Passive Imaging
Using SAR and ISAR Technology

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- 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
Optical Image
SAR Image


Azimuth + Range compression = 2D SAR image
SAR - How Does It Work?

Azimuth + Range compression = 2D SAR image
Range compression

Slant range resolution:

\[ r_s = \frac{c}{2\beta} \]

Relief displacement in slant-range representation:

\[ r_s \approx h \cdot \sin \theta \]

Relief displacement in slant-range representation:

\[ r_g \approx h \cdot \tan \theta \]

**Ground range resolution:**

\[ r_g = \frac{c}{2\beta \cdot \cos \theta} \]

\[ \beta = 1 \text{GHz} \]

\[ \theta = 30^\circ \]

\[ r_g \approx 17.5 \text{cm} \]
**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:

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

Received phase:

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

Received frequency:

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

LFM signal

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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

\[ \phi(t) = \phi_0 - \frac{4\pi}{\lambda} \left[ R + \frac{(v \cdot t)^2}{2R} \right] \]
SAR Processing
– Limitations and Practical Difficulties:

\[ \phi(t) = \varphi_0 - \frac{4\pi}{\lambda} \left[ R + v \cdot t + \frac{(v \cdot t)^2}{2R} + \ldots \right] = \varphi_0 - \left[ \xi + \chi t + \eta^2 + \ldots \right] \]
SAR Processing
– Limitations and Practical Difficulties:

Fully focus image

\[ \phi(t) = \varphi_o - [\xi + \chi t + \eta^2 + ...] \]

\[ \gamma_2 = \gamma_1 \]

Blurred image (velocity error)

\[ \gamma_2 \neq \gamma_1 \]

Autofocus techniques are required!

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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)

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

\[
\varphi(t) = \varphi_o - \left[ \xi + \chi t + \eta^2 + \ldots \right]
\]
SAR Processing – Limitations and Practical Difficulties:

CO Autofocus Technique

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

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

SAR Processing – Limitations and Practical Difficulties:

CMD Autofocus Technique

CMD cross-correlation function:

\[ r_C(\tau) = \int_{t=-\infty}^{\infty} I_1(t) \cdot I_2^*(t - \tau) e^{-j \Delta f \cdot t} dt \]

where:

\[ \Delta f = 2k\beta T_{ob} / \pi \]

Estimated velocity (**):

\[ \hat{v}_2 = \sqrt{\frac{R \cdot \theta \cdot v_1}{2 \left( \Delta x + \frac{R \cdot \theta}{f_{PRF}} \right) \frac{1}{v_1}}} \]


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

\[ V_r = V \sin(\theta) = \omega R \sin(\theta) \]

Doppler frequency

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

Frequency resolution

\[ \Delta f_d = \frac{1}{T} \]
**ISAR – Inverse SAR**

**Simple ISAR Processing**

- **range (fast time)**
- **azimuth (slow time)**
- **Doppler frequency**


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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, ...)

![Graph showing detection range and range resolution for different systems]
Passive SAR Imaging

- Passive SAR Imaging using non-cooperative satellite-based illumination
- Passive SAR Imaging using commercial ground based illuminators
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
- Unknown Tx trajectory

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


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Passive SAR Imaging Results

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

2012 April 07

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


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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

Passive SAR Imaging Results

2012 July 19


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Challenges:

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


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Passive SAR Imaging

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

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System Geometry

Illuminator: Ground-based DVB-T transmitter
System Geometry

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

\[ l_{\text{TxRx}}(t) \approx L_{\text{TxRx}} + \frac{(vt)^2}{2L_{\text{TxRx}}} + \frac{vt}{2L_{\text{TxRx}}} \]

Rx to target distance:

\[ l_{\text{ORx}}(t) \approx L_{\text{ORx}} + \frac{(vt)^2}{2L_{\text{ORx}}} + \frac{vt}{2L_{\text{ORx}}} \]

Signal phase in reference channel:

\[ \varphi_{\text{Ref}}(t) = \frac{2\pi \cdot l_{\text{TxRx}}(t)}{\lambda} \]

Signal phase in reference channel:

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

Range compression:

\[ s_{\text{xcorr}}(\tau) = \int s_{\text{Ref}}(t) \cdot s_{\text{Echo}}^*(t + \tau)dt \]
System Geometry

Ground objects are imaged at the distance:

\[ R_{Obj}(t) = L_{TxO} + l_{ORx}(t) - l_{TxRx}(t) \]

Target Phase:

\[ \varphi_{Obj}(t) = \frac{2\pi R_{Obj}(t)}{\lambda} = \varphi_{Surv}(t) - \varphi_{Re_f}(t) = \]

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

Distance to target:

\[ R_{Obj}(t) = \frac{1}{2}(\frac{1}{L_{ORx}} - \frac{1}{L_{TxRx}})(vt)^2 + \]

\[ + \frac{1}{2}(\frac{1}{L_{ORx}} - \frac{1}{L_{TxRx}})vt + \]

\[ + (L_{TxO} + L_{ORx} - L_{TxRx}) \]

The Doppler frequency:

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

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


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Verifications via Experiments

Trial No 1
Verifications via Experiments

40 seconds of integration time
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


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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:

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

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:

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

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Pionner work in passive ISAR imaging:


Next step – use an autofocus techniques in passive ISAR imaging
Passive ISAR - System geometry

Geometry No. 2

\[ y(r, v) = \int_{0}^{t_{\text{int}}} X_M(t) \cdot X_R^\ast \left( t - \frac{r(t)}{c} \right) \cdot e^{2\pi f_c \frac{v}{c} t} \ dt \]
Processing Stages

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

Verifications via Simulations

Simulated targets

MIG-29

A-380
Verifications via Simulations
Simulated targets

ISAR image

MIG-29
(B=400MHz)

A-380
(B=400MHz)
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)


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Autofocusing in Passive ISAR imaging
Parametric autofocus

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

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

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

\[ h(t) = s_{surv}^*(-t) \]
Simulations & verifications

**Simulated parameter**
- Radius of curvature: $R_{crv} = 3000 \, m$
- Target radial speed: $\omega = 0.02 \frac{rad}{s}$
- Center angle: $\delta_0 = -\pi/2$

---

**estimated initial parameters** from Kalman Tracker

- $\omega_i = 0.026 \, rad/s$
- $R_{crv_i} = 2294 \, m$
- $\delta_i = -1.5681 \, rad$. 

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Results

**Real parameters:**
Radius of curvature: $R_{crv} = 3000 \text{ m}$
Target radial speed: $\omega = 0.02 \text{ rad/s}$
Center angle: $\delta_0 = -\frac{\pi}{2} \approx 1.5708$

**Estimated initial parameters**
$R_{crv,i} = 2294 \text{ m}$
$\omega_i = 0.026 \text{ rad/s}$,
$\delta_i = -1.5681 \text{ rad}$

$max_t | I(t, \omega, R_{crv}, \delta) |$
Next steps: use MapDrift Autofocus

\[ f_d(t) \approx \frac{1}{\lambda} \left\{ v \left[ \cos(\delta) + \cos(\alpha) \right] + v^2 t \left[ \frac{\sin^2(\alpha)}{R_R} + \frac{\sin^2(\delta)}{R_T} \right] + \frac{3v^3 t^2}{2} \cos(\alpha) \left[ \frac{\sin^2(\alpha)}{R_R^2} + \frac{\sin^2(\delta)}{R_T^2} \right] \right\} \]
Next steps: use MapDrift Autofocus

ISAR image – unfocus image
Next steps: use MapDrift Autofocus

Autofocusing and velocity estimation

\[ f_d(t) \approx \frac{1}{\lambda} \left\{ v [\cos(\delta) + \cos(\alpha)] + v^2 t \left[ \frac{\sin^2(\alpha)}{R_R} + \frac{\sin^2(\delta)}{R_T} \right] + \frac{3v^3 t^2}{2} \cos(\alpha) \left[ \frac{\sin^2(\alpha)}{R_R^2} + \frac{\sin^2(\delta)}{R_T^2} \right] \right\} \]
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 challenge...*
- 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!!