Tomographic SAR Algorithms Performance in Co-Fliers Mission Concept Formulation

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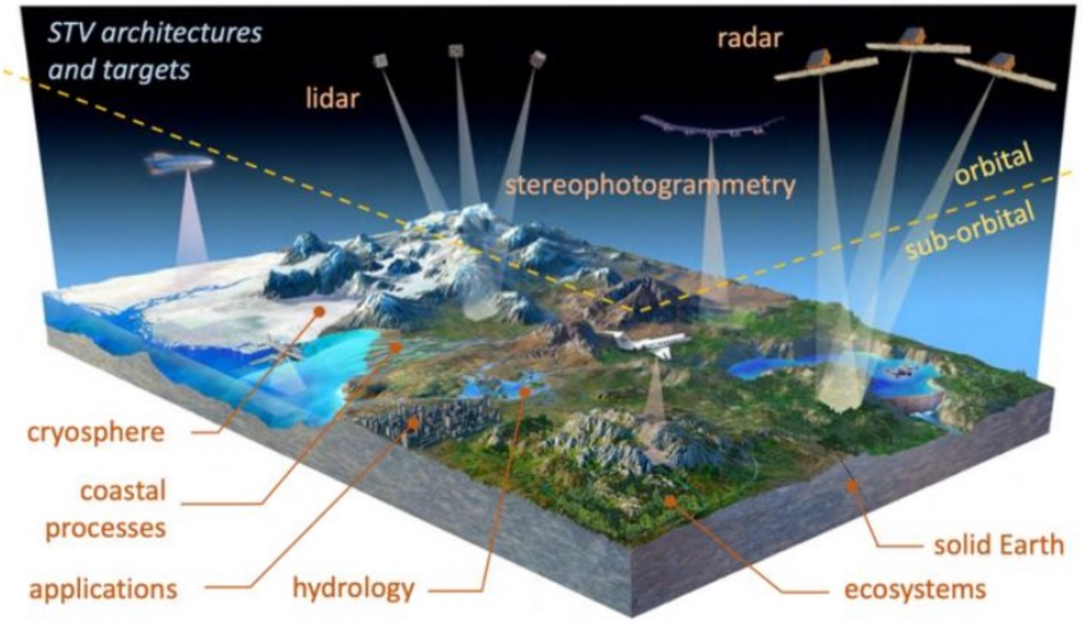
Background: Surface Topography and Vegetation (STV)

- Global, fine-scale observations of surface topography and vegetation structure (STV) are critical to address key science questions and applications in Solid Earth[SE], Ecosystems[V], Cryosphere[C], Hydrology[H], and Coastal Processes[CP]
- 2017 Decadal Survey recommended Surface Topography and Vegetation (STV) as "Incubator Observable"
- In 2020 NASA conducted a 1-year study to identify STV products needs and science and technology gaps. STV Study generated the STV Study Report with SATM and list of technology maturation activities (Donnellan et Al., 2021)
- On-going funded projects on science and technology maturation activities under the Decadal Survey Incubator (DSI) Call



STV Product Parameter		Aspirational			Threshold		
		Median Need	Most Stringent Need	Most Stringent Discipline	Median Need	Most Stringent Need	Most Stringent Discipline
Coverage Area of Interest	%	90	95	C, H	55	90	C
Latency	Days	5	0.5	SE	60	1	SE
Duration	Years	9	10	SE, C, A	3	3	SE, V, C, CP
Repeat Frequency	Months	0.1	0.03	SE, A	3	0.2	SE
Horizontal Resolution	m	1	1	SE, C, H, A	20	3	SE
Vertical Accuracy	m	0.2	0.0	SE, C, H	0.5	0.1	C
Vegetation Vertical Resolution	m	1	0.5	H, A	2	0.2	CP
Bathymetry Max Depth	m	25	30	C, CP	10	10	SE, C, CP
Geolocation Accuracy	m	1	1.0	SE, V, H, A	5	3	SE, V
Rate of Change Accuracy	cm/yr	5	1	SE, C, A	35	1	SE

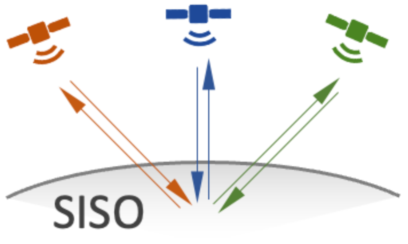
Study report: science.nasa.gov/earth-science/decadal-stv

Background: Why co-fliers to meet STV needs?

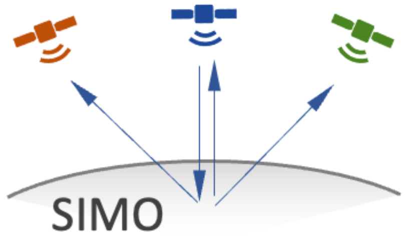
1. Repeated single-radar observations are generally not sufficient to meet the STV products needs
2. Costs for multiple active platforms can be high and beyond a single-agency's cost cap
3. Co-fliers allow for flexibility and reconfigurability, e.g., using multi-static modes (SISO, SIMO, and MIMO)
4. Passive co-fliers can take advantage of NISAR (launch: 2024) and ROSE-L (launch: 2028-2030) as transmitters

GOAL Identify the most viable TomoSAR mission architecture by assessing the TomoSAR global performance for various options of the mission trade space

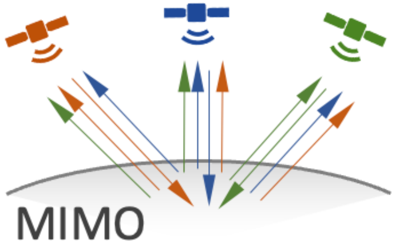
CHALLENGE The trade space for a multi-static SAR mission is complex as it involves multiple platforms and how they cooperate



Single-Input/Single-Output

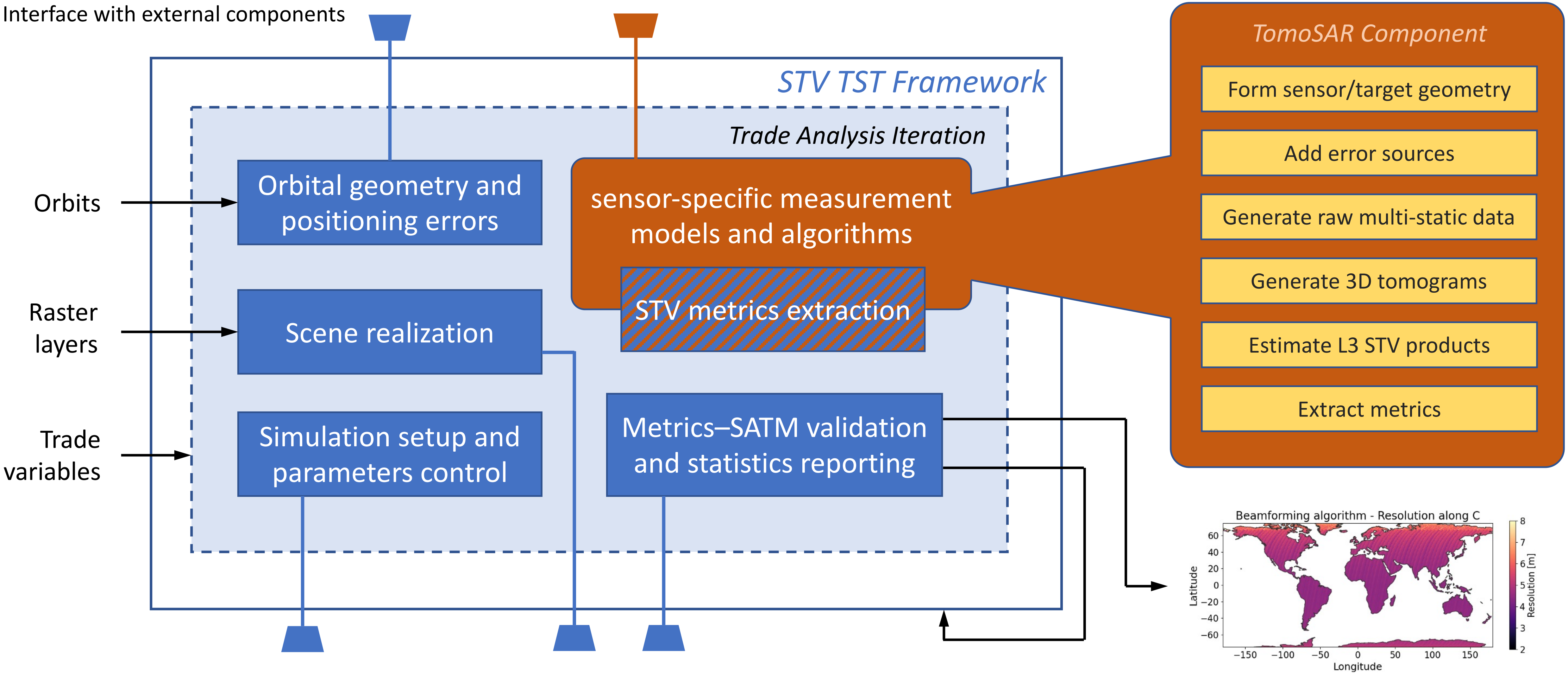


Single-Input/Multiple-Output

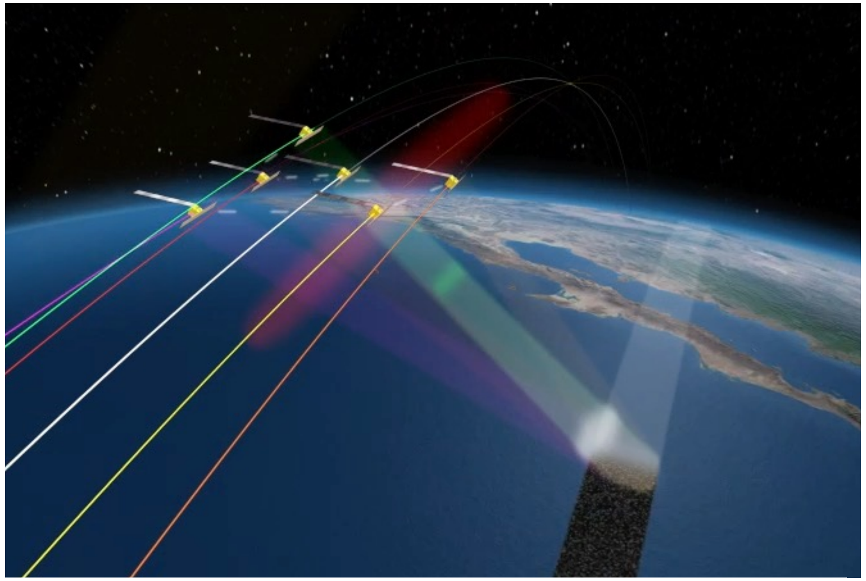


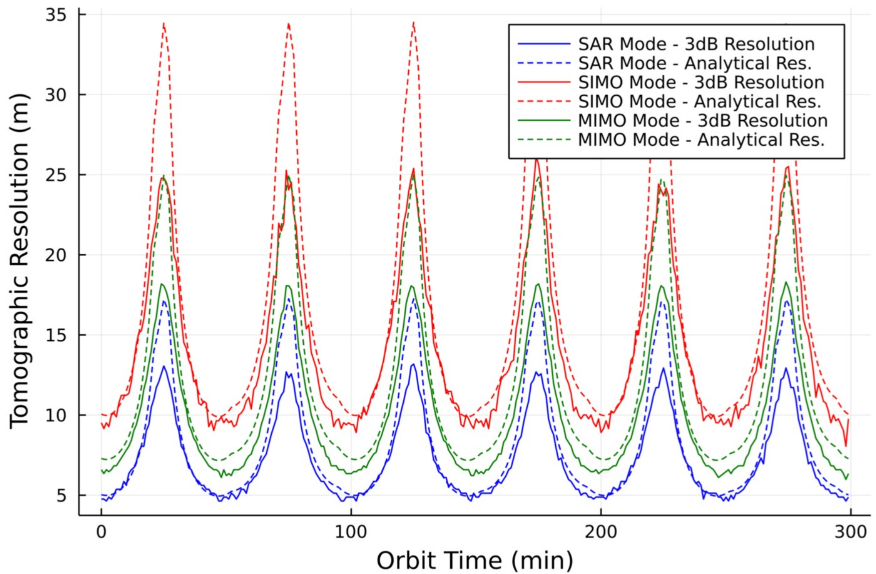
Multiple-Input/Multiple-Output

Approach: End-to-end TomoSAR Trade Study Tool



Trade Space in end2end TomoSAR Mission Design

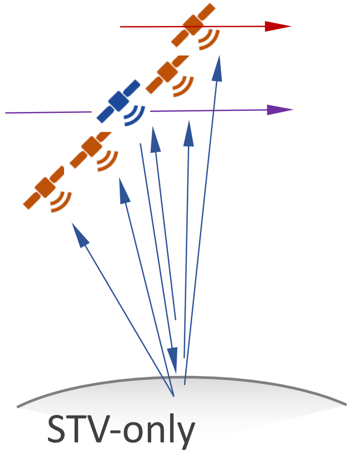




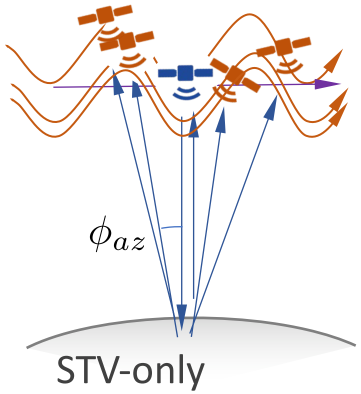
Main trade variables	Options
formation size and geometry	3-15 platforms
radar frequency/bandwidth	L, S, 40/80 MHz
multi-static mode	SIMO, MIMO, SISO
radar mode	Stripmap, SweepSAR, HRWS
processing	real-time, post-processing
synchronization	GNSS-only, inter-sat link
positioning	GNSS-only, range-measurement
tomographic algorithm	Back-projection, Beamforming, Capon, Phase-backscatter Histogram

L1 Performance metrics (point)	L1 Performance metrics (distributed)
Resolution	In/out profile correlation
Integrated Side-Lobe Ratio (ISLR)	In/out profile RMSE
Peak Side-Lobe Ratio (PSLR)	Number of output peaks
Location error	Vertical location of peaks
Peak amplitude	
Relative radiometric accuracy	

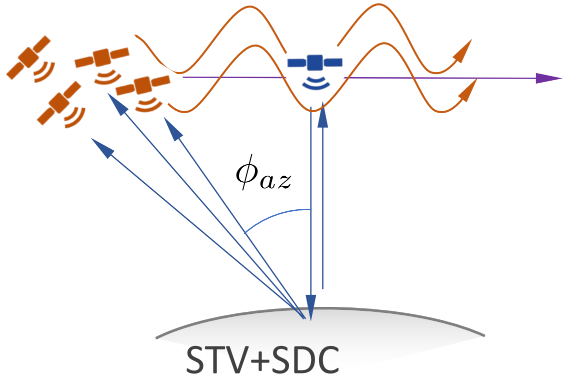
Initial reference architectures evaluated for STV



Ideal case, rectilinear orbits
(4 co-fliers, 6 or 10 baselines)



topography + vegetation
(4 co-fliers, 6 baselines)



topography + vegetation
(4-cofliers, 6 baselines)

Evaluated for different

Target types

single point OR GEDI vertical profiles OR distributed targets

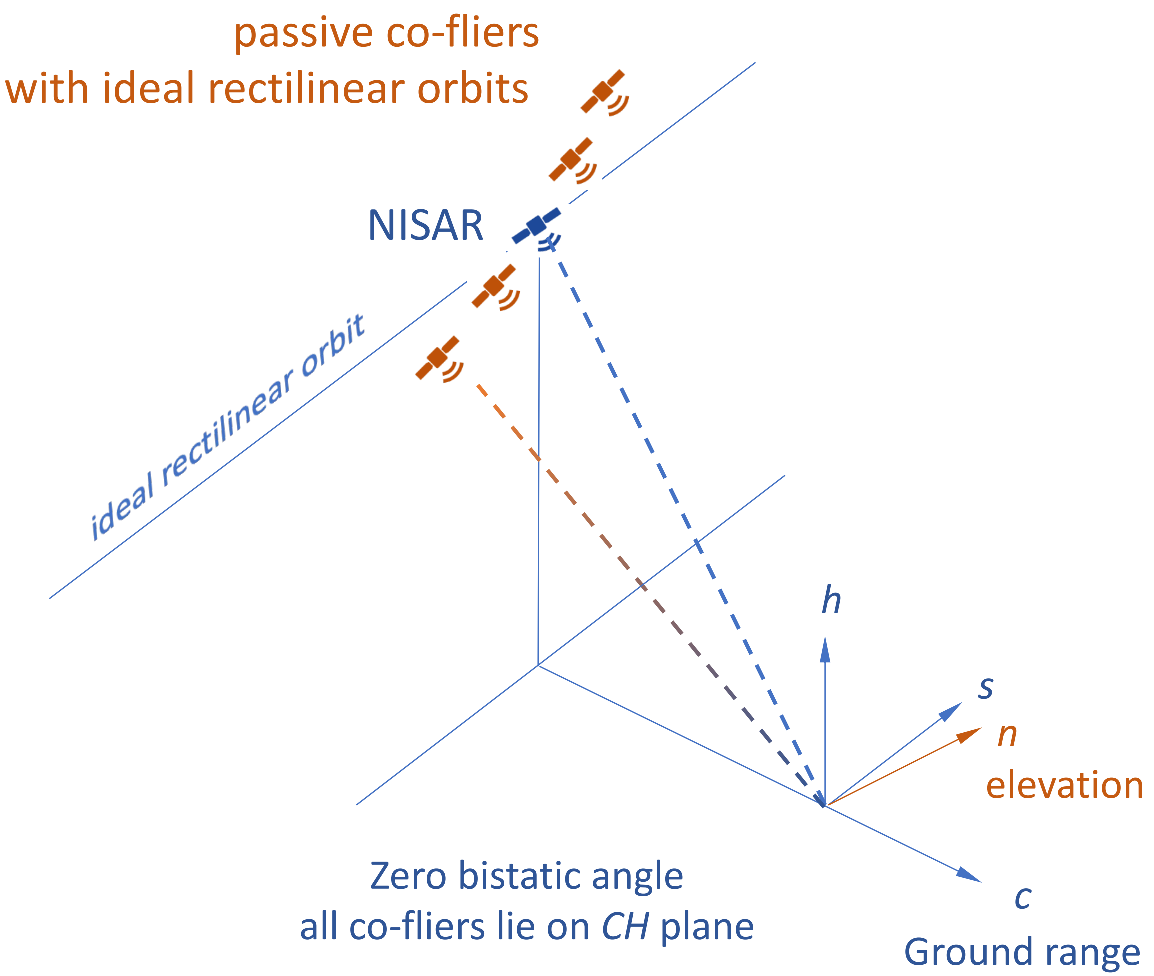
Multi-static modes

MIMO OR SIMO OR SISO

Tomographic algorithms

back-projection OR Beamforming
Capon OR Histogram Tomography

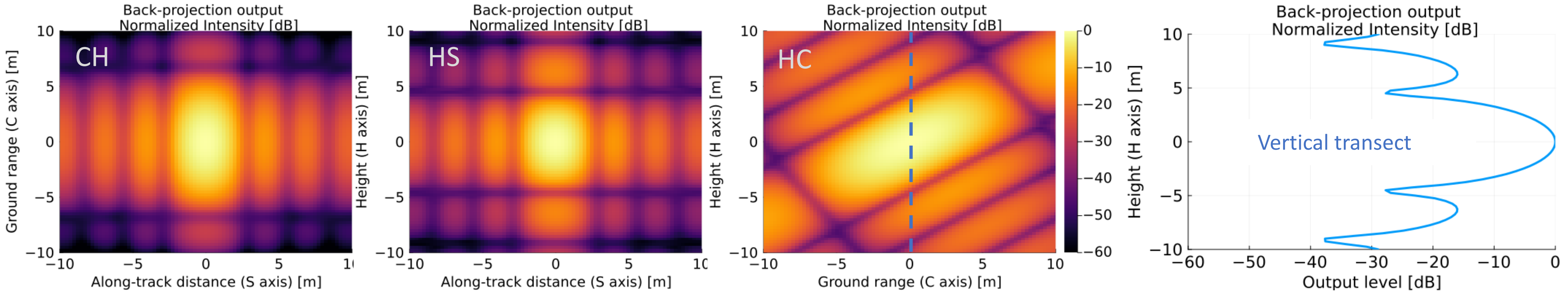
4 passive co-fliers with ideal rectilinear orbits



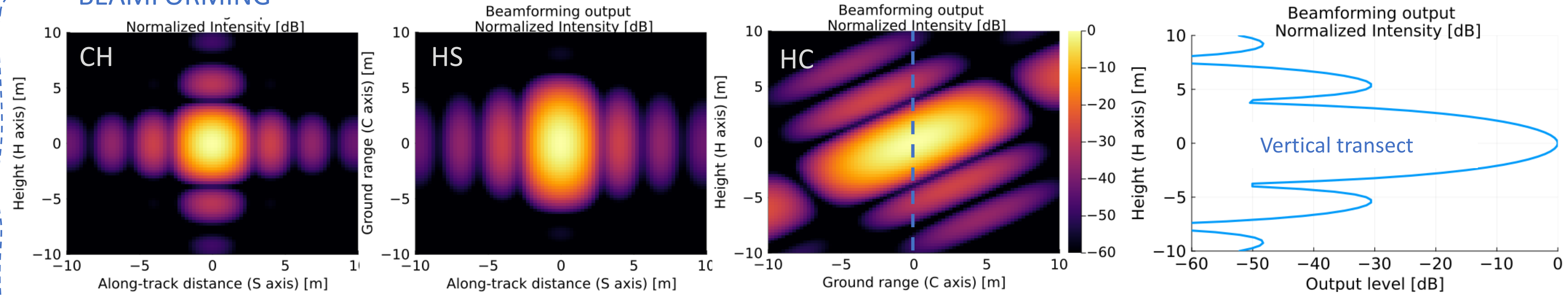
- Simplified geometry with ideal orbits
- SCH reference frame
  - S = along-track
  - C = ground-range
  - H = height
- Single point target
- Zero bistatic angle
- Uniform array along elevation *n*
- Used for sanity check

4 passive co-fliers with ideal rectilinear orbits

BACKPROJECTION



BEAMFORMING



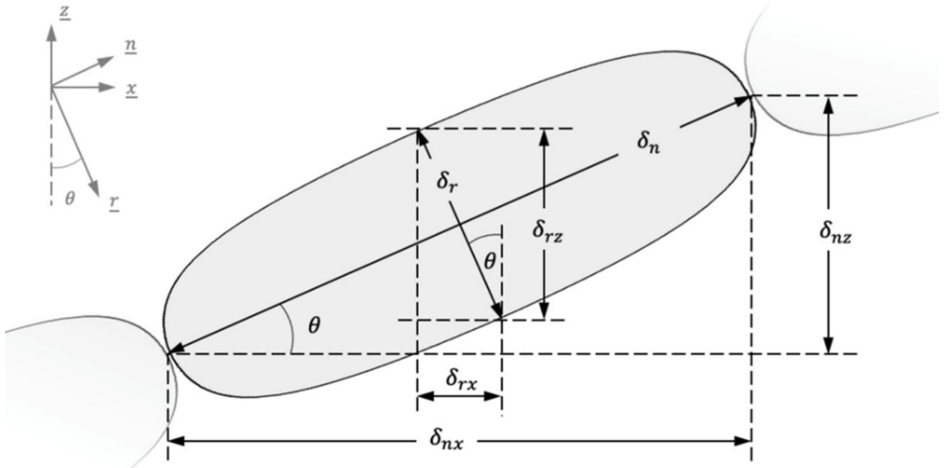
4 passive co-fliers with ideal rectilinear orbits

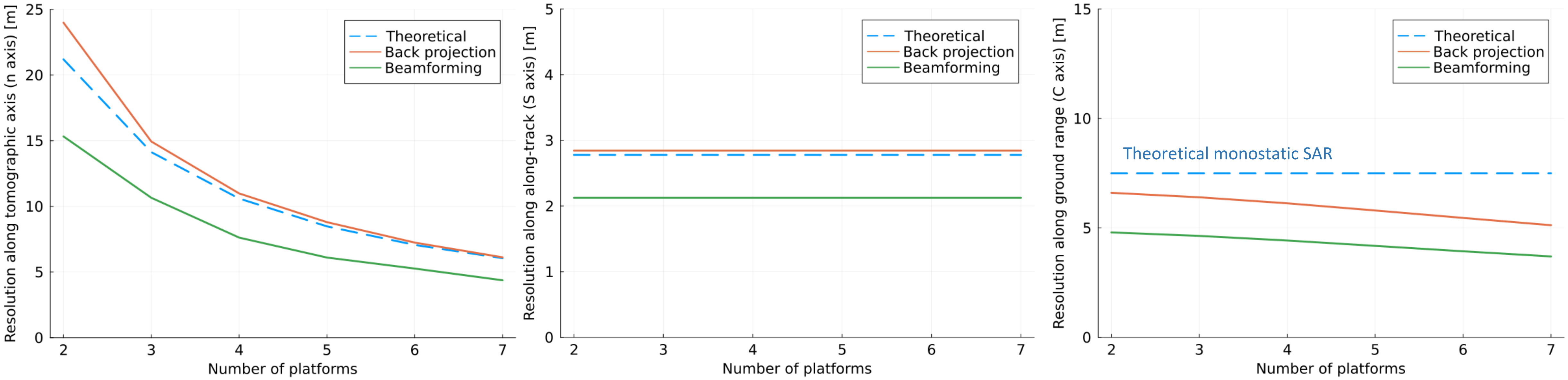
- Resolution analysis of simulations vs analytical formulas; increasing number of platforms and tomographic baseline (from 5km to 30km)
- Vertical resolution can be affected by range bandwidth, and horizontal resolution can be affected by tomographic aperture (*Seker and Lavalle, Remote Sensing 2021*)

Vertical $\delta_z = \max(\delta_{nz}, \delta_{rz}) = \max(\delta_n sin\theta, \delta_r cos\theta)$

Ground-range $\delta_x = \max(\delta_{nx}, \delta_{rx}) = \max(\delta_n cos\theta, \delta_r sin\theta)$

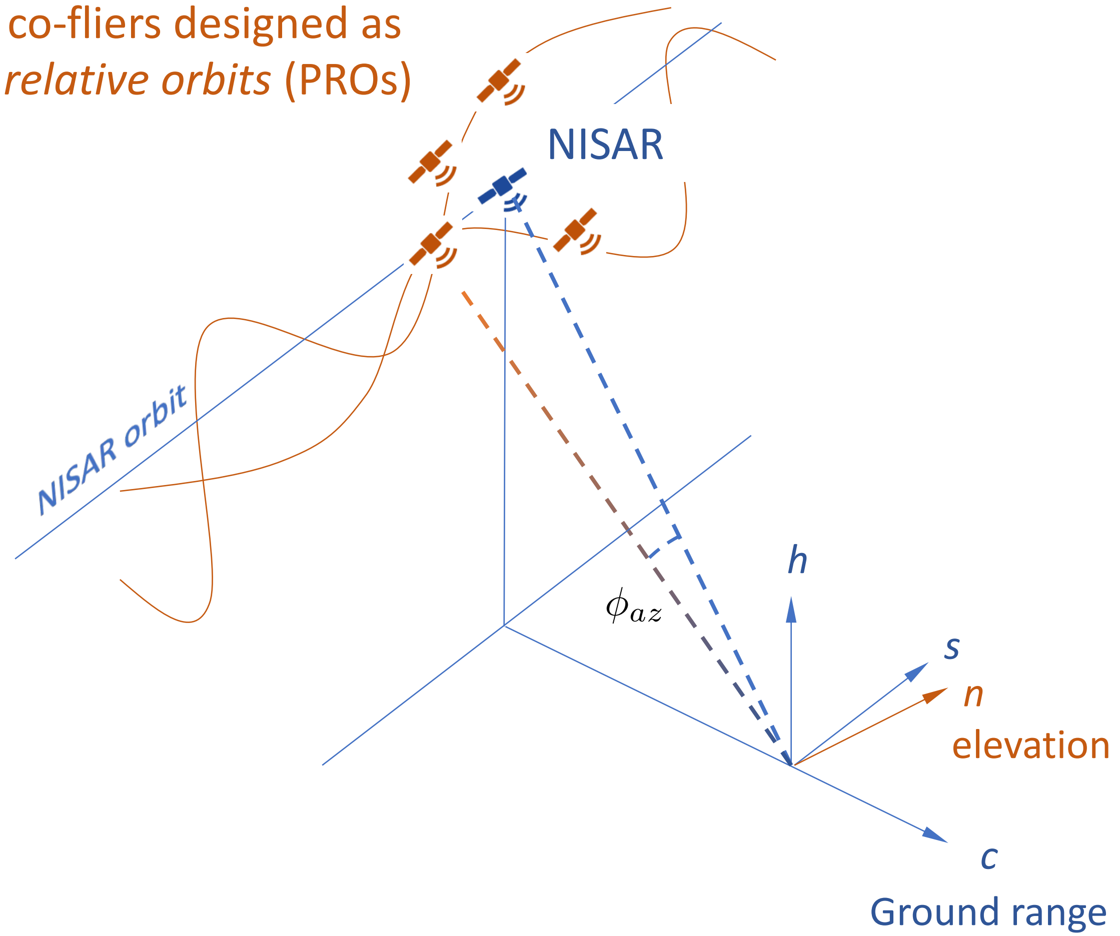
Tomographic resolution cell on the *r, n* plane

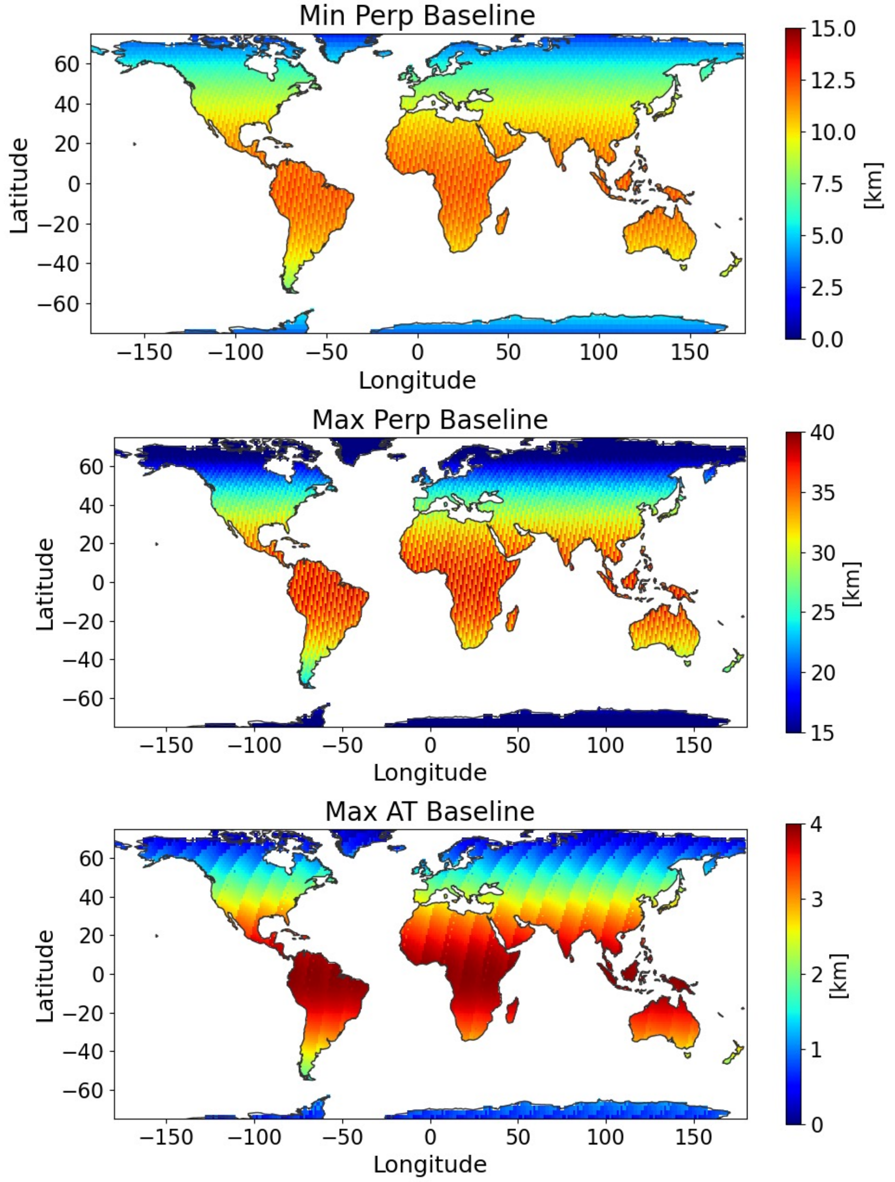




4 passive co-fliers with transmitter in close formation

passive co-fliers designed as *passive relative orbits* (PROs)





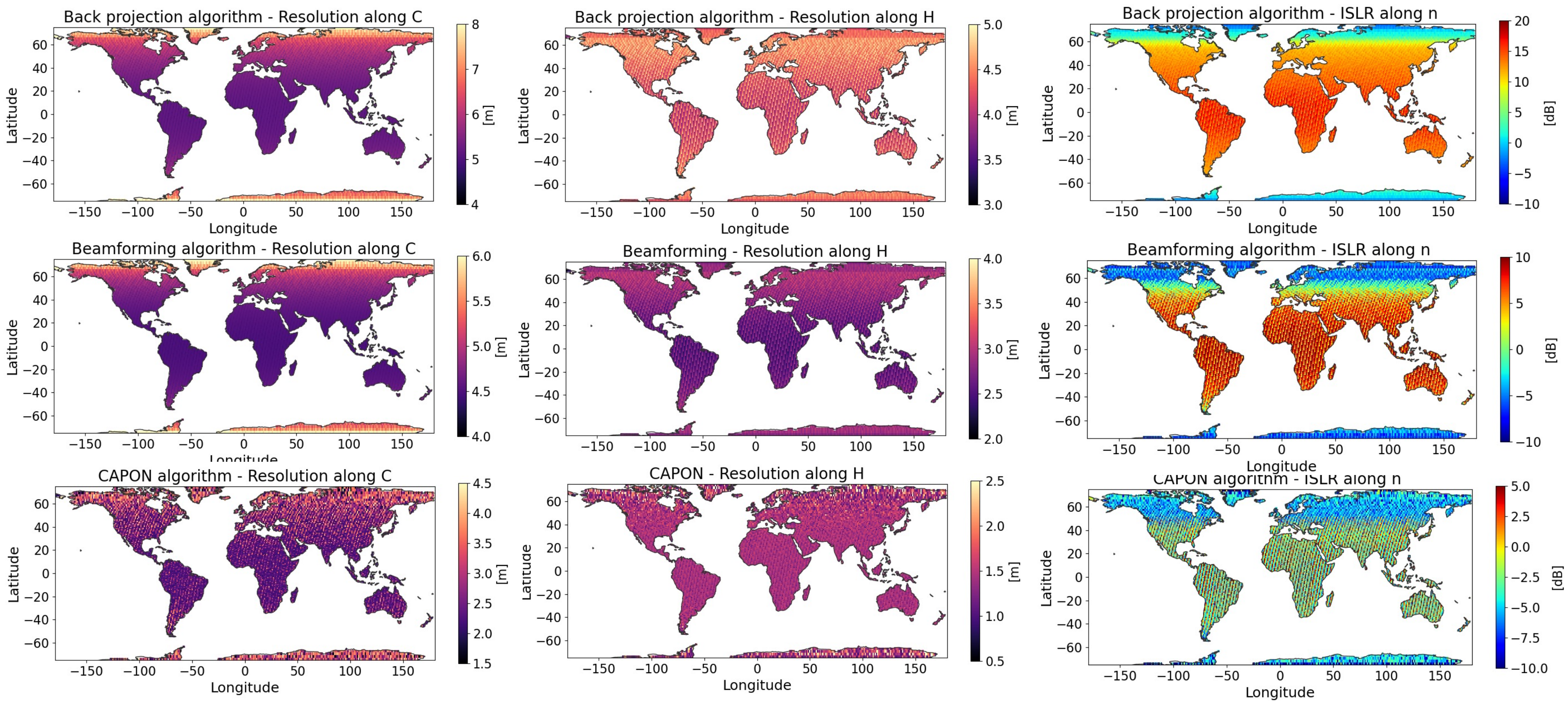
4 passive co-fliers with transmitter in close formation

Ground-range resolution | Vertical resolution | Integrated Side-Lobe Ratio

Back-projection

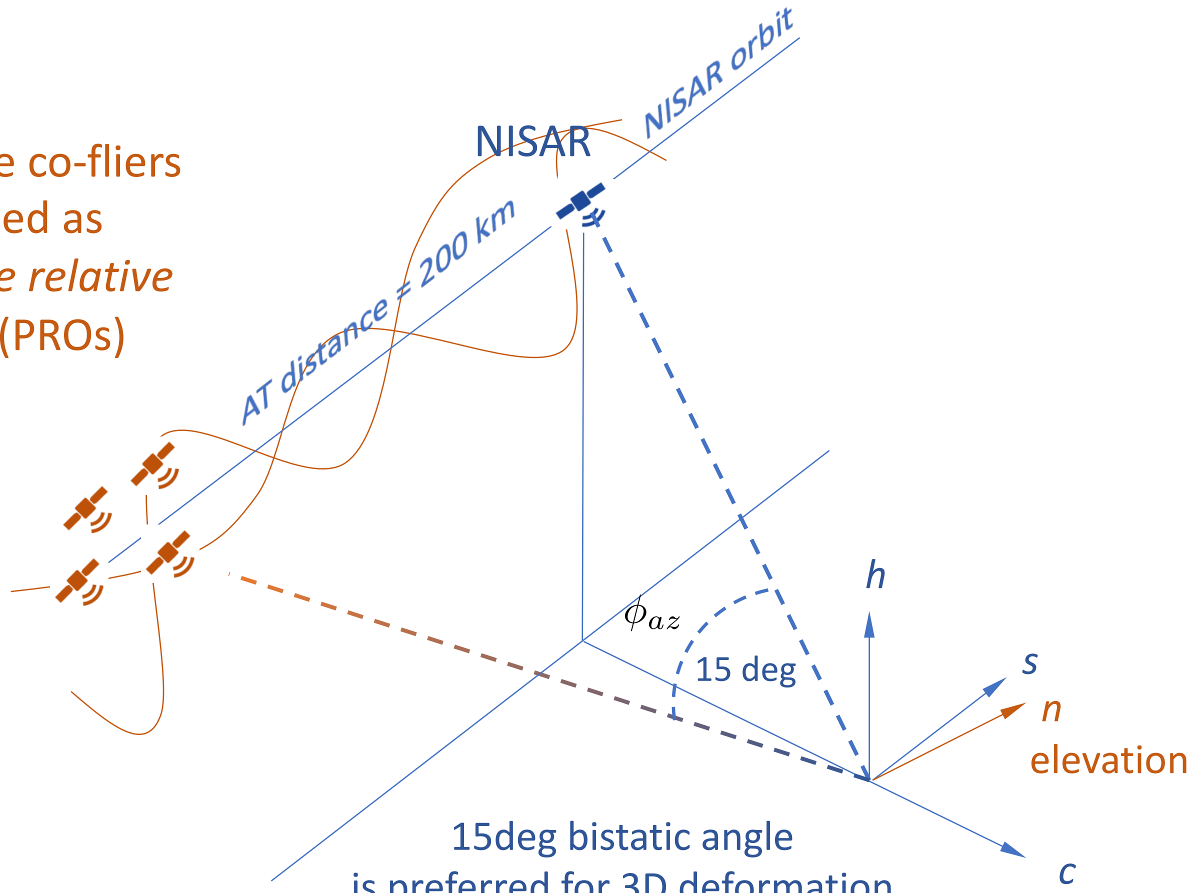
Beamforming

Capon

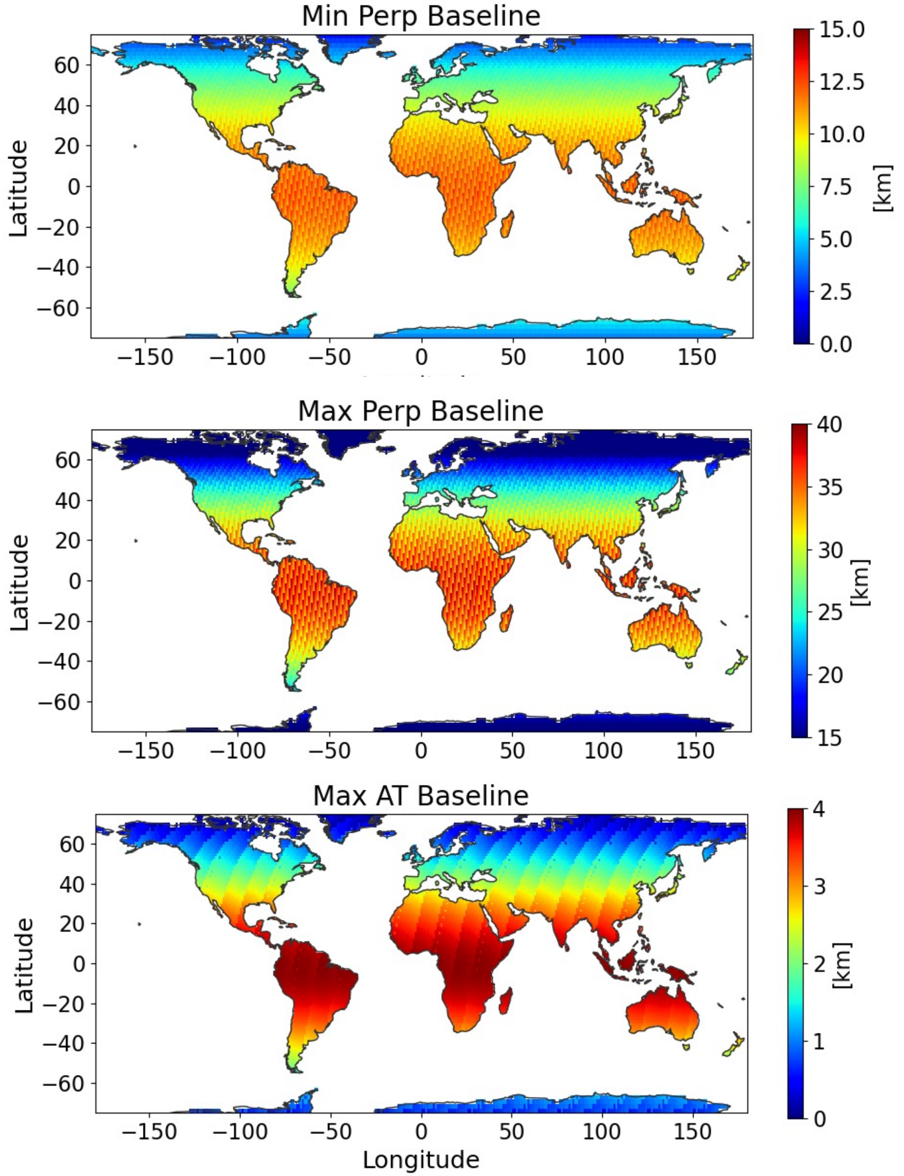


4 passive co-fliers with leading transmitter

passive co-fliers designed as *passive relative orbits* (PROs)



15deg bistatic angle
is preferred for 3D deformation



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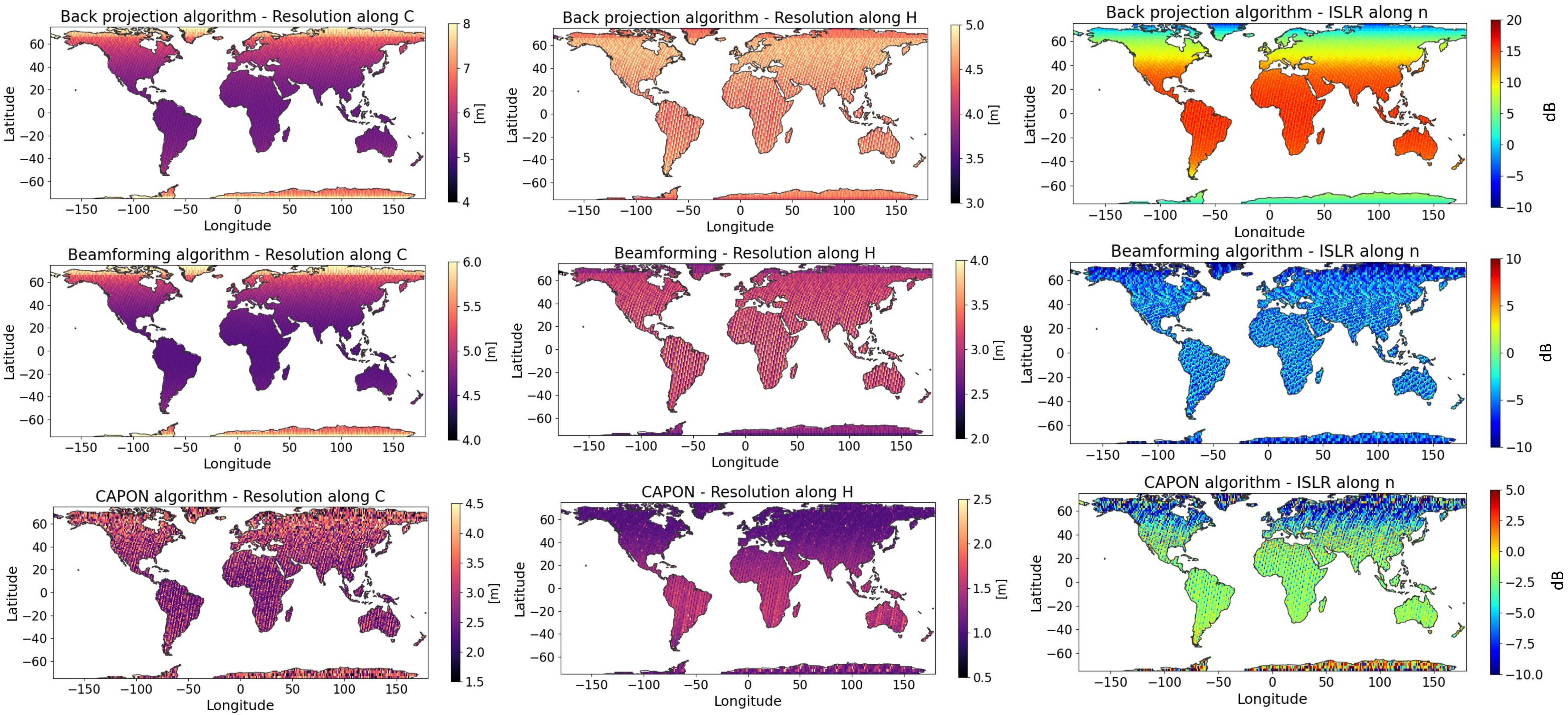
4 passive co-fliers with leading transmitter

Ground-range resolution | Vertical resolution | Integrated Side-Lobe Ratio

Back-projection

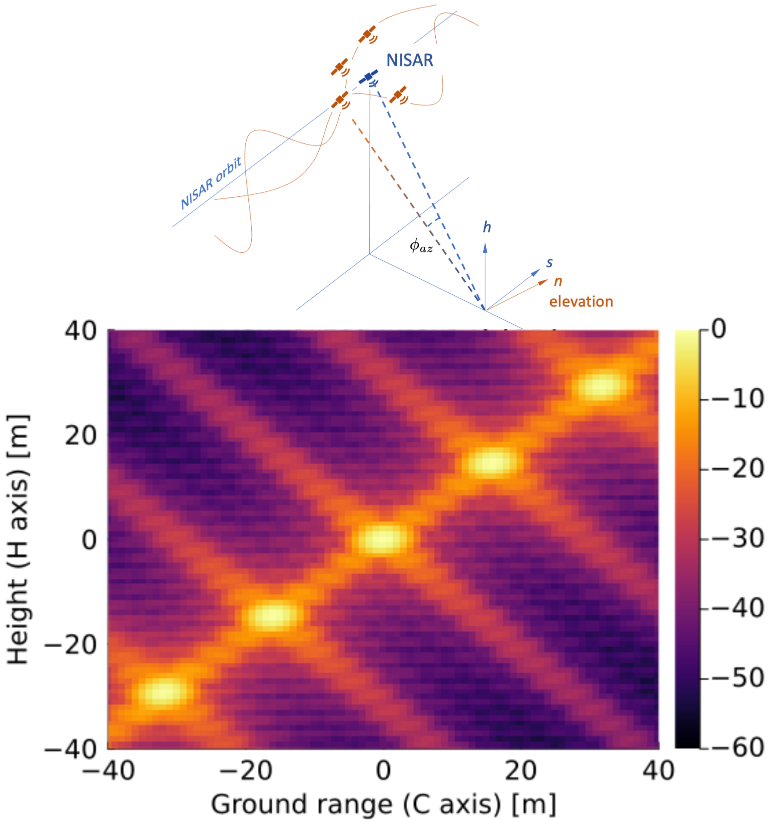
Beamforming

Capon



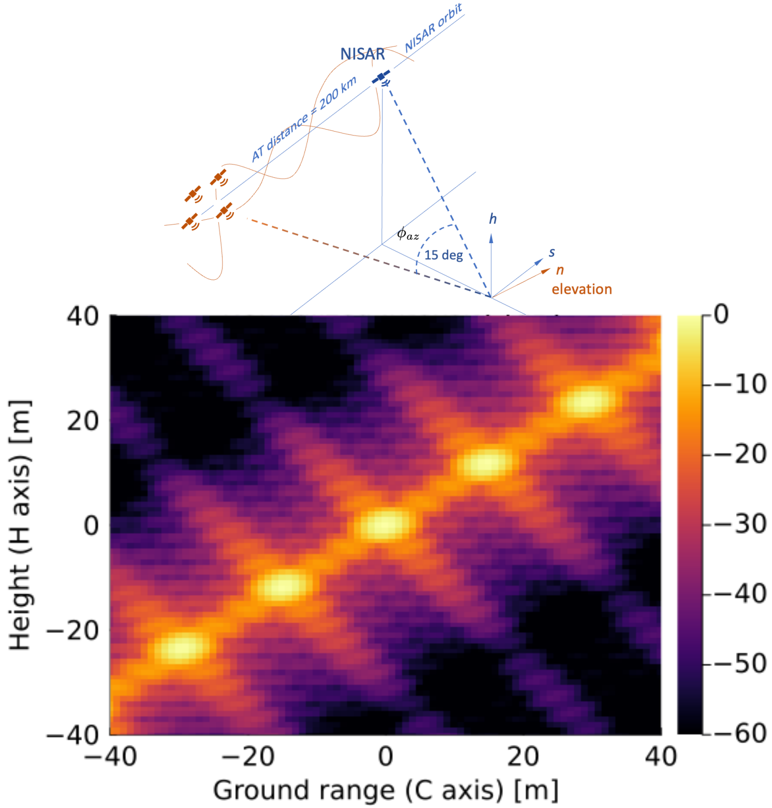
Tomographic Point Target Response Across Architectures

4 co-fliers in close formation



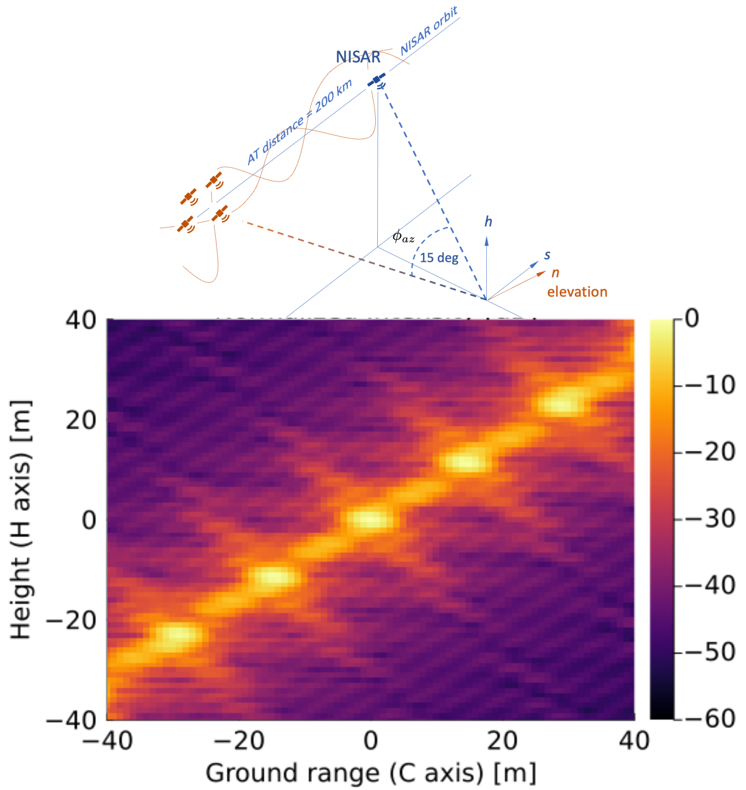
Resolution	Backproj	Beamform
Ground-range	5.0 m	4.42 m
Vertical	3.89 m	2.40 m

4 co-fliers with leading Tx
4 platforms in Tomo processing



Resolution	Backproj	Beamform
Ground-range	5.15 m	4.47 m
Vertical	4.07 m	2.82 m

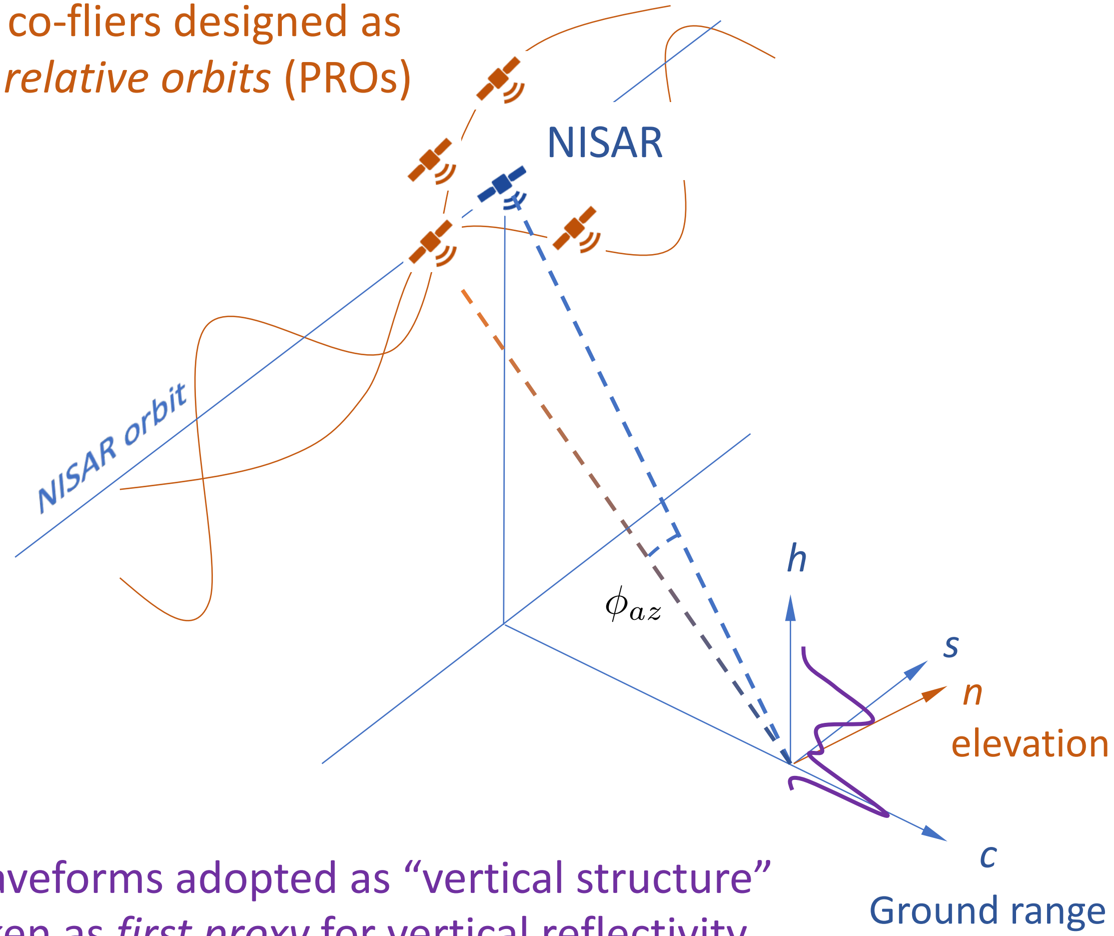
4 co-fliers with leading Tx
5 platforms in Tomo processing



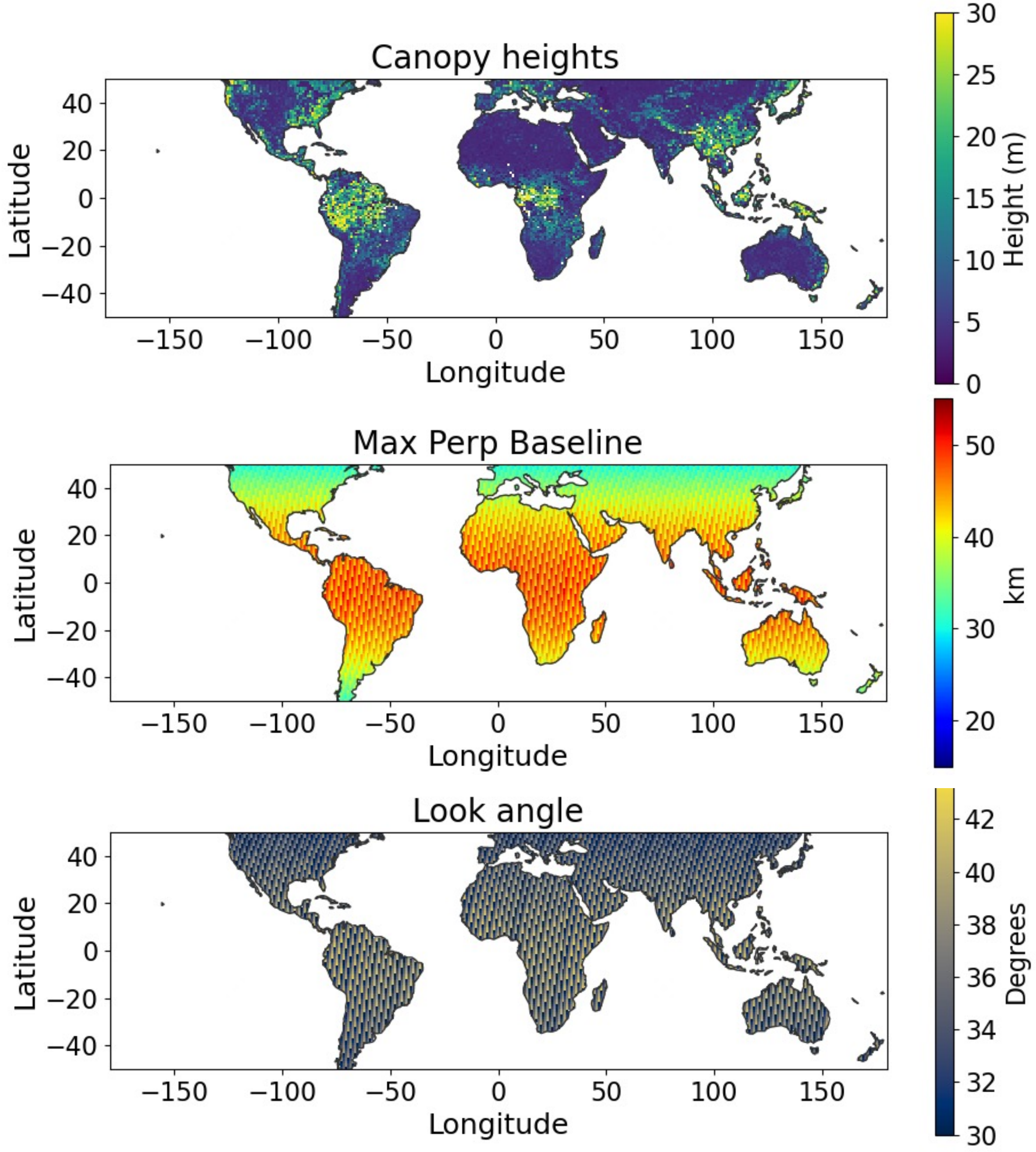
Resolution	Backproj	Beamform
Ground-range	4.81 m	4.36 m
Vertical	2.90 m	1.56 m

4 passive co-fliers with a transmitter and many GEDI profiles

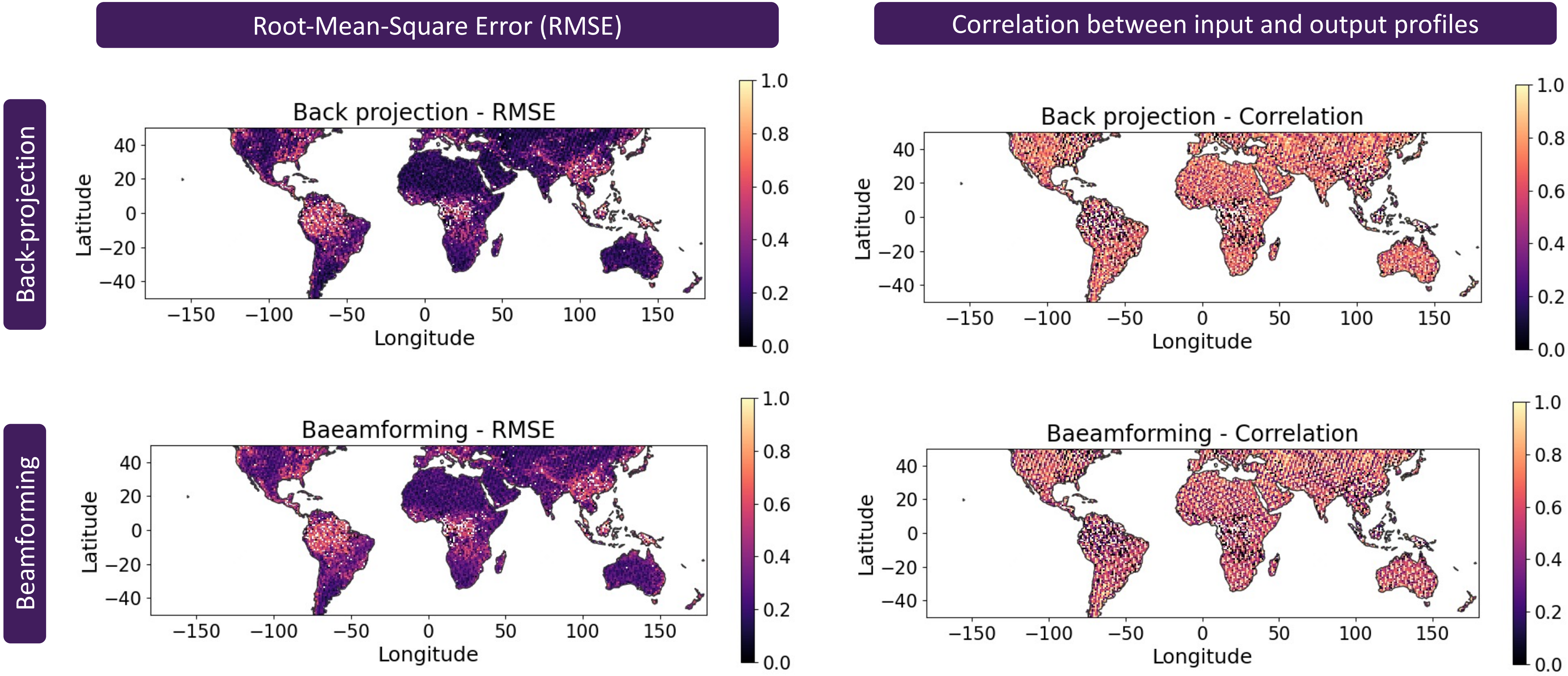
passive co-fliers designed as *passive relative orbits* (PROs)



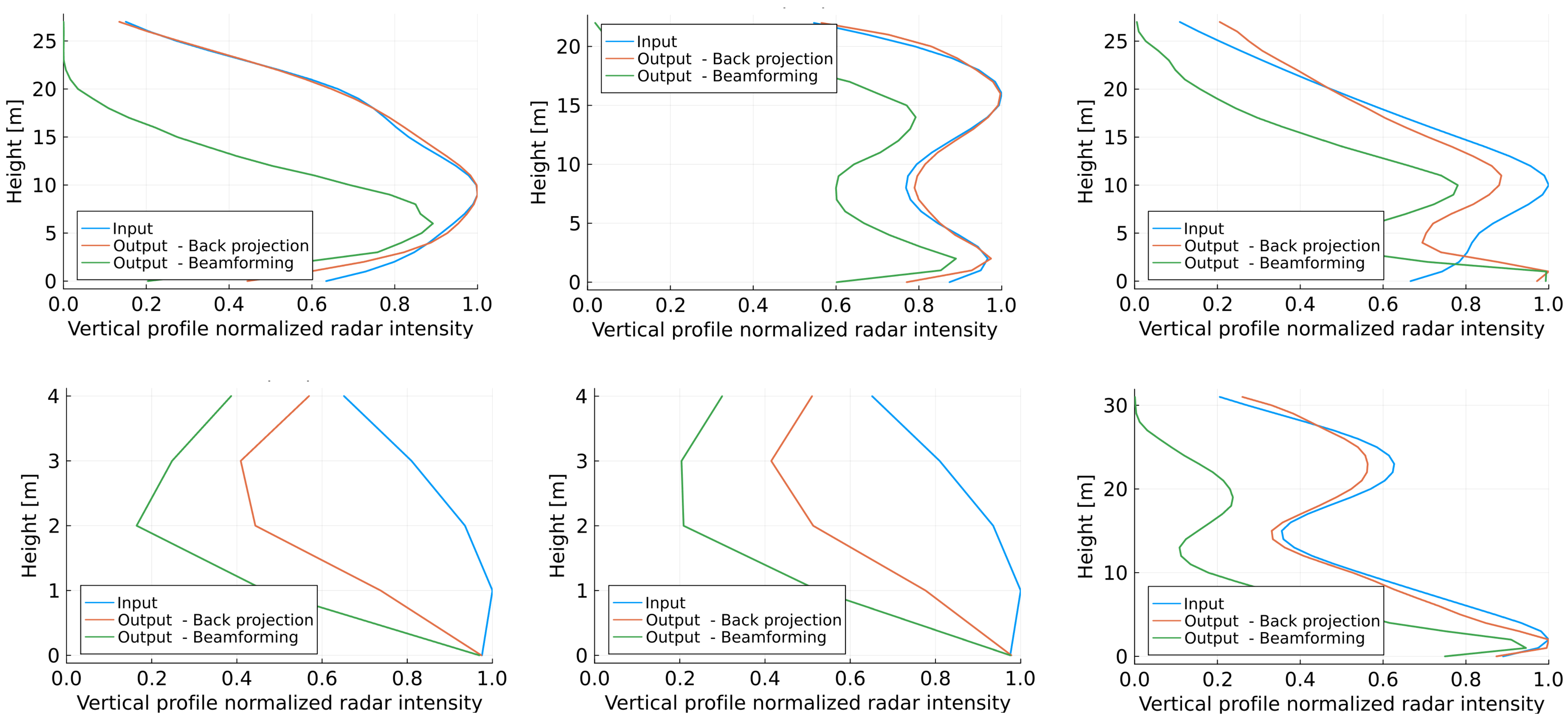
GEDI waveforms adopted as "vertical structure" and taken as *first proxy* for vertical reflectivity



4 passive co-fliers with a transmitter and many GEDI profiles

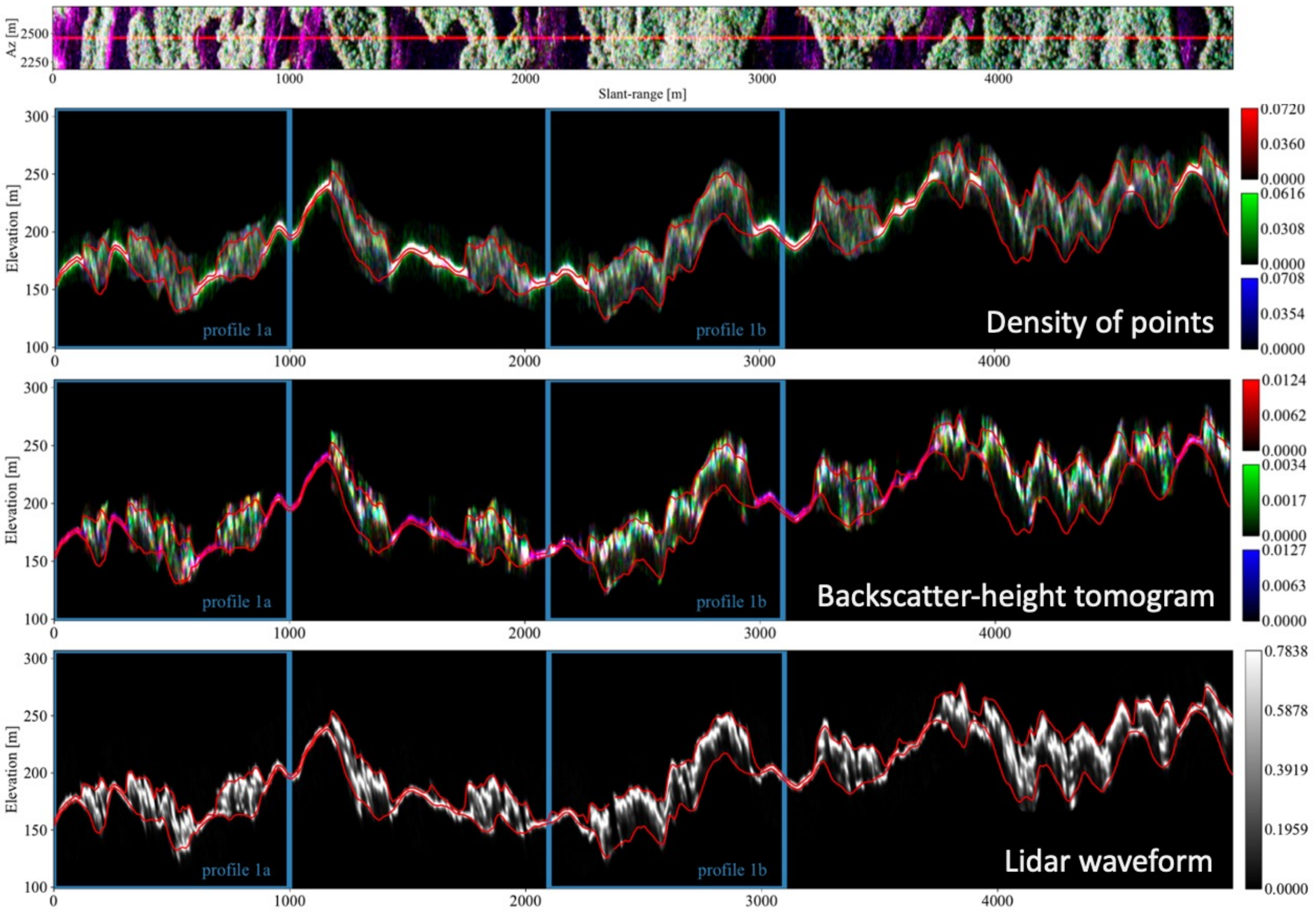


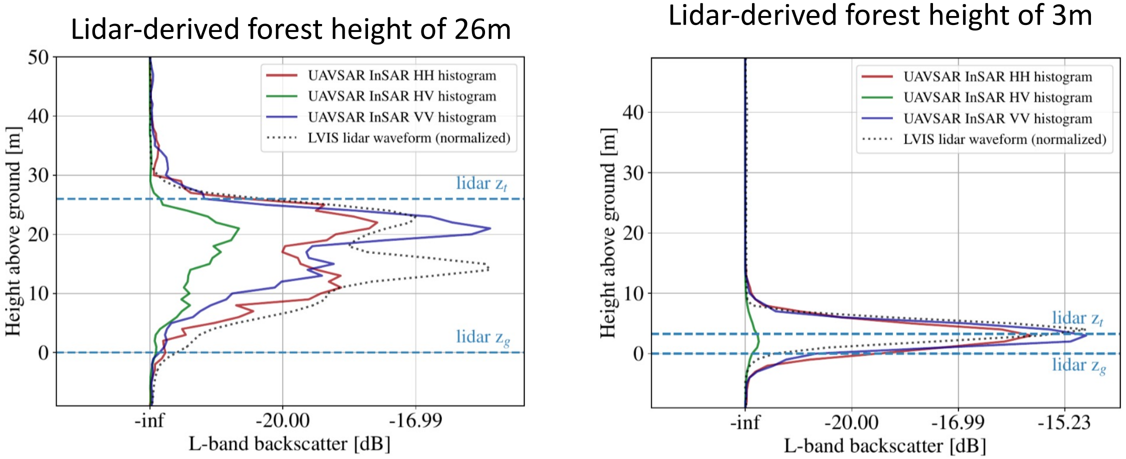
4 passive co-fliers with a transmitter and many GEDI profiles

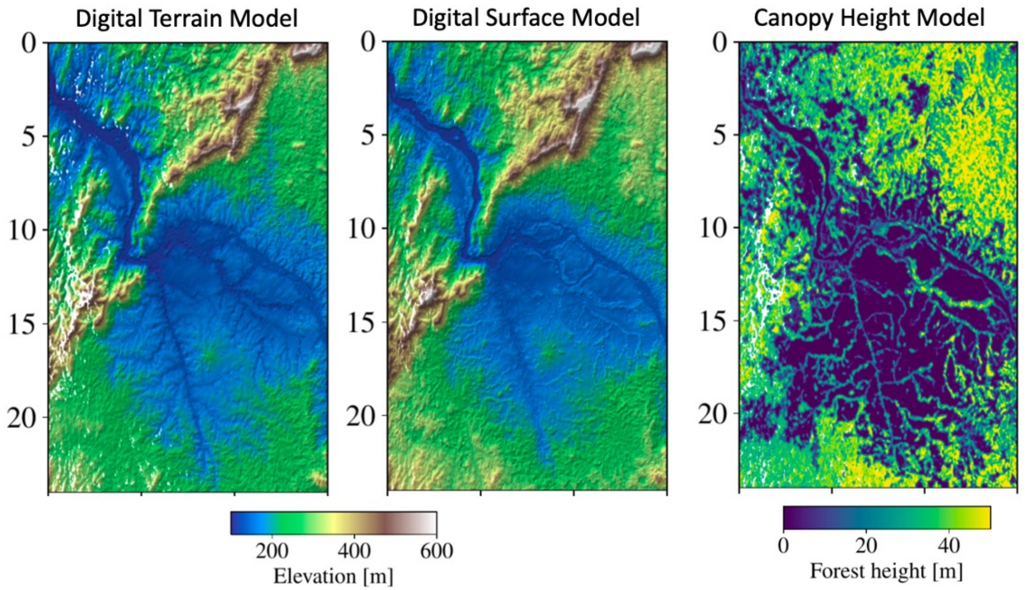


Histogram Tomography Algorithm to Inform Trade Studies

G. Shiroma and M. Lavalle, “Digital terrain, surface, and canopy height models from InSAR backscatter-height histograms”, *IEEE Transactions on Geoscience and Remote Sensing*, 58 (6), 2021







Shiroma and Lavalle, TGRS 2021

Take-away messages

1. JPL is developing an end-to-end simulation environment to conduct trade studies towards the design of a multi-static/tomographic space mission

2. Initial (and partial) results comparing back-projection and beamforming algorithms show agreement with theory and some promise to map STV in various configurations

3. Several simulations and reporting capabilities, error sources, and data layers (e.g., DEM) will be added throughout the 3-year NASA STV study

4. Postdoc opportunities (email to: marco.lavalle@jpl.nasa.gov)
   - TomoSAR/3D structure/biomass mapping with real-data (sci) and/or simulations (eng)
   - NISAR algorithms development (time-series, polarimetry, InSAR fusion, AI)