SPACEBORNE FDM MIMO SAR TOMOGRAPHY

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Introduction

The number of SAR sensors in space is clearly destined to increase in the next years

Examples of commercial SAR constellations (as of September 2022)

- ***IceEye***: *We've launched 20 satellites since 2018 with 10+ more planned for 2022 and beyond*. https://www.iceye.com/satellite-missions
- ***Synspective***: *We aims to build a constellation of 6 satellites by 2023 and 30 satellites by the late 2020s*. https://synspective.com/satellite/
- ***Capella Space***: *… is developing the Capella X-SAR (Synthetic Aperture Radar) constellation consisting of 36 microsatellites…Two microsatellites were launched in December 2018 … joined by six operational Capella microsatellites as of January 2022.* https://www.eoportal.org/satellite-missions/capella-x-sar

Does that make a new SAR paradigm?

The main goal is to improve the current capabilities of SARs systems, primarily in terms of revisit rate and coverage, to address applications that guarantee immediate returns and leverage consolidated concepts

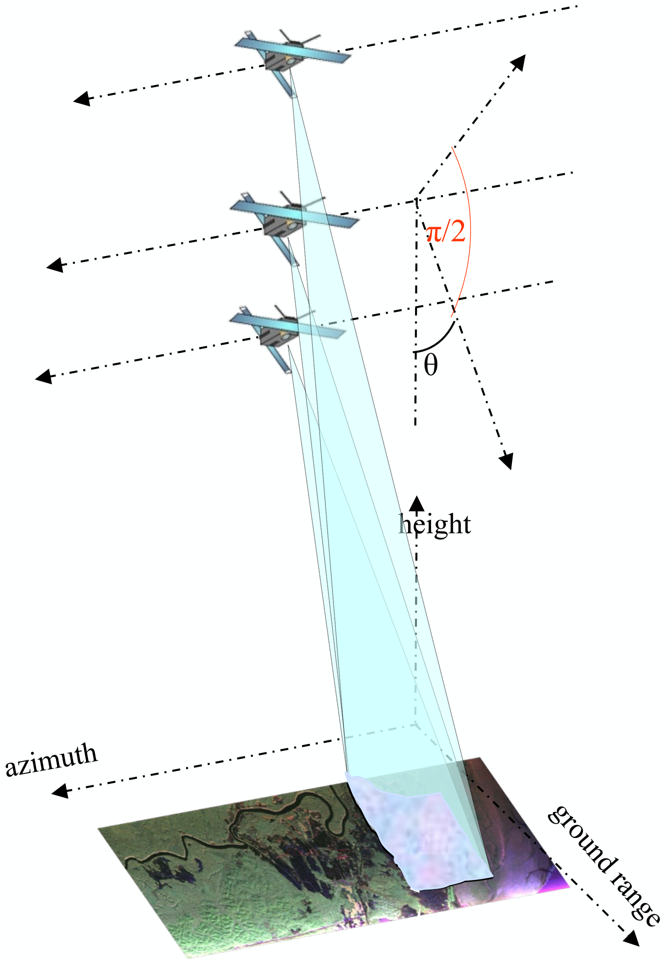
Commercial companies are demonstrating a new technological paradigm to build SAR systems

Research should commit to demonstrating new paradigms to use them

SAR Tomography

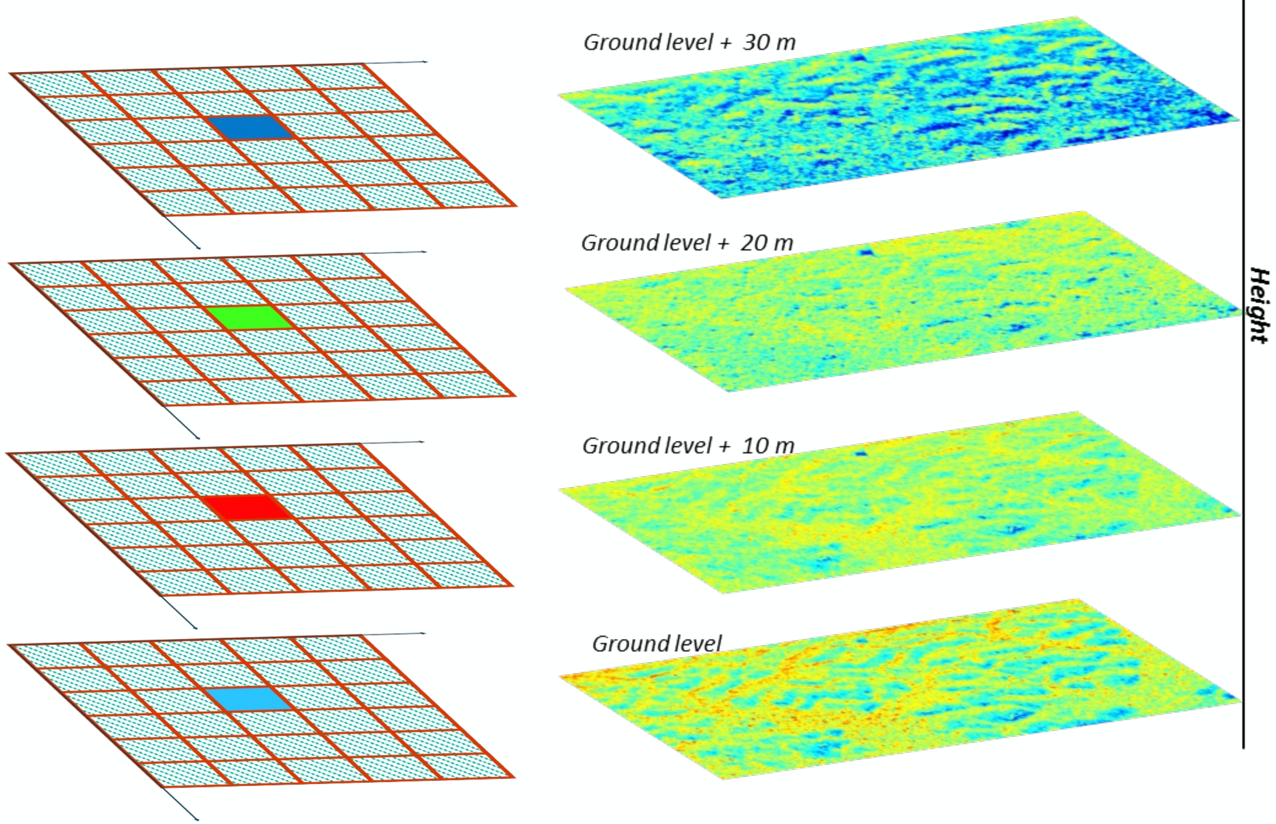
POLITECNICO MILANO 1863 · ISAE SUPAERO · aresys

TomoSAR provides direct access to the 3D structure of Radar scattering from natural media by coherent processing of SAR data from multiple flights



SAR produces pixels

TomoSAR produces voxels



SAR Tomography

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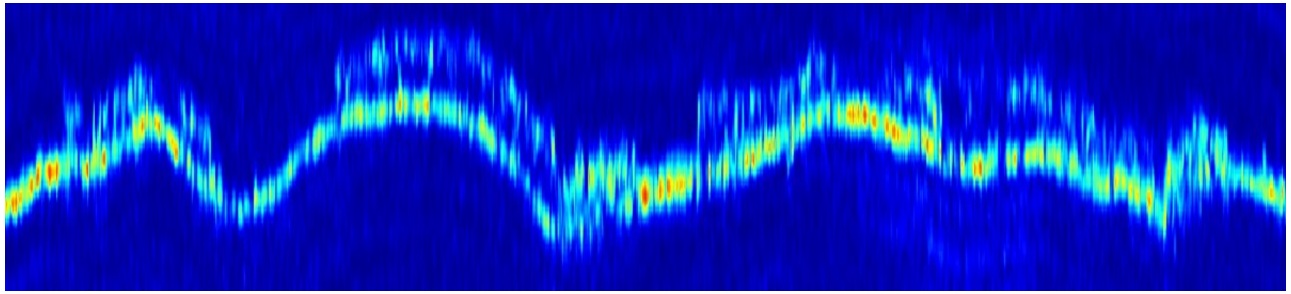
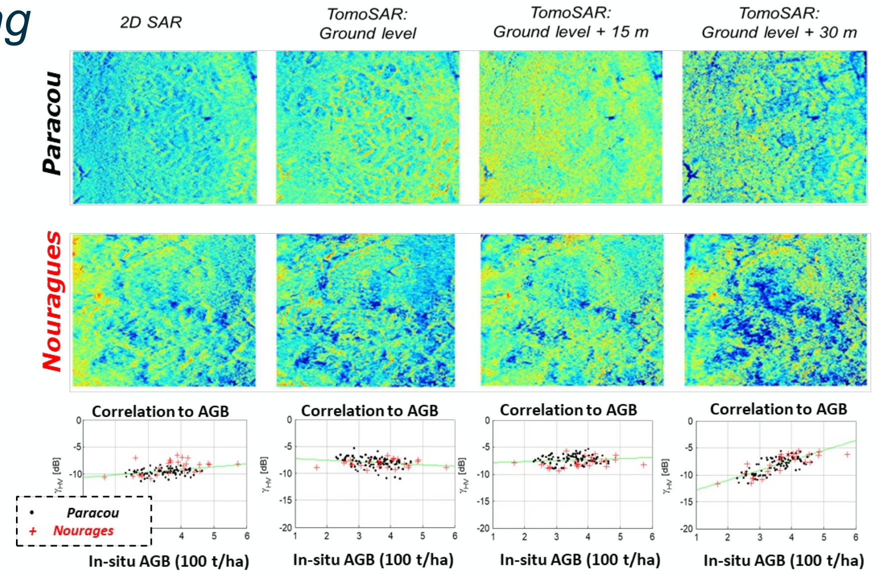
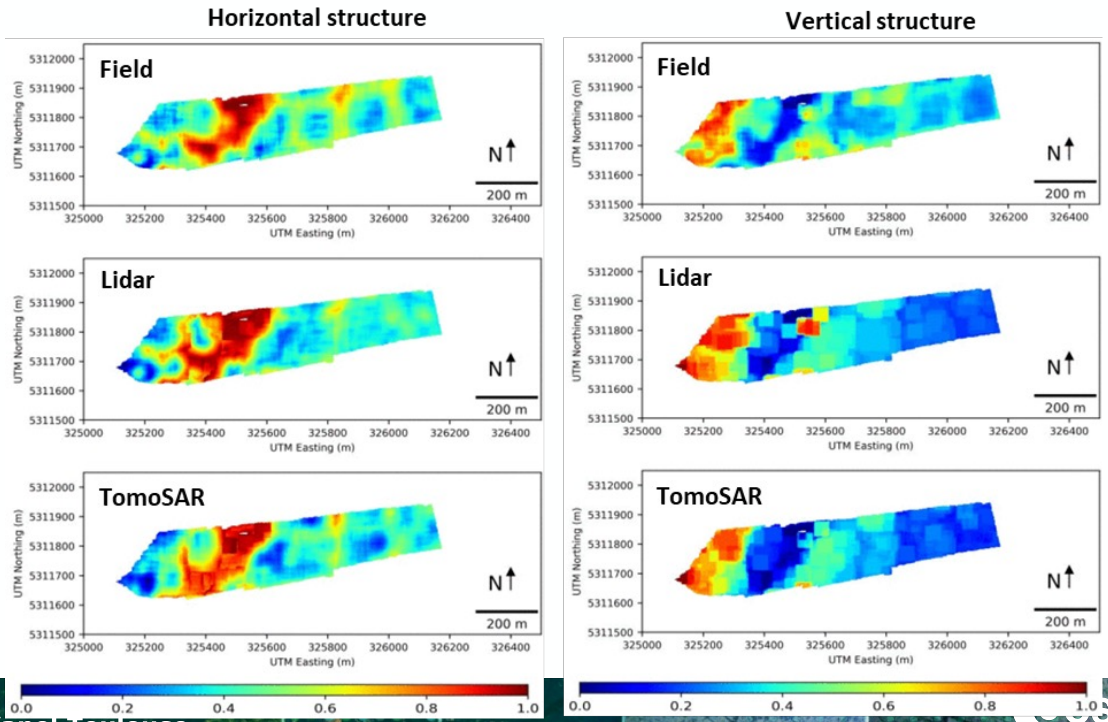
Forested areas:

- ✓ *Forest height*
- ✓ *True terrain elevation below the vegetation*
- ✓ *Improved AGB retrieval*
- ✓ *Vegetation structure*
- ✓ *BIOMASS tomographic phase tasked with global forest 3D mapping*





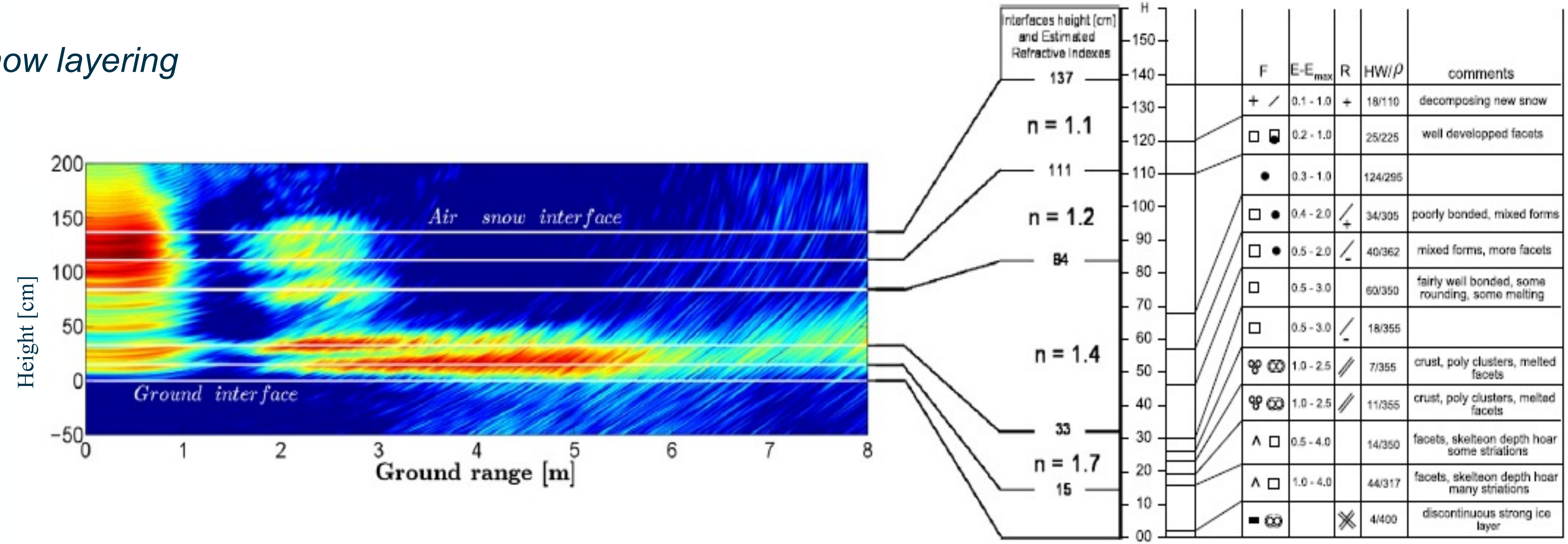


SAR Tomography

TomoSAR provides direct access to the 3D structure of Radar scattering from natural media by coherent processing of SAR data from multiple flights

Snow:

- ✓ *Snow depth*
- ✓ *Refraction index*
- ✓ *SWE*
- ✓ *Internal snow layering*

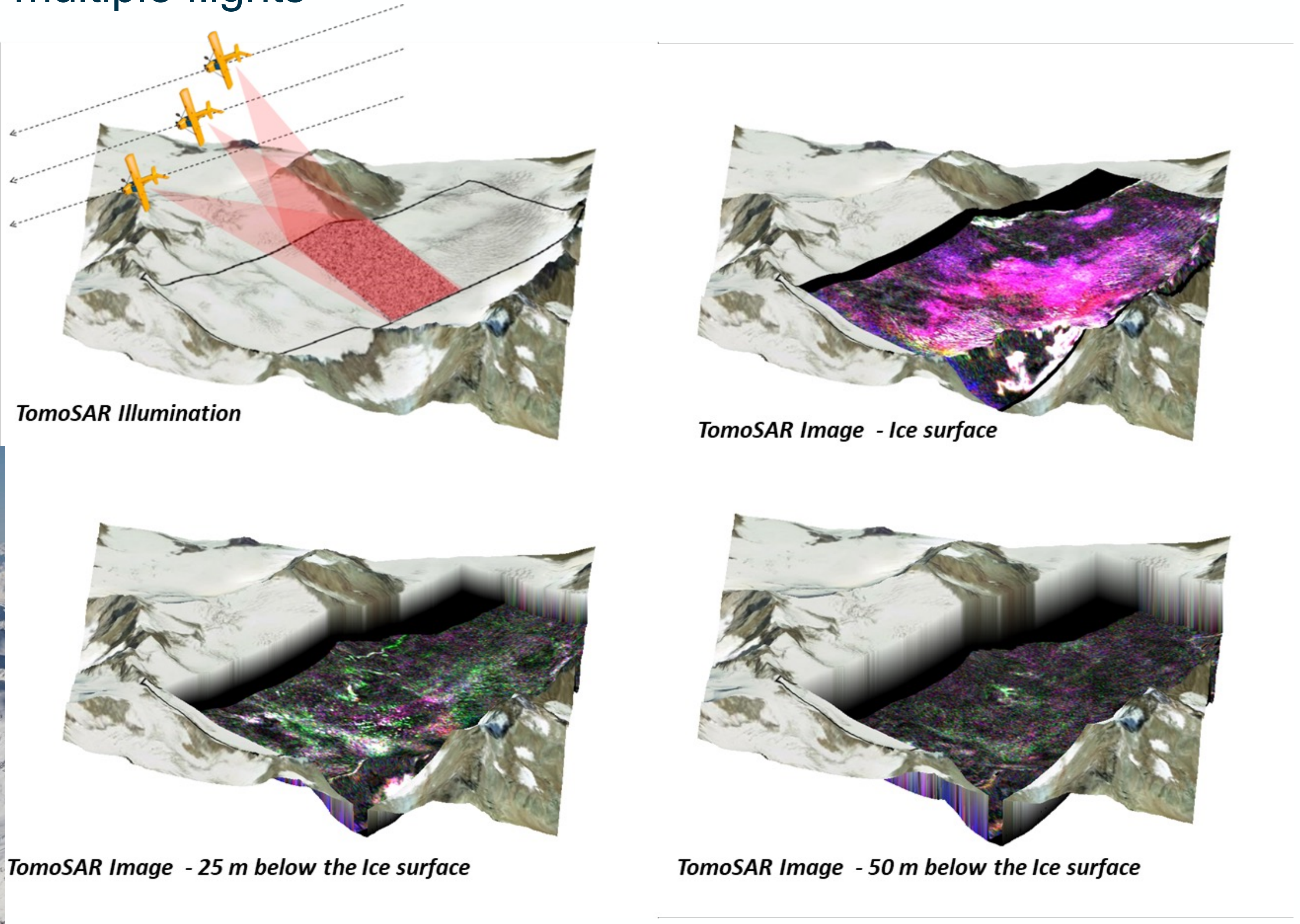


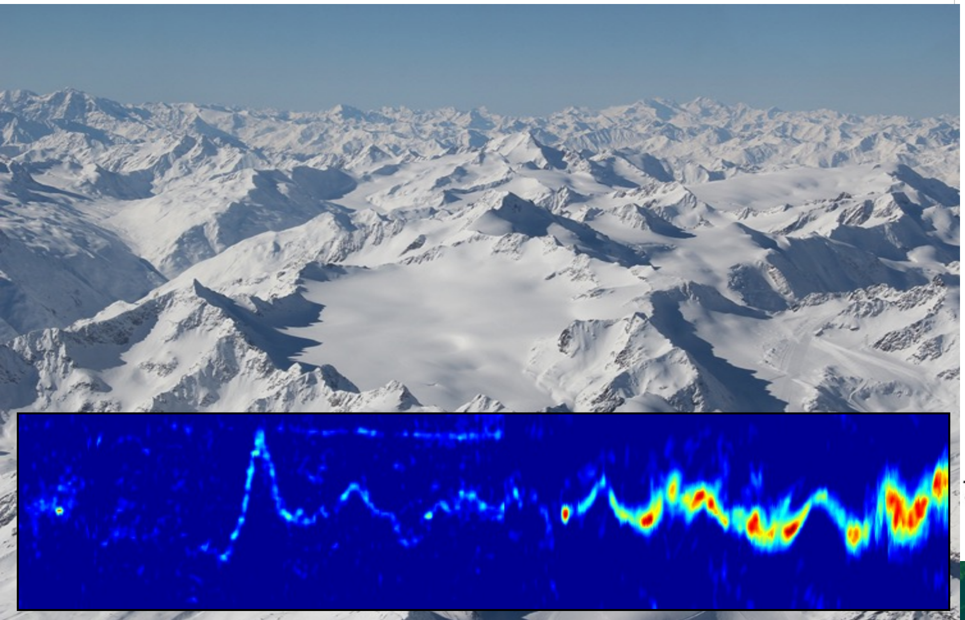
SAR Tomography

TomoSAR provides direct access to the 3D structure of Radar scattering from natural media by coherent processing of SAR data from multiple flights

Ice and glaciers:

- ✓ *Ice surface elevation*
- ✓ *Internal structure (ice/firn, crevasses, presence internal scatterers, bedrock)*





Spaceborne SAR Tomography

Despite the many successful experimental campaigns, spaceborne tomography is yet to come for what concerns of natural scenarios.

This is largely due to the fact that that the vertical resolution provided by SAR tomography is inherently linked to the number of available view points, which - for the case of a single satellite - corresponds to the number of orbits over a given area

Some examples:

- ***Afrisar**: 11 passes*
- ***TomoSense**: 20 to 30 passes*
- ***AlpTomoSAR**: 20 passes*
- ***AlpSAR**: 36 passes*
- ***SnowLab**: up to 50 passes*

Spaceborne SAR Tomography

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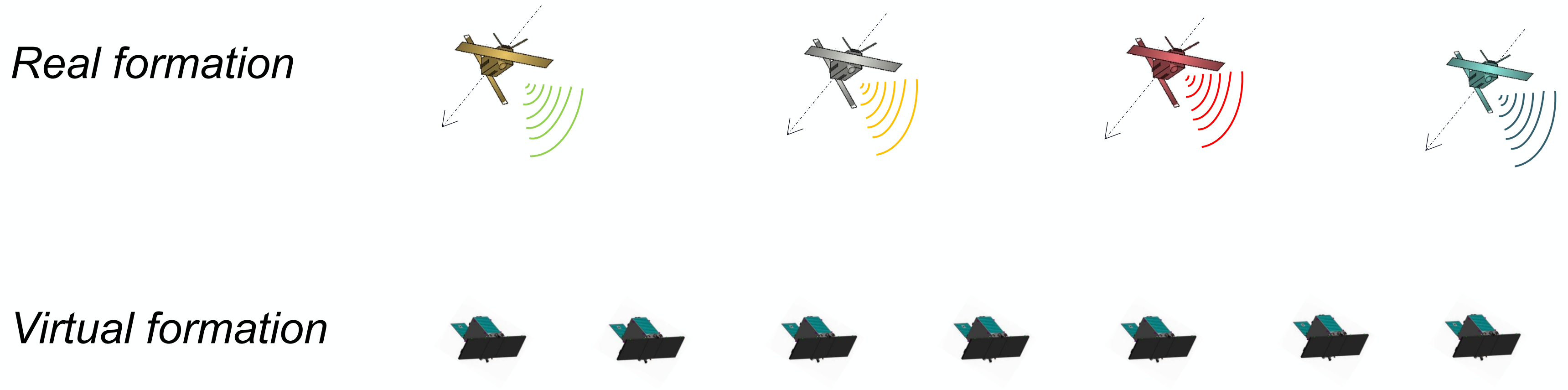
The one mission currently appointed to gather tomographic acquisitions of forested areas is the forthcoming ESA Earth Explorer BIOMASS, for which temporal decorrelation is predicted to be successfully mitigated by the three-day revisit time and the long wavelength

Yet, vertical resolution is limited to ≈ 23 m

Multiple Input Multiple Output (MIMO) SAR is a most attractive solution for spaceborne tomography

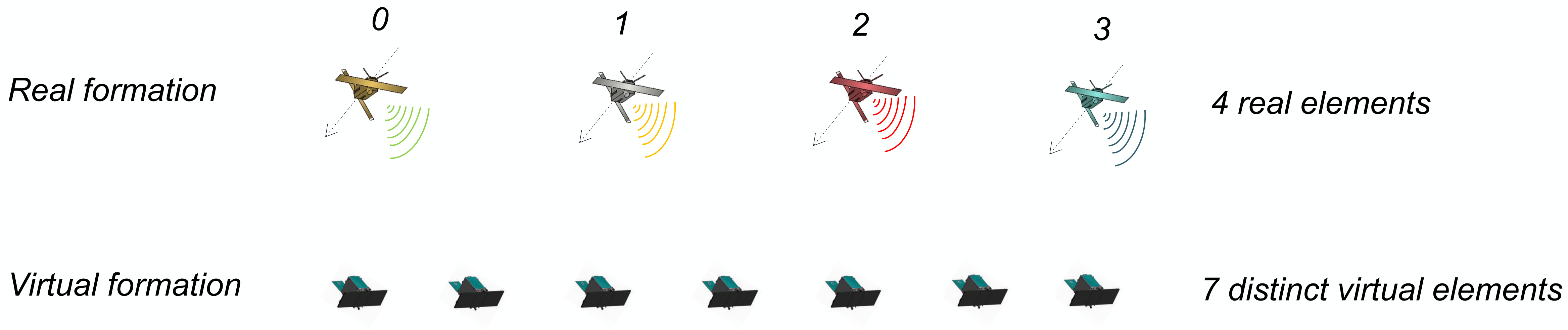
In simple terms:

- All satellites act both as Tx and Rx
- The data acquired by a given Tx/Rx pair can be thought of as acquired by a ***virtual*** monostatic SAR placed in the middle (*in the limit of small bistatic angles*)



Key question is how to deploy real elements to maximize the number of distinct and uniformly spaced virtual satellites

- Upper theoretical bound: $N_v = \frac{N(N+1)}{2}$
- Approximate rules exist for sub-optimal deployment
- Optimal deployment by exhaustive search possible for few satellites



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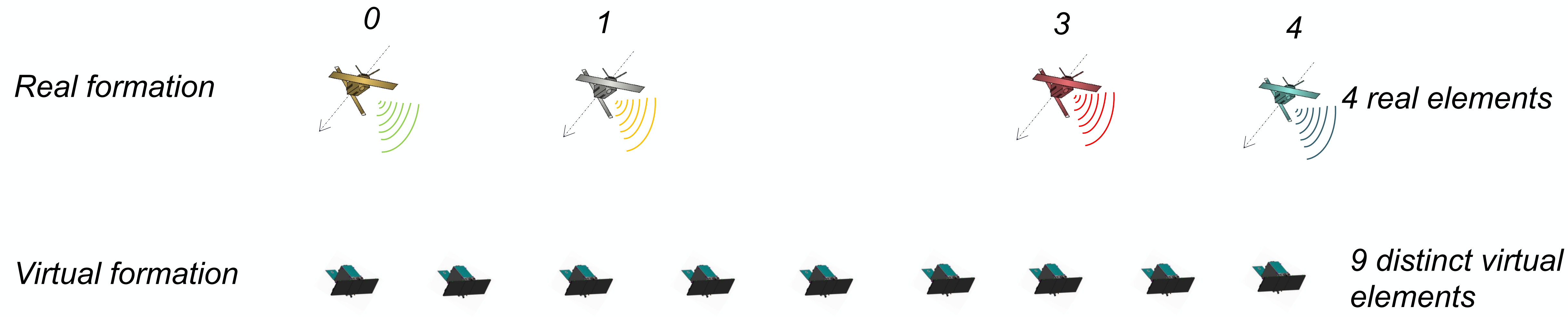
Optimal deployment for a 4 satellite MIMO formation



Spaceborne MIMO SAR Tomography

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Optimal deployment of 3 to 6 sats

N	Optimal deployment	N_v
3	0 1 2	5
4	0 1 3 4	9
5	0 1 3 5 6	13
6	0 1 3 5 7 8	17

With 4 (5) optimally deployed physical satellites the number of virtual sensors is just 9 (13)

Still far from state-of-the-art tomographic campaigns.

MIMO Correlation tomography

Correlation tomography is an alternative approach to tomographic imaging that proceeds from the set of InSAR coherences gathered at different baselines

- Proposed in the context of SAR by *Treuhaft* (2000) and *Claude* (2007)
- Largely considered in the context of bistatic mission proposals like SAOCOM-CS and PARSIFAL

Assuming correlation tomography, tomographic imaging depends on the set of available baselines, i.e.: the set of the **differences** in sensor positions

Keeping mind that sensors can be *virtual*, it is immediate to see the benefit:

N real MIMO satellites → **Up to $N_v = \frac{N(N+1)}{2}$ virtual satellites** → **Up to $N_d = \frac{N_v(N_v-1)}{2}$ baselines**

The number of available baselines ideally goes with up to the *4-th* power of the number of physical satellites

Minimum Redundancy Virtual Array

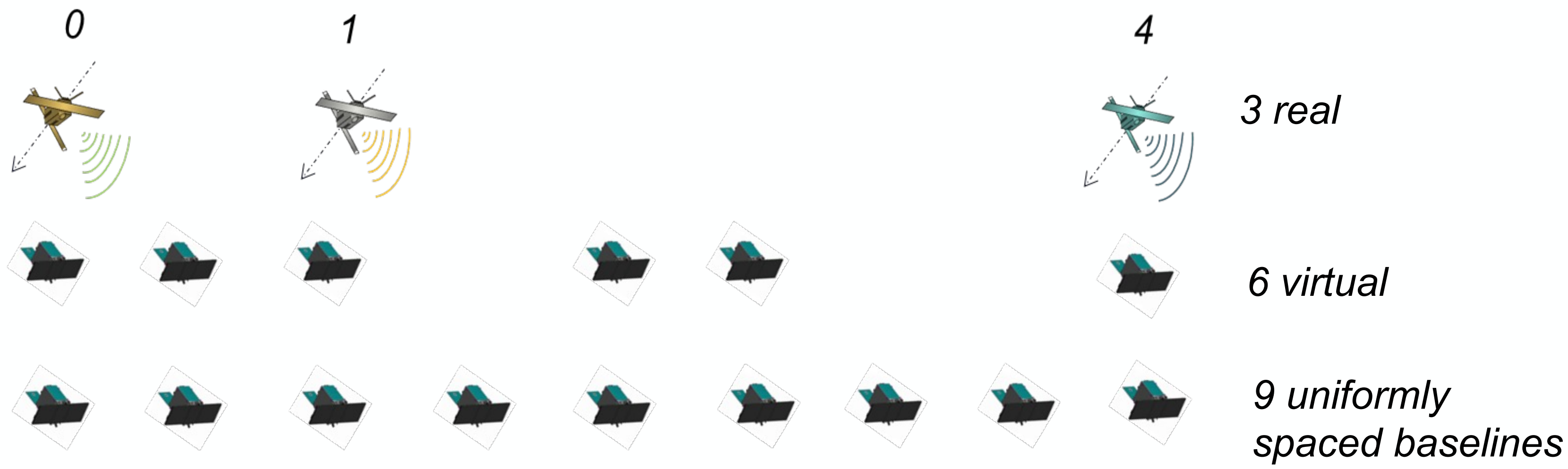
Optimal sensor deployment can then be cast in the following terms:

find the positions of N physical Rx/Tx sensors such that the set of position differences among all resulting virtual sensors form a uniformly-spaced array of maximum length.

Well known concept in array literature

Optimal deployment is referred to as Minimum Redundancy Virtual Array (MRVA)

N	Optimal deployment	N_d
3	0 1 4	9
4	0 1 9 12	25
5	0 1 14 19 22	45
6	0 1 9 10 34 37	75



Two problems

Channel access: a tacit assumption in MIMO literature is that the echoes associated with different transmissions can be perfectly separated at the Rx. To do that, transmission of orthogonal waveforms is generally assumed.

This is simply impossible for the case of SAR*, unless:

- Waveform design is coupled with beamforming in elevation at Rx
- The transmissions occur in separated frequency bands

***G. Krieger, MIMO-SAR, Opportunity and Pitfalls, TGRS, 2014.**

Spatial decorrelation: array literature assumes always isotropic point scatterers. No consideration is present about target decorrelation as a function of baseline

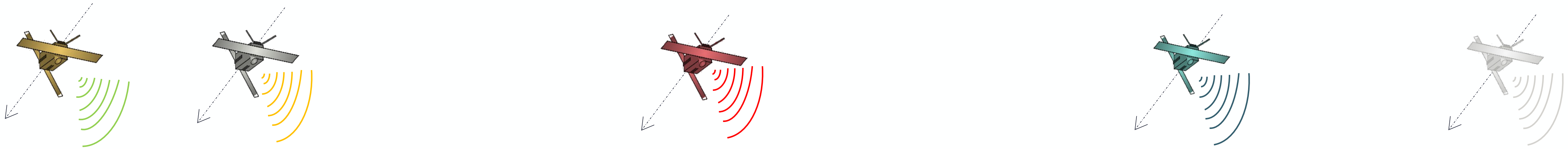
$\Rightarrow$ The concept of MRVA is not directly applicable to the case of TomoSAR

Spaceborne MIMO SAR Tomography

Two solutions

Channel access: assume Frequency Division Multiplexing (FDM)

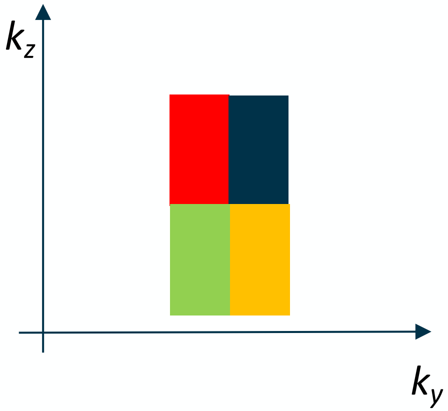
- All satellites transmit simultaneously on different frequency bands and receive all transmitted bands
- Guided by the idea to enable an increase of the number of satellites by simplifying individual elements



Spatial decorrelation: design the formation to optimize resolution while accounting for which spatial wavenumbers are captured to ensure spectral overlap

Diffraction Tomography*

- The information retrieved about an illuminated weak-scattering object corresponds to a specific region in the wavenumber domain, depending on wavelength, bandwidth, *Tx* and *Rx* position



- In a multistatic experiment, different regions can be combined to form a bigger one by properly positioning different Tx/Rx pairs
- Largely used in crystallography and seismic exploration

*Diffraction tomography and multisource holography applied to seismic imaging, Wu and Toksoz, GEOPHYSICS, VOL. 52, NO. 1 (JANUARY 1987);

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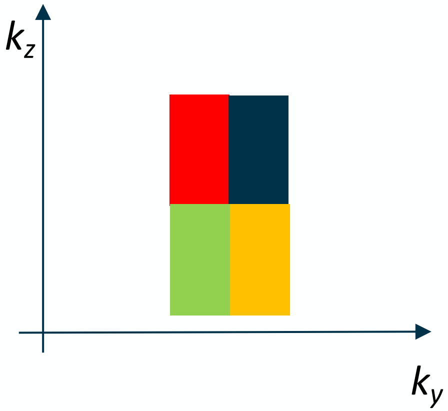


- In a multistatic experiment, different regions can be combined to form a bigger one by properly positioning different Tx/Rx pairs
- ***Kz is here the vertical wavenumber. Don't confuse it for the interferometric wavenumber!***

Diffraction tomography and multisource holography applied to seismic imaging, Wu and Toksoz, GEOPHYSICS, VOL. 52, NO. 1 (JANUARY 1987);

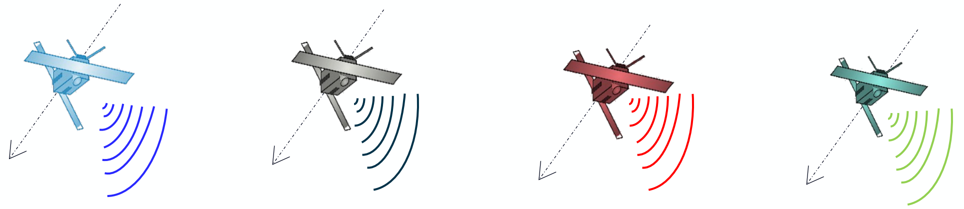
FDM MIMO TomoSAR

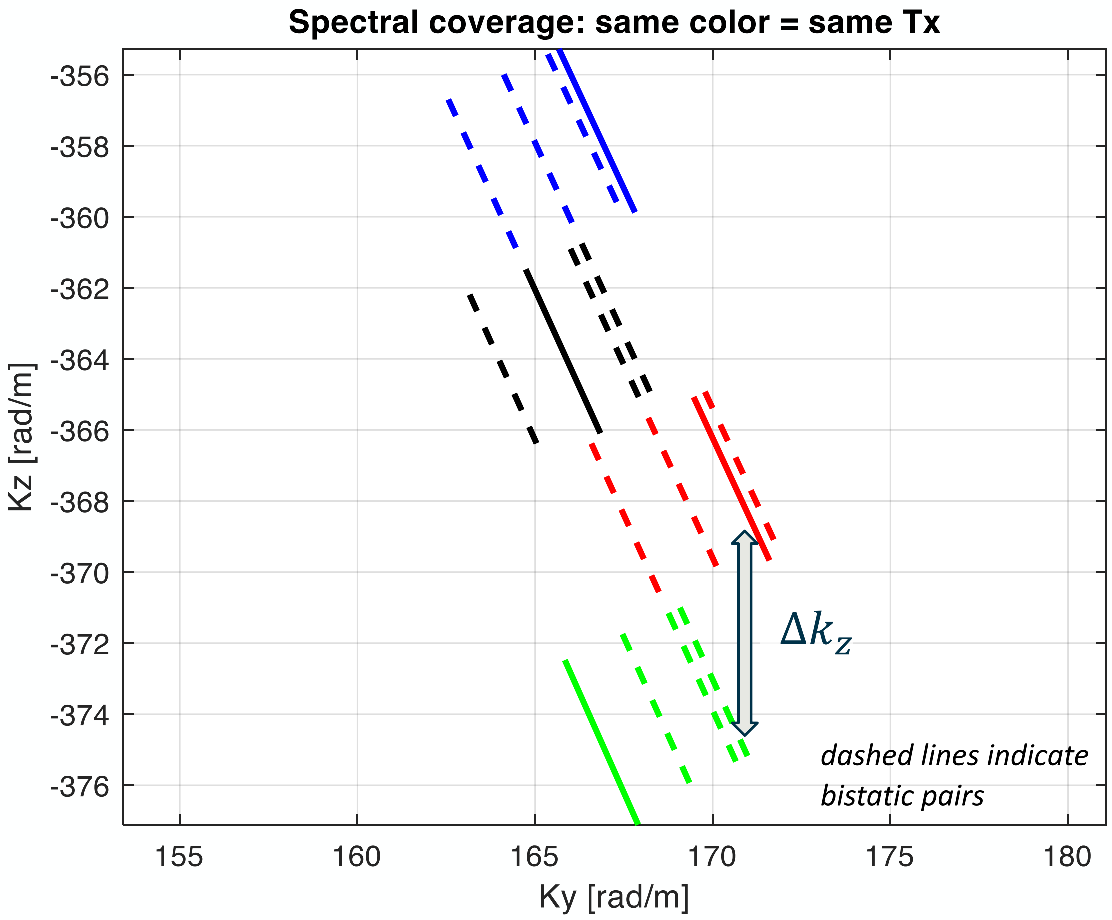
Mapping from (f, θ) to (k_y, k_z) is given as:

$$k_y = \frac{2\pi f_{Tx}}{c}\left(sin(\theta_{Rx}) + sin(\theta_{Tx})\right)$$

$$k_z = -\frac{2\pi f_{Tx}}{c}\left(cos(\theta_{Rx}) + cos(\theta_{Tx})\right)$$

- Each Tx/Rx SAR acquisition is represented by a segment in the (k_y, k_z) plane
- Spatial resolution is the reciprocal of the extent of wavenumber coverage
- Spatial ambiguity is given by spacing between segments
- The interferometric wavenumber between any two acquisitions is obtained as the vertical separation between any two segments





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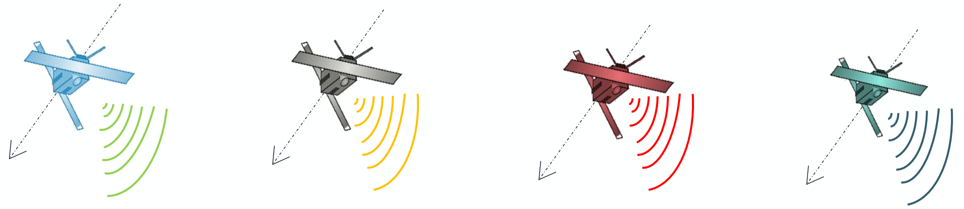
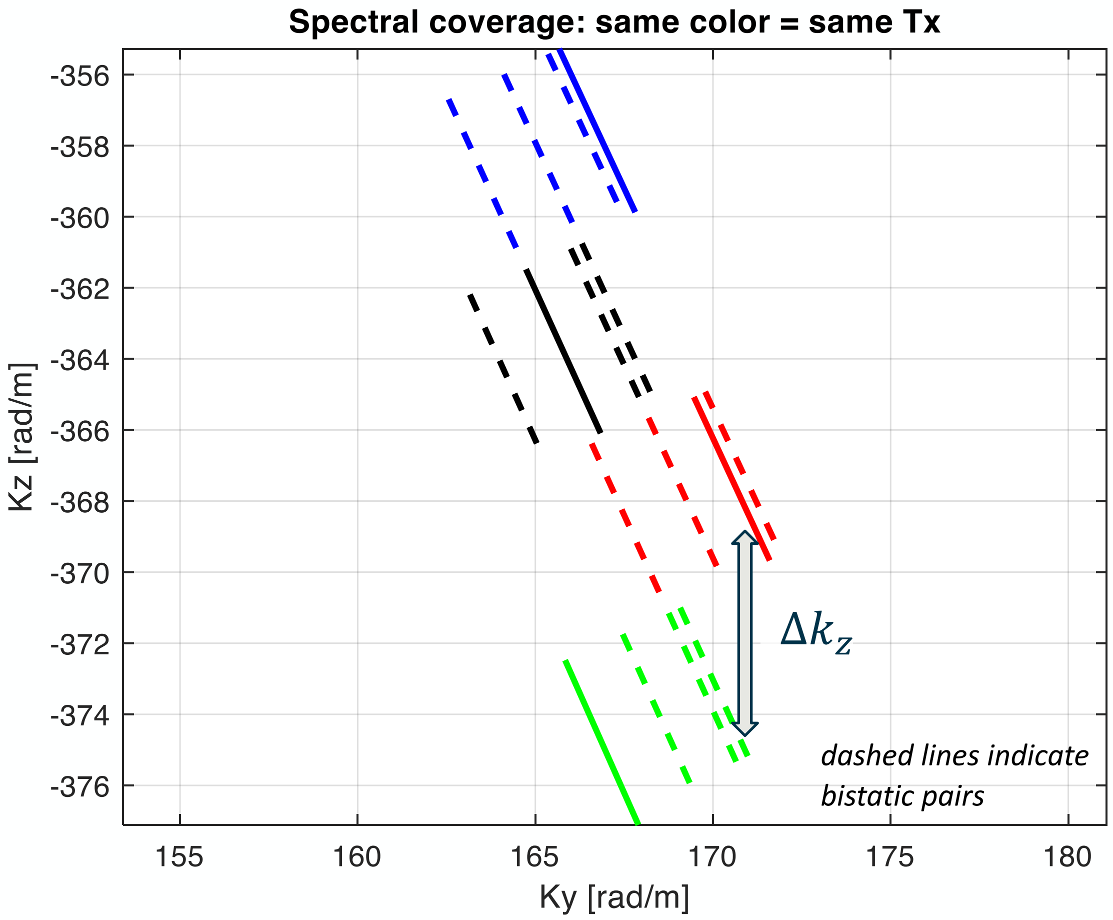
this is what is conventionally called k_z but we call it here Δk_z to avoid confusion





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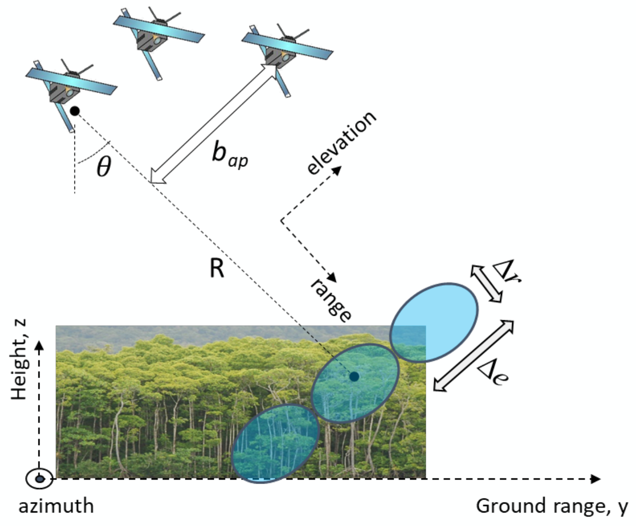
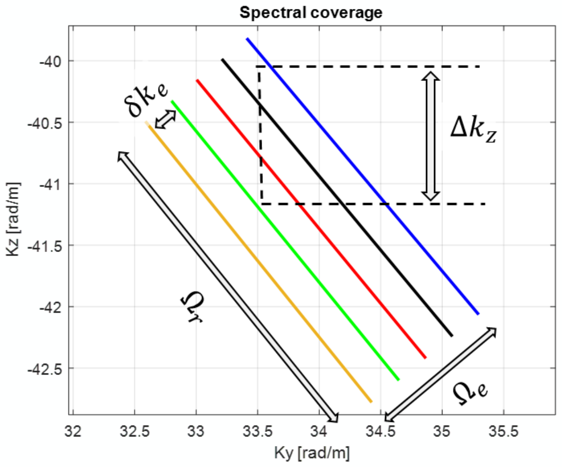
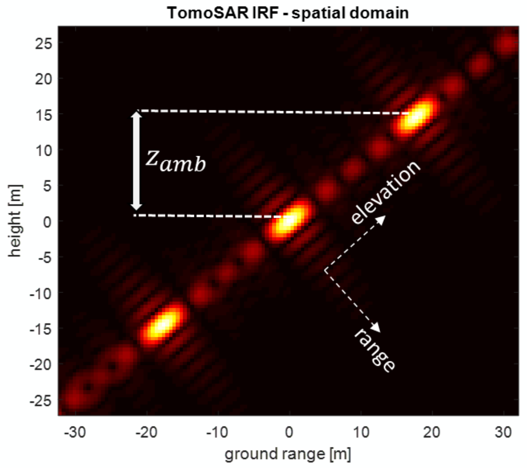


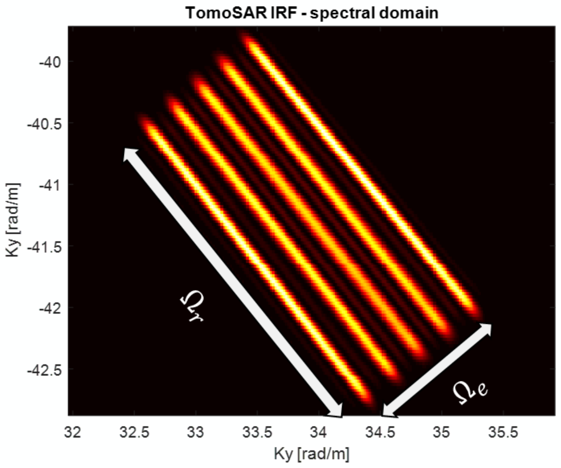
(a)



(b)



(c)



(d)

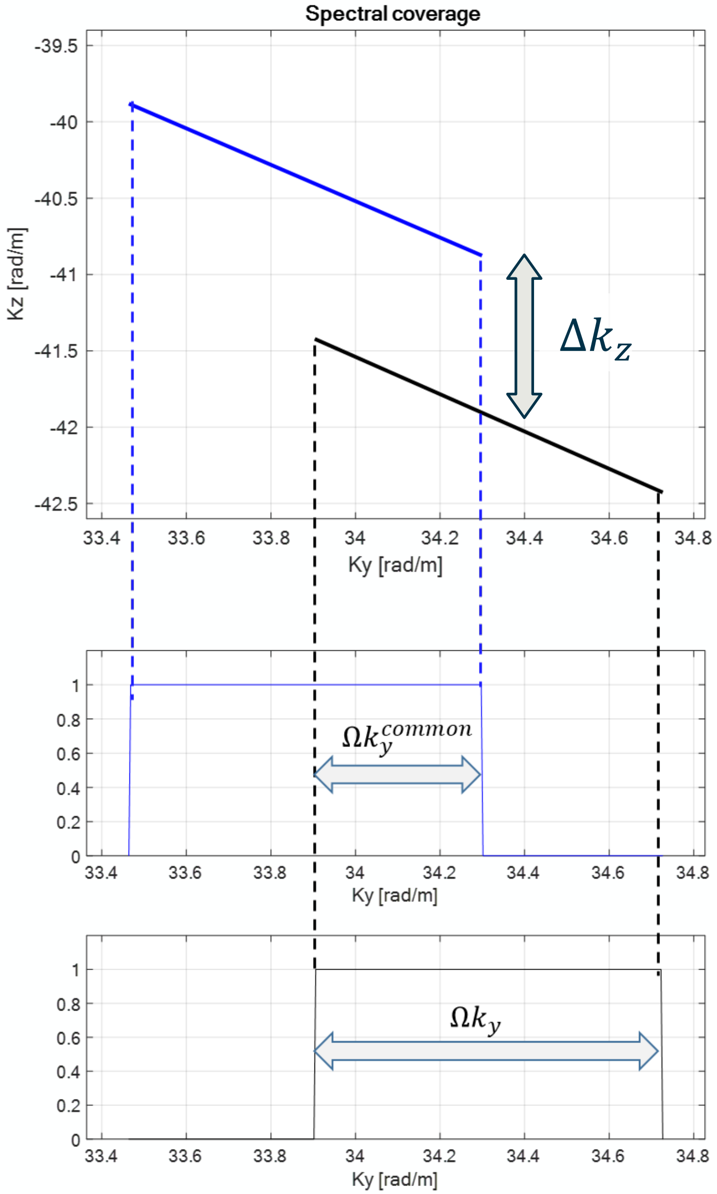
Spatial decorrelation in any two images is accounted for by taking the projection of individual wavenumber segments onto the k_y axis

⇒ straightforward evaluation of the interferometric coherence magnitude based on a visual analysis of the overlapping regions between the projections of any two segments

$$\gamma = \frac{\Omega k_y^{common}}{\Omega k_y}$$

On this ground, optimal deployment of a formation of N MIMO Rx/Tx sensors can be discussed in a graphical manner.

- Interferometric pairs are marked as **valid** depending on the overlap between their projections onto the k_y axis.
- For valid pairs, the interferometric wavenumber is obtained as the vertical separation between the associated segments



The resulting optimization principle is referred to as **Minimum Redundancy Wavenumber Illumination**

PATENT PENDING

*find the positions of N physical Rx/Tx sensors such that the set of **valid** vertical separations among all illuminated wavenumbers is as close as possible to forming a uniformly spaced array of maximum length.*

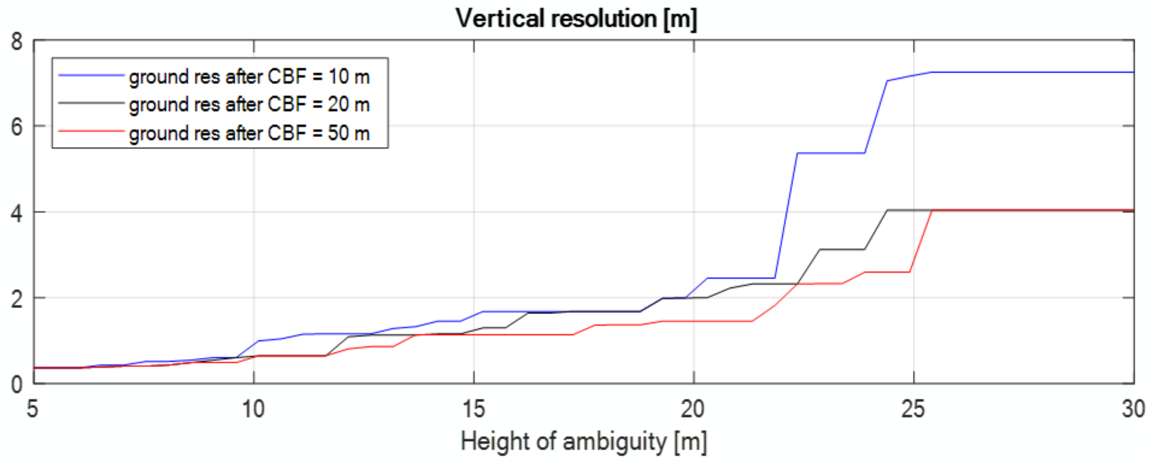
PATENT PENDING

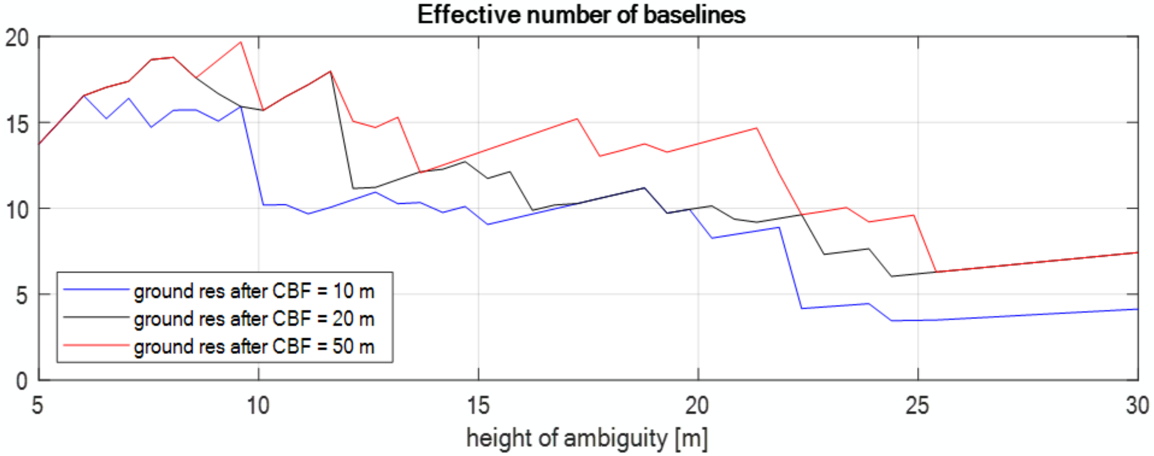
Optimization is carried out via exhaustive search:

- Start with perfect alignment along k_y
- Explore all possible combinations of satellite positions
- For every possible combination, annotate:
  - ✓ Resulting vertical resolution
  - ✓ Height of ambiguity
  - ✓ Spectral overlap, quantified as the resulting ground resolution after Common Band Filtering is performed

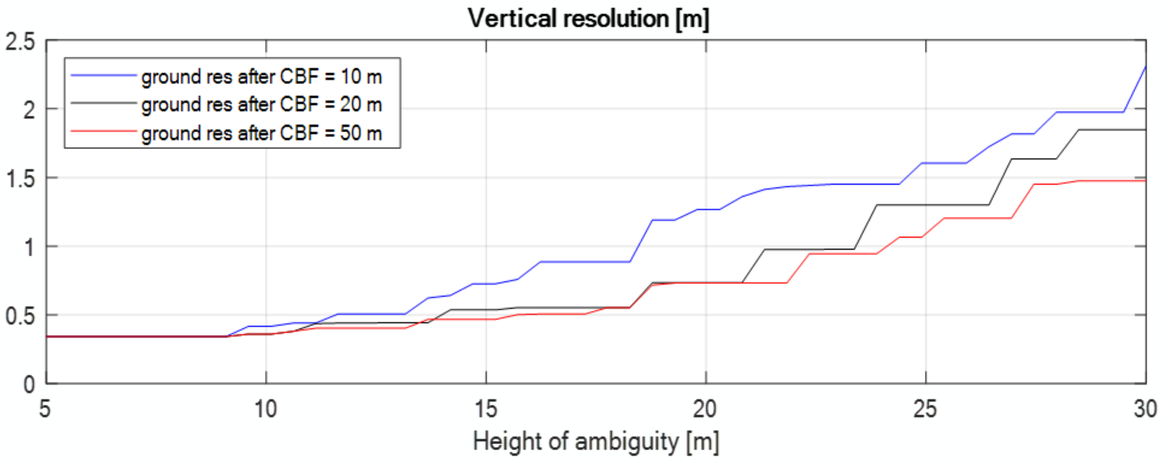
MRWI

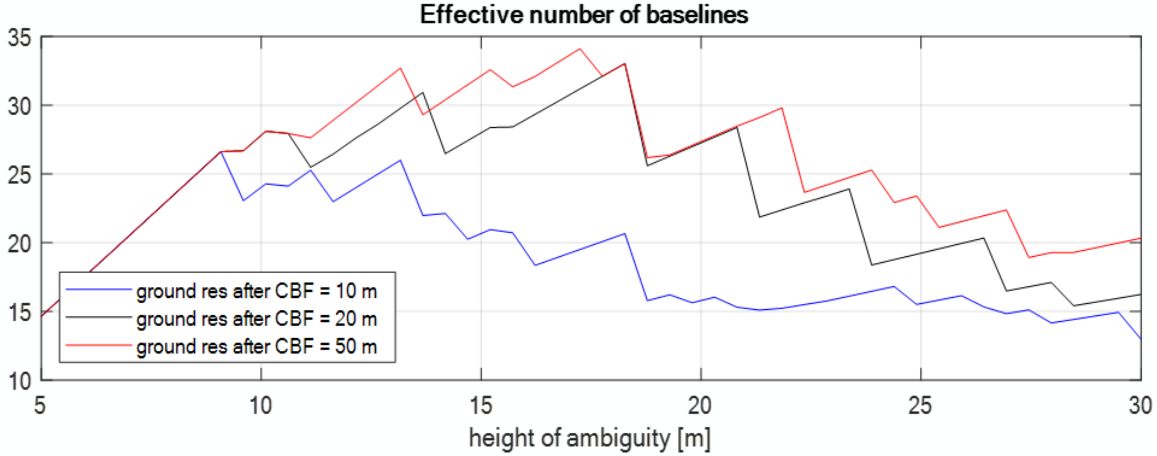
4 satellites





5 satellites





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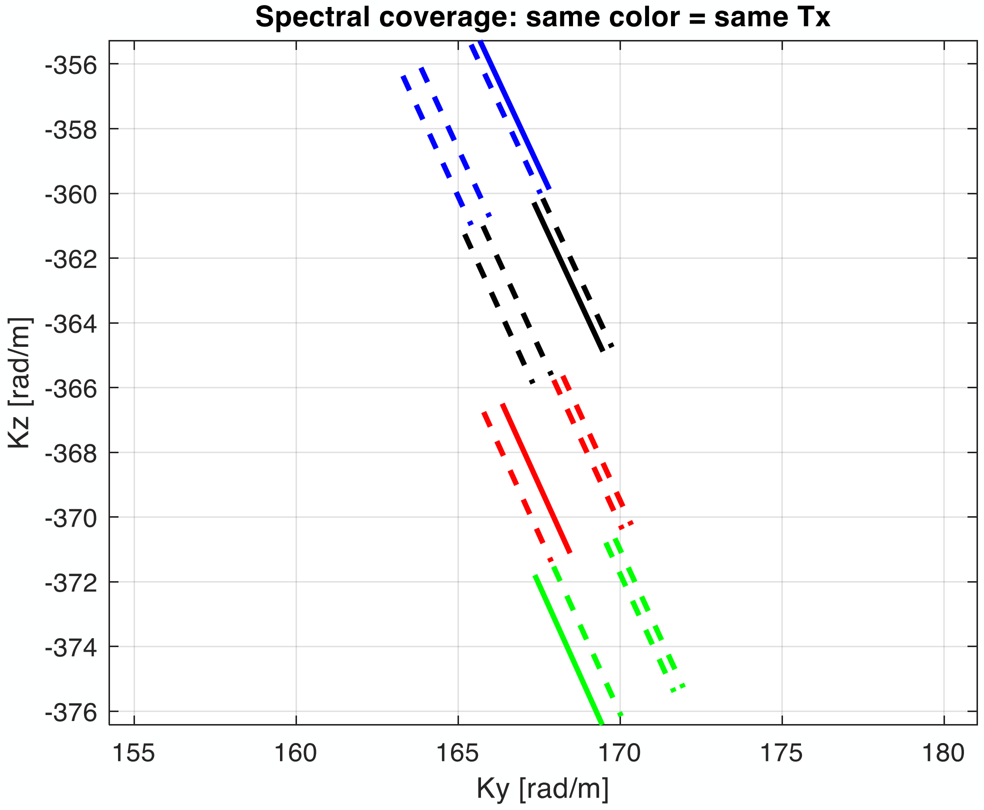
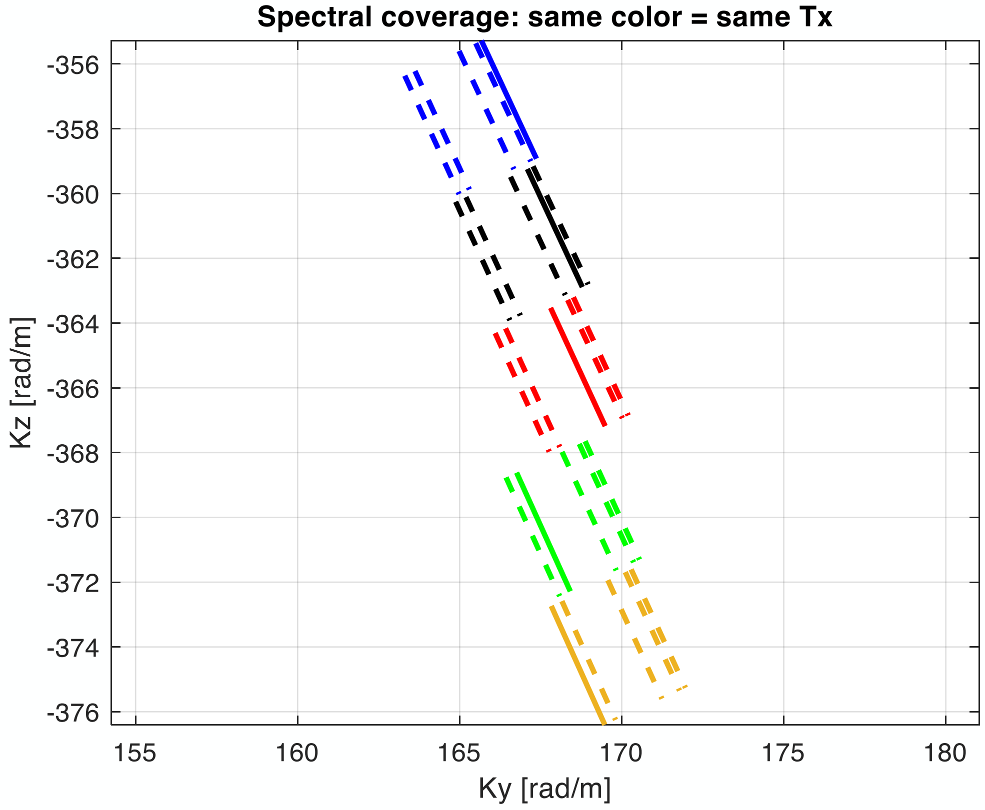


5 satellites



N	Worse ground resolution after CBF (m)	Optimal deployment (°)	z_{amb} (m)	δz (m)	N_{eff}
4	10	25.00 24.91 24.41 24.24	8.4	0.51	16
5	10	25.00 24.93 24.64 24.22 24.08	10.5	0.41	25

Numerical simulations

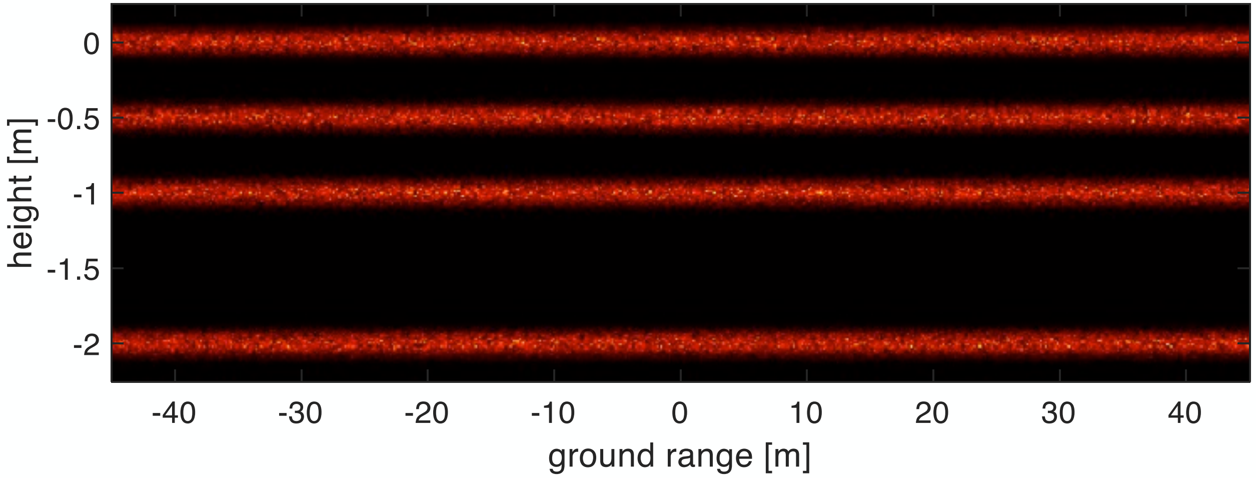
Geometrical simulation by projection of random scatterers based on bistatic delays
$\Rightarrow$ Spatial decorrelation is automatically accounted for

Simulated scenario accounts for 4 closely spaced layers

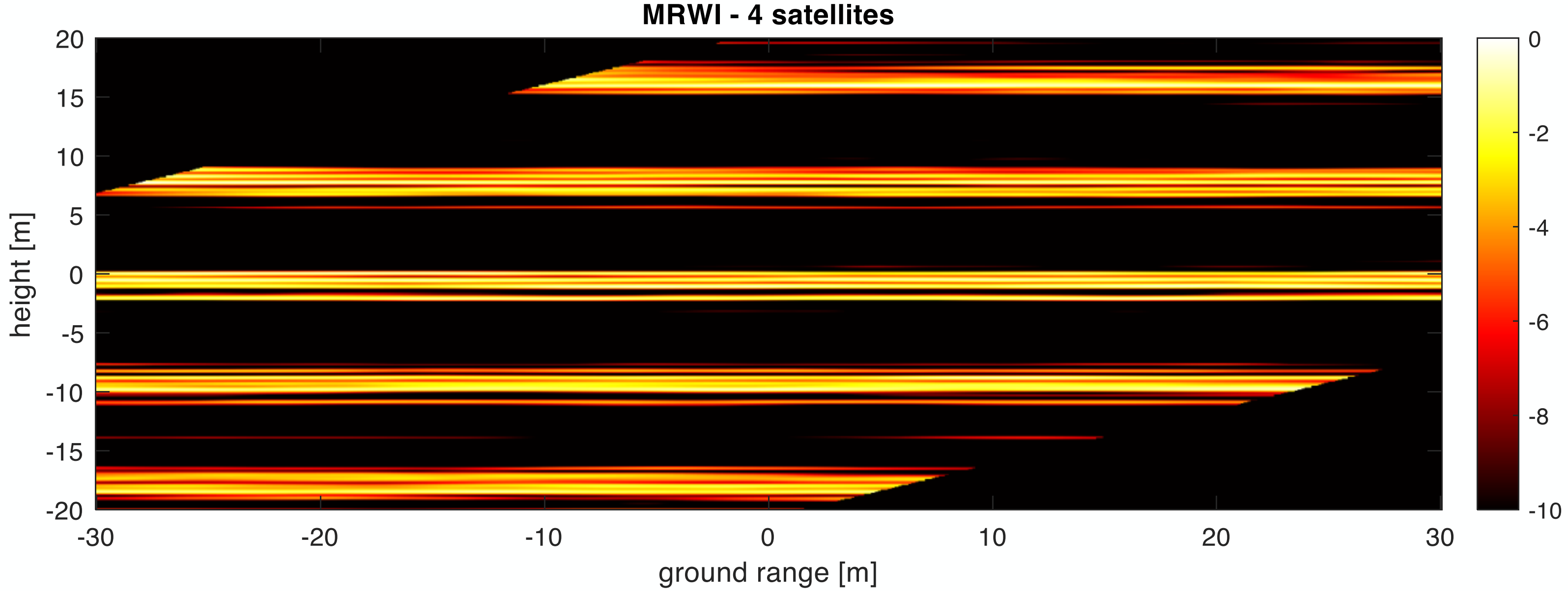
Simulation parameters

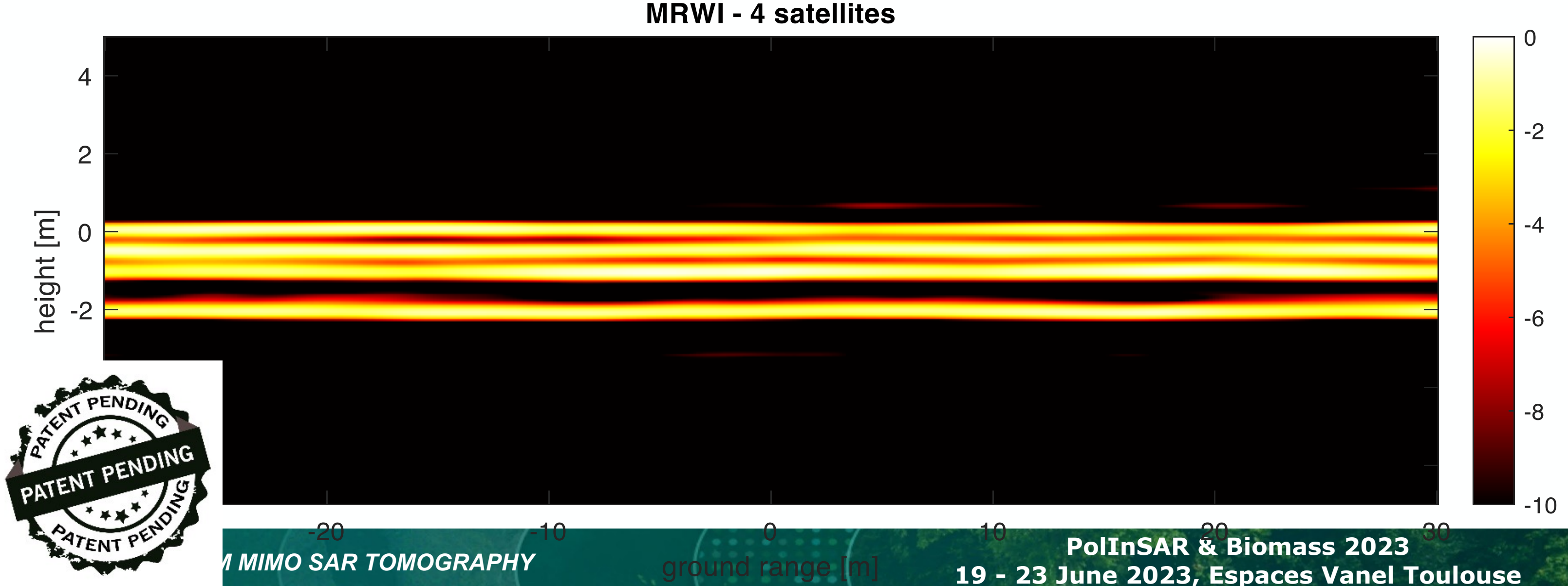
- *N* = 4 or 5 satellites
- Formation deployment according to MRVA and MRWI
- Total bandwidth 500 MHz (split among the *N* satellites)
- Guard band of 6 MHz
- Reference incidence angle $\theta = 25°$

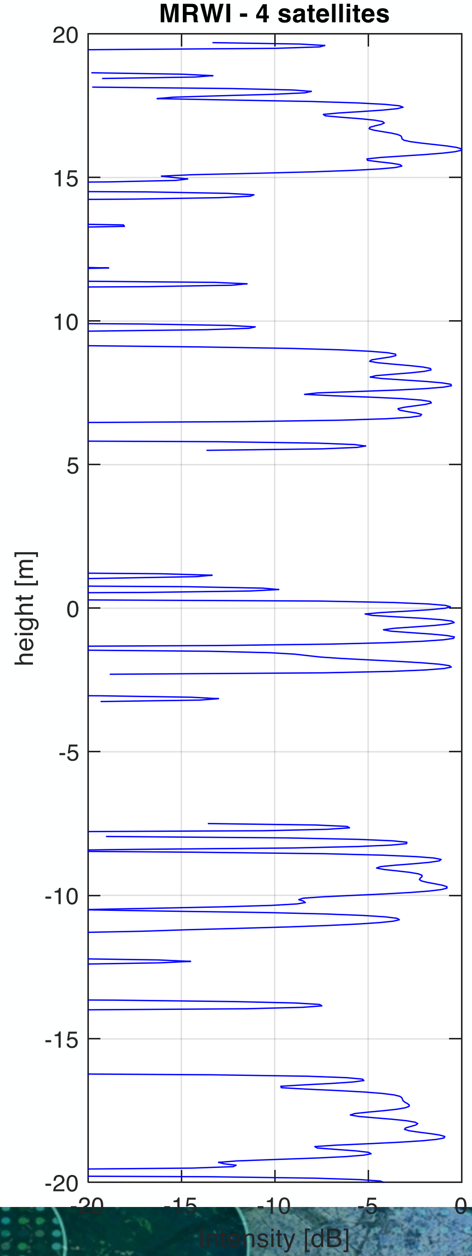
Simulated scenario



MRWI

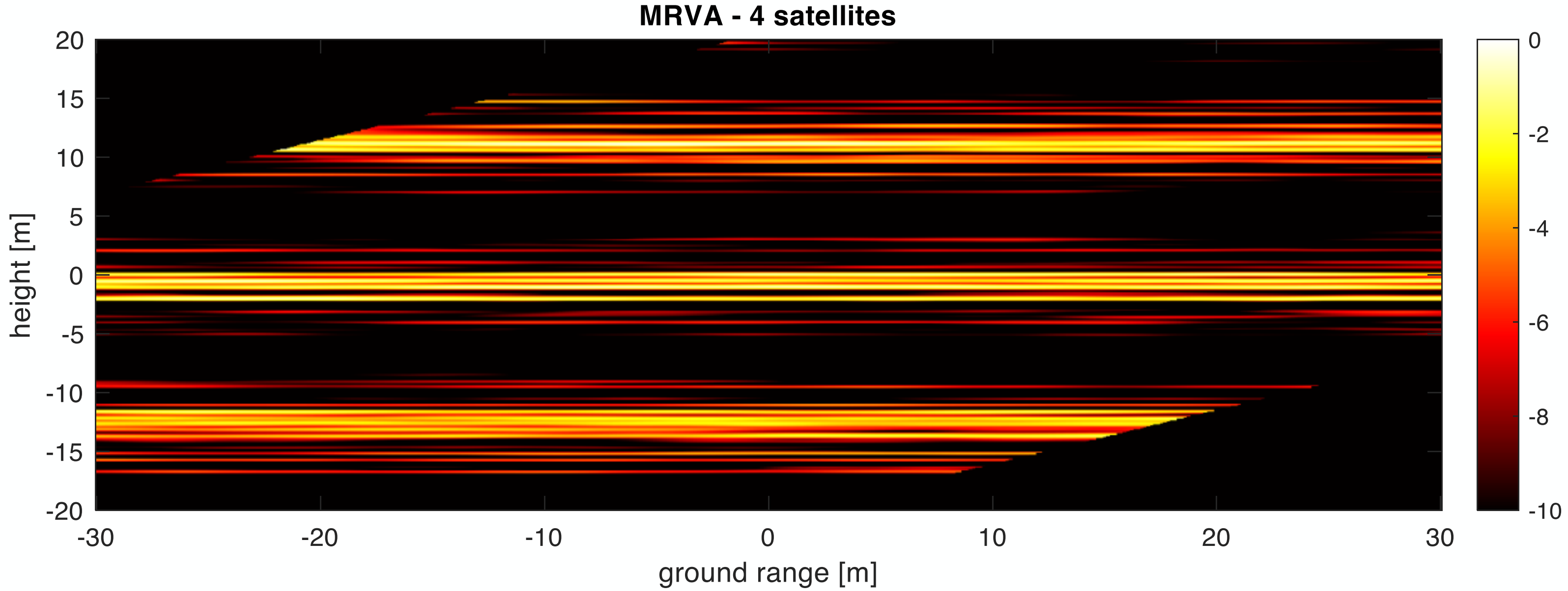


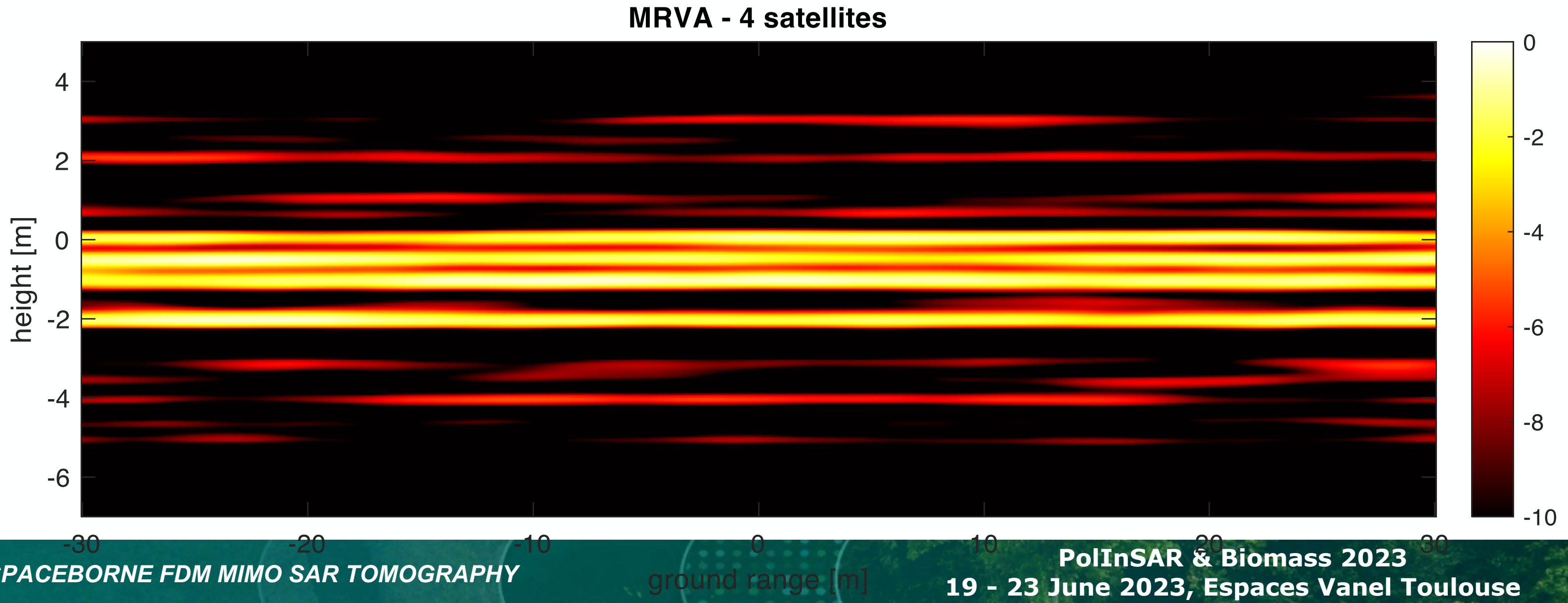


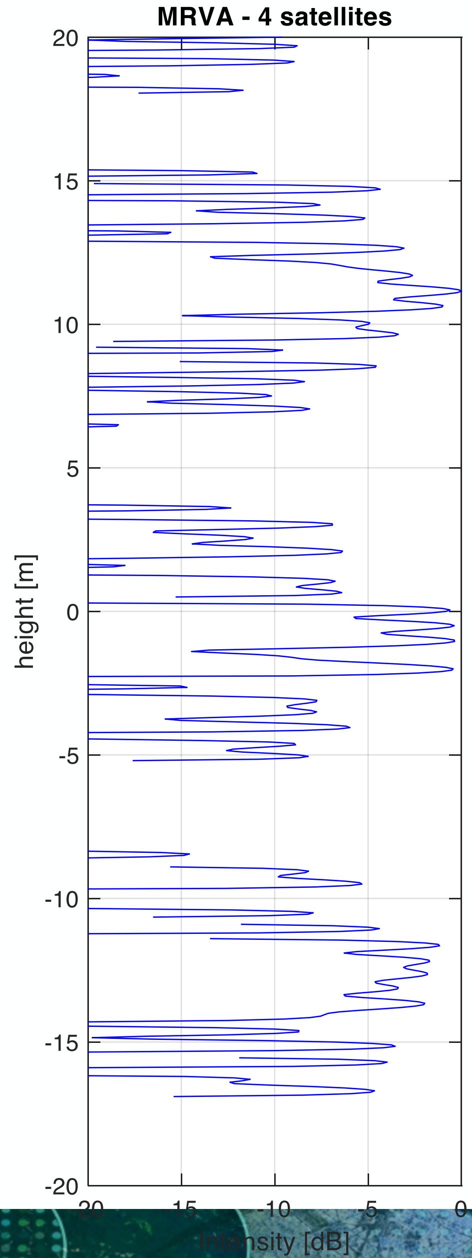


PATENT PENDING

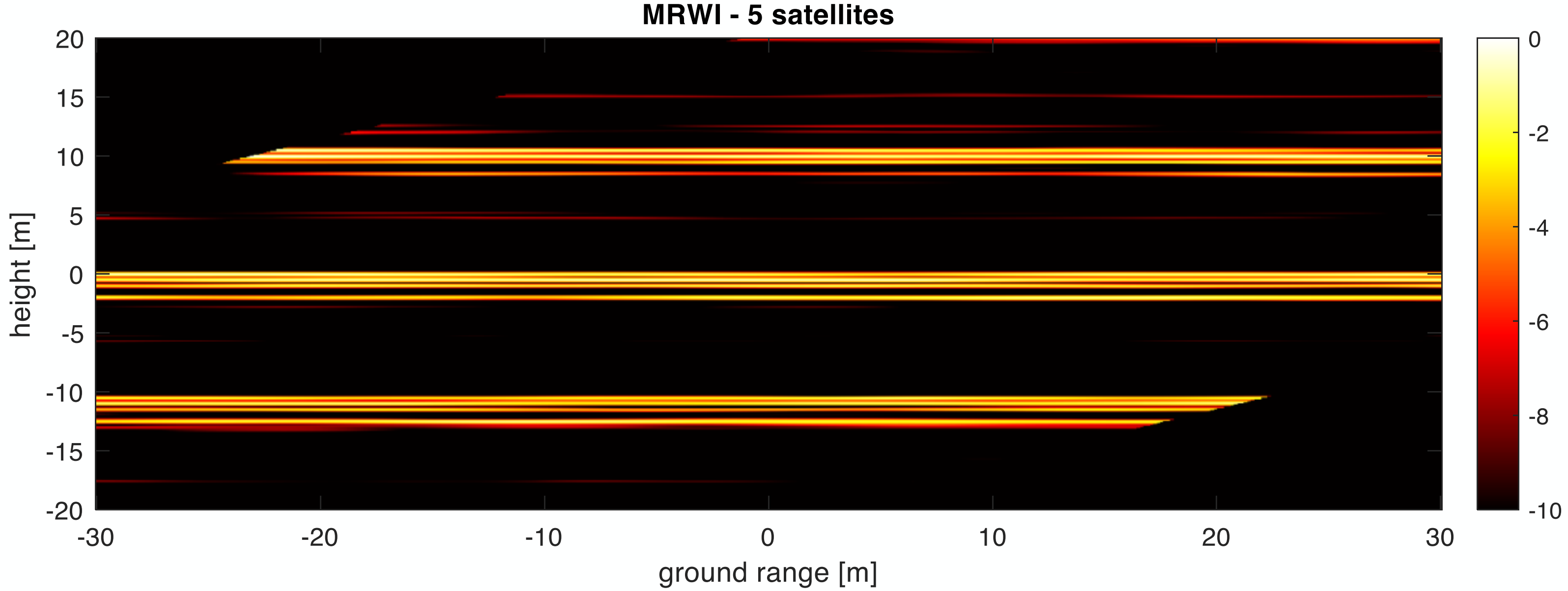
MRVA

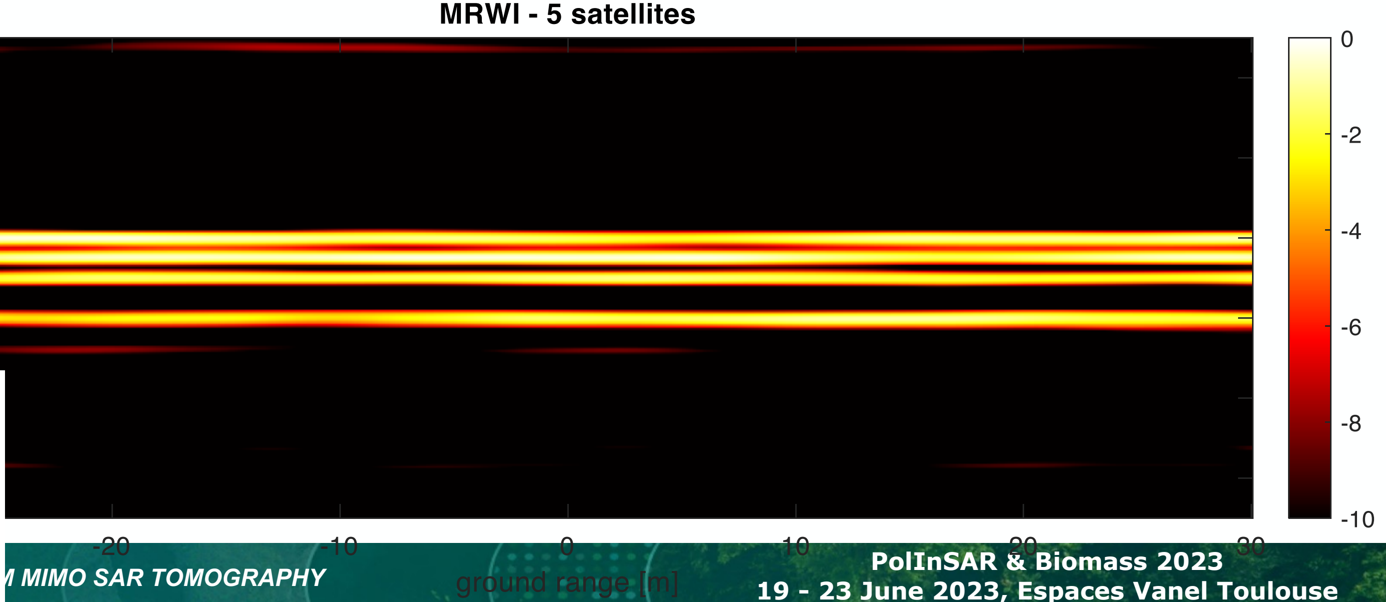

MRVA - 4 satellites
height [m]
ground range [m]
20
15
10
5
0
-5
-10
-15
-20
-30
-20
-10
0
10
20
30
0
-2
-4
-6
-8
-10

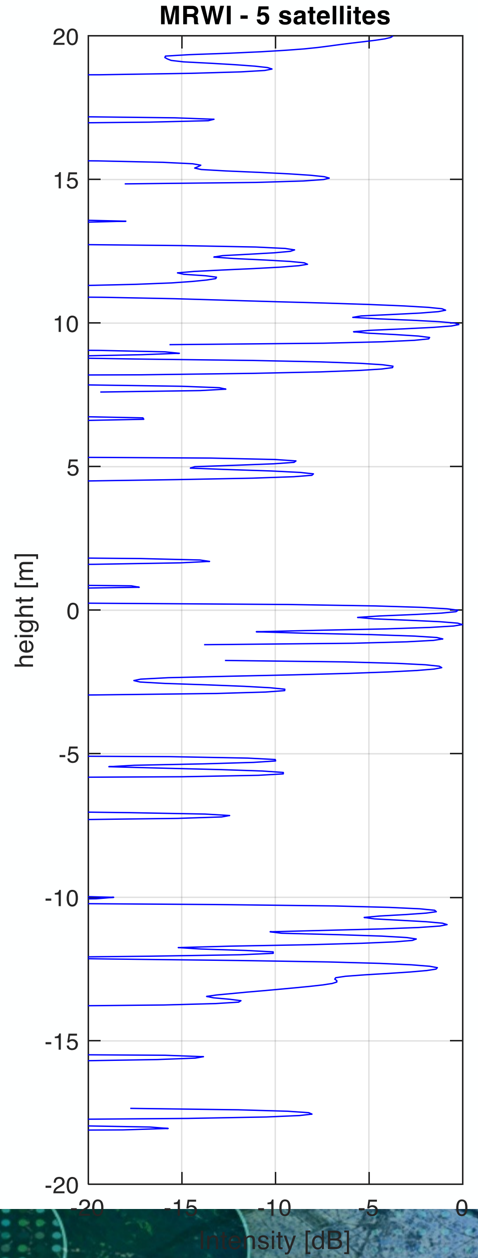

MRVA - 4 satellites
height [m]
ground range [m]
4
2
0
-2
-4
-6
-30
-20
-10
0
10
20
30
0
-2
-4
-6
-8
-10


MRVA - 4 satellites
height [m]
Intensity [dB]
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0

MRWI

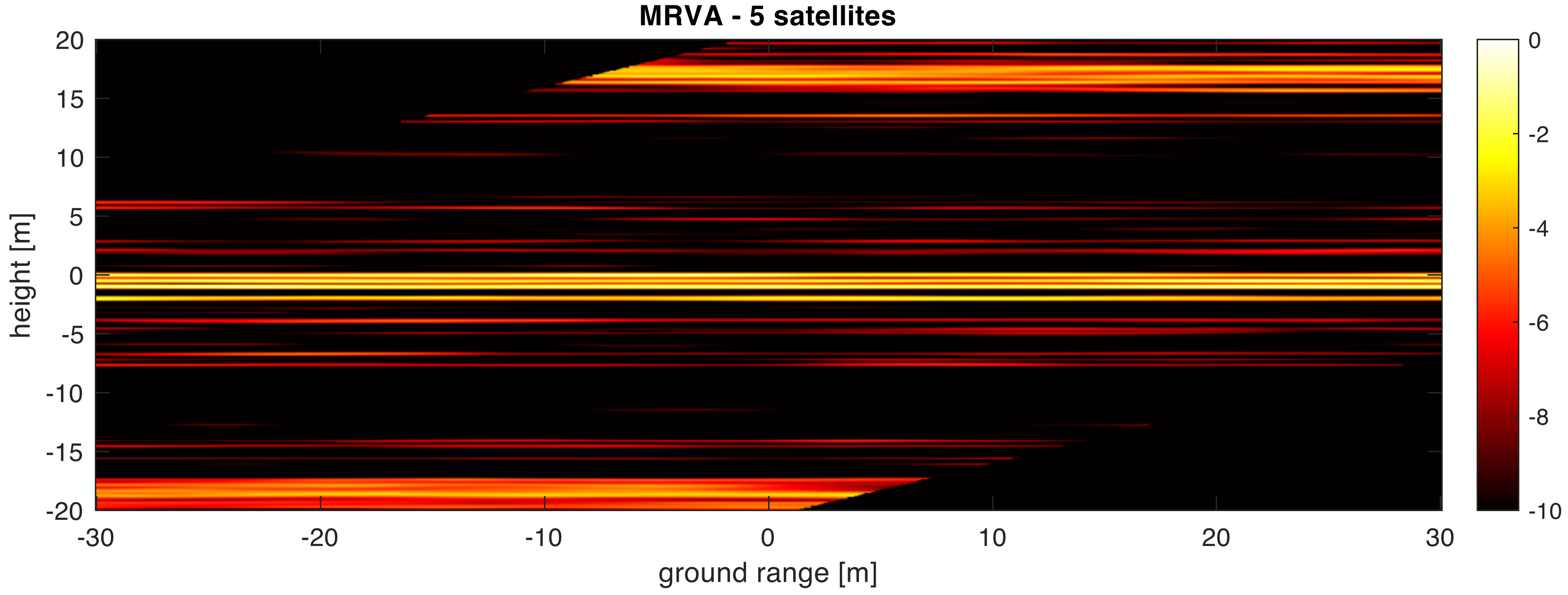

MRWI - 5 satellites
height [m]
ground range [m]
20
15
10
5
0
-5
-10
-15
-20
-30
-20
-10
0
10
20
30
0
-2
-4
-6
-8
-10


MRWI - 5 satellites
height [m]
ground range [m]
4
2
0
-2
0
-2
-4
-6
-8
-10

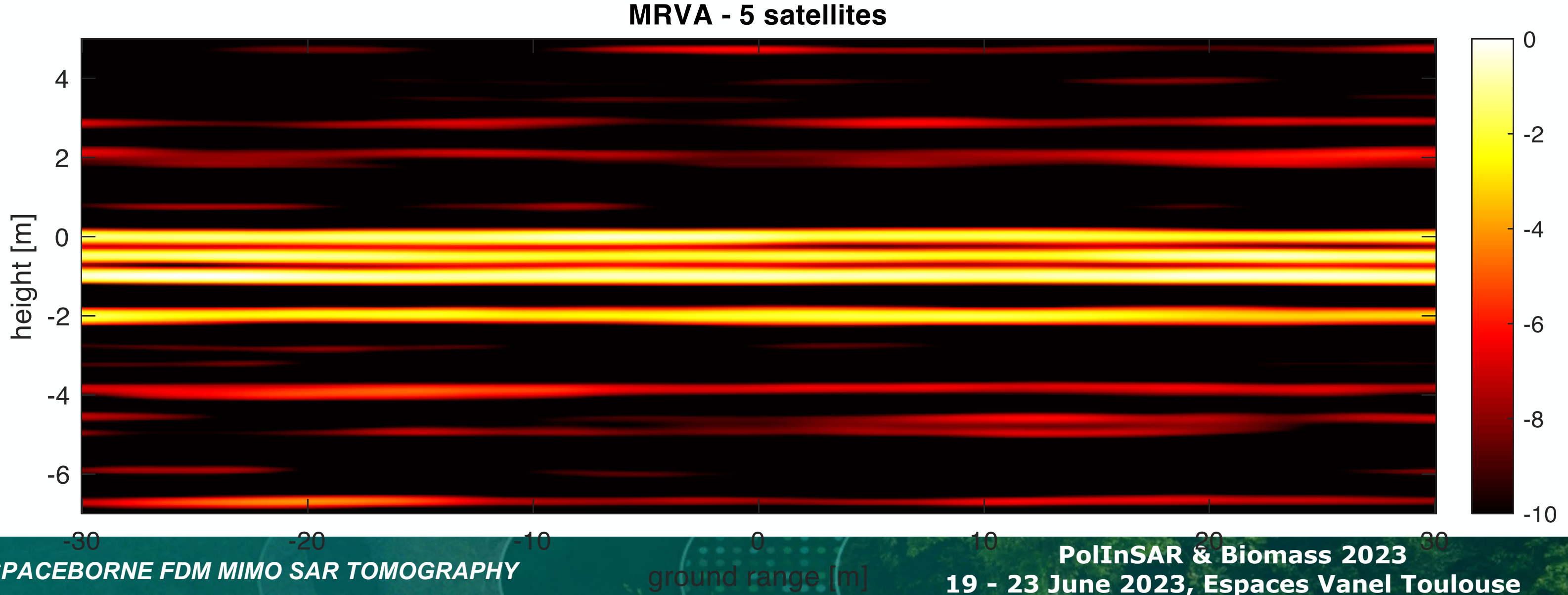

MRWI - 5 satellites
height [m]
intensity [dB]
20
15
10
5
0
-5
-10
-15
-20
-20
-15
-10
-5
0


PATENT PENDING
PATENT PENDING
PATENT PENDING

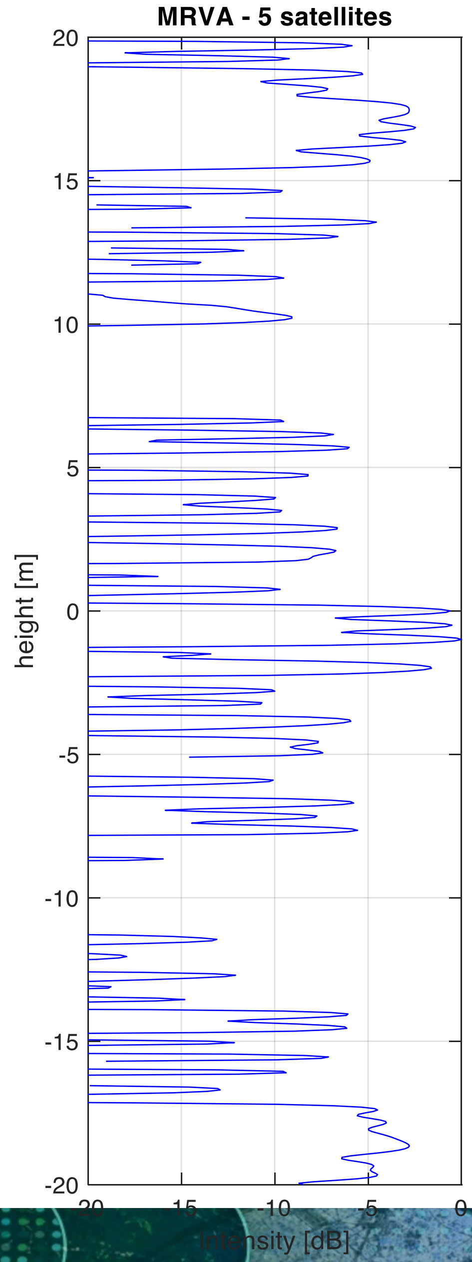
MRVA



MRVA - 5 satellites
height [m]
ground range [m]



MRVA - 5 satellites
height [m]
ground range [m]



MRVA - 5 satellites
height [m]
Intensity [dB]

Conclusions

The work in this paper provides a theoretical ground to the possibility of building a high-resolution spaceborne tomographic SAR system while using a reasonably low number of satellites.

- Distributed MIMO technology is a strict requirement
- FDM is a viable alternative to complex hardware solutions involving onboard beamforming and multiplication of channels on individual satellites

Formation deployment was discussed by extending the concept of MRVA to the case of distributed scatterers, resulting in a new criterion referred to as MRWI

- Numerical simulations support the possibility to deploy a formation of 4 or 5 satellites to provide the equivalent of 16 and 25 monostatic orbits.
- Such figures are comparable to the best airborne and ground-based systems available as of today, and indicate the concrete possibility to image the vertical structure of natural targets from space at fine resolution.

A **roadmap** for future development of this concept should address technological issues, orbital control, and the development of methods specific to FDM MIMO to recover clock synchronization and fine positioning