GNSS-based passive radar

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GNSS-based passive radar

... as a Synthetic Aperture Radar (SAR)

- Basic concepts
  - SAR fundamentals
  - Intro to passive SAR using GNSS
  - GNSS-SAR image formation and experimental results
- Advanced future concepts:
  - CCD – Coherent Change Detection
  - Multi-perspective imaging
  - Multi-static imaging

... as a radar

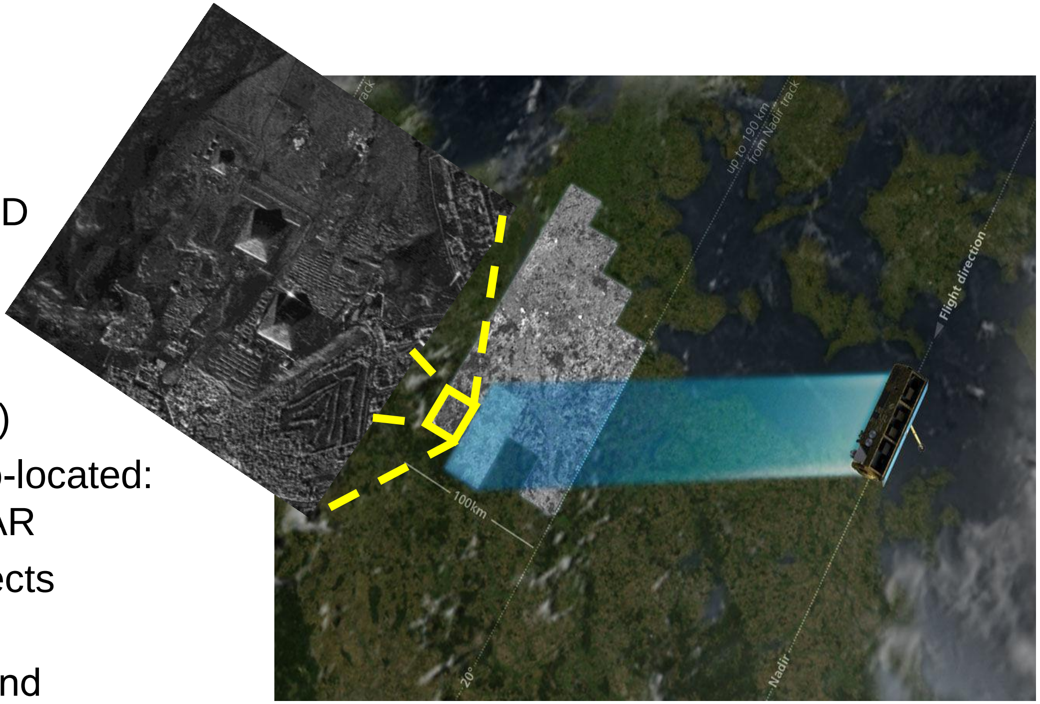
- GNSS-passive radar for maritime surveillance:
  - Intro to using GNSS for passive sea target detection;
  - Basic/advanced processing and experimental results

SAR Fundamentals

The basics

- Synthetic Aperture Radar (SAR):
  An imaging radar that can generate 2-D images

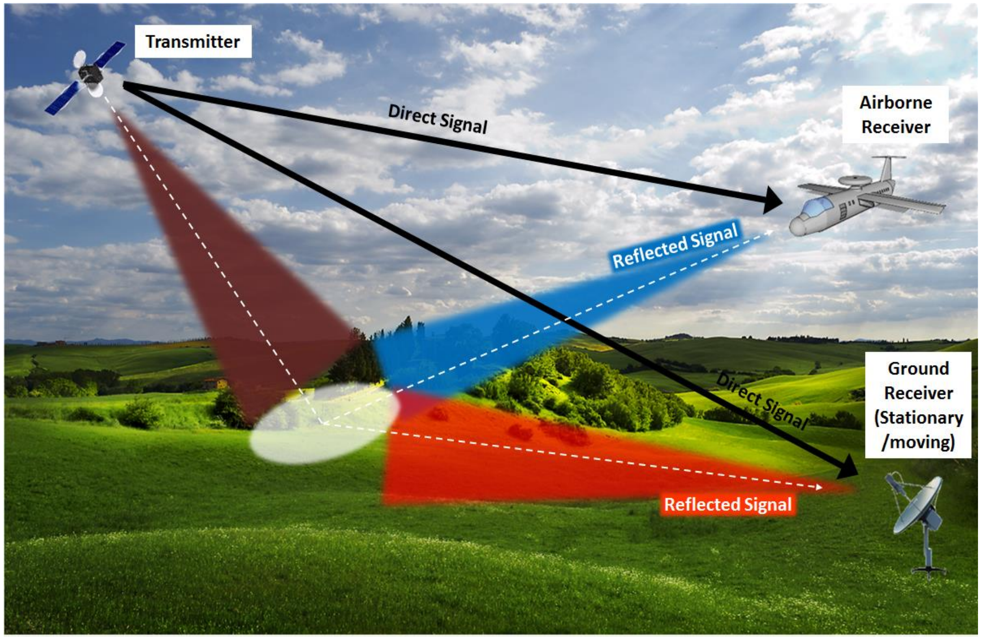
- How it works:
  - Mount radar on moving platform(s)
  - If transmitter/receiver antennas co-located: monostatic SAR. If not, bistatic SAR
  - As the platform moves, radar collects echoes from an observed scene
  - Echoes are "focused" in forward and lateral ranges using DSP to give a 2-D image (radar reflectivity map) of the scene
  - Main point: Through DSP, a "synthetic" antenna aperture is formed that is equal to the physical length travelled by the platform- SAR requires motion of transmitter of receiver (or both)



Images © DLR

GNSS-based SAR

- A bistatic, and passive SAR
- Transmitter: A navigation satellite (GPS, GLONASS, Galileo, Beidou etc.)
- Receiver: On or near the Earth's surface, can be fixed or moving.
- 2-channel receiver:
- One antenna looking towards the satellite(s)- signal synchronisation
- One towards the imaging scene- image formation
- Same configuration for all passive/bistatic SAR



Why GNSS?

Advantages

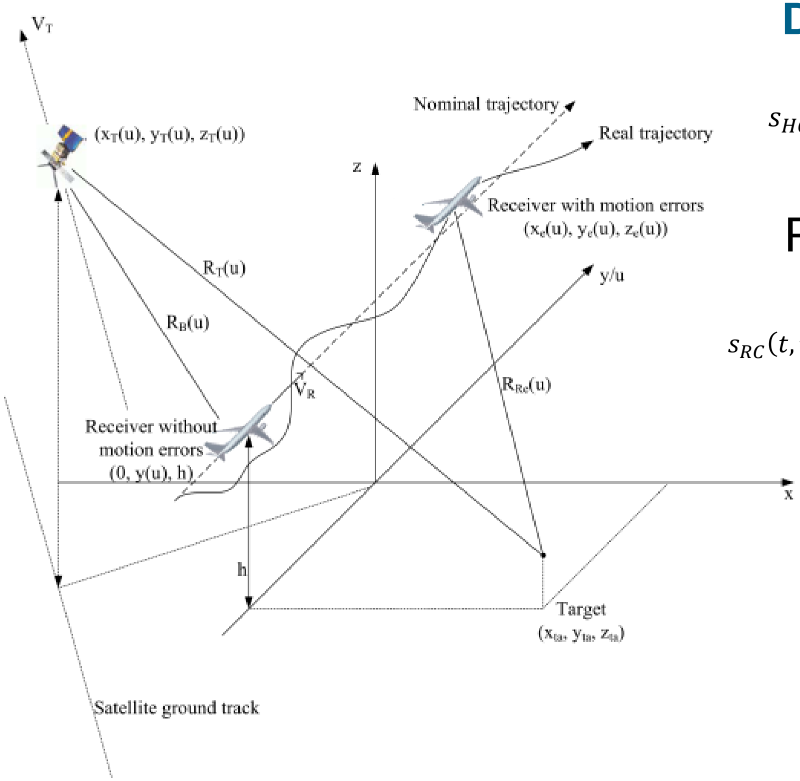
- Low cost– receiver only, standard navigation receiver (even lower).
- Covert operation.
- Persistent and global monitoring – at any time of the day, at any point on Earth, there are 6-8 satellites overhead, and up to 32 when all 4 GNSS systems are fully operational.
- Choice of optimal positions of the satellites– better resolution and less shadowing.
- Multi-angle and multi-static capabilities

Challenges

- Coarse resolution– 30m for GLONASS L1,15m for GALILEO E5a/b band (quasi-monostatic). Not good for hi-res applications, but good enough for Earth Observation.
- Low Signal-to-Noise Ratio (SNR)– due to low GNSS power flux density near the Earth. But can be fixed by long dwell times on target (5mins to see buildings up to few km range)

Clearly, active SAR is better in terms of resolution/power budget. But GNSS structure offers features not currently available with active systems

Geometry and signal model



An example of GNSS-based SAR geometry (with airborne receiver)

Direct signal (Heterodyne Channel):

$$s_{HC}(t,u) = p\left\{t - \left[\frac{R_B(u)}{c} + t_{e_{Rx}} + t_{e_{atm}}\right]\right\} exp\left\{-j\left[\frac{2\pi}{\lambda}R_B(u) + \varphi_{e_{Rx}} + \varphi_{e_{atm}}\right]\right\}$$

Reflected signal (Radar Channel):

$$s_{RC}(t,u) = p\left\{t - \left[\frac{R_T(u) + R_R(u)}{c} + t_{e_{Rx}} + t_{e_{atm}}\right]\right\} \times exp\left\{-j\left[\frac{2\pi}{\lambda}(R_T(u) + R_R(u)) + \varphi_{e_{Rx}} + \varphi_{e_{atm}}\right]\right\}$$

t, fast time
u, slow time
c, the speed of light
λ, the wavelength
$R_B(u)$, the instantaneous transmitter-receiver baseline
$R_T(u)$, the instantaneous transmitter-target range
$R_R(u)$, the instantaneous receiver-target range
$t_{e_{Rx}}$, time delay errors due to receiver artefacts
$\varphi_{e_{Rx}}$, phase errors due to receiver artefacts
$t_{e_{atm}}$, time delay errors due to atmospheric propagation
$\varphi_{e_{atm}}$, phase errors due to atmospheric propagation

Signal processing

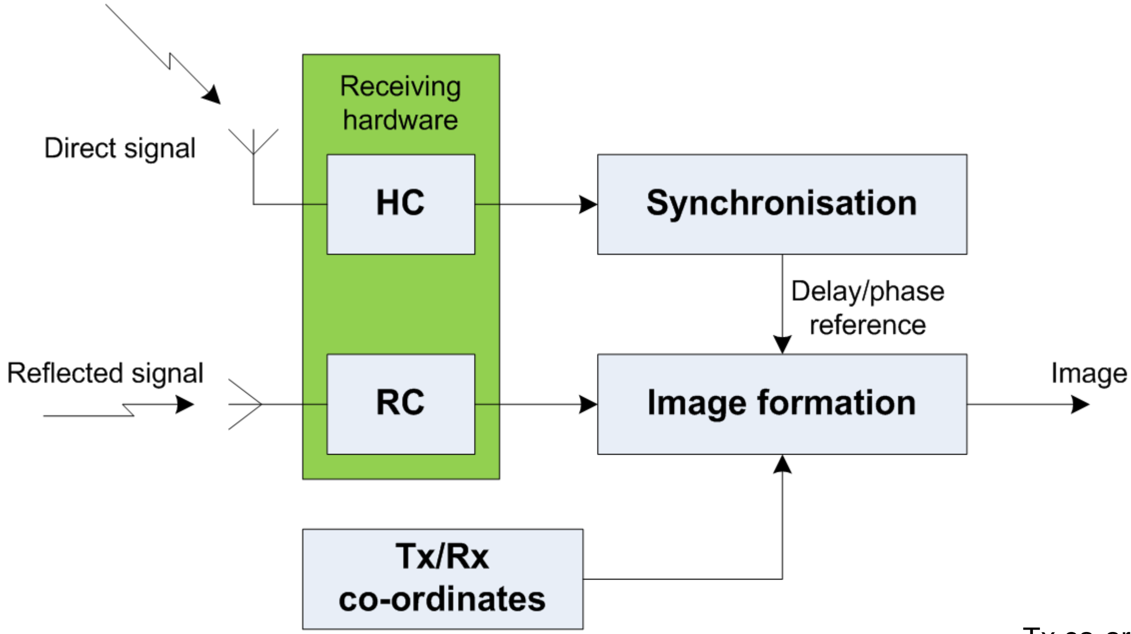


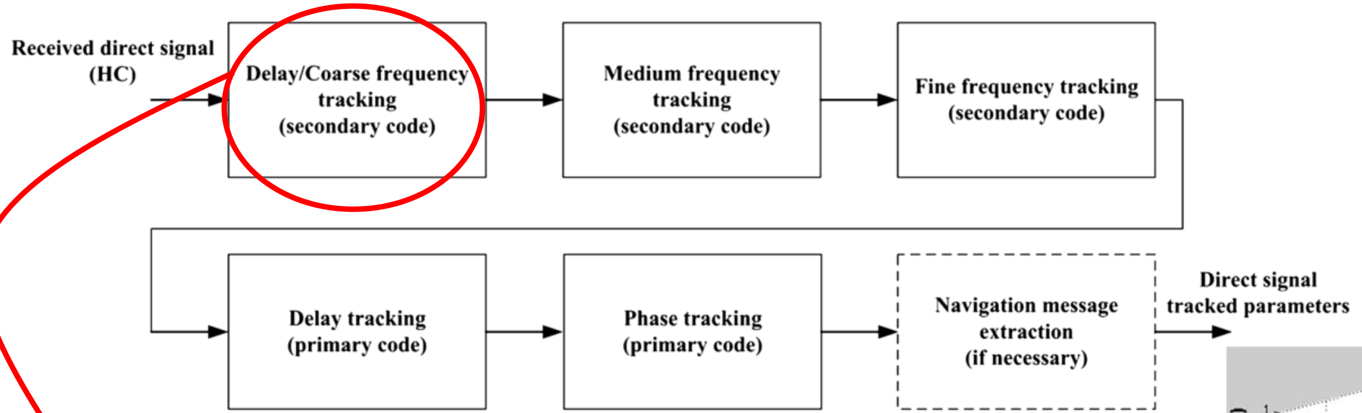
Image formation block diagram

Tx co-ordinates are taken from the online database (Satellite Ephemerides)

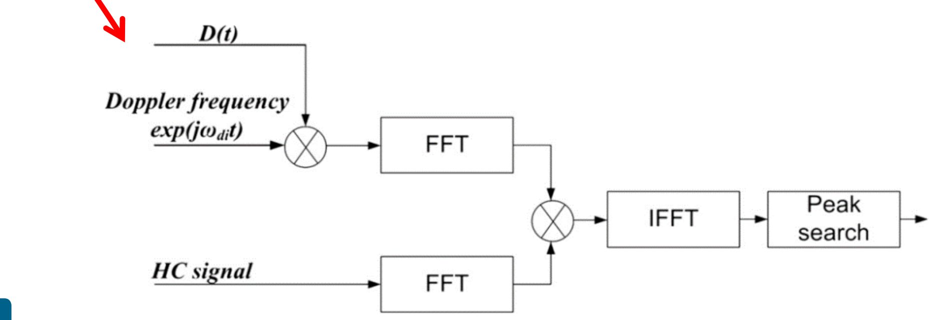
- Direct signal is collected by antenna looking at the satellite (Heterodyne Channel, HC)
- Reflected signal is collected by helical antenna looking at the observed area (Radar Channel, RC)

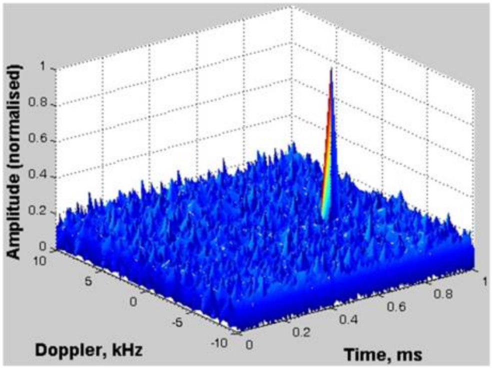
Synchronisation

- SNR at HC antenna output: ~-25 dB, so cannot correlate HC and RC signals directly
- Signal synchronisation: Tracks direct signal properties, then creates a local, noise-free replica- very much same as navigation receiver processing
- This local signal is then used for range compression



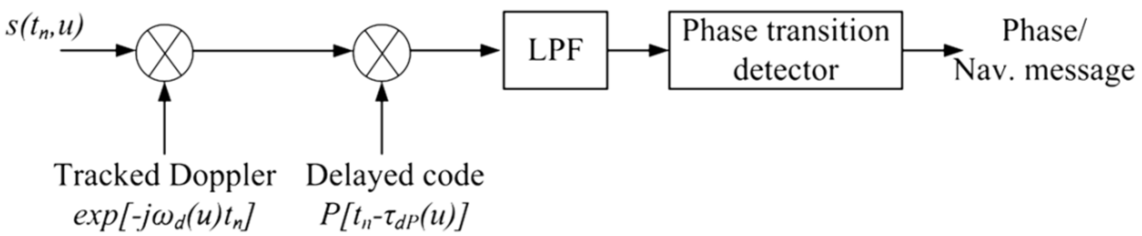
Synchronisation Block Diagram



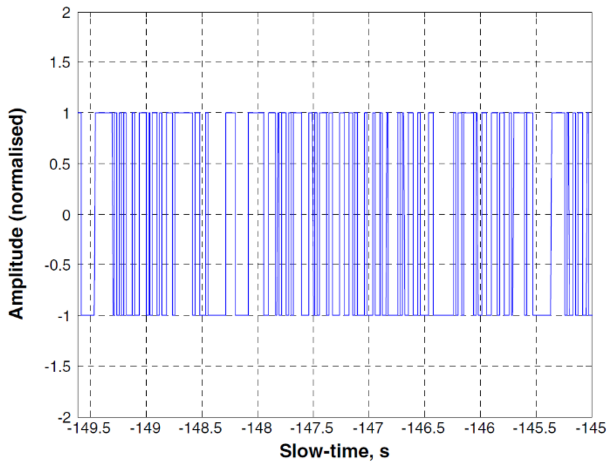


First stage of satellite signal detection

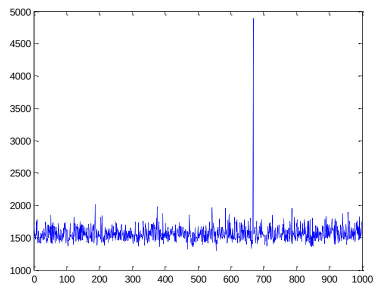
Synchronisation



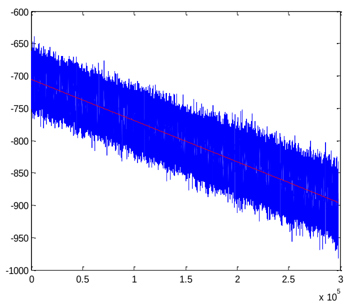
Navigation message extraction block diagram



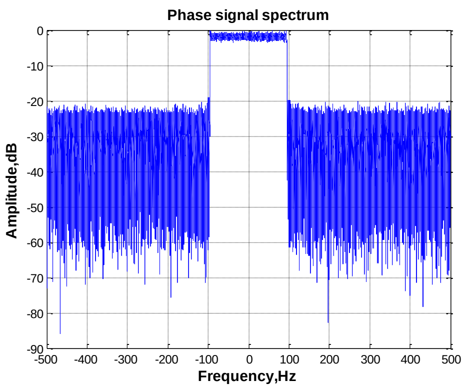
Navigation message extraction



Detect the start of the Primary code in the received signal

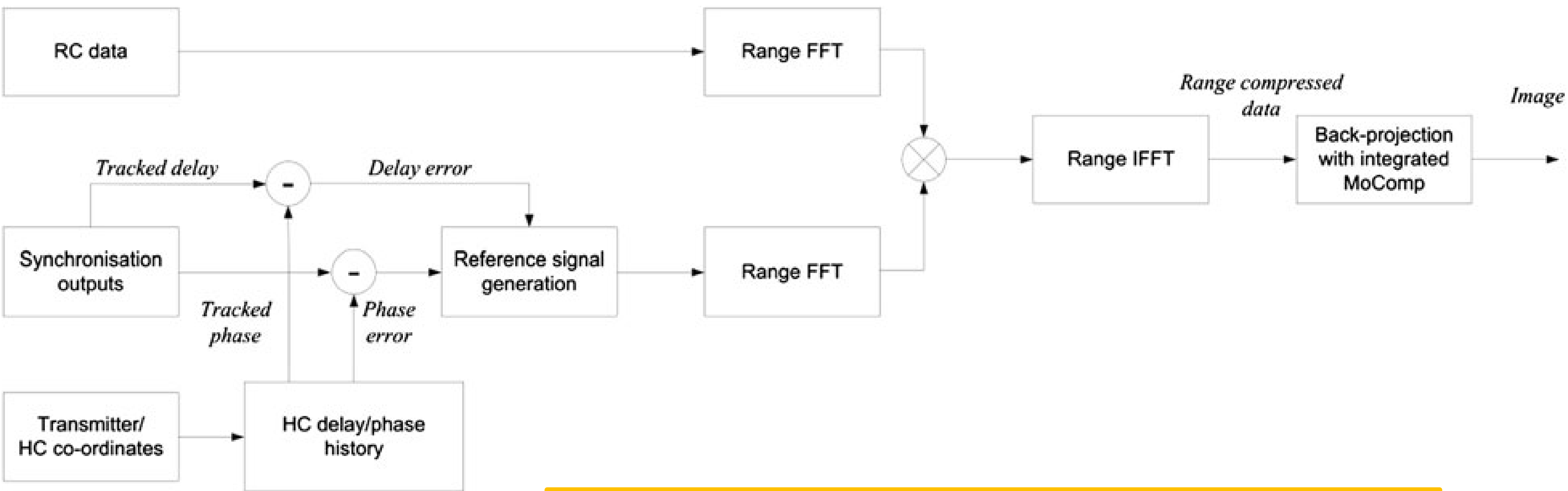


Tracked phase (Doppler)



Signal phase Spectrum

Image formation via back-projection



Phase error = $\left(\varphi_{e_{Rx}} + \varphi_{e_{atm}}\right)$

Delay error = $\left(t_{e_{Rx}} + t_{e_{atm}}\right)$

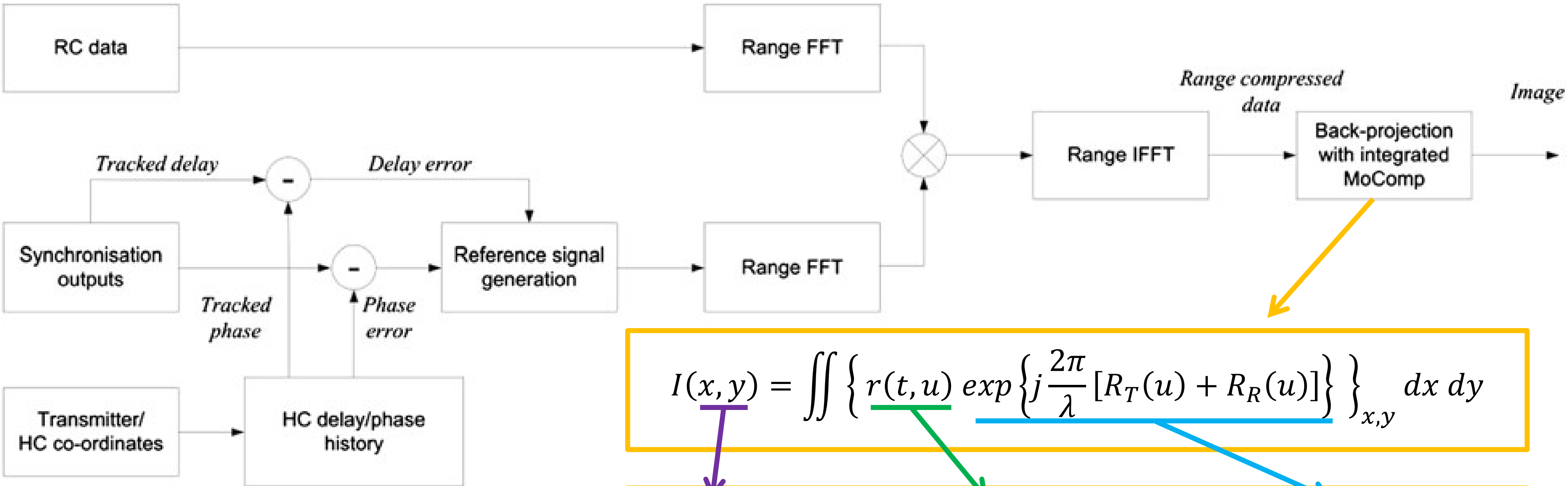
Reference signal:

$$s_0(t,u) = p\left[t - \left(t_{e_{Rx}} + t_{e_{atm}}\right)\right] exp\left[-j\left(\varphi_{e_{Rx}} + \varphi_{e_{atm}}\right)\right]$$

Range-compressed RC data:

$$r(t,u) = R_x\left[t - \frac{R_T(u) + R_R(u)}{c}\right] exp\left\{-j\frac{2\pi}{\lambda}\left[R_T(u) + R_R(u)\right]\right\}$$

Image formation via back-projection



$$I(x,y) = \iint \left\{ r(t,u)\, exp\left\{ j\frac{2\pi}{\lambda}[R_T(u) + R_R(u)] \right\} \right\}_{x,y} dx\, dy$$

Scene grids — Range compression output — Phase

compensation

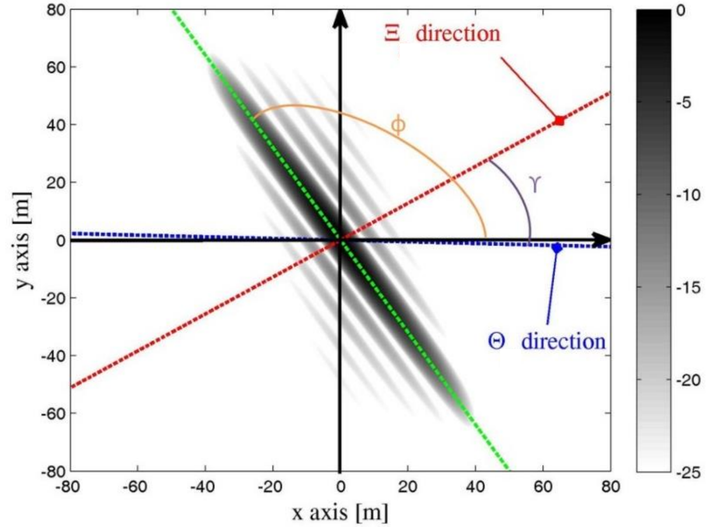
WHY BPA?

- Long dwell-time on target (5mins)- satellite trajectory not a straight line, so frequency-based, more efficient algorithms not so straightforward
- Coarse resolution, limited scene size- not so much data to be processed, so despite bigger computational complexity, the actual difference in processing time can be neglected for offline processing.

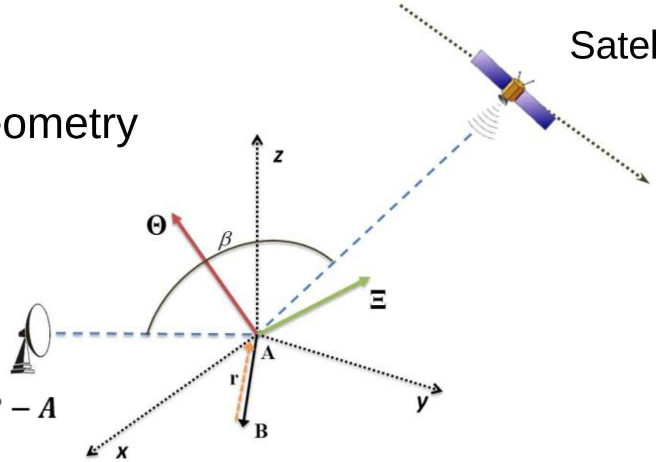
Point Spread Function (PSF)

$$|\chi(A,B)| = \left| p\left(\frac{2\cos\left(\beta/2\right)\boldsymbol{\Theta}^T(\mathbf{B}-\mathbf{A})}{c} \right) \right| \cdot \left| m_A\left(\frac{2\omega_E \boldsymbol{\Xi}^T(\mathbf{B}-\mathbf{A})}{\lambda} \right) \right|$$

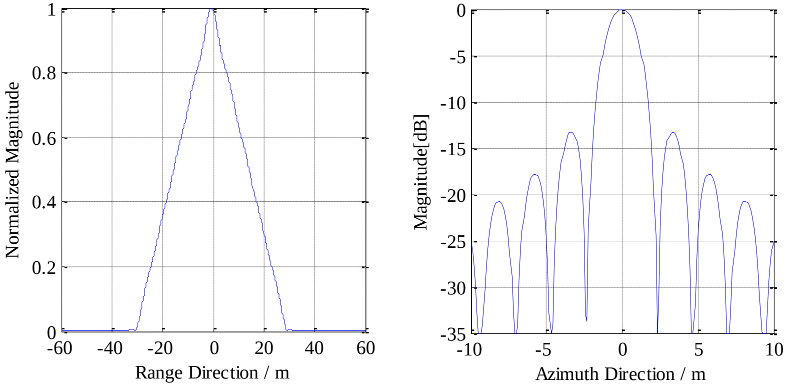
- $\boldsymbol{A}$, the desired point reflector to be evaluated
- $\boldsymbol{B}$, an arbitrary position of another reflector in the vicinity of $\boldsymbol{A}$
- β, the bistatic angle
- $\boldsymbol{\Theta}$, a unit vector in the direction of the bisector
- ω_E, the equivalent angular speed
- $\boldsymbol{\Xi}$, the equivalent motion direction
- c, the speed of light
- λ, the wavelength



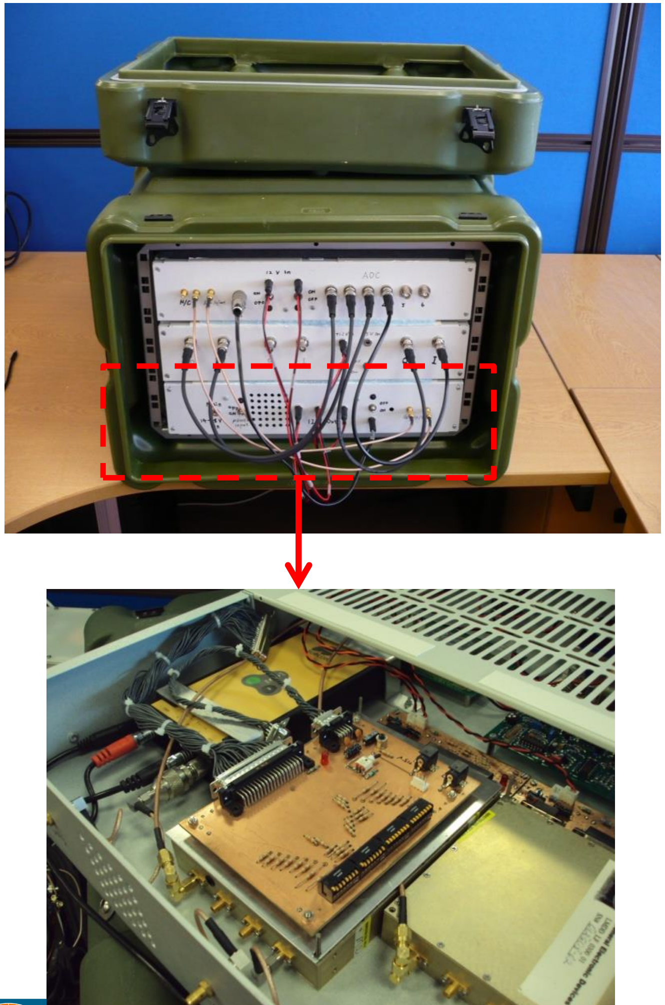
BSAR Geometry



Cross-sections

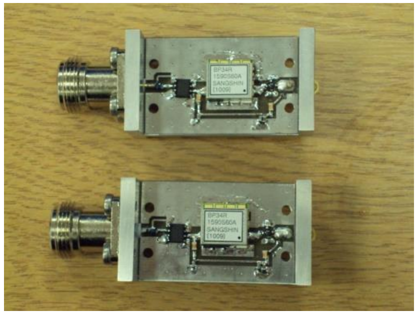


Experimental prototype

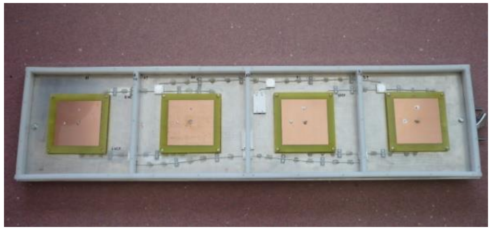


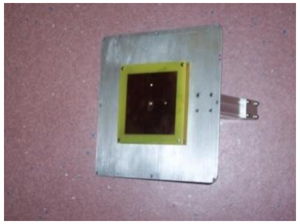
- Receiver prototype
  - 2-channel, super-heterodyne receiver
  - Digital I/Q outputs
  - All channels locked on same clocks/L.O.'s
  - GLONASS /GPS/Galileo E5

- RF front-end (filter+LNA)



- High- (RC) and low-gain (HC) antennas (15 dBi, 6 dBi) – RHCP and LHCP (dual-pol)

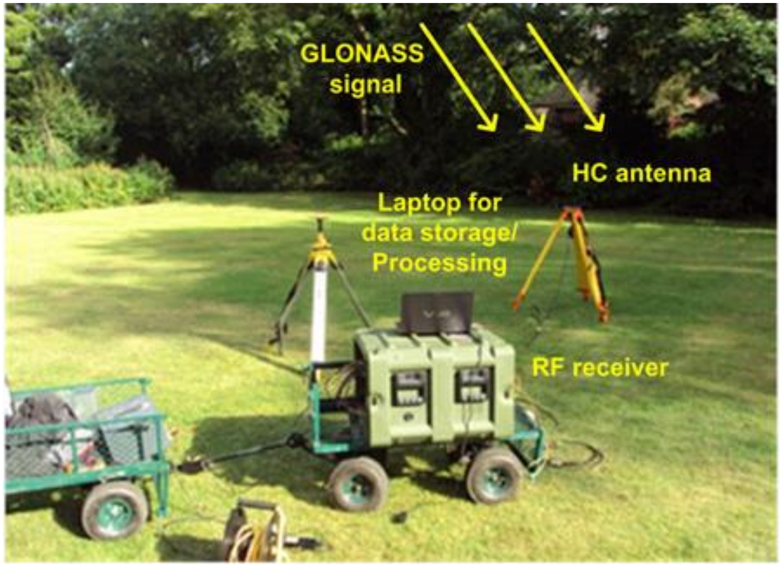




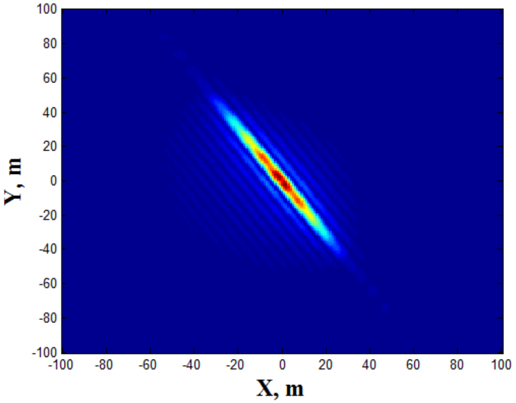
Experimental PSF

Tab.1 Experimental parameters of the fixed receiver trail

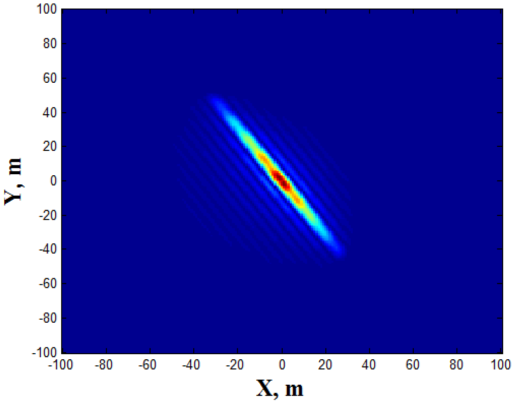
Parameters	Value
Satellite	GLONASS COSMOS 736
Satellite signal	P-code
Signal bandwidth	5.11 MHz
Carrier frequency	1600.875 MHz
Equivalent PRF	1 KHz
Dwell time	300s
Satellite elevation during acquisition(relevant to HC antenna)	70.6°-72.7°



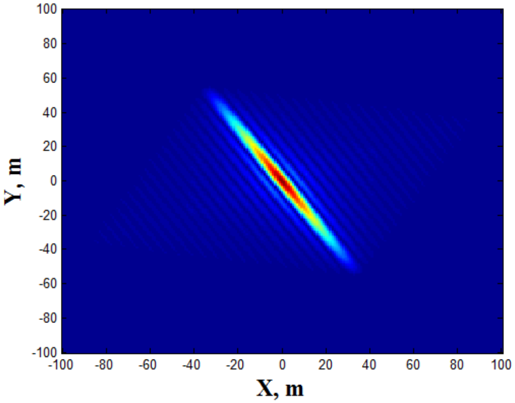
Experimental PSF



BP simulated PSF

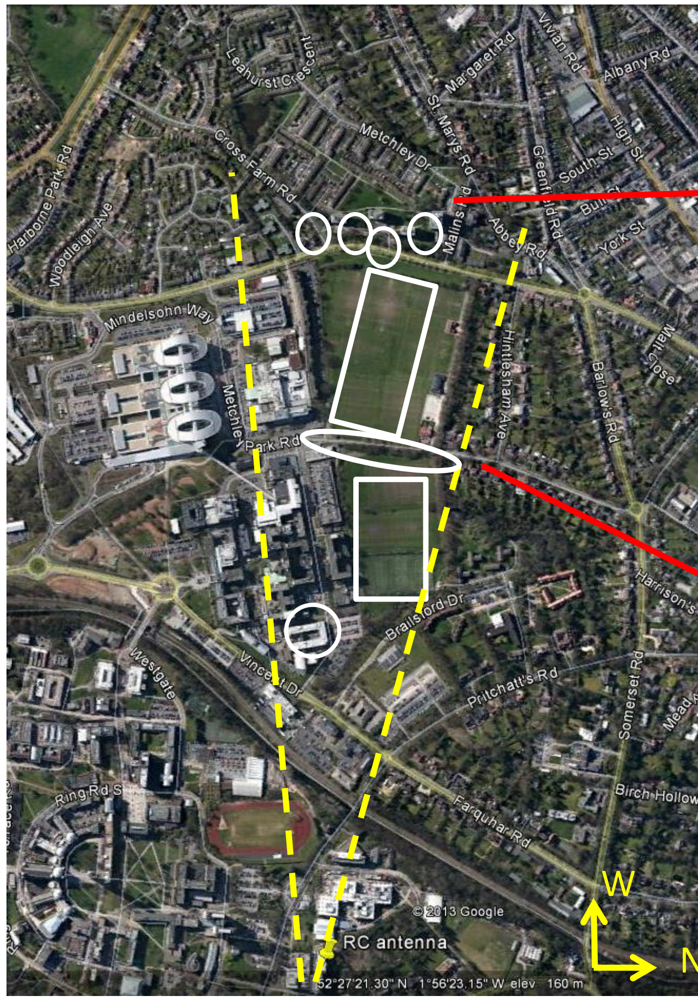


Theoretically computed PSF

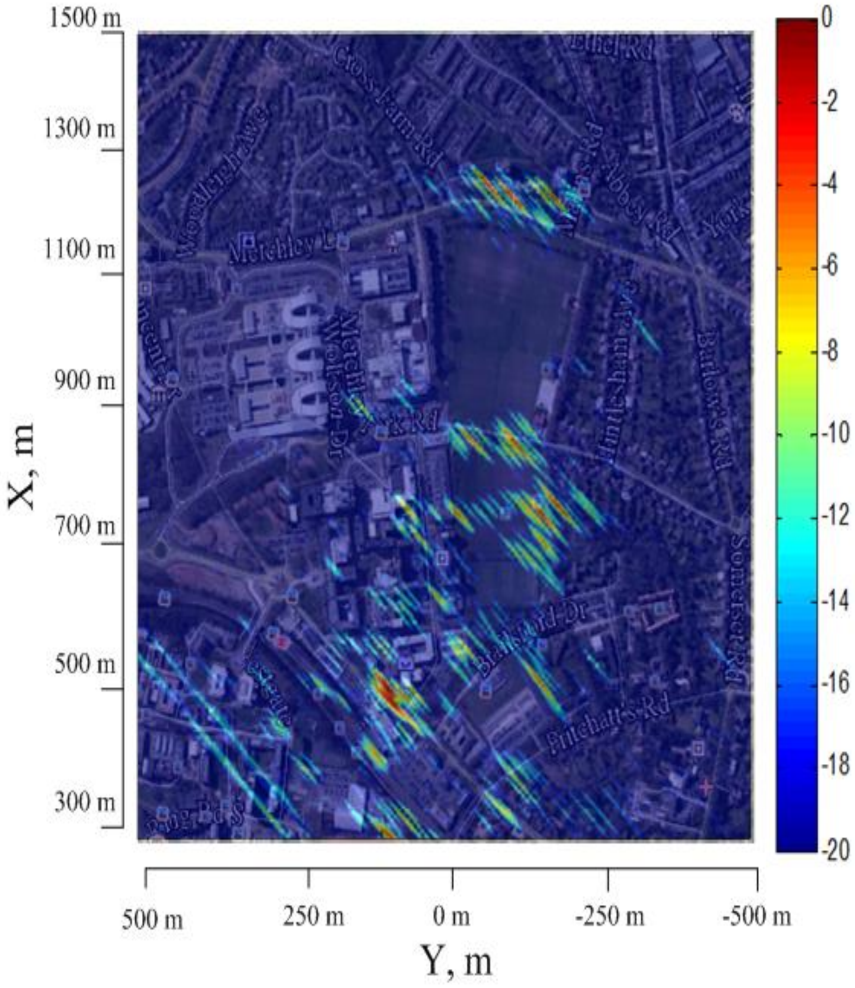


Experimental images- fixed receiver

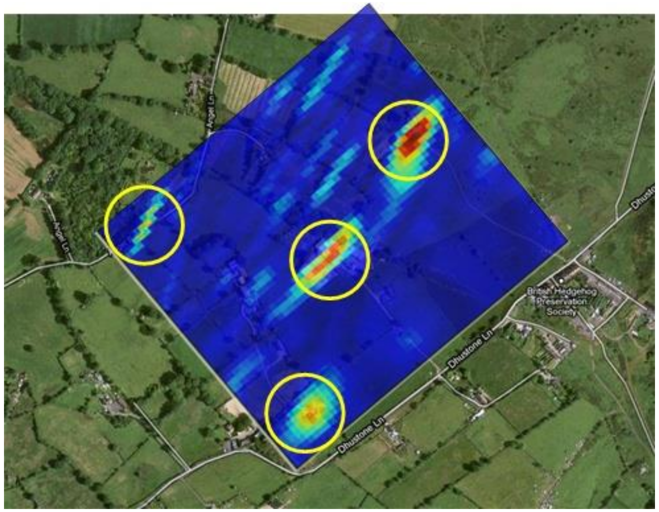
Experimental setup



Experimental images- fixed receiver

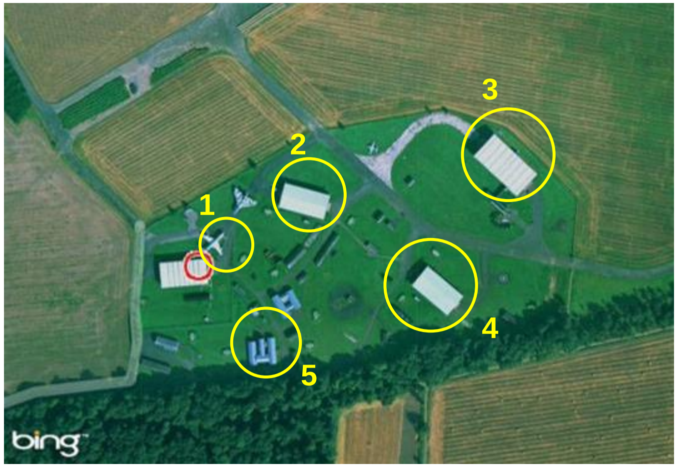


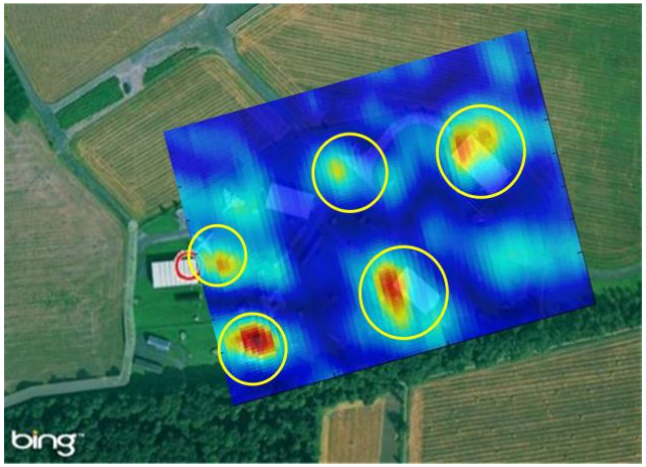
Experimental images- moving receiver



Experimental images- moving receiver

- Image blurry and de-focused
- First attempt- lack of accurate helicopter positioning and a lot of motion errors
- Also, dense area not so suitable for our resolution
- Even so, main reflectors in the image visible
- Currently planning second set of trials





GNSS-based passive radar

… as a Synthetic Aperture Radar (SAR)

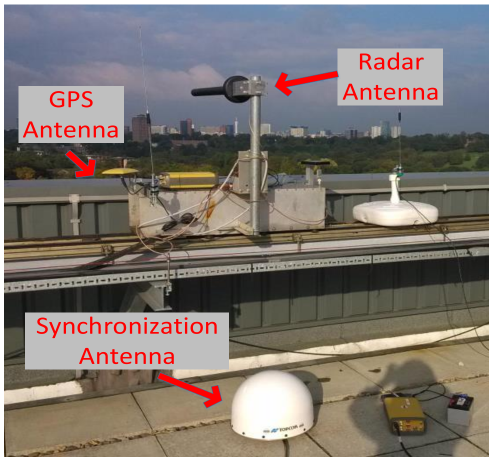
- ❑ Basic concepts
  - SAR fundamentals
  - Intro to passive SAR using GNSS
  - GNSS-SAR image formation and experimental results
- ❑ Advanced concepts:
  - CCD – Coherent Change Detection
  - Multi-perspective imaging
  - Multi-static imaging

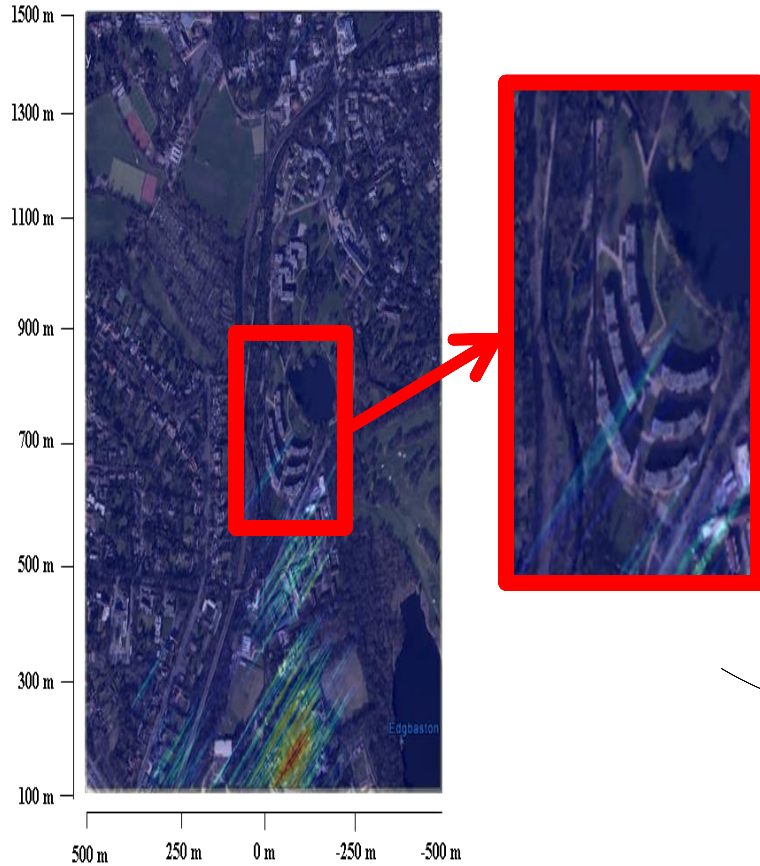
… as a radar

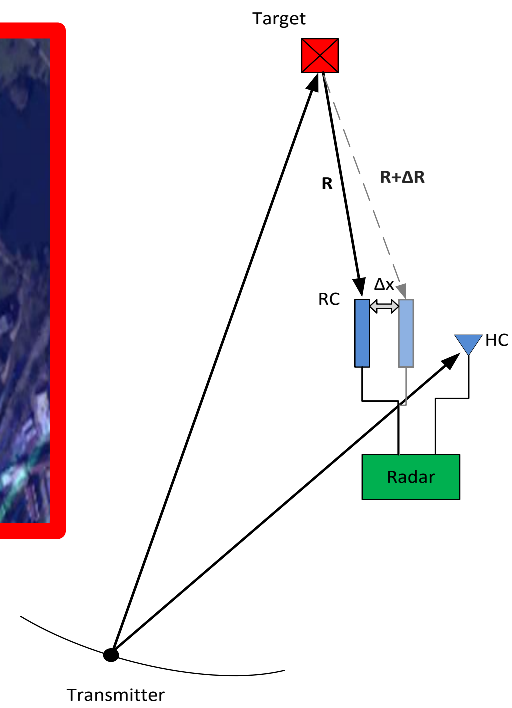
- ❑ GNSS-passive radar for maritime surveillance:
  - Intro to using GNSS for passive sea target detection;
  - Basic/advanced processing and experimental results

Coherent Change Detection

- Can we compare temporally separated GNSS-based SAR images to detect surface displacements?

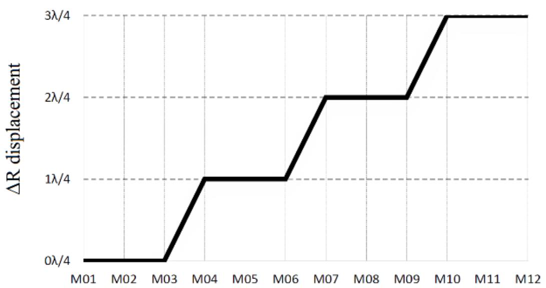




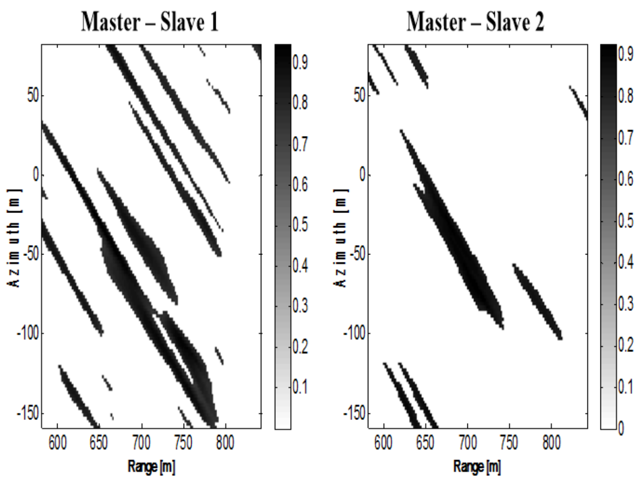


- Need a strong reference target (high SNR) – like a building for proof of concept.
- We also need a controlled displacement- we cannot move the building! But we can move the radar to emulate the corresponding shift

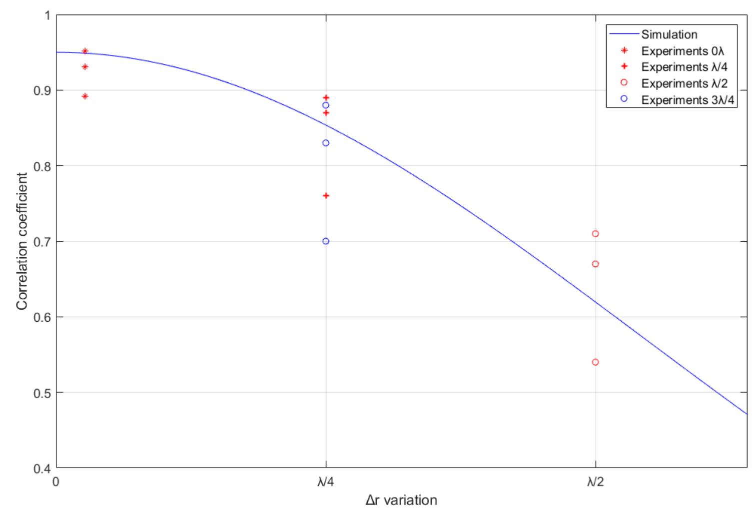
Coherent Change Detection



- Use a single satellite, acquire images at satellite revisit
- First measurements at zero displacement- master
- Then shift receiver to emulate target displacement of fraction of wavelength, and take slave images
- Then compute coherence between master and slave images and their phase difference, and use that to translate to actual phase shift



λ/4 λ/2



- Coherence map threshold 0.7
- Correlation coefficient: Experiment vs model

Coherent Change Detection

Parameter	ΔR=λ/4	ΔR=λ/2
Measured phase	105 °	163 °
Measured ΔR	5.45 cm	8.46 cm
Expected ΔR	4.67 cm	9.34 cm
Error in ΔR	**0.78 cm**	**0.88 cm**
Phase error	15°	17°

- Under good SNR conditions, small (cm) emulated target displacements are detected with <cm accuracy
- And only with a ground based receiver that would be stationary in reality
- Could be useful for persistent monitoring applications in local areas

Multi-perspective/multistatic GNSS SAR

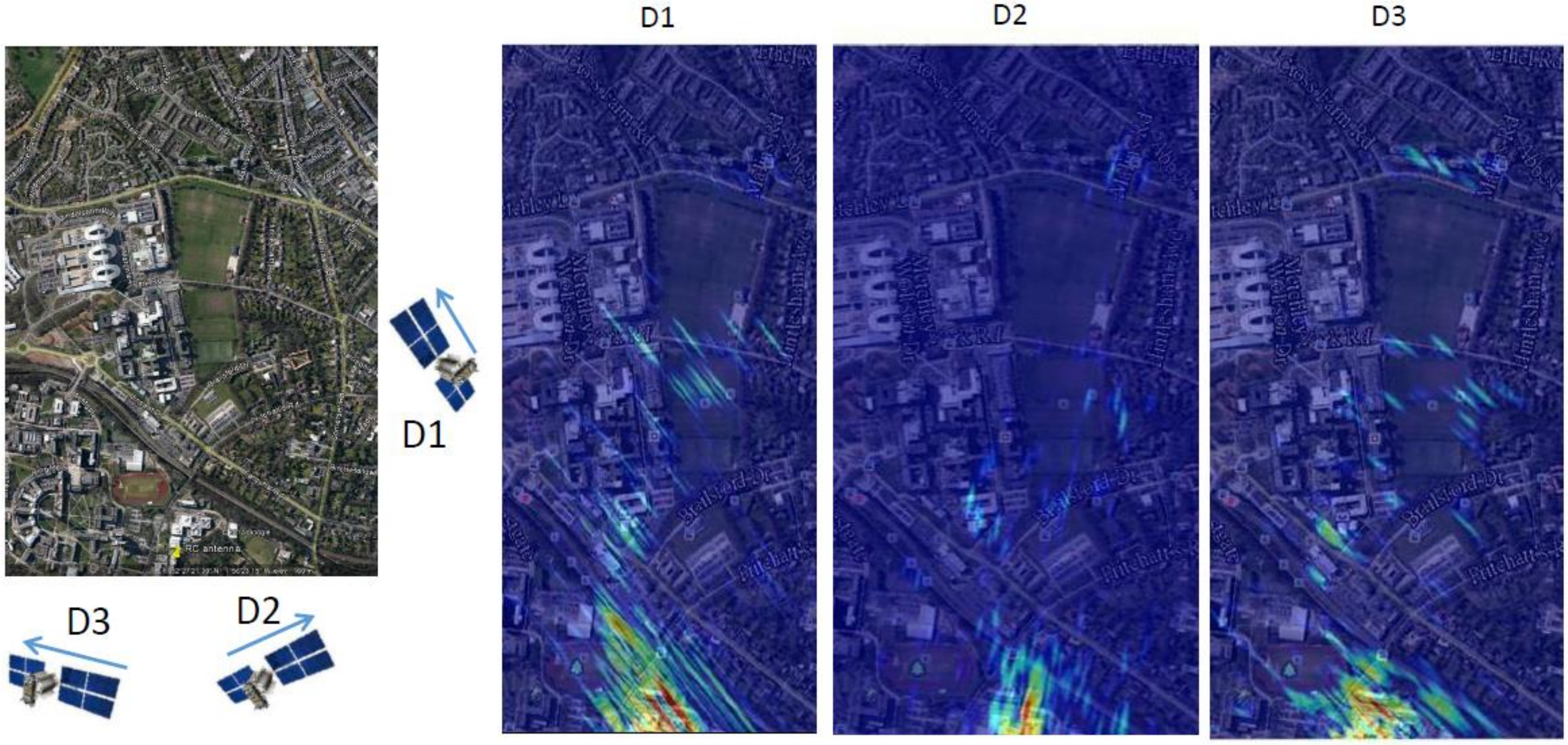
- Two different strategies of the single bistatic data can be adopted
  - The information contained in the single images can be extracted and then combined

    ➡ **Multi-perspective GNSS-based SAR**
  - Very little restriction on separation between satellites
  - The set of images can be combined, and then the information can be extracted directly from the multistatic image

    ➡ **Multistatic GNSS-based SAR**
  - Imposes more strict limits on angular separation among the transmitters

Multi-perspective SAR imaging

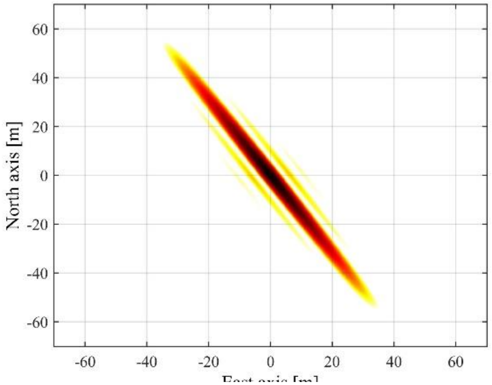
- Images of the same scene obtained at different bistatic angles naturally look different
- Can this be used as a degree of freedom to enhance image information space?
- Current area of research: terrain classification using multi-perspective GNSS-based SAR



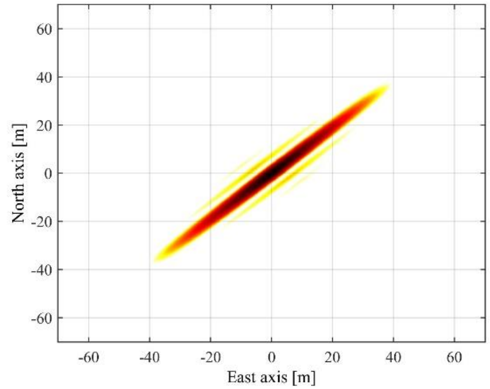
Bi-/Multistatic image response

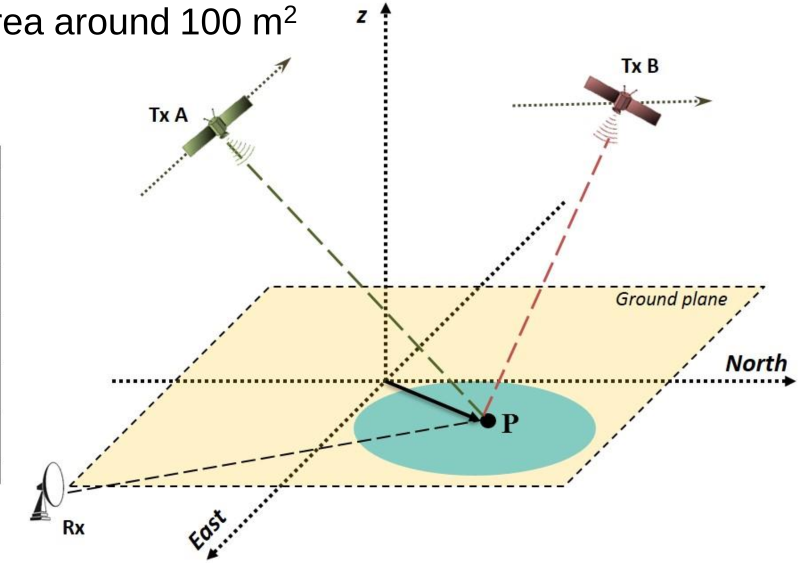
- Bistatic PSF is approximately an ellipse with resolution cell area around 100 m²

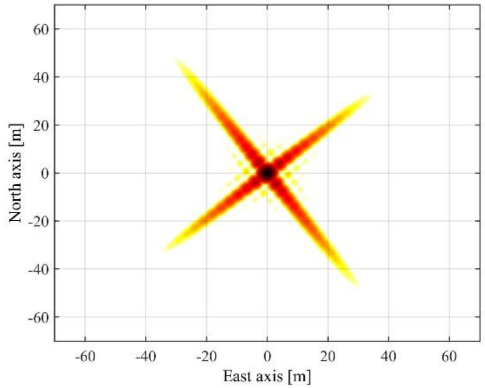
Tx A



Tx B







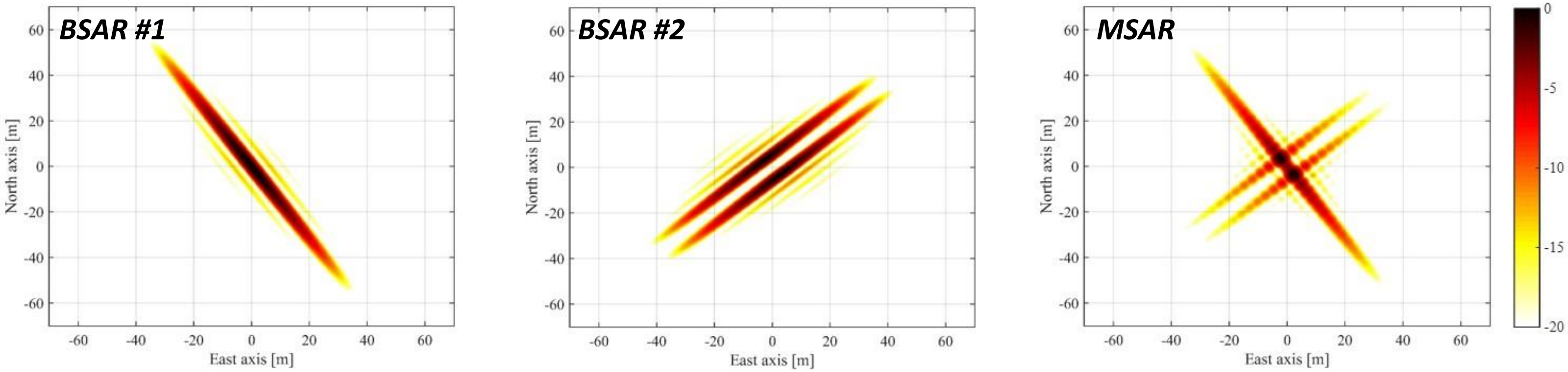
- A non-coherent combination of the individual images results in a multistatic image whose resolution cell area is the overlapping segment of the single bistatic PSFs, and therefore may be essentially reduced

PSF AREA

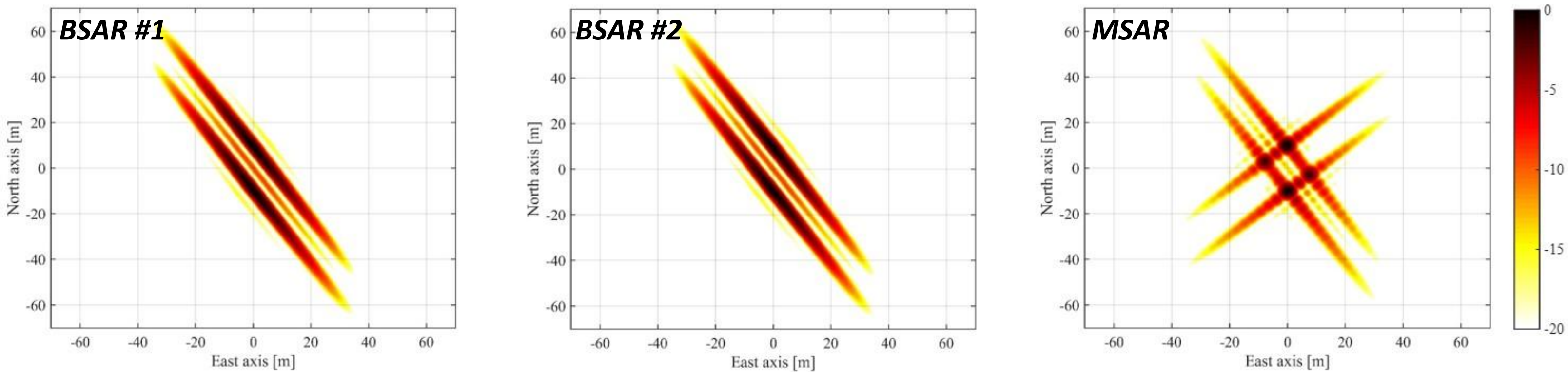
PSF A	PSF B	MPSF
98 m^2	80 m^2	17 m^2

Multistatic image of two close point scatterers

- Example #1 → improved resolution allows to resolve multiple scatterers



- Example #2: → false target positions due to intersection of PSF from different scatterers (ghosts)



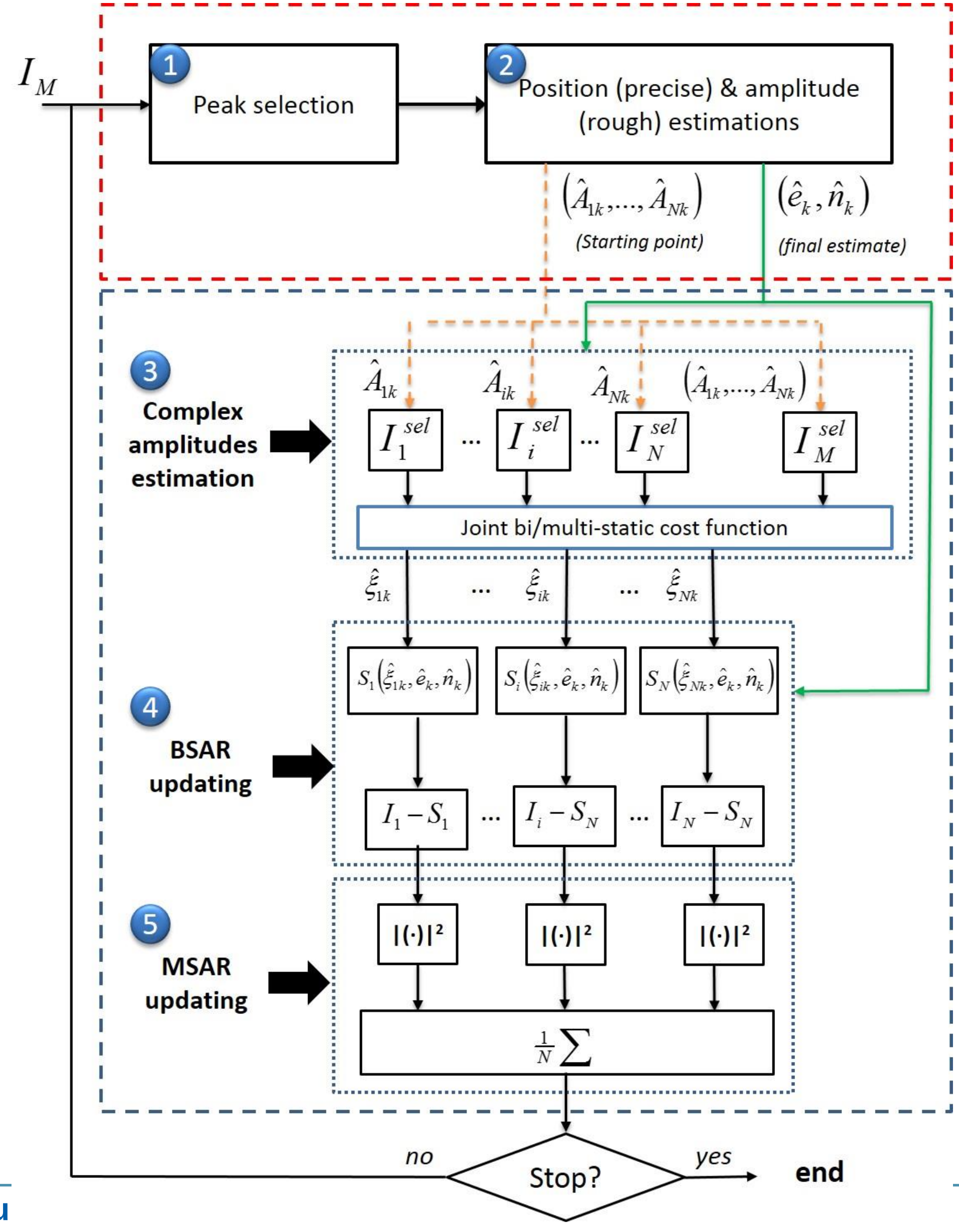
- **Point-features of the image are extracted by means of an ad-hoc CLEAN technique**
- Such a technique jointly exploits spatial resolution improvement provided by the MSAR image and the phase information preserved in the BSAR images to correctly recover the features of the scene

Joint bi-/multistatic CLEAN

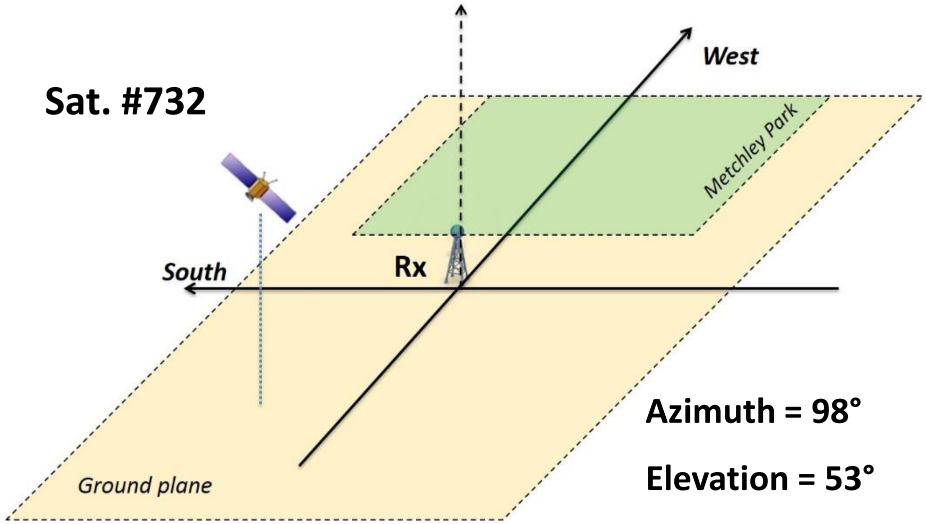
- Iterative procedure comprising the following steps:

1. Brightest point of the MSAR image is selected
2. Scatterer's position and the N amplitudes (absolute values, one for each bistatic image) are estimated from the multistatic image
3. To recover the complex amplitudes information, a cost function is defined by using both bistatic (still preserving phase information) and multistatic images
4. Bistatic images are updated by coherently subtracting estimated scatterer's responses
5. Updated bistatic images are non-coherently added to update the multistatic image

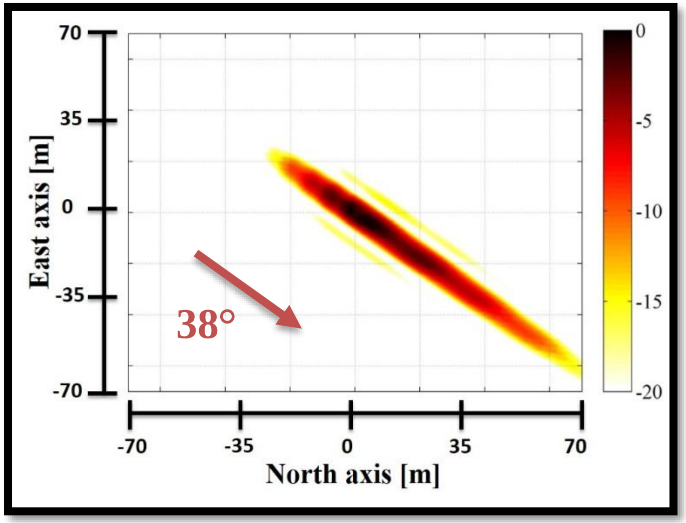
- Process carries on until residual energy threshold is reached

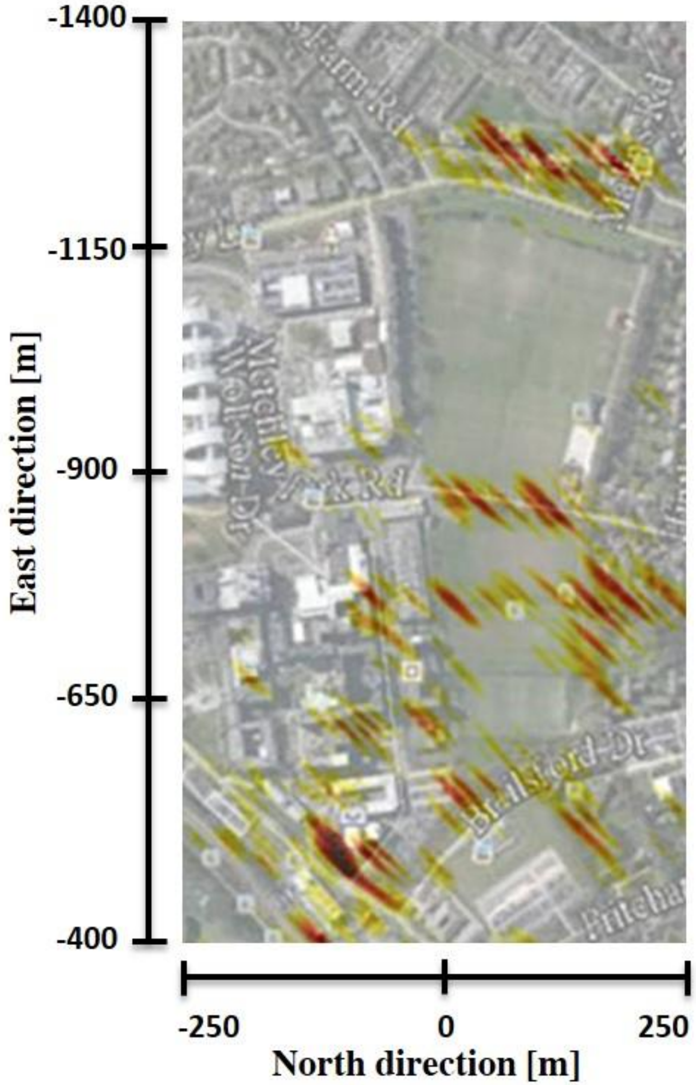


Experimental bistatic image 1



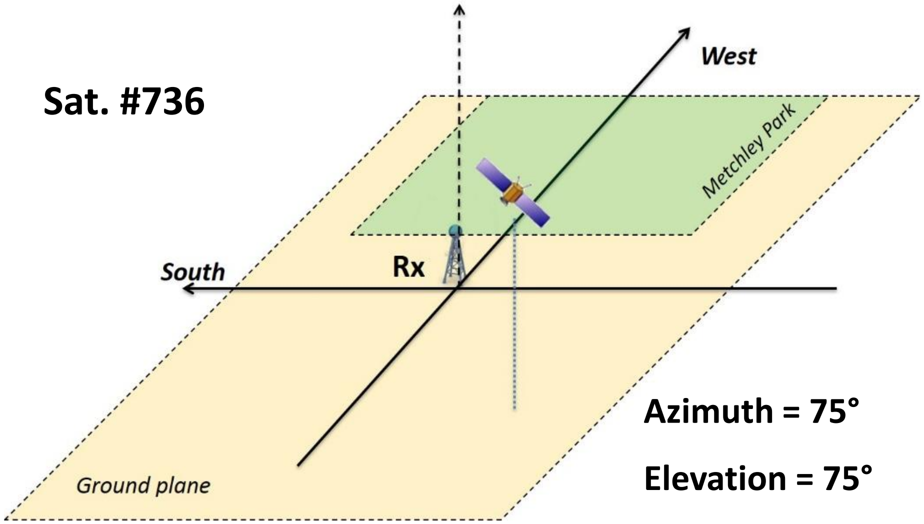
Experimental Bistatic PSF #1





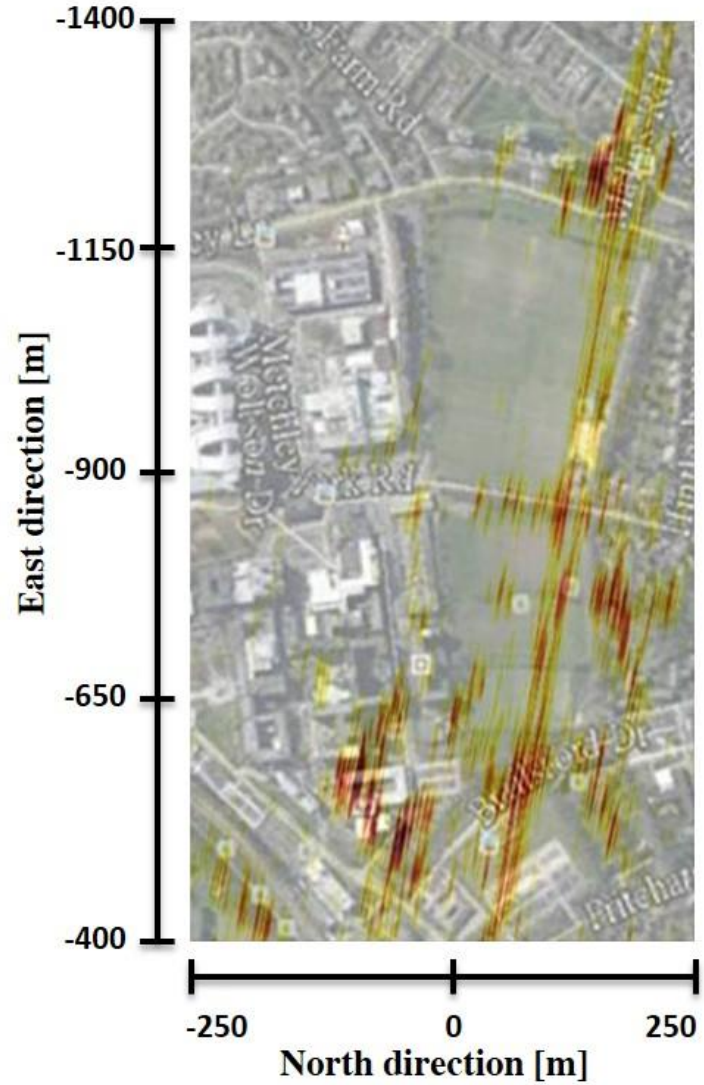
Experimental bistatic image 2

Sat. #736

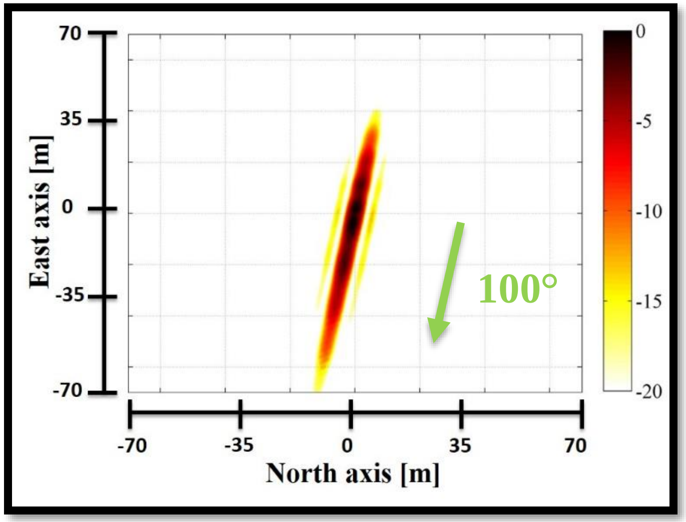


Azimuth = 75°

Elevation = 75°



Experimental Bistatic PSF #2



Experimental multistatic image

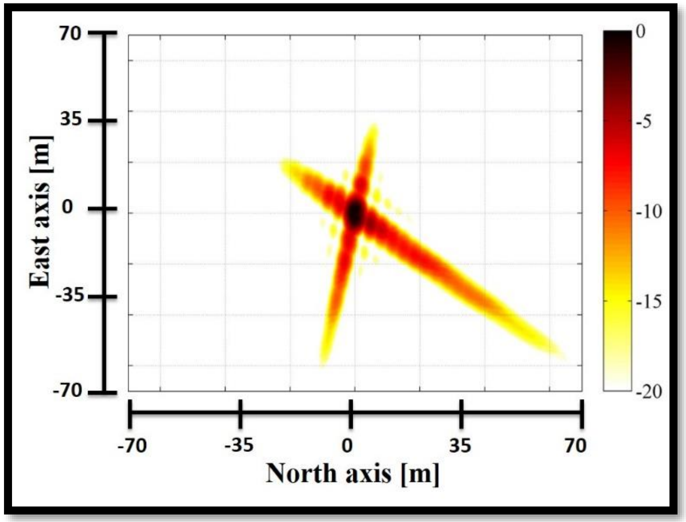
- Different orientation of the bistatic PSFs

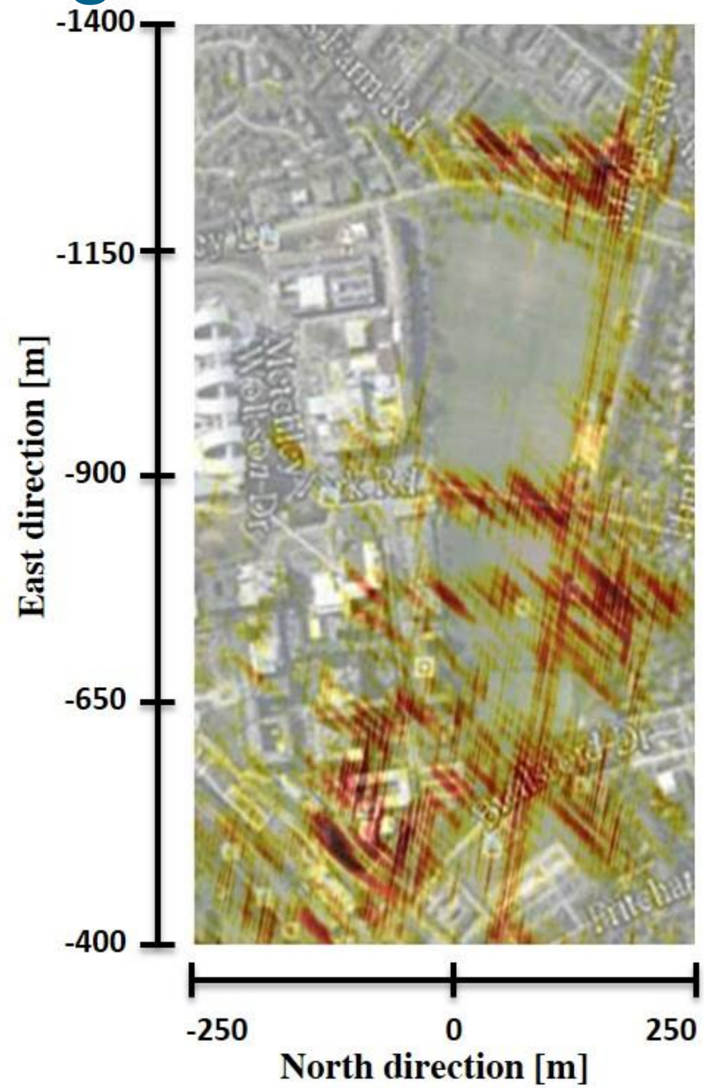
  → **improved resolution**

Case	PSF #1	PSF #2	MPSF
Area [m^2]	153	84	39

- We expect improved capability to discriminate features of the scene
- Joint bi/multi-static CLEAN applied to correctly recover point features

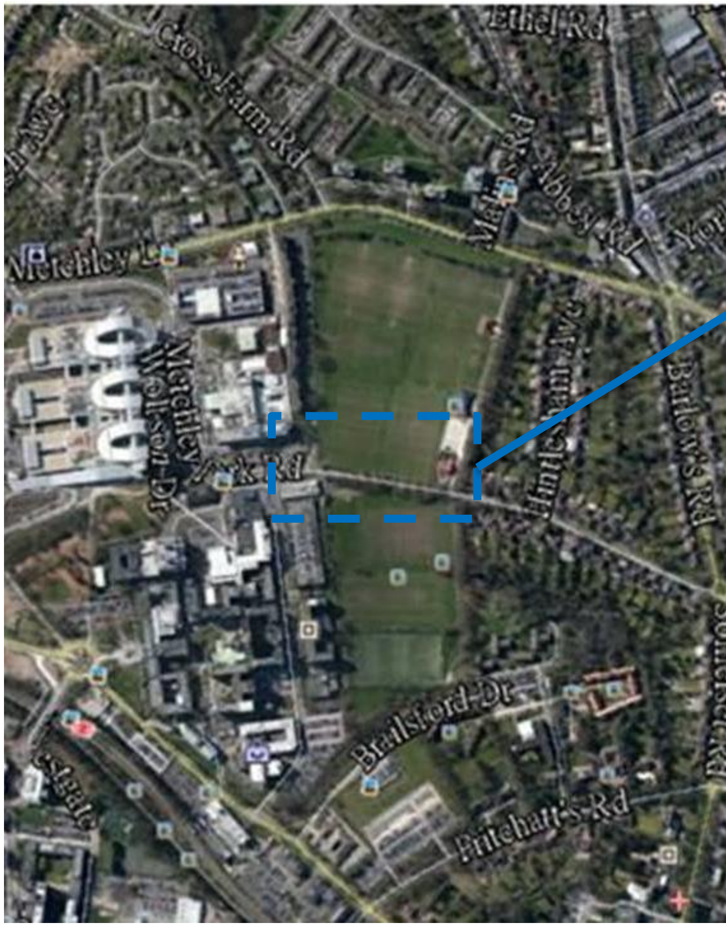
Experimental Multistatic PSF





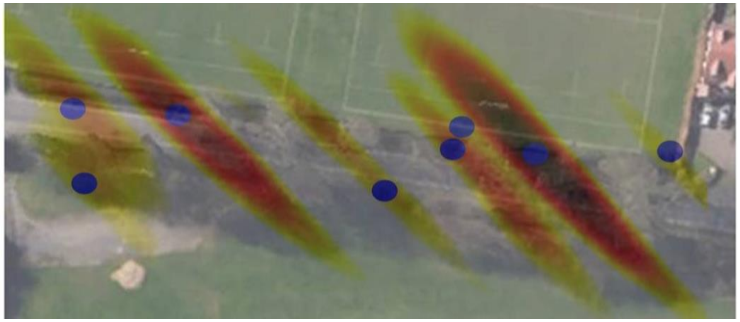
Experimental results

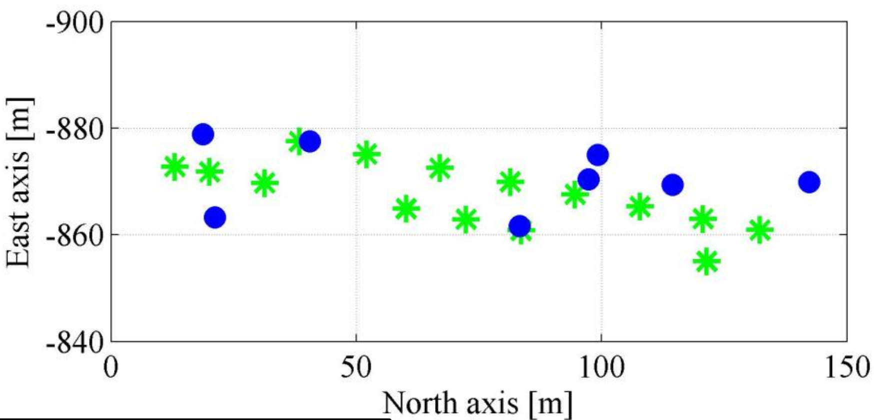
- Isolated trees in the middle of a grassy area facing toward the receiver



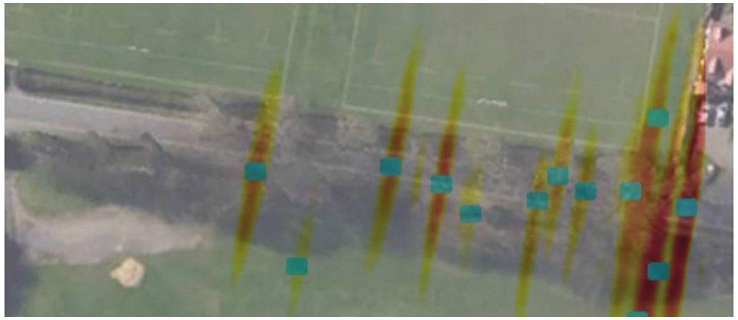
Tree lines-bistatic images

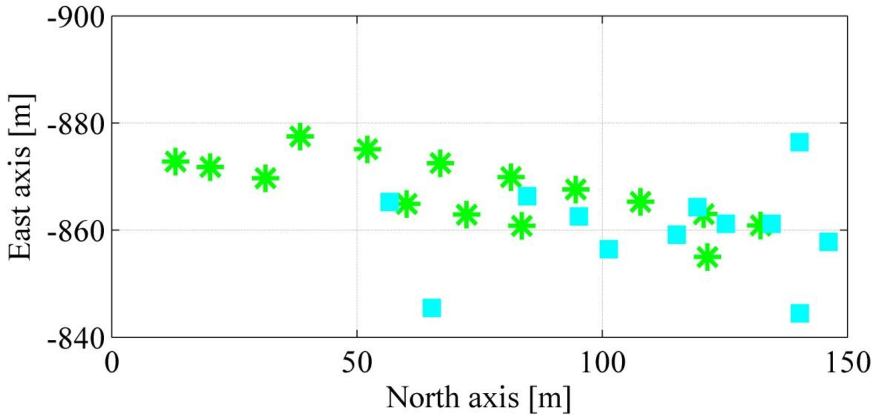
BSAR #1





BSAR #2



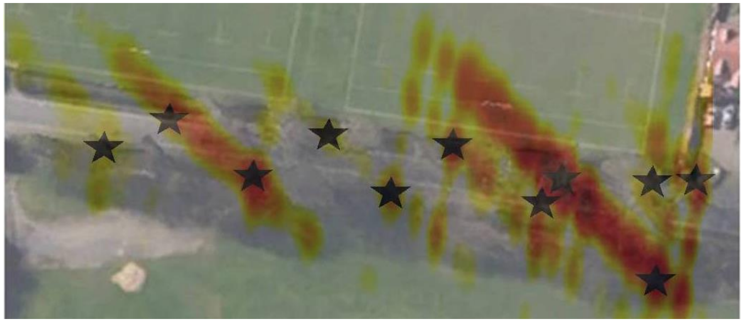


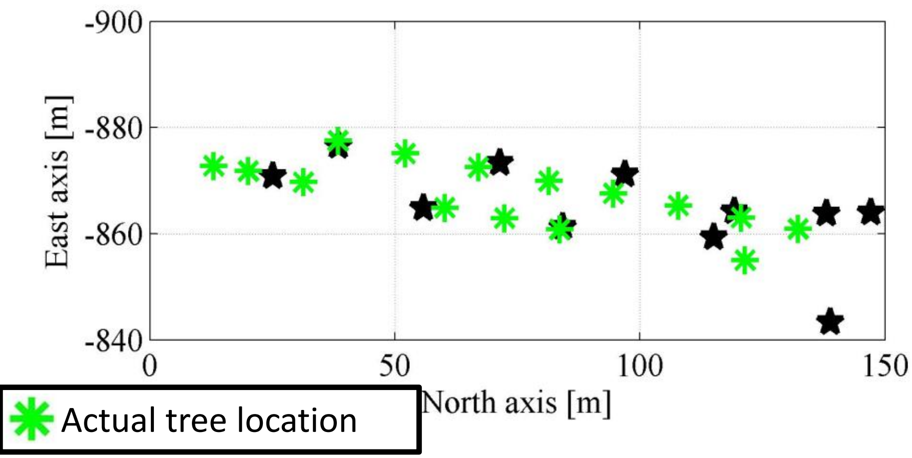
Actual tree location

- A number of scatterers have been extracted from the BSAR images
- The accuracy of their localization is severely affected by the coarse resolution

Tree lines-multistatic image

MSAR





# tree	δp BSAR #1 [m]	δp BSAR #1 [m]	δp MSAR [m]
1	2.10	-	1.01
2	-	-	-
3	-	-	4.56
4	-	4.90	-
5	3.93	5.04	4.32
6	-	-	-
7	8.91	2.14	1.91
8	-	2.20	6.48
9	-	-	-
10	7.11	-	5.22
11	-	-	-
12	-	3.52	4.29
13	-	-	-
14	0.95	-	0.90
15	-	7.27	7.69
Mean error	4.60	4.18	4.04
Sensed trees	**5/15**	**6/15**	**9/15**

- Enhanced accuracy of estimated locations
- A limited number of artifacts have been extracted
- A greater number of trees has been sensed, allowing **a more detailed scene reconstruction**

GNSS-based passive radar

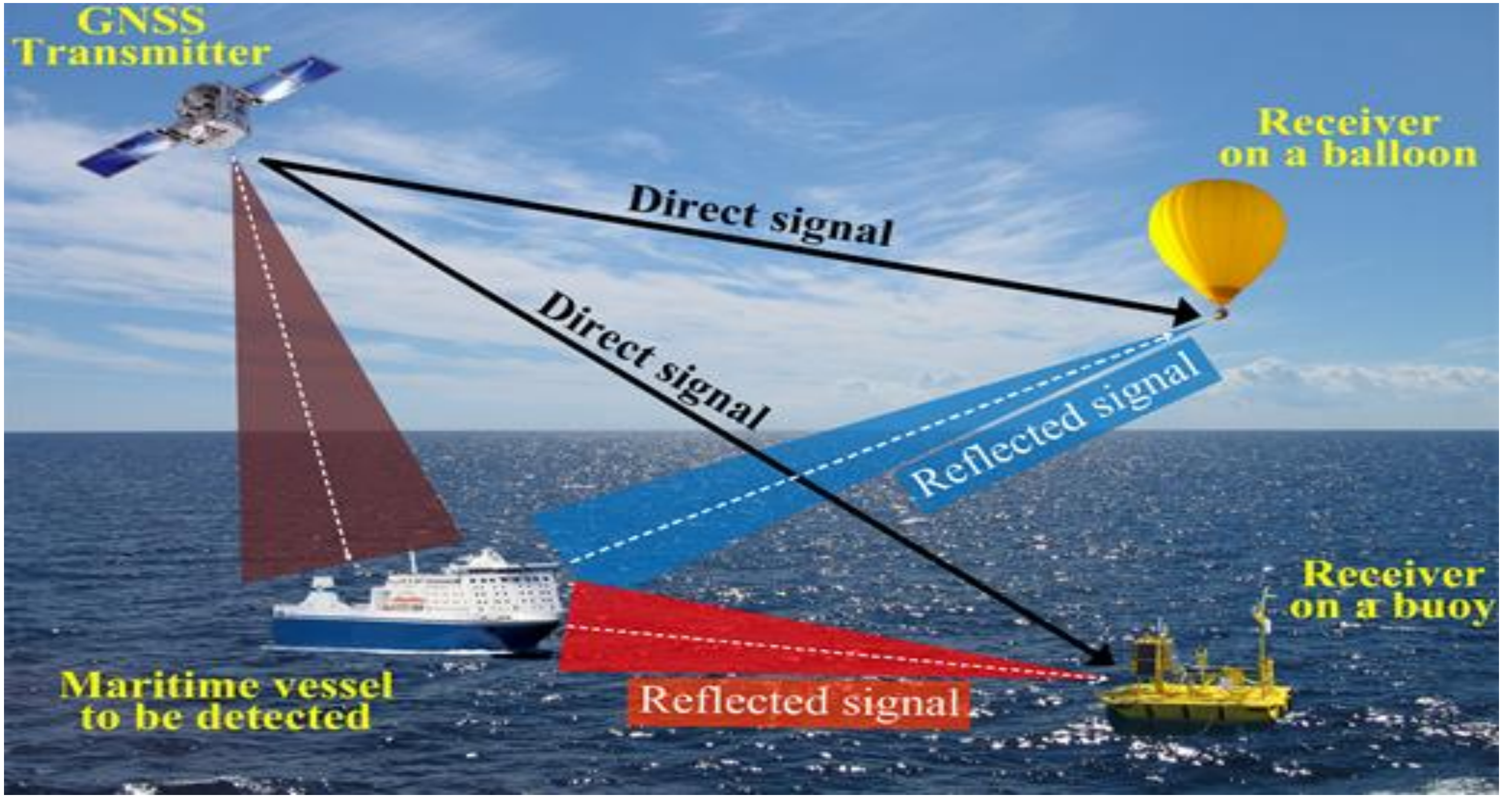
… as a Synthetic Aperture Radar (SAR)

- Basic concepts
  - SAR fundamentals
  - Intro to passive SAR using GNSS
  - GNSS-SAR image formation and experimental results
- Advanced concepts:
  - CCD – Coherent Change Detection
  - Multi-perspective imaging
  - Multi-static imaging

… as a radar

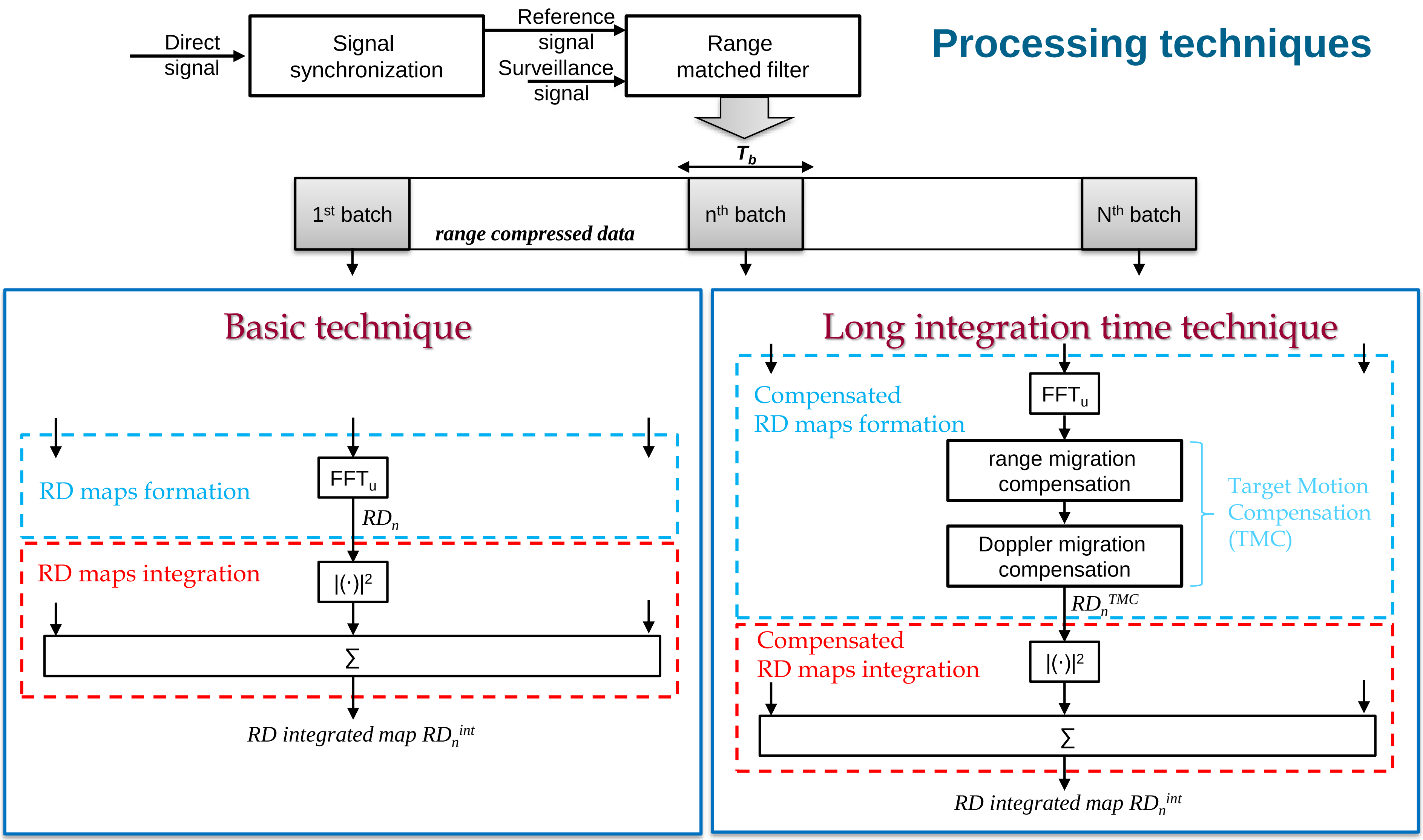
- GNSS-passive radar for maritime surveillance:
  - Intro to using GNSS for passive sea target detection;
  - Basic/advanced processing and experimental results

GNSS-based radar... for target detection

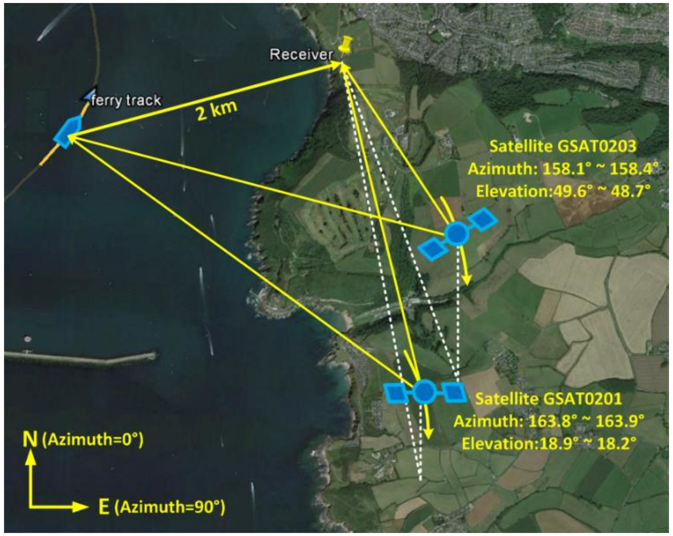


Passive Bistatic Radar (PBR) system exploiting GNSS (Galileo, Glonass, GPS) constellation signals for maritime surveillance purposes.

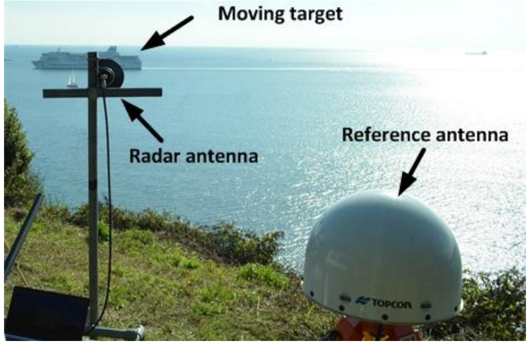
Processing techniques



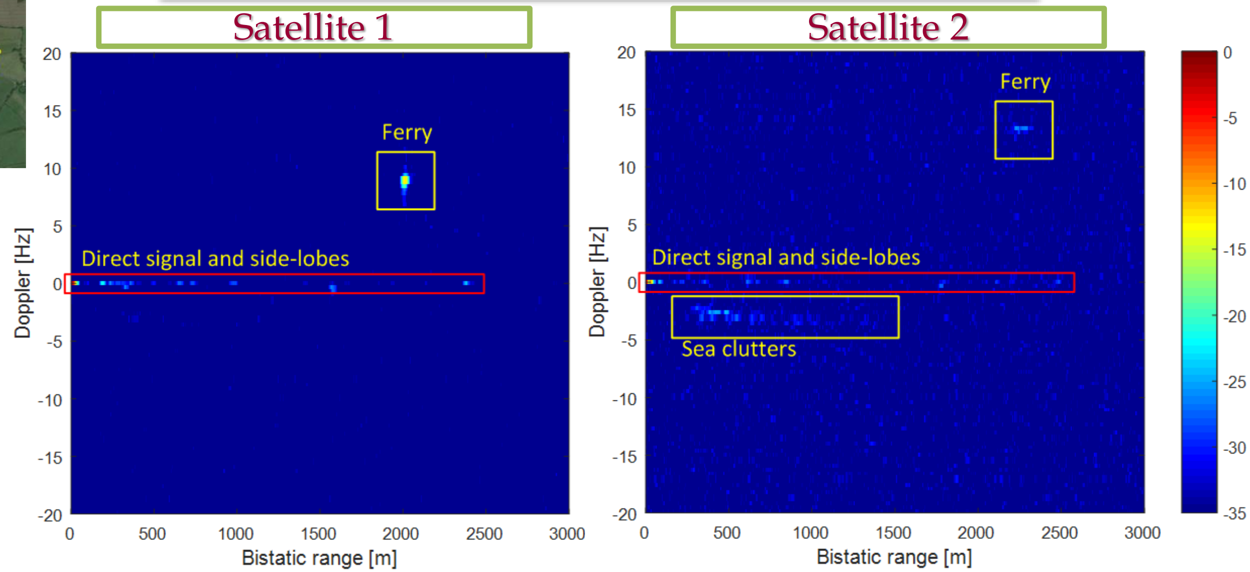
Experimental results (High RCS target)



- Experimental trials in Plymouth Harbour, UK
- Two Galileo transmitters
- High RCS target (ferry) equipped with Automatic Identification System (AIS)

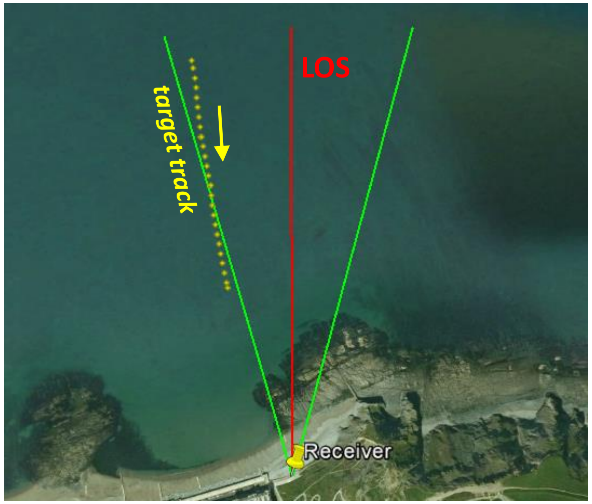


Basic technique - T_{batch} = 2.5 s, T_{obs}= 10 s

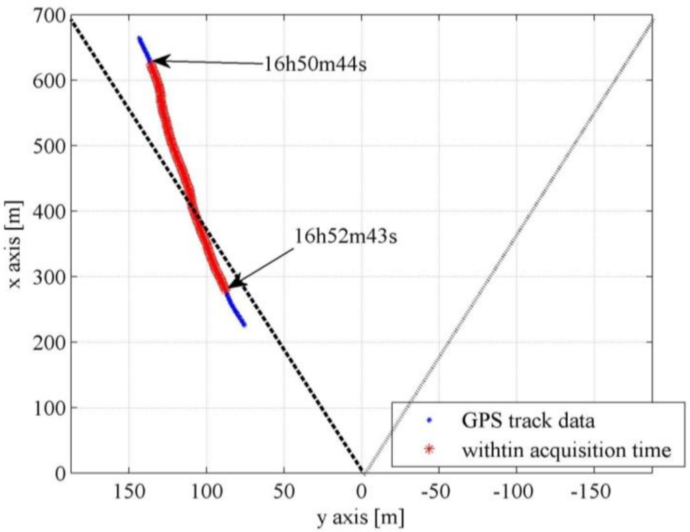


- ✓ Target visible in both maps
- ✓ Clutter reflections from satellite 1 is weaker than that from satellite 2

Experimental campaign (Low RCS target)



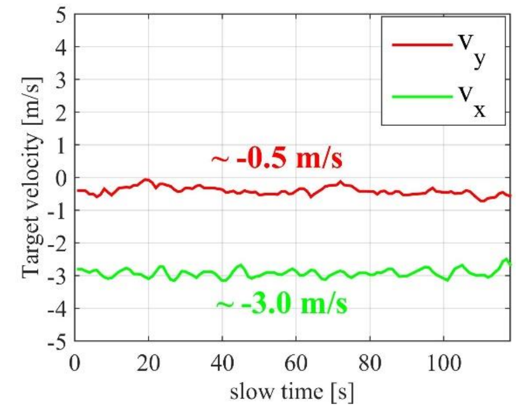
- Experimental trials in July 2015
- Aberystwyth, Wales, UK
- Single GLONASS transmitter
- Receiver prototype by UoB team
- Cooperative target equipped with GPS receiver

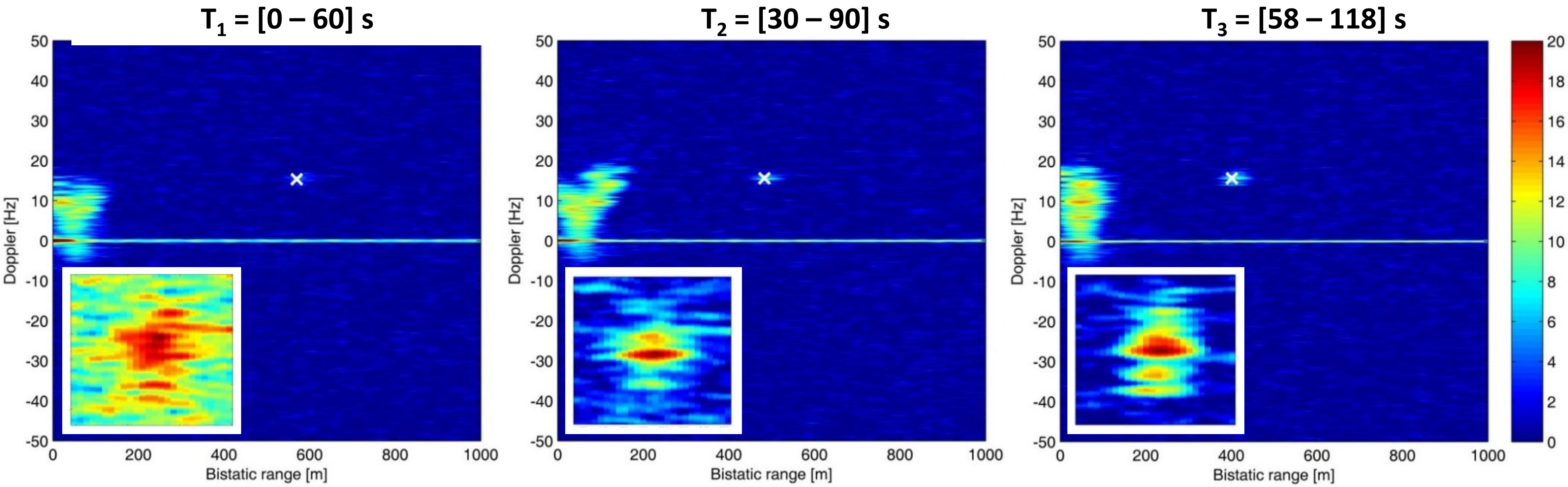


Parameter		Value	Unit
Satellite	number	732	-
	carrier frequency	1603.6875	MHz
	azimuth (clockwise from N)	3.0 ~ 6.8	deg
	elevation	73.2 ~ 73.1	deg
Processing parameters	sampling frequency	50	MHz
	pulse repetition interval	1	ms
	dwell time	118	s
	batch duration (CPI)	3	s
	non-coherent processing interval	60	s

Experimental results (Low RCS target)

- Frame duration: 1 s
- Non-coherent integration time: 60 s
- Integrated maps pertaining the actual target velocity
- Three intervals: T_1 = [0 - 60]s; T_2 = [30 - 90]s; T_3 = [58 - 118]s
- ×: actual target location





- Bright spots corresponding to target actual locations
- The target can be isolated from the disturbance background

… and for more results on GNSS-based target detection stay tuned!

Conclusions

- GNSS- one of the possible illuminators of opportunity
- Very limited range compared to other illuminators
- But
  - Global, persistent coverage anywhere in the world (even poles, open sea etc)
  - Inherently multi-static/multi-perspective system
- So plenty of scope for more local applications, as a gap filler to other systems etc
- The vision for the future of GNSS radar
  - Multi-perspective/multi-static radar/SAR.
  - Not only for GNSS, but also other systems, active or passive. When all constellations fully operational, 24-48 satellite transmitters in space- ideal for exploring capability
  - Already started, but only scratched the surface!

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Dr. **Marta Bucciarelli** (University of Rome "La Sapienza", Italy)

Federica Pieralice (PhD student @ University of Rome "La Sapienza", Italy)

Bibliography- Our books/journal papers

1. M. Cherniakov (ed.), “Bistatic radar- Emerging technology”, John Wiley & Sons Ltd, 2008
2. H. Ma, M. Antoniou, D. Pastina, F. Santi, F. Pieralice, M. Bucciarelli, M. Cherniakov, “Maritime Moving Target Indication Using Passive GNSS-based Bistatic Radar”, IEEE Transactions on Aerospace and Electronic Systems, to appear.
3. F. Santi, M. Bucciarelly, D. Pastina, M. Antoniou, M. Cherniakov, “Spatial resolution improvement in GNSS-based SAR using multi-static acquisitions and feature extraction”, IEEE Transactions on Geoscience and Remote Sensing, vol. 54, no. 10, pp. 6217-6231, October 2016.
4. H. Ma, M. Antoniou, M. Cherniakov, “Passive GNSS-based SAR resolution improvement using joint Galileo E5 signals”, IEEE Geoscience and Remote Sensing Letters, vol. 12, no. 8, pp. 1640-1644, August 2015.
5. F. Santi, M. Antoniou, D. Pastina, “Point Spread Function analysis for GNSS-based multi-static SAR”, IEEE Geoscience and Remote Sensing Letters, vol. 12, no. 2, pp. 304-308, February 2015.
6. Q. Zhang, M. Antoniou, W. Chang, M. Cherniakov, “Spatial de-correlation in GNSS-based SAR Coherent Change Detection”, IEEE Transactions on Geoscience and Remote Sensing, vol. 53, no. 1, pp. 219-228, January 2015.
7. T. Zeng, M. Zhu, C. Hu, T. Zhang, M. Antoniou, “DEM generation using bistatic interferometry: high-coherence pixel selection and residual reference phase compensation”, Science China: Information Science, vol. 58, no. 6, pp. 1-14, June 2015.
8. M. Antoniou, M. Cherniakov, H. Ma, “Space-Surface bistatic Synthetic Aperture Radar with navigation satellite transmissions: a review”, Science China: Information Science, vol. 58, no. 6, pp. 1-20, June 2015 (review article).
9. T. Zeng, F. Liu, M. Antoniou, M. Cherniakov, “GNSS-based BiSAR using modified range migration algorithm ”, Science China: Information Science, vol. 58, no. 6, pp. 1-13, June 2015.
10. H. Ma, M. Antoniou, M. Cherniakov, “Passive GNSS-based SAR imaging and opportunities using Galileo E5 signals”, Science China: Information Science, vol. 58, no. 6, pp. 1-11, June 2015.
11. M. Antoniou, Z. Hong, Z. Zhangfan, R. Zuo, Q. Zhang, M. Cherniakov, “Passive BSAR imaging with Galileo transmitters: analytical and experimental results”, IET Proc. Radar, Sonar and Navigation, vol. 7, no.9, pp. 985-993, December 2013.
12. M. Antoniou, M. Cherniakov, “GNSS-based bistatic SAR: a signal processing view”, EURASIP Journal of Advances in Signal Processing, 2013:98, available online at http://asp.eurasipjournals.com/content/2013/1/98
13. F. Liu, M. Antoniou, Z. Zeng, M. Cherniakov, “Coherent change detection using passive GNSS-based SAR: Experimental proof of concept”, IEEE Transactions on Geoscience and Remote Sensing, vol. 51, no. 8, pp. 4544-4555, January 2013.
14. F. Liu, M. Antoniou, Z. Zeng, M. Cherniakov, “Point Spread Function analysis for BSAR with GNSS transmitters and long dwell times: theory and experimental confirmation”, IEEE Geoscience and Remote Sensing Letters, vol. 10, no.4, pp.781-785, July 2013.

Bibliography- Our Books/Journal papers

15. M. Antoniou, Z. Zeng, L. Feifeng, M. Cherniakov, “Experimental demonstration of passive BSAR imaging using navigation satellites and a fixed receiver”, IEEE Geoscience and Remote Sensing Letters, vol. 9, issue 3, pp. 477-481, May 2012.

16. M. Antoniou, M. Cherniakov, C. Hu, “Space-Surface Bistatic SAR image formation algorithms”, IEEE Transactions on Geoscience and Remote Sensing, vol. 47, no. 6, pp. 1827-1843, June 2009.

17. M. Cherniakov, R. Saini, R. Zuo, M. Antoniou, “SS-BSAR with GNSS transmitter of opportunity – experimental results”, IET Radar, Sonar and Navigation, vol. 1, no. 6, pp. 447-458, December 2007.

18. M. Antoniou, R. Saini, M. Cherniakov, “Results of a Space-Surface Bistatic SAR image formation algorithm”, IEEE Transactions on Geoscience and Remote Sensing, vol. 45, no. 11, pp. 3359-3371, November 2007.

19. M. Cherniakov, R. Saini, R. Zuo, M. Antoniou, “Bistatic Synthetic Aperture Radar with transmitters of opportunity”, Journal of Defence Science, vol. 10, no. 3, pp. 136-140, April 2006.

Bibliography- Our Conference papers

1. H. Ma, M. Antoniou, M. Cherniakov, F. Santi, D. Pastina, F. Pieralice, M. Bucciarelli, “Maritime Target Detection Using GNSS-Based Radar: Experimental Proof of Concept”, IEEE International Radar Conference, May 2017.

2. F. Santi, D. Pastina, M. Bucciarelli, "Maritime Moving Target Detection Technique for Passive Bistatic Radar with GNSS Transmitters", International Radar Symposium (IRS 2017), Prague, Czech Republic, June 28-30th, 2017.

3. F. Pieralice, F. Santi, D. Pastina, M. Bucciarelli, H. Ma, M. Antoniou, M. Cherniakov, “GNSS-Based Passive Radar for Maritime Surveillance: Long Integration Time MTI Technique” , IEEE International Radar Conference, May 2017.

4. H. Ma, D. Tzagkas, M. Antoniou, M. Cherniakov, “Maritime Moving Target Detection and Localisation with GNSS-based Multi-Static Radar: Experimental Proof of Concept”, International Radar Symposium, June 2017.

5. H. Ma, M. Antoniou, M. Cherniakov, T. Pany , J. Dampf, C. Stober, J. Winkel, C. Buck, “Galileo-based Bistatic SAR Imaging Using The SX3 GNSS Receiver”, NAVITEC 2016.

6. D. Tzagkas, M. Antoniou, M. Cherniakov, “Coherent change detection experiments with GNSS-based passive SAR”, European Radar Conference 2016, pp. 262-265.

Bibliography- Our Conference papers

7. F. Santi, M. Bucciarelli, D. Pastina, M. Antoniou, M. Cherniakov, “Passive multi-perspective GNSS-based SAR using CLEAN technique: an experimental study”, EUSAR 2016, pp. 1063-1066.

8. F. Santi, M. Bucciarelli, D. Pastina, M. Antoniou, M. Cherniakov, “Passive multistatic SAR with GNSS transmitters and using joint bi/multi-static CLEAN technique”, IEEE International Radar Conference 2016.

9. F. Santi, M. Bucciarelli, D. Pastina, M. Antoniou, “CLEAN technique for passive bistatic and multi-static SAR with GNSS transmitters”, IEEE International Radar Conference, May 2015.

10. F. Santi, D. Pastina, M. Bucciarelli, M. Antoniou, D. Tzagkas, M. Cherniakov, “Passive multi-static SAR with GNSS transmitters: preliminary experimental study”, European Radar Conference (EuRad), 2014.

11. F. Santi, M. Antoniou, D. Pastina, D. Tzagkas, M. Cherniakov, “Point spread function analysis for non-coherent, multistatic GNSS-based SAR”, EUSAR 2014, 2014.

12. M. Antoniou, M. Cherniakov, “Experimental demonstration of GNSS-based SAR imaging modes”, IET International Radar Conference 2013.

13. F. Liu, C. Hu, M. Antoniou, T. Zeng, M. Cherniakov, “Experimental image formation of SS-BiSAR systems with fixed receiver using modified RMA algorithm”, IET International Radar Conference 2013.

14. Z. Zeng, M. Antoniou, Q. Zhang, H. Ma, M. Cherniakov, “Multi-perspective GNSS-based SAR: preliminary experimental results”, International Radar Symposium (IRS) 2013.

15. M. Antoniou, F. Liu, Z. Zhangfan, V. Sizov, M. Cherniakov, “Coherent change detection using GNSS-based passive SAR: experimental results”, IET RADAR 2012, 2012.

16. M. Antoniou, Z. Zhangfan, F. Liu, M. Cherniakov, “Passive radar imaging with GNSS transmitters and a fixed receiver: latest results”, EUSAR 2012, 2012 (invited).

17. Z. Zhangfan, M. Antoniou, F. Liu, M. Cherniakov, “First space-surface bistatic fixed receiver SAR images with a navigation satellite”, International Radar Symposium 2011, 2011.

18. M. Antoniou, M. Cherniakov, R. Zuo, E. Plakidis, “Motion comprensation algorithm for passive Space-Surface Bistatic SAR”, IET International Radar Conference, Bordeaux, 2009.