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Distributed RF Apertures

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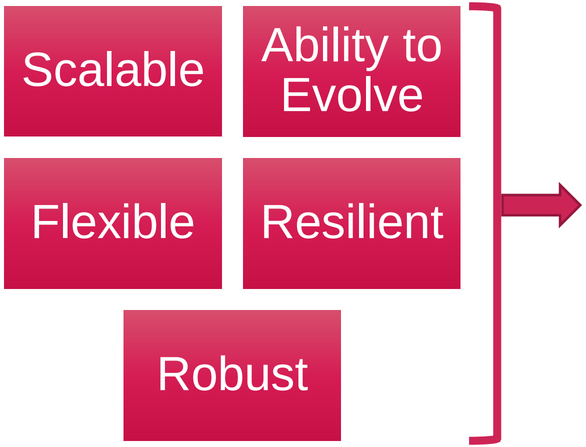
Ministry
of Defence

Motivation

Responsive Space:
The capability of space systems to respond to uncertainty



Scalable

Ability to Evolve

Flexible

Resilient

Robust

DISTRIBUTED SOLUTION

ICEYE

Synspective

Capella Space

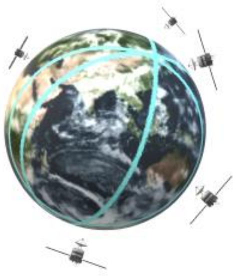
PredaSAR

SPACETY

UMBRA

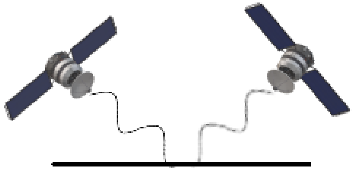
Imagery courtesy of: iceye.com, synspective.com, capellaspace.com, predasar.com, en.spacety.com, umbra.space

Distributed RF Apertures



Multiple SAR platforms Tx and Rx capability

Coherence is maintained across the array.

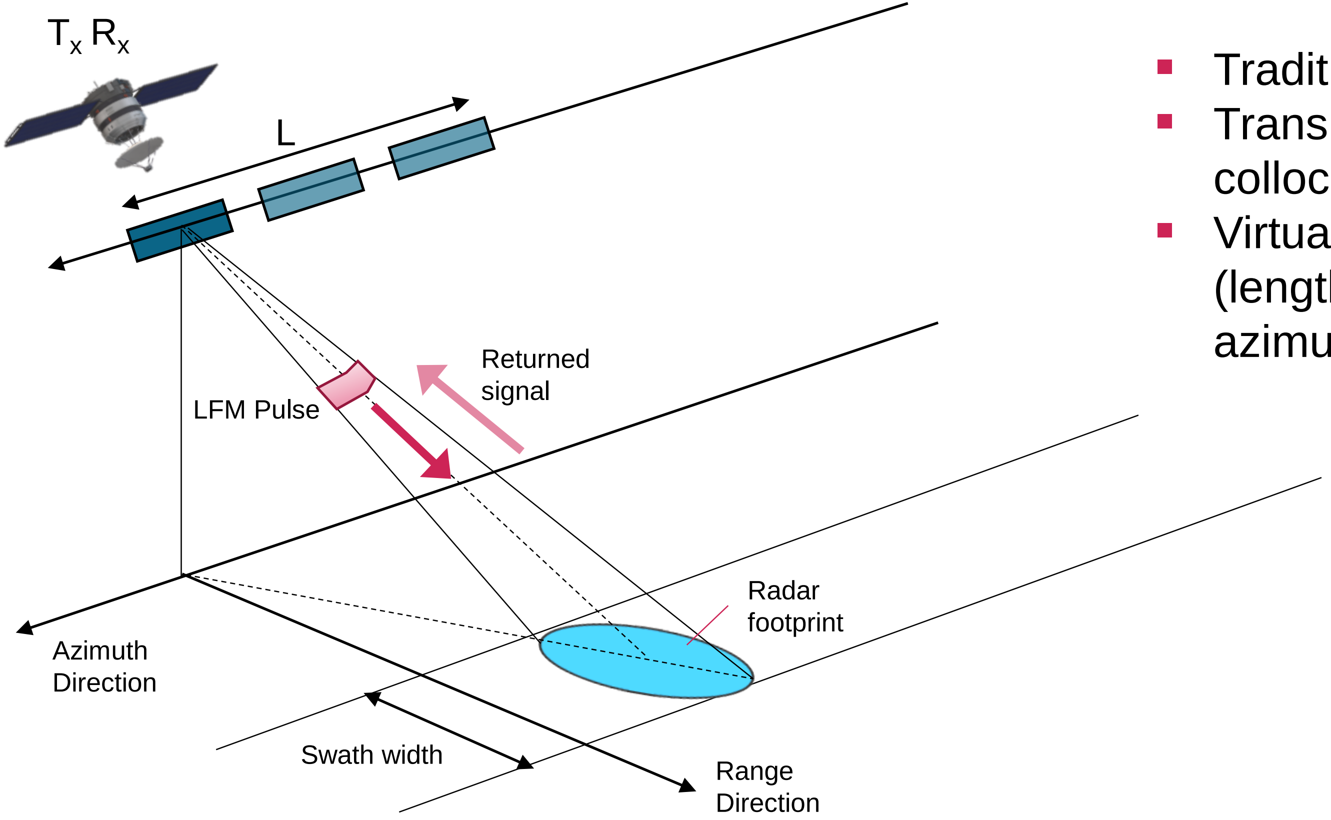


Niche Products

Possibility of exceeding traditional SAR constellation capability

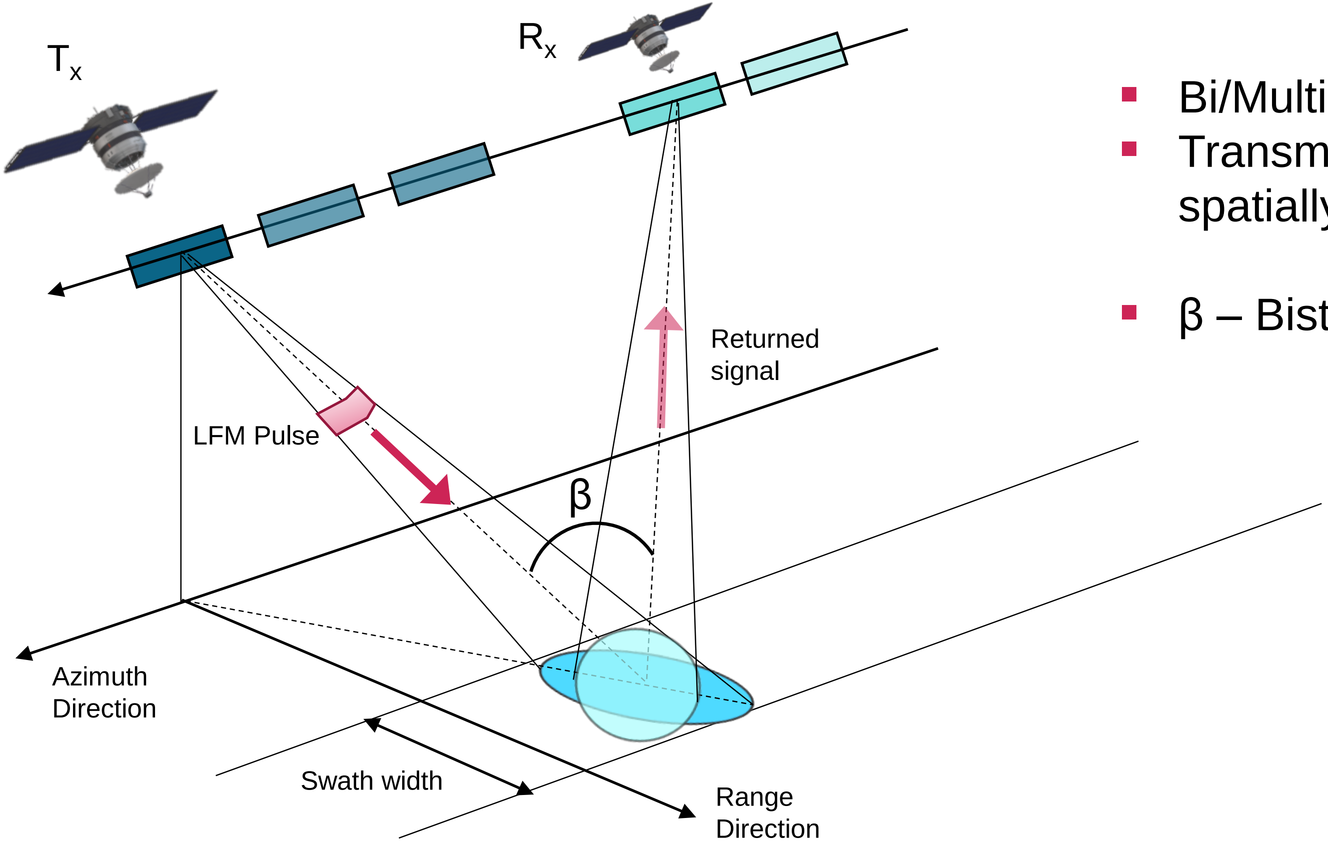
- Increased Resolution
- ATI/XTI
- 3D point cloud
- Increased Swath
- Improved CNR
- Bistatic Imaging

Synthetic Aperture Radar (SAR)



- Traditional Monostatic SAR
- Transmitter and Receiver collocated.
- Virtual antenna synthesized (length L) to increase azimuth resolution.

Synthetic Aperture Radar (SAR)

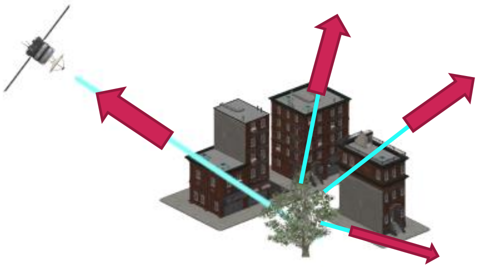


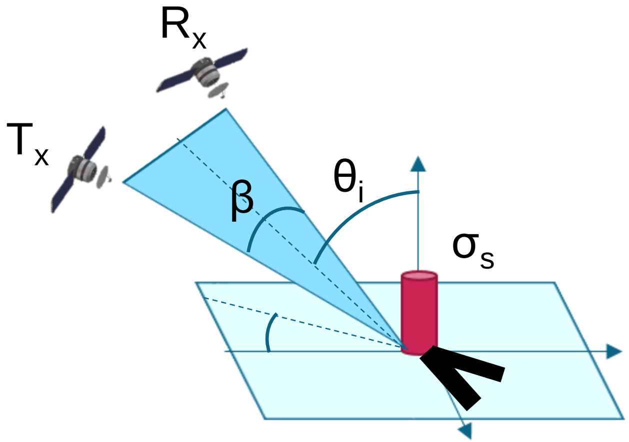
- Bi/Multistatic SAR
- Transmitter and Receiver spatially separated.

- β – Bistatic angle

Distributed RF Apertures

Measurement diversity is key to understanding complex targets.





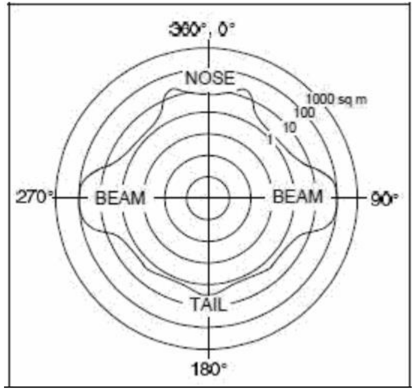


Figure taken from [1] Electronic Warfare and Radar Systems Engineering Handbook.

- Full exploitation of such a system requires development of novel signal processing techniques and creation of target signature databases.

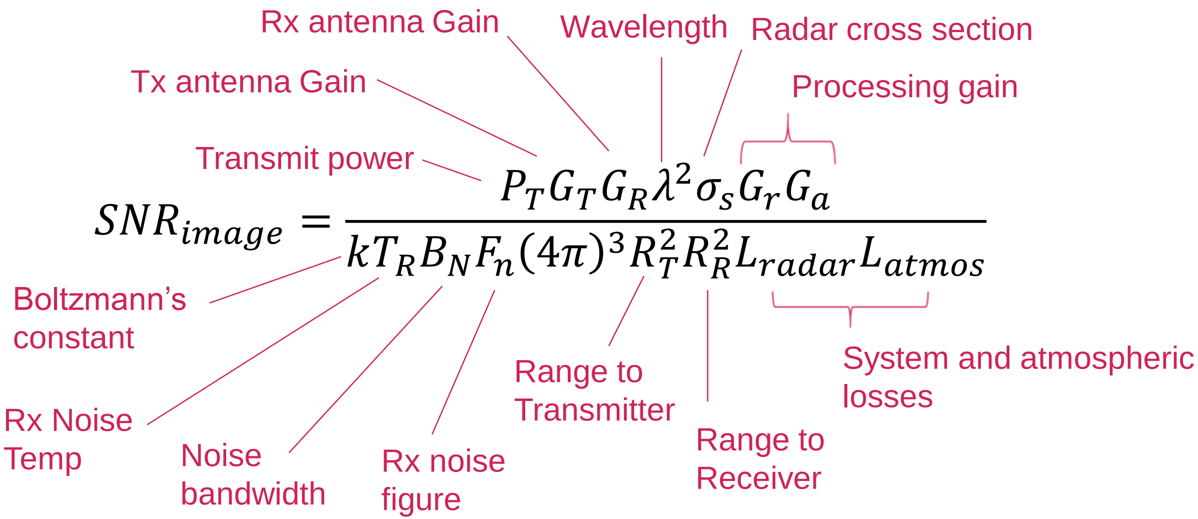
Hardware requirements: Small SAR satellite

Mass and size limits provide fundamental limits on:

- Antenna area (αG_T and G_R)
- Maximum average power available (P_{avg})

→

Drives system trades to optimize for KPIs such as SNR, range and azimuth resolution.



$$SNR_{image} = \frac{P_T G_T G_R \lambda^2 \sigma_s \overbrace{G_r G_a}^{\text{Processing gain}}}{k T_R B_N F_n (4\pi)^3 R_T^2 R_R^2 \underbrace{L_{radar} L_{atmos}}_{\text{System and atmospheric losses}}}$$

Rx antenna Gain

Wavelength

Radar cross section

Tx antenna Gain

Processing gain

Transmit power

Boltzmann's constant

Rx Noise Temp

Noise bandwidth

Rx noise figure

Range to Transmitter

Range to Receiver

System and atmospheric losses

Hardware requirements: Coherent cluster

- Coherent integration is only possible if the entire system, including propagation paths, is stable to a small fraction of the RF wavelength on the scale of an aperture. Requires:
  - Very precise position and time measurement
  - Stable frequency references
  - Means of relating time between sensors

- For an X-band system, using ~λ/10 as a conservative estimate for coherent combination
  - Time measurement precision ~10ps
  - Position measurement precision ~3mm

- Sync links enable time and coherence transfer between platforms.

Processing and Exploitation Workflow

Image Formation Processor

Advanced Product Formation

Exploitation and Dissemination

Imagery taken from [2] Shahzad, M. et al. 2015

Processing: Bi/Multistatic Image Formation

- Various IFPs are commonly used for monostatic SAR: Polar Format Algorithm (PFA), Range Doppler (RD), Chirp Scaling Algorithm (CSA) and **Back Projection Algorithm (BPA).**

- Assumptions:
  - Isotropic point target scattering model
  - Simple linear forward model
  - Simplified inversion, e.g. IFFT

- Appropriate for monostatic small angles, however for geometrically diverse, sparsely sampled apertures may need a new approach. E.g. Bayesian inference.

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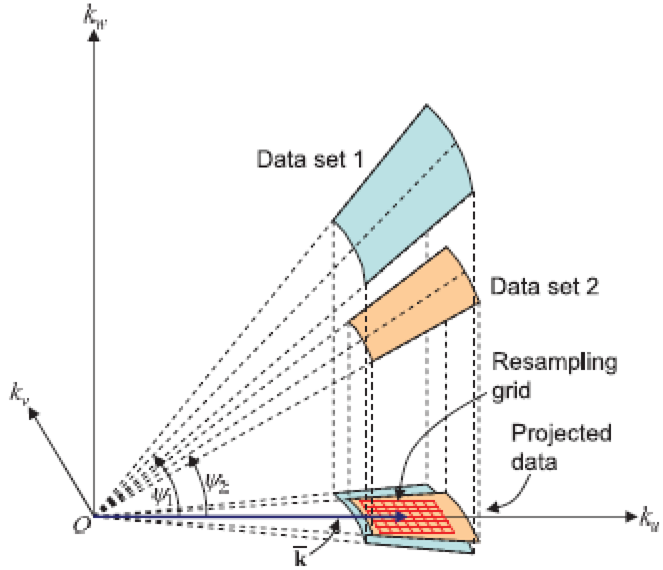
Processing: Increased resolution



- Resolution of a SAR image is given by the extent of the k-space support.
- It is possible, by selecting specific acquisition geometries of a pair of coherent platforms, to extend the k-space support and hence resolution in either range or azimuth without changing Tx bandwidth.
- Useful in areas of congested spectrum or in resource management of a distributed system.
- Assumes target persistence throughout collection aperture.

Imagery taken from [3] Goh, A. 2012

Processing: Single Pass 3D Point Cloud

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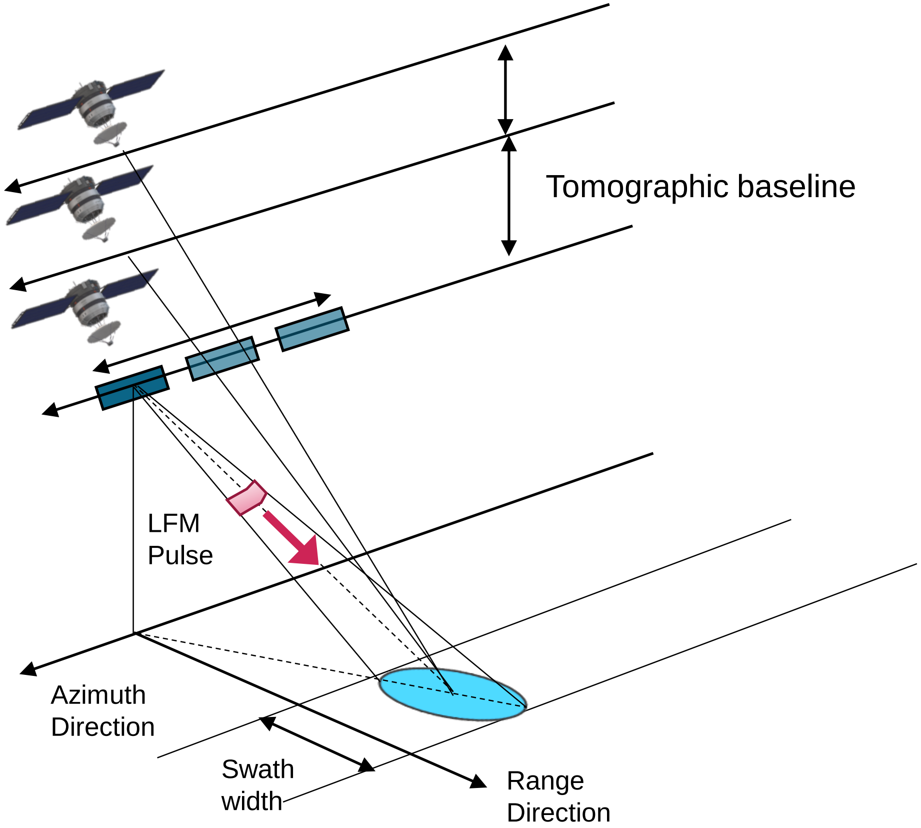

- As for along track aperture, synthesize a vertical aperture using multiple platforms to resolve scatterers in height.
- 3D volumetric image can be created using a tomographic approach to image formation.
- Prominent scatterers can be extracted from volumetric image to generate 3D point cloud product.

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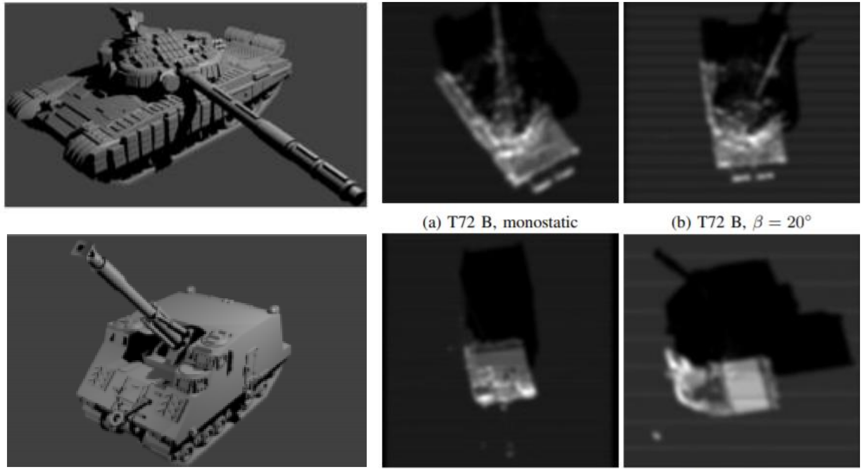
Exploitation: Bistatic/Multistatic SAR

Automatic Target Recognition (ATR)



(a) T72 B, monostatic (b) T72 B, $\beta = 20°$

(c) L33, monostatic (d) L33, $\beta = 90°$

Figures taken from [4]. Woollard et al. 2020

Divergence from monostatic SAR

- Illumination and reconstruction shadows.
- Difference in scattering mechanisms.
- Difference in clutter processes.

Challenges

- Lack of representative training data sets
- Lack of validated simulated data
- Lack of validated bistatic clutter models.
- Large parameter space.

Exploitation: 3D Point Cloud

Automatic Target Recognition (ATR)

- LIDAR work has shown 3D target recognition to be superior to 2D ATR as extracted features are less dependent on target pose changes.
- Requires data to be collected in a single pass – impossible with traditional SAR constellations.

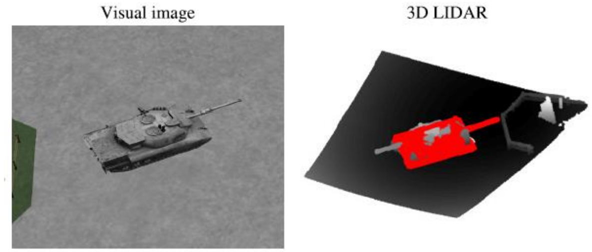
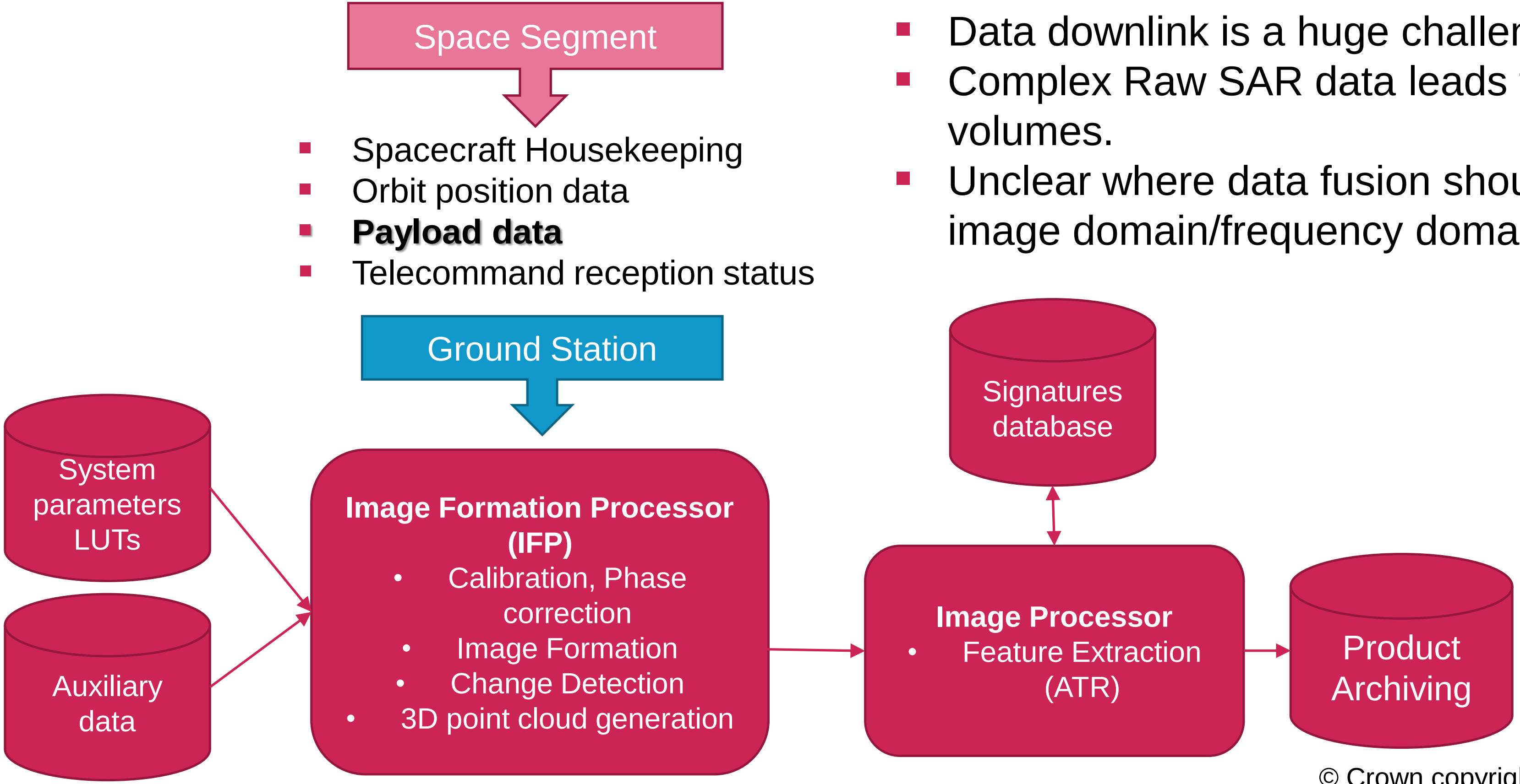


Image from [8] Kechagias-Stamatis et al. 2019

Urban area intelligence

- Urban SAR data can be difficult to interpret given strong dihedral/trihedral returns and large amounts of layover.
- 3D point clouds of urban areas would vastly increase interpretability of data in a more timely fashion than a typical SAR constellation.

Architecture and workflow



Space Segment

- Spacecraft Housekeeping
- Orbit position data
- **Payload data**
- Telecommand reception status

Ground Station

System parameters LUTs

Auxiliary data

Image Formation Processor (IFP)
- Calibration, Phase correction
- Image Formation
- Change Detection
- 3D point cloud generation

Signatures database

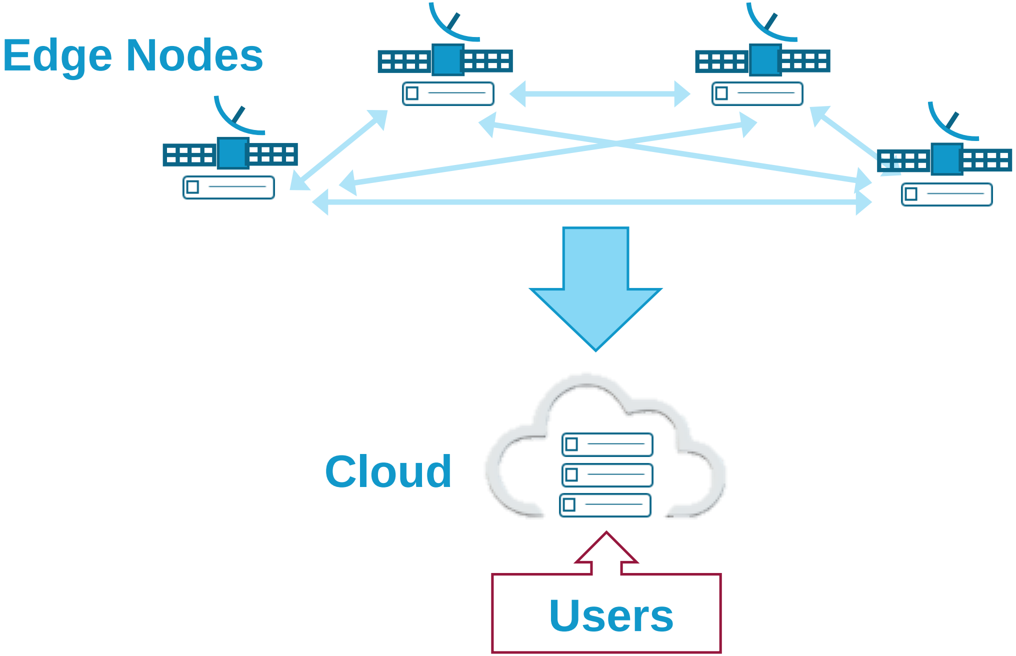
Image Processor
- Feature Extraction (ATR)

Product Archiving

- Data downlink is a huge challenge
- Complex Raw SAR data leads to large volumes.
- Unclear where data fusion should occur, image domain/frequency domain.

Cognitive Radar

Radar system that can perform online learning, execute better actions and adapt operational parameters to suit its environment.



- First level on board processing feasible with GPU and FPGA advances.
- Transition of processing to edge nodes on platform.
- Automated resource management.
- Only move data that is required to lower data overhead.

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Summary and Conclusions

- Advances in technology and the adoption of a new space approach to production mean that reasonably capable small sat SAR systems can be placed in orbit for a fraction of the cost of a large monolithic system.

- Coherent, distributed SAR systems offer many potential advantages over monolithic systems.

- Rapid rate of technology development has somewhat outpaced the signal processing and phenomenological understanding that supports maximum exploitation of a distributed SAR system.

- Need to ensure that ground architecture put in place is flexible, scalable and able to evolve to ensure a smooth transition path of exploitation techniques from bench to asset.

References

[1] Electronic Warfare and Radar Systems Engineering Handbook, 2013, Naval Air Warfare Center Weapons Division, California.
[2] Shahzad, M., Zhu, X., Robust Reconstruction of Building Facades for Large Areas Using Spaceborne TomoSAR Point Clouds. 2015, IEEE Transactions on Geoscience and Remote Sensing. 53(2), pp752-769.
[3] Goh., A. 2012 Bistatic Synthetic Aperture Radar Data Processing and Analysis. PhD Thesis. University of Adelaide.
[4] Woollard, M., Ritchie, M. and Griffiths, H. Investigating the effects of bistatic SAR phenomenology on feature extraction. 2020 IEEE International Radar Conference (RADAR), 906-911, DOI:10.1109/RADAR42522.2020.9114766.
[5] Laubie, E. Aspect diversity for bistatic Synthetic Aperture Radar. Doctoral Thesis, 2017, University of Dayton.
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[7] Gurbuz, S., Griffiths, H., Charlish, A., Rangaswamy, M., Greco, M., Bell, K. An Overview of Cognitive Radar: Past, Present and Future. 2019. IEEE Aerospace and Electronic Systems Magazine. DOI: 10.1109/MAES.2019.2953762
[8] Kechagias-Stamatis, O. Aouf, N. A New Passive 3D Automatic Target Recognition Architecture for Aerial Platforms. 2019, IEEE Transactions on Geoscience and Remote Sensing. 57(1), pp406-415.

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