Jet Propulsion Laboratory
California Institute of Technology

Detection of Forest Disturbance Using Spaceborne Single-pass and Repeat-pass SAR Interferometry

Yang Lei[1], Robert Treuhaft[1], Paul Siqueira[2], Richard Lucas[3], Michael Keller[1], Michael Schmidt[5], Maxim Neumann[1], Fabio Goncalves[4]

1 NASA Jet Propulsion Laboratory, USA

2 University of Massachusetts Amherst, USA

3 University of New South Wales, Australia

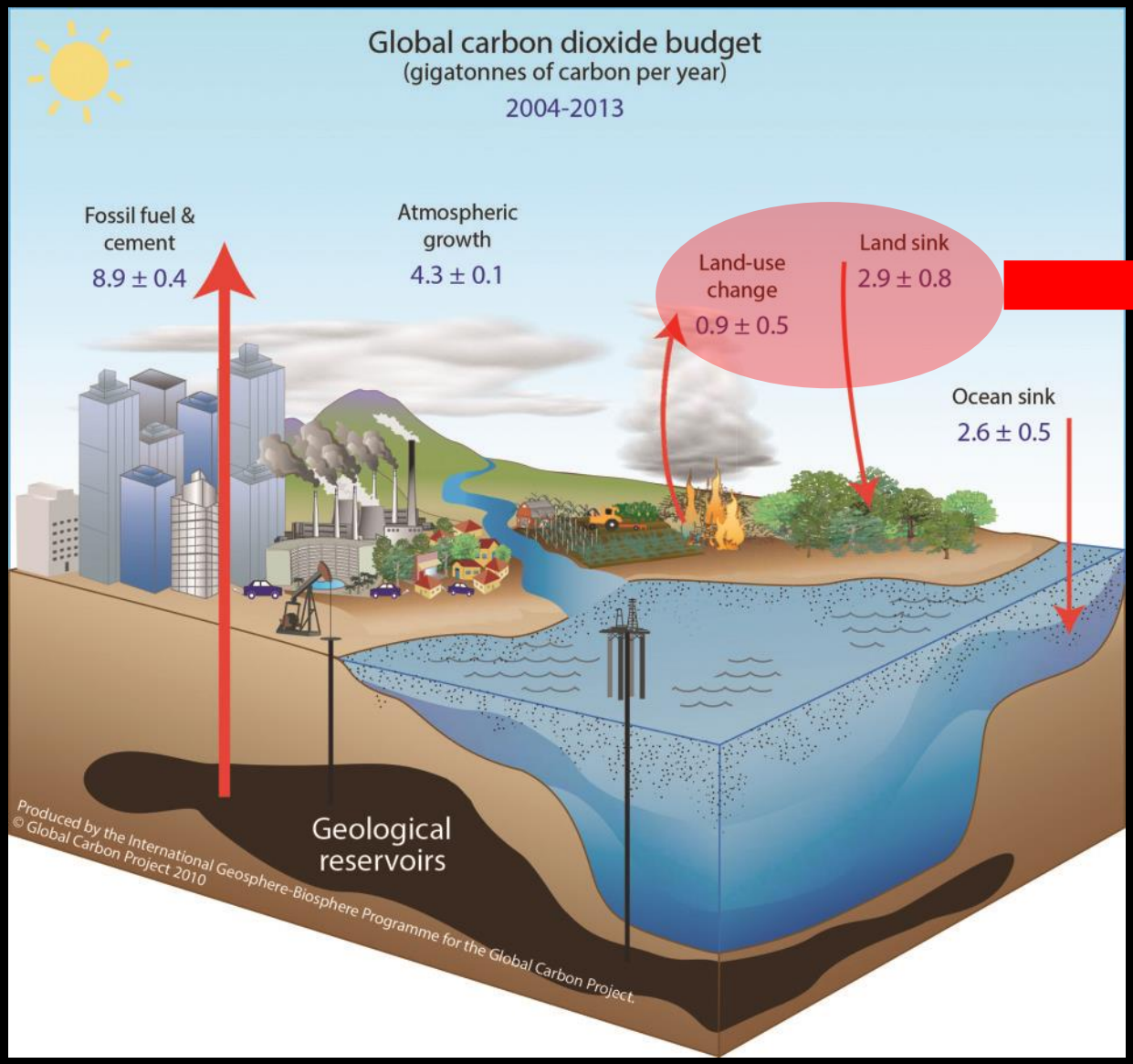
4 Agrosatelite, Brazil

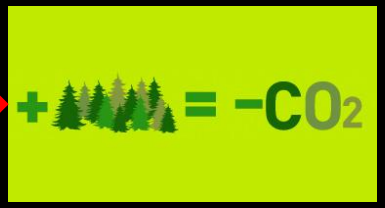
5 Department of Science, Information Technology, Innovation and the Arts, Australia

Outline

1. Motivation
2. Forest disturbance detection using spaceborne repeat-pass InSAR coherence
    1. Methodology
    2. Validation results over Queensland, Australia
3. Forest disturbance detection using spaceborne single-pass InSAR phase
    1. Methodology
    2. Validation results over Tapajos, Brazil
4. Conclusions

Impact of forest in Carbon Cycle





Forest disturbance

Selective logging

Clear cut

Fire

Quantify forest disturbance

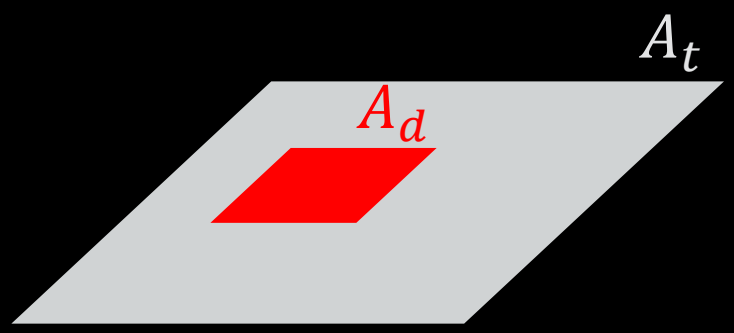
- ✓ ***When?***
- ✓ ***Where?***
- ✓ ***How much?***

Quantify forest disturbance

✓ *When?*

✓ *Where?*

✓ ***How much?***



InSAR pixel area

Disturbance Index $DI = \frac{A_d}{A_t}$

where A_d is the disturbed area;
A_t is the total area

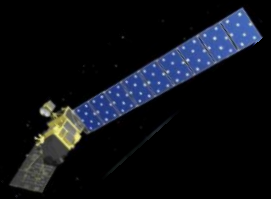
$DI = 0$ No disturbance

$DI = 1$ Complete deforestation

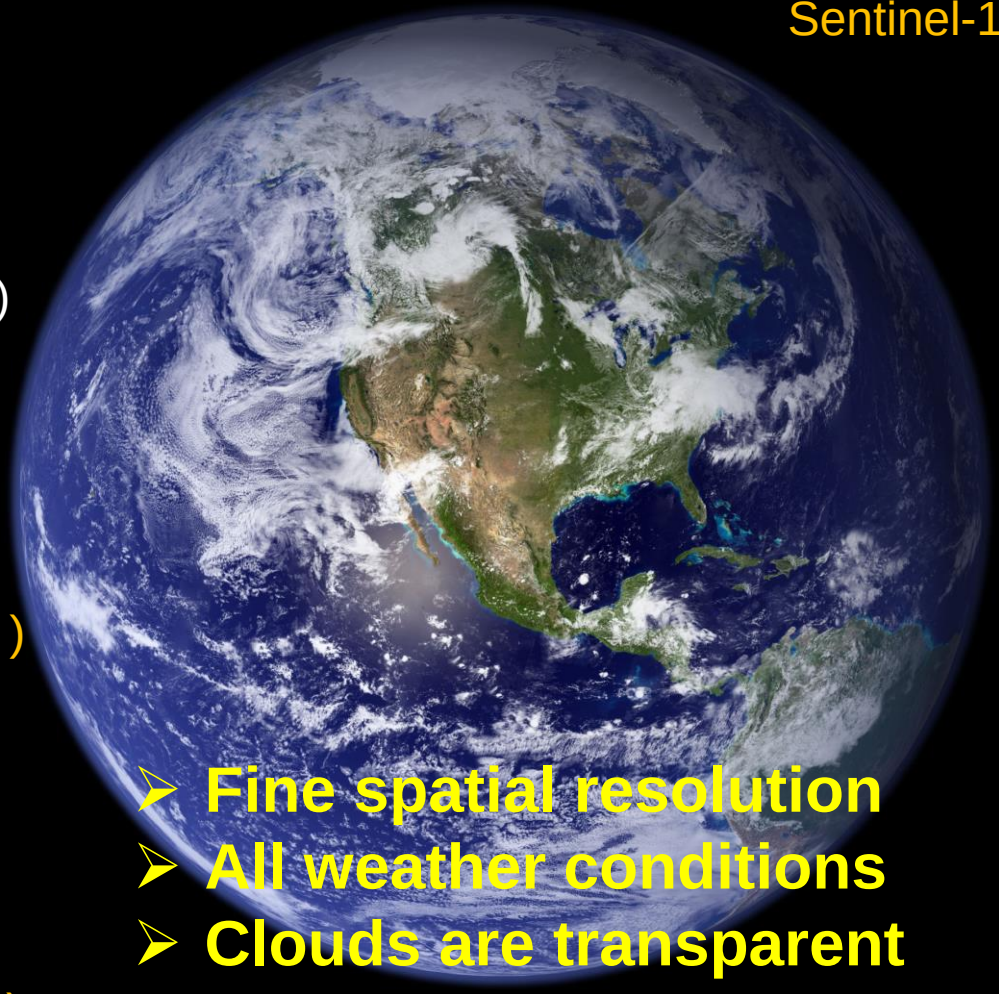
$$LOSS = AGB \times DI$$

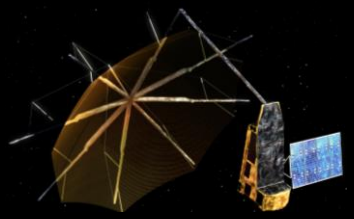
Spaceborne SAR/InSAR

Sentinel-1 (2014-)



ALOS (2006-2011)





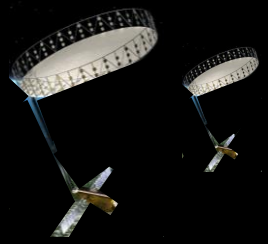
BIOMASS (2021-)

TanDEM-X (2010-)

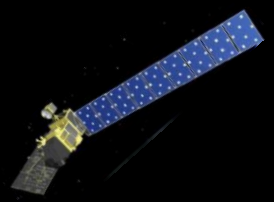
NISAR (2022-)

ALOS-2 (2014-)

- **Fine spatial resolution**
- **All weather conditions**
- **Clouds are transparent**
- **Global coverage**



TanDEM-L (2022-)

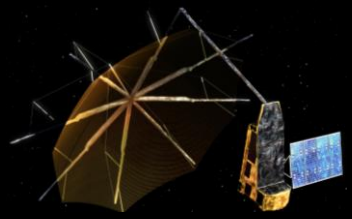


ALOS

ALOS-2

Sentinel-1

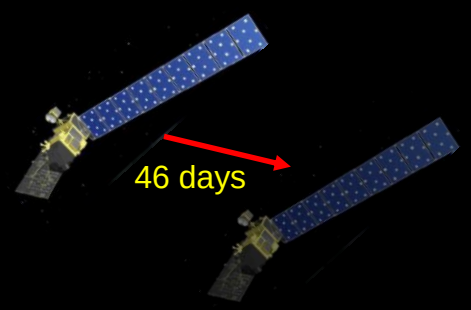
Repeat-pass InSAR



BIOMASS

NISAR

Repeat-pass InSAR observations



InSAR complex correlation

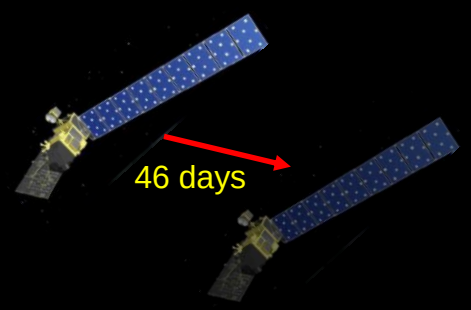
InSAR phase

Correlation magnitude
(coherence)

Atmospheric Delay
(ionosphere, troposphere)

Temporal Decorrelation
(moisture-induced dielectric change,
Wind-induced positional change)

Repeat-pass InSAR observations



InSAR complex correlation

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Correlation magnitude
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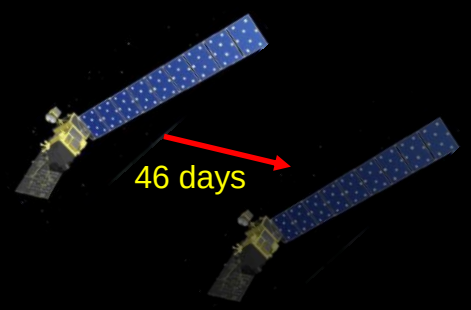
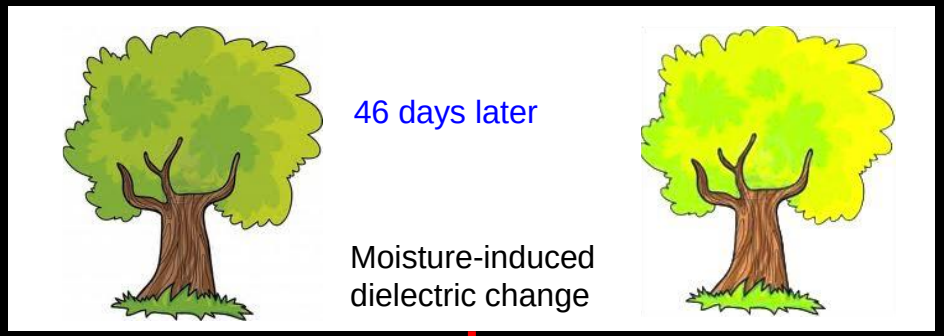
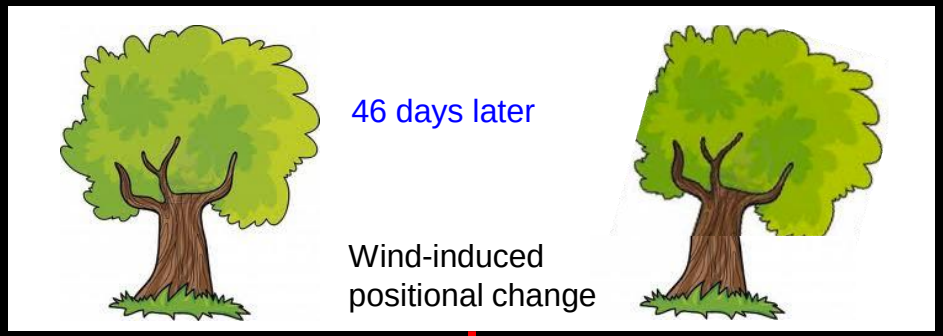
Repeat-pass InSAR model***



$$\gamma_{v\&t} = \mathbf{M}\begin{pmatrix} \text{forest vertical structure} \\ \text{moisture−induced dielectric change} \\ \text{wind−induced positional change} \end{pmatrix}$$





correlation profile

coupled with

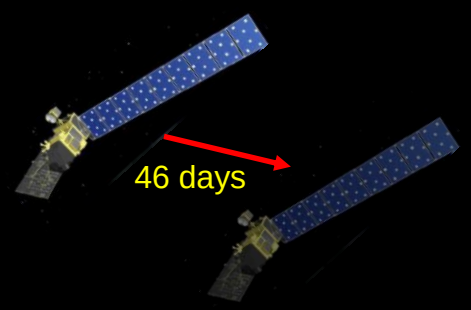
extinction-weighted
backscatter profile

correlation profile

coupled with

*** Lei, Yang, Paul Siqueira, and Robert Treuhaft. "A physical scattering model of repeat-pass InSAR correlation for vegetation." *Waves in Random and Complex Media*, 27(1) 129-152, 2017.

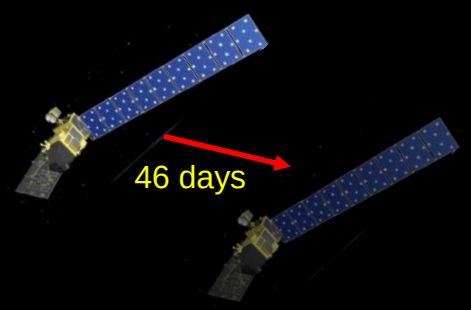
Repeat-pass InSAR methodology



Forest vertical structure ***Temporal decorrelation*** ***Forest disturbance***

All lumped together

Repeat-pass InSAR methodology

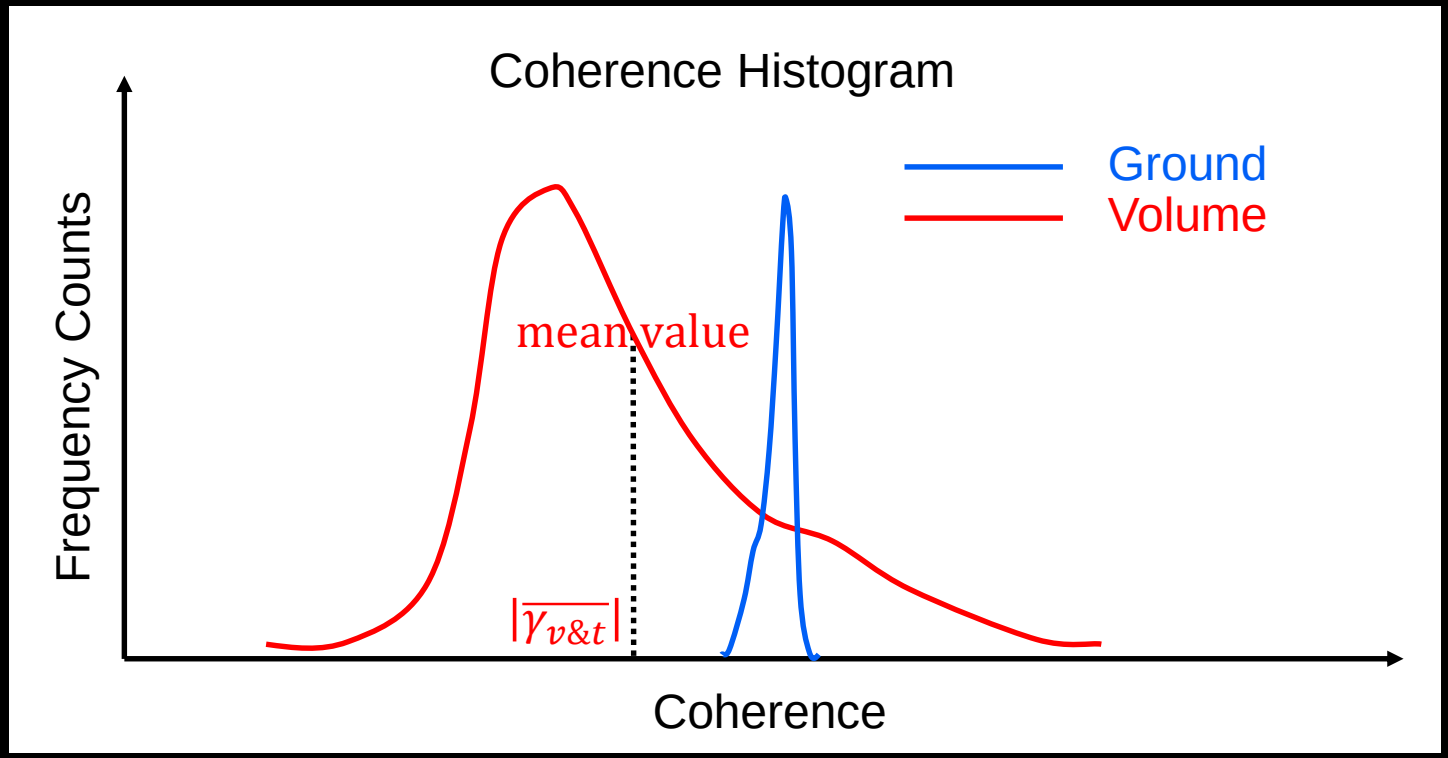


Mean-behavior captured

Forest vertical structure ***Temporal decorrelation*** ***Forest disturbance***

All lumped together

Forest disturbance detection approach



The mean coherence of forest areas captures the mean behavior of the temporal decorrelation effect over the mean forest vertical structure.

Forest disturbance detection approach

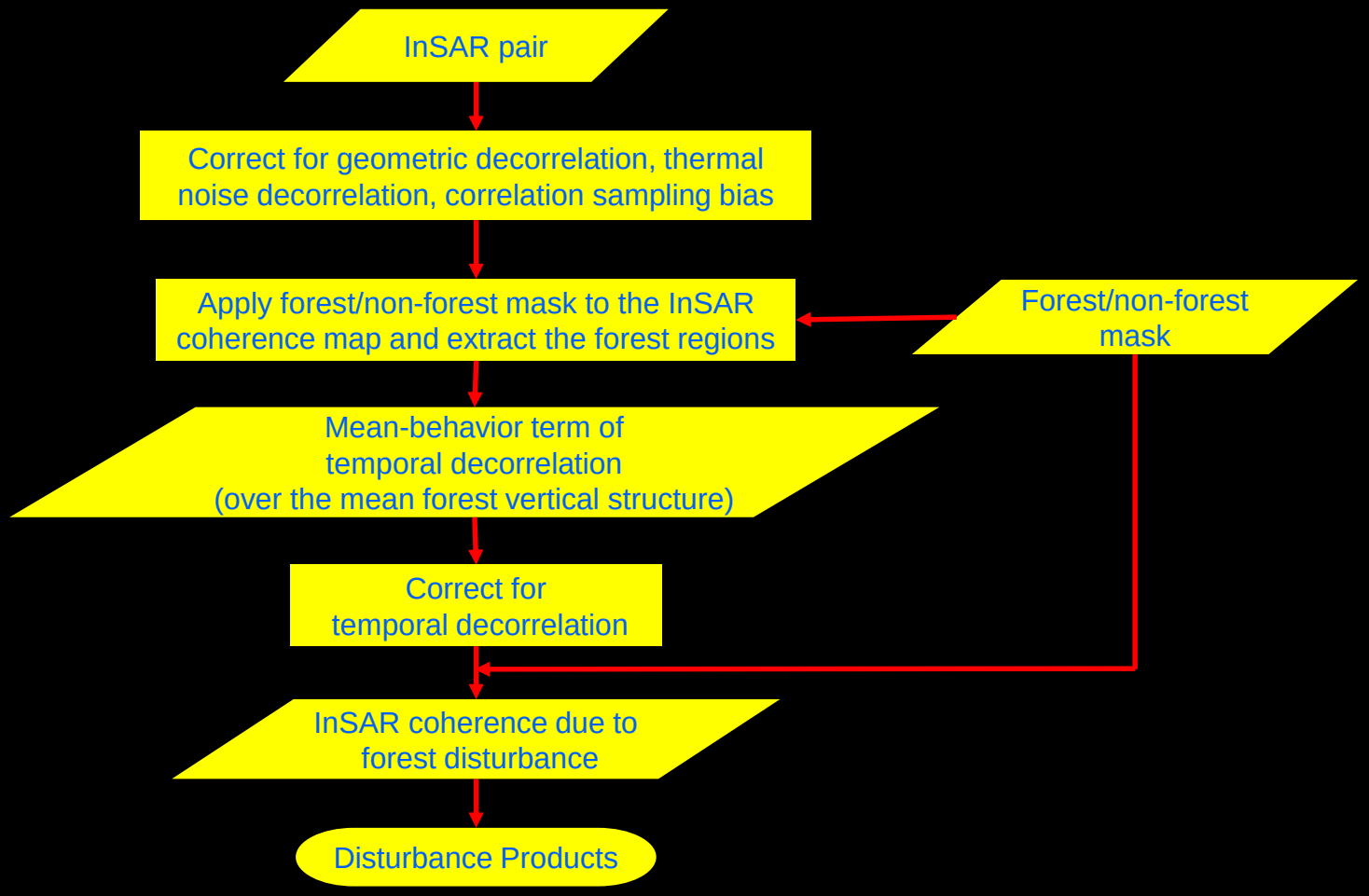
InSAR correlation component due to disturbance

$$\gamma_{dist} = \frac{|\gamma_{v\&t}|}{|\overline{\gamma_{v\&t}}|} \Longrightarrow \begin{cases} \gamma_{dist} = 1, & \text{normal forest} \\ 0 \leq \gamma_{dist} < 1, & \text{disturbed forest} \end{cases}$$

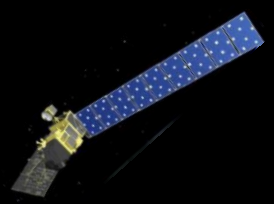
Disturbance index

$$DI = 1 - \gamma_{dist} \Longrightarrow \begin{cases} DI = 0, & \text{normal forest} \\ 0 < DI \leq 1, & \text{disturbed forest} \end{cases}$$

Forest disturbance detection flowchart

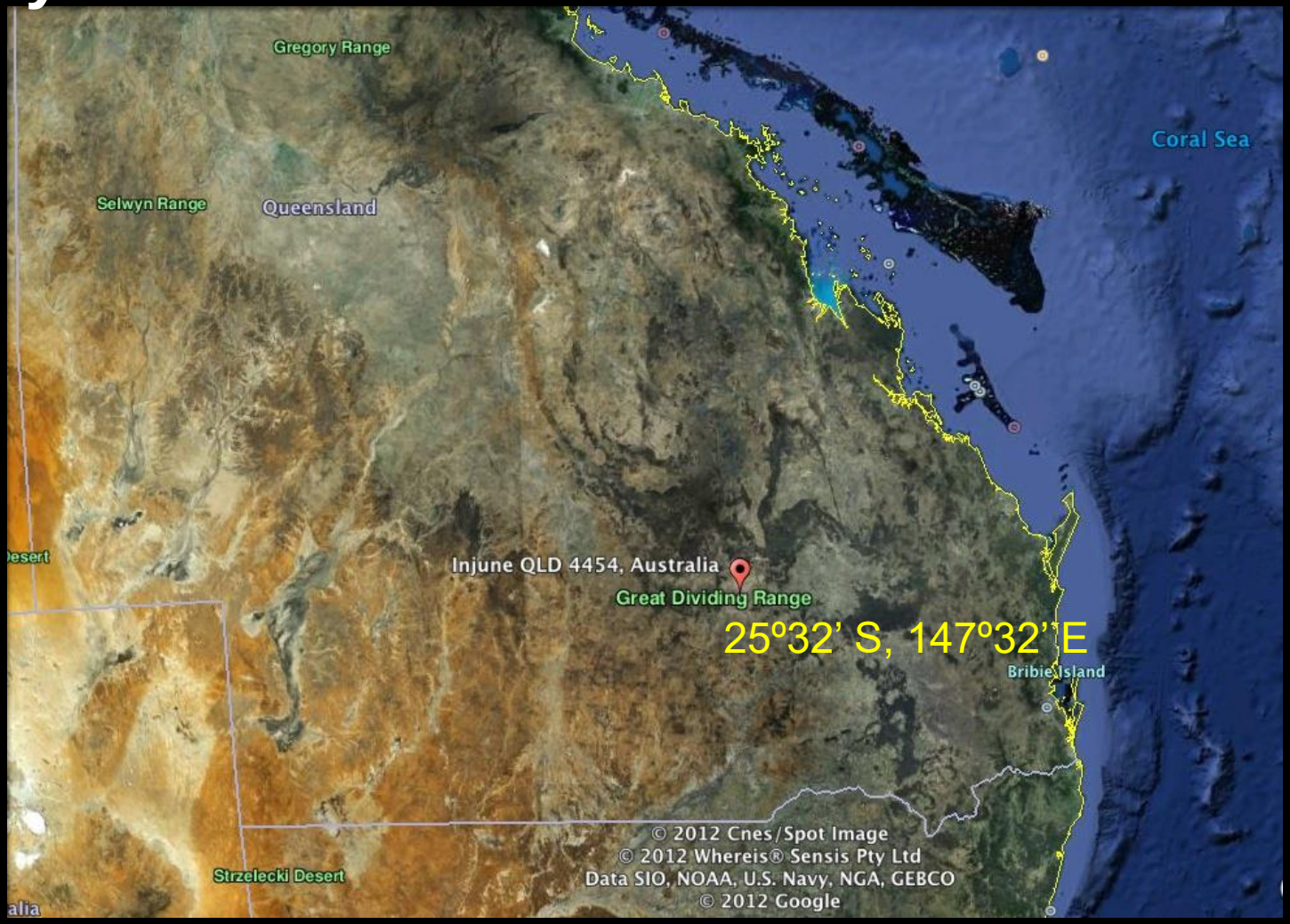


Validation with ALOS (Queensland, Australia)



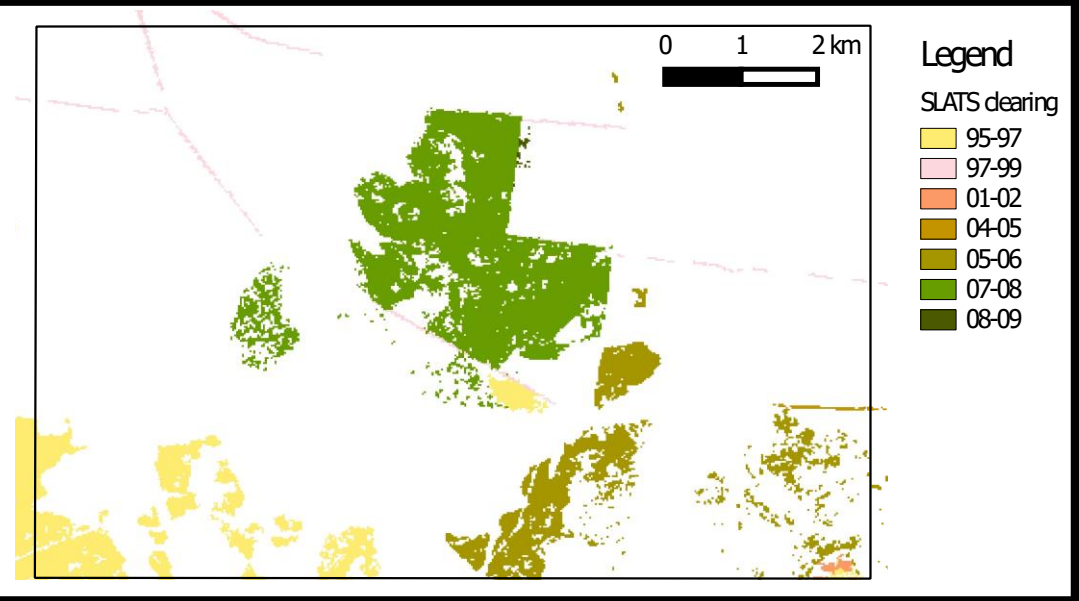
ALOS

Study site overview



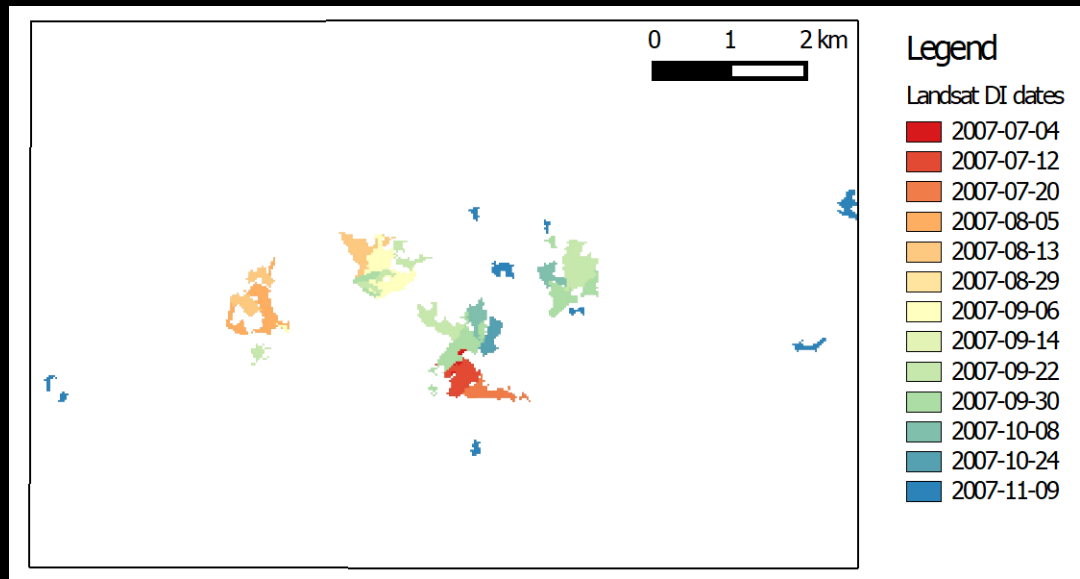
Clear-cut happened around mid-2007 through mid-2008;
ALOS InSAR pair 20070716-20071016 thus detected the beginning of the logging process, which turns out to be a selective logging event

Validation dataset



Field inventory data (SLATS)

Optical data (Landsat-derived Disturbance Index)



ALOS InSAR data

GAMMA REMOTE SENSING

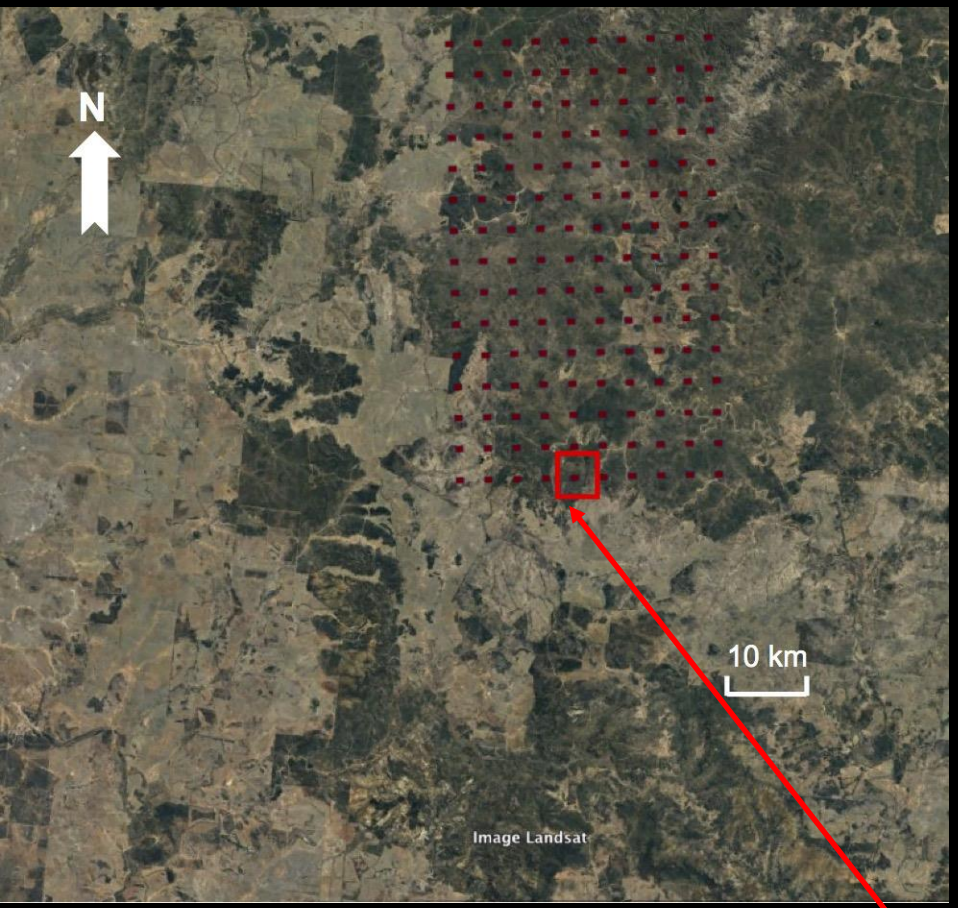
Date	κ_z (rad/m)	Scene-wide coherence
20070716-20071016	0.0419	0.71

Polarization (HH+HV)

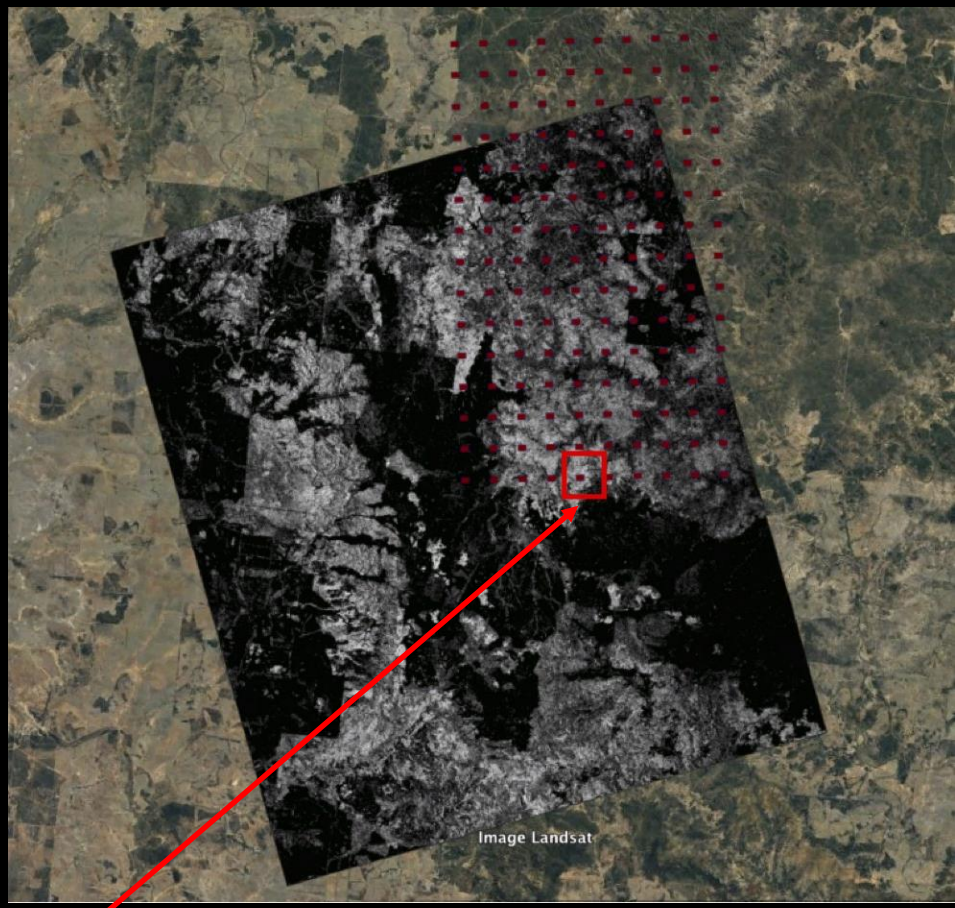
Incidence angle (34.3º)

Orbit Direction (Ascending)

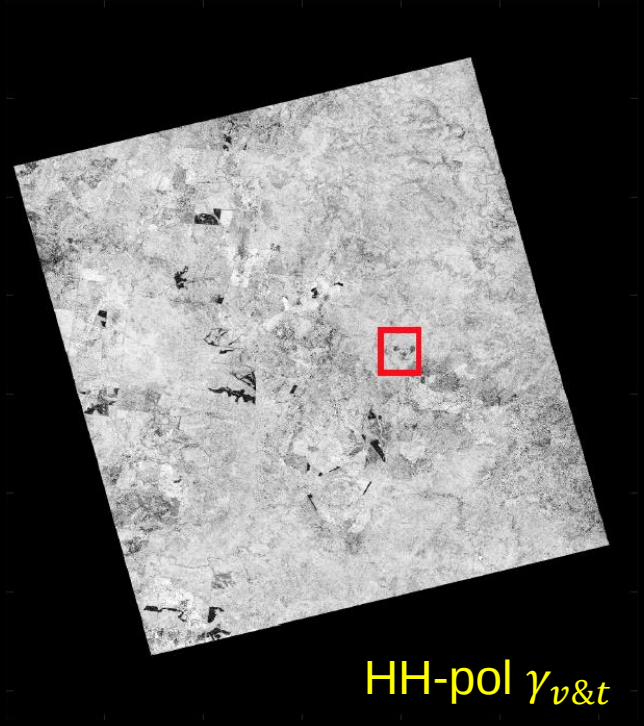
Optical Image

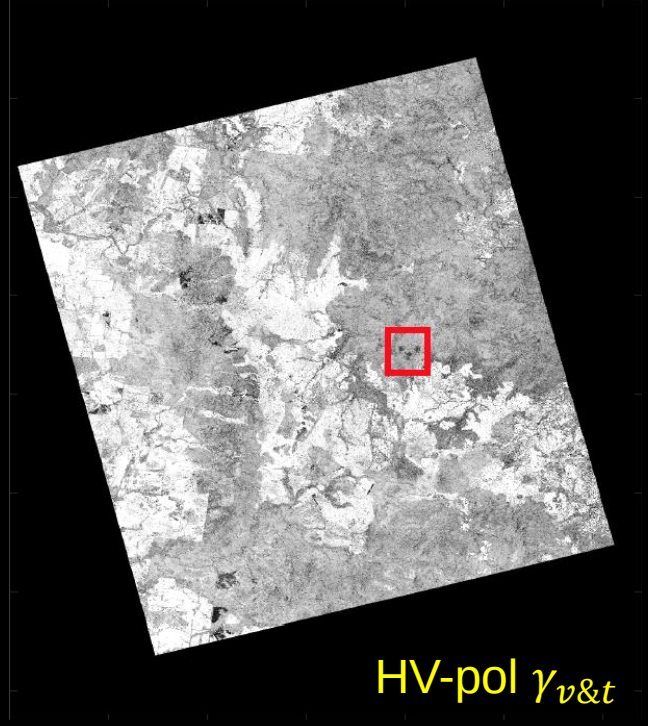


ALOS SAR backscatter

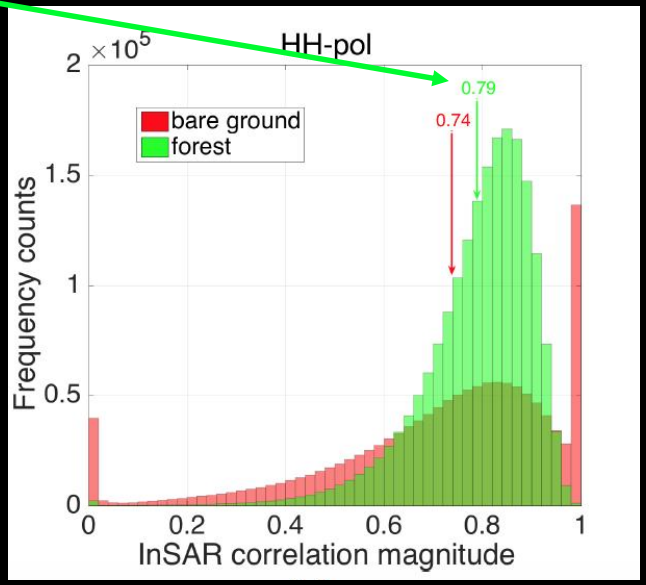


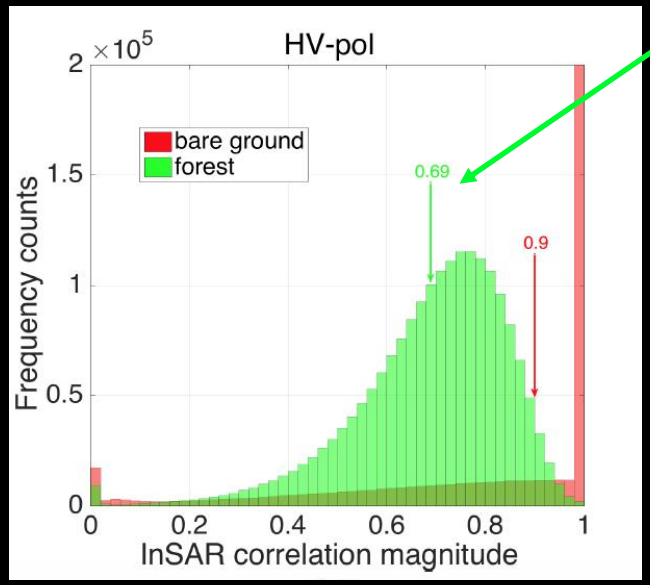
Selective logging area





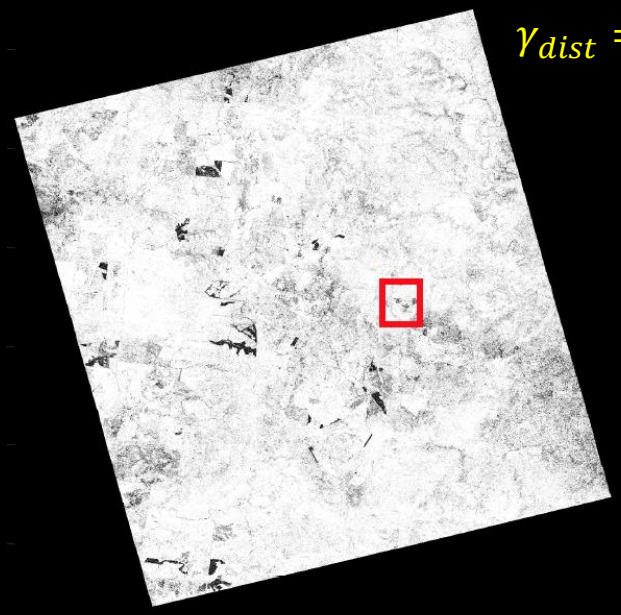
$|\overline{\gamma_{v\&t}}|$



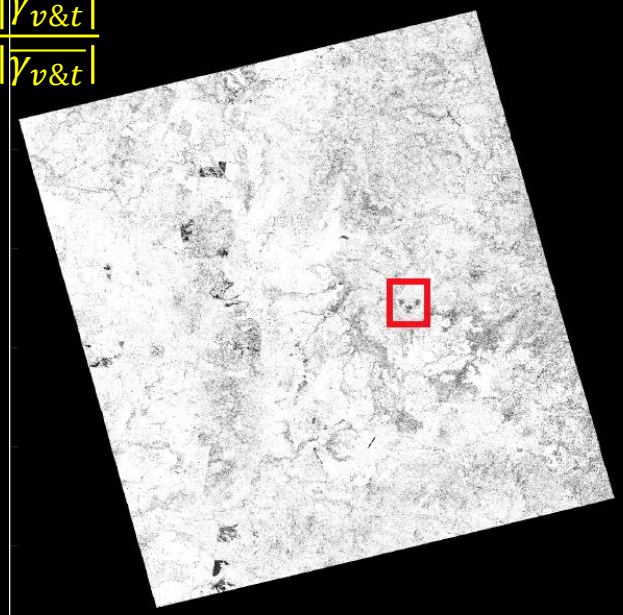


$|\overline{\gamma_{v\&t}}|$

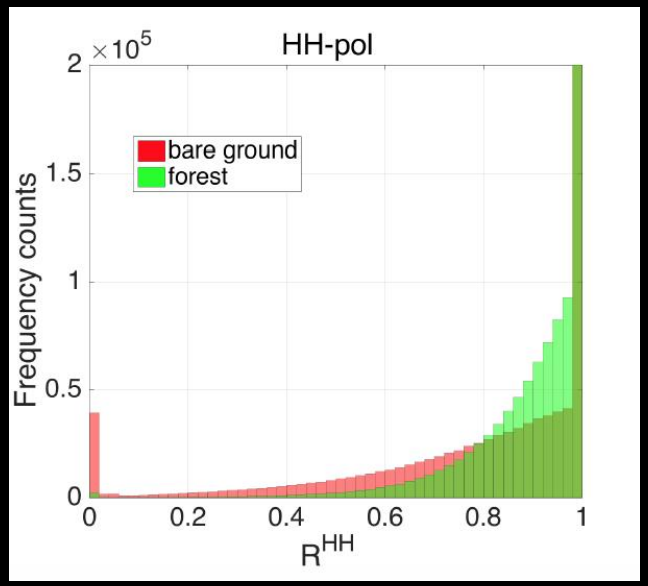
$$\gamma_{dist} = \frac{|\gamma_{v\&t}|}{\overline{|\gamma_{v\&t}|}}$$

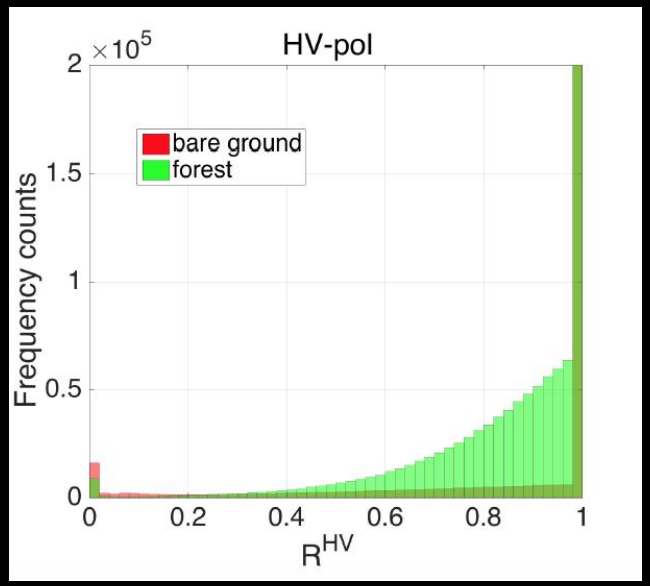


HH-pol γ_{dist}

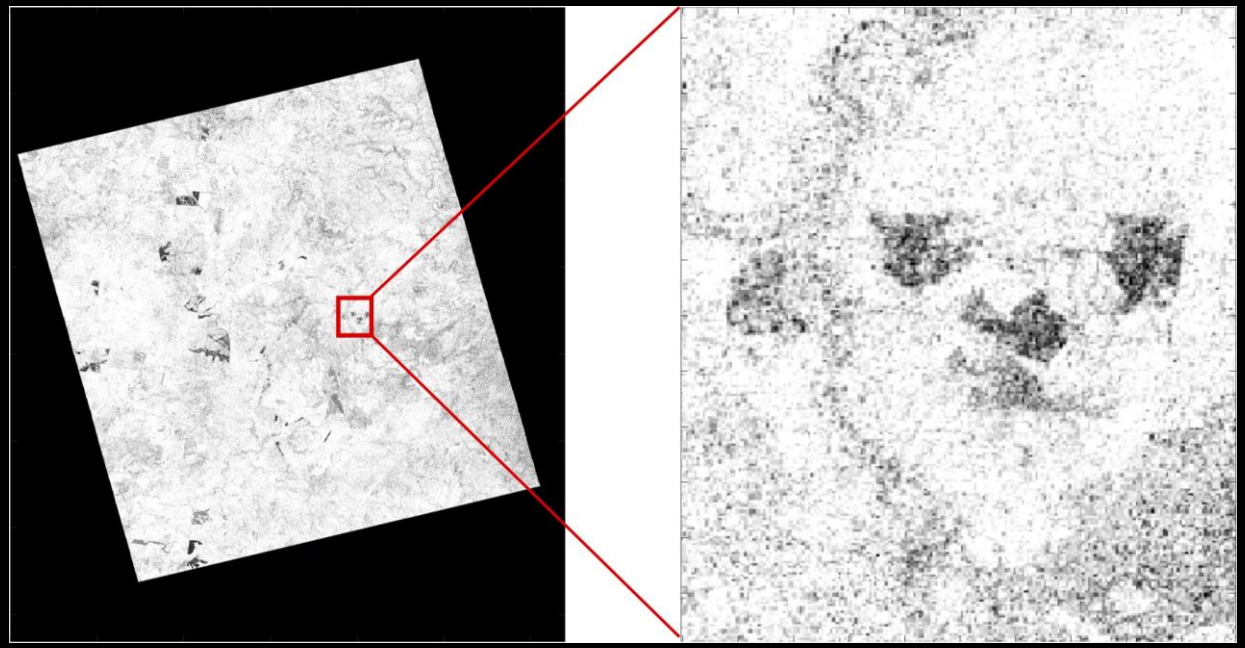


HV-pol γ_{dist}

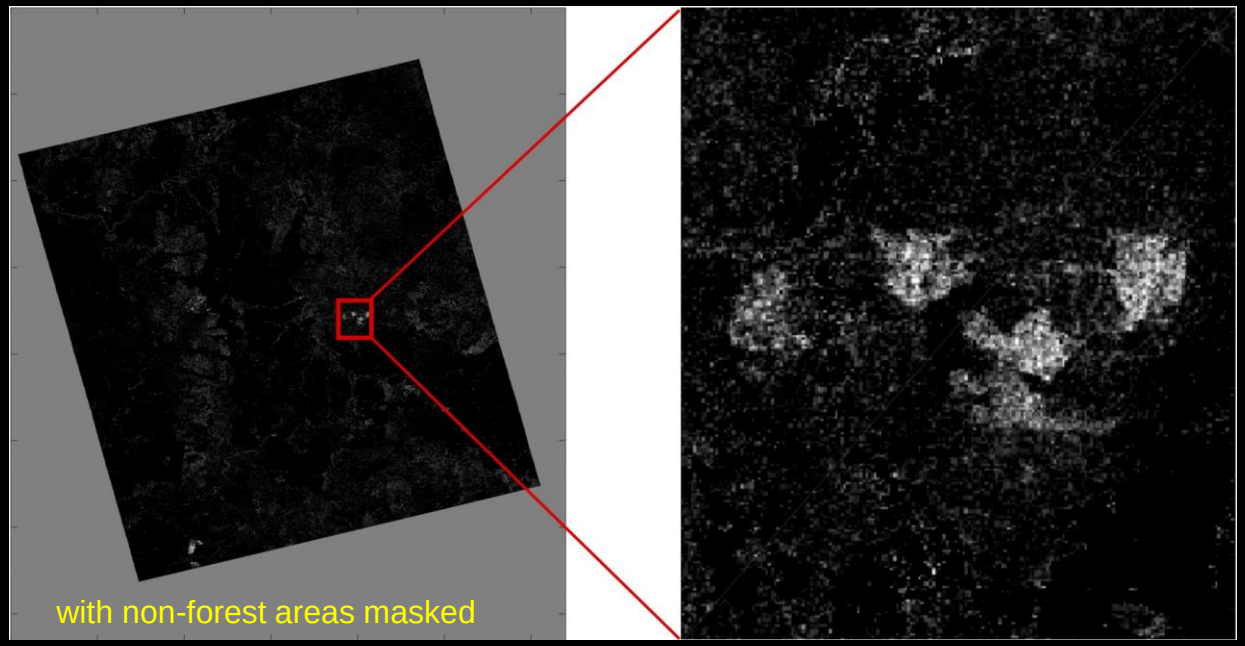




Dual-pol γ_{dist}

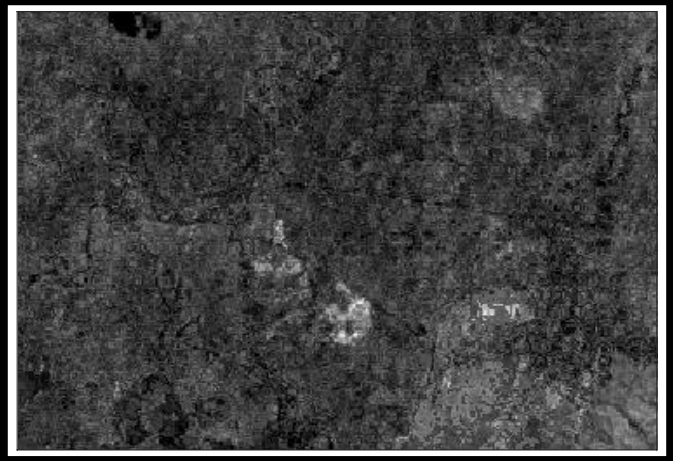


Dual-pol DI

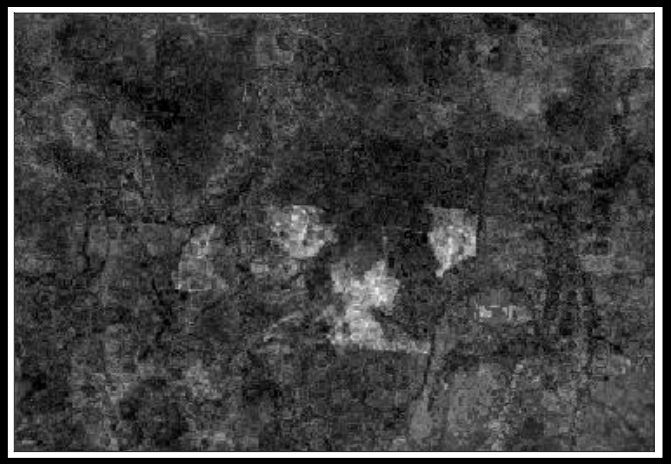


Validation with Landsat-derived DI***

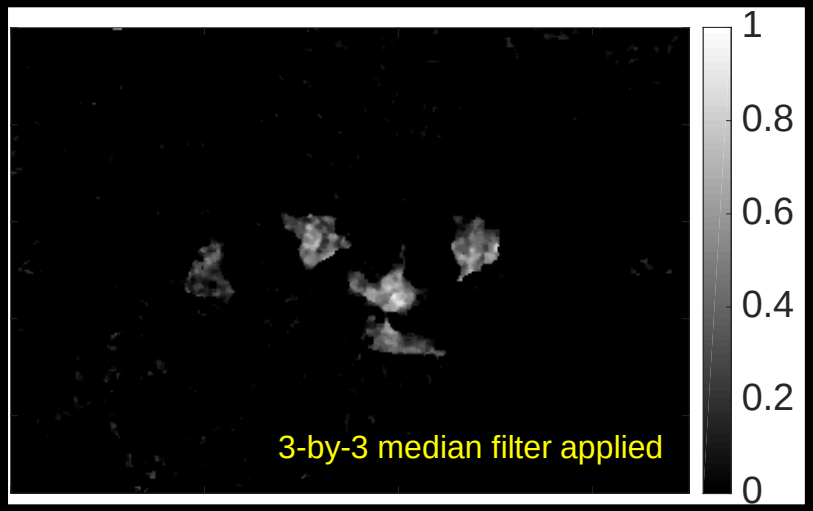
Landsat-derived DI (20070627)



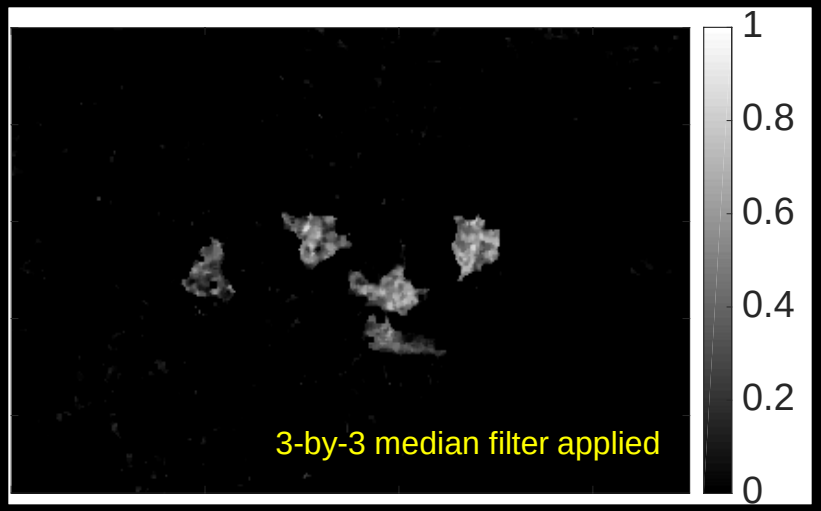
Landsat-derived DI (20071008)



Landsat-derived differential DI

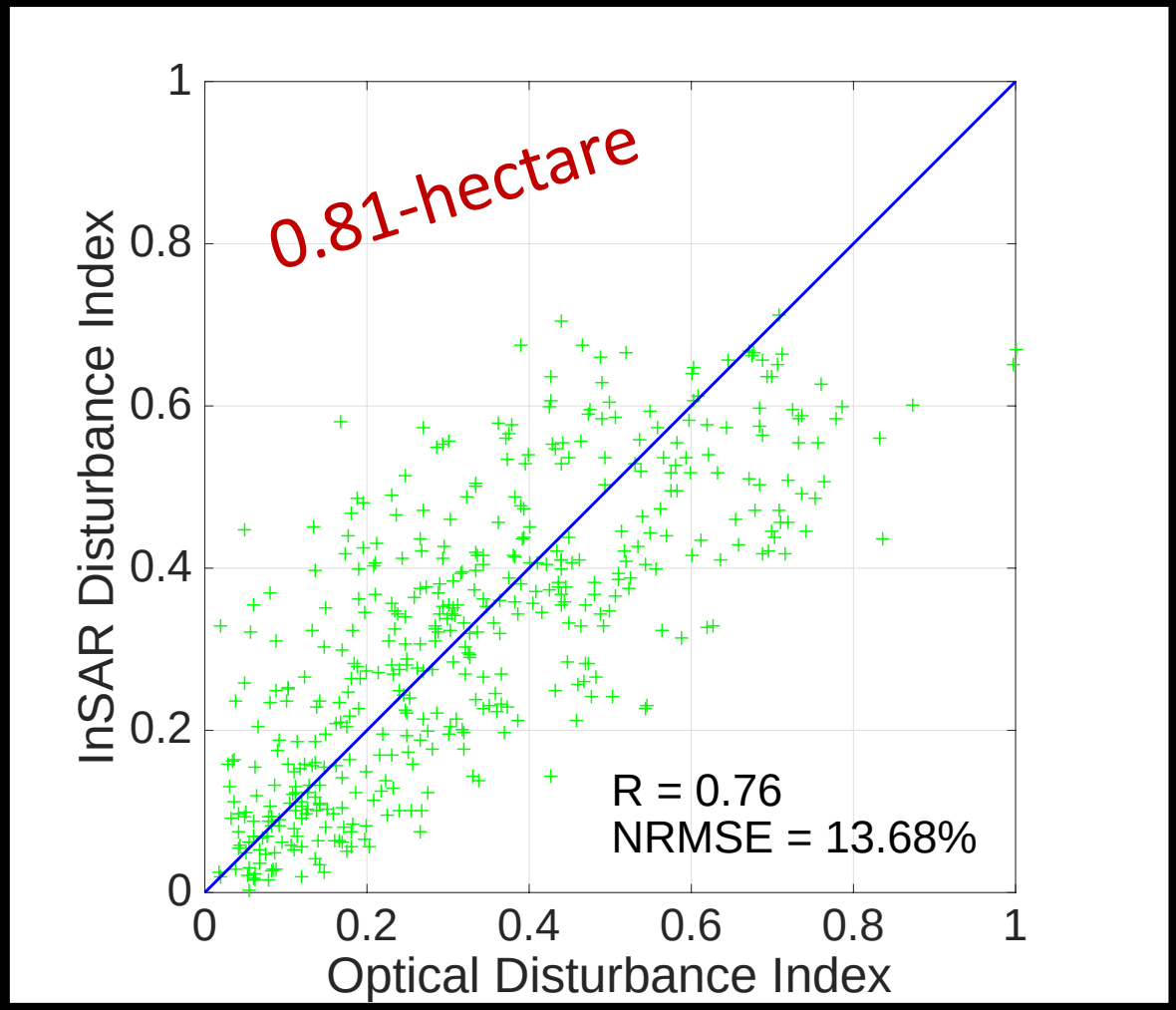


ALOS-derived DI



*** Frantz, David, et al. "Forest Disturbance Mapping Using Dense Synthetic Landsat/MODIS Time-Series and Permutation-Based Disturbance Index Detection." *Remote Sensing* 8.4 (2016): 277.

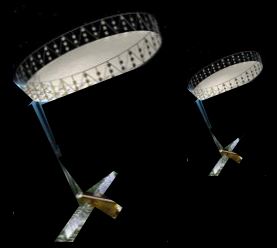
Validation with Landsat data



with pixels out of the selective logging area masked out

Single-pass InSAR

TanDEM-X



TanDEM-L

Single-pass InSAR/PolInSAR methods

Single-pass InSAR observations → Phase-to-height conversion → ***Phase-center height*** (forest mean height)

Single-pass InSAR observations → PolInSAR inversion → ***Forest height***, Extinction coefficient, Ground topography

Polarimetric diversity → PolInSAR inversion

Single-pass InSAR/PolInSAR methods

Single-pass InSAR observations → Phase-to-height conversion → ***Phase-center height*** (forest mean height)

(Sub) Meter-level RMSE for a time series over quarter-hectare forest stands*

Single-pass InSAR observations → PolInSAR inversion → ***Forest height***, Extinction coefficient, Ground topography

Polarimetric diversity

Few Meter-level RMSE over few-hectare forest stands

*** Treuhaft, R. N., et al. "Biomass change in disturbed, secondary, and primary tropical forests from TanDEM-X." *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International*. IEEE, 2016.

Single-pass InSAR/PolInSAR methods

Single-pass InSAR observations → Phase-to-height conversion → ***Phase-center height*** (forest mean height)

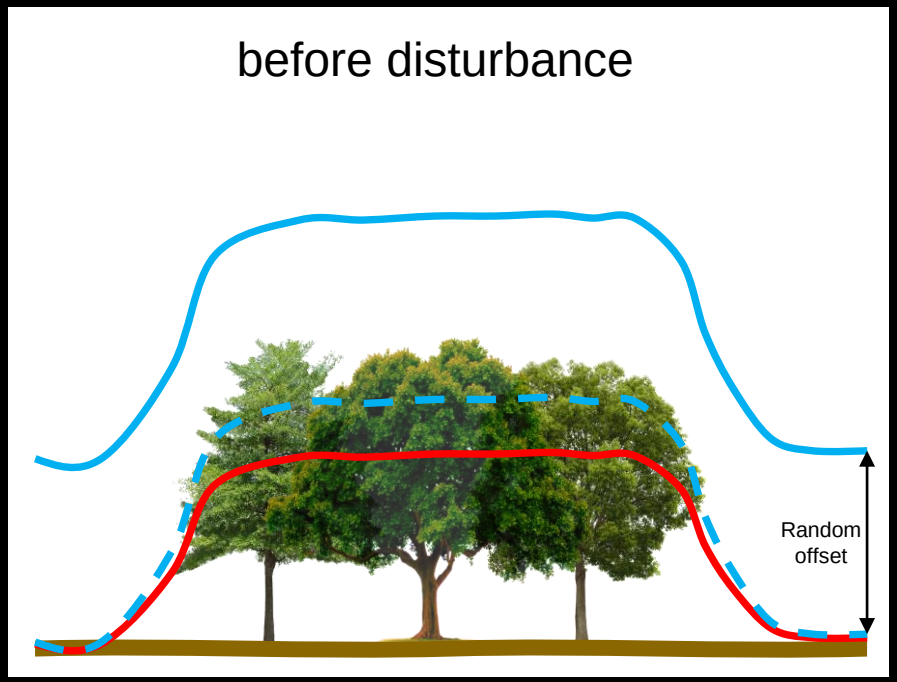
(Sub) Meter-level RMSE for a time series over quarter-hectare forest stands

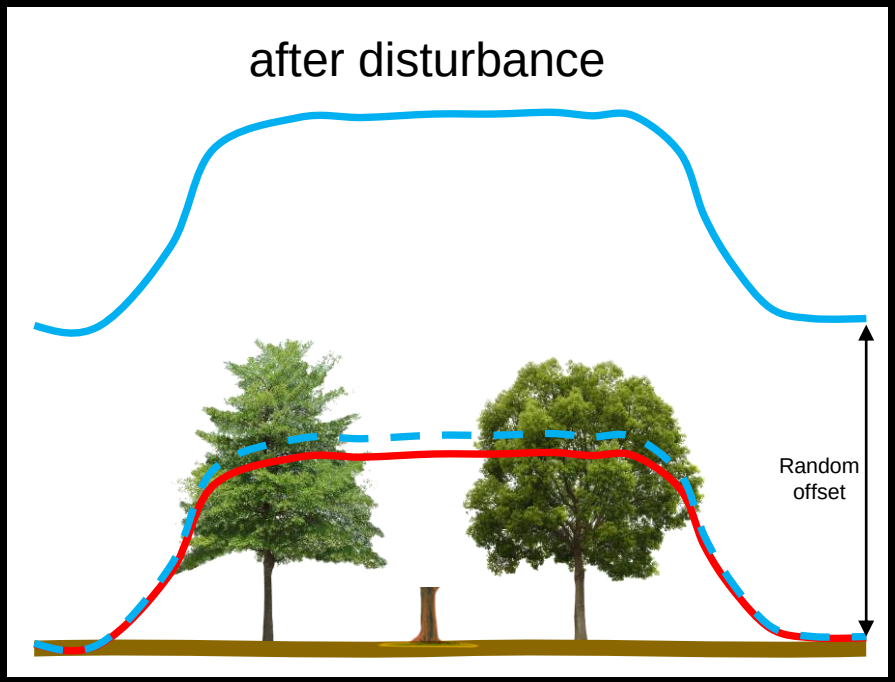
Single-pass InSAR observations → PolInSAR inversion → ***Forest height***, Extinction coefficient, Ground topography

Polarimetric diversity

Few Meter-level RMSE over few-hectare forest stands

Forest disturbance detection approach





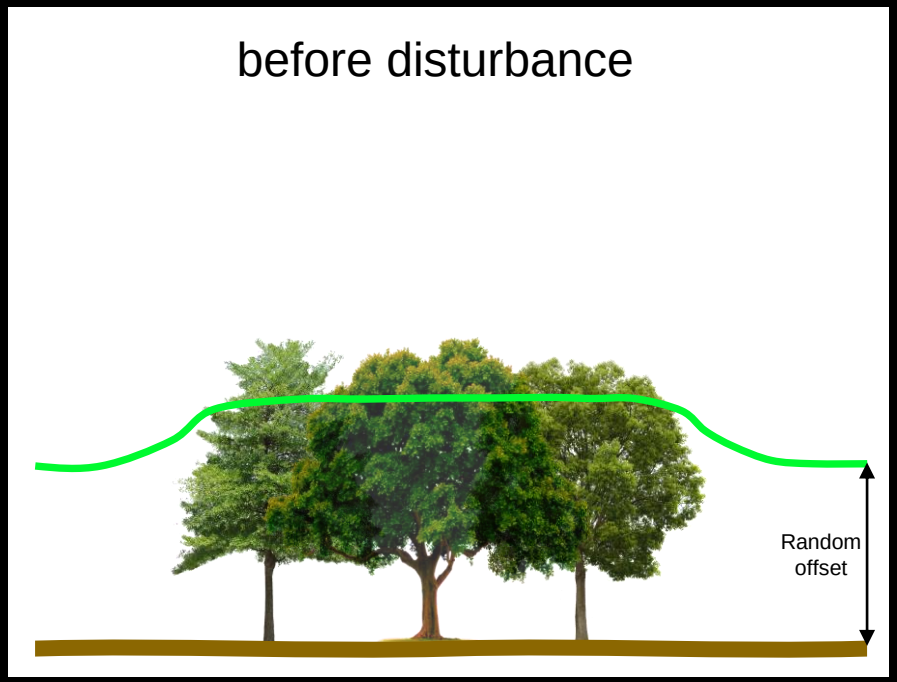
SRTM phase-center height

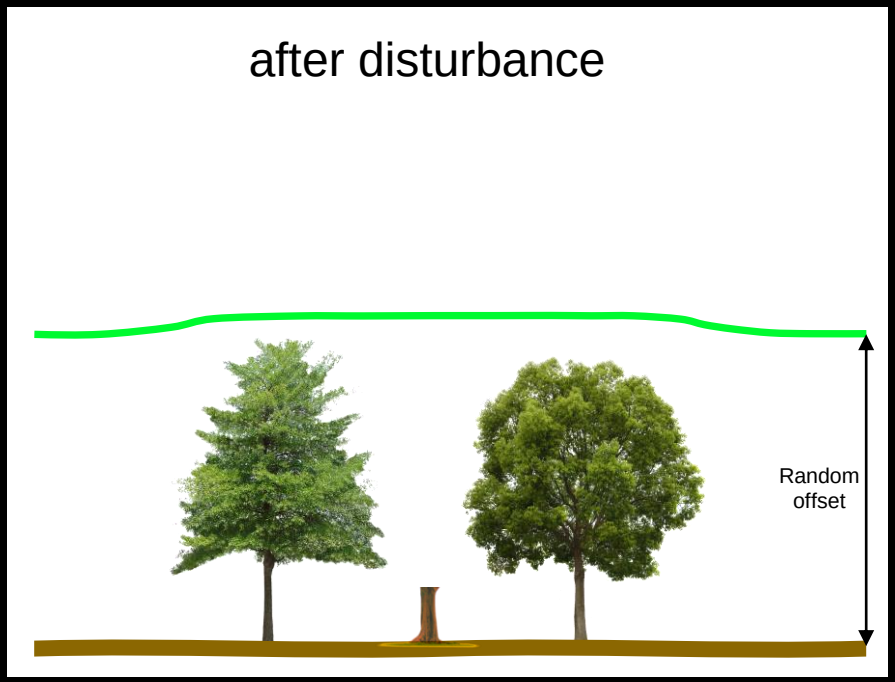
TanDEM-X phase-center height (apparent)

TanDEM-X phase-center height (random offset removed)

Forest disturbance detection approach

Flattening

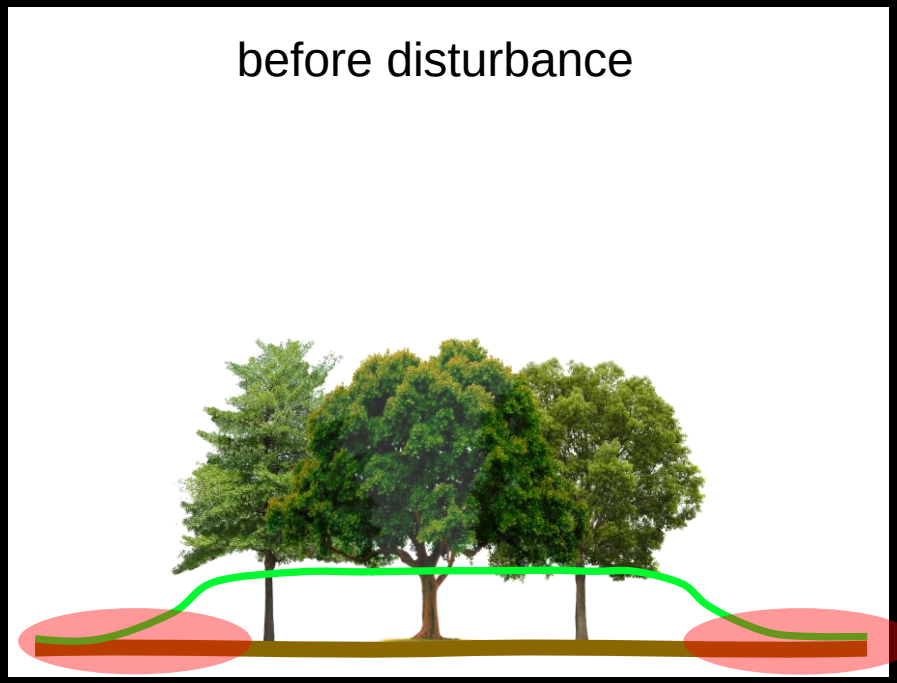


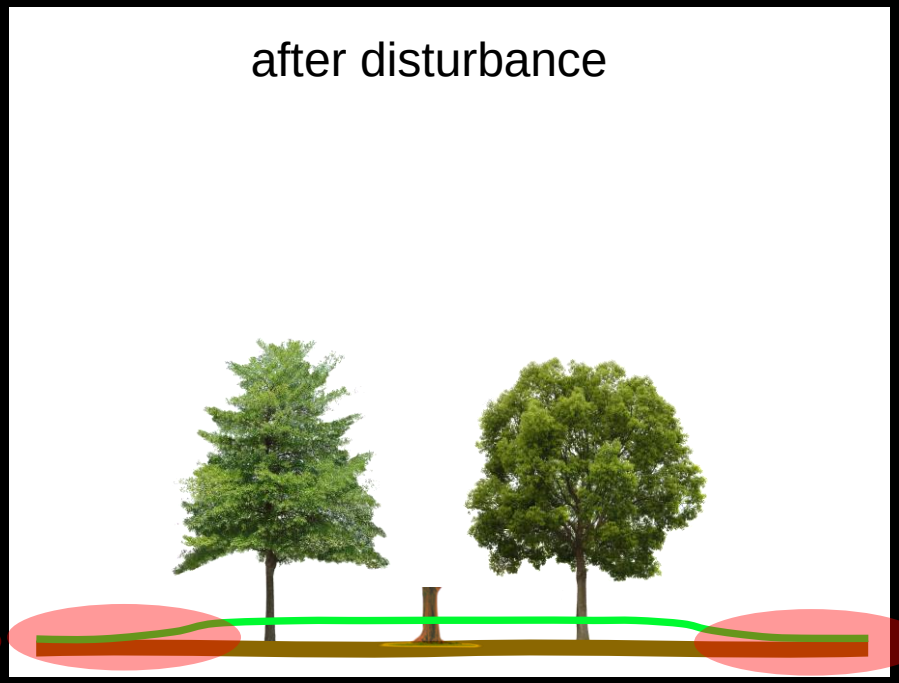


relative TanDEM-X phase-center height flattened with SRTM DEM

Forest disturbance detection approach

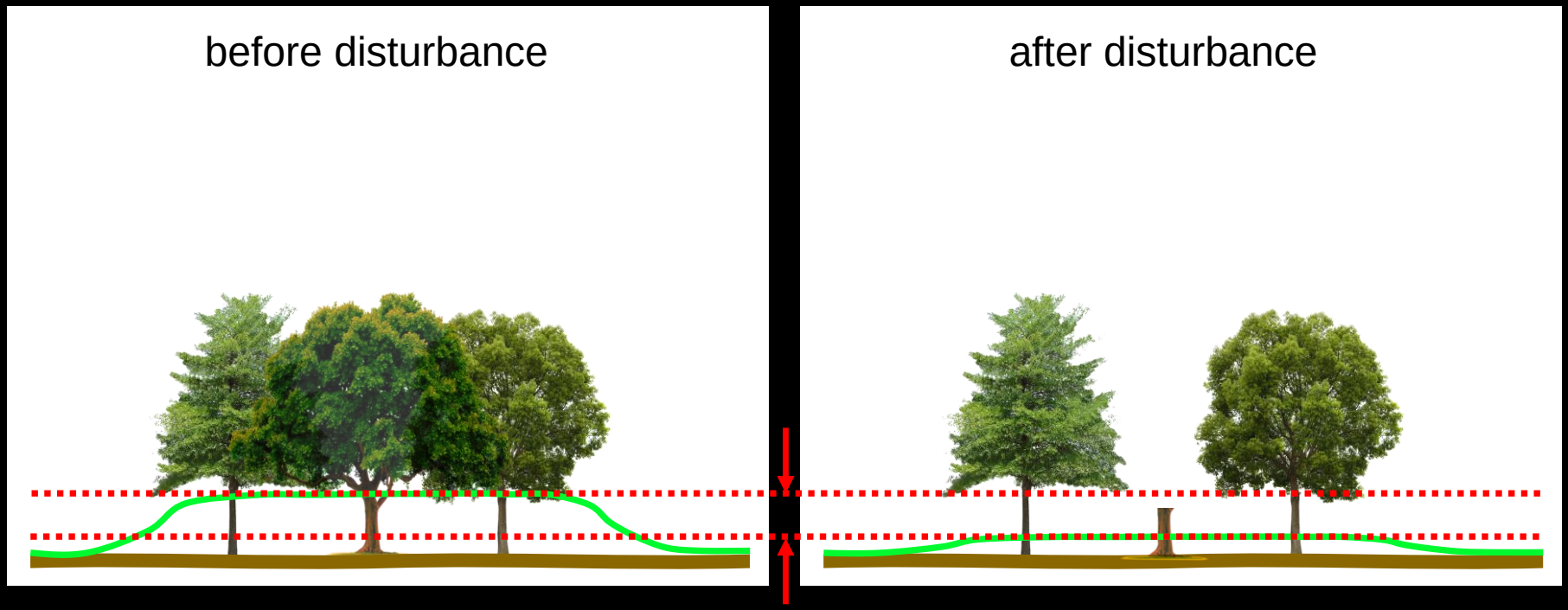
Offset Removal





corrected TanDEM-X phase-center height
using high-coherence points

Forest disturbance detection approach



Time series of relative phase-center height***

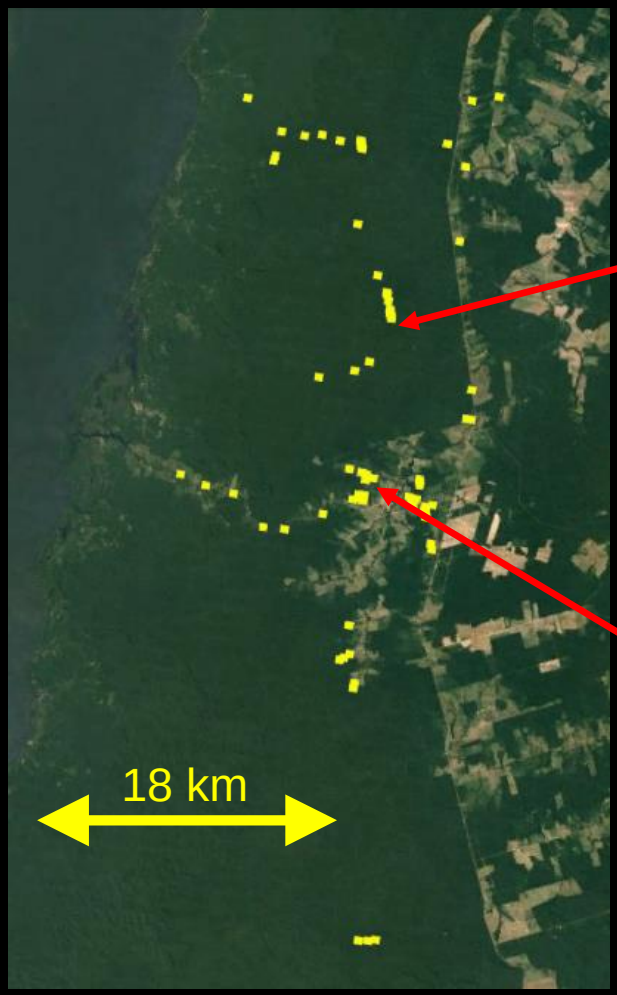
*** ***Absolute*** ***phase-center height can be achieved if a perfect DEM is available***

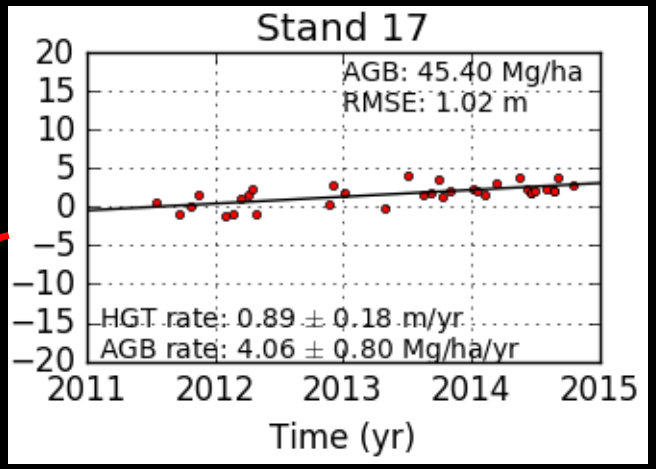
Forest disturbance detection approach

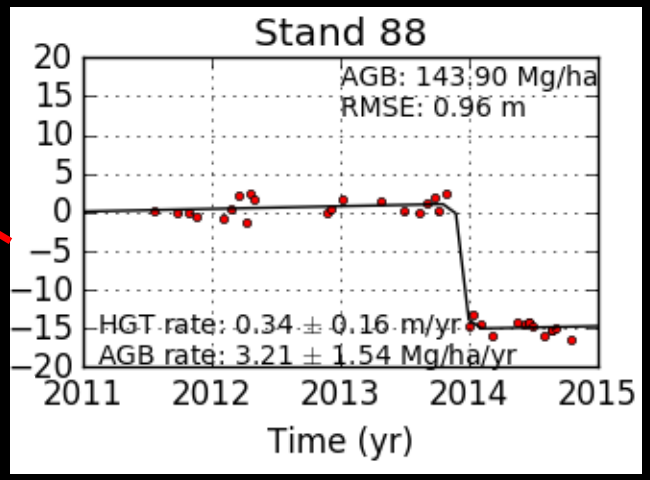
$$h^i = \frac{\phi^i - \phi^i_{topo} - \phi^i_{high}}{\kappa^i_z}$$

where h^i is the relative phase-center height;
ϕ^i is the apparent InSAR phase;
ϕ^i_{topo} is the topographic InSAR phase (simulated from external DEM);
ϕ^i_{high} is average flattened phase ($\phi^i - \phi^i_{topo}$) of the high-coherence points;
κ^i_z is the interferometric vertical wavenumber (phase-to-height conversion factor);
superscript i means the ith-epoch

Single-pass InSAR time-series analysis

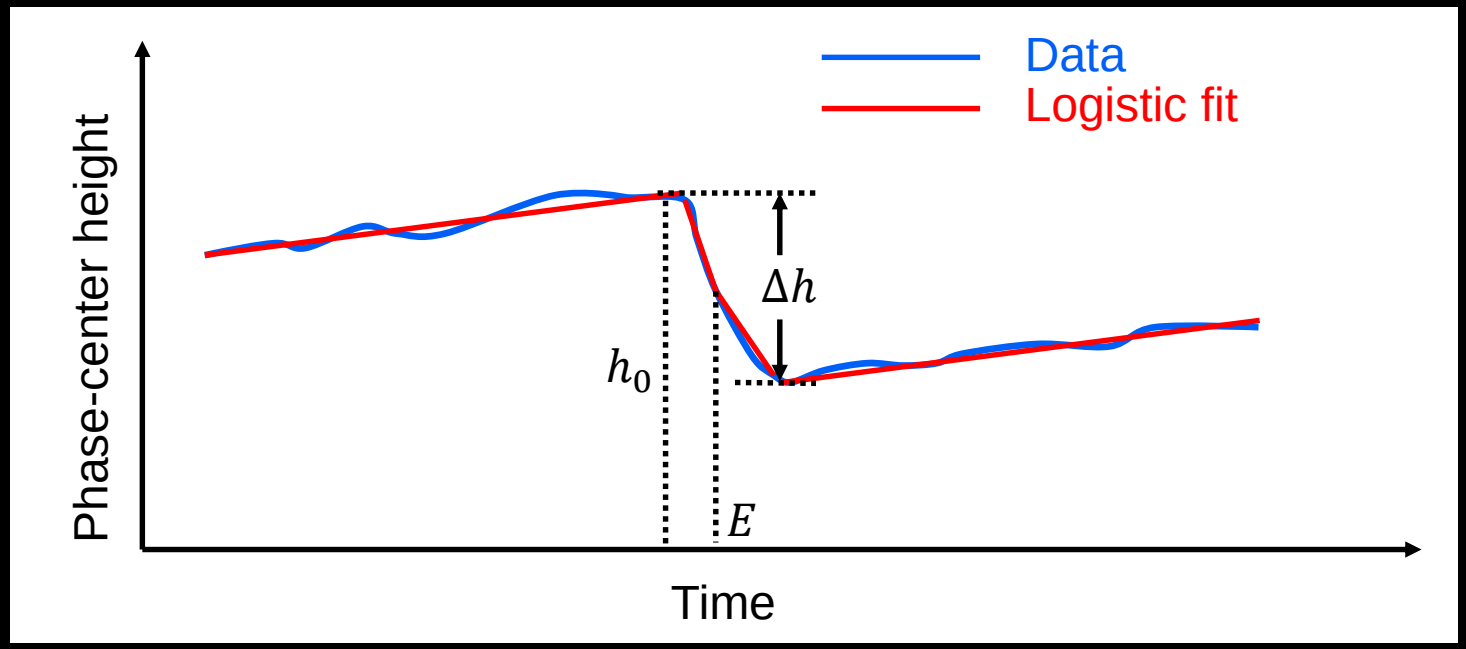






Treuhaft, R. N., et al. "Biomass change in disturbed, secondary, and primary tropical forests from TanDEM-X." *Geoscience and Remote Sensing Symposium (IGARSS), 2016 IEEE International*. IEEE, 2016.

Single-pass InSAR time-series analysis



Logistic function

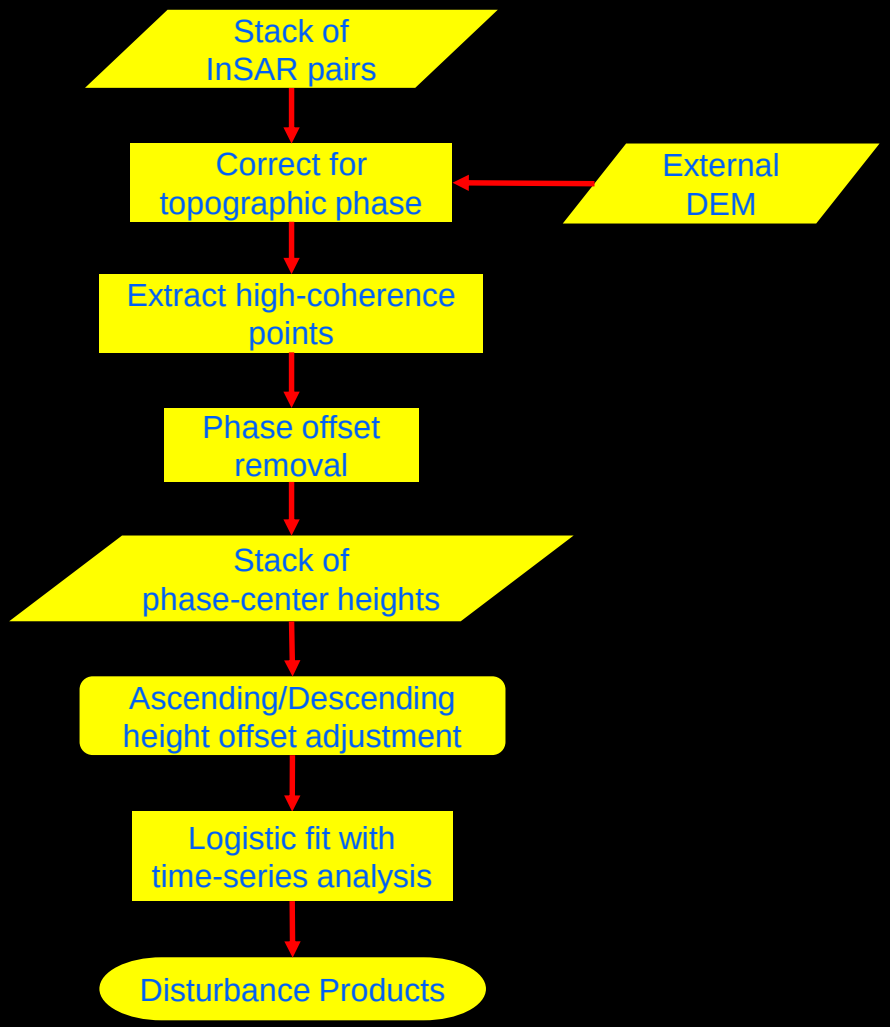
$$y = A + B \cdot x + \frac{C}{1 + e^{-D \cdot (x - E)}}$$

Disturbance index

$$DI = \frac{\Delta h}{h_0}$$

where h_0 is the absolute phase-center height before disturbance

Forest disturbance detection flowchart



Validation with TanDEM-X and ALOS-2 (Tapajos, Brazil)

TanDEM-X

ALOS-2

Study site overview

Selective logging scheduled around October 2015 through January 2016 by Brazilian Agricultural Research Corporation
(affiliated with the Brazilian Ministry of Agriculture)

Field measurements

plot	date felling	date skidding	damaged trees	total trees	number DI	damaged DBH	total DBH	DBH DI
1	1101-1209	1212-1215	5	155	0.032258065	88.8	2924.2	0.03036728
2			0	133	0	0	2821.3	0
3			0	112	0	0	2512.4	0
4	1101-1209	1212-1215	8	116	0.068965517	203.4	2246.5	0.090540841
5			0	69	0	0	1735.5	0
6	1101-1209	1212-1215	7	100	0.07	356.7	2629.7	0.135642849
7	1101-1209	1212-1215	8	115	0.069565217	236.7	2598.8	0.091080499
8			0	135	0	0	2751.1	0
9	1112-0118	1223-0105	3	122	0.024590164	99.1	3247.1	0.030519541
10	1112-0118	1223-0105	13	116	0.112068966	396.6	2618.7	0.151449192
11	1112-0118	1223-0105	10	122	0.081967213	201.1	2497.6	0.080517297
12	1112-0118	1223-0105	2	102	0.019607843	35.8	2851.7	0.012553915
13	1112-0118	1223-0105	1	104	0.009615385	15.9	2503.7	0.006350601
14	1112-0118	1223-0105	10	148	0.067567568	178.8	3008.7	0.05942766
15	1112-0118	1223-0105	2	138	0.014492754	30.1	3019.4	0.009968868
16	1112-0118	1223-0105	11	100	0.11	445.7	2377	0.187505259
17	1118-1209	1209-1211	25	138	0.18115942	757.1	3164.9	0.239217669
18	1118-1209	1209-1211	16	133	0.120300752	286.7	3010	0.095249169
19	1118-1209	1209-1211	1	90	0.011111111	54	2065.6	0.026142525
20	1118-1209	1209-1211	15	119	0.12605042	307.7	2668.9	0.115290944
21	1109-1119	1124-1127	6	123	0.048780488	254.6	3045.6	0.083596007
22	1109-1119	1124-1127	6	95	0.063157895	161.1	2265.3	0.071116408
23	1109-1119	1124-1127	1	116	0.00862069	24.6	2840.5	0.008660447
24	1109-1119	1124-1127	6	101	0.059405941	159.1	2961	0.053731847
25			0	92	0	0	2202.1	0
26	1109-1119	1124-1127	17	129	0.131782946	334.2	2582.7	0.129399466
27			0	144	0	0	3190.2	0
28			0	99	0	0	2609.5	0
29	1118-1209	1209-1211	25	138	0.18115942	552.1	2934.7	0.188128258
30	1118-1209	1209-1211	11	106	0.103773585	314.2	2714.4	0.115753021
31	1118-1209	1209-1211	7	121	0.05785124	134.4	2844.4	0.047250738
32			0	132	0	0	3137.4	0

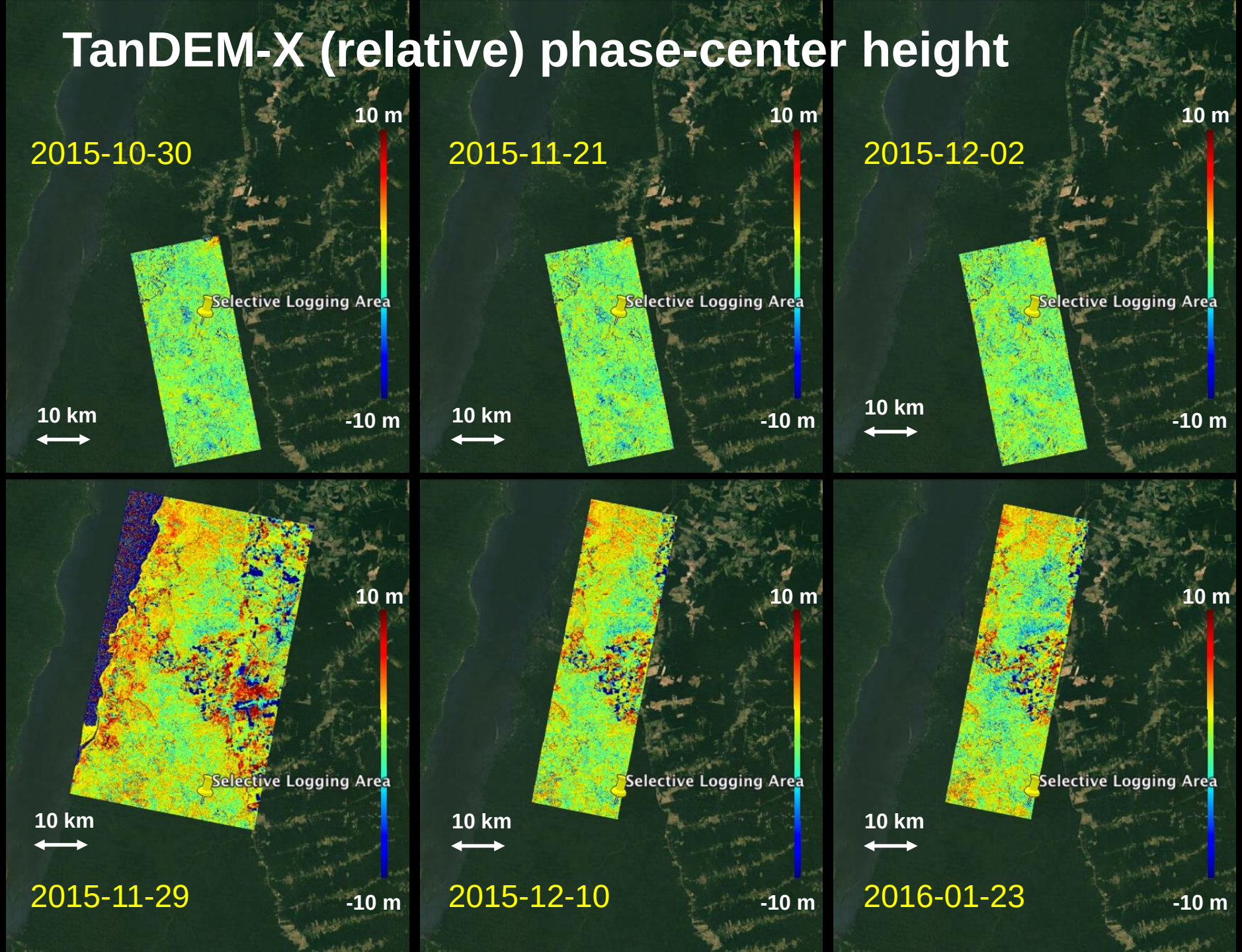
TanDEM-X InSAR data

ISCE software

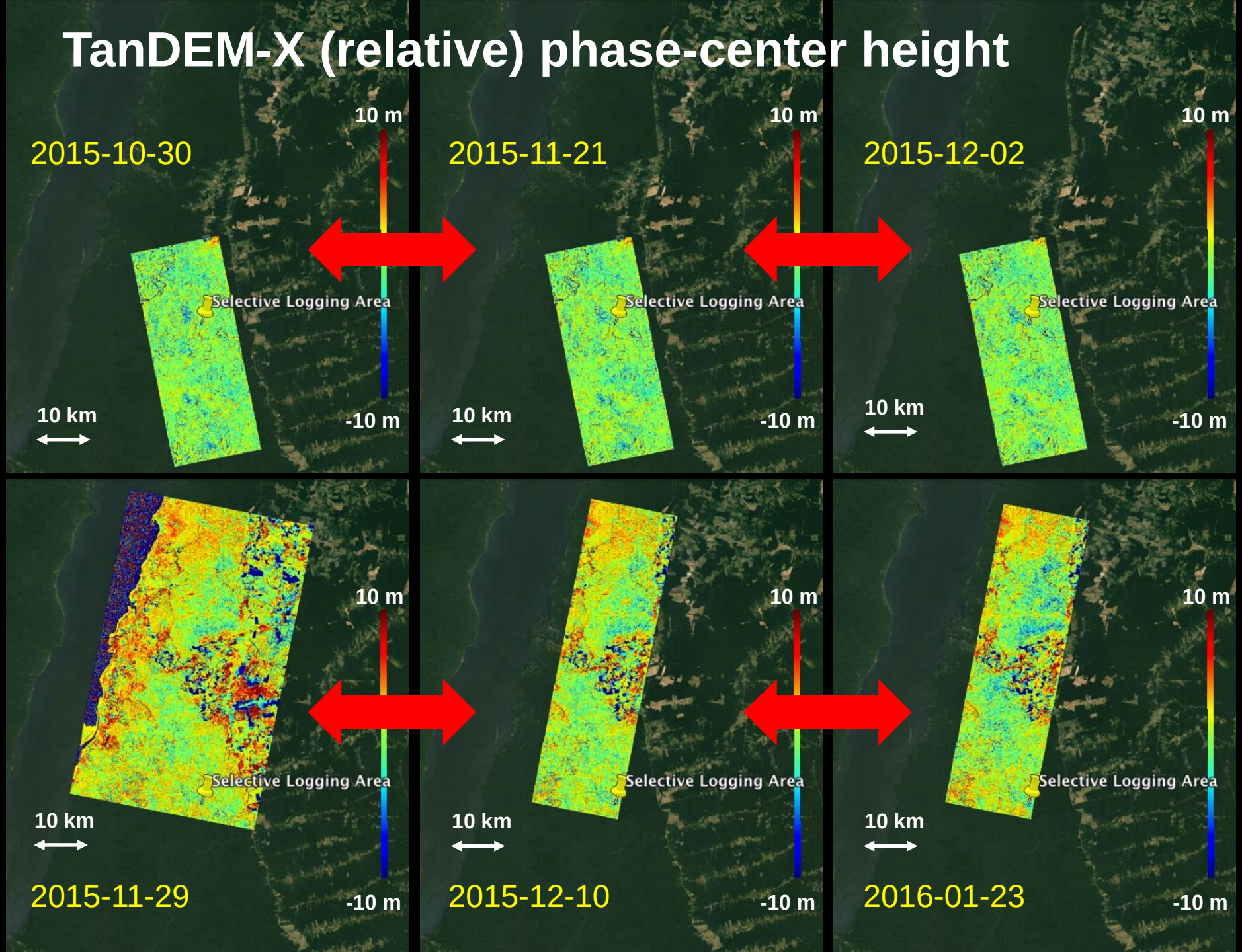
Date	Orbit Direction	HoA (m)	κ_z (rad/m)	Polarization	Bandwidth (MHz)	Master Satellite
20151030	Ascending	70.97	0.0893	HH+VV	150	TSX
20151121	Ascending	63.27	0.1002	HH+VV	150	TDX
20151129	Descending	71.91	0.0885	HH	100	TDX
20151202	Ascending	64.91	0.0976	HH+HV	150	TSX
20151210	Descending	71.41	0.0886	HH+VV	150	TDX
20160123	Descending	65.40	0.0967	HH+VV	150	TSX

Incidence angle (41º)

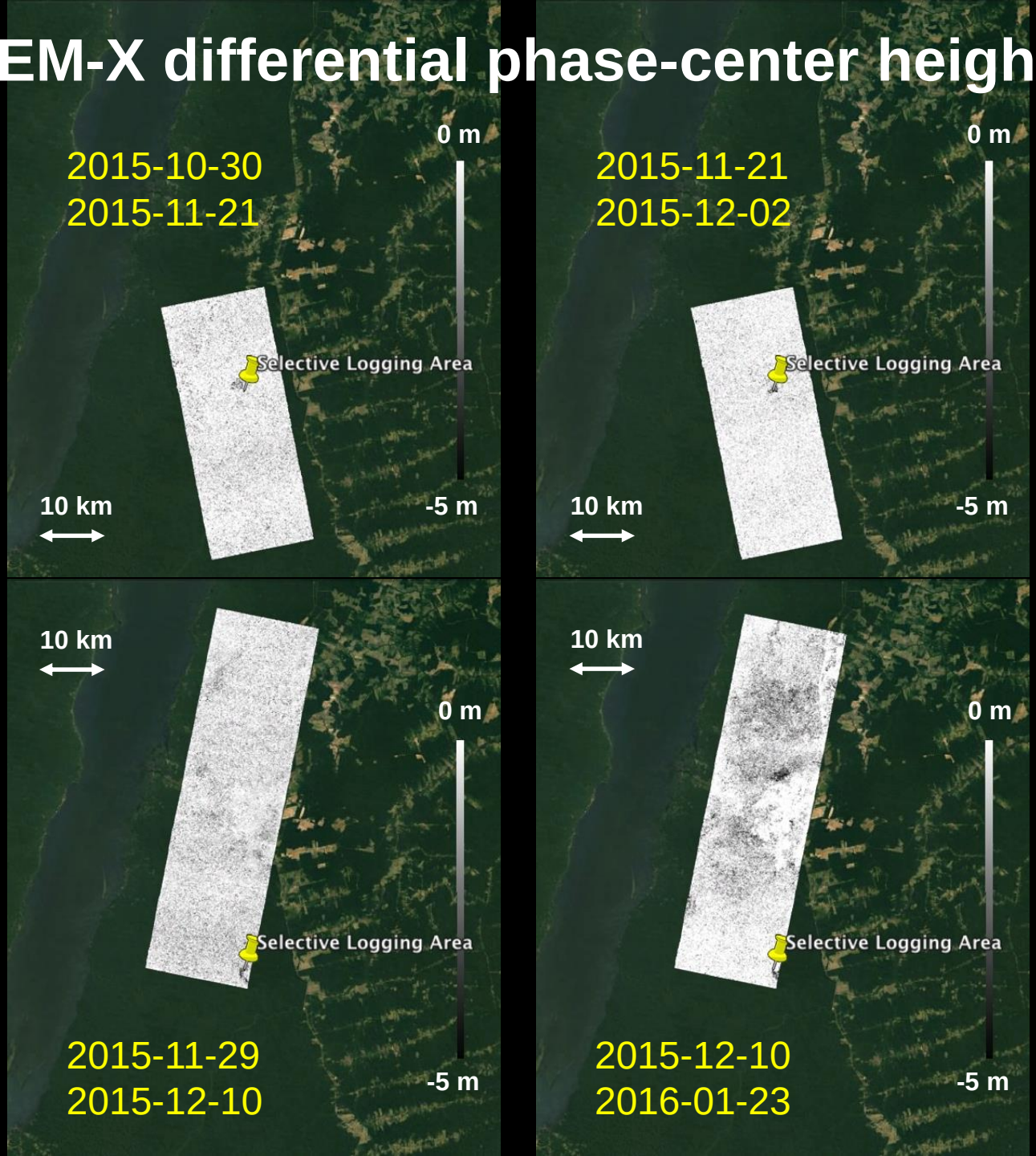
TanDEM-X (relative) phase-center height



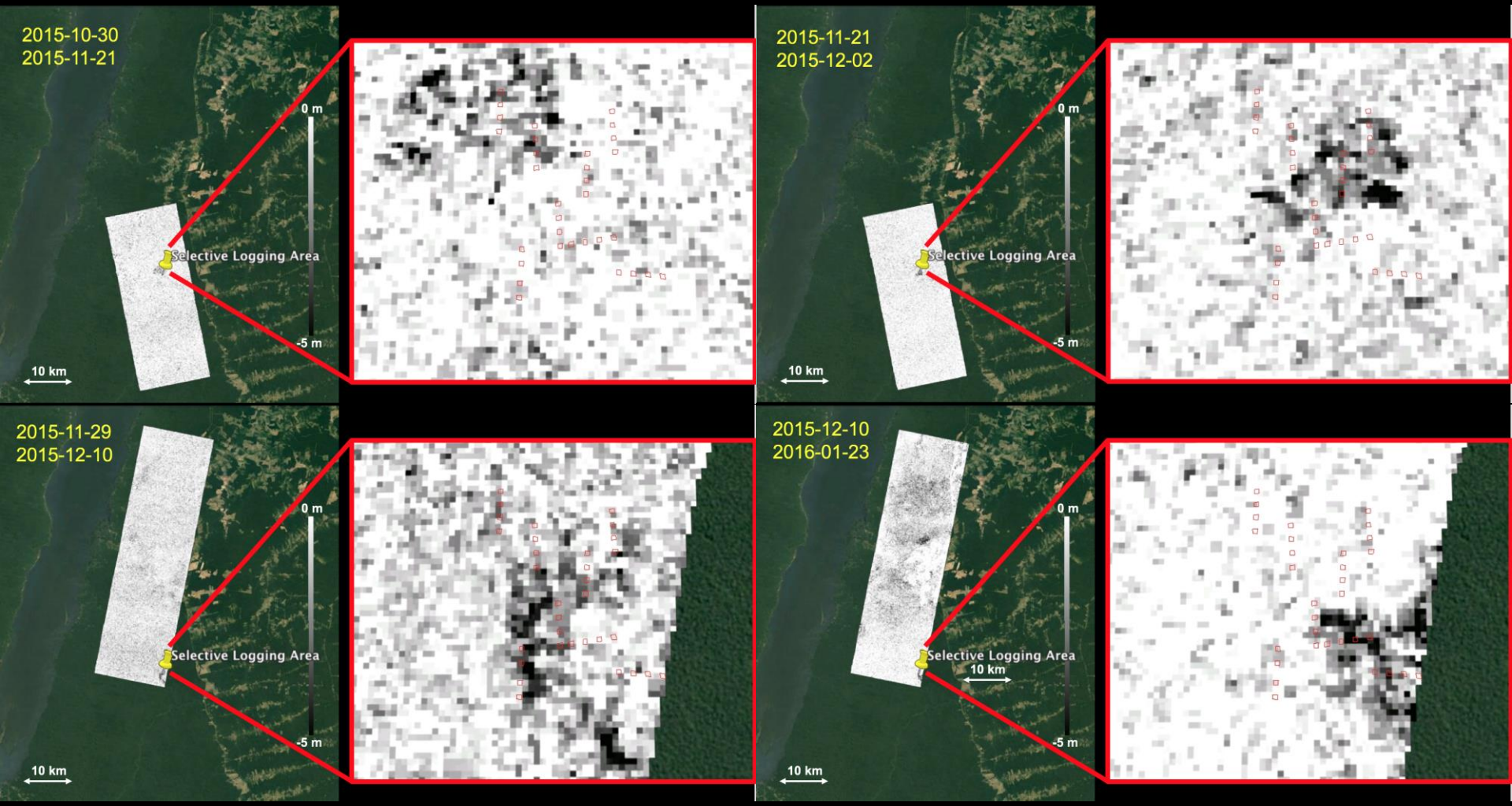
TanDEM-X (relative) phase-center height



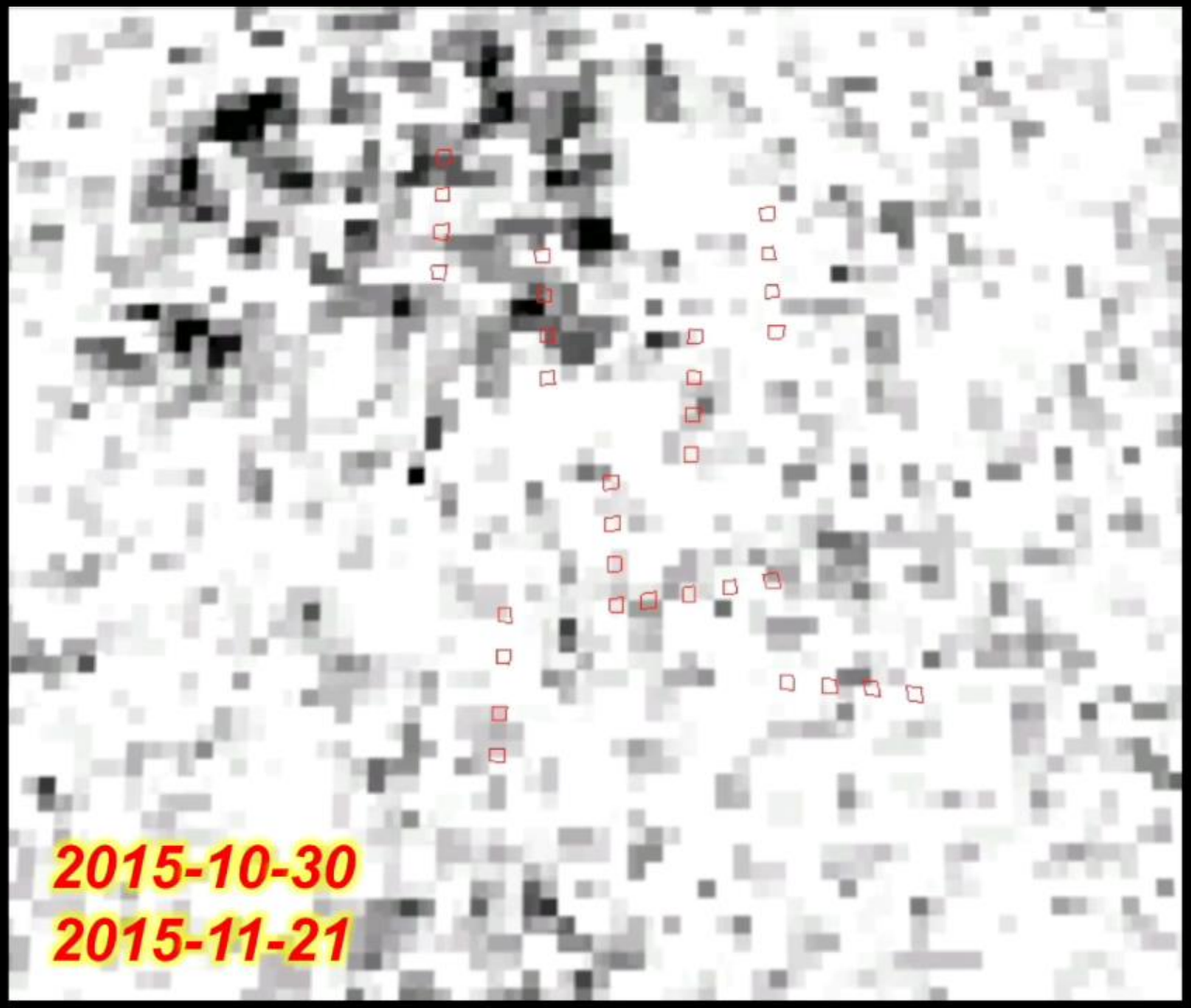
TanDEM-X differential phase-center height



TanDEM-X differential phase-center height

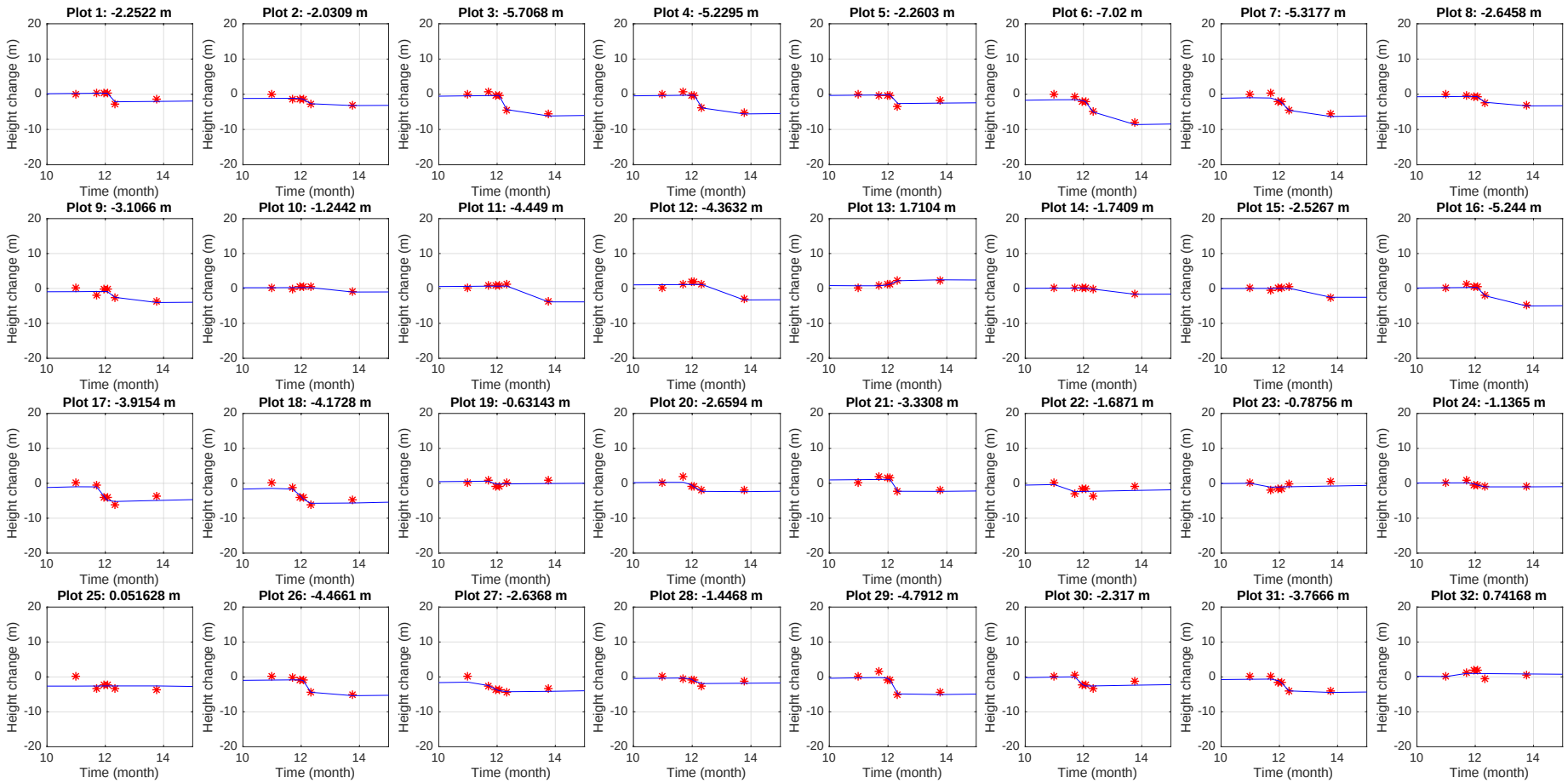


TanDEM-X differential phase-center height



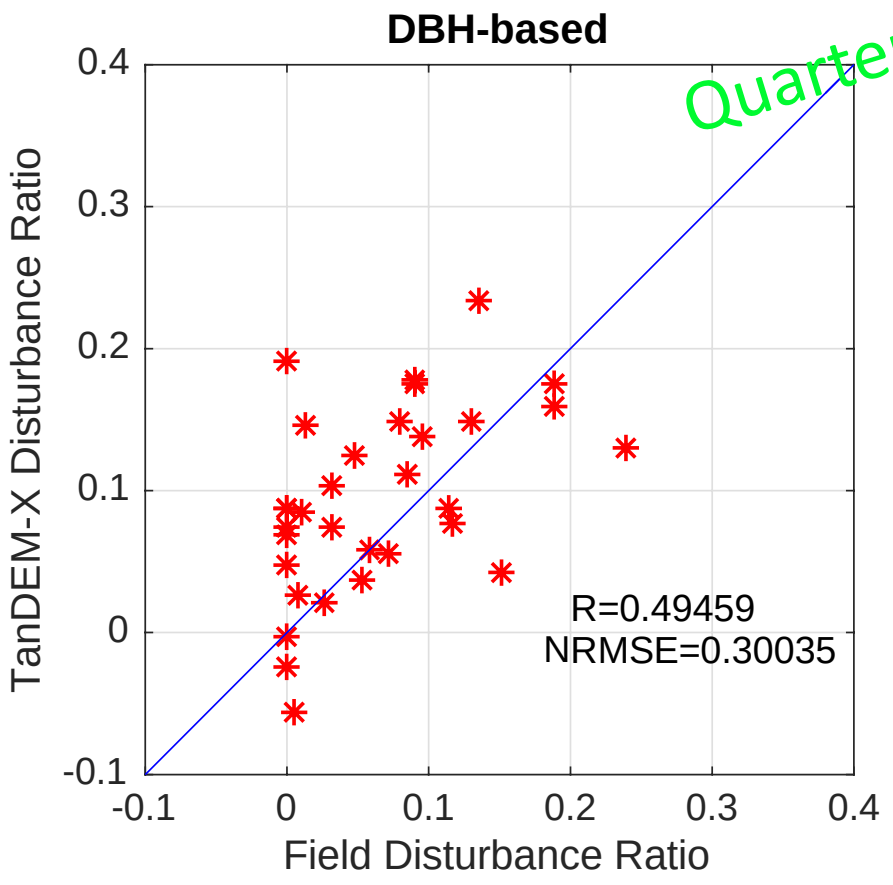
TanDEM-X time-series of phase-center height

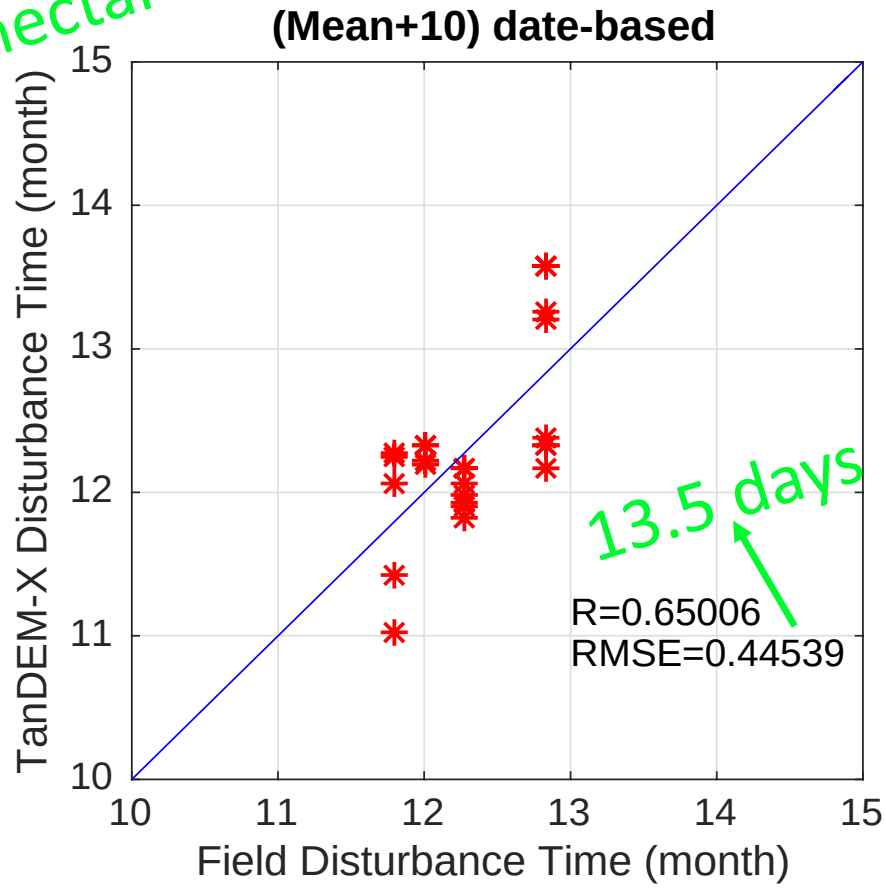
Curve fit with a logistic function



Amount of Disturbance

Time of Disturbance





$h_0 = 30$ m is assumed

ALOS-2 InSAR data

ISCE software

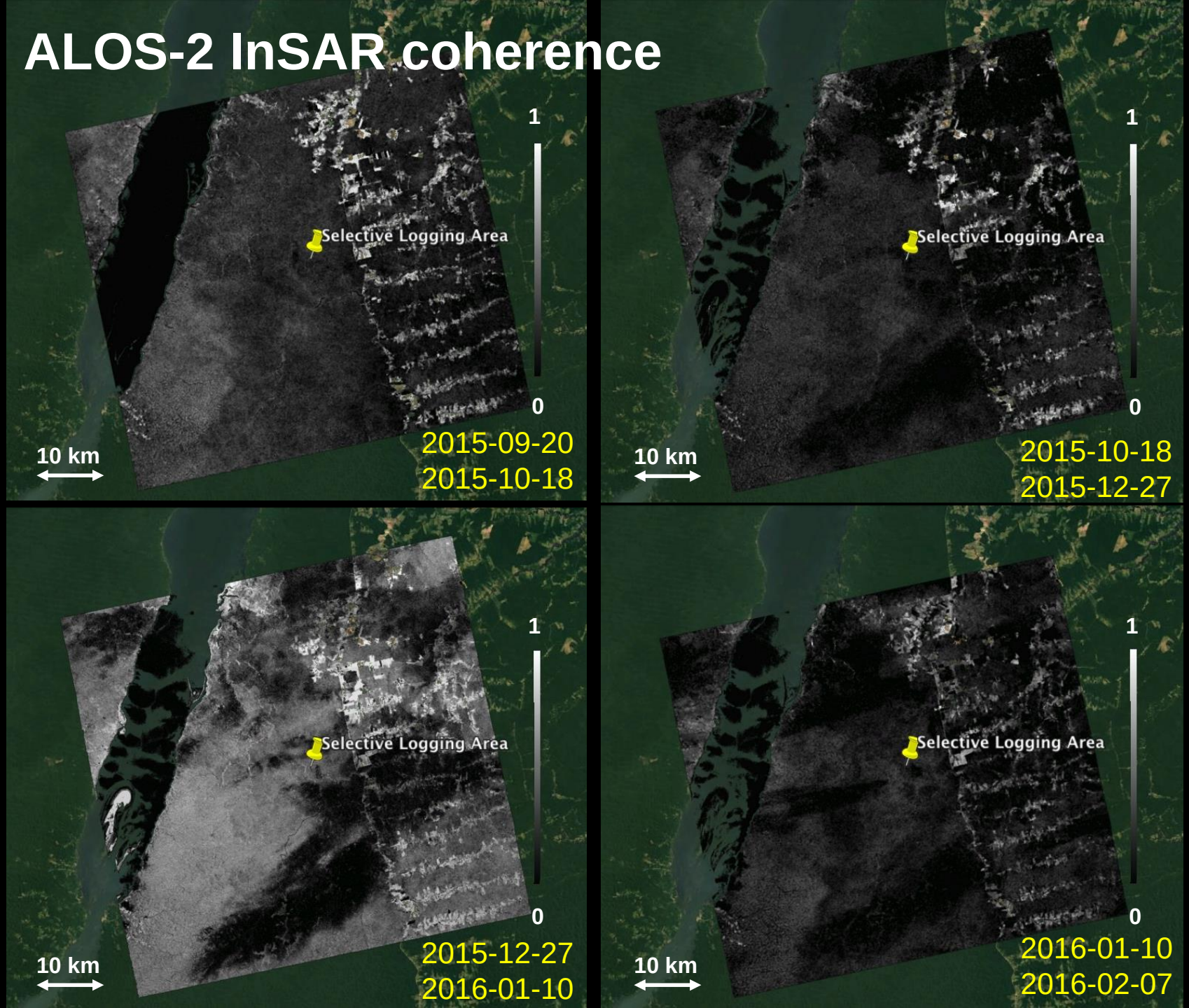
Date	κ_z (rad/m)	Scene-wide coherence	Forest Temporal coherence
20150920-20151018	0.0034	0.1866	0.2015
20151018-20151227	0.0024	0.1464	0.1785
20151227-20160110	0.0079	0.3433	0.4941
20151227-20160207	0.0033	0.1294	0.1264

Polarization (HH+HV)

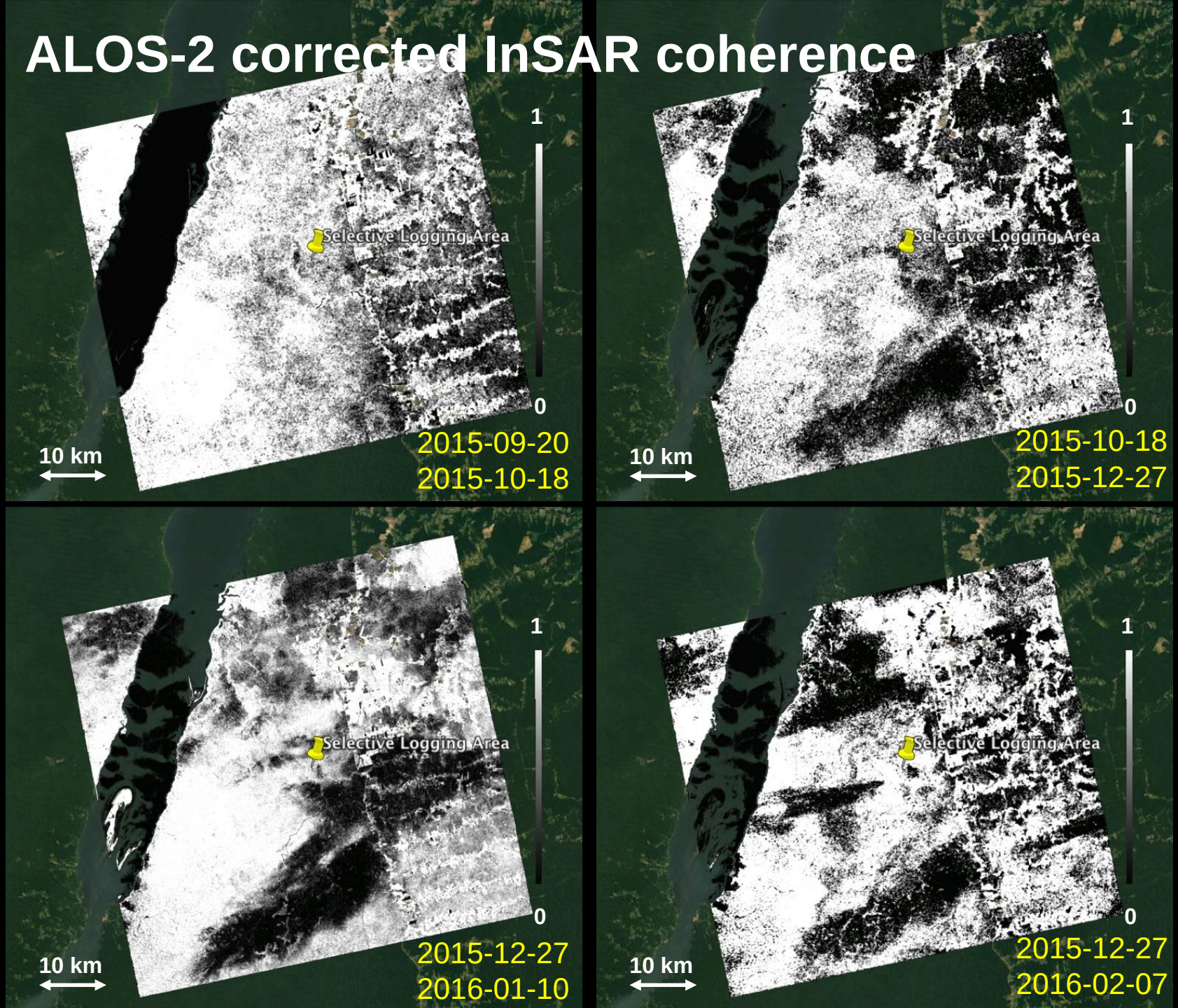
Incidence angle (28.2º)

Orbit Direction (Ascending)

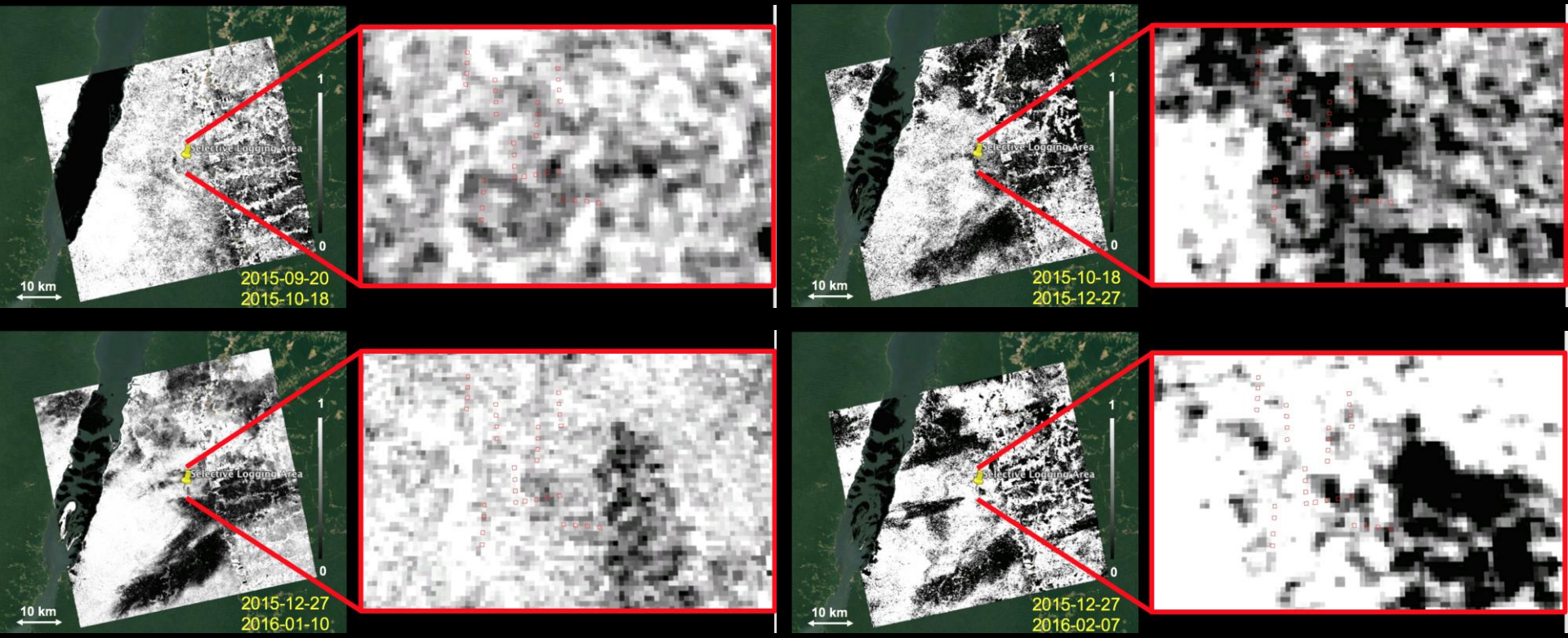
ALOS-2 InSAR coherence



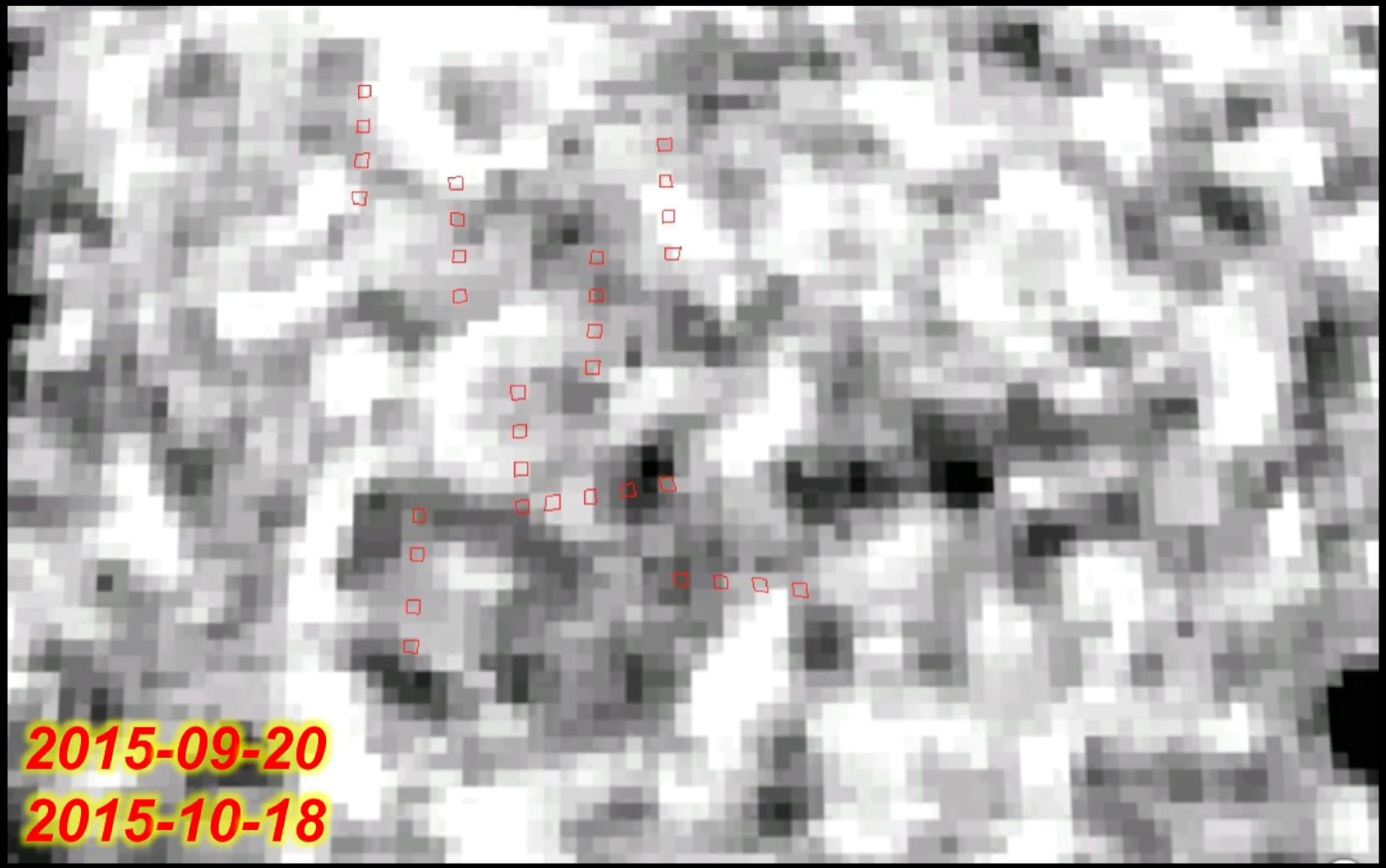
ALOS-2 corrected InSAR coherence



ALOS-2 corrected InSAR coherence

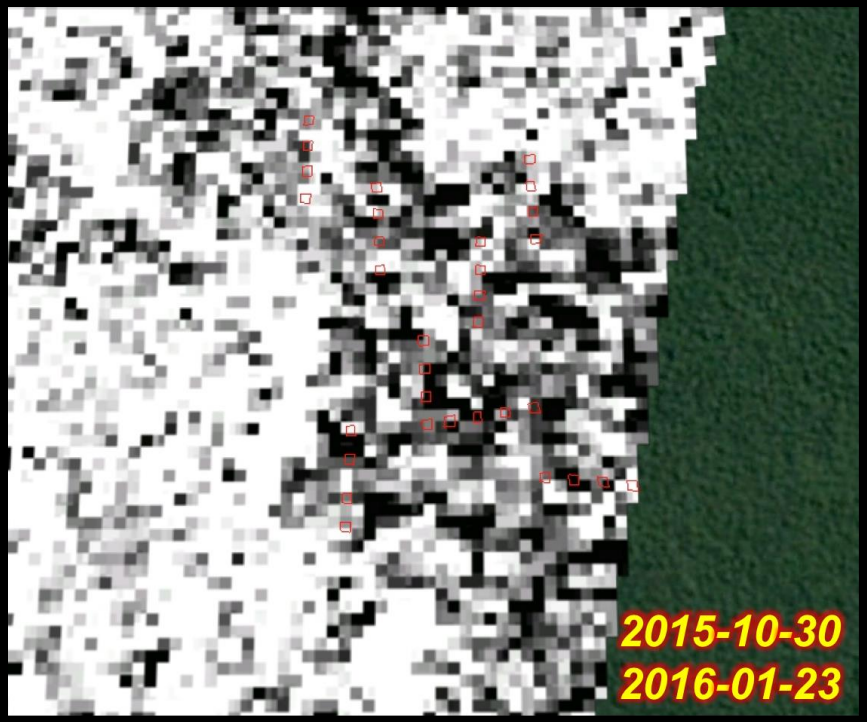


ALOS-2 corrected InSAR coherence

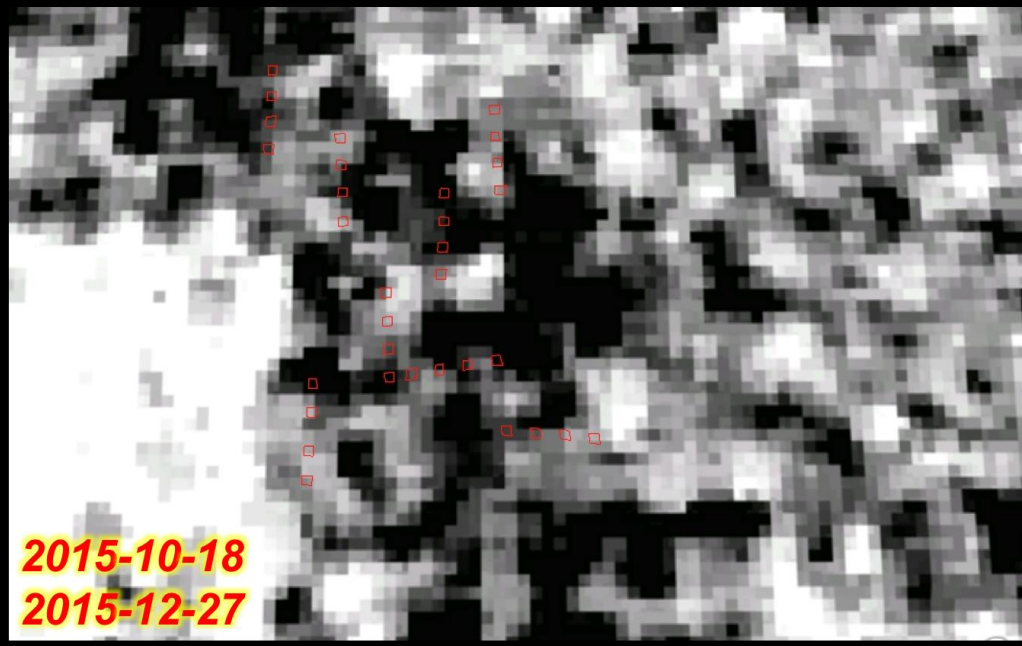


TanDEM-X vs. ALOS-2

TanDEM-X differential
phase-center height



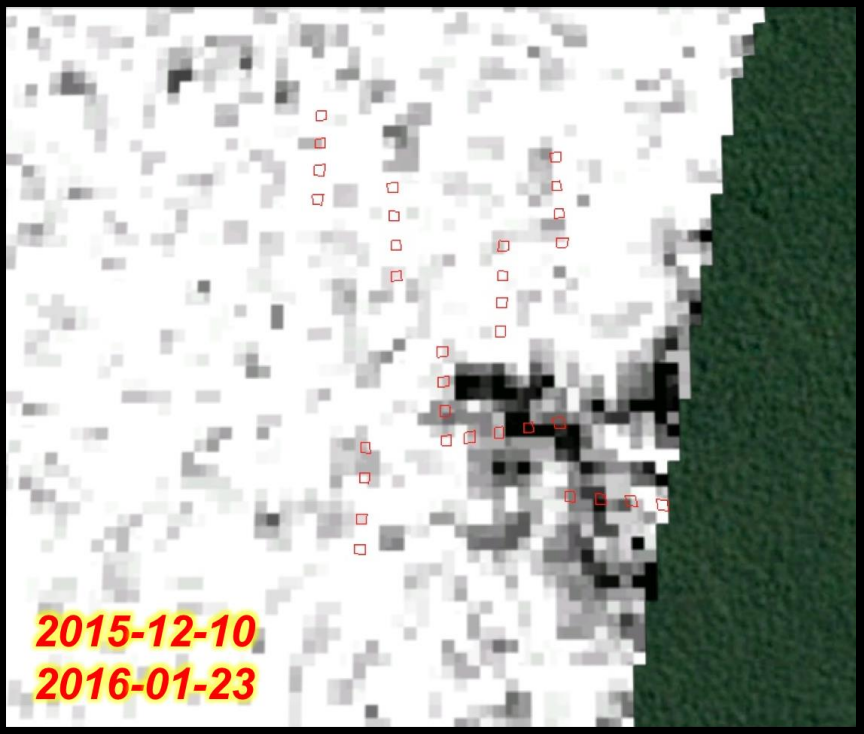
ALOS-2 corrected
InSAR coherence



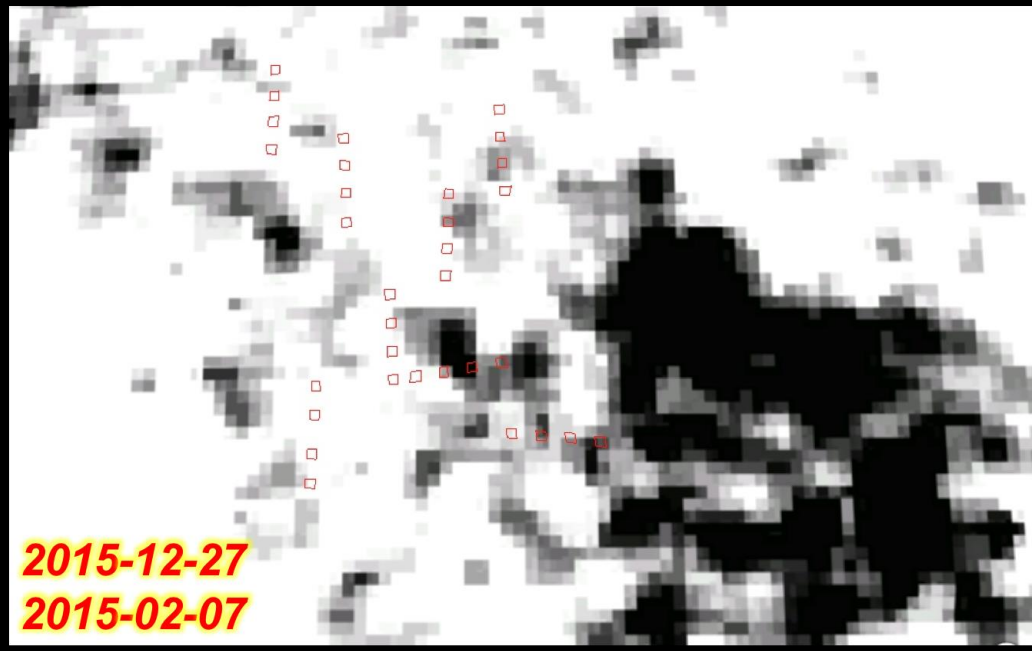
Net change due to logging

TanDEM-X vs. ALOS-2

TanDEM-X differential
phase-center height



ALOS-2 corrected
InSAR coherence



Post-logging activities

Conclusions

- Simple and efficient (single-baseline, single-polarization) approaches have been developed for characterizing forest disturbance on a large scale (dozens of km) with fine spatial resolution (< 1 hectare) based on spaceborne SAR interferometry.

- As for spaceborne repeat-pass SAR interferometry, the InSAR correlation magnitude has been utilized to generate a disturbance index with NRMSE of 13.68% over forest stands of 0.81 hectare using ALOS InSAR data in Injune field, Queensland, Australia.

- For spaceborne single-pass SAR interferometry, the InSAR correlation phase is exploited to generate a disturbance index with NRMSE of 30% over forest stands of 0.25 hectare using TanDEM-X InSAR data in Tapajos, Brazil.

- Both approaches could serve as observing prototypes for the future spaceborne InSAR missions (e.g. NASA-ISRO's NISAR and DLR's TanDEM-L), as well as provide a practical solution to monitor large-scale (potentially global-scale) forest disturbance as relevant to United Nation's Reducing Emissions from Deforestation and forest Degradation (REDD) programme.

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- The authors would like to thank Piyush Agram from the ISCE developer team at NASA Jet Propulsion Laboratory for the valuable discussions and generous support on InSAR processing of TanDEM-X and ALOS-2 data using the ISCE software package.

- Our sincere gratitude also goes to Maiza dos-Santos at Embrapa Agricultural Informatics for providing the field measurements of the selective logging event at Tapajos forest.

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Thanks for your attention !

Jet Propulsion Laboratory
California Institute of Technology

Any questions ?