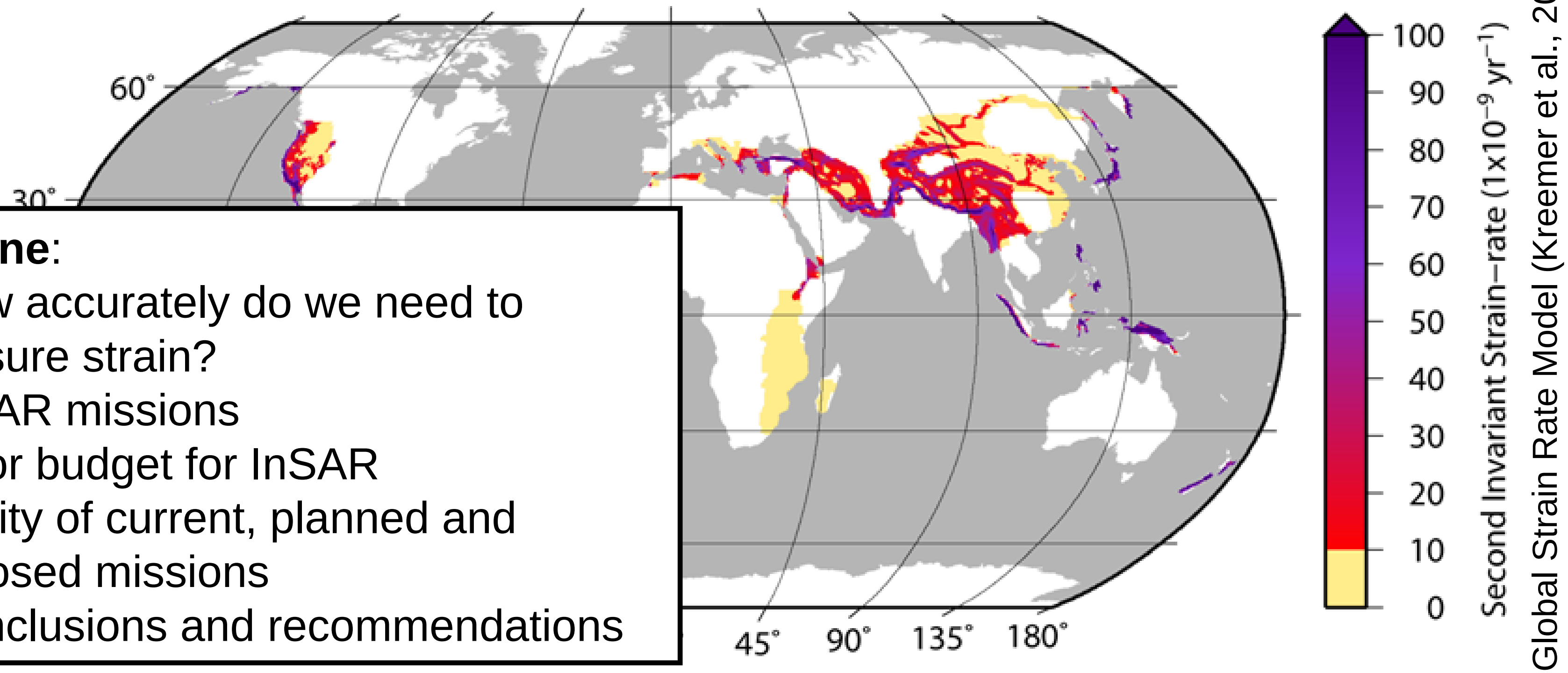
How accurately can current and futureInSAR missions map tectonic strain?



Outline:
- How accurately do we need to measure strain?
- InSAR missions
- Error budget for InSAR
- Ability of current, planned and proposed missions
- Conclusions and recommendations

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NATURAL ENVIRONMENT RESEARCH COUNCIL

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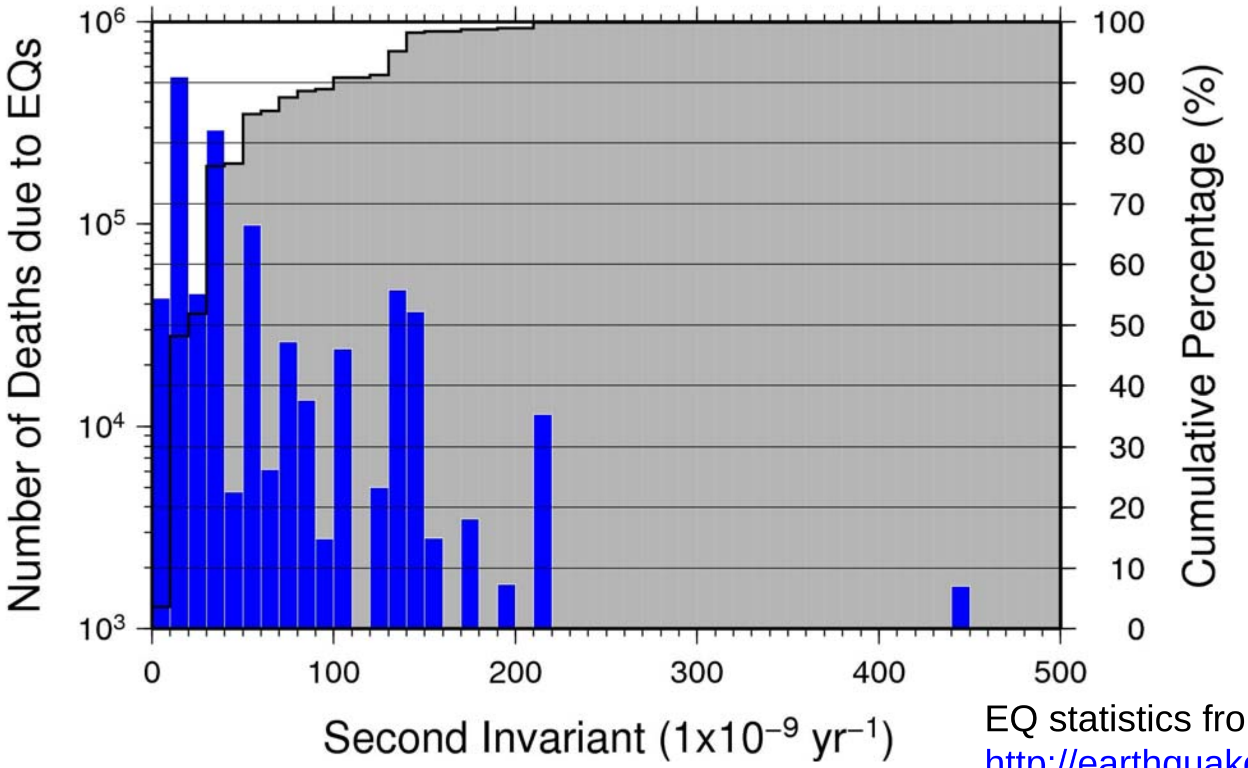
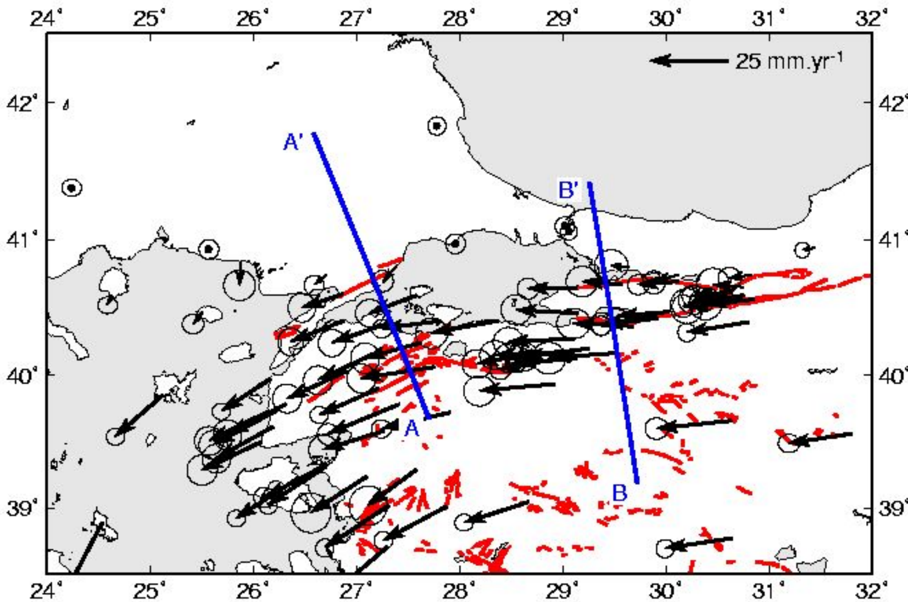
Required Accuracy for Tectonic Deformation: 1. Strain and EQ deaths



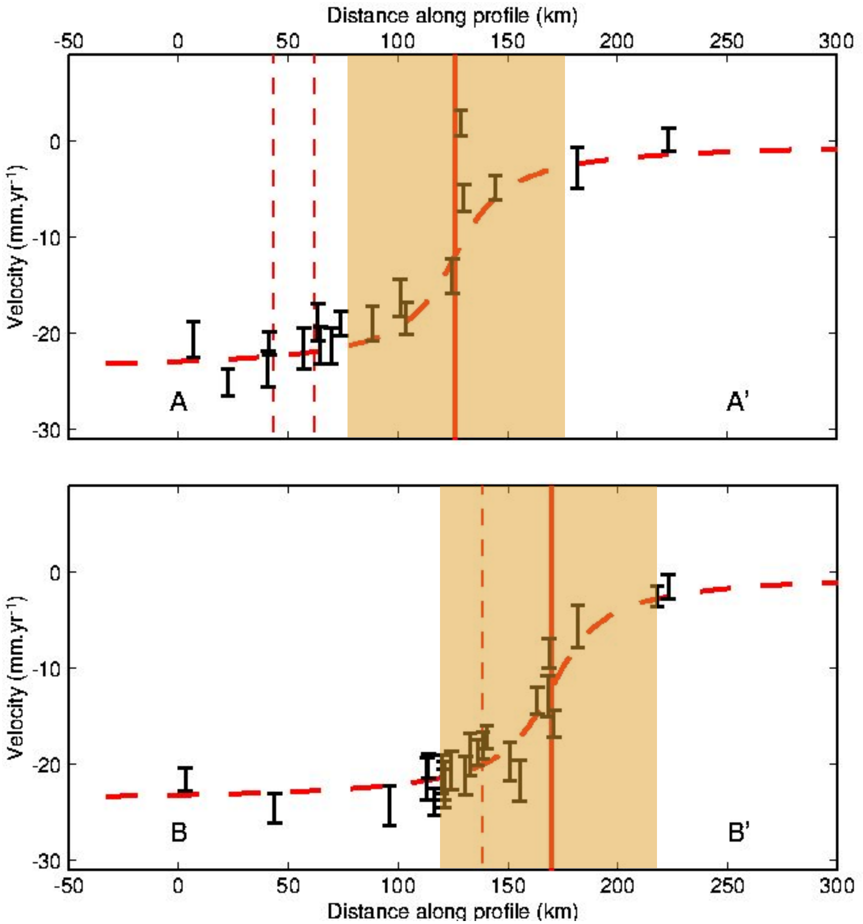
EQ statistics from USGS.
http://earthquake.usgs.gov/earthquakes/world/world_deaths.php

- 90% of all earthquake-related deaths occur in regions which are straining at rates above 1.2 x 10^{-8} yr^{-1}

Required Accuracy for Tectonic Deformation: 2. Length scale



Data from McClusky et al. (2000)



- ~90% of strain from locked faults occurs in ~100 km wide region centred on fault.

Target threshold for measuring tectonic strain: velocity gradients of 1.2 mm/yr over 100 km

Current/Planned/Proposed InSAR Missions

Mission	Λ	Revisit Time	% Aquis.	Geometry
Envisat 2003-2010	C (~6 cm)	35 days	~50%	R-looking, usu. 23° inc, mostly descending
ALOS 2006-2011	L (~20 cm)	46 days	40-60%	R-looking, usu. 34° inc, mostly ascending
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DESDynI-shelved	L	16 days	100%	R-looking (occasionally left), ~40° inc, Asc+Desc
SuperSAR-Not funded	L	13 days	100%	R-looking, forwards + backwards, ~40° inc, Asc+Desc

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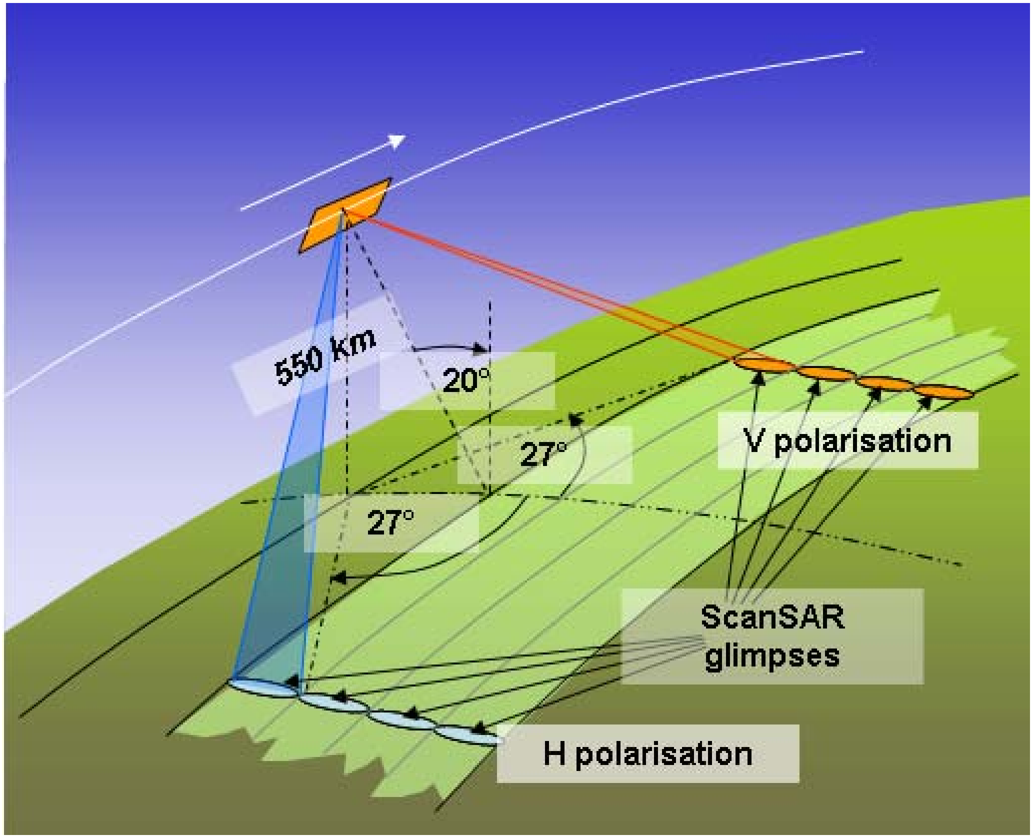
None of the other current/planned missions have global acquisition strategies or data policies that could allow them to be useful for global strain mapping.

SuperSAR Concept



- L-band, ScanSAR
- **Forward and Rear beams**
- Achieved through phased array antenna
- Optimised for mapping tectonic strain
- Proposed to ESA's EE8 call in 2010

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Orbital errors ⇨ long-wavelength ramps.
- Envisat: ~0.3 mm/km (across-track) and 0.1 mm/km (along-track) [Wang, Wright and Biggs, GRL 2009].
- Can correct by processing long strips and tying to GPS **(see. Fringe presentations by Wang, Pagli and Hamlyn)**
- Should be negligible for future missions with onboard GPS receivers.

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Single interferogram

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$$\sigma_{topo} = \frac{\bar{r}_{slant} B_{\perp}}{\sin \theta_{inc}} \sigma_{DEM}$$

- SRTM error ~ 4 m absolute, of which 2.5 m is not spatially correlated [Rodriguez et al., PERS 2006]

B_{perp}	σ_{topo} (40° incidence)
150 m	1.1 mm
300 m	2.3 mm
1000 m	7.8 mm

Error Budget (1)
Single interferogram

$$\sigma^2_{def} = \sigma^2_{gm} + \sigma^2_{topo} + \sigma^2_{atm} + \sigma^2_{coh} + \sigma^2_{sys} + \sigma^2_{unw}$$

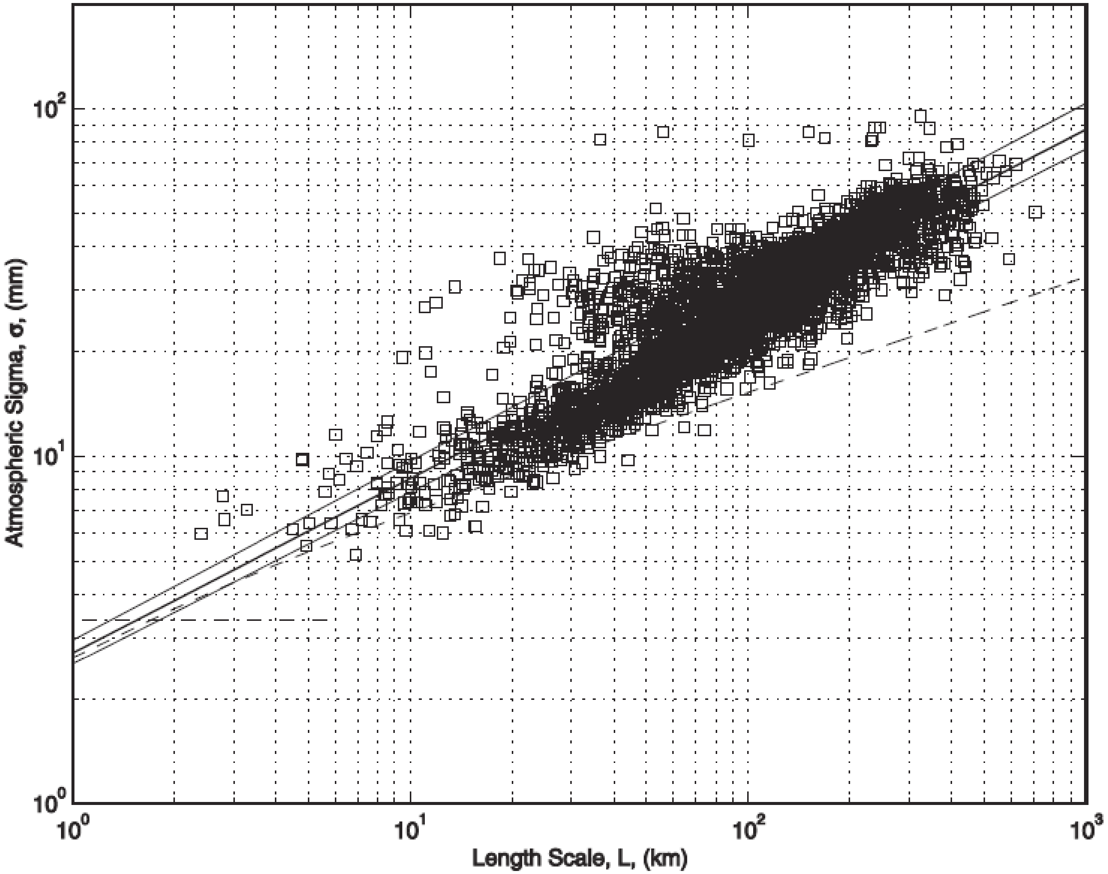
- Troposhere

Emardson et al., 2003:

$\sigma = cL^{\alpha}$ [c~2.5, α~0.5]

σ= 25 mm at 100 km

(assume no corrections)



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- Ionosphere ($1/f^2$ dependence). Important at L-band, but not at C-band.
- Can correct with split band processing (e.g. 1200 and 1260 MHz) in future missions
- Ionospheric error on 100 km wavelength ~ 1mm after spatial averaging

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Single interferogram

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- Coherence, γ
  - important at short wavelengths, but can be averaged through multilooking to < 1 mm for most ground cover types

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- Coherence, γ
  - important at short wavelengths, but can be averaged through multilooking to < 1 mm for most ground cover types
- System (thermal) - modifies coherence
  - reduces effective coherence, but still insignificant after spatial averaging.

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Unwrapping errors difficult to quantify.
- Assume = 0 in this analysis (probably OK for L-band missions with short revisits).

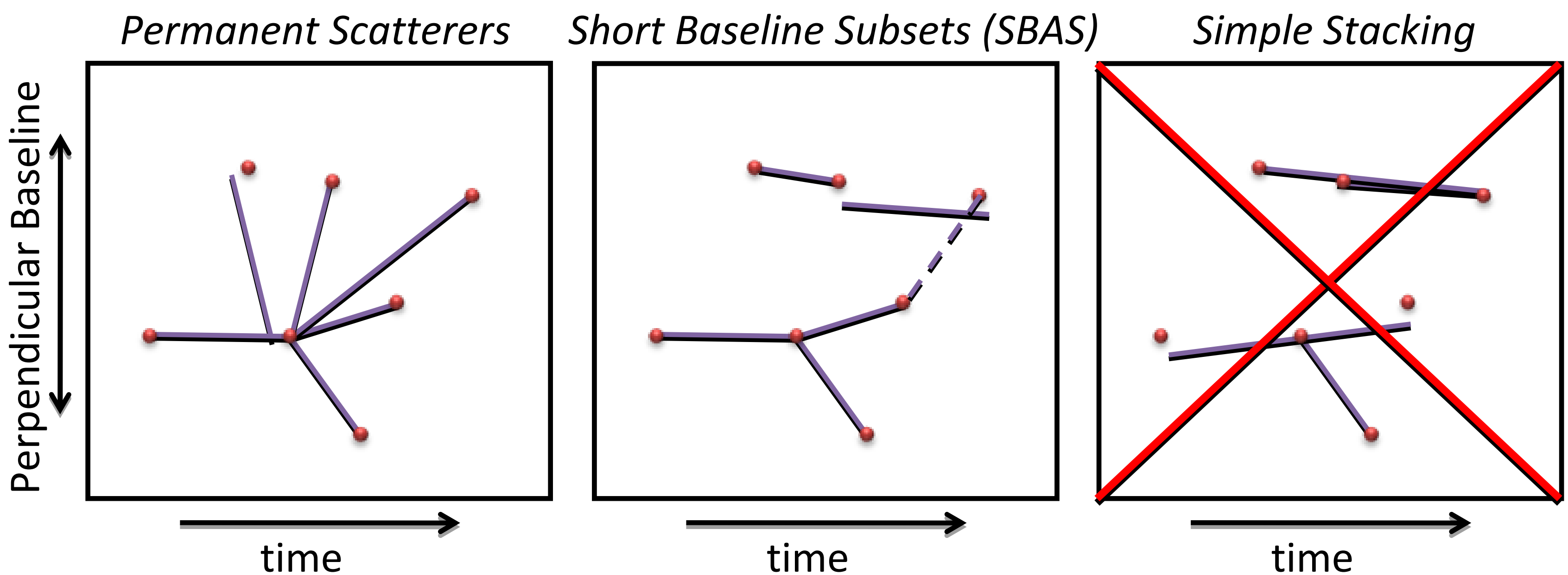
Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

Atmospheric (tropospheric) error dominates at 100 km length scales, at which single interferograms have error of ~25 mm.

Error Budget (2)

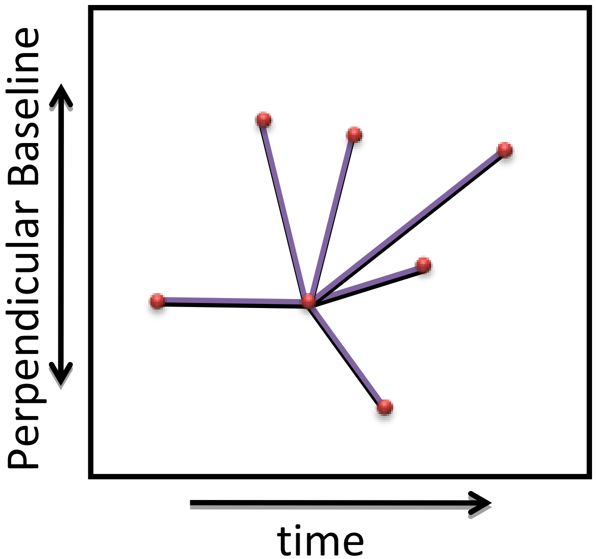
Optimum determination of Linear Deformation Rates



For the determination of linear deformation rates, optimum errors are determined through a connected network, since noise terms are associated with individual acquisitions not interferograms.

Error Budget (2)

Optimum determination of Linear Deformation Rates



- Error on linear rate is independent of how network is connected (but of course short-baseline, short-time interferograms are best).

Error Budget (2)

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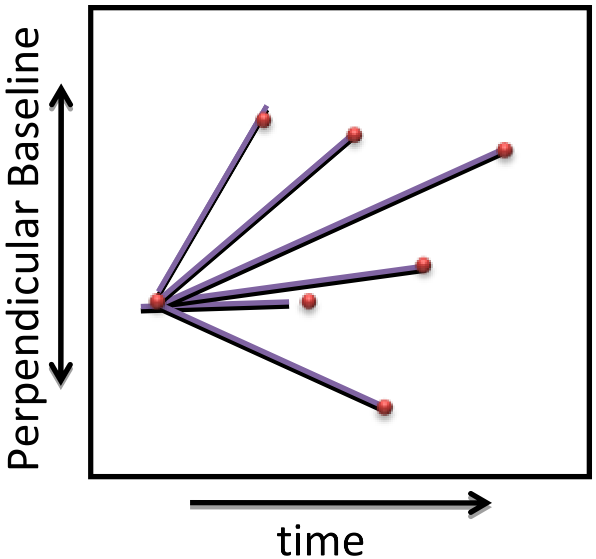

- Error on linear rate is independent of how network is connected (but of course short-baseline, short-time interferograms are best).
- To simplify mathematics, assume all connections to date d1...

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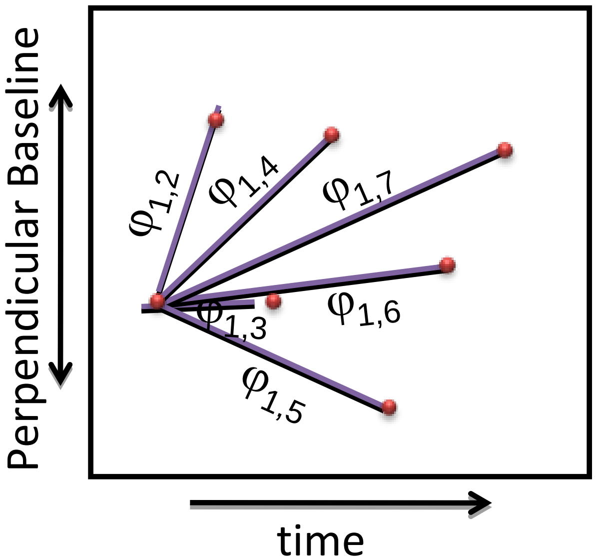

• Error on linear rate is independent of how network is connected (but of course short-baseline, short-time interferograms are best).

• To simplify mathematics, assume all connections to date d1...

...and regular acquisition spacing, t_m

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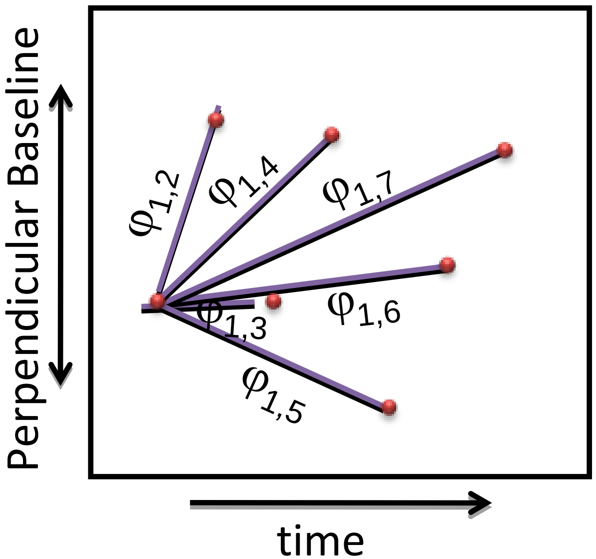


- Error on linear rate is independent of how network is connected (but of course short-baseline, short-time interferograms are best).
- To simplify mathematics, assume all connections to date d1...

...and regular acquisition spacing, t_r

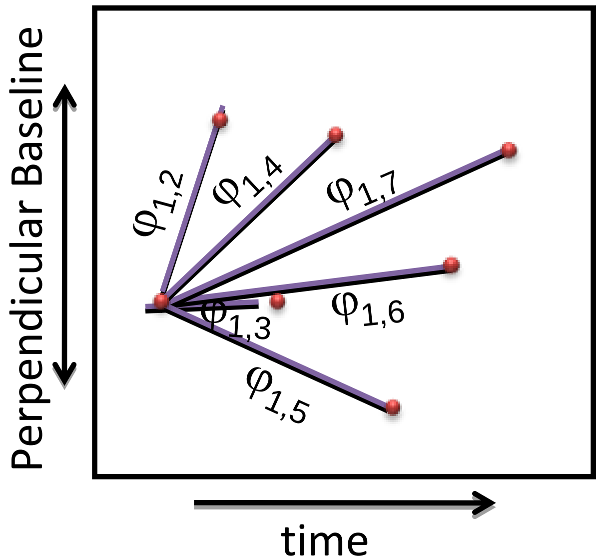
- We can determine the best-fit linear rate of phase change due to deformation, $\frac{d\varphi}{dt}$, using weighted least squares:

$$\mathbf{\Sigma}_{\mathbf{P}}^{-1}\mathbf{T}\frac{d\varphi}{dt} = \mathbf{\Sigma}_{\mathbf{P}}^{-1}\mathbf{P}$$

where **T** = $[t_r, 2t_r, \ldots Nt_r]^{\mathrm{T}}$, **P** = $[\varphi_{1,2}, \varphi_{1,3}, \ldots \varphi_{1,N}]^{\mathrm{T}}$, and $\mathbf{\Sigma}_{\mathbf{P}}^{-1}$ is the inverse of the variance-covariance matrix for the range change observations, **P**.

Error Budget (2)

Optimum determination of Linear Deformation Rates



- Using the correct VCM, $\mathbf{\Sigma_P}$, is essential.
- In this particular network, all interferograms share a common acquisition (epoch 1).

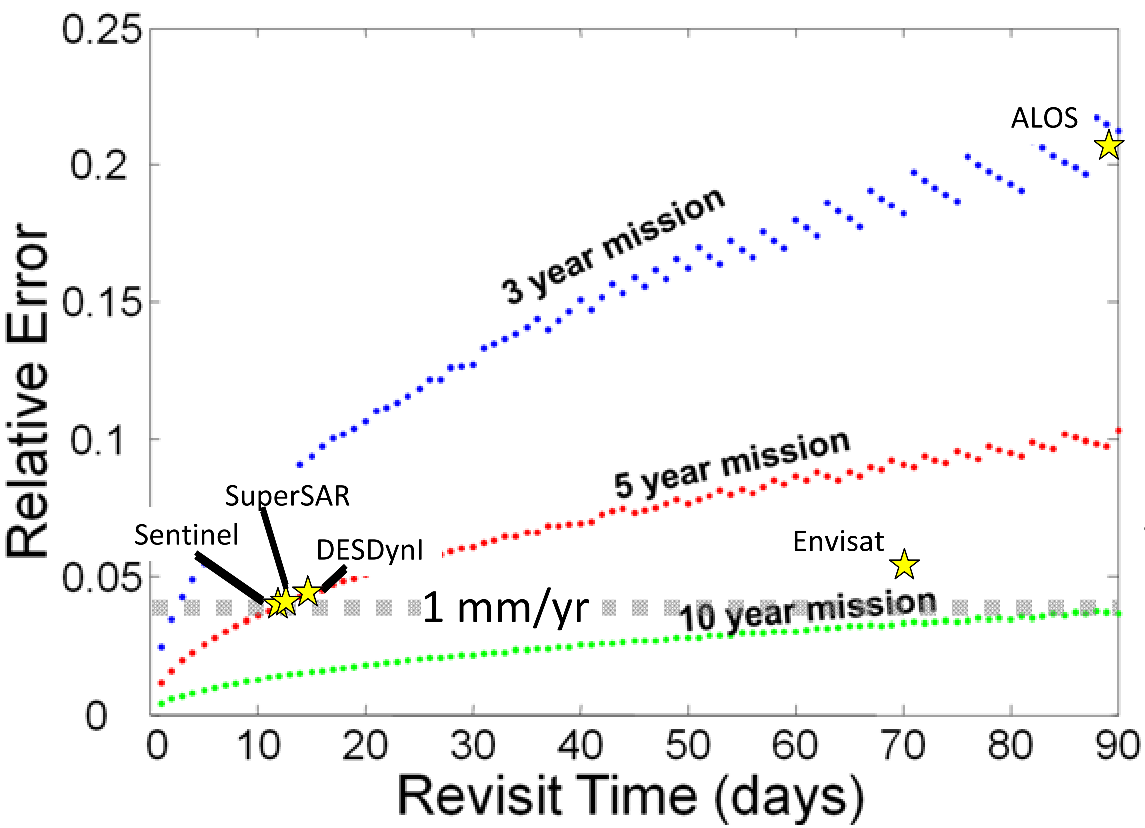
⇨ Cov ($\varphi_{1,i}$, $\varphi_{1,j}$) = σ_1^2 (the variance on epoch 1)

and Var ($\varphi_{1,i}$) = $\sigma_1^2 + \sigma_i^2$

= $2\sigma^2$ (assuming noise is identical on all epochs)

Error Budget (2)

Optimum determination of Linear Deformation Rates



Error $\propto$ ***(revisit time)***$^{0.5}$

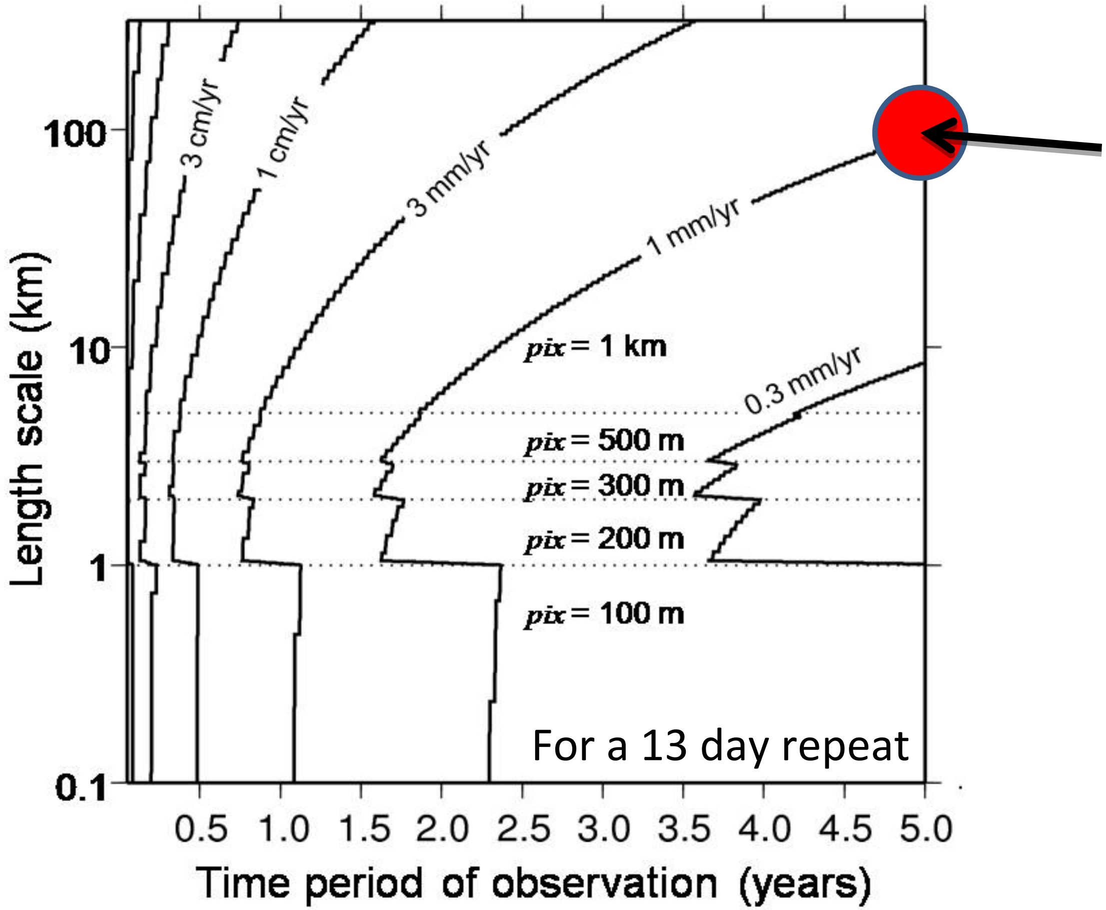
$\propto$ ***(mission length)***$^{-1.5}$

i.e.

- For a **fixed length mission**, cut revisit time by 4 to halve the linear rate error.
- For a **fixed revisit time**, increase mission length by ~60% to halve the linear rate error.

Error Budget (2)

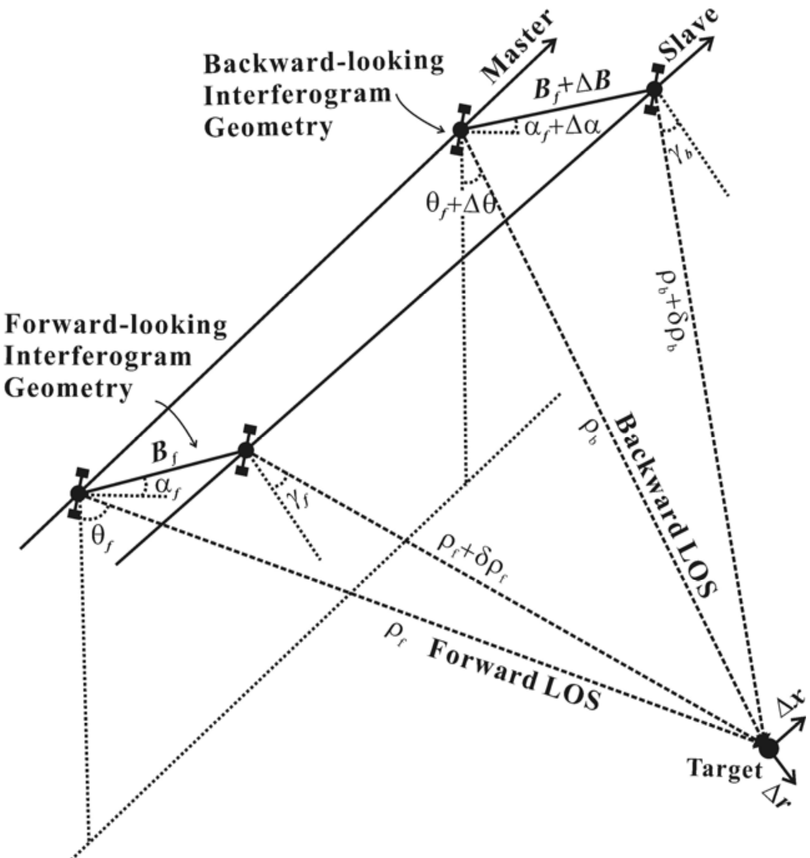
Optimum determination of Linear Deformation Rates



Reaching the target precision is tough!

Everything so far has been for Line-of-sight deformation

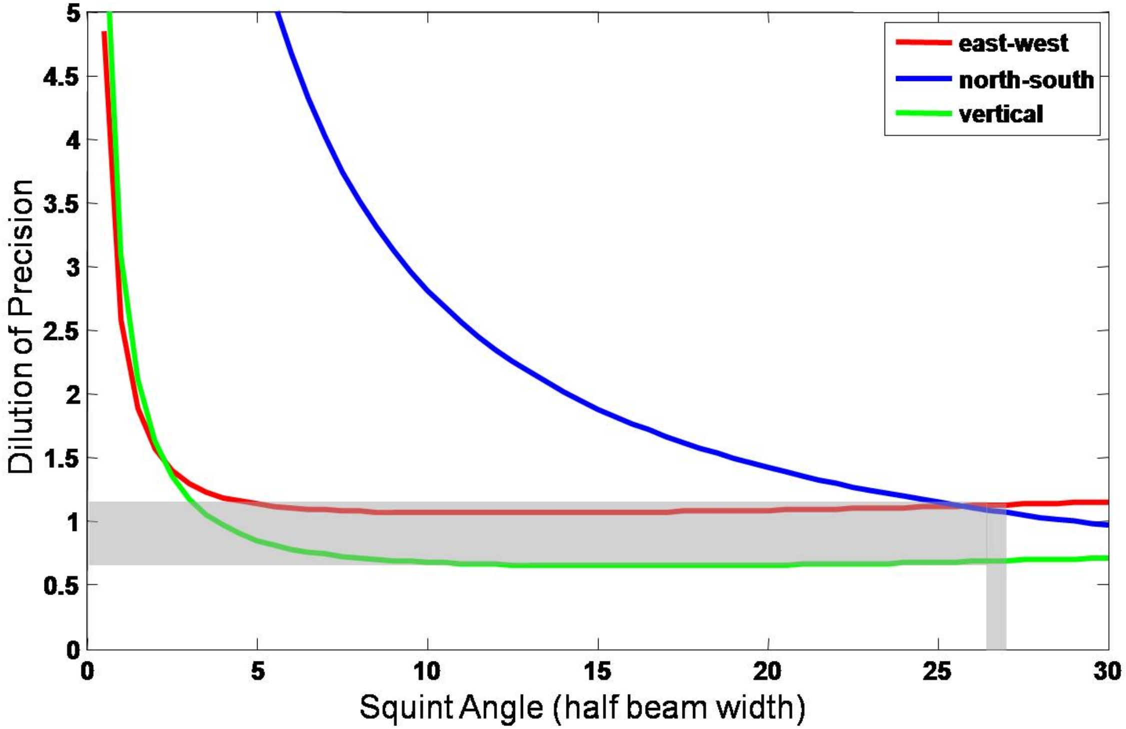
Error Budget (3)
3D deformation retrieval



SuperSAR imaging geometry

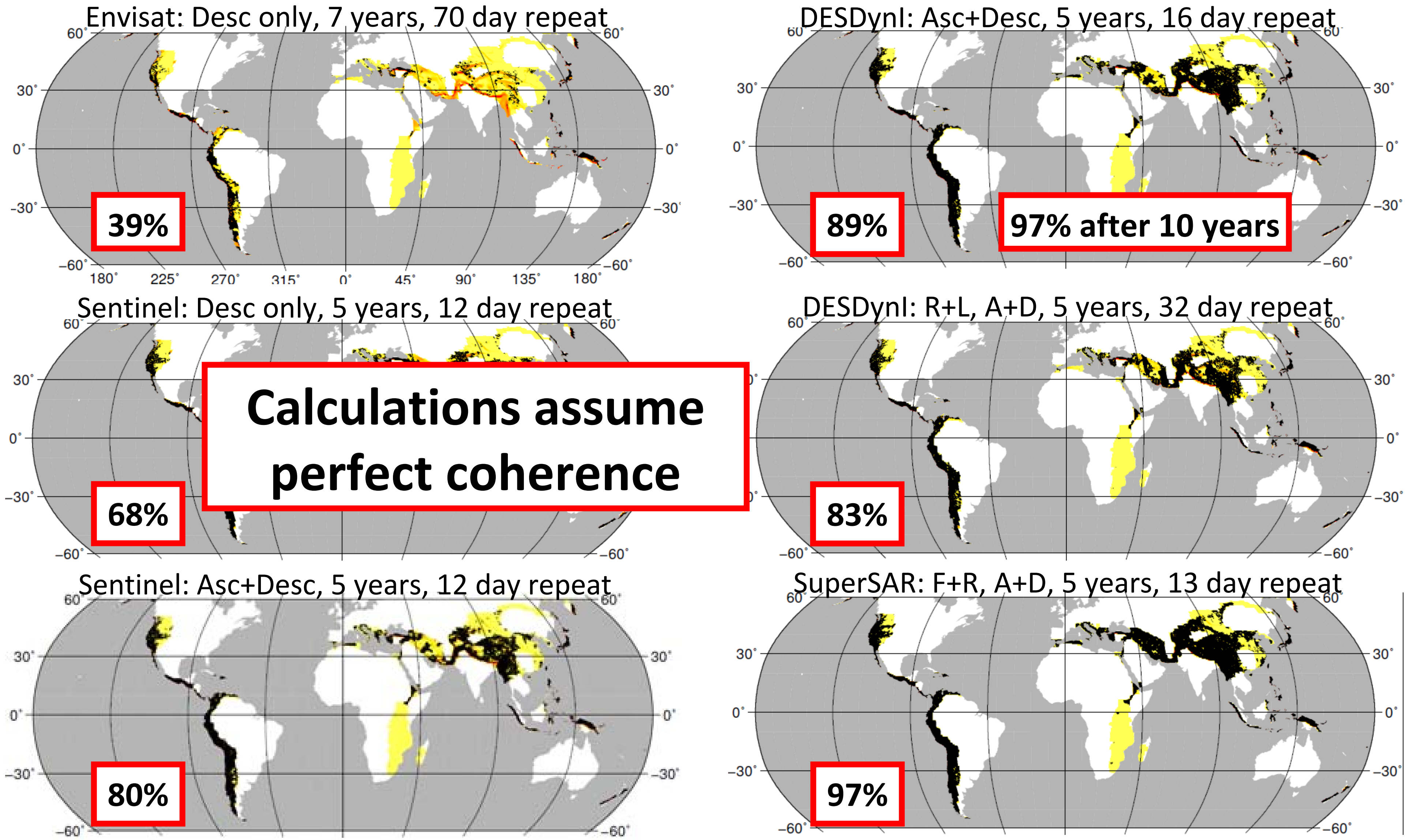
- SuperSAR and DESDynI were designed to retrieve 3D deformation.
- SuperSAR – forward and backward looking beams. 3D from 1 Asc + 1 Desc pass.
- DESDynI – L & R looking capability (although routine acquisitions were not planned). 3D from e.g 1 Asc + 2 Desc passes.

Error Budget (3)
3D deformation retrieval

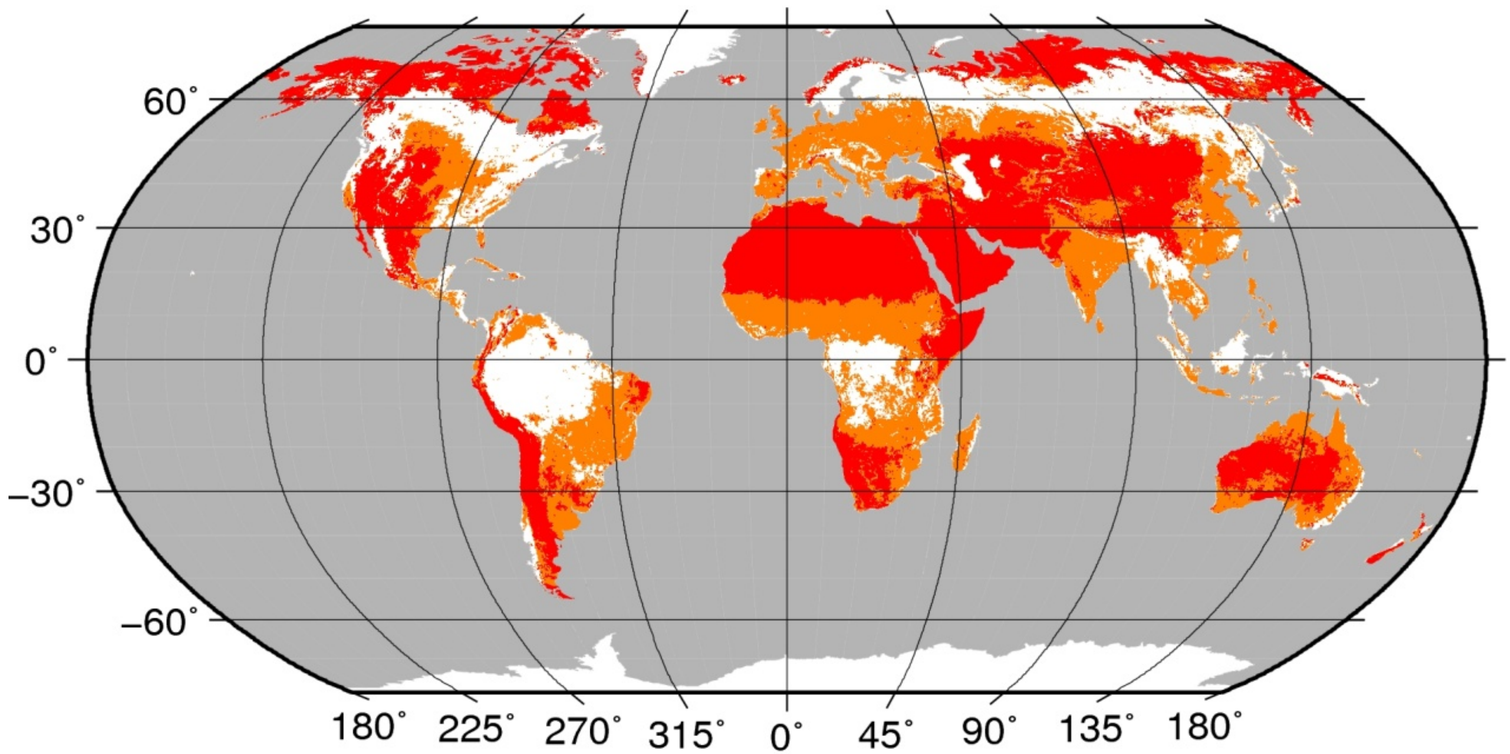


- Dilution of precision for SuperSAR ~1 for all 3 components if angle between beams > ~50 degrees
- Dilution of precision for DESDynI is ~1.1/5.1/0.9 in East/North/Up using 3 acquisitions (~0.8/3.6/0.7 using 4)

Abilities of missions to map tectonic strain above target threshold (1.2 mm/yr over 100 km)



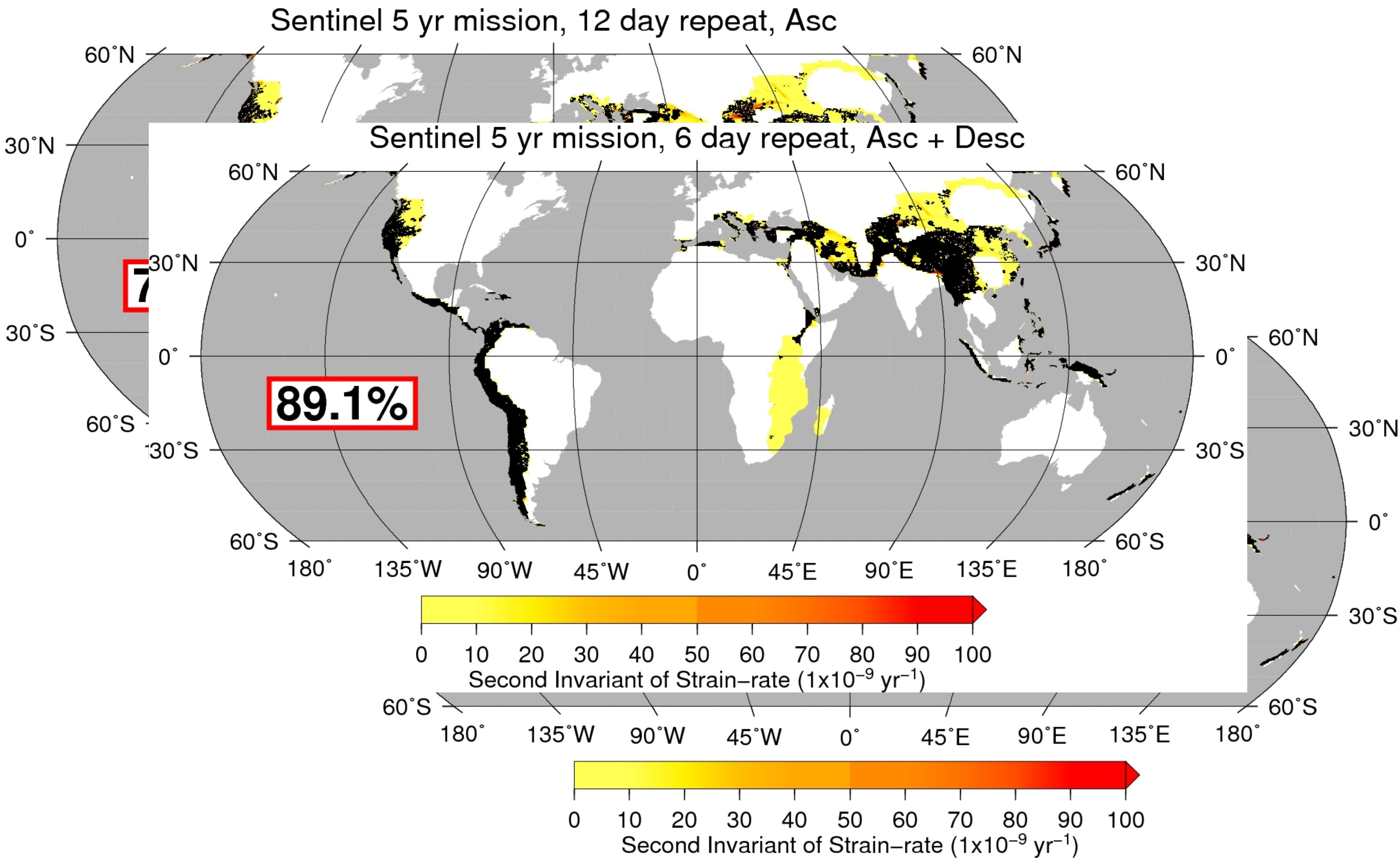
Abilities of missions to map tectonic strain: Coherence at C-band



C-band coherence (1 year = red; 1 cycle = red+orange)

L-band should be coherence in **most** places over 13 days

Abilities of missions to map tectonic strain above target threshold (1.2 mm/yr over 100 km)



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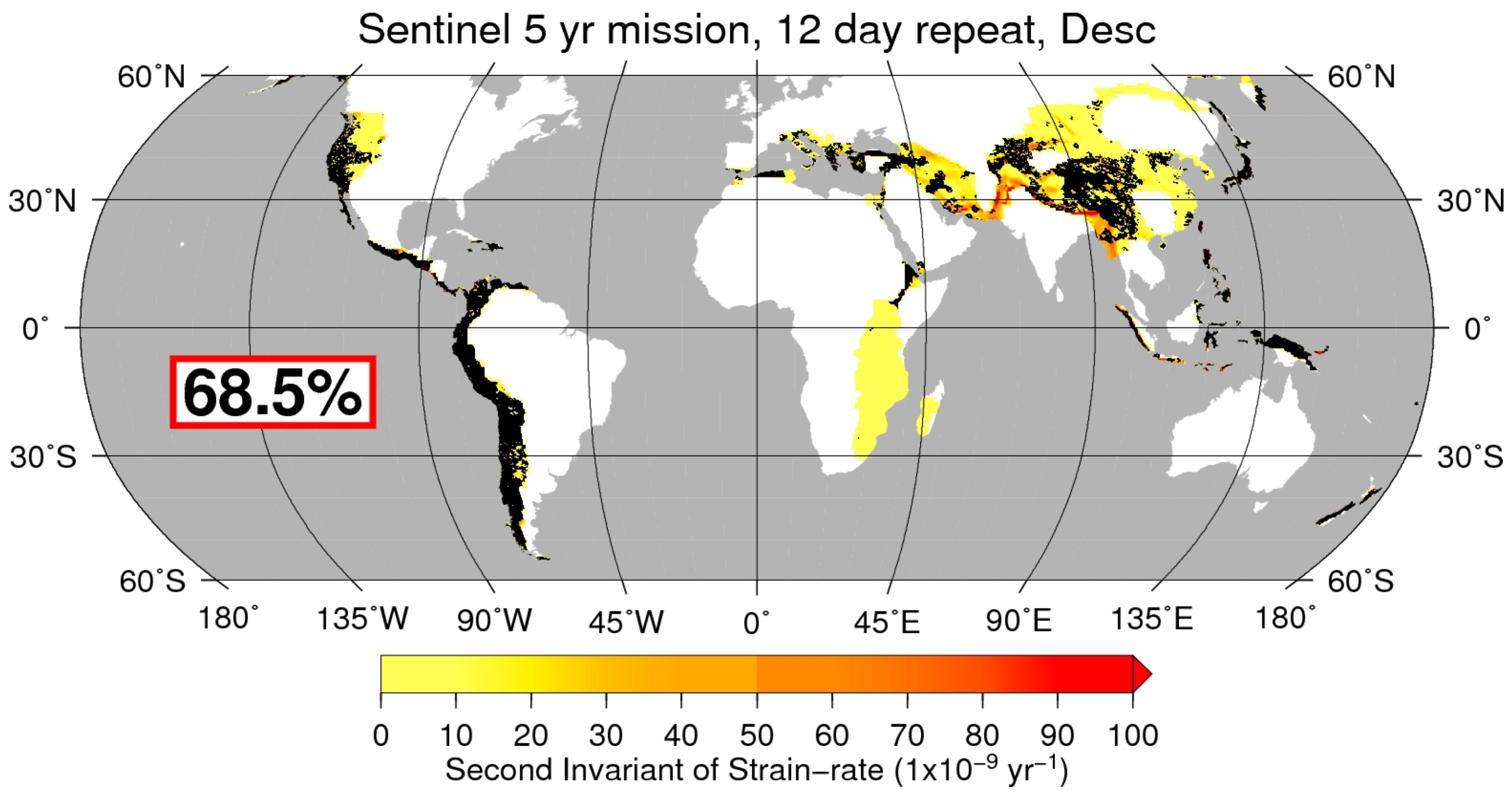
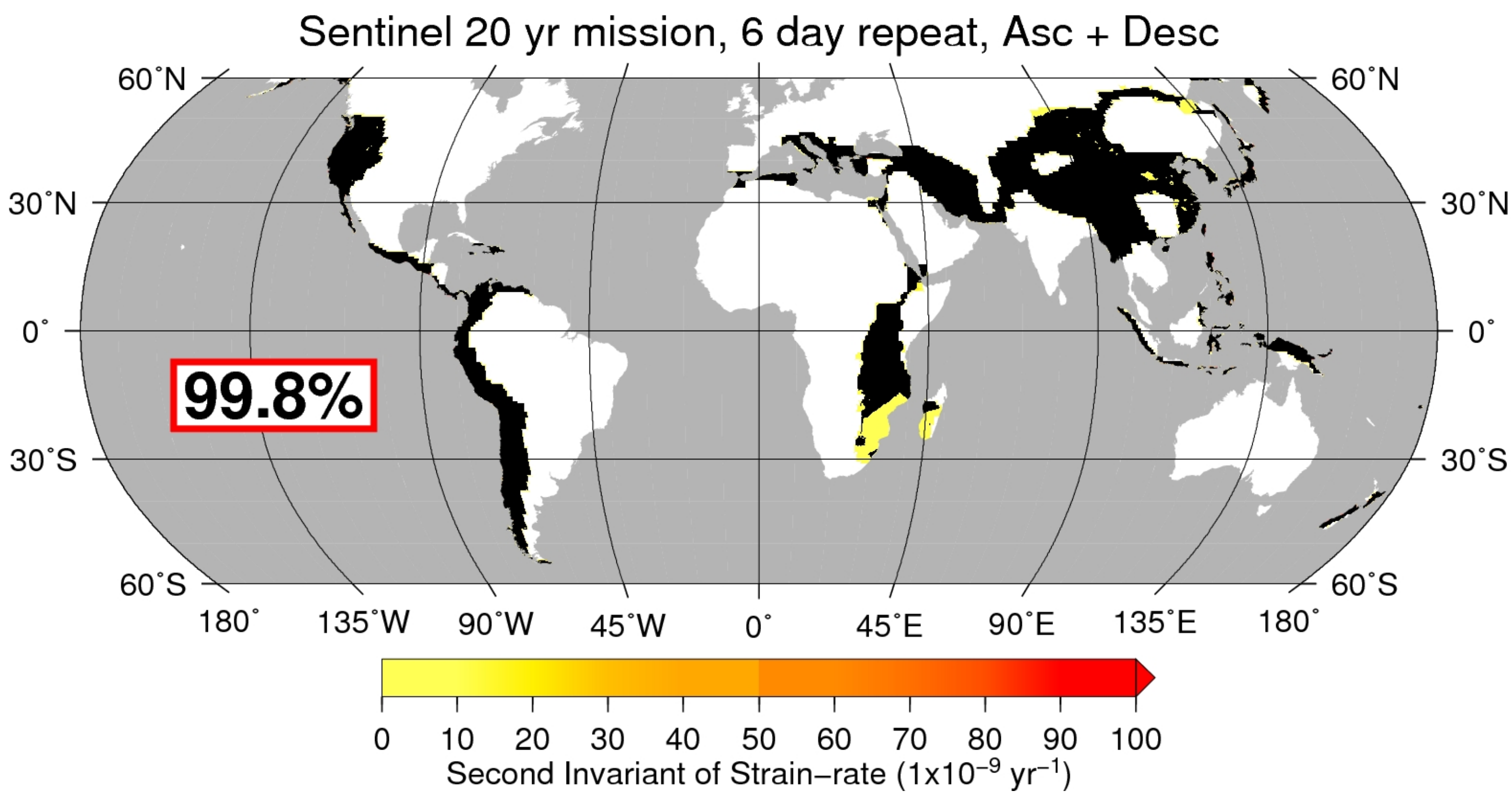


Conclusions and Recommendations

- Atmospheric errors are limiting factor for using InSAR to map strain accumulation
  - **Further research on routine adoption of weather models required**
- Sentinel-1 will greatly improve capability
  - **It should acquire ascending + descending data**
- DESDynI mission would have further improvements
  - **But there is no great benefit (for tectonic strain) in having left- and right- looking capability**
  - **Maximising the mission length is vital**
- SuperSAR's forward and rear squinted beams would enable 3D deformation to be retrieved with comparable accuracies in all three dimensions
  - **Future missions should consider adopting this concept**

Abilities of missions to map tectonic strain above target threshold (1.2 mm/yr over 100 km)



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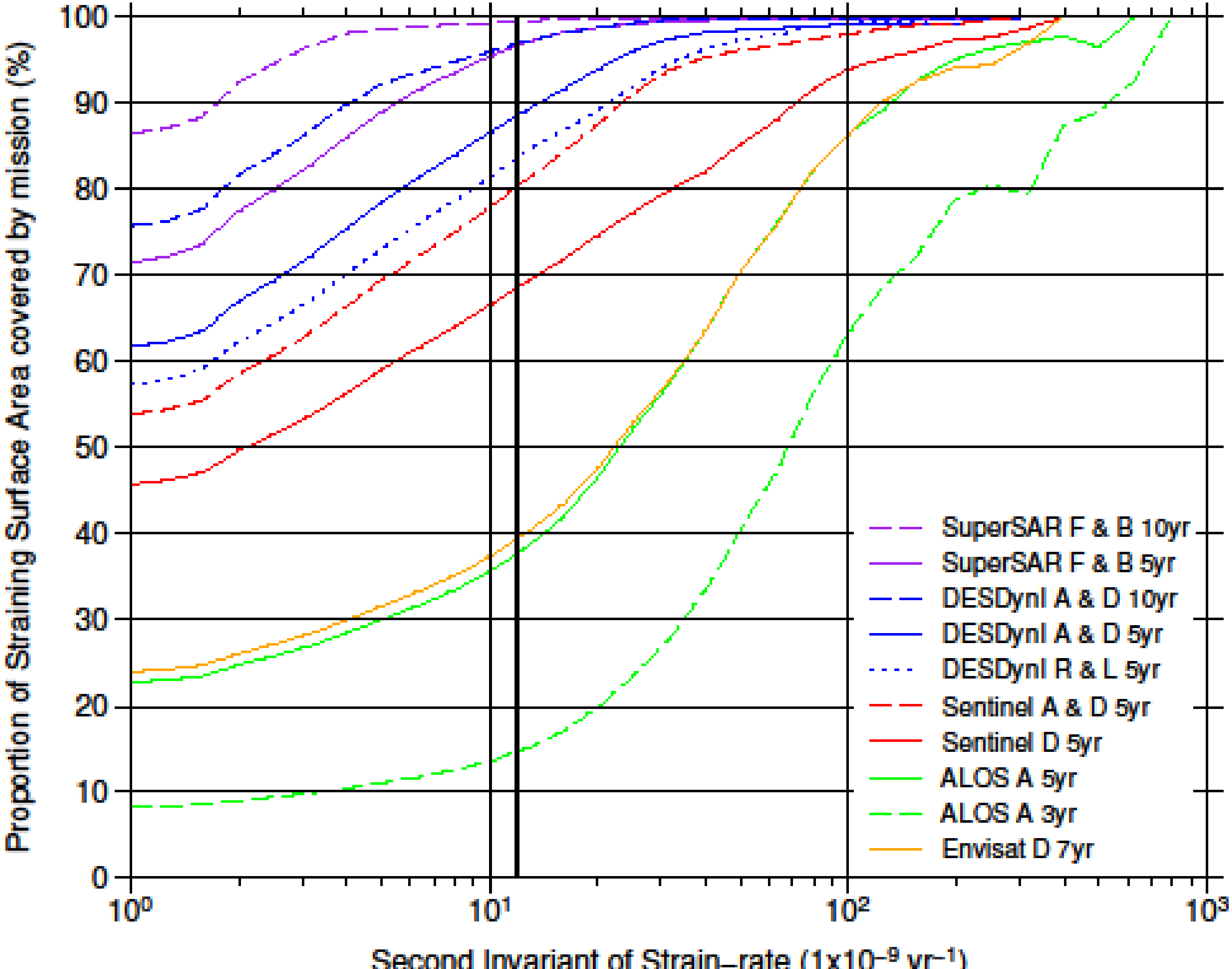

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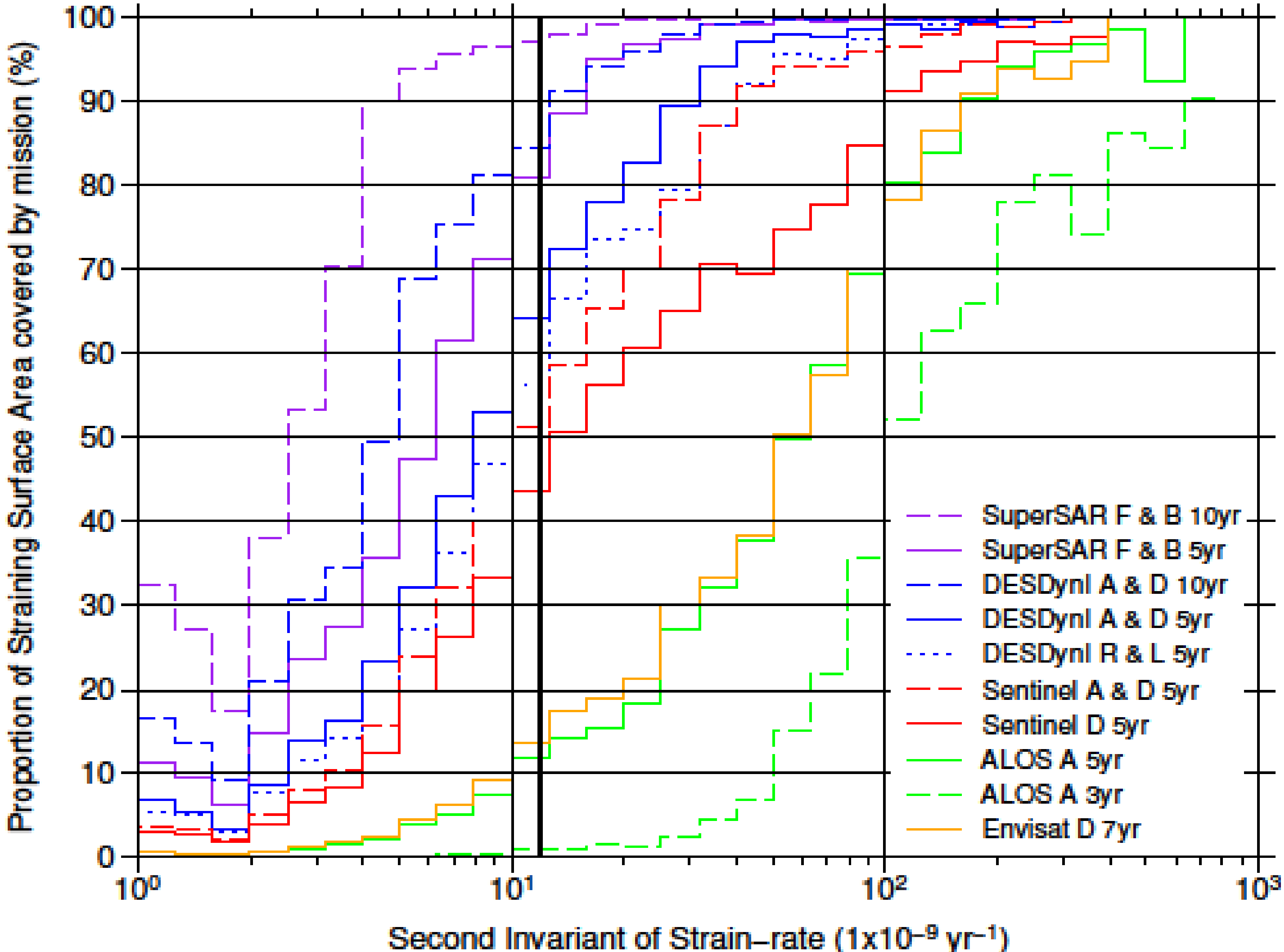


Error Budget
4. Unobserved uncertainties
b. Other

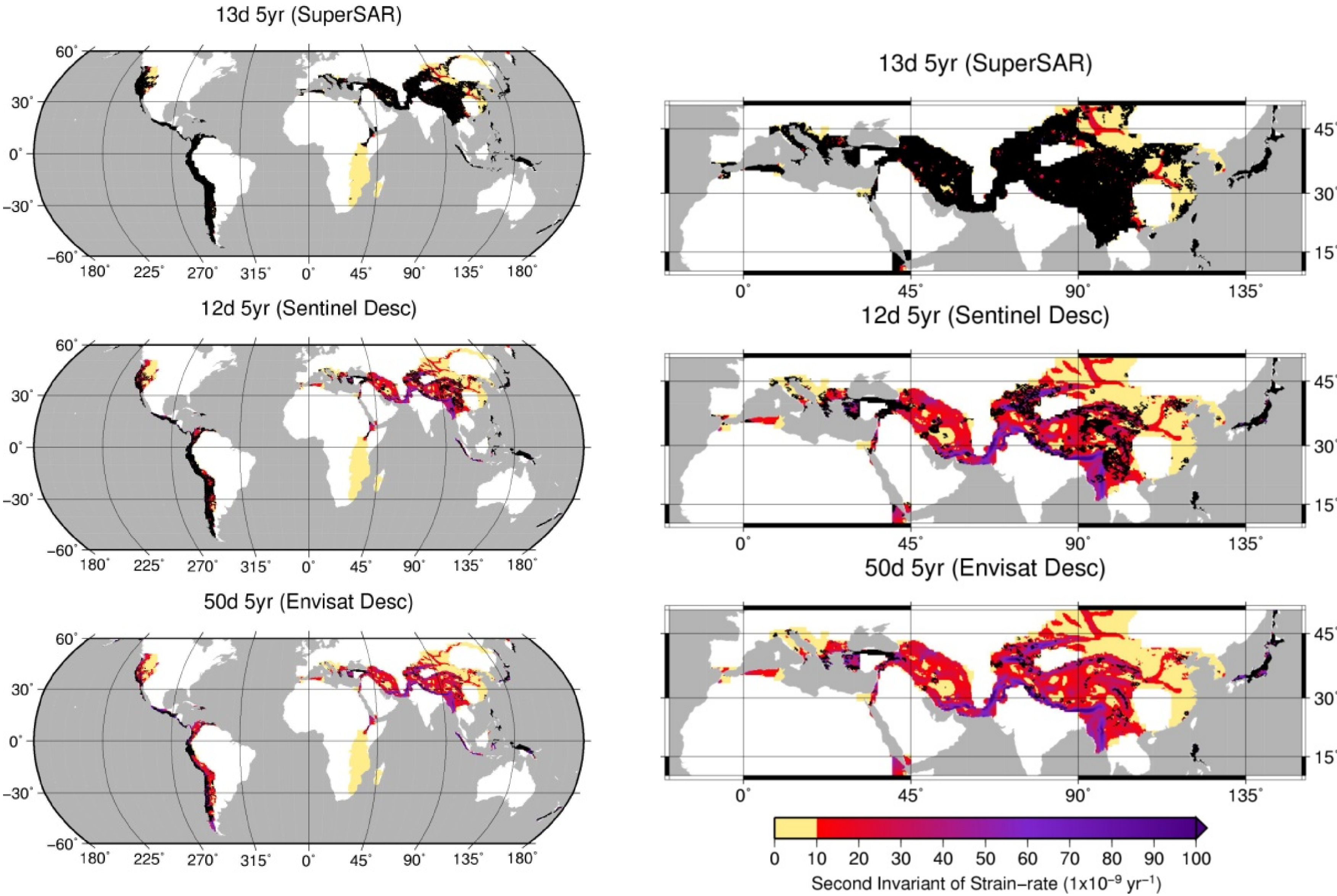
- Snow cover – reduces accuracy
- Water – no strain in oceanic plates can be observed
- Orbit – no observations north of 81.5^{o}
- Pixel size – limits max gradient to 60 cm per kilometre (17 m per year).
- Viewing geometry (layover/shadow), impacts on < 1% of straining zones.

Duty cycle

Target	**Frequency of Observation**	**Duty Cycle**	**Notes**
Tectonic Strain	Every pass, Asc + Desc	7.1%	All areas straining above 10^{-8} / year
Volcanoes	Every pass, Asc + Desc	0.14%	~300 volcanoes outside tectonic strain zones
Ice	Two passes from four, Asc + Desc	0.6%	Complete spatial coverage
Background Archive	One image per year, Asc + Desc	0.9%	All remaining areas
Economic/Other	450 targets, every pass, Asc + Desc	1.25%	Each target covers an area 100 x 310 km. # targets could be increased by decreasing the revisit time
Total		**10%**	An increase or decrease in this value would directly impact on the number of economic/other targets that could be imaged.

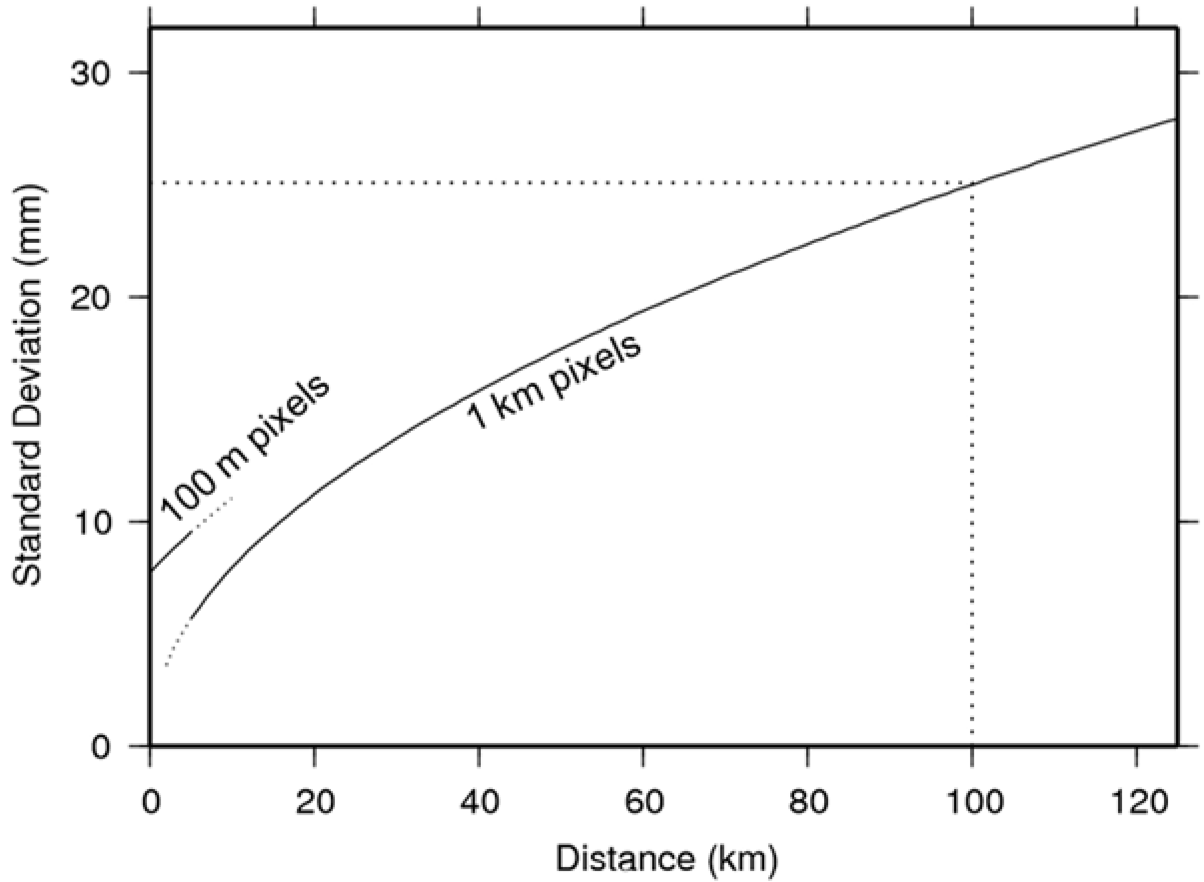
Table D4.3.1: Estimates for the total duty cycle load for each of our scientific targets

SuperSAR vs Envisat and Sentinel-1



Error Budget
1. Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{trop}^2 + \sigma_{ion}^2 + \sigma_{coh+sys}^2 + \sigma_{unw}^2$$



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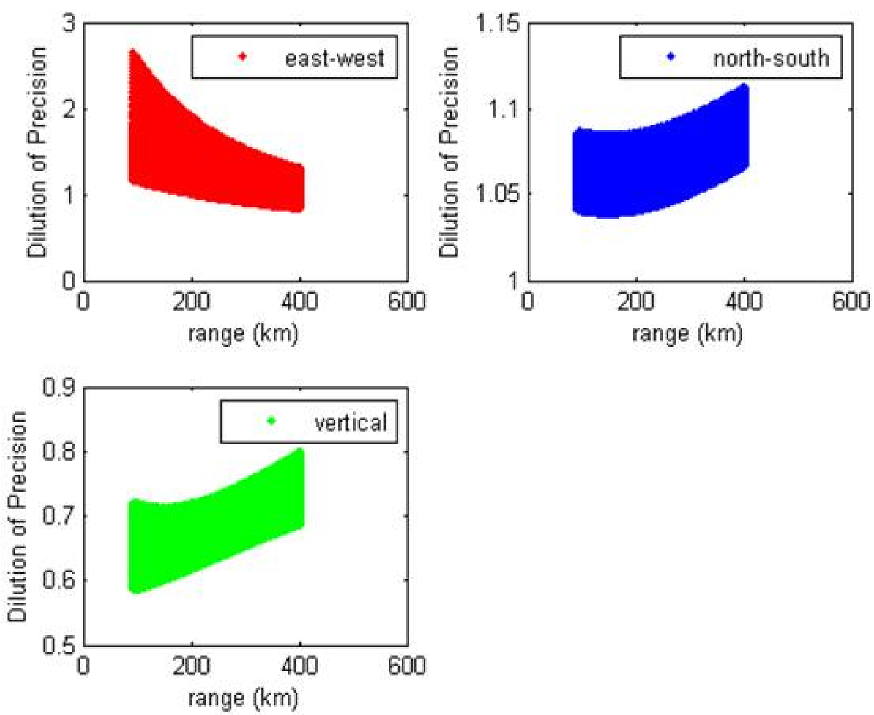
Component	**Error (1 sigma)**			**Comments**
	L = 100 m	L = 1 km	L = 100 km	
σ_{gm}	Negligible	Negligible	≤ 1.6 mm (future missions)	Short wavelength orbital error is negligible;
σ_{topo}	1.1 mm	1.1 mm	0.9 mm	Assuming SRTM elevation model and 1 km pixels for 100 km error.
σ_{trop}	0.8 mm	2.5 mm	25 mm	
σ_{ion}	Negligible	Negligible	0.9 mm	After correction using dual frequencies, and filtering over 10 km length scale.
$\sigma_{coh+sys}$	7.6 mm	7.6 mm	0.76 mm	Assuming 100 m pixels for L ≤ 1 km; 1 km pixels for L = 100 km, coherence of 0.9, and system of 6.9dB.
σ_{unw}	Negligible	Negligible	Negligible	High coherence, long wavelength, and short repeat times should minimise unwrapping errors.
$\boldsymbol{\sigma_{def}}$	**7.7 mm**	**8.1 mm**	**25.1 mm**	**The phase noise is dominated by $\boldsymbol{\sigma_{coh+sys}}$ over short distances and $\boldsymbol{\sigma_{trop}}$ at long lengthscales**

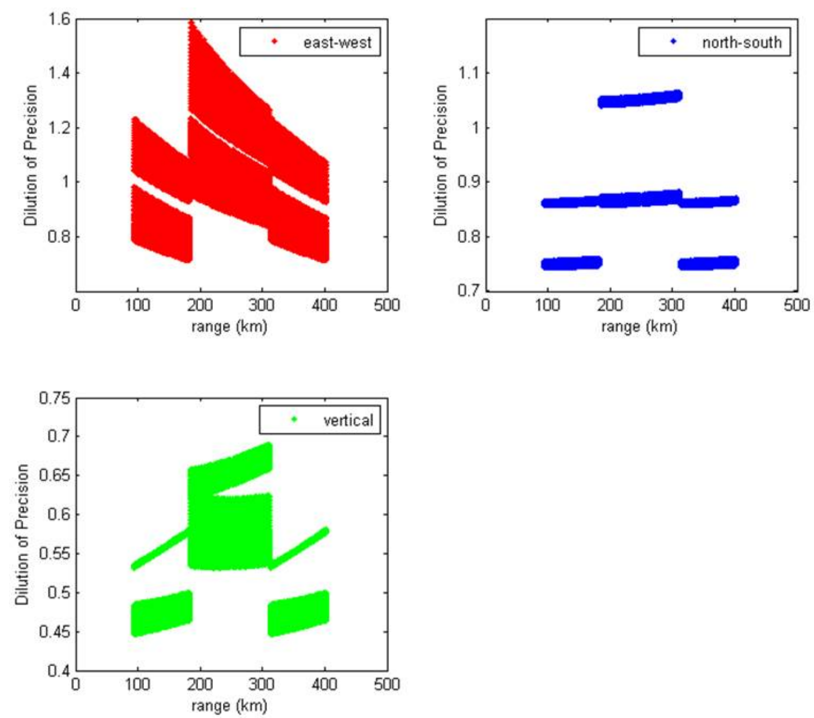
Table D3.1.1: Error budget for SuperSAR at different lengthscales

Error Budget
3. Accuracy of 3D retrieval

DOP for all positions within swath (27 degree half-squint)

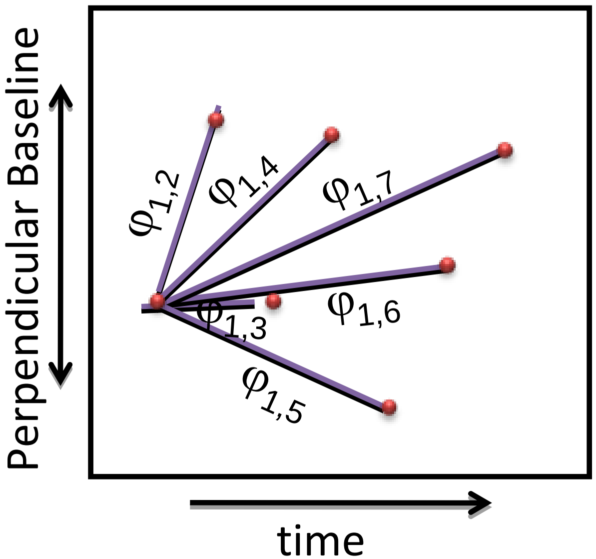


No overlap



Overlap of 90 km

Error Budget
2. Optimum determination of Linear Deformation Rates



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- We can determine the best-fit linear rate of phase change due to deformation, $\frac{d\varphi}{dt}$, using weighted least squares:

$$\mathbf{\Sigma_P^{-1}T}\frac{d\varphi}{dt} = \mathbf{\Sigma_P^{-1}P}$$

where $\mathbf{T} = [t_r, 2t_r, \ldots Nt_r]^{\mathrm{T}}$, $\mathbf{P} = [\varphi_{1,2}, \varphi_{1,3}, \ldots \varphi_{1,N}]^{\mathrm{T}}$, and $\mathbf{\Sigma_P^{-1}}$ is the inverse of the variance-covariance matrix for the range change observations, **P**.

Therefore: $\frac{d\varphi}{dt} = (\mathbf{T^T\Sigma_P^{-1}T})^{-1}\mathbf{\Sigma_P^{-1}P}$, and $\sigma_r = \sqrt{(\mathbf{T^T\Sigma_P^{-1}T})^{-1}}$

Current/Planned/Proposed InSAR Missions

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Radarsat-1/2 1995-	C	24 days	Low (usually)	R-looking, usu. 23° inc, mostly descending
ALOS 2006-	L	46 days	40-60%	R-looking, usu. 34° inc, mostly ascending
Terrasar-X 2008-	X (~2 cm)	12 days	Very Low	R-looking, Variable acquisition modes.
Sentinel-1A 2012/13-	C	12 days	100%	R-looking, 25-45° inc, Mostly descending??
DESDynI 2016?-	L	16 days	100%	R-looking (occasionally left), ~40° inc, Asc+Desc
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- Coherence, γ

$$\sigma_{coh} = \left(\frac{\lambda}{4\pi}\right)\frac{1}{\sqrt{N_L}}\frac{\sqrt{1-\gamma^2}}{\gamma}$$

C-band (λ=60 mm)

γ = 0.7

-> ~5 mm for ~100 m pixels

-> 0.5 mm for 1 km pixels

L-band (λ=240 mm)

γ = 0.9

-> ~4 mm for ~100 m pixels

-> 0.4 mm for 1 km pixels

Error Budget (1)
Single interferogram

$$\sigma_{def}^2 = \sigma_{gm}^2 + \sigma_{topo}^2 + \sigma_{atm}^2 + \sigma_{coh}^2 + \sigma_{sys}^2 + \sigma_{unw}^2$$

- Coherence, γ

$$\sigma_{coh} = \left(\frac{\lambda}{4\pi}\right)\frac{1}{\sqrt{N_L}}\frac{\sqrt{1-\gamma^2}}{\gamma}$$

C-band (λ=60 mm)

γ = 0.7

-> ~5 mm for ~100 m pixels

-> 0.5 mm for 1 km pixels

L-band (λ=240 mm)

γ = 0.9

-> ~4 mm for ~100 m pixels

-> 0.4 mm for 1 km pixels

- System (thermal) - modifies coherence

$$\gamma_c = \frac{\gamma}{1 + SNR^{-1}}$$

e.g. Noise of 6.9dB (L-band SuperSAR)

-> 7.6 mm for 100 m pixels

-> 0.76 mm for 1 km pixels (coh + sys)