Co-Fliers Mission Concepts for NISAR and ROSE-L to Address Emerging Measurements Needs in Earth Science

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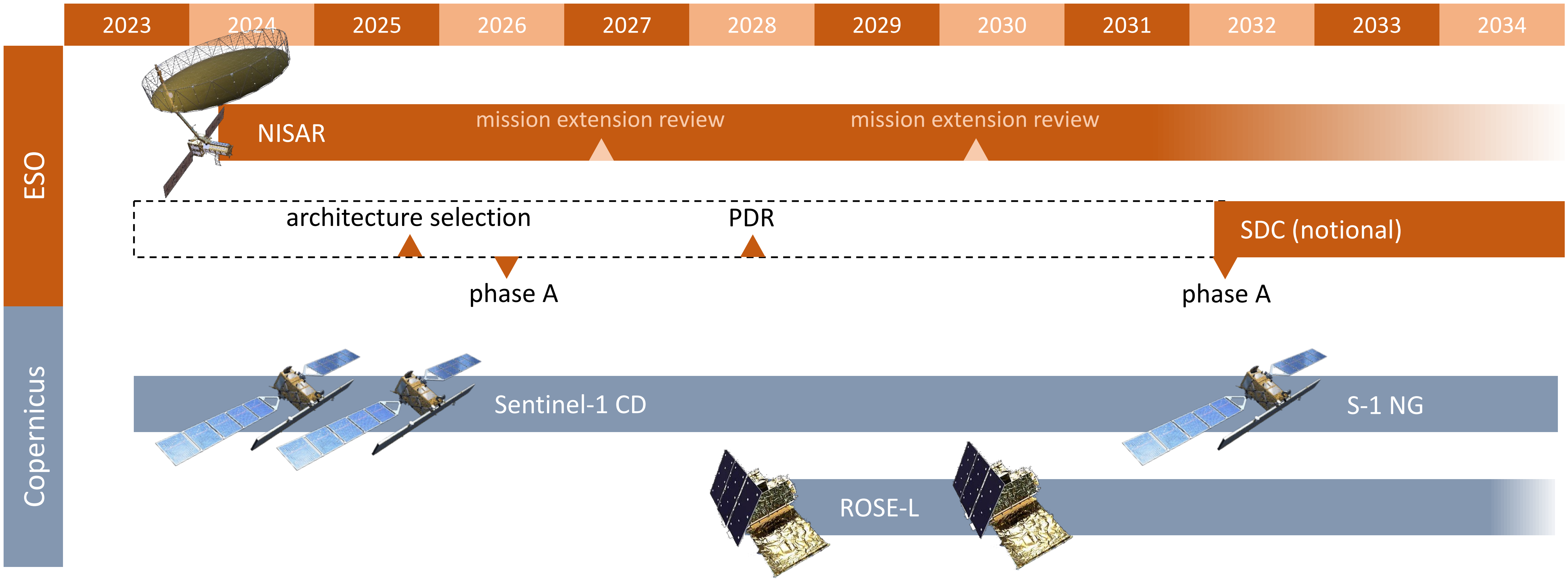
Background: Surface Deformation and Change (SDC)

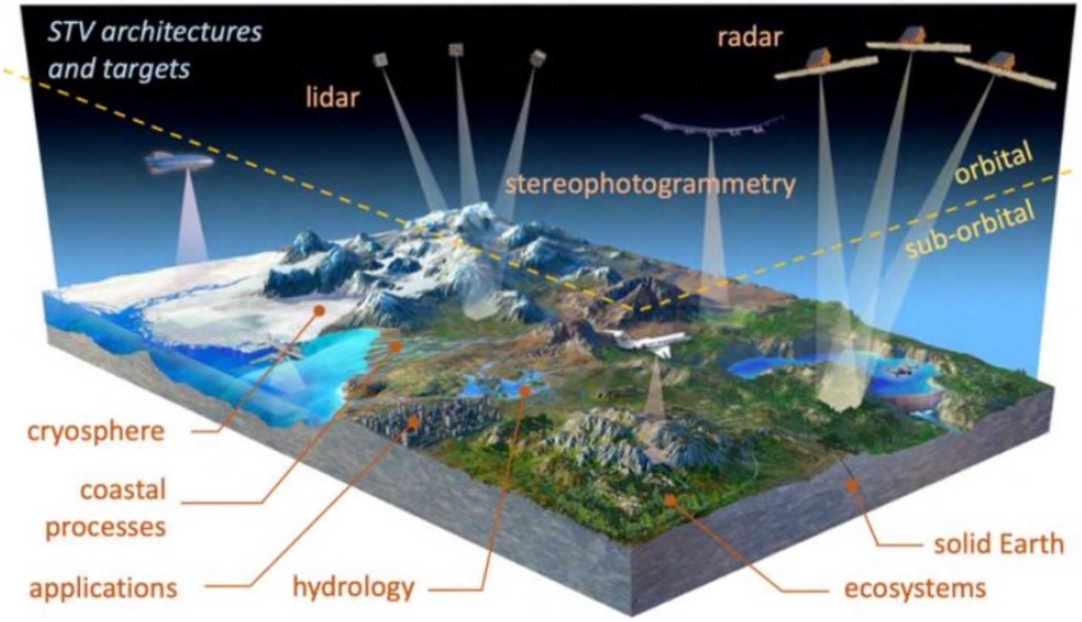
- 2017 Decadal Survey recommended SDC as "Designated Observable"
- Science and Application Traceability Matrix (SATM) available at *science.nasa.gov/earth-science/decadal-sdc*
    - InSAR repeat-pass L/S-band at sub-weekly to daily rates
    - Resolution ranging from 5m to 15m
    - Sensitivity to height changes between 1-10mm
    - Time series measurements from 1 mm/week to 1 mm/year
    - Continuous global monitoring of all land and coastal areas (>70%)
    - Noise equivalent sigma^0 < -20dB and ambiguity < -20dB
- SDC architectures down-selected from 40+ to ~12 in 3/2022, and further to 5 architectures currently being studied in phase 3
- NASA cost is capped, so partnerships may be needed to fully implement the Decadal Survey vision

Background: Surface Deformation and Change (SDC)



Background: Surface Topography and Vegetation (STV)

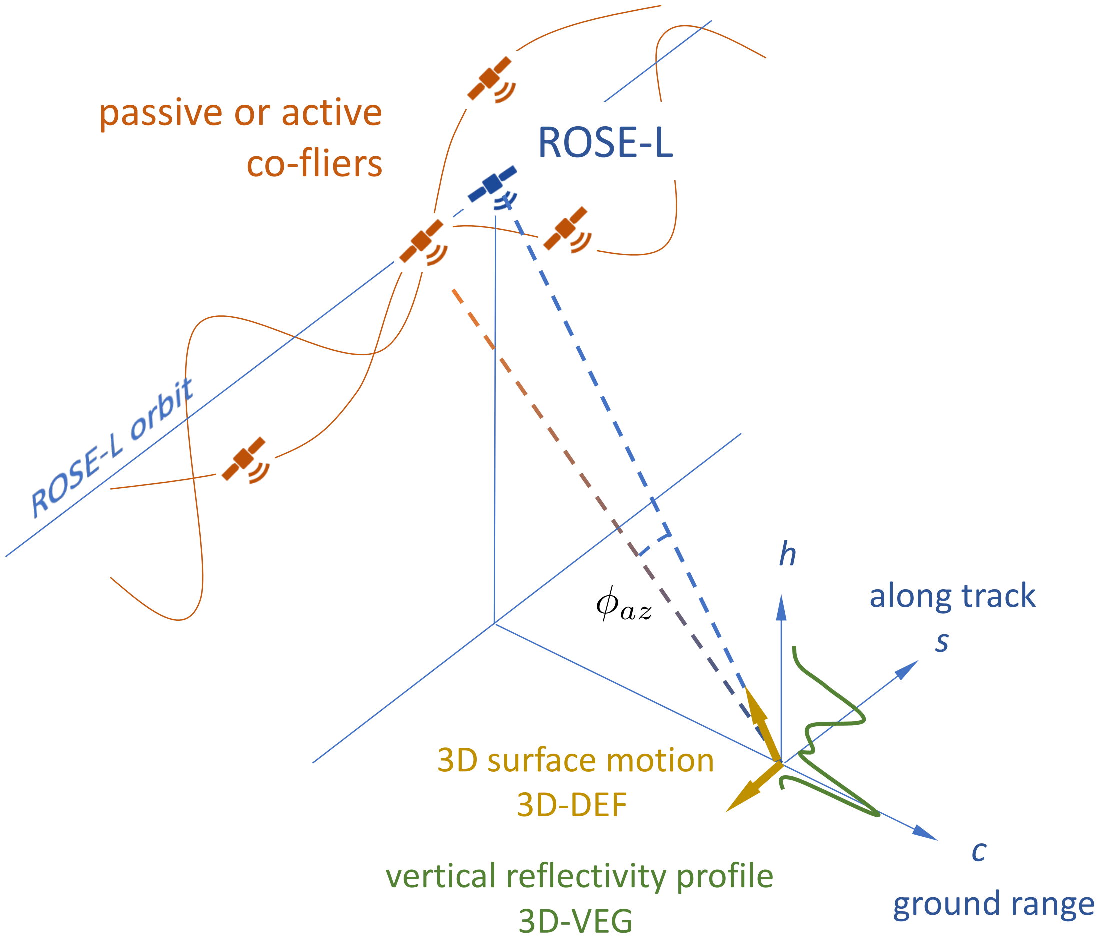
- Global, fine-scale observations of surface topography and vegetation structure (STV) are critical to address key science questions and applications in Solid Earth[SE], Ecosystems[V], Cryosphere[C], Hydrology[H], and Coastal Processes[CP]
- 2017 Decadal Survey recommended Surface Topography and Vegetation (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)



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

Why co-fliers for ROSE-L and NISAR

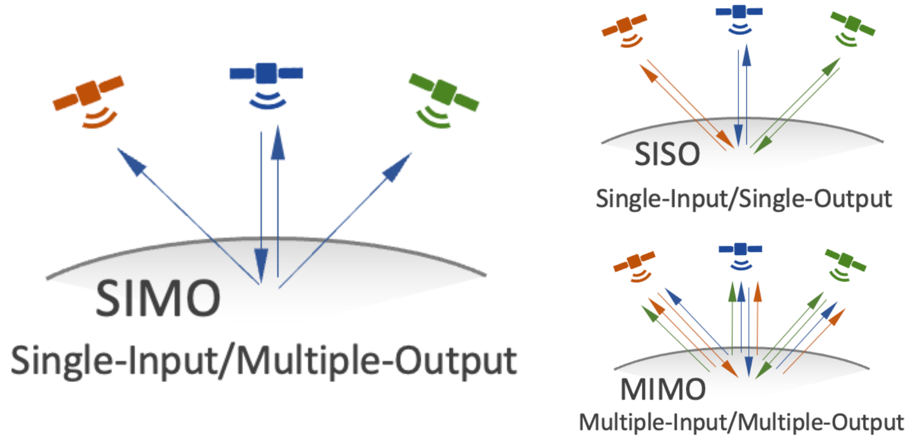


- Co-fliers or companion satellites enable new types of measurements
  - 3D-DEF: Along-track (AT) co-fliers
  - 3D-VEG: Cross-track (XT) co-fliers
- Affordable, flexible, and scalable
- NISAR (2024) and ROSE-L (2028) will be in orbit providing an "L-band source" for co-fliers
- Parallel NASA/JPL efforts are on-going to develop concepts and evaluate performance
  - Simplified analytical equations
  - End-to-end scattering simulations (e.g., DARTS Trade Study Tool)
  - Multi-static SAR campaigns with drones and fixed-wing aircrafts

Can small co-fliers for NISAR/ROSE-L meet the SDC + STV needs?

	Geophysical measurement		Technique		Geometry
SDC	retrieval of 3D deformation vector with atmospheric correction	➔	Multi-squint InSAR	➔	Along-track co-fliers
STV	retrieval of 3D vegetation structure and topography	➔	TomoSAR/PolInSAR	➔	Cross-track co-fliers

Multi-static mode



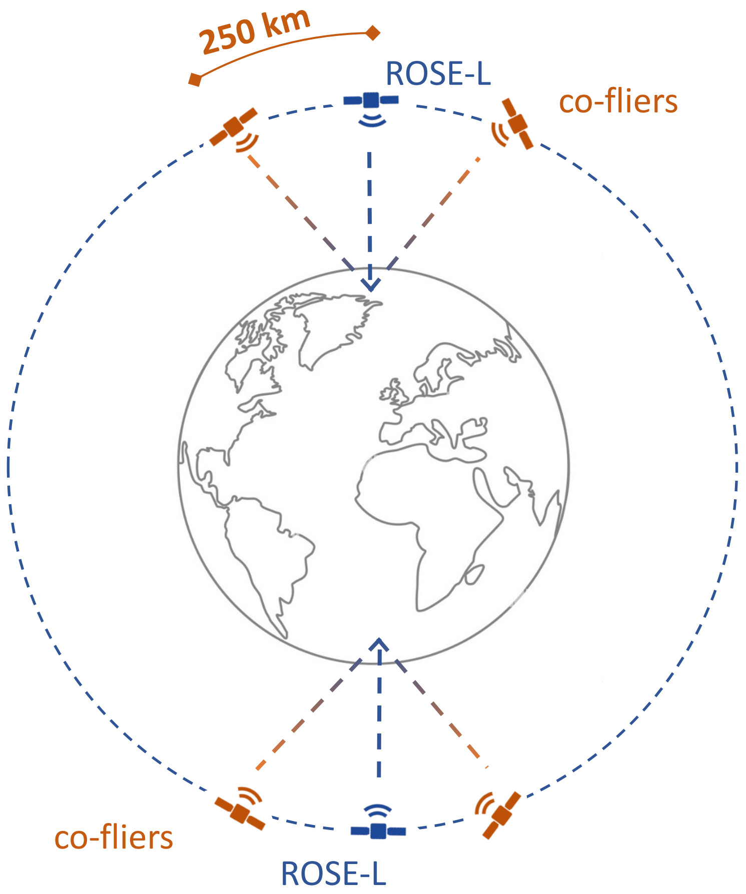
Instruments

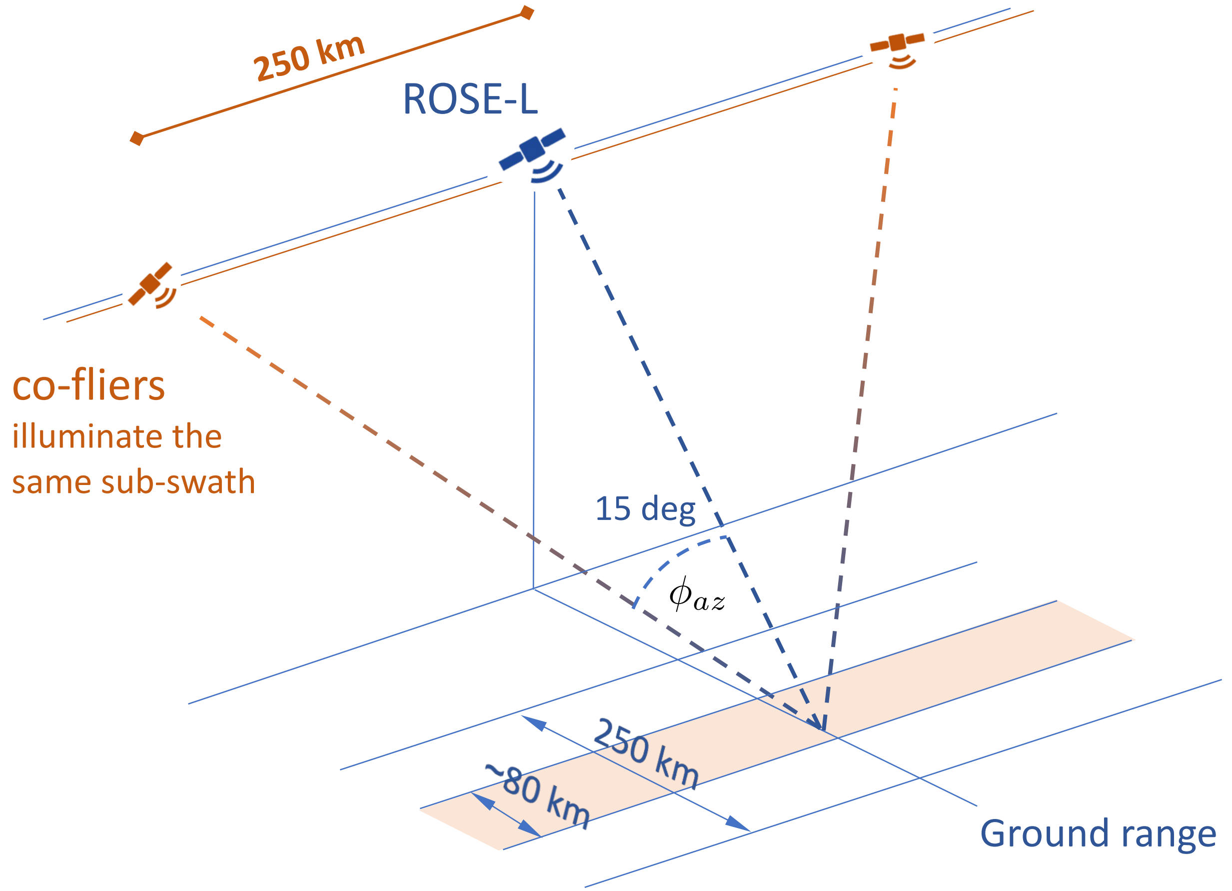
- 1 transmitter
  - ROSE-L (and NISAR)
  - 250 km swath
  - S-1 orbit (710 km altitude)
  - L-band (1.26 GHz)
- 2 to 4 receivers
  - SmallSat (ESPA/ESPA Grande)
  - No SweepSAR/SCORE (60/80/120km swath width)
- Radar mode
  - HRWS (ROSE-L)
  - SweepSAR (NISAR)

Option A: 4 along-track co-fliers, 2 for each ROSE-L s/c

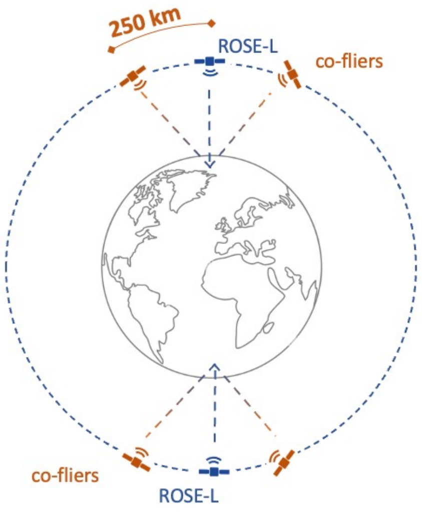
PROS 3D surface deformation and atmospheric correction with 6-day interferograms

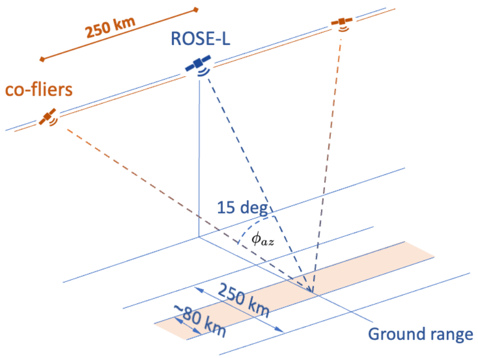
CONS Illuminates 1/3 of the ROSE-L swath and can't do STV (even with helical orbits)



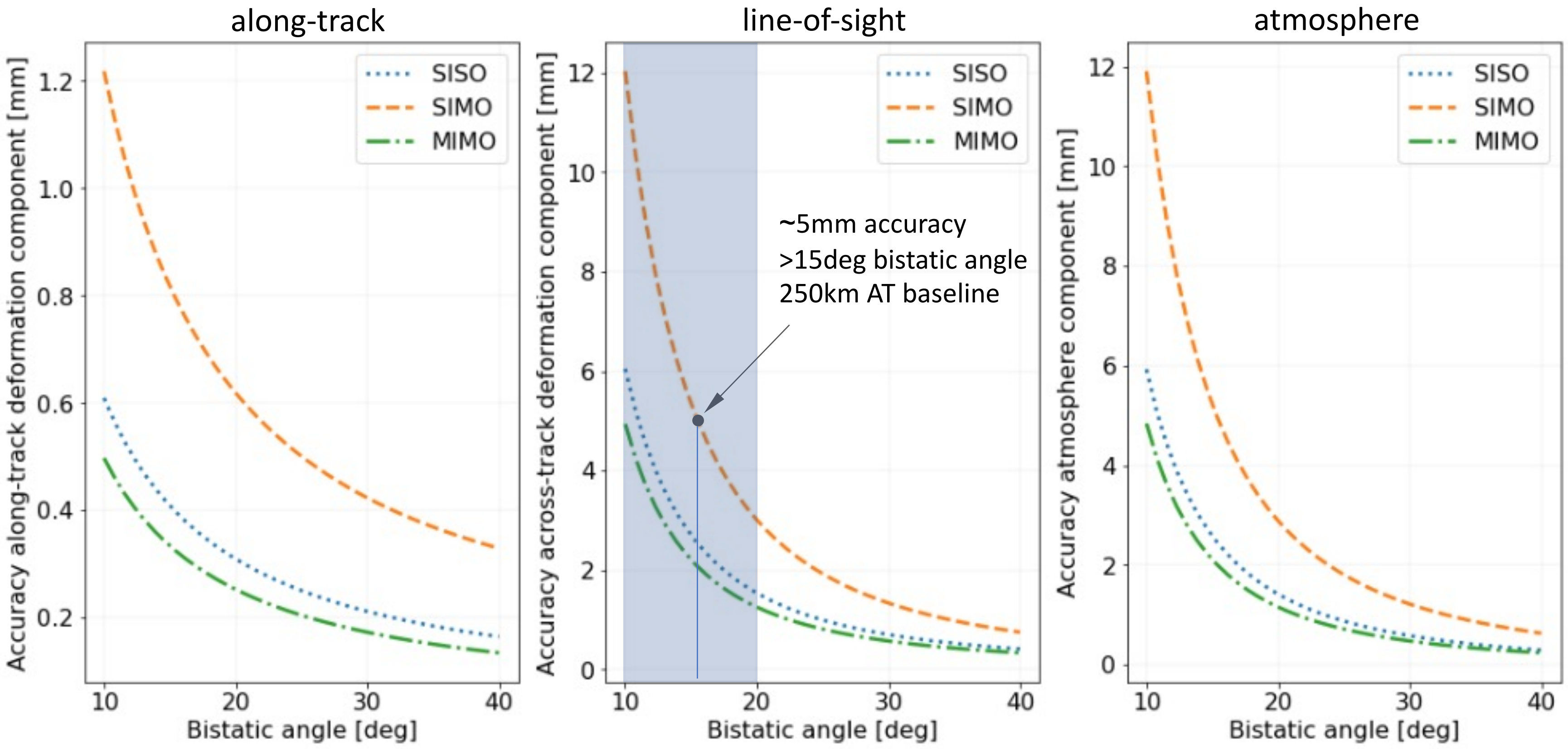


Option A: Retrieval of 3D-DEF vector with atmospheric correction

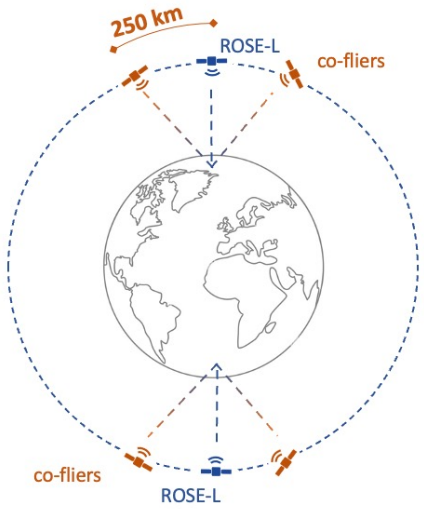


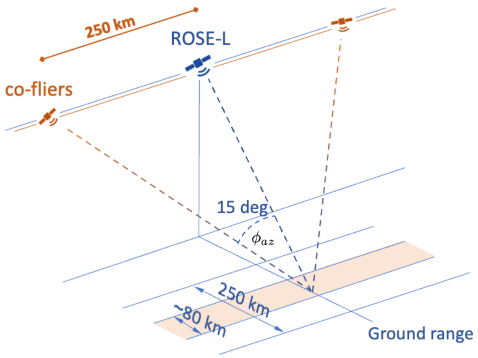


- Linear system of equations with 3 multi-squint repeat-pass InSAR phase observations and retrieval of along-track, line-of-sight, and atmosphere components of the 3D deformation vector
- MIMO outperforms SIMO and is similar to SISO. Bistatic angle can be 10-20deg depending on number of looks (100), correlation (0.67), perp. baseline (0m), and deformation accuracy (5mm)



Option A: Limitations of along-track co-fliers for STV



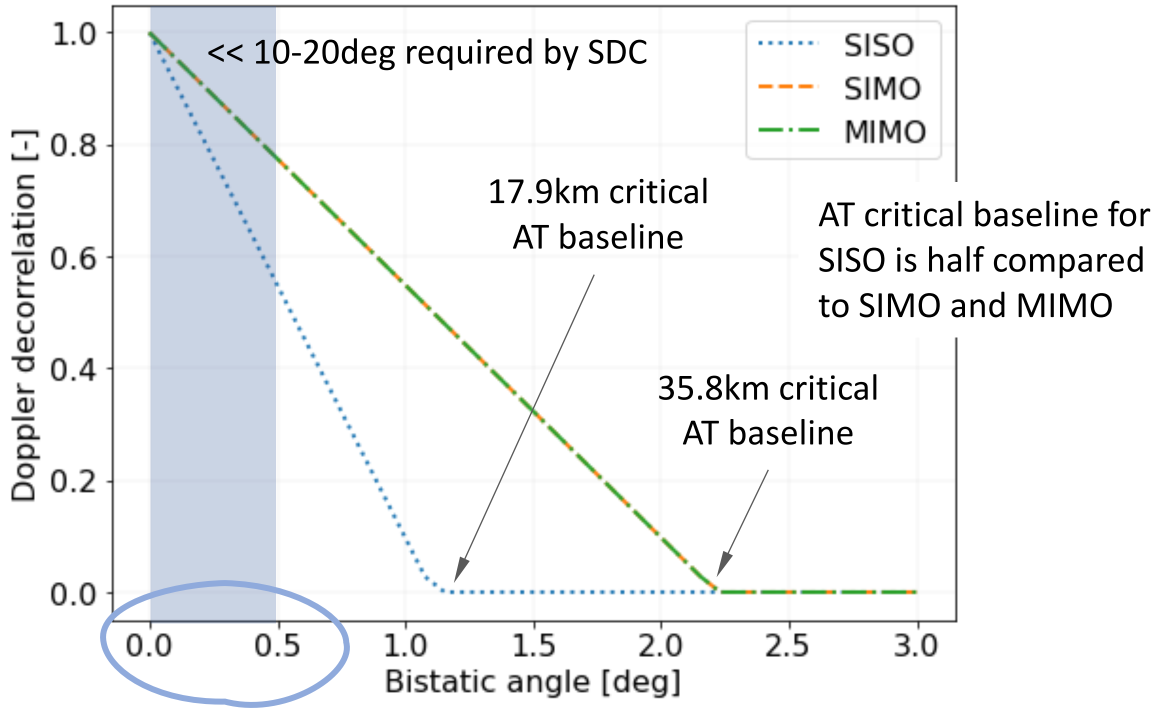


- Doppler decorrelation between two SLCs acquired with different squinted geometries poses a limit on the along-track (AT) baseline length similarly to the spectral shift along range
- Critical along-track baseline for a transmitter and a receiver located on the same orbit with range vectors forming a bistatic angle ϕ_{az} depends on multi-static mode

STV via histogram tomography relies on dominant (~coherent) targets.

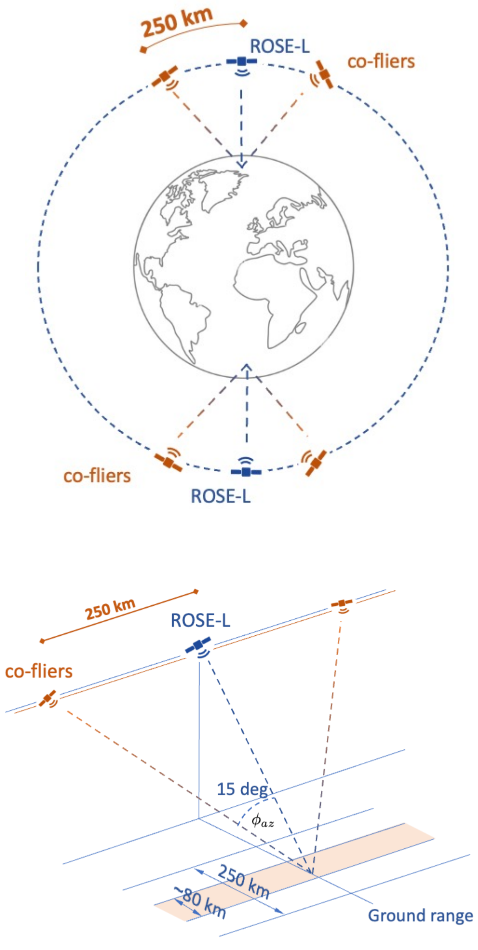
Whether HistTomo can tolerate larger bistatic angles (> 0.5deg) needs to be investigated

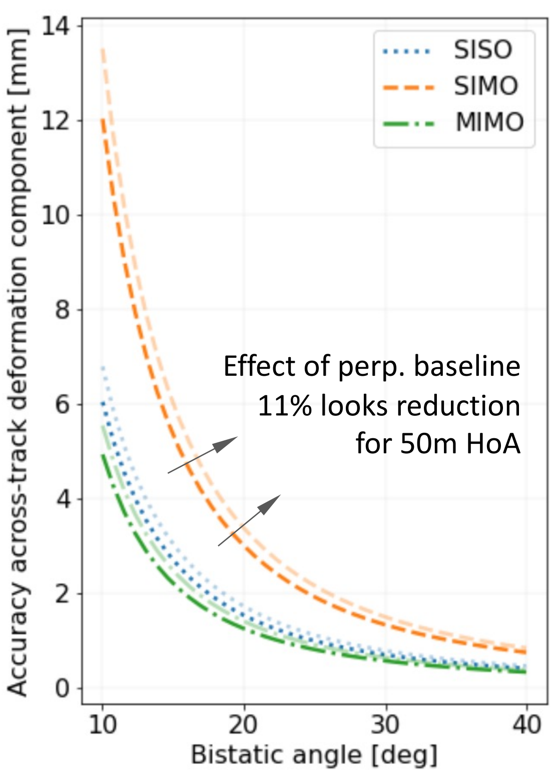
HistTomo: Shiroma and Lavalle, IEEE TGRS (2021)

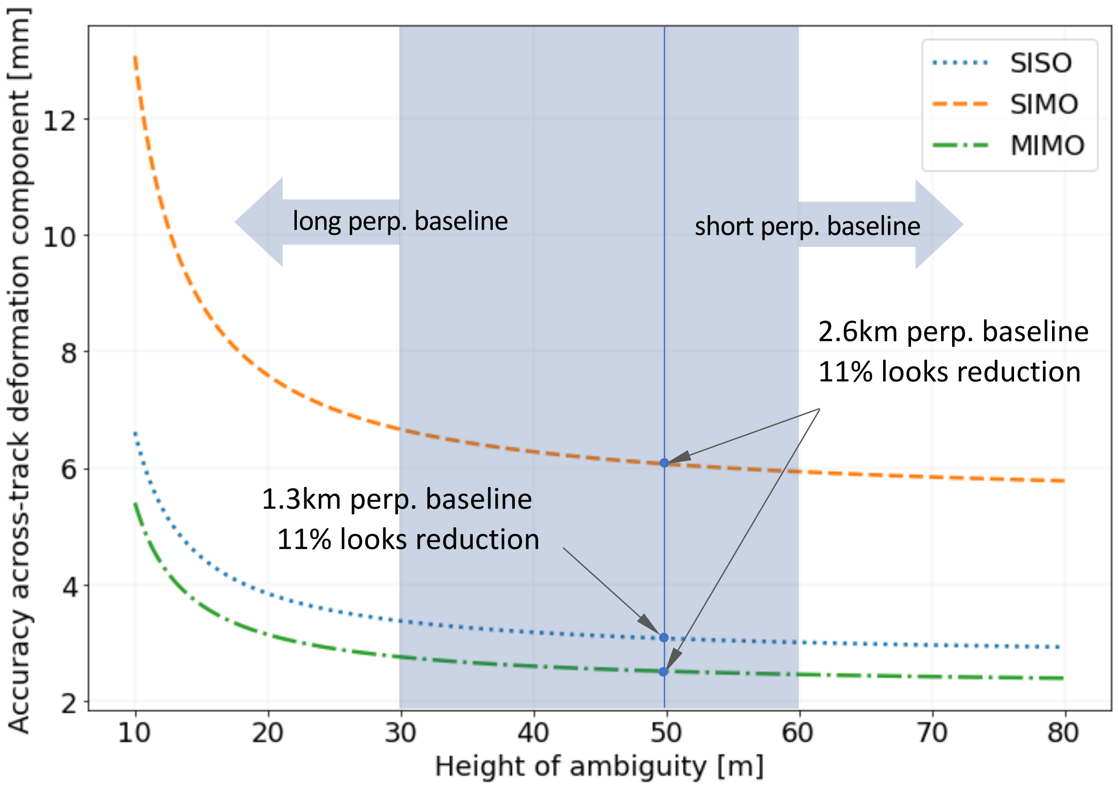


Drift co-fliers orbits cross-track for STV in option-A: Impact for SDC

- Number of looks is reduced by increasing the InSAR cross-track baseline, which in turn affects the deformation retrieval accuracy
- Deformation accuracy is affected only slightly by a height of ambiguity (HoA) of 30-60m for a given reference geometry and a bistatic angle (15deg)
- Repeat-pass TomoSAR/PolInSAR is possible, but results will be affected by temporal decorrelation



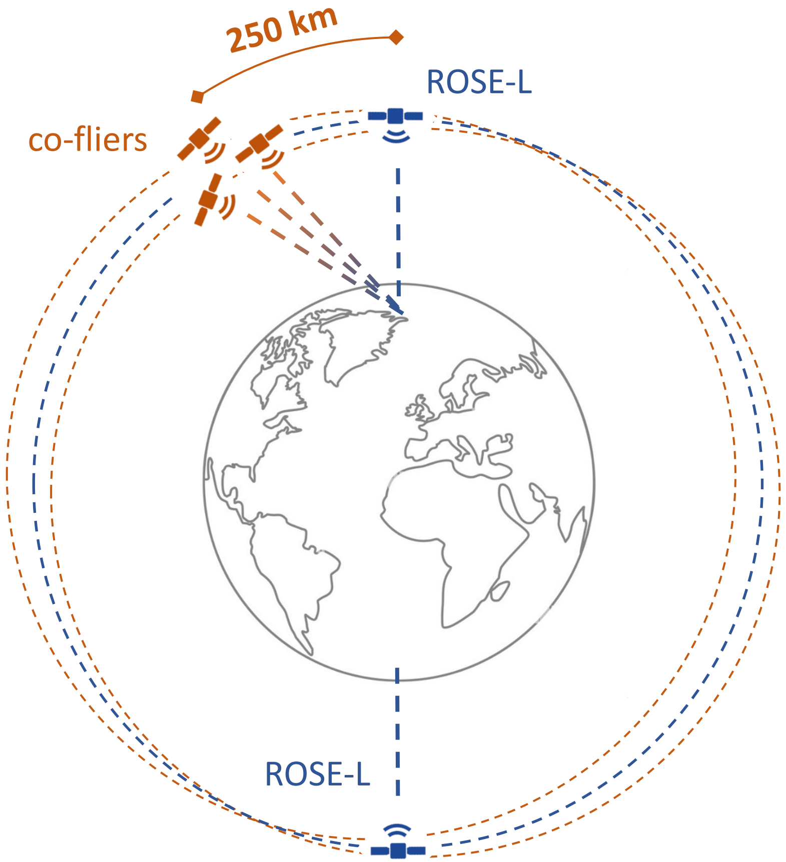


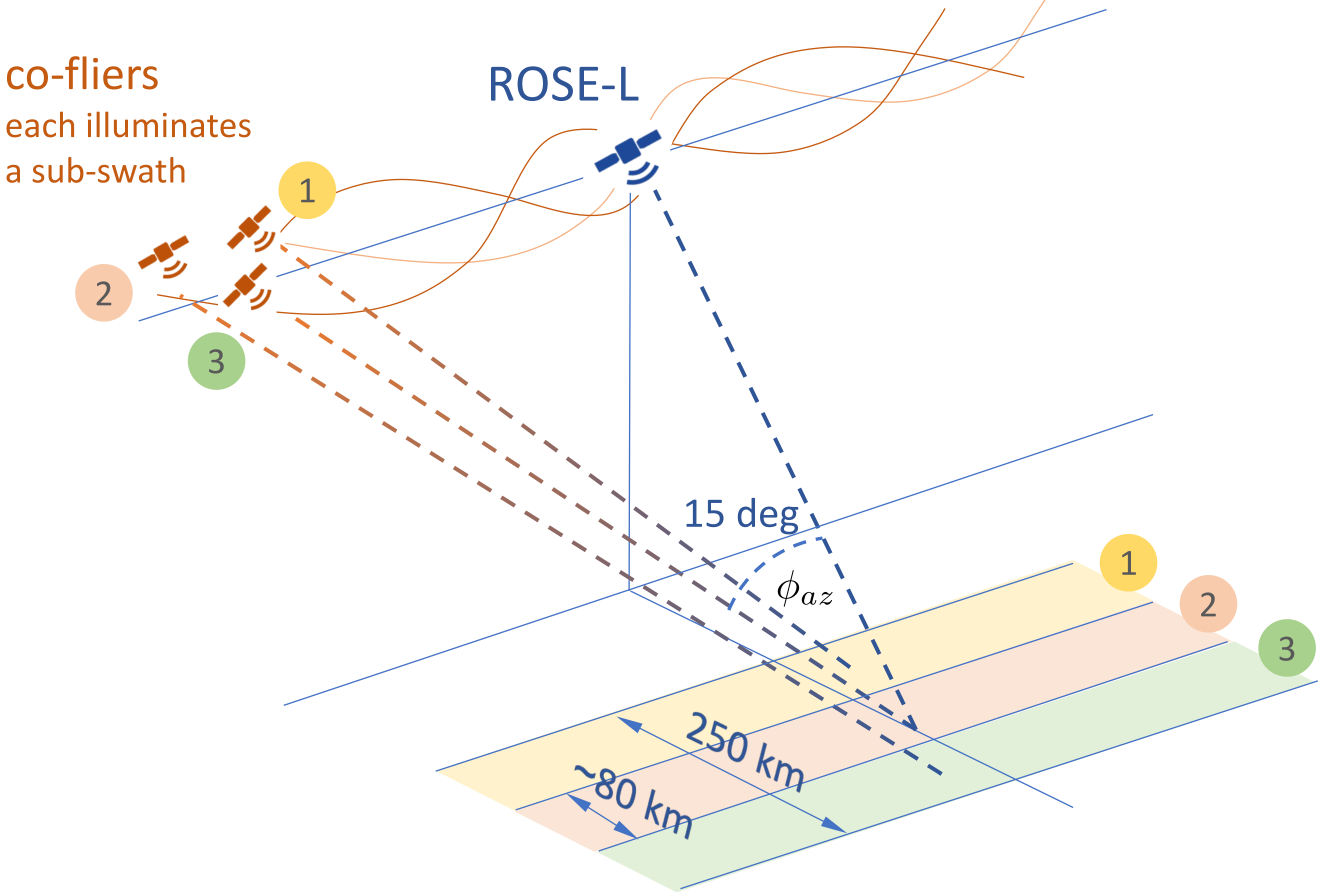


Option B: 3 along/cross-track co-fliers for 1 ROSE-L s/c

PROS Illuminates full ROSE-L swath in 1 cycle with 3D-DEF or atmospheric correction, can support STV in 3 cycles by repointing the co-fliers beams

CONS Cannot do both 3D-DEF and atmospheric correction, requires re-pointing to switch SDC/STV phases





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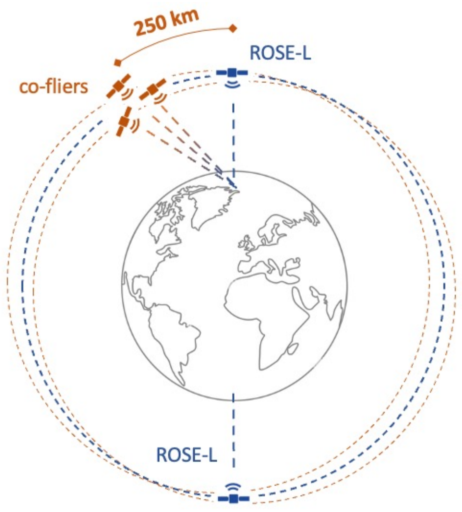
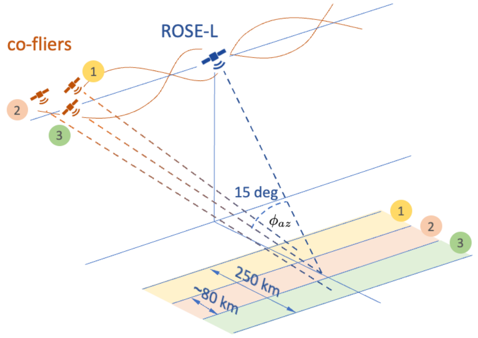
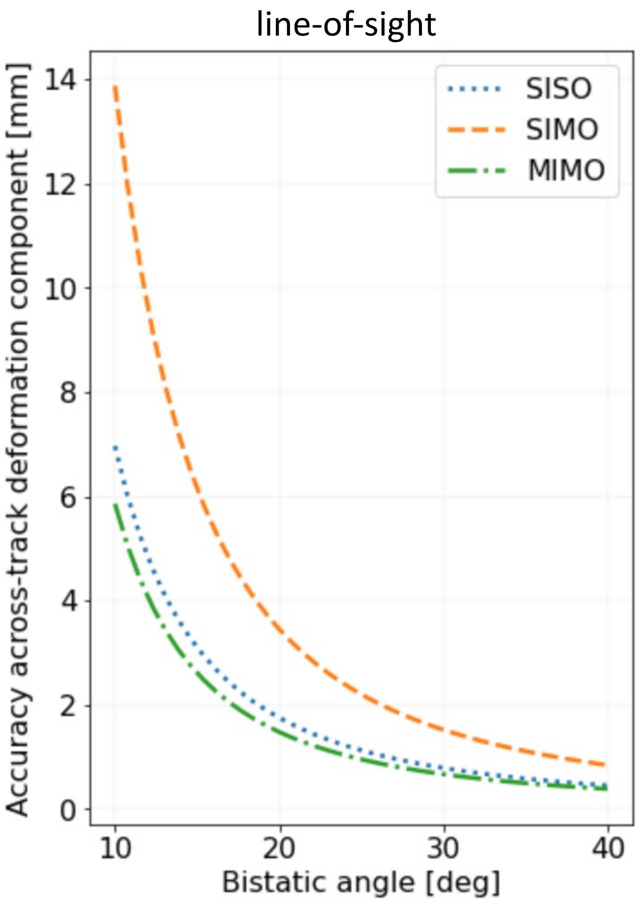
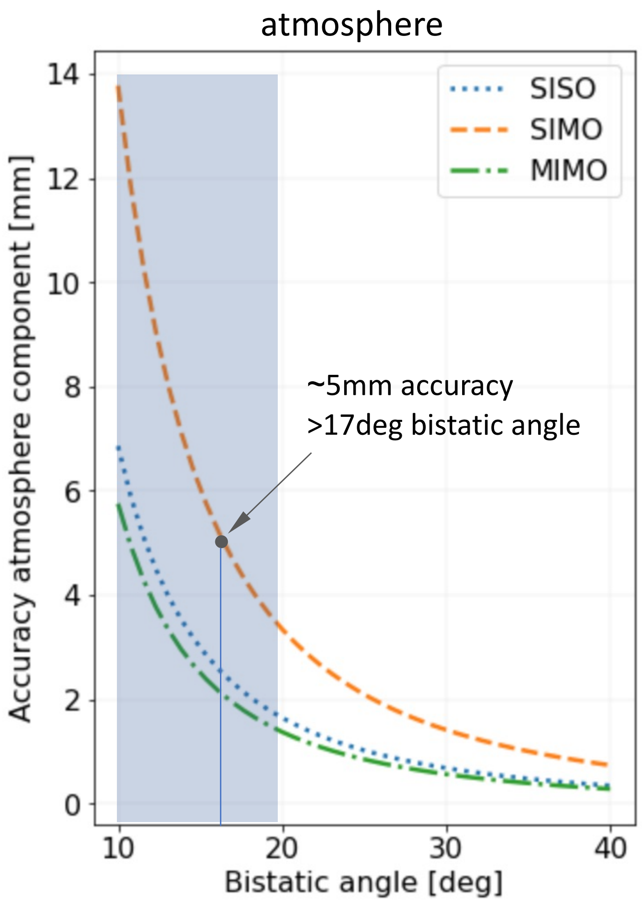
Option B: 3 along/cross-track co-fliers for 1 ROSE-L s/c

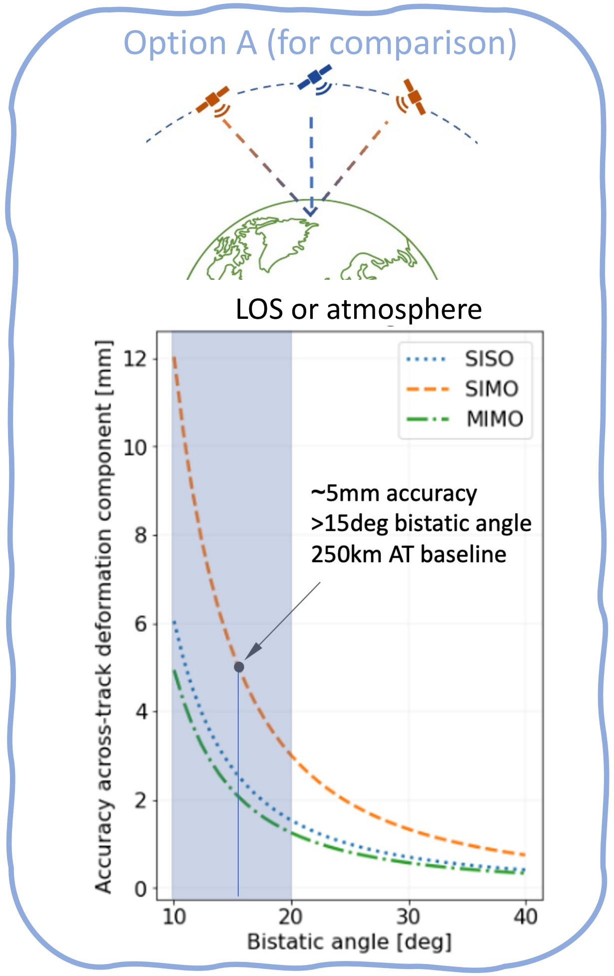




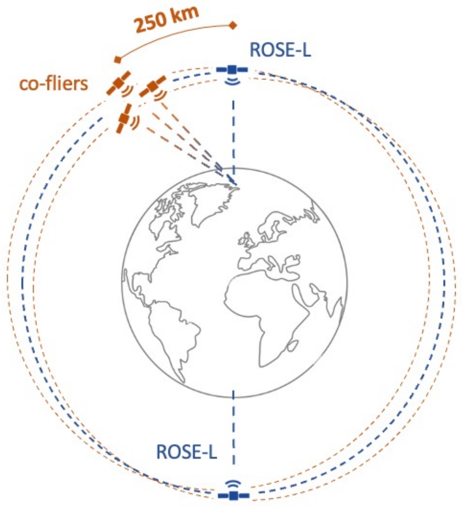
- Slightly poorer accuracy than option-A, it may need slightly larger bistatic angle or number of looks
- Perpendicular baseline has no effect because bistatic geometry is the same at each pass

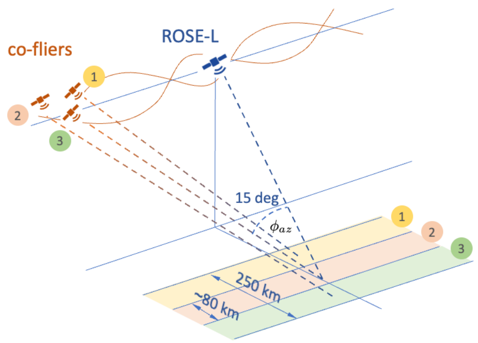




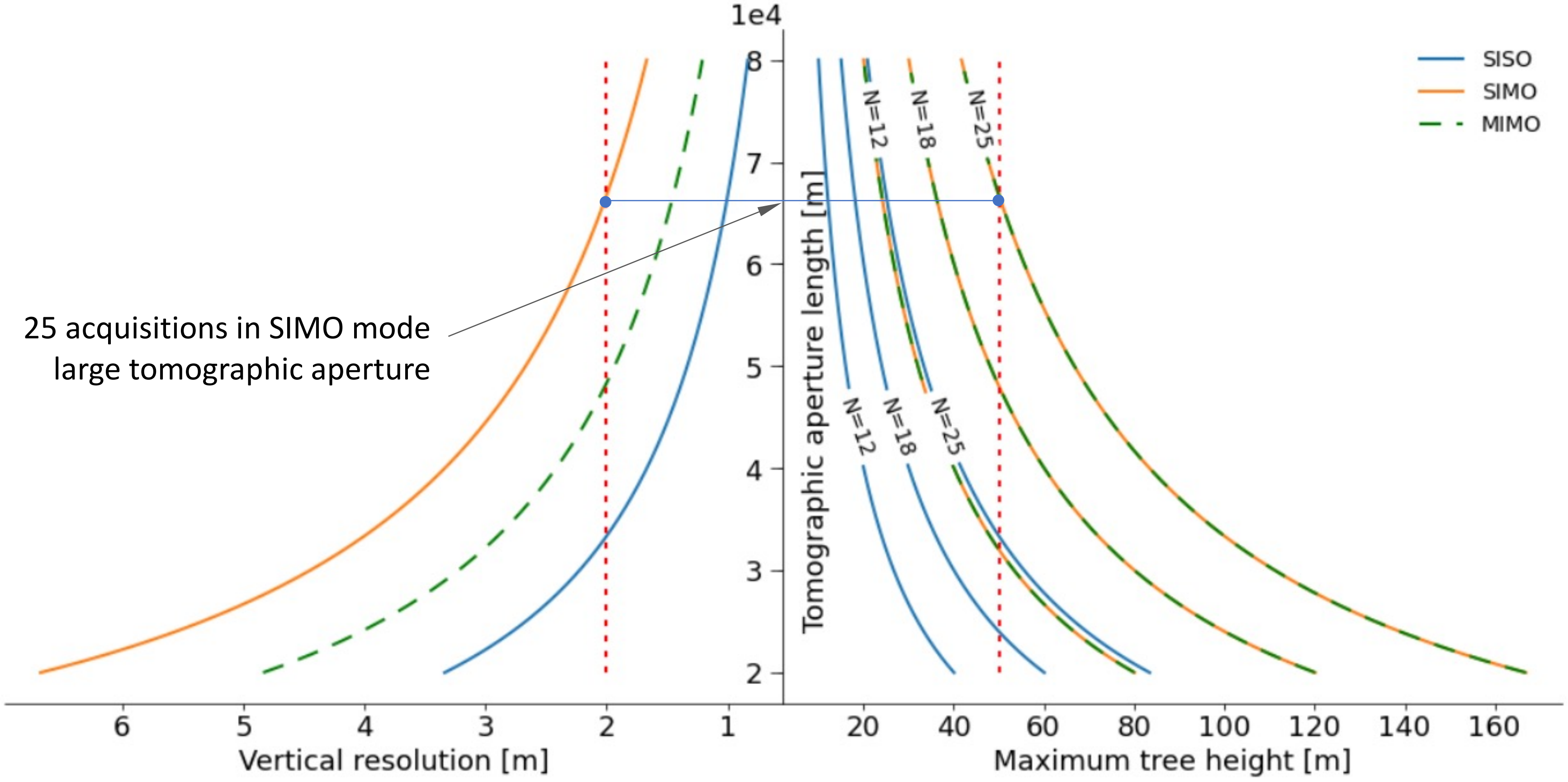


Option B: Traditional tomographic equations to meet STV needs





- Design of tomographic aperture (L) and number of uniformly-spaced acquisitions (N) based on target vertical resolution (2m) and height of ambiguity (50m) using traditional SAR tomography
- SISO = best resolution, worst ambiguity; SIMO = worst resolution, same ambiguity as MIMO. MIMO = good balance between resolution and ambiguity, higher SNR and lower sidelobes

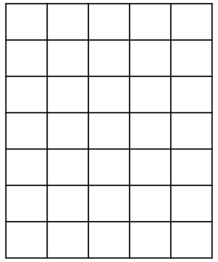


Seker I. and Lavalle M. "Tomographic Performance of Multi-Static Radar Formations: Theory and Simulations." *Remote Sensing*. 13(4):737, 2021

Design of STV co-flier concepts: Histogram tomography

L-band UAVSAR data over tropical forests (Gabon) with 20m baseline after multi-looking to about 20m sample size

M pixels, multi-looked cell



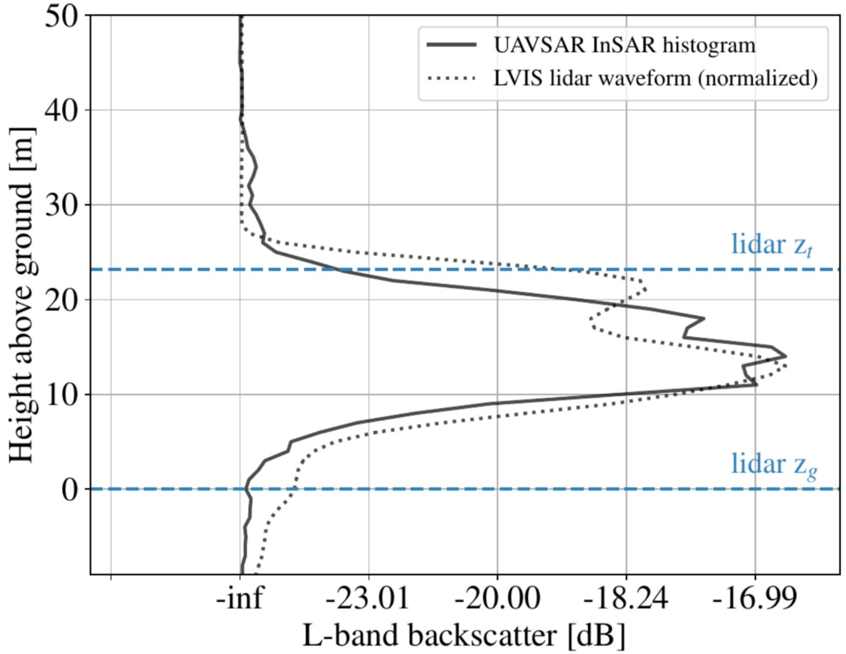
InSAR histogram function

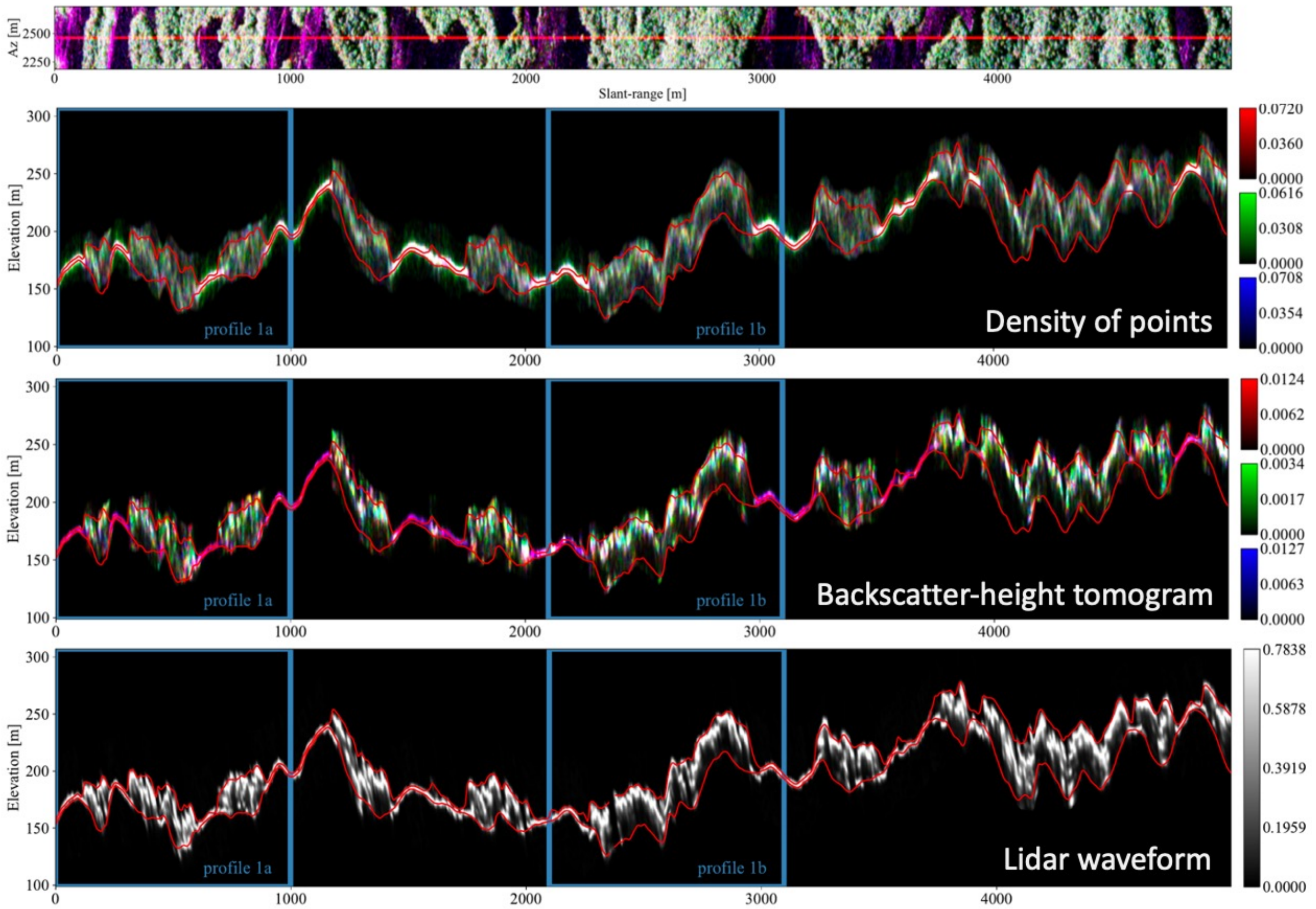
$$g(z_n) = \sum_{i=1}^{M} w_i f(s_1, s_2) \chi(z_n, \phi_i)$$

Height-backscatter histogram ~ tomogram

$f = |s_1 s_2^*|$ ~ backscatter

$f = 1$ ~ density of points

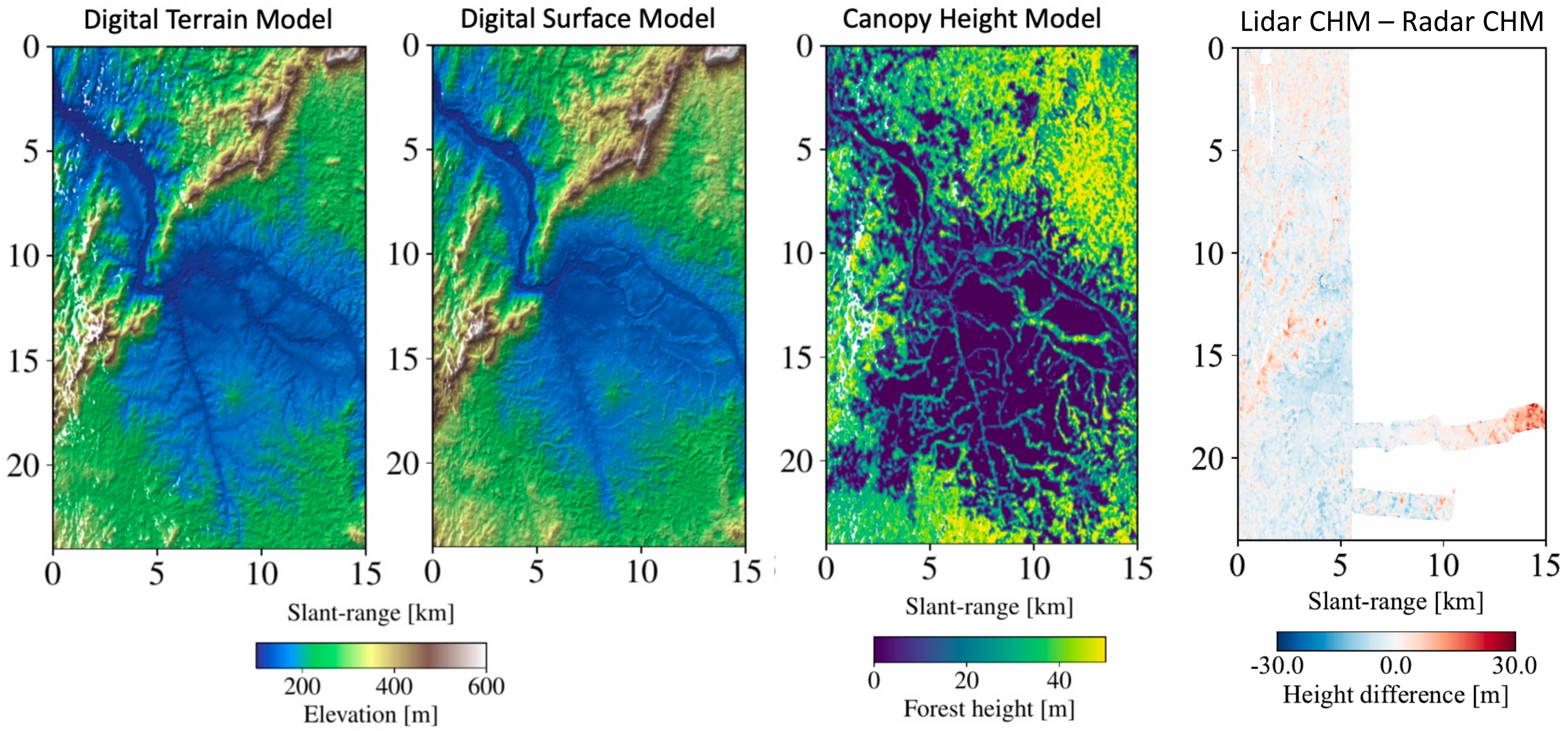




Shiroma, G. and M. Lavalle, "Digital Terrain, Surface, and Canopy Height Models From InSAR Backscatter-Height Histograms," *IEEE Transactions on Geoscience and Remote Sensing*, vol. 58, no. 6, pp. 3754–3777, 2020

Design of STV co-flier concepts: Histogram tomography

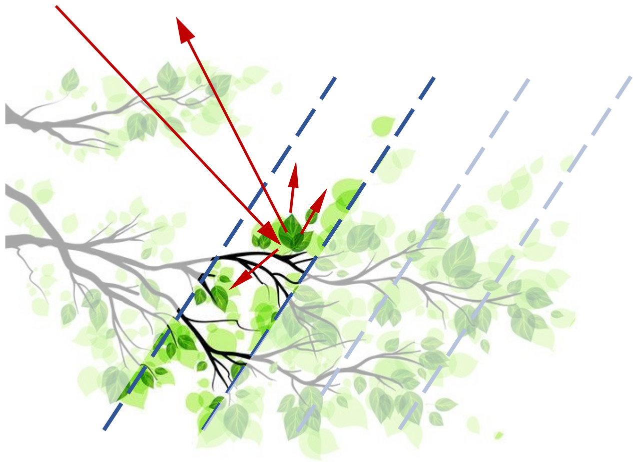
HistTomo algorithm demonstrated L-band UAVSAR data with single baseline (40m) during AfriSAR campaign



Shiroma, G. and M. Lavalle, "Digital Terrain, Surface, and Canopy Height Models From InSAR Backscatter-Height Histograms," *IEEE TGRS*, vol. 58, no. 6, pp. 3754–3777, 2020

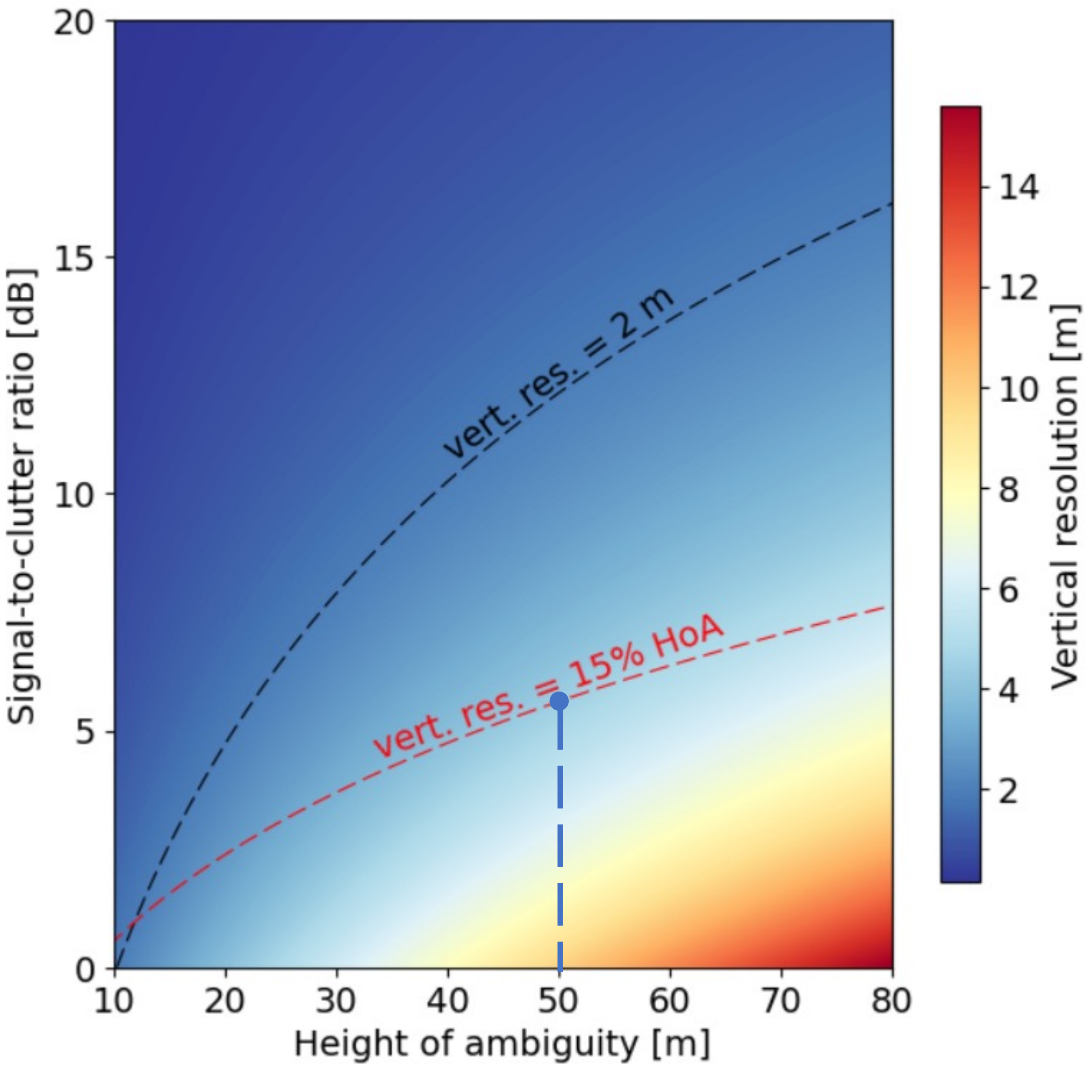
Design of co-flier concepts for STV: Histogram tomography

- Simple model based on phase noise from coherence of dominant scatterer surrounded by clutter
- Model links vertical resolution to perpendicular baseline and signal-to-clutter ratio
- Vertical resolution requirement defined by absolute value (2m) or relative to maximum tree height (15%)
- Higher SCR values and shorter height of ambiguity lead to fine vertical resolution



$$\Delta z = \frac{\sigma_\phi}{k_z}$$

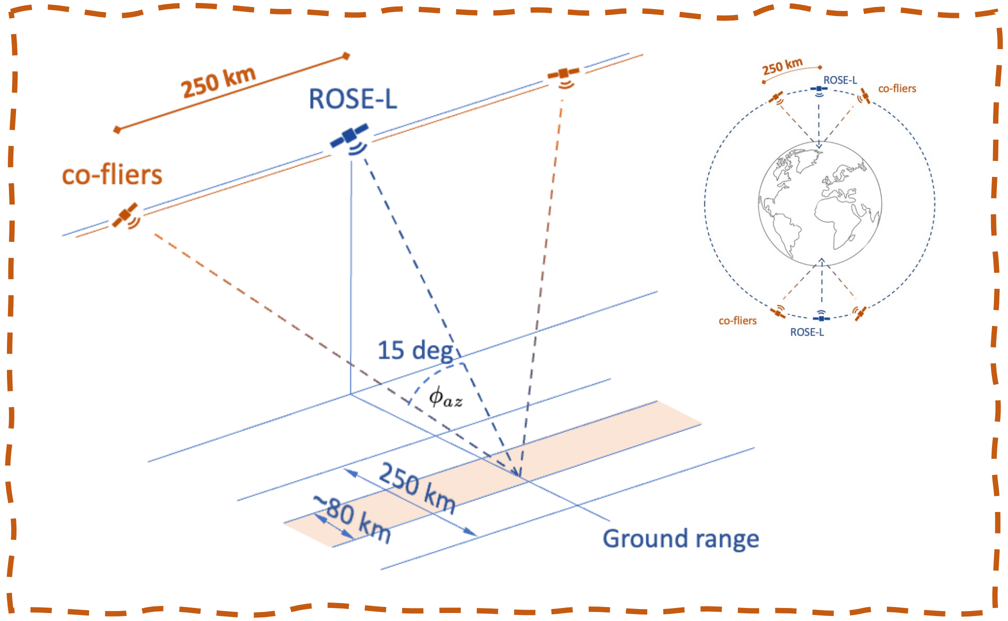
$$\sigma_\phi = \sqrt{\frac{1-\gamma_{SCR}^2}{2L\gamma_{SCR}^2}}$$



Takeaway messages

- Passive co-fliers concepts for NISAR and ROSE-L are attractive because they enable 3D-DEF and 3D-VEG
- Various options are being studied as part of the “SDC ROSE-L architecture” by exploring a large trade space
- Competing system requirements: 3D-DEF needs repeat-pass AT co-fliers; 3D-VEG needs single-pass XT co-fliers
- Scientific and applications goals ultimately drive the options (e.g., option-A vs option-B)
- Work is in progress to build end-to-end simulators and address open challenges (e.g., HRWS compatibility)

Option A: 4 AT co-fliers, 2 for each ROSE-L s/c



Option B: 3 AT/XT co-fliers for 1 ROSE-L s/c