Co-flier Concepts for NISAR and ROSE-L

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with contributions from DARTS (I. Seker, B. Hawkins, R. Amhed, E. Loria) and SDC (S. Oveisgharan, S. Horst, K. Tymofyeyeva) teams

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Background: Surface Deformation and Change (SDC)

- 2017 Decadal Survey recommended SDC as "Designated Observable"
  - Interferometric repeat-pass L/S-band SAR 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

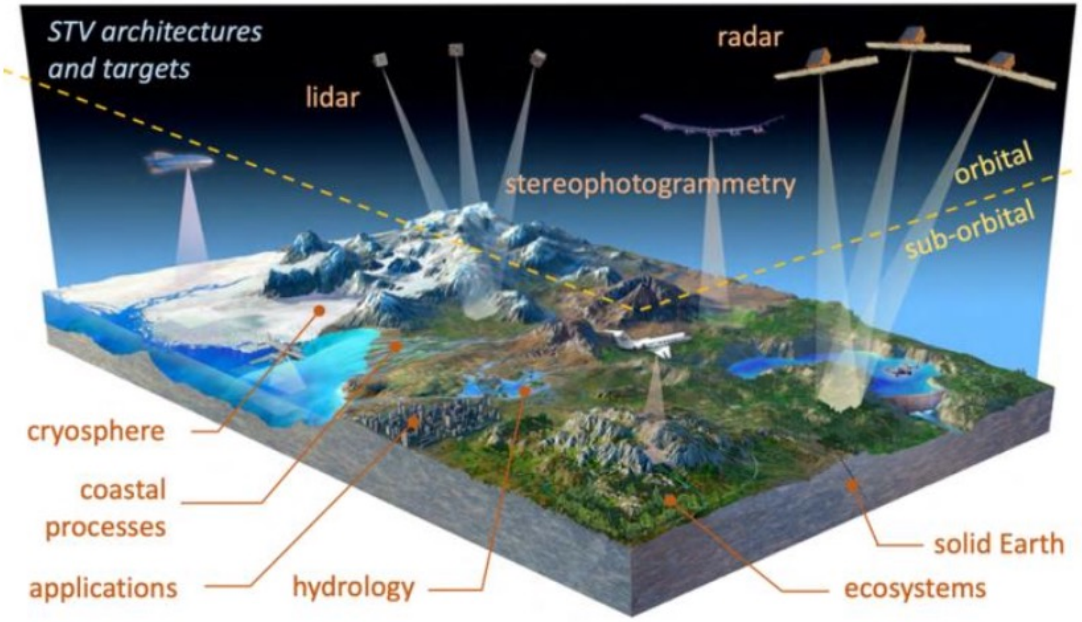
- Science and Application Traceability Matrix (SATM) available at https://science.nasa.gov/earth-science/decadal-sdc

- SDC architectures down-selected from 40+ to ~12 (3/2022)

- NASA cost is capped so partnerships may be needed to fully implement the DS vision

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)

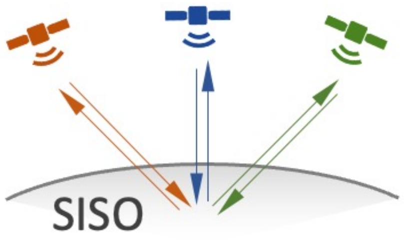


STV Product Parameter		Aspirational			Threshold		
		Median Need	Most Stringent Need	Most Stringent Discipline	Median Need	Most Stringent Need	Most Stringent Discipline
Coverage Area of Interest	%	90	95	C, H	55	90	C
Latency	Days	5	0.5	SE	60	1	SE
Duration	Years	9	10	SE, C, A	3	3	SE, V, C, CP
Repeat Frequency	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

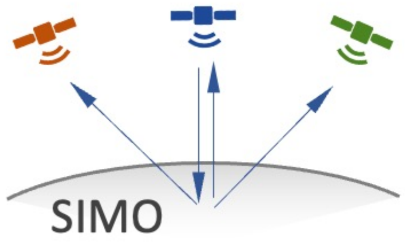
Study report: science.nasa.gov/earth-science/decadal-stv

Can L-band SAR co-fliers meet the SDC + STV needs?

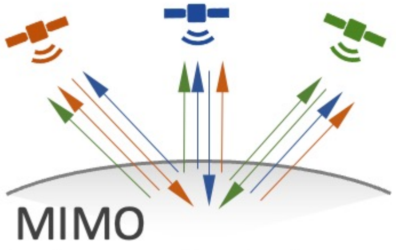
SDC	retrieval of 3D deformation vector with atmospheric correction	→ Multi-squint InSAR technique	→ Co-flier concepts for NISAR/ROSE-L
STV	retrieval of 3D vegetation structure and topography	→ Multi-baseline PolInSAR / TomoSAR technique	



Single-Input/Single-Output



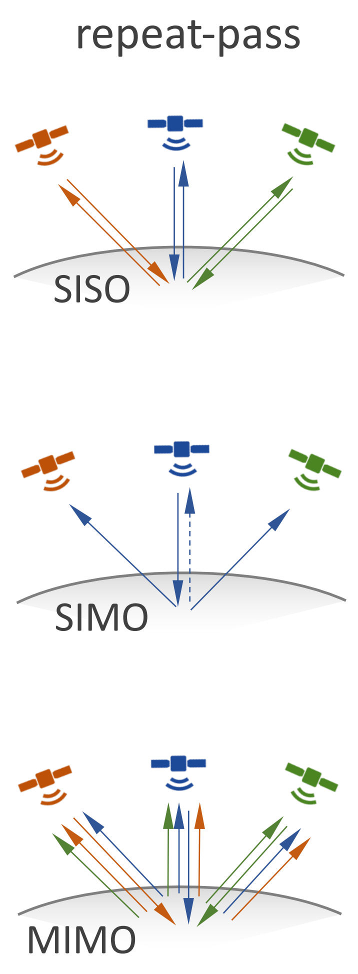
Single-Input/Multiple-Output



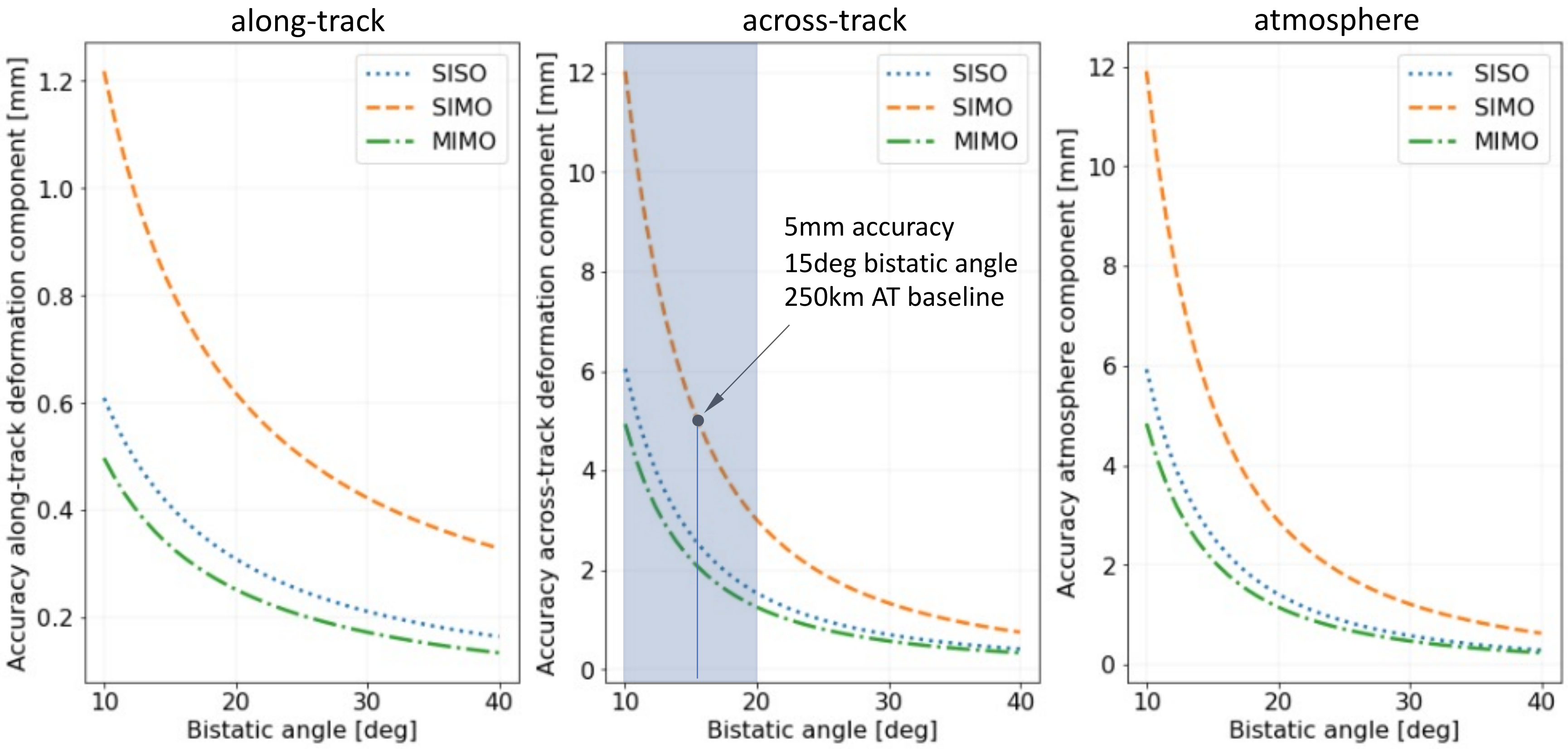
Multiple-Input/Multiple-Output

- ROSE-L (2 L-band satellites, repeat-pass interferometric, 12-day repeat, 6-day separation, 240 km swath) and NISAR (1 L-band satellite, repeat-pass interferometric, 12-day repeat, 240 km swath)
- Parallel NASA efforts (e.g., via IIP or DSI) are funded to mature radar-based technologies for SDC and STV such as phase synchronization and timing, lightweight deployable antennas, compact radar electronics

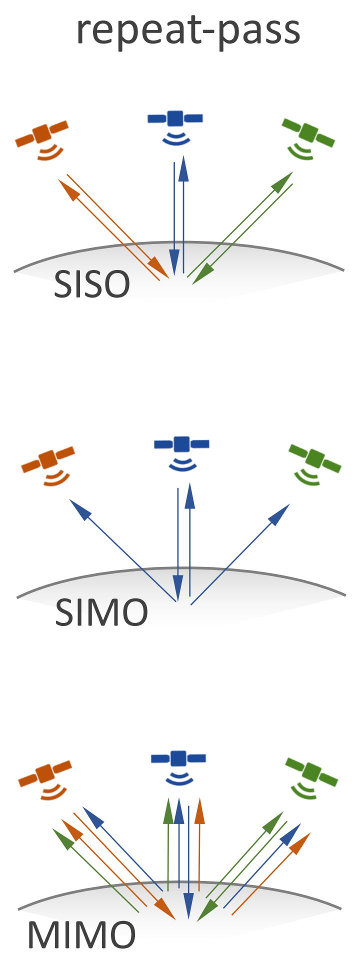
Orbital configurations of co-flier concepts: SDC perspective



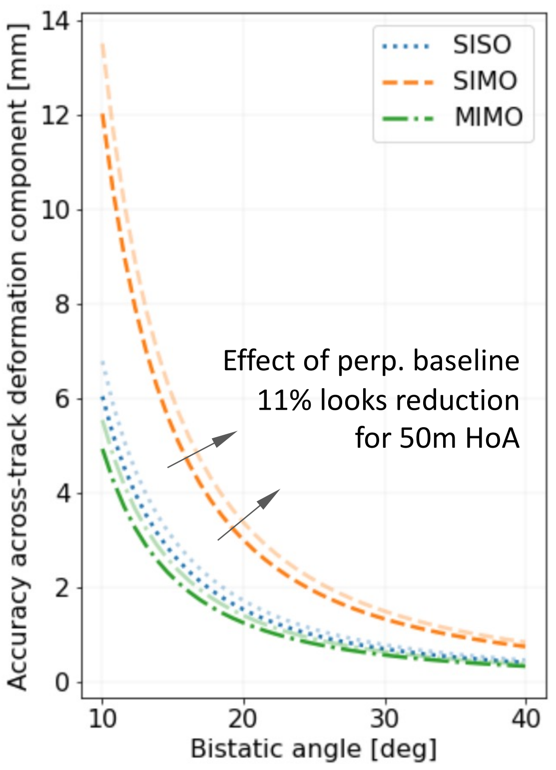
- Linear system of equations with 3 multi-squint repeat-pass InSAR phase observations and retrieval of along-track, across-track, and atmosphere components of the 3D deformation vector
- MIMO outperforms SIMO and is similar to SISO. Bistatic angle can be 10-20deg depending on number of looks (100), correlation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

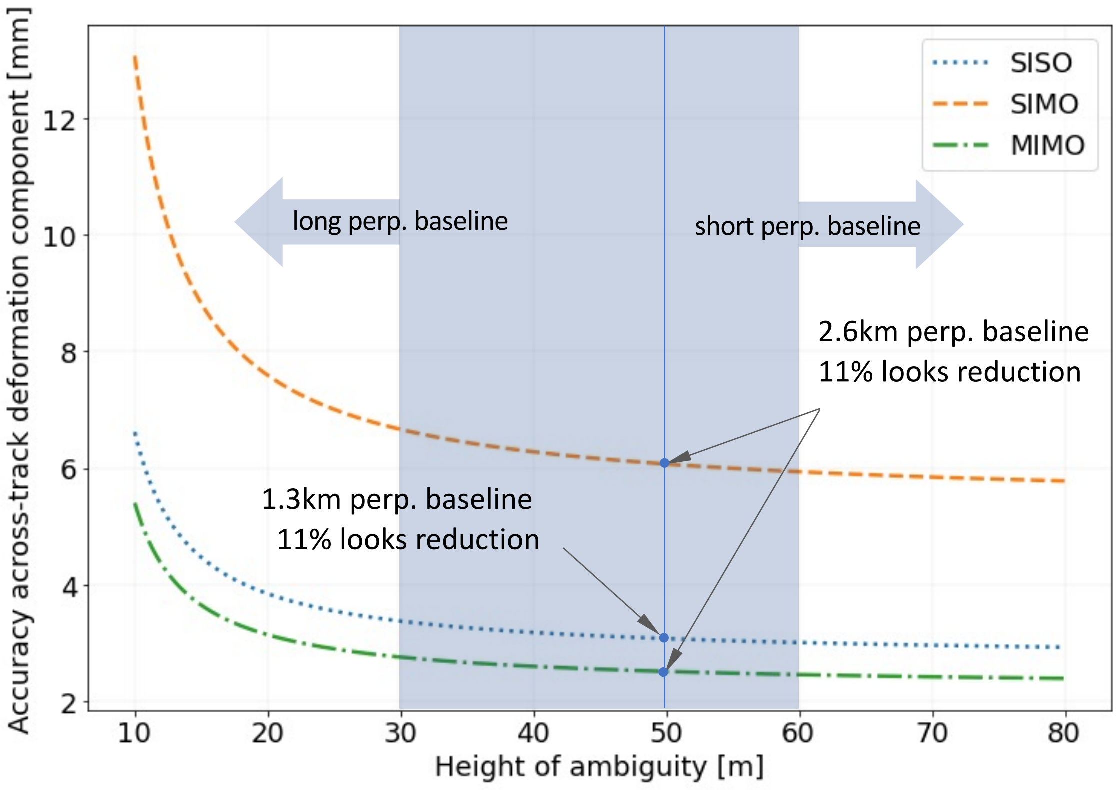


Orbital configurations of co-flier concepts: SDC perspective



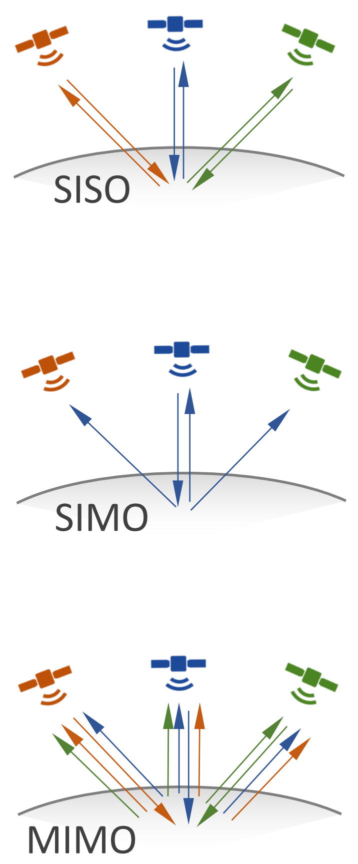
- Number of looks is reduced by increasing the InSAR perpendicular (across-track) baseline, which in turn affects the deformation retrieval accuracy
- Deformation accuracy is affected only slightly by a height of ambiguity (HoA) of 30-60m for a given reference NISAR geometry and a bistatic angle (15deg)



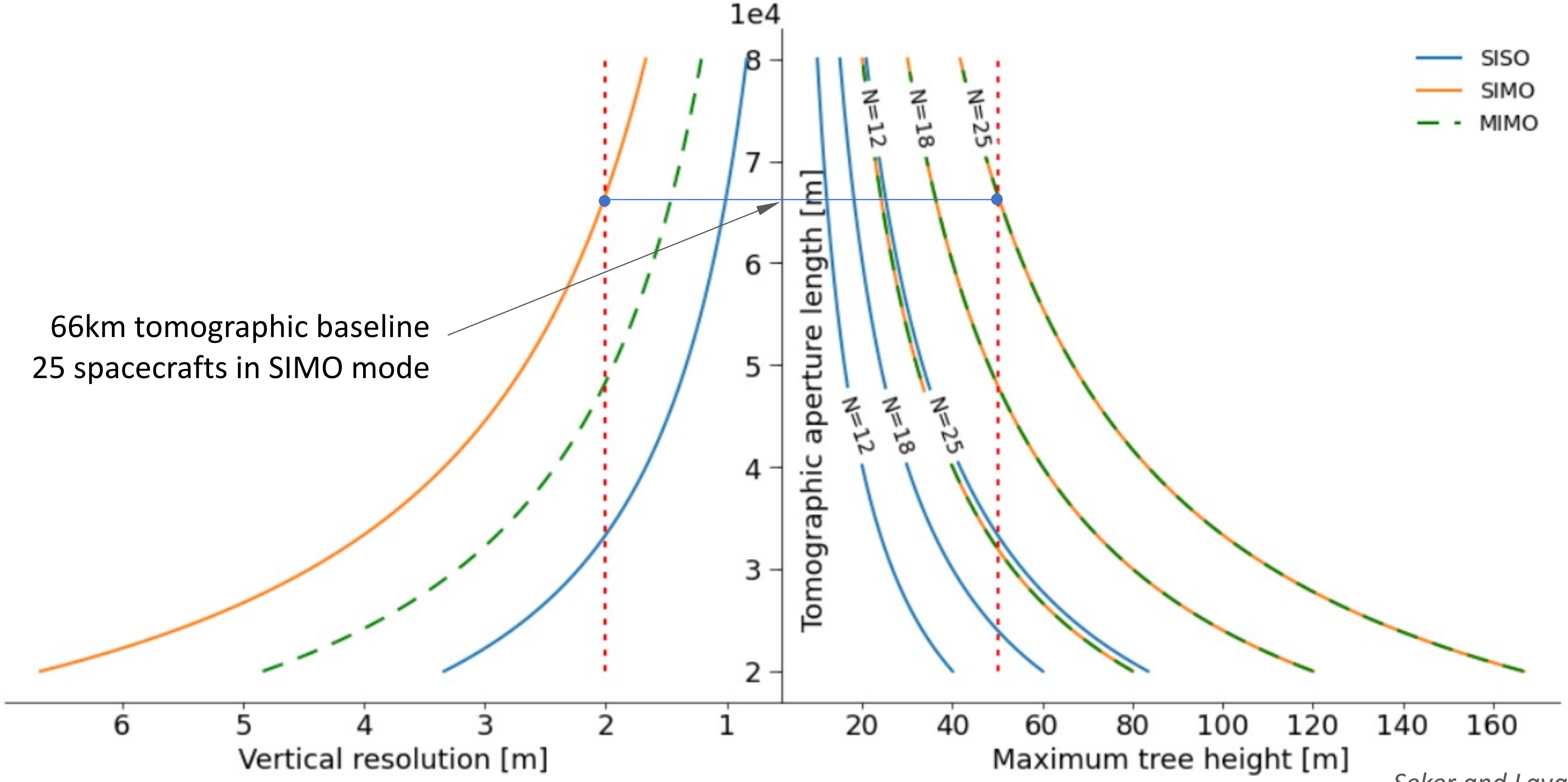


Orbital configurations of co-flier concepts: STV perspective

single-pass



- In traditional SAR tomography, design of tomographic aperture (L) and number of uniformly-spaced spacecrafts (N) based on target vertical resolution (2m) and height of ambiguity (50m)
- SISO = best vertical resolution but worst height of ambiguity; SIMO = worst vertical resolution and same ambiguity as MIMO. MIMO = good balance between resolution and ambiguity



Seker and Lavalle, RS 2021

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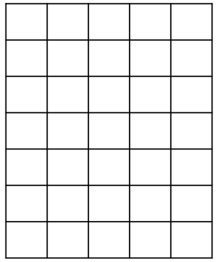
Design of STV co-flier concepts: Histogram tomography

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

M pixels, multi-looked cell



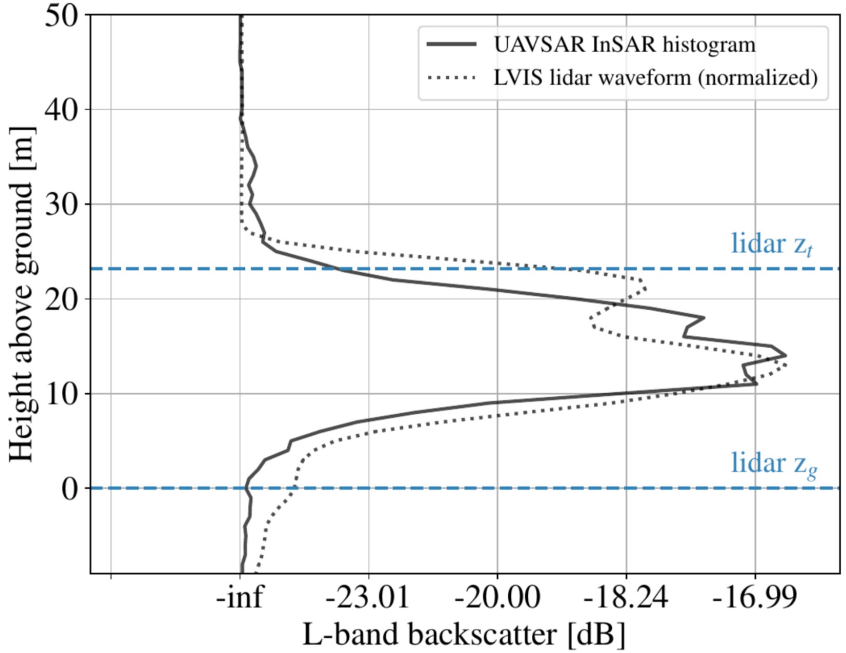
InSAR histogram function

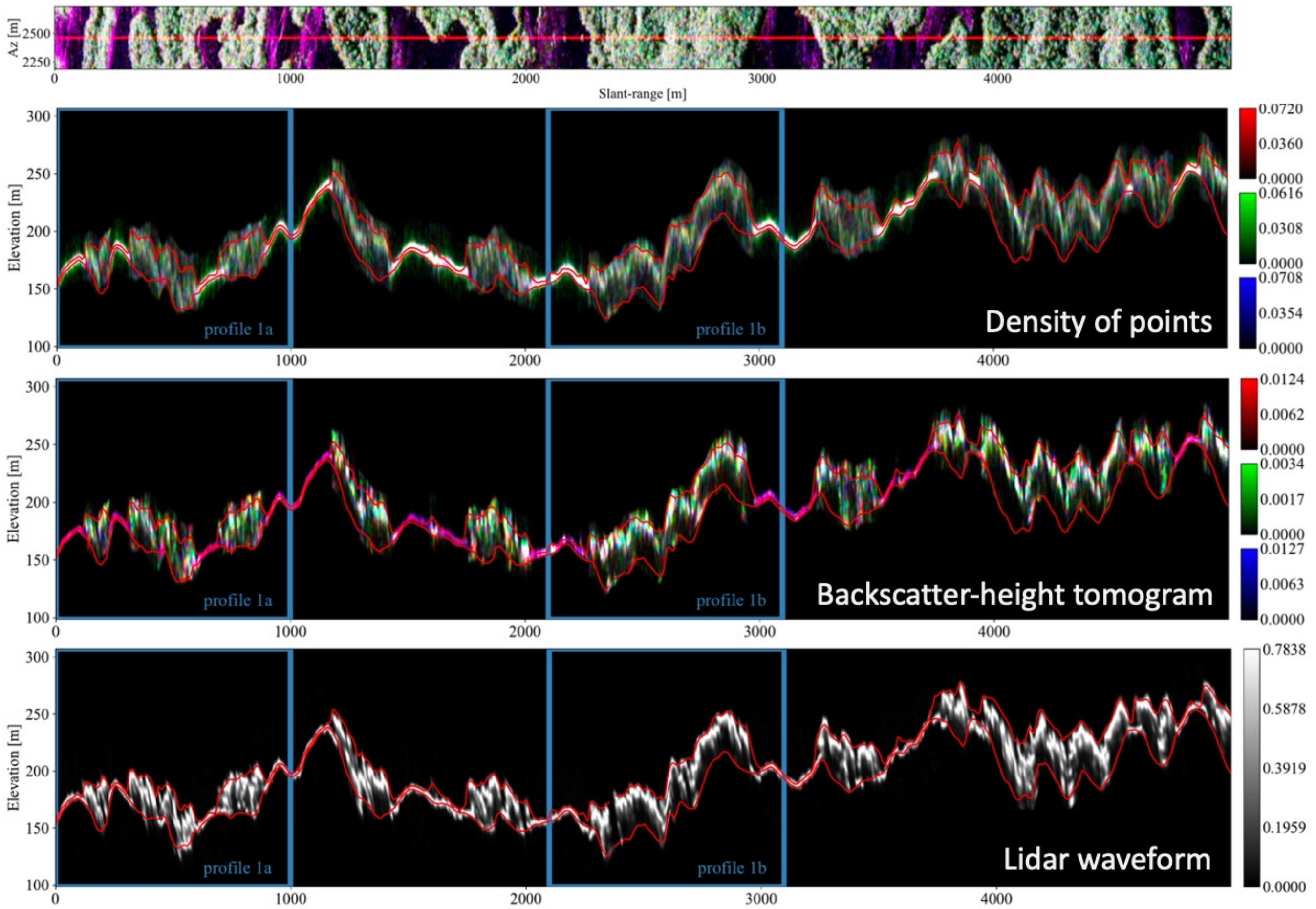
$$g(z_n) = \sum_{i=1}^{M} w_i f(s_1, s_2)\chi(z_n, \phi_i)$$

Height-backscatter histogram ~ tomogram

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

$f = 1$ ~ density of points

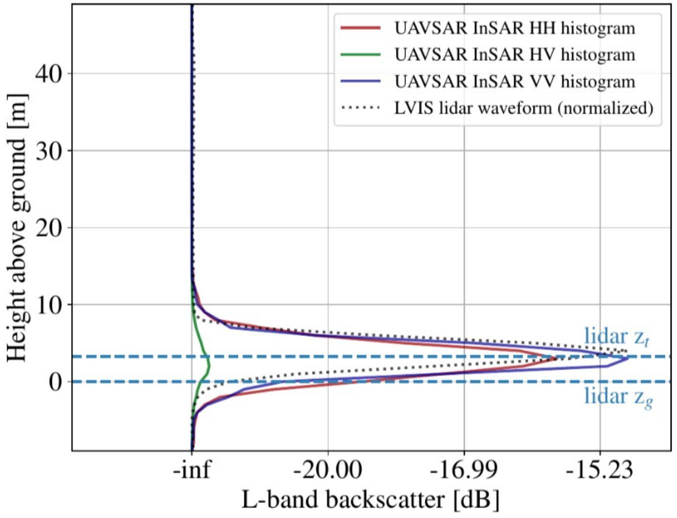




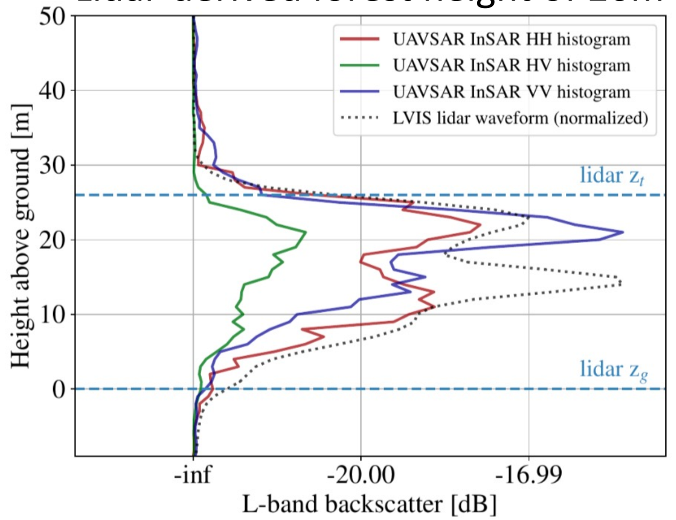
Shiroma and Lavalle, TGRS 2021

Design of STV co-flier concepts: Histogram tomography

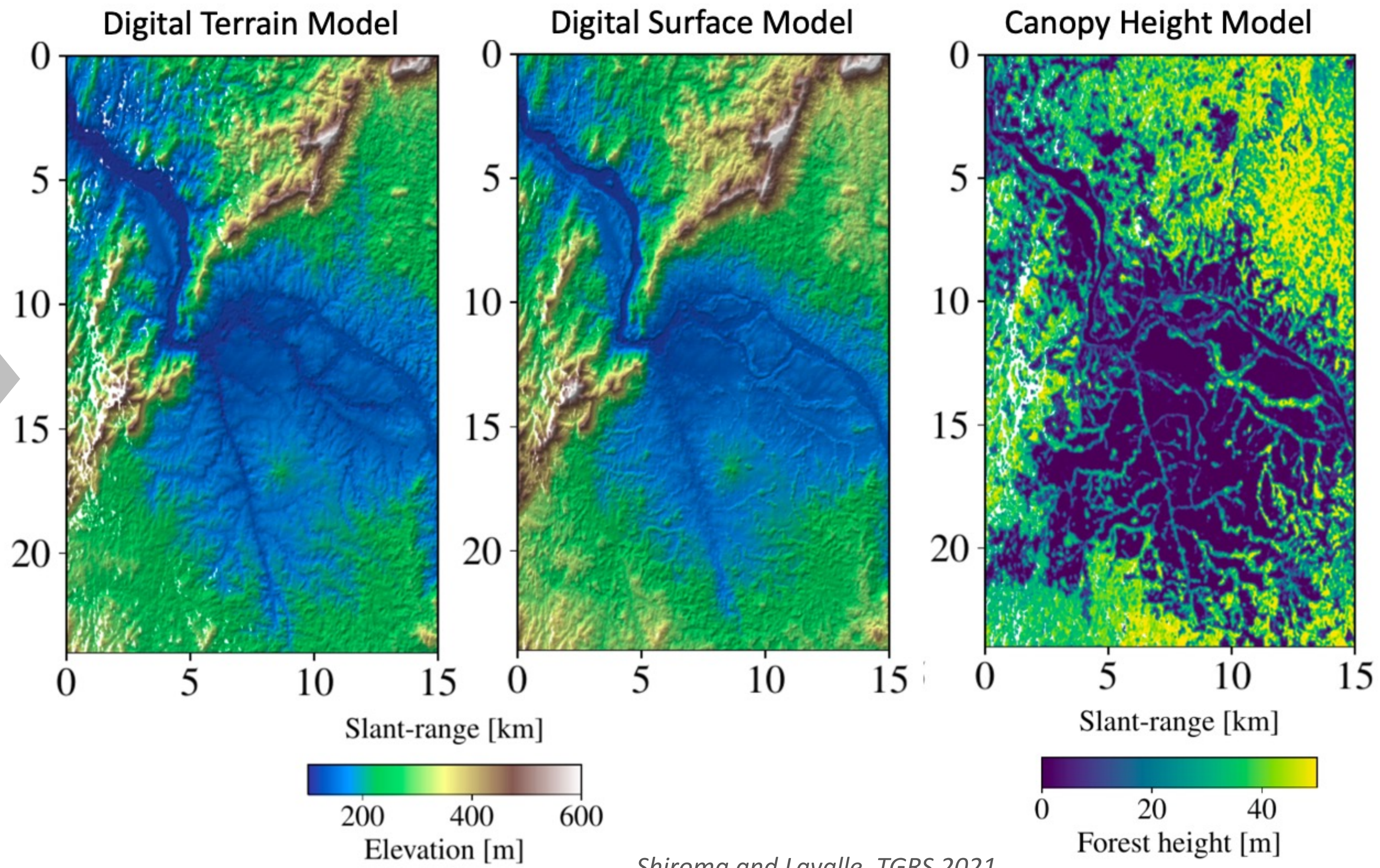
Lidar-derived forest height of 3m



Lidar-derived forest height of 26m

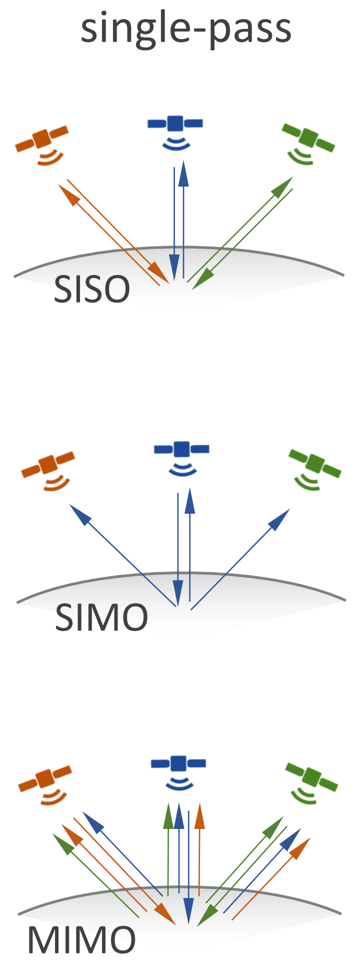


L-band UAVSAR data with 40m baseline and 1.8m x 1m resolution multi-looked down to 20m sample size and compared with lidar waveforms and tree height

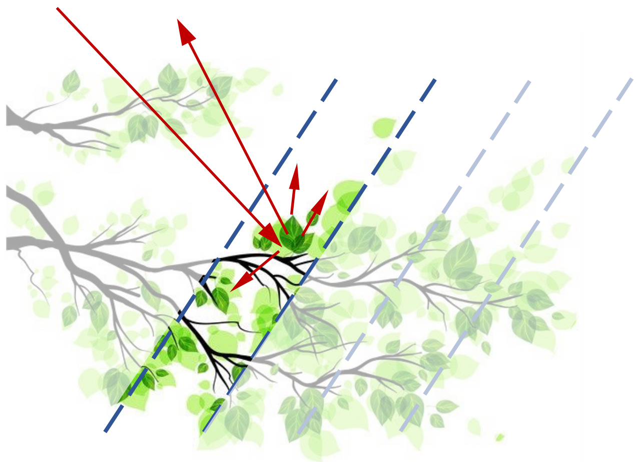


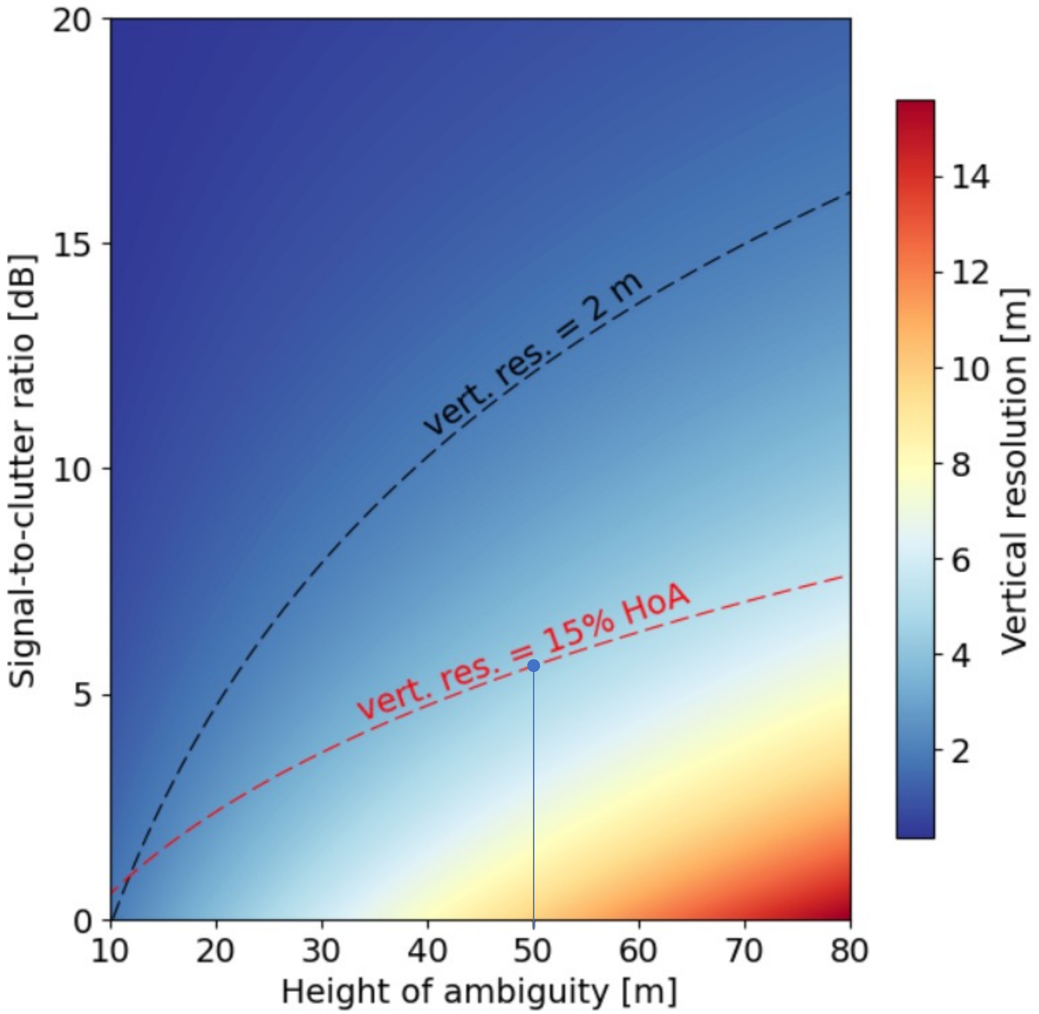
Shiroma and Lavalle, TGRS 2021

Design of STV co-flier concepts: Histogram tomography



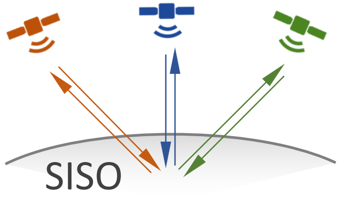
- Single-baseline SAR interferometer with variable perpendicular baseline
- Assumes dominant scatterer in the single-look resolution cell: performance driven by signal-to-clutter ratio (SCR)
- Vertical resolution requirement defined by absolute value (2m) or relative to maximum tree height (15%)

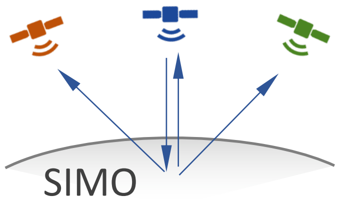


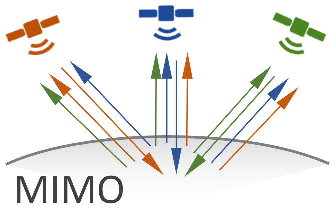


Orbital configurations of co-flier concepts: STV perspective

single-pass

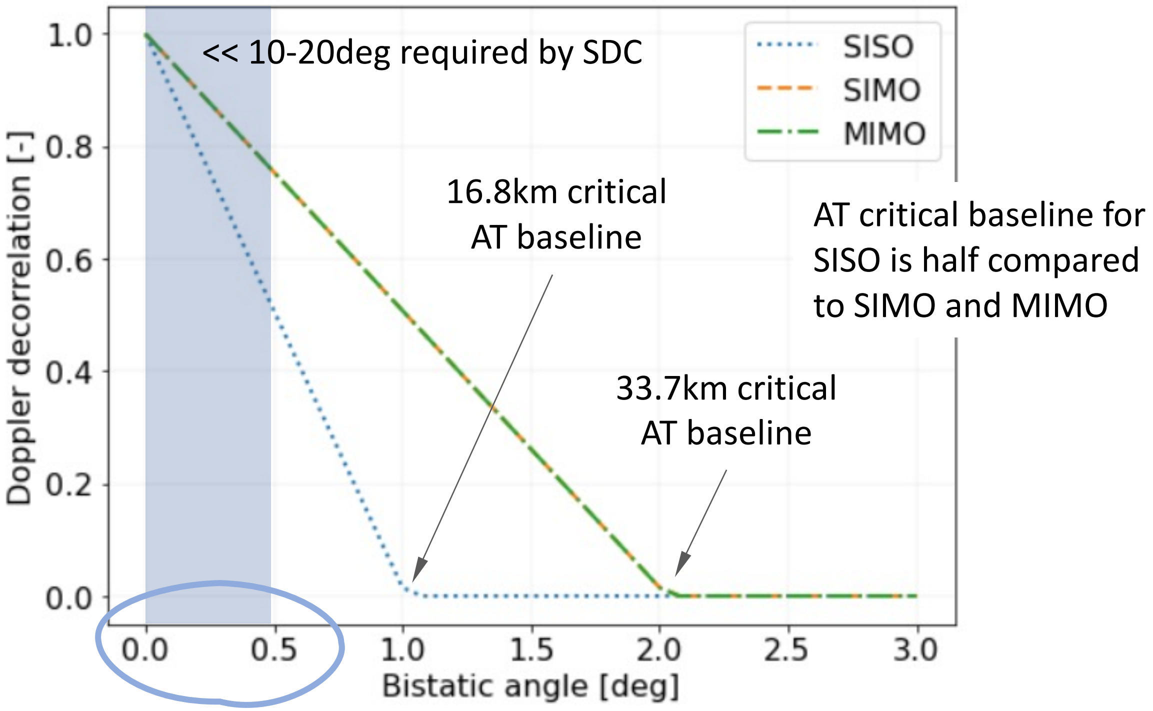






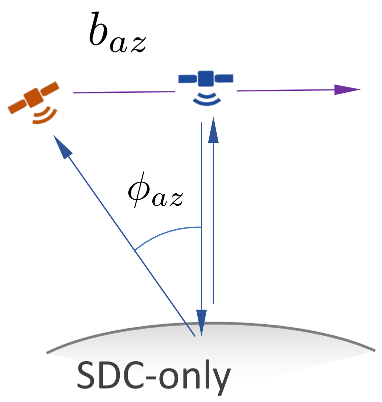
- Doppler decorrelation between two SLCs acquired with different squinted geometries poses a limit on the along-track (AT) baseline similarly to the spectral shift along range
- Critical along-track baseline for a transmitter and a receiver located on the same orbit with range vectors forming a bistatic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

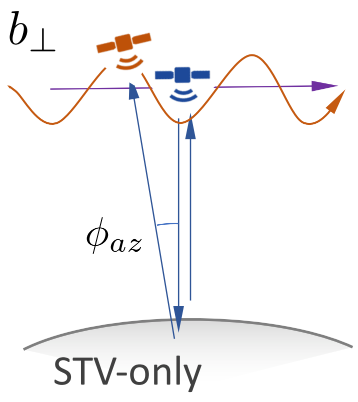
- STV via histogram tomography can tolerate only very small (<0.5deg) bistatic angles
- Other tomographic algorithms may be robust to doppler decorrelation (similarly to range spectral decorrelation)



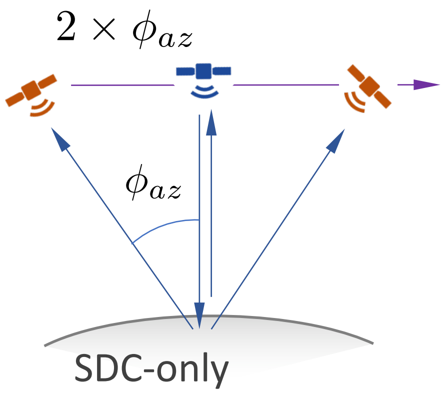
Orbital configurations of co-flier concepts: SDC + STV needs

- One co-flier
  - SDC: repeat-pass multi-squint b_{az} = 250km (SIMO/MIMO), $b_\perp \backsimeq$ 0m, 3D deform, no atmosphere
  - STV option 1: single-pass single-baseline HistTomo $b_\perp \backsimeq$ 2.5km (SIMO/MIMO), b_{az} < 10km
  - STV option 2: pair-wise single-pass, drift co-flier to implement tomographic stack over time

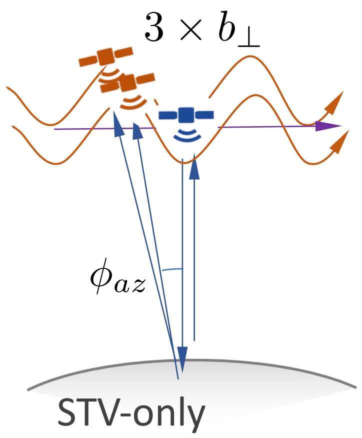




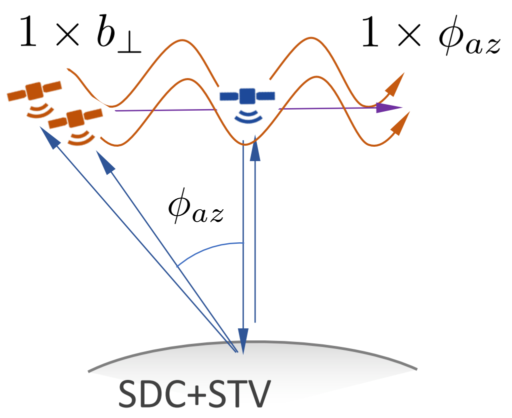
- Two co-fliers



3D deformation (with atmosphere)



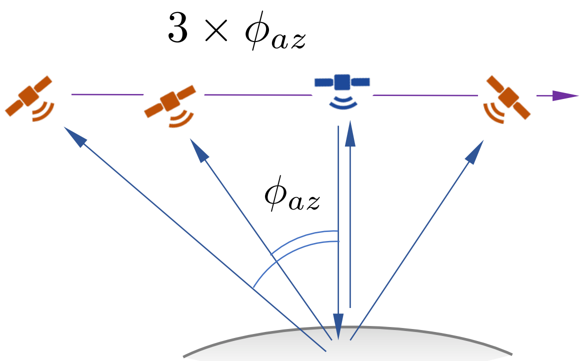
topography + vegetation (3 baselines)



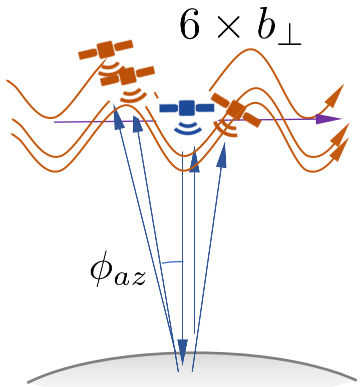
3D deformation (no atmosphere)
topo + veg (1 baseline)

Orbital configurations of co-flier concepts: SDC + STV needs

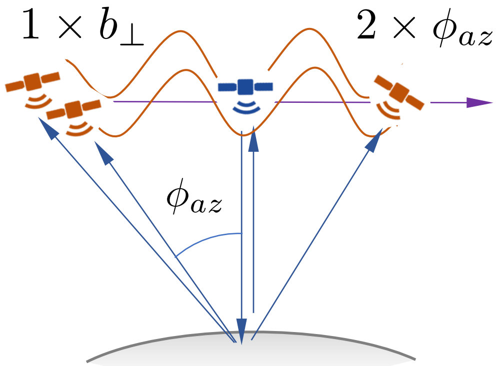
- Three co-fliers



SDC-only
3D deformation (with atmosphere)



STV-only
topography + vegetation
(6 baselines)



SDC+STV
3D deformation (with atmosphere)
topo + veg (1 baseline)
OR
3D deformation (no atmosphere)
topo + veg (3 baseline)

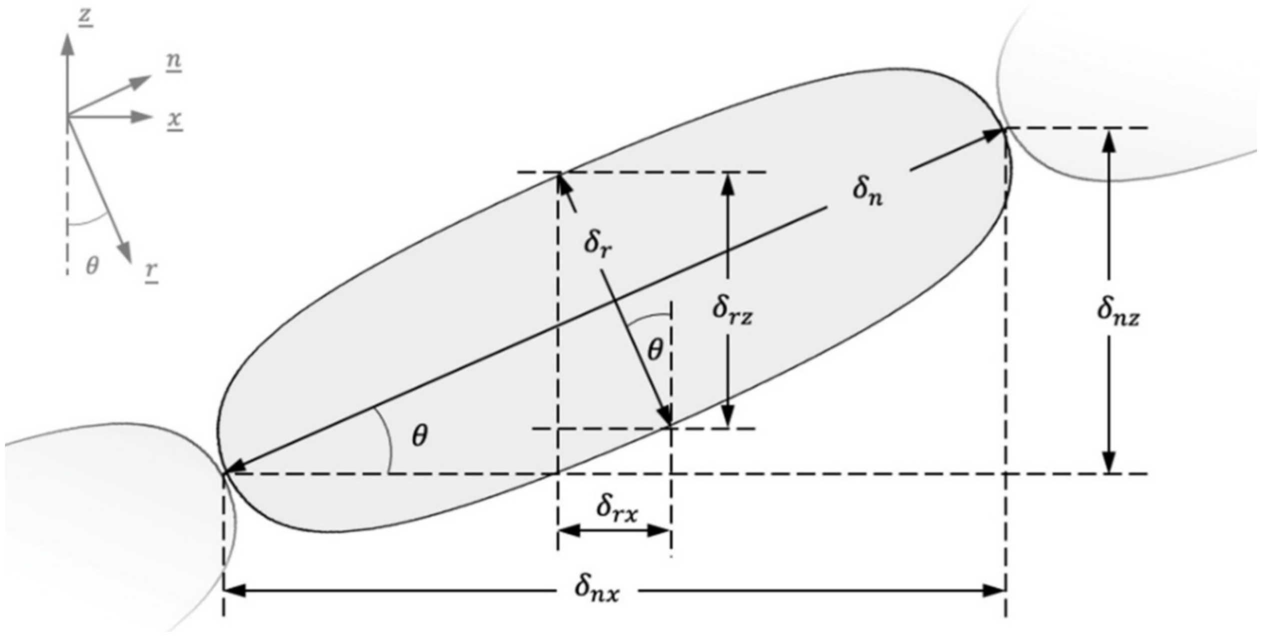
- N>3 co-fliers
  - Add co-fliers with large along-track or across-track baseline to benefit either or both SDC and STV
  - Constraints on orbital dynamics leads to time-varying along-track and across-track baselines
  - Opportunity for fractionated SAR

A note on vertical and horizontal resolutions of tomograms

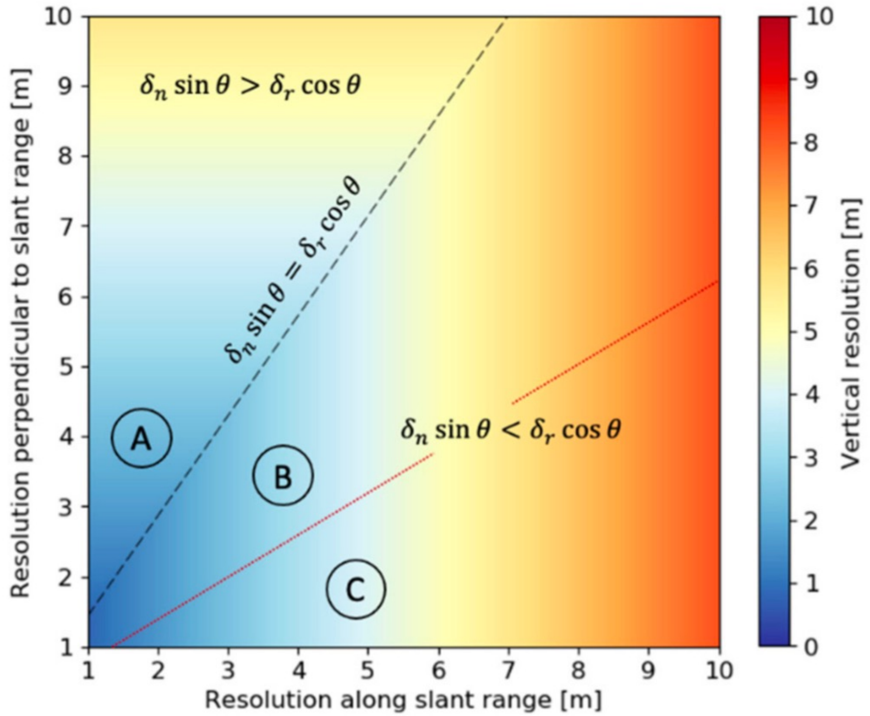
- The projection of resolutions along look direction (*r*) and perpendicular to look direction (*n*) onto vertical (*z*) and horizontal (*x*) axes depends on look angle and relative size of *r* and *n* resolutions (*Seker and Lavalle, RS 2021*)
- Vertical resolution can be affected by range bandwidth, and horizontal resolution can be affected by tomographic aperture

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

Tomographic resolution cell on the *r, n* plane



Vertical resolution [m]



Take-away messages

1. SDC and STV address the same science disciplines with complementary goals so it makes sense to look for a joint mission concept
2. SDC aims to repeat-pass, long azimuth and short range baselines; STV aims to single-pass, short azimuth and long range baselines
3. Possible concept is with two or more co-fliers clustered at 250 km along-track from transmitter and variable across-track baselines between co-fliers
4. For both SDC and STV, SIMO performs worse than SISO and MIMO but SIMO remains an attractive solution for system implementation
5. Partnership tech demos with NISAR or ROSE-L would pave the way to uninterrupted SDC time-series and unprecedented STV measurements