Least squares combination of INSAR and GNSS measurements for ground displacement monitoring

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Outline

1. **Research aims**
2. **Previous works**
3. **Combination method**
   - **mathematical model**
   - **experiment using simulated data**
4. **Conclusions and perspectives**

1. Research aims

Ground deformation measurement techniques

Terrestrial topometry
(total station, level)

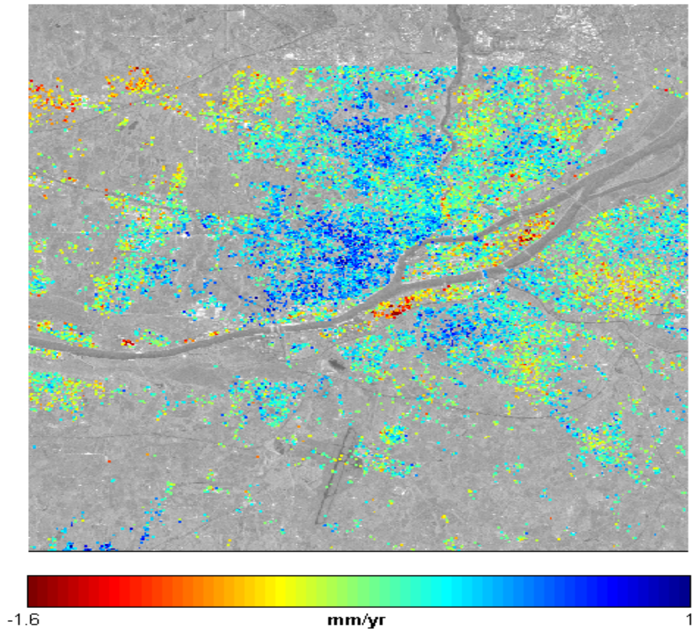
↓

3D relative location: angle and distance measurements

GNSS

↓

3D positioning



SAR interferometry

↓

displacement measurement
(1 component)

GNSS / INSAR complementarity

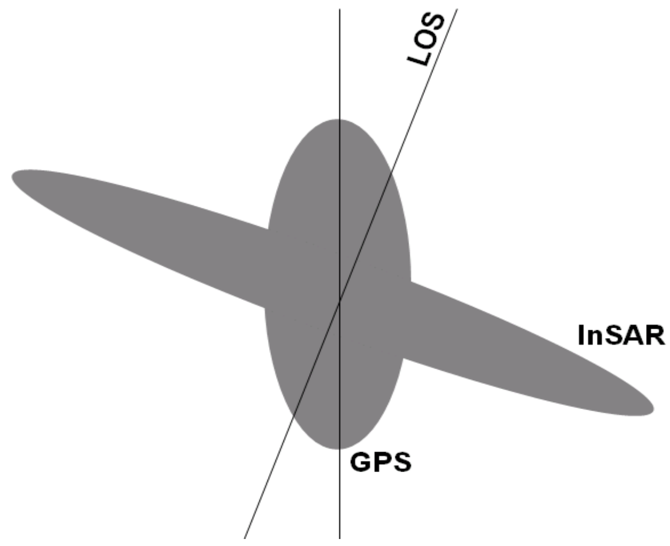
Ambiguous INSAR phase

High spatial sampling in INSAR

High temporal sampling in GNSS

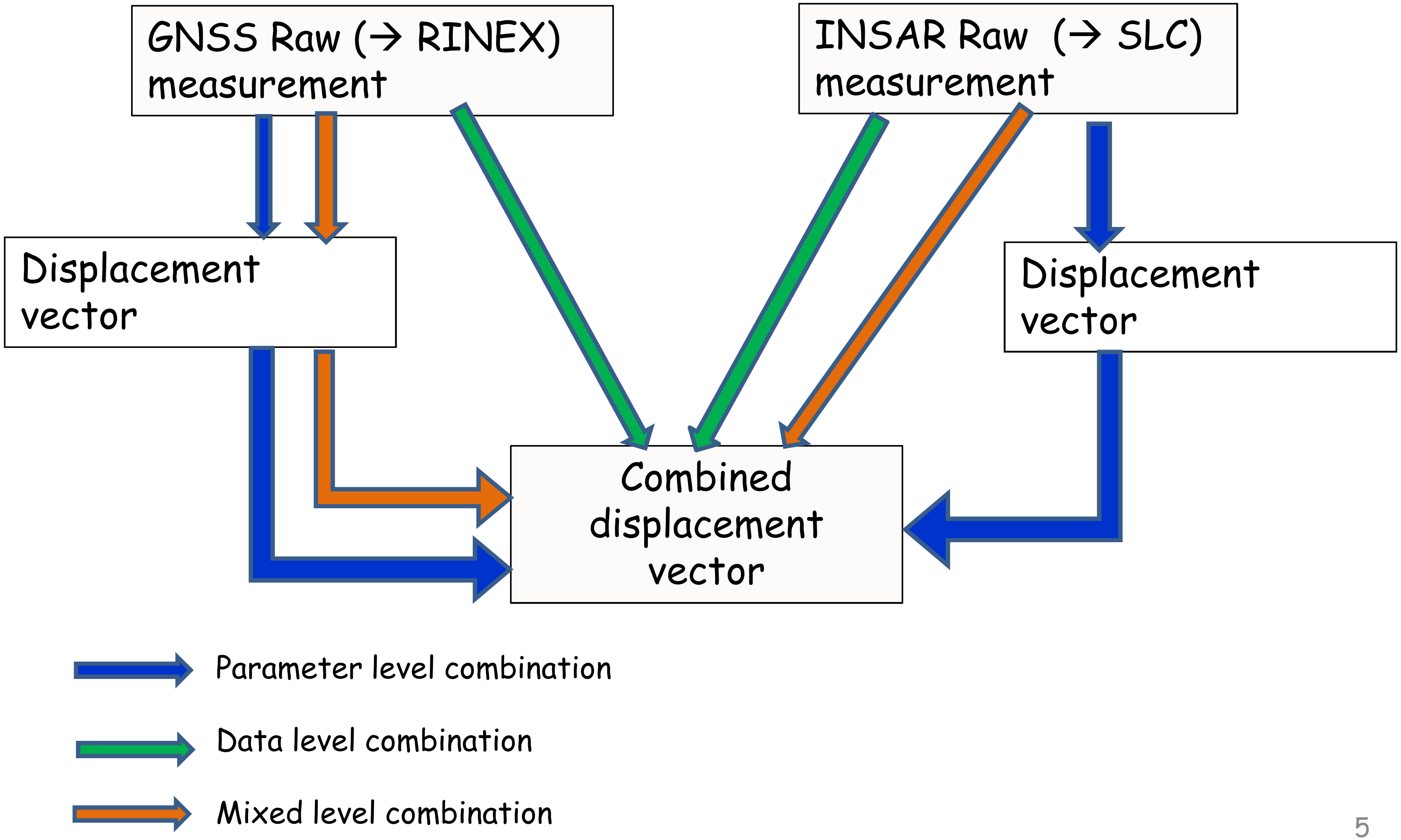
Different error behaviors

Similar wavelengths



Error ellipses in both techniques

Different combination strategies



2. Previous works

GNSS + total station

Similar information
Point measurement at 1 date

Very different physical principles
GNSS (GPS) : microwave
Total station : optical

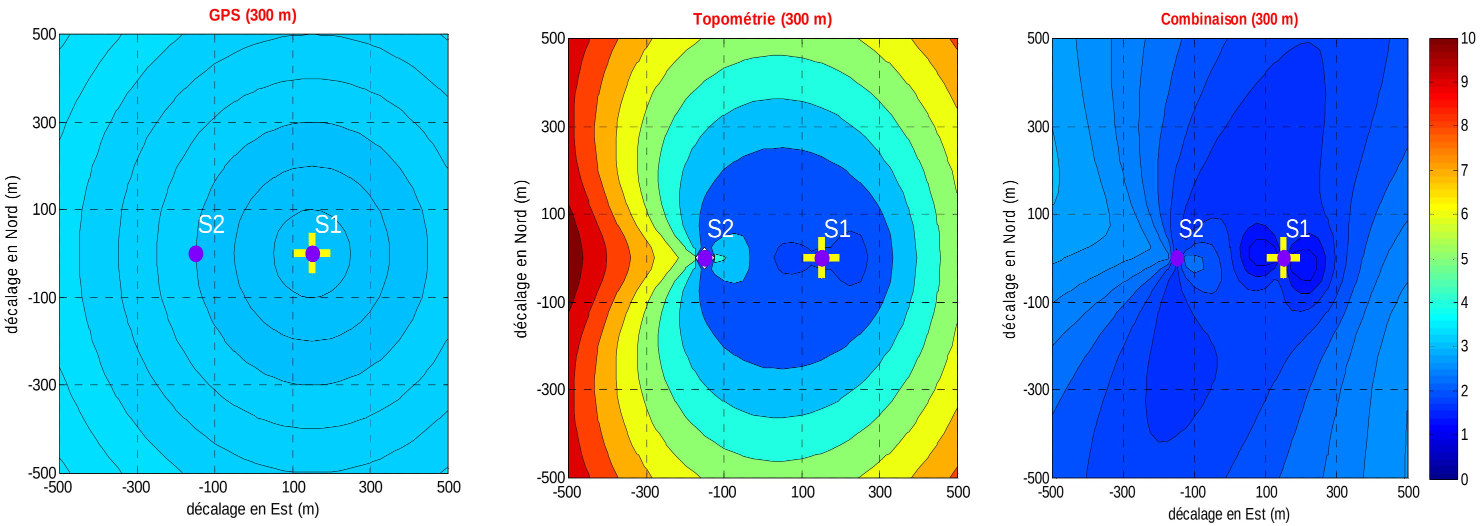
Different behaviours
→ **possible synergy ?**

Parameter level combination
Hybrid triangulation, Merging points obtained from both techniques

Data level combination
Single least squares adjustment with both GPS and total station observations

Experiments: Using simulated data and then real data

Accuracy of the planimetric coordinates of one point measured from two known stations



Measurement accuracy of the planimetric coordinates with the data level combination always better, up to 40% of those of the most accurate technique

INSAR + GNSS

Parameter level combination
Atmospheric phase estimation from GNSS measurements

Analysis according to :

- INSAR configuration
- GNSS configuration: receiver number, receiver locations
- GNSS processing: atmospheric model
- atmospheric delay map interpolation method

→ Experiments using simulated data

Deformation measurement errors according to the GNSS station number

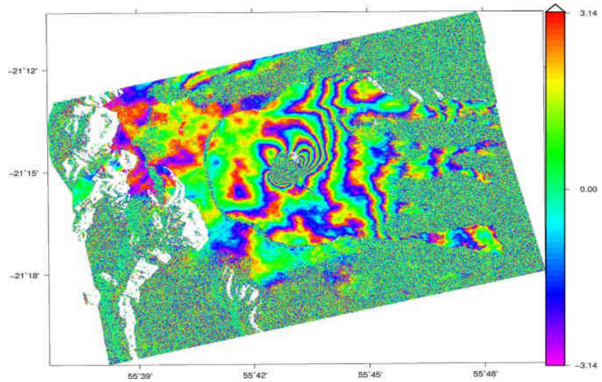
Number of GNSS stations	Mean error (mm)	Standard deviation (mm)
0	-19.40	1.33
5	0.78	1.31
10	0.09	1.05
20	-0.59	0.64

Usefulness of the atmospheric correction for assessment of small displacement measured by millimeters to centimeters

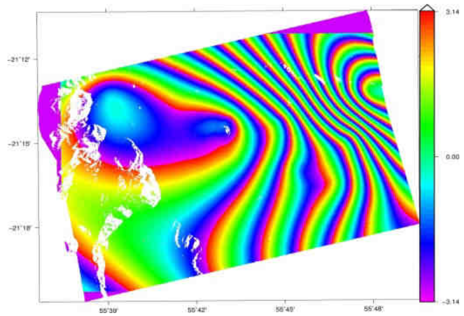
→ Experiments using real data (Piton de la Fournaise, France)

- Processing of 2 radar CSK data using DORIS software
- Two dates : 04/28/2014 and 07/09/2014
- Processing of 27 GNSS stations using GAMIT (based on VZHD and VMF1 models)

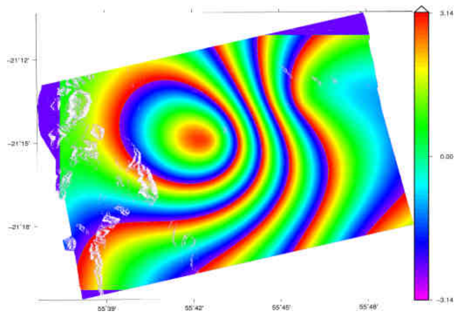
Differential phase [rad]



Simulated tropospheric differential phase [rad]

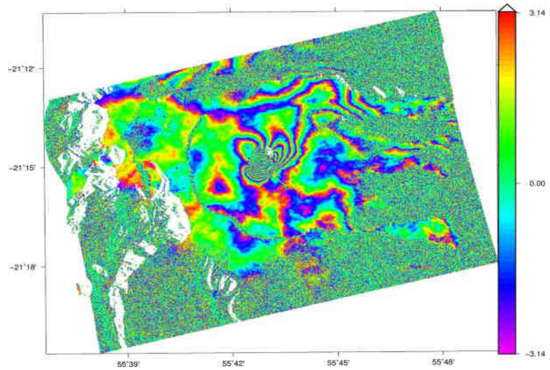


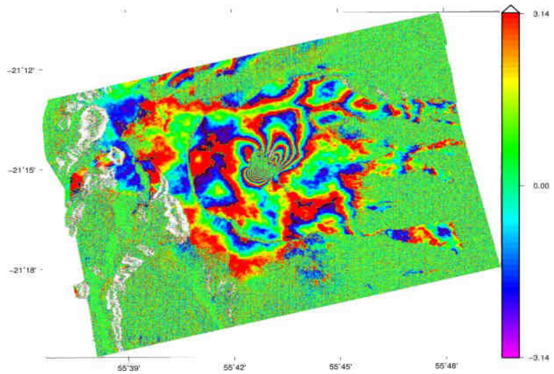
from all available GNSS stations and triangular interpolation



from 5 available GNSS stations and cubic spline interpolation

Corrected differential phase [rad]





Influence of the number of GNSS stations, spatial distribution and tropospheric map interpolation method

3. Combination method

Approach:

Data level raw measurement combination

Based on least squares adjustment for INSAR and GNSS measurements

Limitations of this work:

Combination benefit not proved in this work

Equations presented for non ambiguous phases (preliminary unwrapped)

No weighting

Atmospheric effects not considered

Assumption of a linear vertical ground displacement velocity model

INSAR processing:

STUN (Spatio-Temporal Unwrapping Network) approach

Kampes BM. Radar Interferometry. Persistent Scatterer technique. Springer; 2006.

Simplified STUN method explanation:

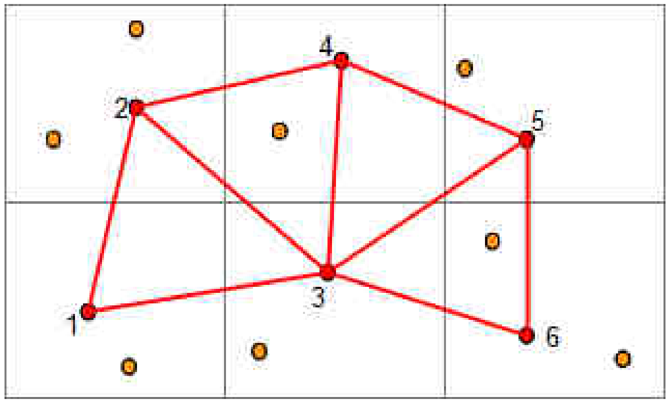
1. Computation of N differential interferograms from N+1 radar images with one single master image

2. Persistent Scatterer detection:

PS detection using average signal to clutter ratio

PS classification according to the amplitude dispersion index

→ PSC network, other PS



PSC

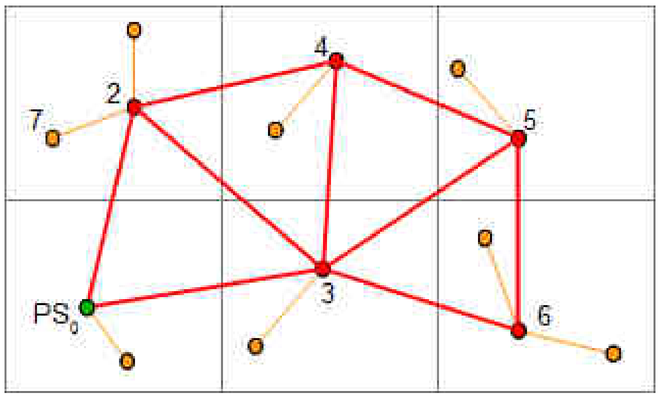
Other PS

3. Parameter inversion (phase ambiguity, DEM error, displacement velocity) for each PSC network arc :

- Least square adjustment of parameters
- LAMBDA (Least squares AMBiguity Decorrelation Adjustment) method for integer adjustment of the phase ambiguity
- Derivation of float parameters (DEM error and displacement velocity)

4. Integration from a reference PS_0 by a linear system inversion

5. Other PS processing: same weighted unwrapping method, MCF refinement, float parameter estimation



INSAR differential phase model:

Between two pixels P and Q:

$$\phi_{diff,P,i} - \phi_{diff,Q,i} + 2\Delta k_{P,Q,i}\pi = \frac{4\pi}{\lambda}\frac{B_{\perp,i}}{r_P \sin\theta_P}\Delta e_{P,Q} + \frac{4\pi}{\lambda}(t_i - t_0)\Delta\alpha_{P,Q}$$

$$\Delta k_{P,Q,i} = k_{P,i} - k_{Q,i} \qquad \Delta e_{P,Q,i} = e_{P,i} - e_{Q,i} \qquad \Delta\alpha_{P,Q,i} = \alpha_{P,i} - \alpha_{Q,i}$$

phase ambiguities (integer)

DEM errors

LOS displacement velocities

GNSS processing:

Double difference concept
Several stations, several sessions, several epochs per session.

GNSS phase model:

Between two stations, 1 and 2, and two GNSS satellites, *k* and *l*:

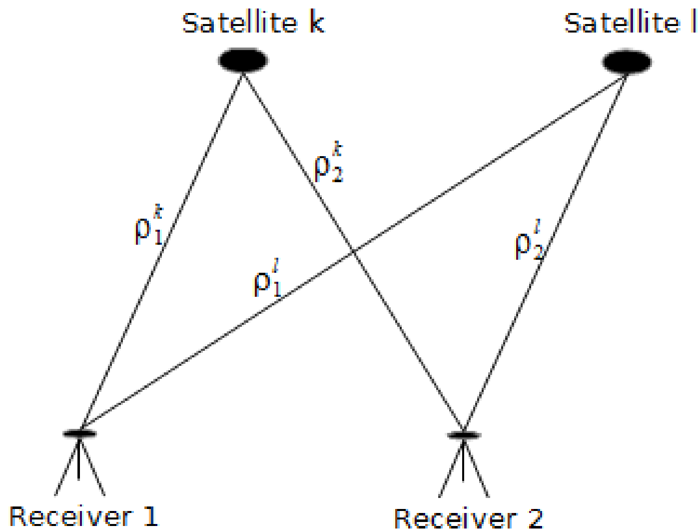
$$\phi_{12}^{kl} = \left(\phi_2^l - \phi_1^l\right) - \left(\phi_2^k - \phi_1^k\right)$$

$$\lambda\phi_{12}^{kl} = \rho_2^l - \rho_1^l - \rho_2^k + \rho_1^k - \lambda N_{12}^{kl} + e_{12}^{kl}$$

distances

DD phase ambiguity (integer)

Residual error



Euclidian distance between *i*-station and *j*-satellite:

$$\rho_i^j = \sqrt{\Delta X^2 + \Delta Y^2 + \Delta Z^2}$$

Considering that *i*-station is located at *P*-pixel:

$$\Delta X = \left(N_j + h_P + e_P + \frac{\alpha_P}{\cos\theta_P}(t - t_0) \right) \cos\varphi_j \cos\lambda_j - X_s$$

$$\Delta Y = \left(N_j + h_P + e_P + \frac{\alpha_P}{\cos\theta_P}(t - t_0) \right) \cos\varphi_j \sin\lambda_j - Y_s$$

$$\Delta Z = \left(N_j (1 - exc^2) + h_P + e_P + \frac{\alpha_P}{\cos\theta_P}(t - t_0) \right) \sin\varphi_j - Z_s$$

Satellite coordinates

DEM height

DEM error

Vertical displacement velocity

Station geographic coordinates

Proposed global inverse processing:

GNSS observation equations are added to the INSAR problem inversion
Estimation of two parameters: DEM error and displacement velocity

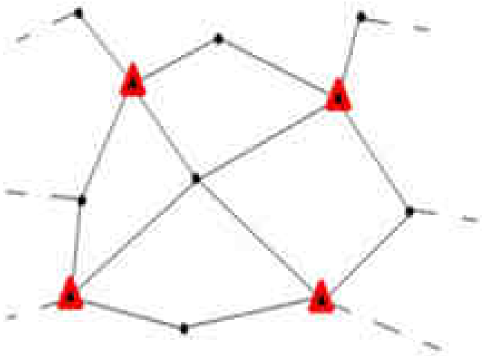
Possible strategies:

Estimation of parameter differences along arcs	Estimation of **parameters** at each PS
Processing of the PSC with GNSS points and then processing of other PS	**Global processing** of PSC, other PS and GNSS points
Combining PS normal equations and GNSS normal equations after convergence	Combining PS linear equations and GNSS linearized equations in an **iterative framework**
GNSS receiver locations not correlated with the PSC locations	**Some PSC equipped** with a GNSS receiver and no other GNSS locations

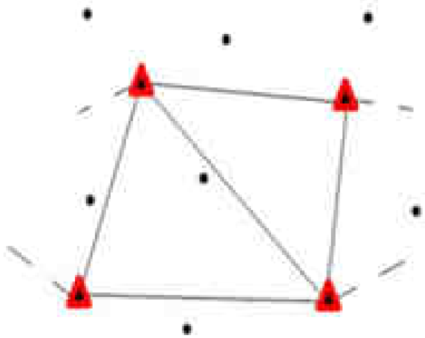
Three networks:

- ▲ PSC equipped with a GNSS receiver
- • PSC
- ▪ Other PS

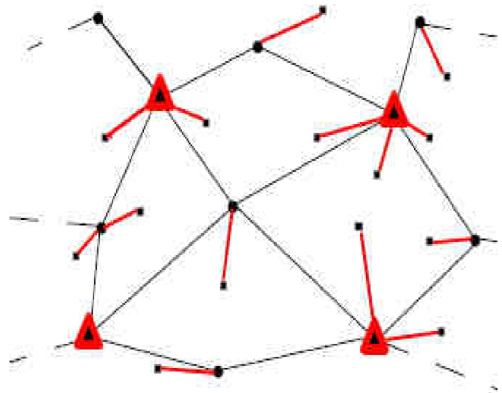
PSC network



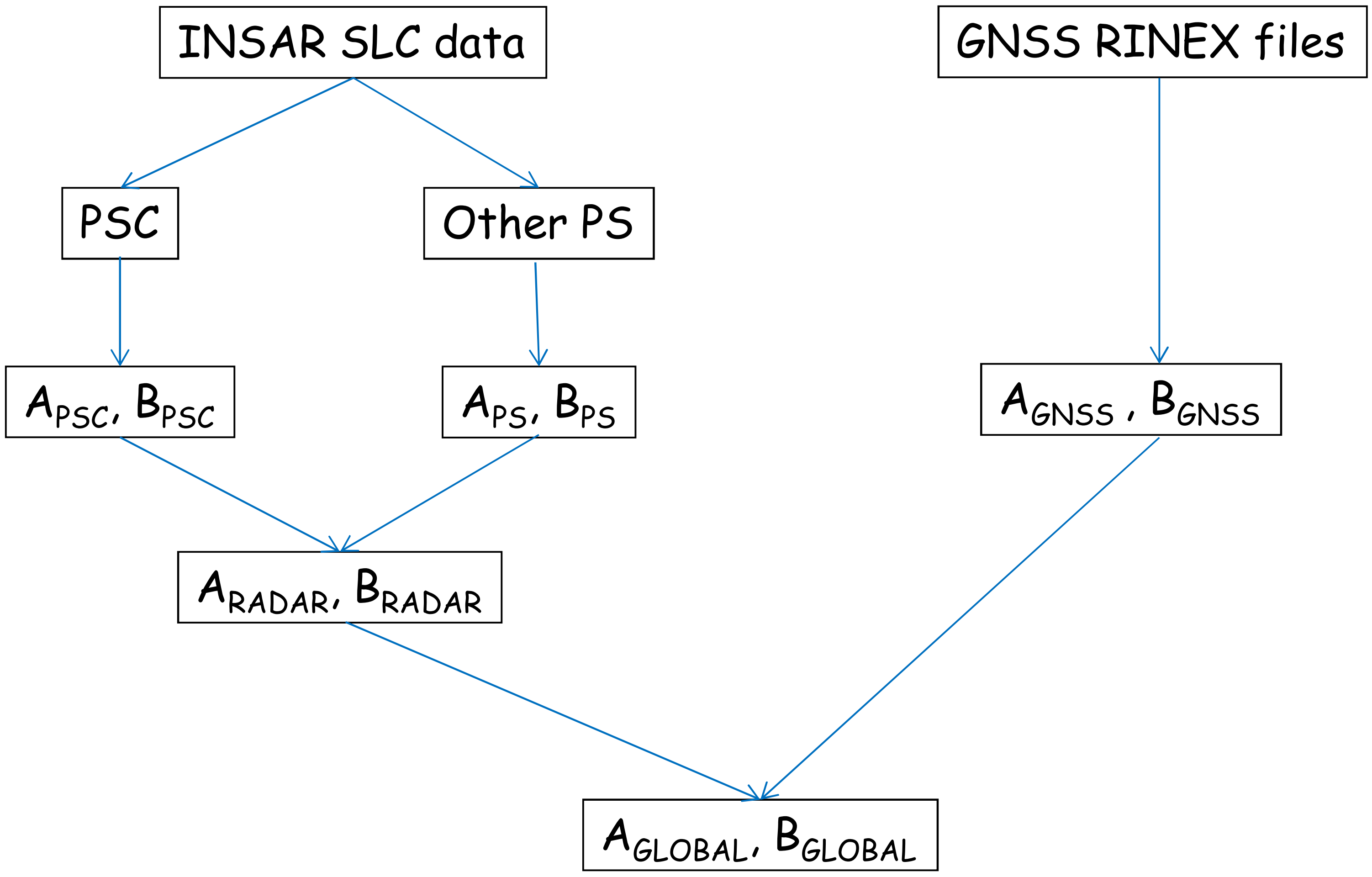
GNSS station network



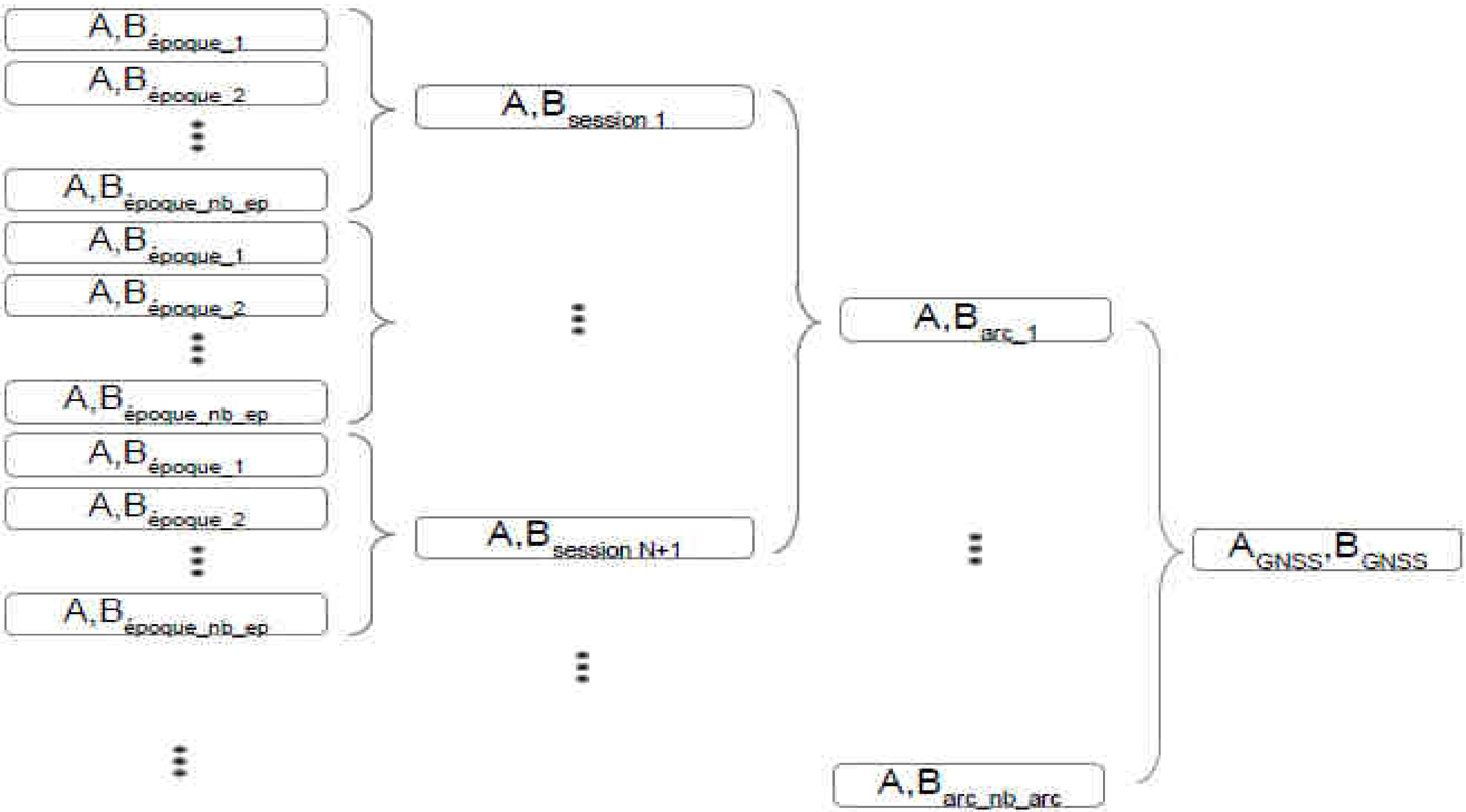
Arcs from other PS



Method synopsis



Linearization of equations related to GNSS station network:



Cumulating linearized equations into an iterative framework:

Linearized equations related to GNSS station network for all sessions:

$$B_{GNSS} = A_{GNSS}.\left(X_{k+1} - X_k\right)$$

Linear equations related to PSC network:

$$B_{PSC} - A_{PSC} X_k = A_{PSC}.\left(X_{k+1} - X_k\right)$$

Linear equations related to PS arcs:

$$B_{PS} - A_{PS} X_k = A_{PS}.\left(X_{k+1} - X_k\right)$$

$$B_{Global} = A_{Global}.\left(X_{k+1} - X_k\right)$$

Experiment

Simulation of 8 unwrapped interferograms from:

- real ERS data parameters,
- real SRTM DEM,
- Simulated DEM error map (uniform random values between -10 and 10 m)
- Simulated vertical displacement velocity map (uniform random values between 0 and 25 mm/yr)

Interferogram index	1	2	3	4	5	6	7	8
Temporal baseline (days)	0	35	70	210	245	385	560	595
Perpendicular baseline (m)	0	53	210	100	-210	-915	614	-264

Random selection of 500 PS in the area (around 1200 km^2)
One PSC selected per mesh with a side length of 50 pixels

→ 179 PSC, 522 reference arcs
→ 321 other PS

Simulation of GNSS data (GPS constellation, L1 and L2 phase measurements) using:

- Receiver geographic coordinates
- Satellite broadcast ephemeris
- Session characteristics (duration, time centered on the radar image acquisition time, time sampling interval)

Result

Without GNSS

	Mean	Std
DEM error estimation error	0,03 m	0,09 m
Displacement velocity estimation error	-0,05 mm/yr	0,86 mm/yr

With GNSS (using 48 or 16 receivers)

Error mean and std greatly reduced

4. Conclusions and perspectives

Conclusions:

- Feasibility of data level combination of GNSS and INSAR measurements
- Several possible strategies

Future works:

- Overcoming limitations of this first work

About input assumptions:	linear and vertical displacement
	no atmosphere, no noise
About processing:	integer ambiguities / unwrapping
	system conditioning
	weighting

- Test on real data

- Data level combination versus parameter level or mixed level combination

- Current work on mixed level combination