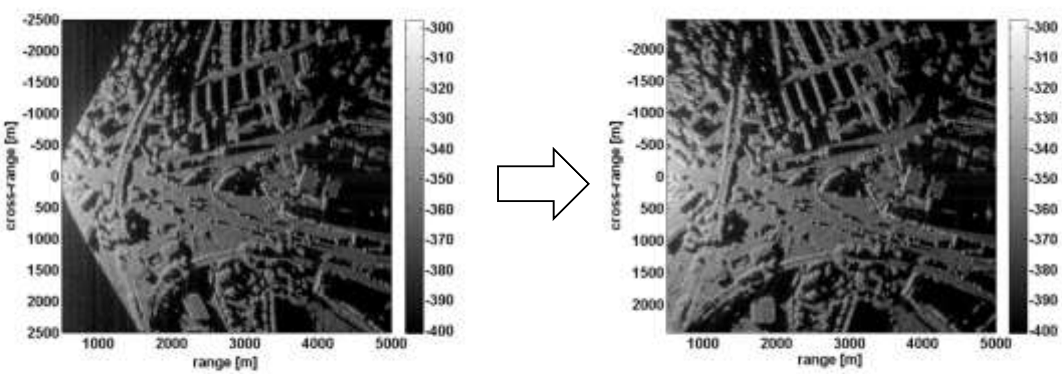
In active SAR radars cross-range resolution equals **L/2.**



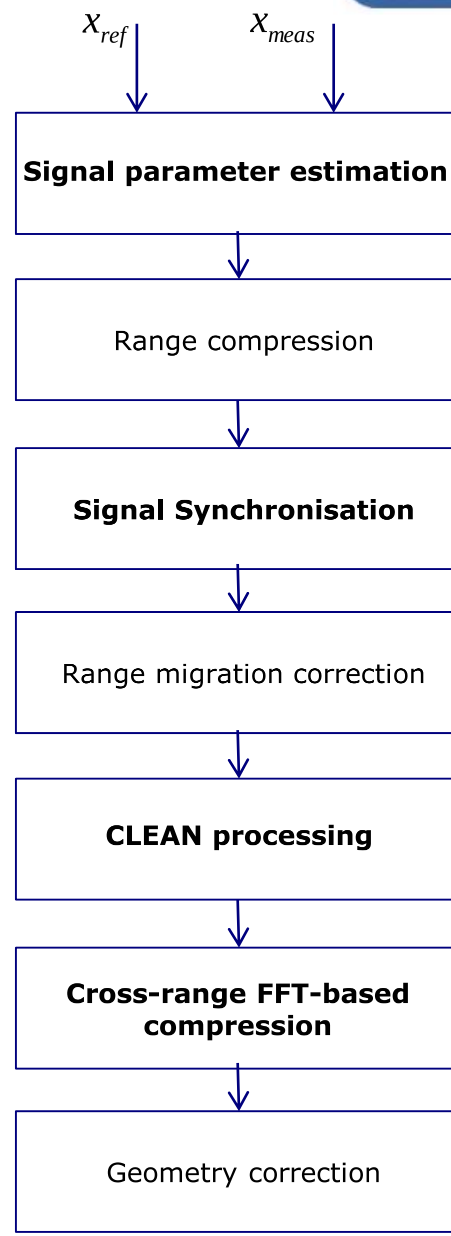
(*) P. Samczynski, K. Kulpa, "Passive SAR imaging using a satellite pulsed radar as an illuminator of opportunity", in Proc. of IRS 2012, May 23-25, 2012, Warsaw, Poland, pp. 157-161

Processing

- Unknown parameters of Tx (PRF, chirp rate, etc.)
- Signal synchronization
- <u>Unknown Tx trajectory</u>



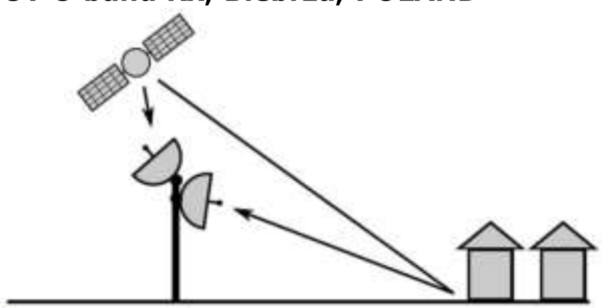
Geometry corrections is required



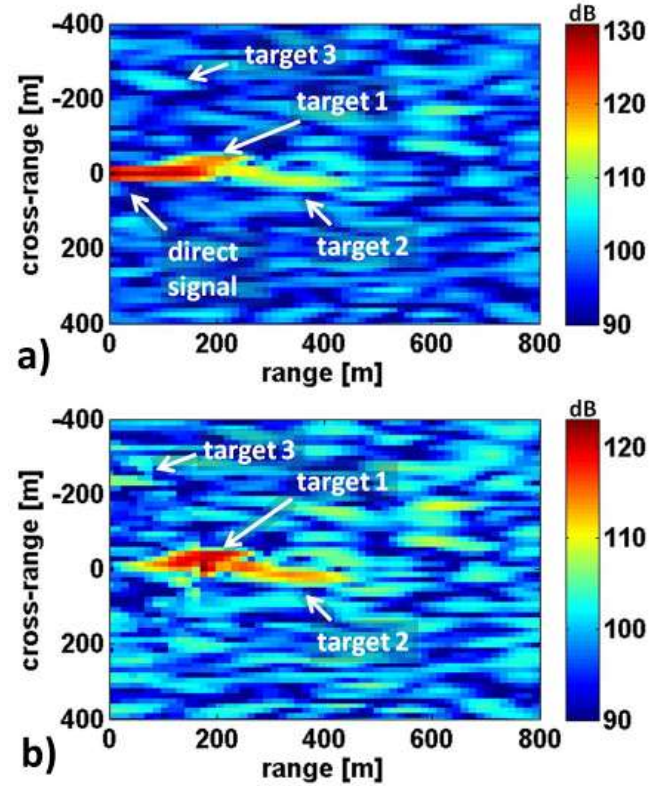
Passive SAR Imaging Results

2011 July 03

The ASAR Tx (EnviSAT-1) of opportunity
WUT C-band Rx, Biebrza, POLAND



Dual channel backward geometry

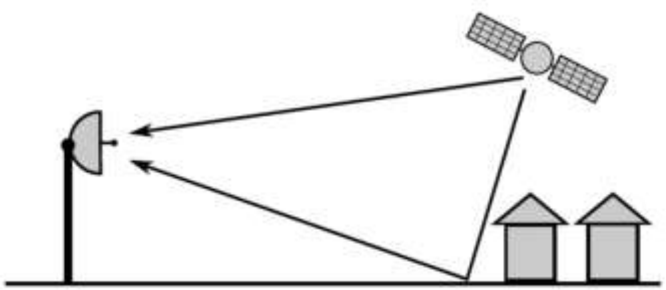


(*) P. Samczynski, K. Kulpa, M. Malanowski, P. Krysik, Ł. Maślikowski: „Trial Results on Passive SAR Measurement using the Envisat-1 Satellite as an Illuminator of Opportunity" – w Proceedings on EuSAR 2012 – 9th European Conference on Synthetic Aperture Radar, April 23-26, 2012, Nurnberg, Germany, pp. 291-294

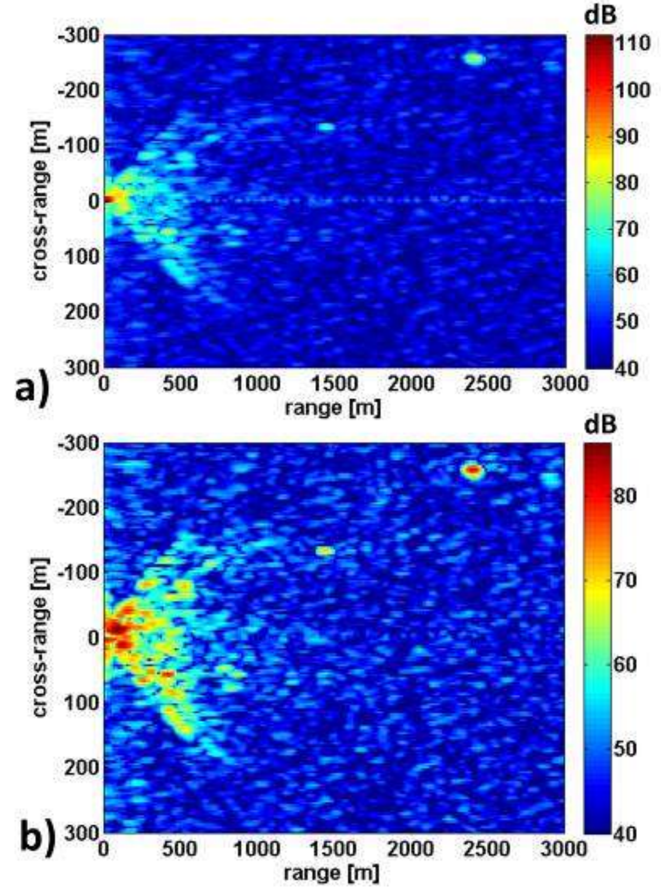
Passive SAR Imaging Results

2012 April 07

The ASAR Tx (EnviSAT-1) of opportunity
RMA C-band Rx, Brussels, BELGIUM

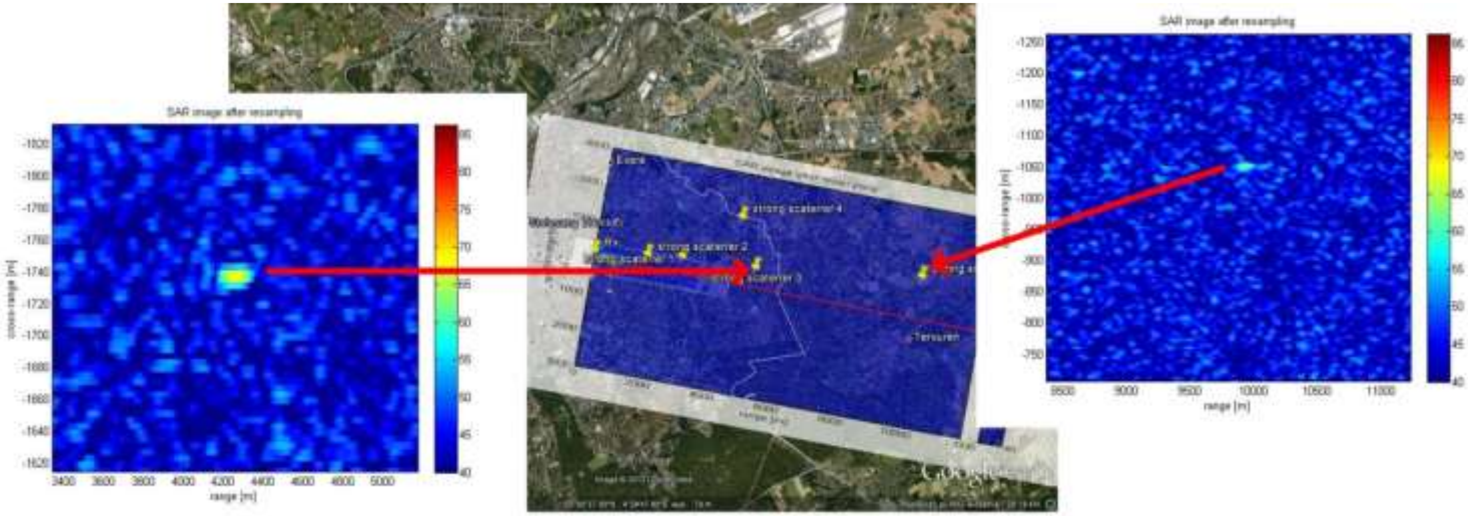


Single channel forward geometry

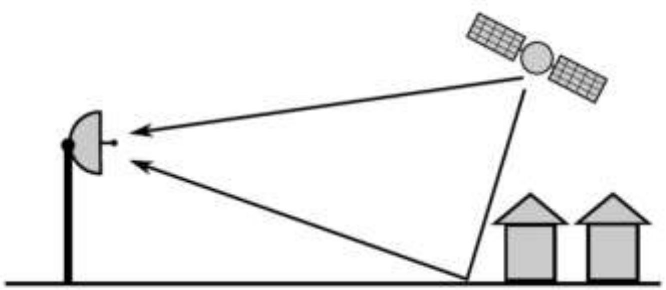


Passive SAR Imaging Results

2012 April 07



The ASAR Tx (EnviSAT-1) of opportunity
RMA C-band Rx, Brussels, BELGIUM



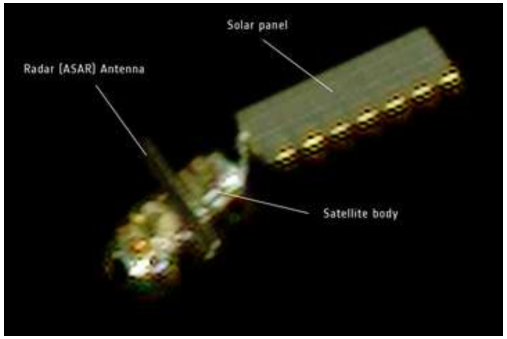
Single channel forward geometry

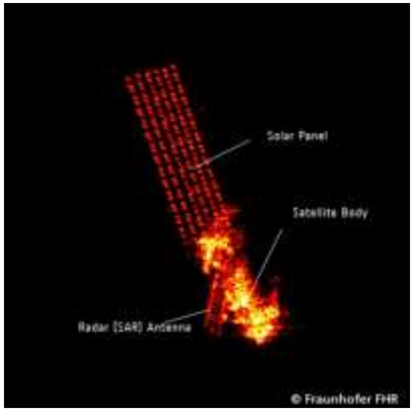
(*) P. Samczyński, K. Kulpa, Ł. Maślikowski, D. Gromek, and V. Kubica: "Challenges in signal processing for passive SAR radars utilizing non-cooperative space-based pulse radars as illuminators," in Proceedings of NATO Specialist Meeting SET-187, Szczecin, Poland, 13–14 May 2013, p. CD

Passive SAR Imaging Results

2012 April 08 - Envisat services interrupted:

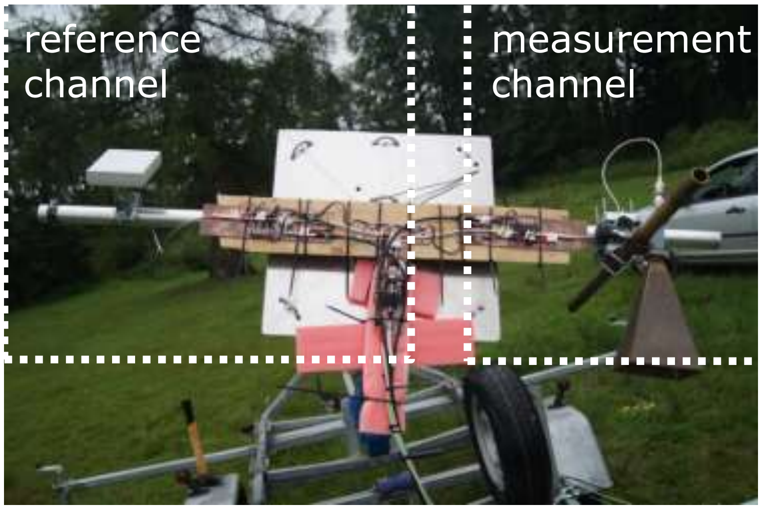
the satellite was unexpectedly lost



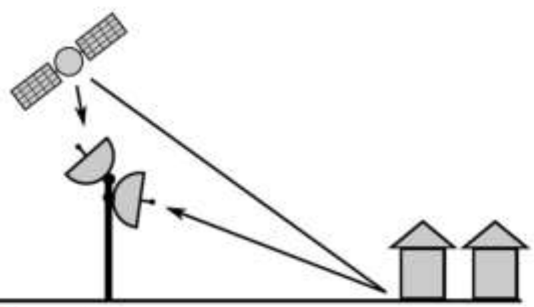


Passive SAR Imaging Results

2012 July 19



The TerraSAR-X Tx of opportunity
WUT X-band Rx, Biebrza, POLAND

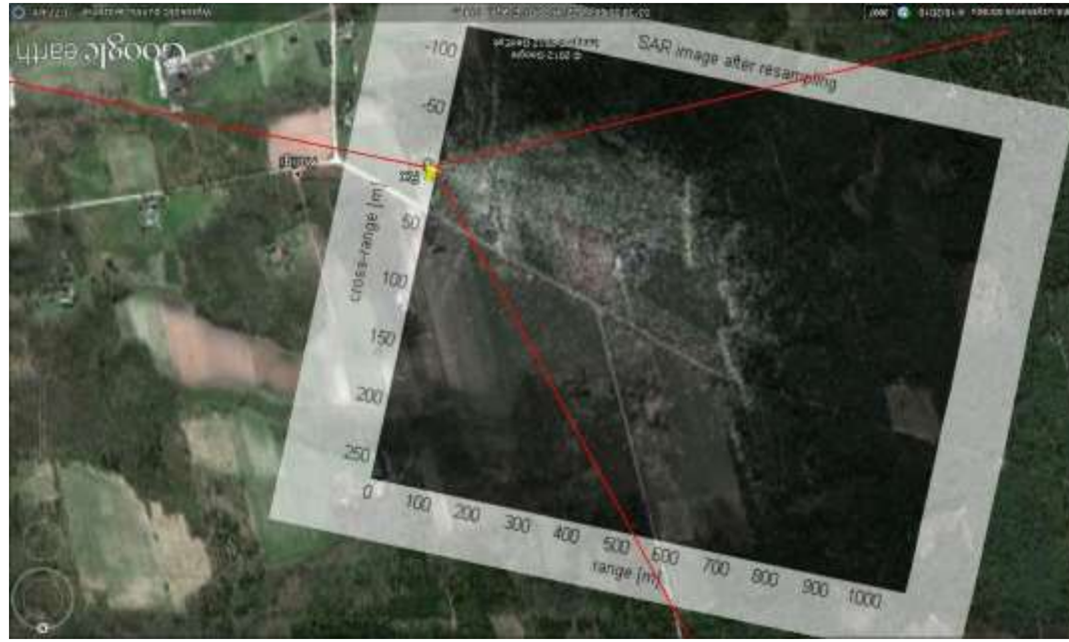


Dual channel backward geometry

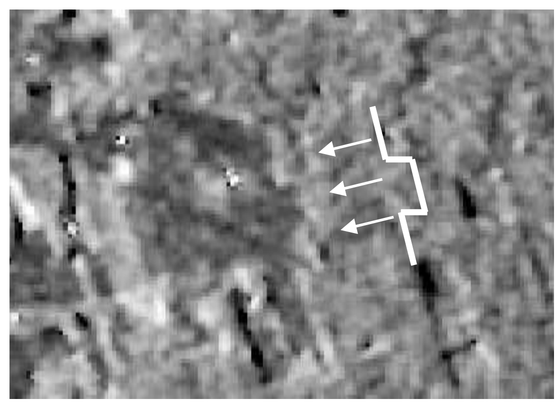
(*) L. Maślikowski, P. Samczyński, and M. K. Bączyk: “X-band receiver for passive imaging based on TerraSar-X illuminator,” in Proceedings of 2013 Signal Processing Symposium (SPS) , 5–7 June 2013, Jachranka, Poland

Passive SAR Imaging Results

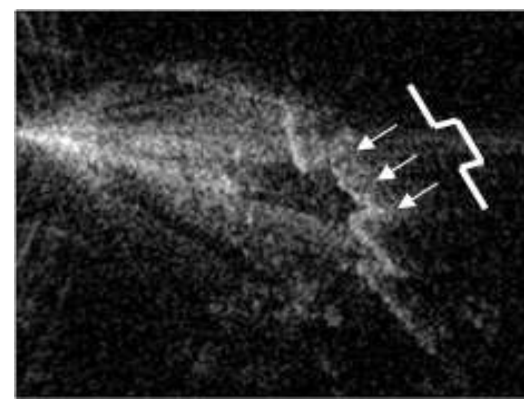
2012 July 19



Optical Image



SAR Image



Passive SAR Image

(*) P. Krysik, Ł. Maślikowski, P. Samczyński, A. Kurowska, “Bistatic Ground-Based Passive SAR Imaging Using TerraSAR-X as an Illuminator of Opportunity”, in 2013 International Conference on Radar,9-12 September 2013, Adelaide, Australia, ISBN 978-1-4673-5177-5, pp. 39-42

Passive SAR Imaging

Challanges:

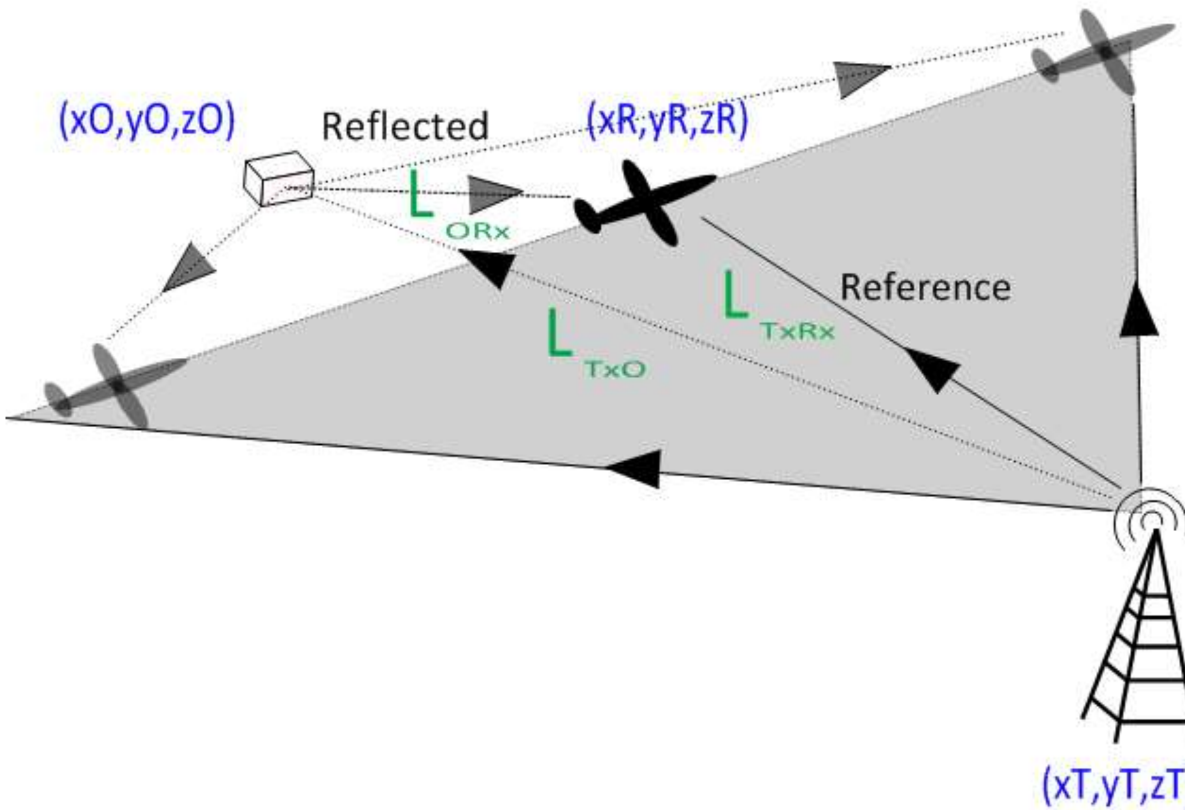
- include satellite geometry in processing
- polarimetry processing
- GMTI processing
- multistatic passive SAR Imaging using various Tx of opportunity and different scenarios

(*) Ł. Maślikowski, P. Samczyński, M. Bączyk, P. Krysik, K. Kulpa, Passive bistatic SAR imaging – Challenges and limitations, Aerospace and Electronic Systems Magazine, IEEE, vol.29, no.7, pp.23,29, July 2014

Passive SAR Imaging

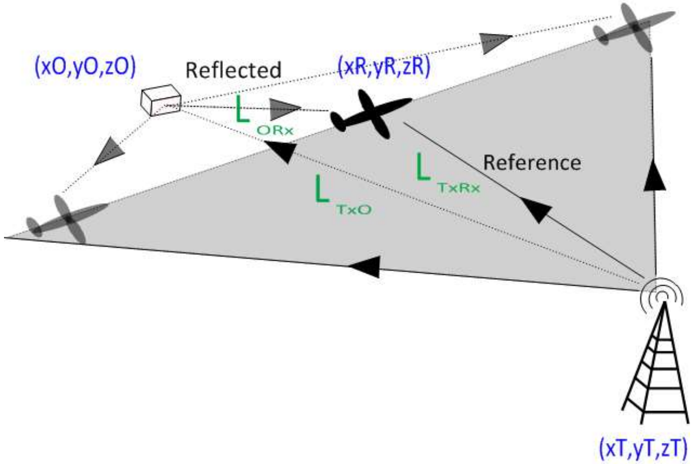
- Passive SAR Imaging using non-cooperative satellite-based illumination
- **Passive SAR Imaging using commercial ground based illuminators**

System Geometry



Illuminator: Ground-based DVB-T transmitter

System Geometry



Tx to Rx distance can be approximated (using Taylor series) by:

$$l_{TxRx}(t) \cong L_{TxRx} + \frac{(vt)^2}{2L_{TxRx}} + \frac{vt}{2L_{TxRx}}$$

Rx to target distance:

$$l_{ORx}(t) \cong L_{ORx} + \frac{(vt)^2}{2L_{ORx}} + \frac{vt}{2L_{ORx}}$$

Signal phase in reference channel:

$$\varphi_{\mathrm{Re}\ f}(t) = \frac{2\pi \cdot l_{TxRx}(t)}{\lambda}$$

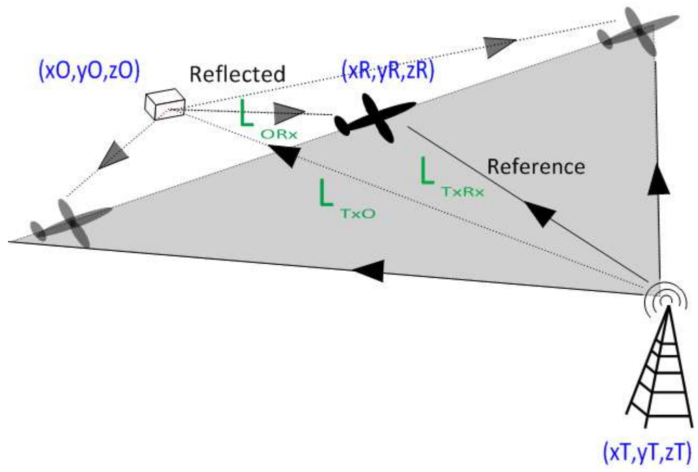
Signal phase in reference channel:

$$\varphi_{Surv}(t) = \frac{2\pi \cdot (L_{TxO} + l_{ORx}(t))}{\lambda}$$

Range compression:

$$s_{xcorr}(\tau) = \int s_{\mathrm{Re}\ f}(t) \cdot s^{*}_{Echo}(t+\tau)dt$$

System Geometry



Ground objects are imaged at the distance:

$$R_{Obj}(t) = L_{TxO} + l_{ORx}(t) - l_{TxRx}(t)$$

Target Phase:

$$\varphi_{Obj}(t) = \frac{2\pi R_{Obj}(t)}{\lambda} = \varphi_{Surv}(t) - \varphi_{\mathrm{Re}\,f}(t) =$$

$$= \frac{2\pi(L_{TxO} + l_{ORx}(t) - l_{TxRx}(t))}{\lambda}$$

Distane to target:

$$R_{Obj}(t) = \frac{1}{2}\left(\frac{1}{L_{ORx}} - \frac{1}{L_{TxRx}}\right)(vt)^2 +$$

$$+\frac{1}{2}\left(\frac{1}{L_{ORx}} - \frac{1}{L_{TxRx}}\right)vt +$$

$$+(L_{TxO} + L_{ORx} - L_{TxRx})$$

The Doppler frequency:

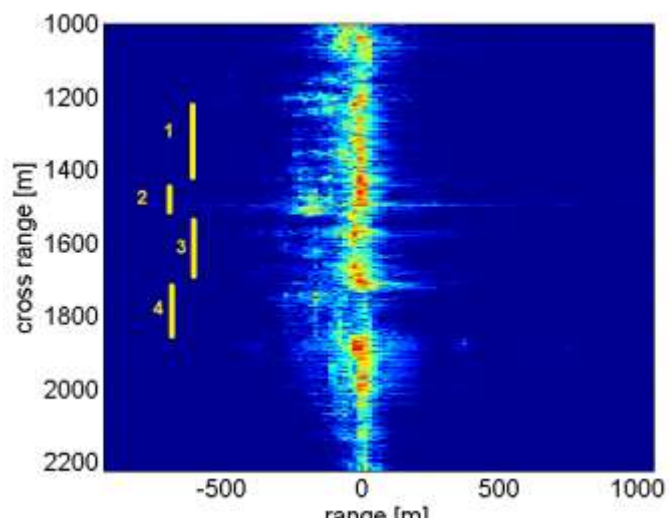
$$f_{Dop}(t) = \frac{2\pi}{\lambda}\left(\frac{1}{L_{ORx}} - \frac{1}{L_{TxRx}}\right)2v^2 t +$$

$$+\frac{\pi}{\lambda}\left(\frac{1}{L_{ORx}} - \frac{1}{L_{TxRx}}\right)v$$

(*) D. Gromek, P. Samczyński, K. Kulpa, J. Misiurewicz, A. Gromek, "Analysis of Range Migration and Doppler History for an Airborne Passive Bistatic SAR Radar" in Proceedings of IRS 2014, Gdansk, Poland, 16–18 June 2014.

Verifications via Experiments

Trial No 1



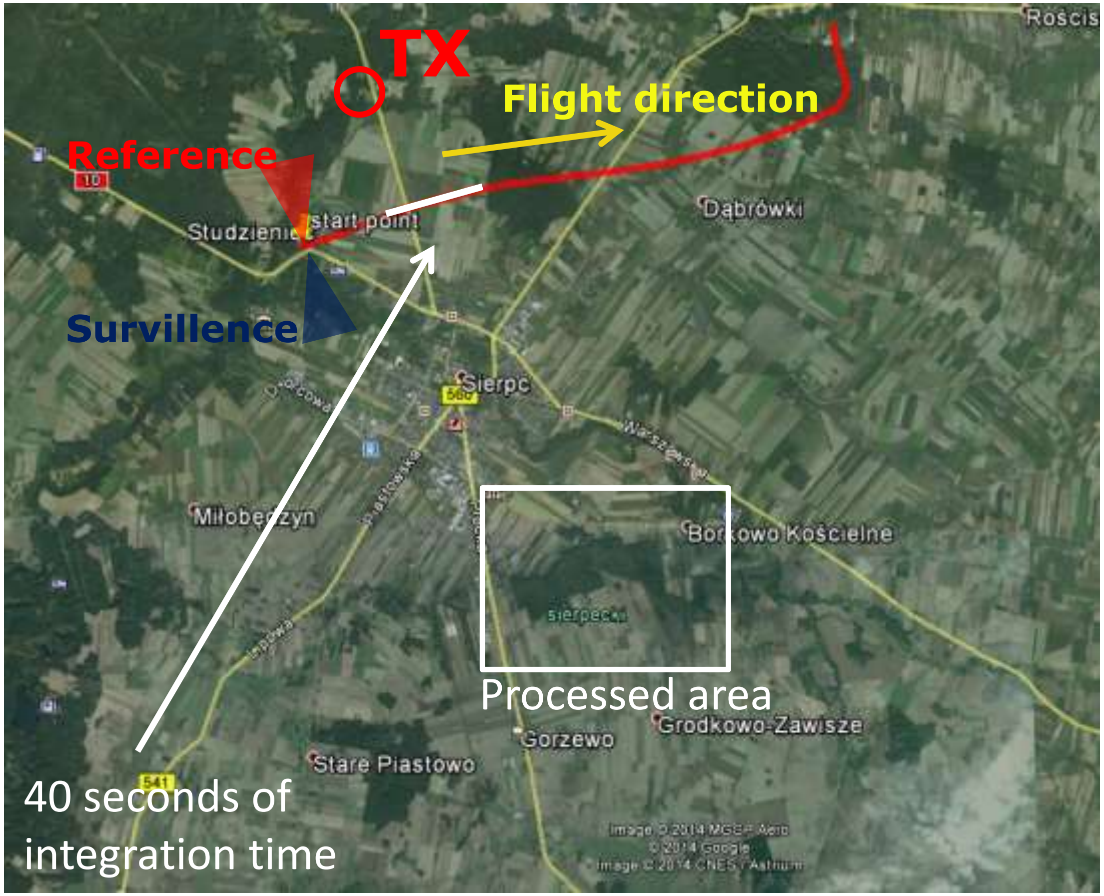
Verifications via Experiments

Trial No 2

WUT

ise

Verifications via Experiments



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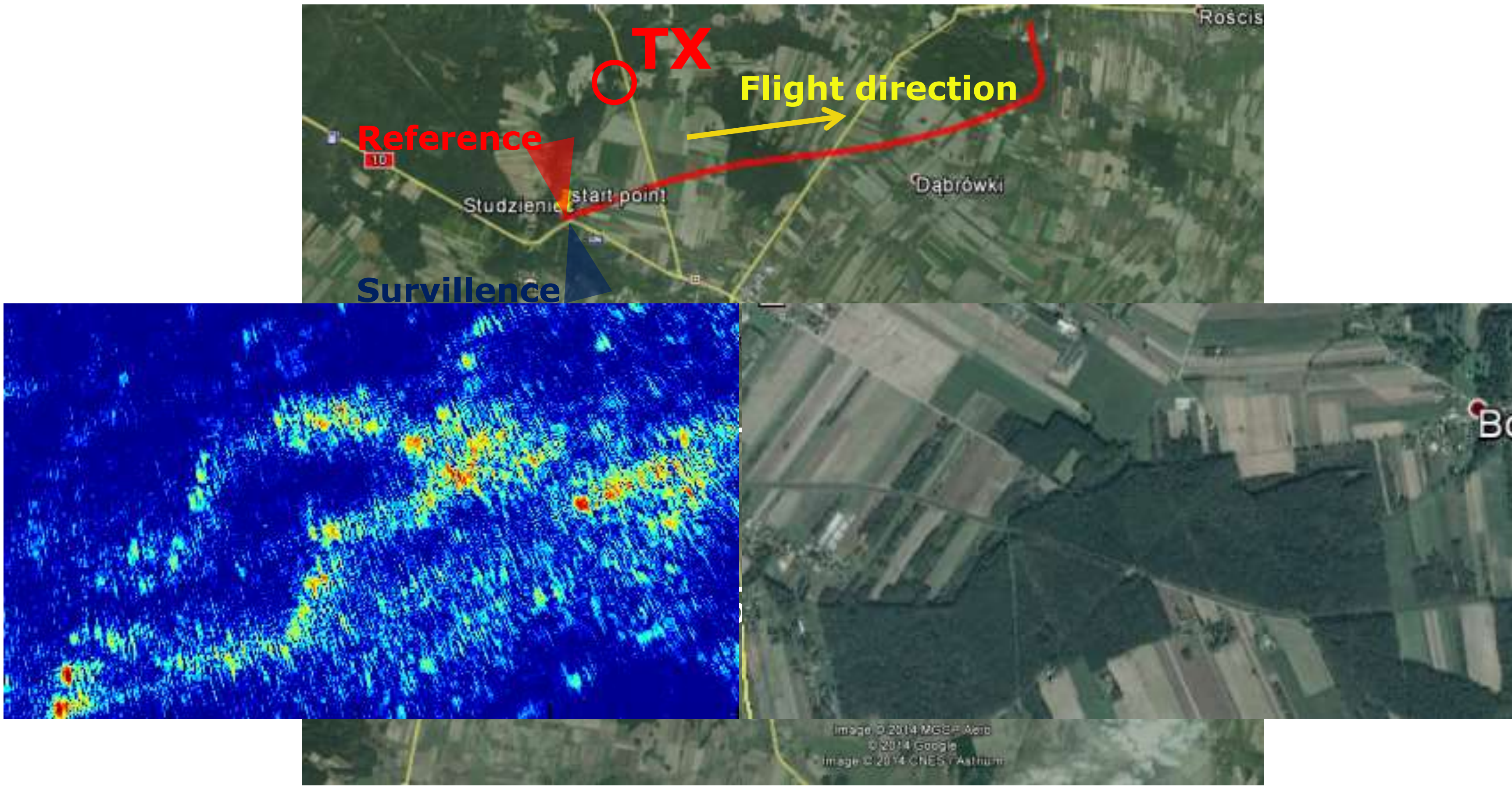
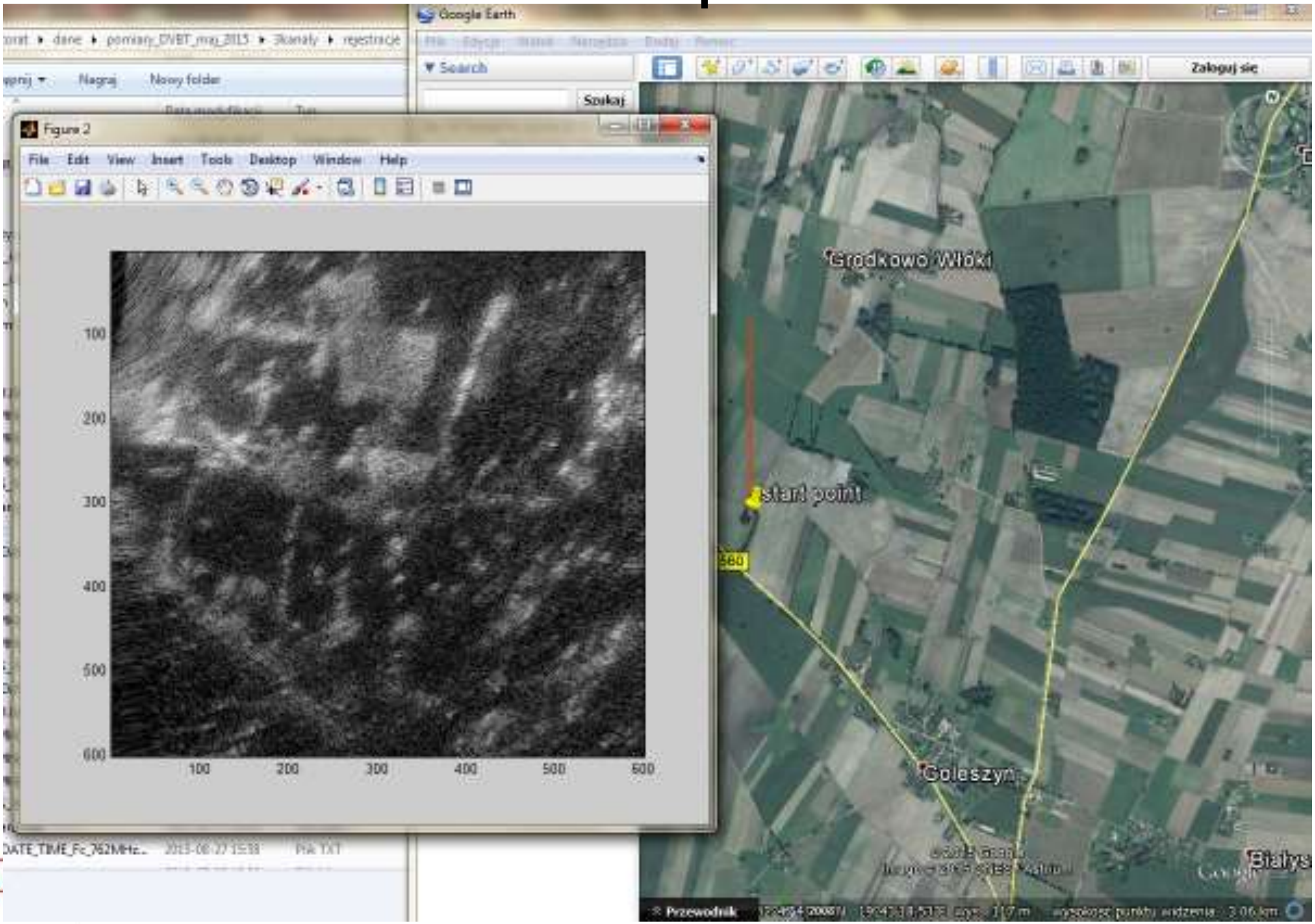
Verifications via Experiments



Verifications via Experiments

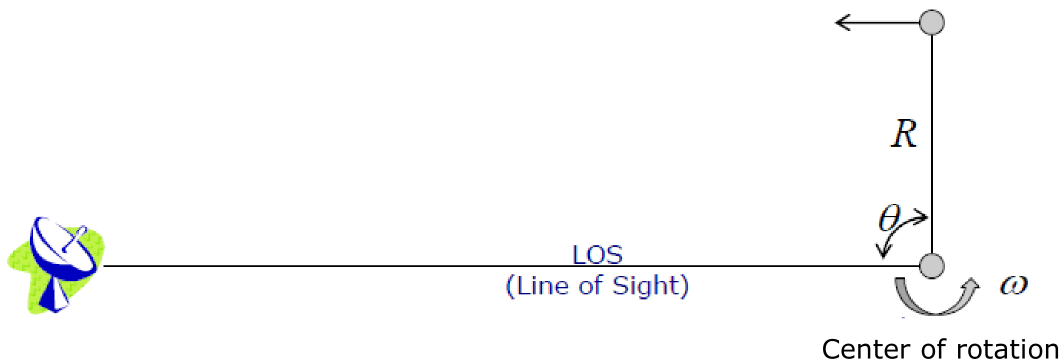


Passive ISAR imaging

ISAR - How does it work?

Geometry No. 1

$$V_r = V\sin(\theta) = \omega R\sin(\theta)$$



Doppler frequency

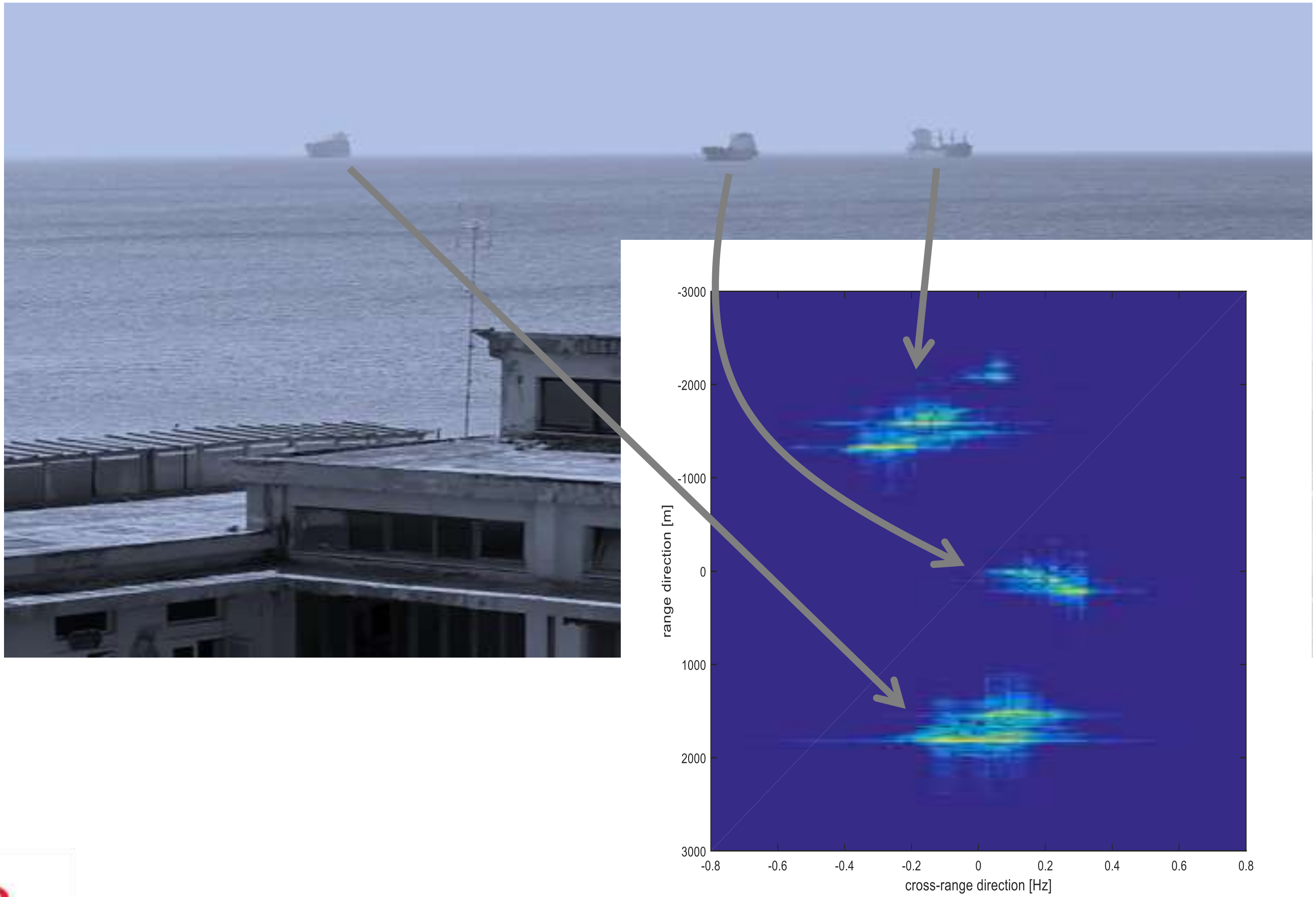
$$f_d = \frac{2V_r}{\lambda} = \frac{2\omega R\sin(\theta)}{\lambda}$$

Frequency resolution

$$\Delta f_d = \frac{1}{T}$$

Passive ISAR results

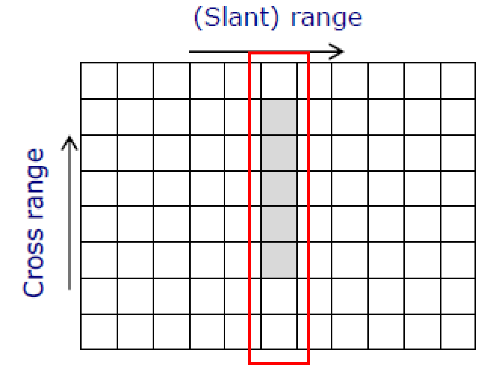
Geometry No. 1



P. Samczynski, K. Kulpa, M. K. Baczyk and D. Gromek, "SAR/ISAR imaging in passive radars," *2016 IEEE Radar Conference (RadarConf)*, Philadelphia, PA, 2016, pp. 1-6

ISAR - How does it work?

Geometry No. 2



Received signal phase:

$$\varphi(t) = \varphi_o - 2 \cdot \frac{2\pi \cdot r(t)}{\lambda}$$

Distance to target:

$$r(t) = \sqrt{R^2 + (v \cdot t)^2}$$

match filter

Taylor extension:

$$r(t) = R + \frac{(v \cdot t)^2}{2R} + \ldots$$

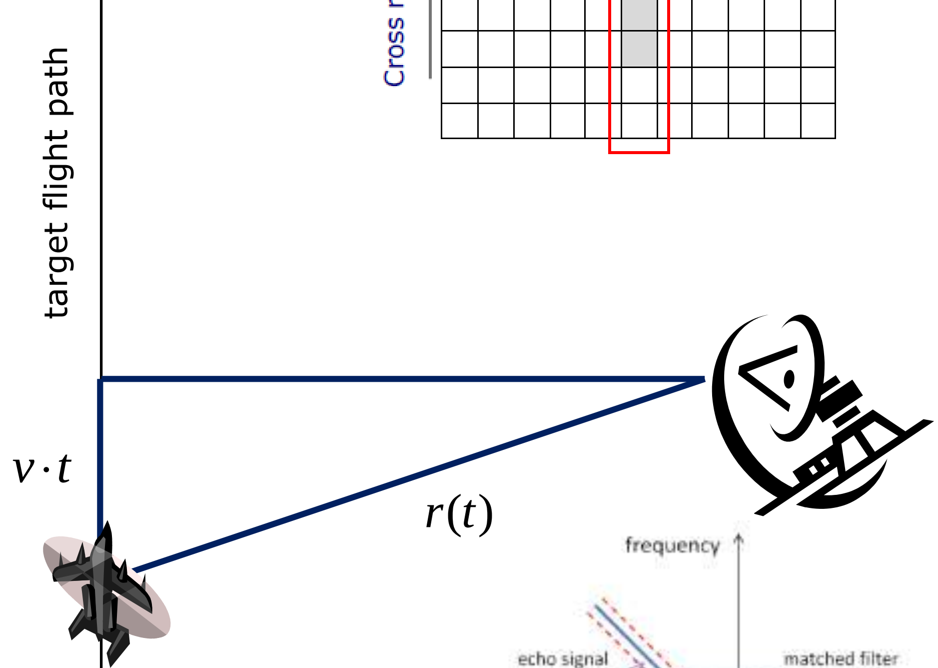
Received phase:

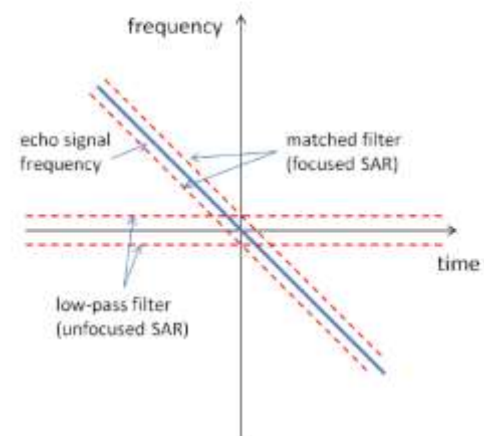
$$\varphi(t) = \varphi_o - \frac{4\pi}{\lambda}\left[R + \frac{(v \cdot t)^2}{2R} + \ldots\right]$$

Received frequency:

$$f(t) = \frac{1}{2\pi}\frac{d\varphi(t)}{dt} \approx -\frac{2v^2}{\lambda R}t$$

LFM signal



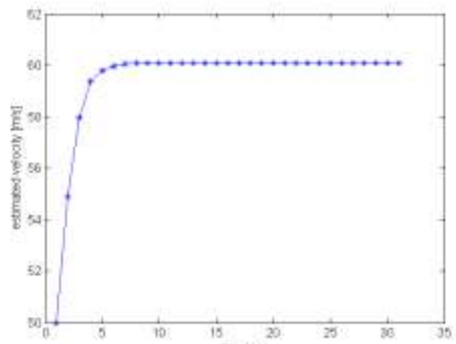


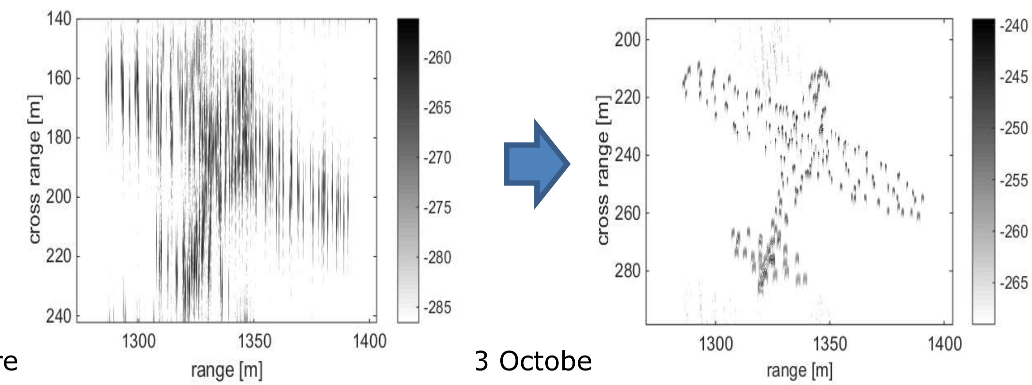
Passive ISAR - Introduction

Pionner work in passive ISAR imaging:

- Martorella, M.; Palmer, J.; Homer, J.; Littleton, B.; Longstaff, I.D., "On Bistatic Inverse Synthetic Aperture Radar," in *Aerospace and Electronic Systems, IEEE Transactions on* , vol.43, no.3, pp.1125-1134, **July 2007**
- D. Olivadese, E. Giusti, D. Petri, M. Martorella, A. Capria, F. Berizzi, R. Soleti, “Passive ISAR imaging of ships by using DVB-T signals”, in Proc. of IET International Conference on Radar Systems 2012
- Olivadese, D.; Giusti, E.; Petri, D.; Martorella, M.; Capria, A.; Berizzi, F., "Passive ISAR With DVB-T Signals," in *Geoscience and Remote Sensing, IEEE Transactions on* , vol.51, no.8, pp.4508-4517, Aug. 2013
- Martorella, M.; Giusti, E., "Theoretical foundation of passive bistatic ISAR imaging," in Aerospace and Electronic Systems, IEEE Transactions on , vol.50, no.3, pp.1647-1659, July 2014
- M. K. Bączyk, P. Samczyński and K. Kulpa, "Passive ISAR imaging of air targets using DVB-T signals," *2014 IEEE Radar Conference*, Cincinnati, OH, 2014, pp. 0502-0506

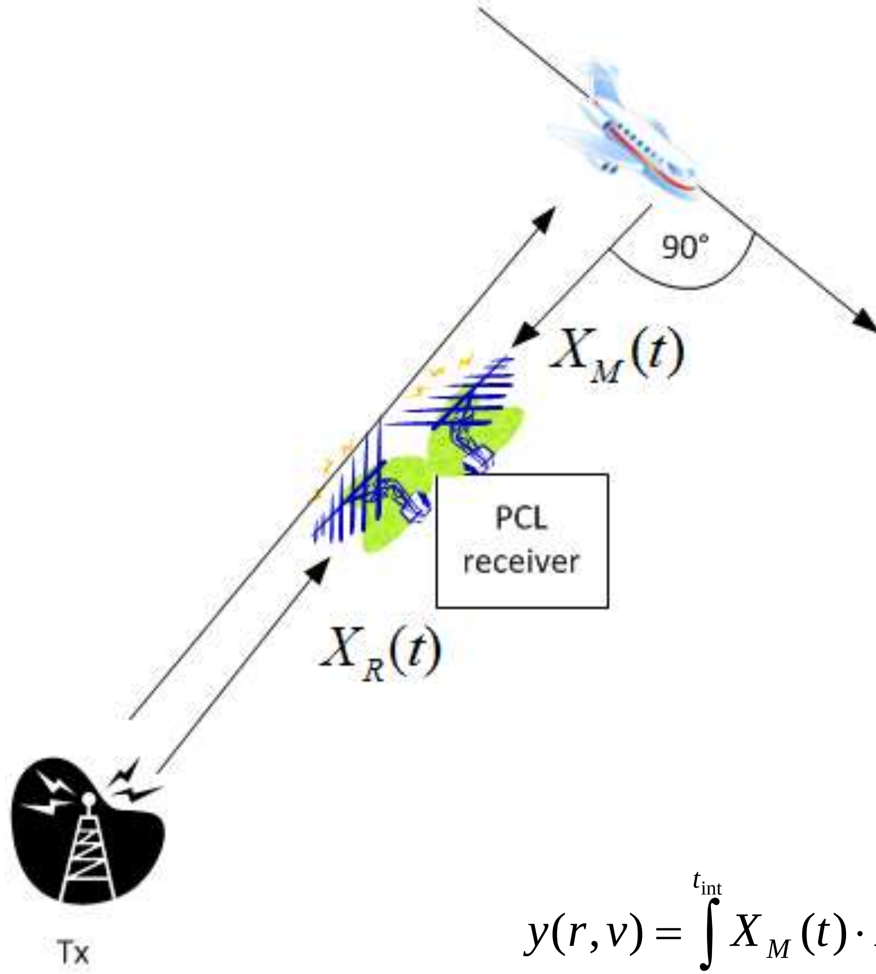
Next step – **use an autofocus techniques** in passive ISAR imaging





Passive ISAR -System geometry

Geometry No. 2



$$y(r,v)=\int_0^{t_{\text{int}}} X_M(t)\cdot X_R^*\left(t-\frac{r(t)}{c}\right)\cdot e^{2\pi\cdot f_C\frac{v}{c}\cdot t}dt$$

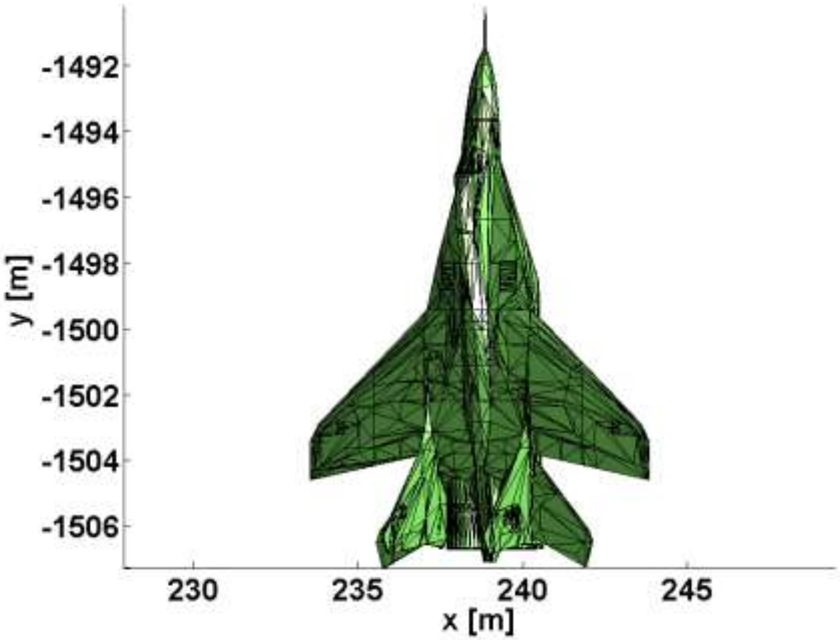
Processing Stages

- Signal acquisition using Commercial-Off-The-Shelf devices
- Seperation of signals from different transmitters
- Clutter cancellation
- Crossambiguity calculation
- CFAR detection
- Bistatic tracking
- Target localization in Cartesian coordinates
  and target trajectory estimation
- ISAR processing

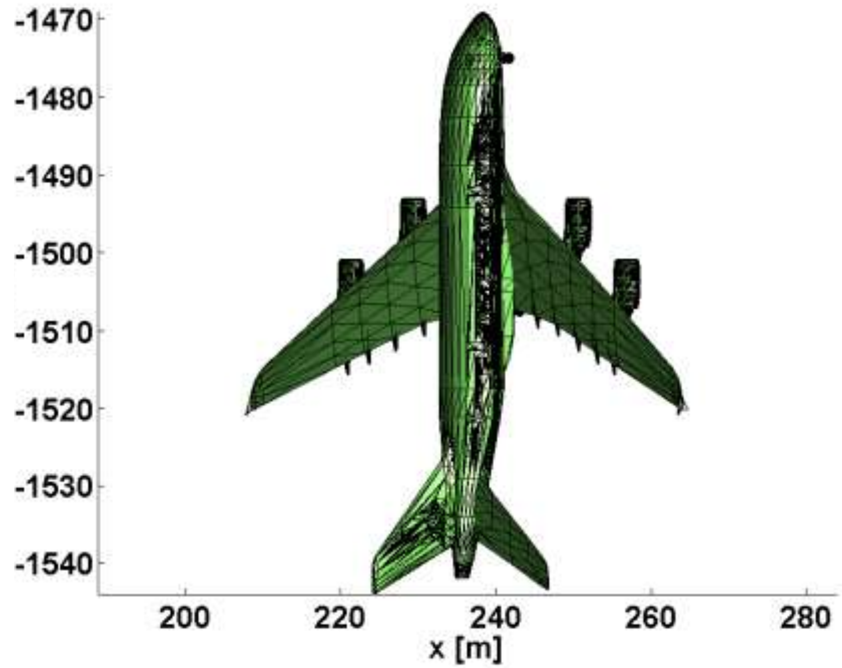
(*) M. K. Bączyk, P Samczyński, K. Kulpa, "Passive ISAR Imaging of air targets using DVB-T signals", in Proceedings of 2014 IEEE Radar Conference, May 19th-23rd, 2014, Cincinnati, OH, USA.

Verifications via Simulations

Simulated targets



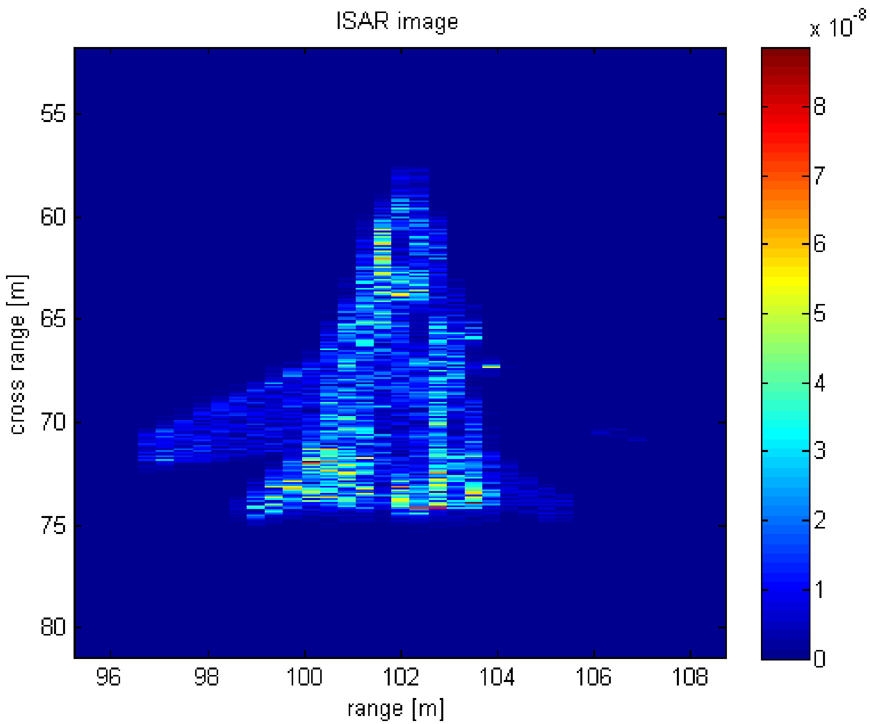
MIG-29



A-380

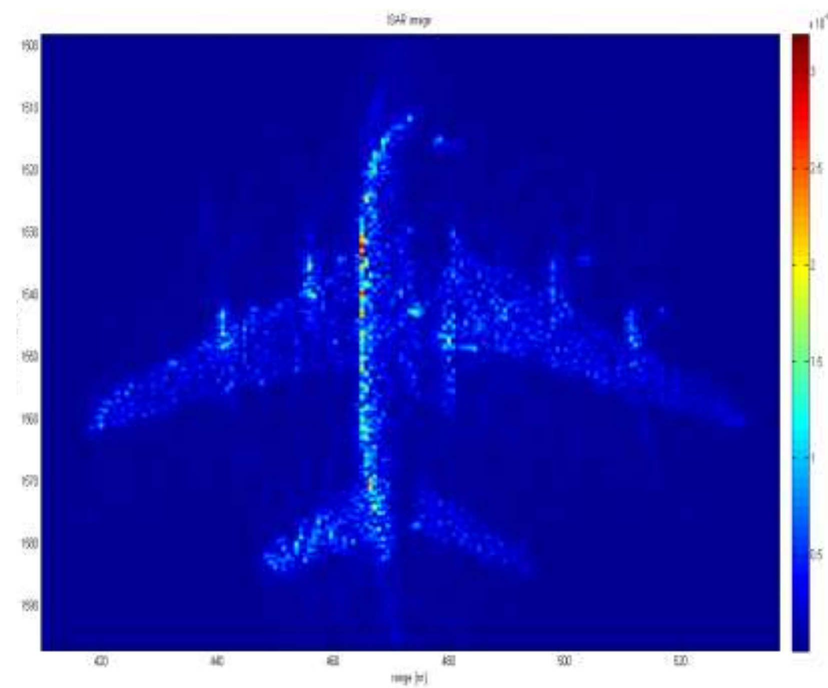
Verifications via Simulations

Simulated targets



MIG-29

(B=400MHz)



A-380

(B=400MHz)

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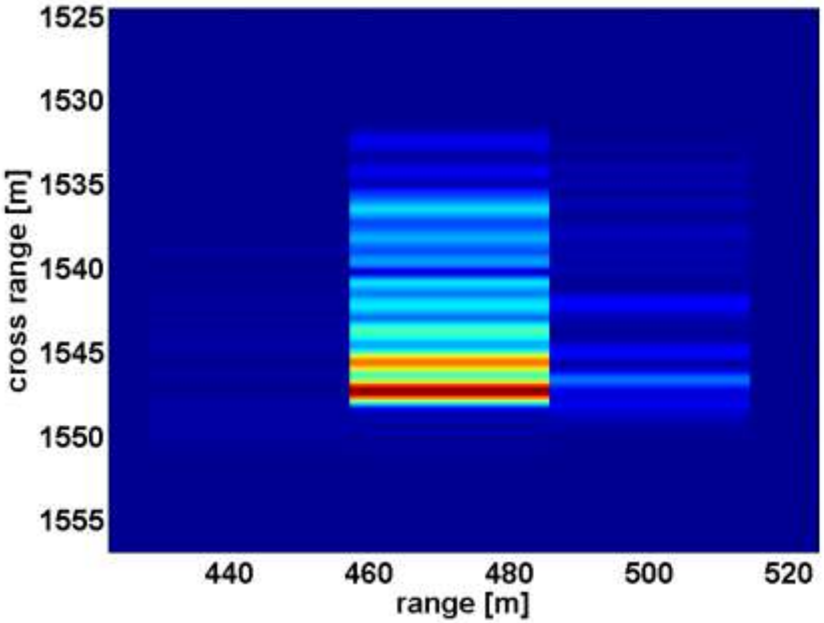
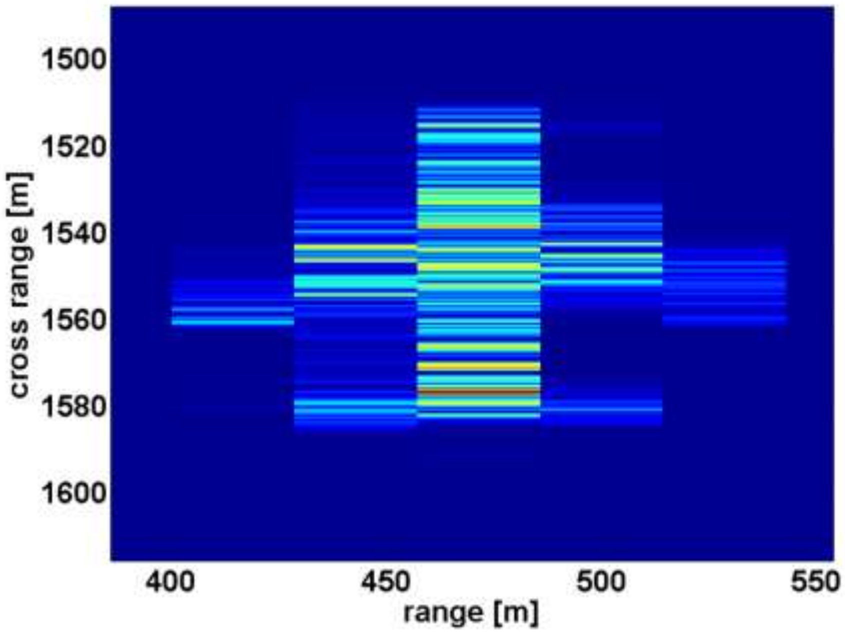
Verifications via Simulations

Simulated targets



MIG-29

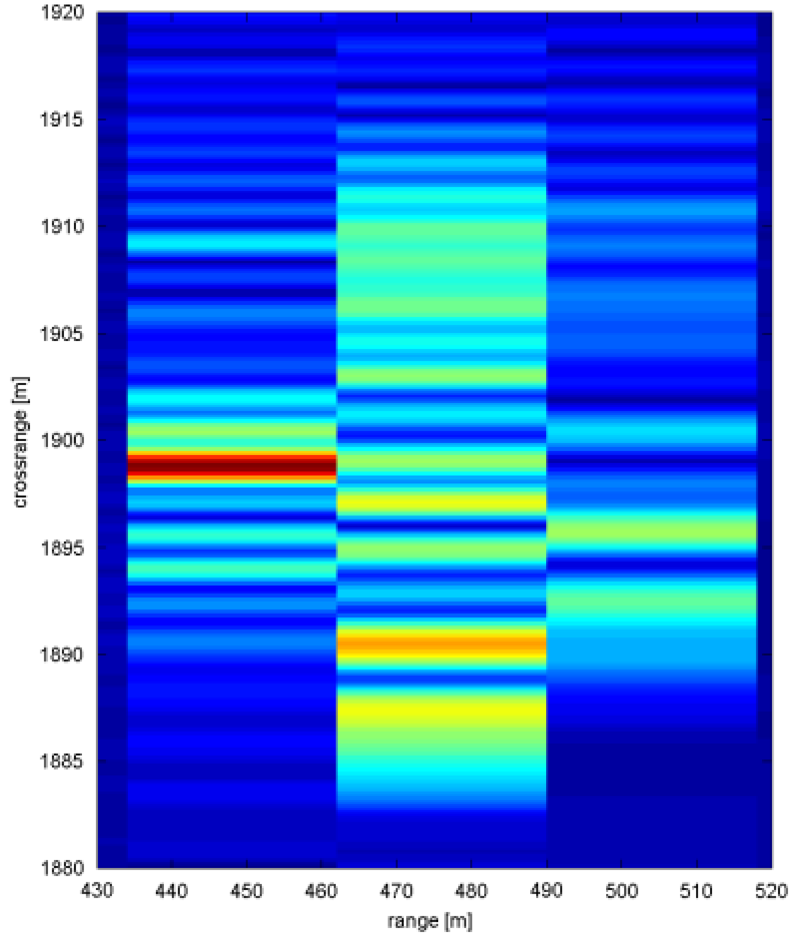
DVB-T illuminator (B=7.8MHz)



A-380

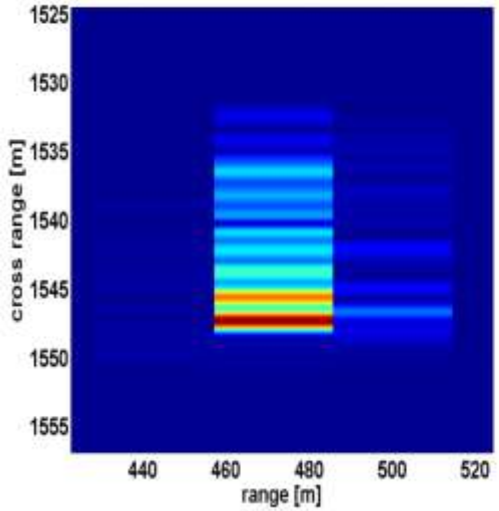
DVB-T illuminator (B=7.8MHz)

Passive ISAR – Measured Results



Passive ISAR image of MIG-29

(real data)

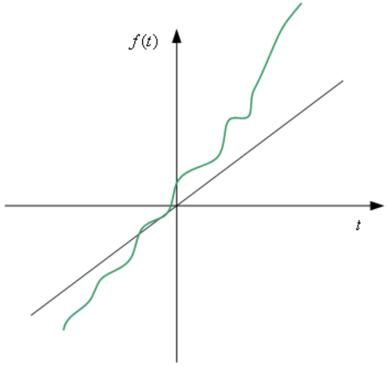


Passive ISAR image of MIG-29

(simulated data)

M. K. Bączyk, P. Samczyński and K. Kulpa, "Passive ISAR imaging of air targets using DVB-T signals," *2014 IEEE Radar Conference*, Cincinnati, OH, 2014, pp. 0502-0506

Autofocusing in Passive ISAR imaging



The 14th European Radar Conference

Present and Future Perspectives of Passive Radar, 13 October 2017, Nuremberg, Germany

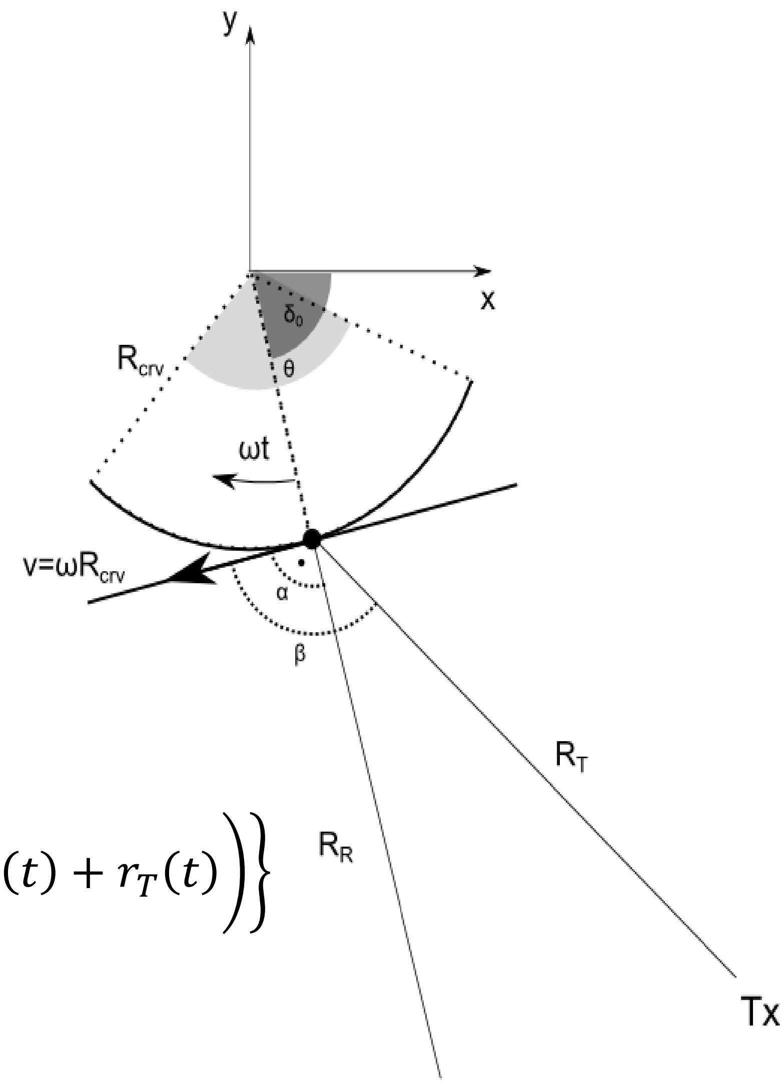
Parametric autofocus

$$C(\omega, R_{crv}, \delta) = \max_t |I(t, \omega, R_{crv}, \delta)|$$

$$I(t, \omega, R_{crv}, \delta) = s_{surv}(t) * h(t, \omega, R_{crv}, \delta)$$

$$s_{surv}(t) = A s_T\left(t - \left(\frac{r_R(t) + r_T(t)}{c}\right)\right) exp\left\{j \frac{2\pi}{\lambda}\left(r_R(t) + r_T(t)\right)\right\}$$

$$h(t) = s^*_{surv}(-t)$$



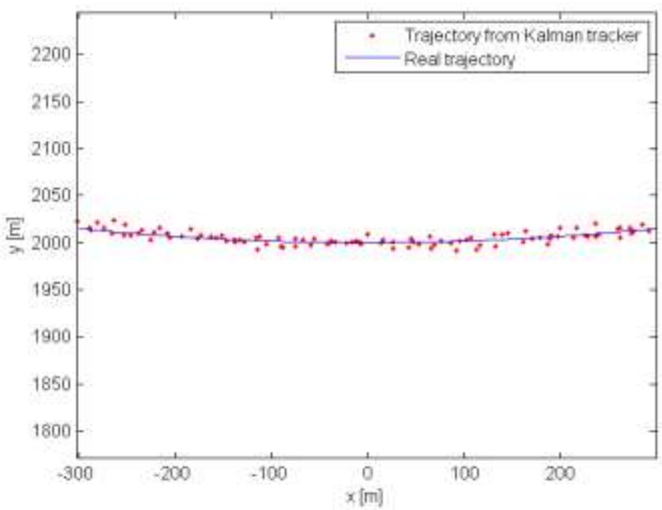
Simulations & verifications

Simulated parameter

Radius of curvature: $\mathrm{R}_{crv} = 3000\,m$

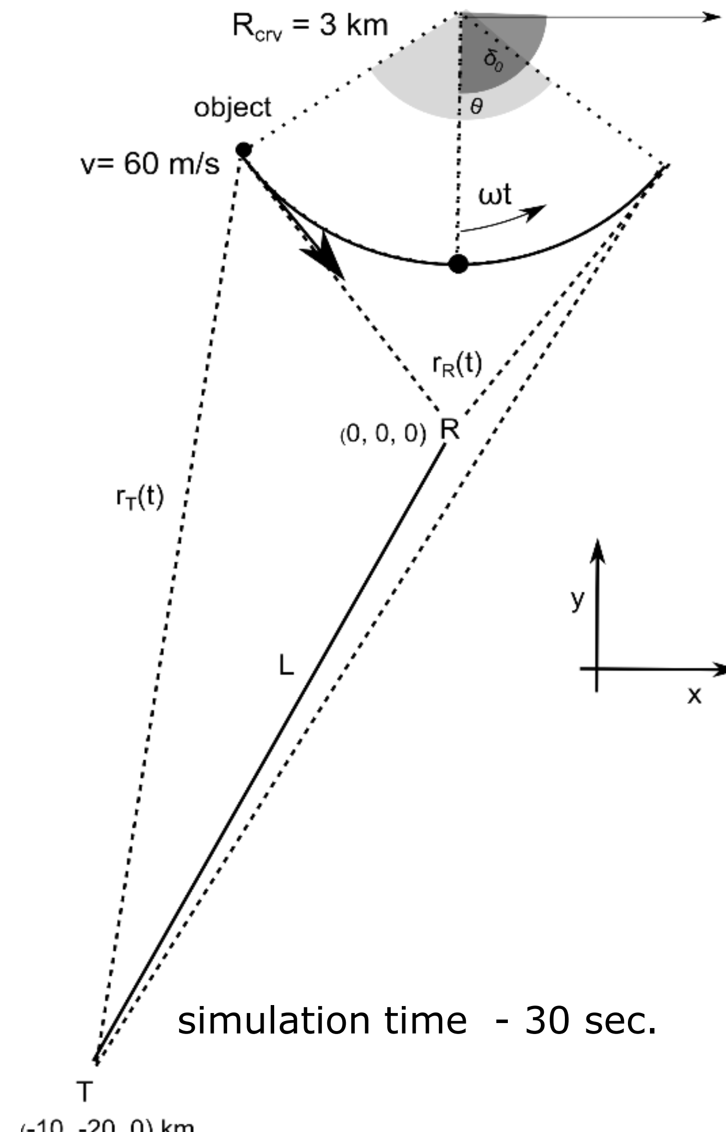
target radial speed: $\omega = 0.02\,\frac{\mathrm{rad}}{\mathrm{s}}$

center angle: $\delta_0 = -pi/2$



estimated initial **parameters** from Kalman Tracker

$$\omega_i = 0.026\,rad/s,$$
$$\mathrm{R}_{crv\_i} = 2294\,m,$$
$$\delta_i = -1.5681\,rad.$$



simulation time - 30 sec.

Results

Real parameters:

Radius of curvature: $R_{crv} = 3000\ m$

target radial speed: $\omega = 0.02 \frac{\text{rad}}{\text{s}}$

center angle: $\delta_0 = -\frac{pi}{2} \approx 1{,}5708$

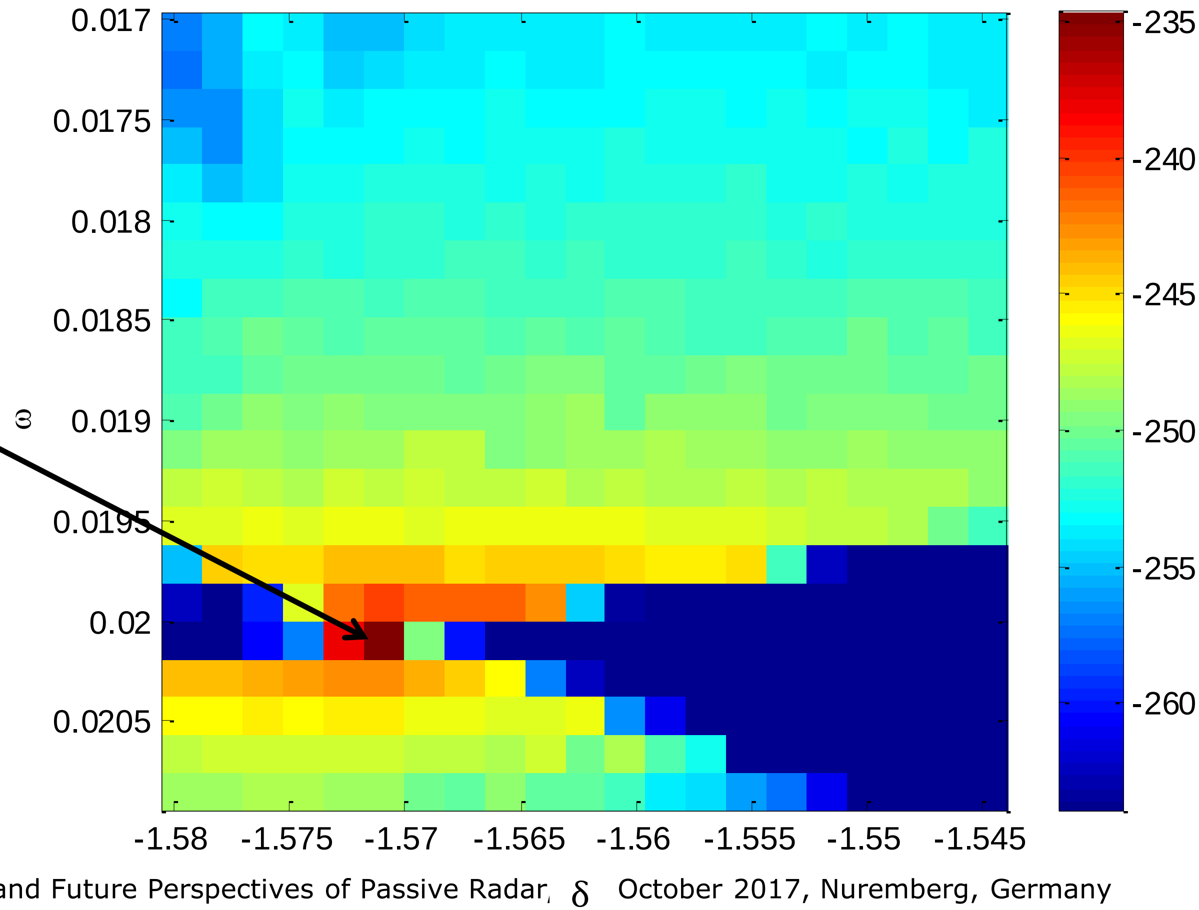
estimated initial **parameters**

$R_{crv\_i} = 2294\ m$

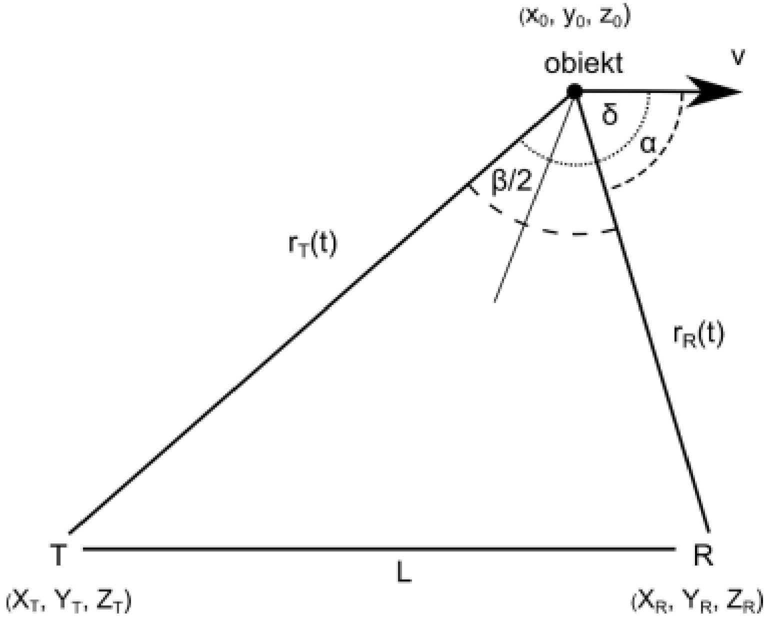
$\omega_i = 0.026\ rad/s,$

$\delta_i = -1.5681\ rad$

$\max_t |I(t, \omega, R_{crv}, \delta)|$



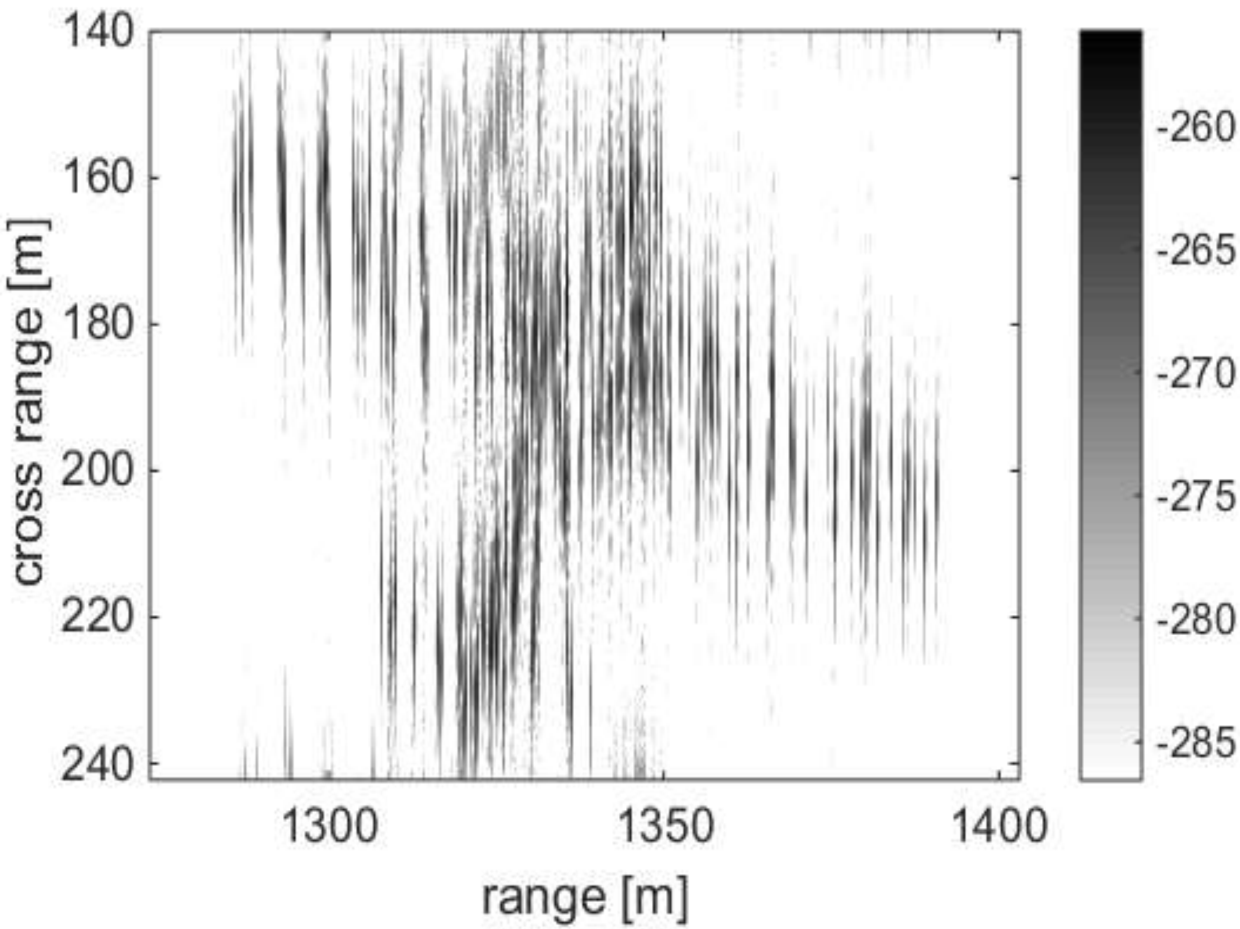
Next steps: use MapDrift Autofocus



$$f_d(t) \approx \frac{1}{\lambda}\left\{v\,[\cos(\delta) + \cos(\alpha)] + v^2 t\left[\frac{\sin^2(\alpha)}{R_R} + \frac{\sin^2(\delta)}{R_T}\right] + \frac{3v^3t^2}{2}\cos(\alpha)\left[\frac{\sin^2(\alpha)}{{R_R}^2} + \frac{\sin^2(\delta)}{{R_T}^2}\right]\right\}$$

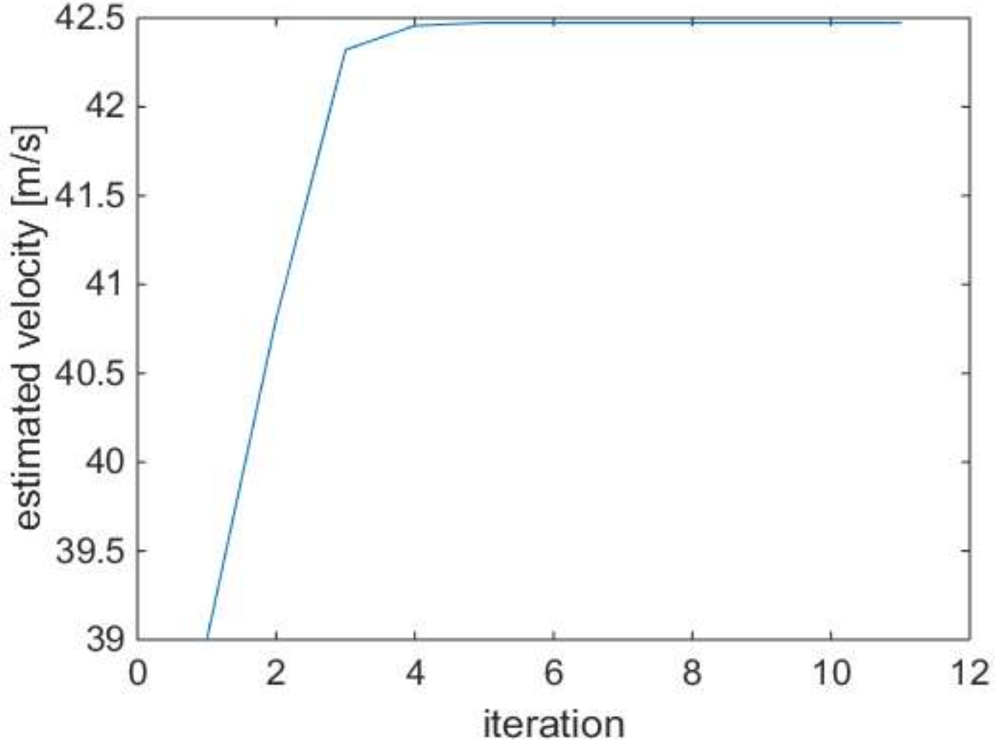
Next steps: use MapDrift Autofocus

ISAR image – unfocus image



Next steps: use MapDrift Autofocus

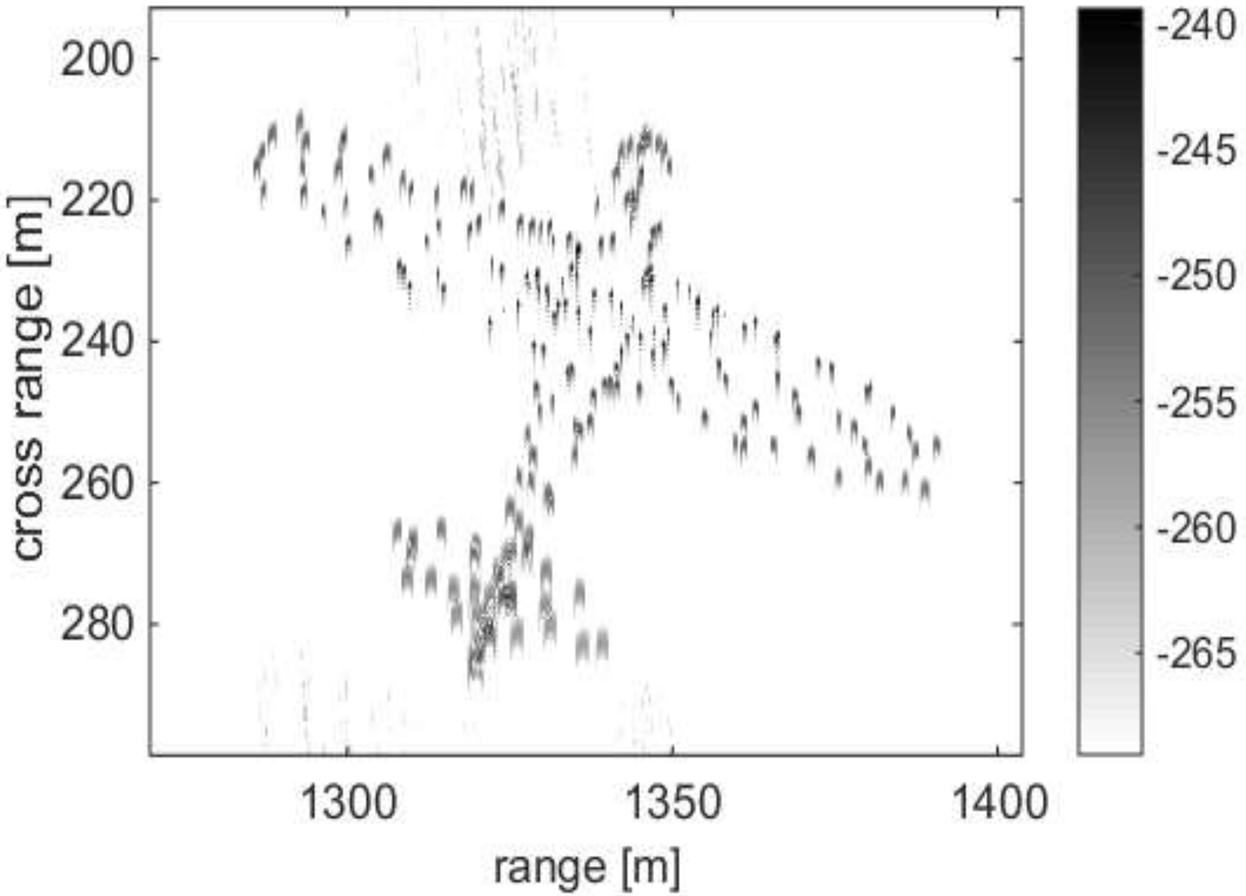
Autofocusing and velocity estimation



$$f_d(t) \approx \frac{1}{\lambda}\left\{v\,[\cos(\delta) + \cos(\alpha)] + v^2 t\left[\frac{\sin^2(\alpha)}{R_R} + \frac{\sin^2(\delta)}{R_T}\right] + \frac{3v^3t^2}{2}\cos(\alpha)\left[\frac{\sin^2(\alpha)}{{R_R}^2} + \frac{\sin^2(\delta)}{{R_T}^2}\right]\right\}$$

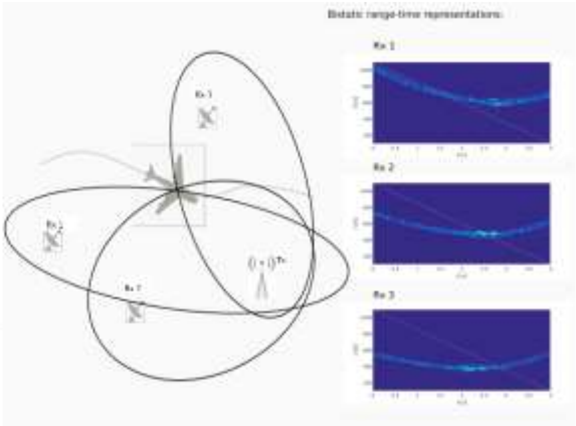
Next steps: use MapDrift Autofocus

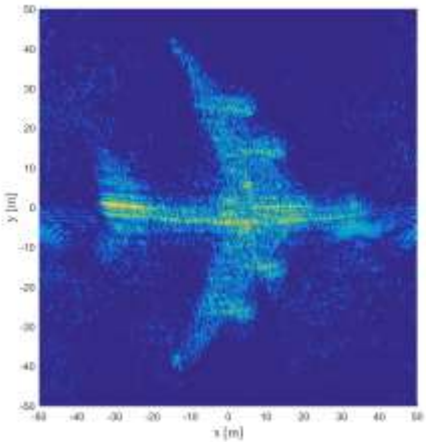
ISAR image – after autofocus



Summary

- Passive SAR/ISAR – still a lot of challenging have to be solved
  An autofocus is one of such a challange…
- Successful verification of the passive SAR/ISAR imaging
- Potential possibility of ground, sea and air target classification
- Enhance functionality - cooperation of active and passive sensors
- Further research is required
- Multiple receivers for passive SAR/ISAR imaging purposes…
  and narrowband passive SAR/ISAR imaging





Thank you for your attention!!