Université de Liège

Relative positioning with Galileo E5 AltBOC code measurements

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Dissertation submitted to the
University of Liège in partial
requirements for the degree of
Master of Geomatics and
Geometrology

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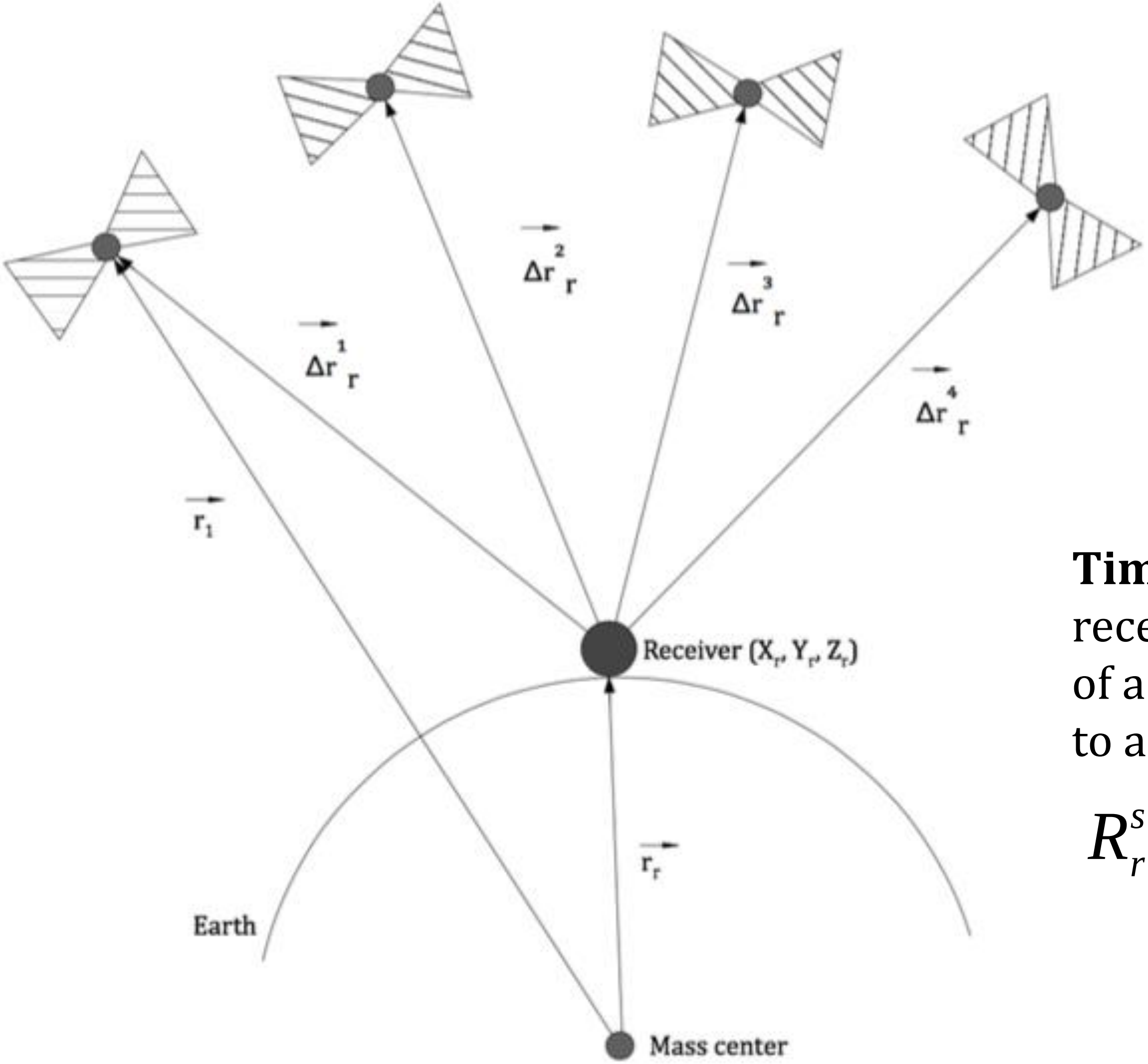
Examiners : R. Billen and A. Demoulin

1. Positioning

Satellite-based positioning principle



Time difference between reception and emission time of a signal sent by a satellite to a receiver:

$$R_r^s = (t_r(t_{r,ref}) - t^s(t^s_{ref})).c$$

1. Positioning

Time difference= **synchronisation** of the clocks

Never reached in practice!

$$t_{r,ref} = t_r(t_{r,ref}) + \P t_r(t_{r,ref}) \qquad t^s_{ref} = t^s(t^s_{ref}) + \P t^s(t^s_{ref})$$

Unknowns:

- The 3 components of the receiver position: X_r, Y_r, Z_r
- The receiver clock error

Requirements:

- At least 4 visible satellites
- The satellite clock error

$$\boxed{\begin{aligned} R^s_r &= c.(t_{r,ref} - t^s_{ref}) + c.(\partial t^s(t^s_{ref}) - \partial t_r(t_{r,ref})) \\ &= D^s_r + c.\mathrm{D}\partial t \end{aligned}}$$

1. Positioning

Errors affecting the signal

- Receiver clock bias $\P t_r(t_{r,ref})$	1-2 metres
- Satellite clock bias $\P t^s(t^s_{ref})$	
- Atmospheric errors	
- Tropospheric errors T_r^s	decimetres
- Ionospheric errors $I_{r,k}^s$	centimetres – 50 meters
- Multipath $M_{r,k,m}^s$	1-2 metres
- Observation noise $e_{r,k,m}^s$	0.2-1 metres
- Satellite hardware delays $d_{k,m}^s$	decimetres - metres
- Receiver hardware delays $d_{r,k,m}$	

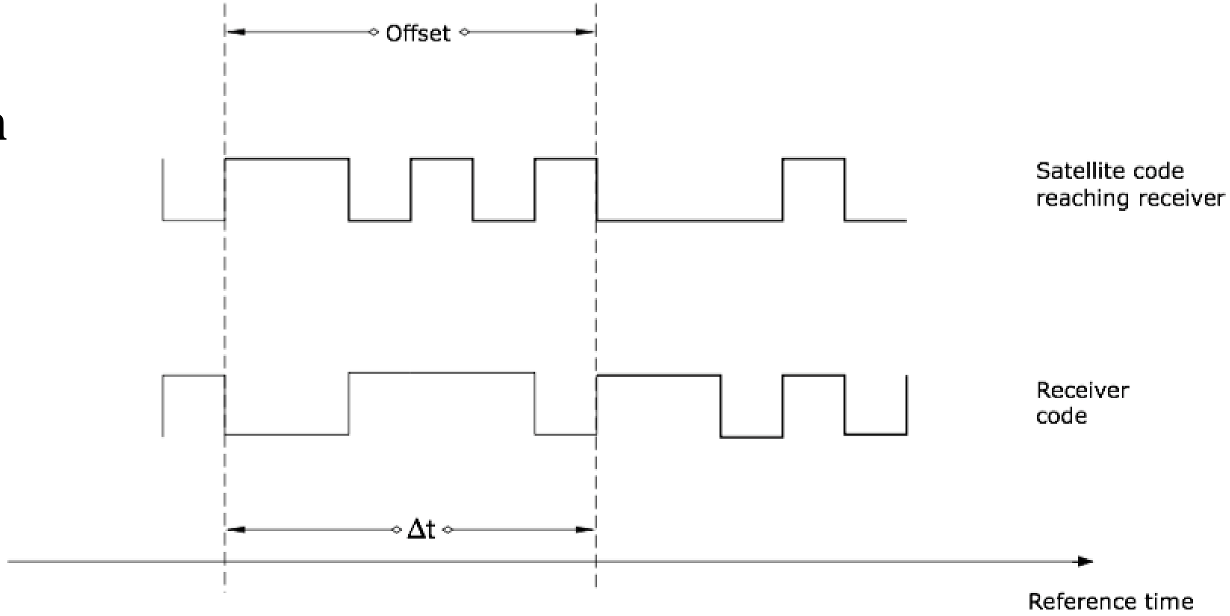
Position equation:

$$R_r^s = D_r^s + c.\mathrm{D}\partial t + T_r^s + I_{r,k}^s + M_{r,k,m}^s + d_{r,k,m} + d_{r,m}^s + e_{r,k,m}^s$$

2. Observables

Codes pseudoranges

- Expected precision: from **decametres** to **metres**
- Basic observable
- Most common for public applications



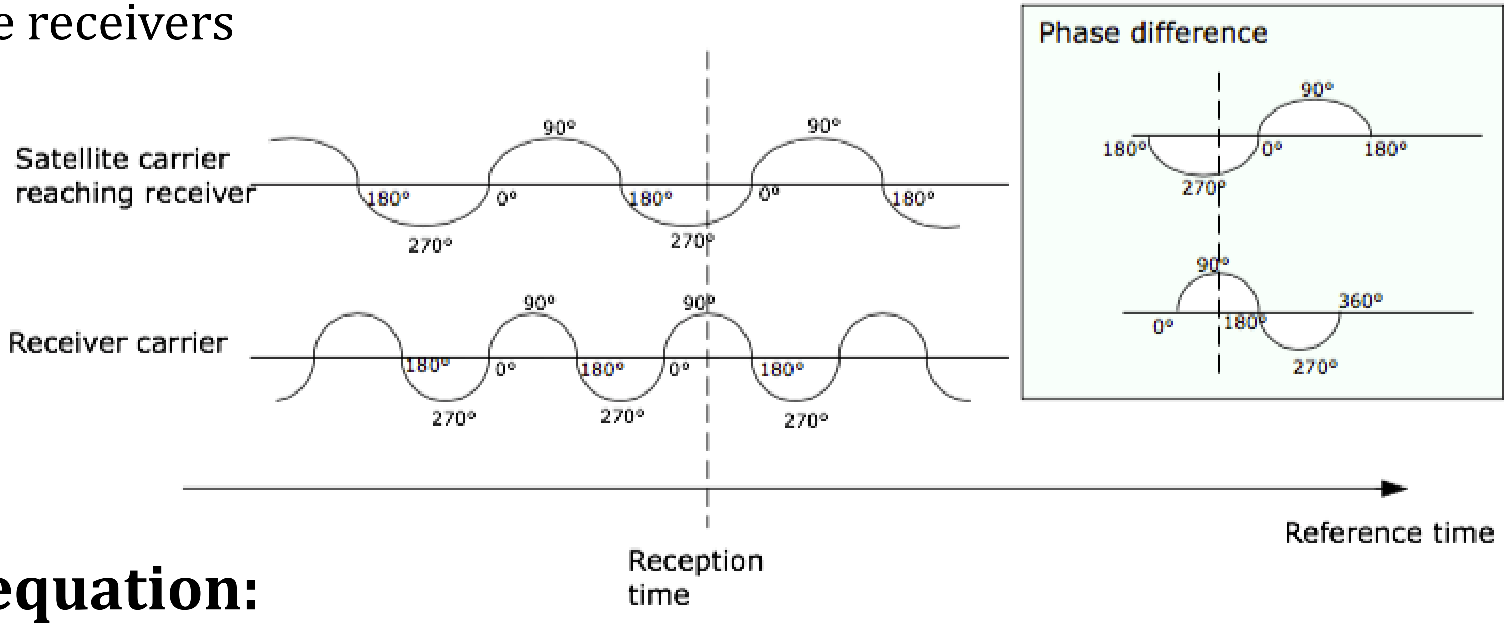
Position equation:

$$P_r^s = D_r^s + c.\Delta\delta t + T_r^s + I_{r,k}^s + M_{r,k,m}^s + d_{r,k,m}^s + d_{k,m}^s + \varepsilon_{r,k,m}^s$$

2. Observables

Carrier phases pseudoranges

- Expected precision: from **centimetres** to **millimetres**
- **Initial ambiguity**
- High precision applications
- Expensive receivers



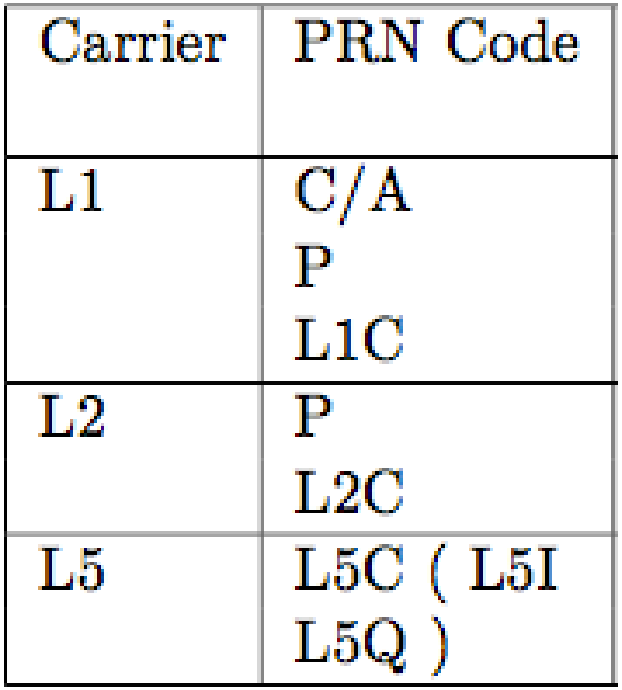
Position equation:

$$F_r^s = D_r^s + c.D\partial t + T_r^s + I_{r,k}^s + M_{r,k,j}^s + d_{r,k,j}^s + d_{k,j}^s + e_{r,k,j}^s + / .N_{r,k}^s$$

3. Global Navigation Satellite Systems

Global Positioning System (GPS)

- American GNSS
- Constellation of 24 satellites
- 12 hours of revolution
- Altitude of 20 200 kilometres
- Operational since 1995
- Modernization:
  - 2 -> 3 carrier frequencies
  - 2 -> 5 codes

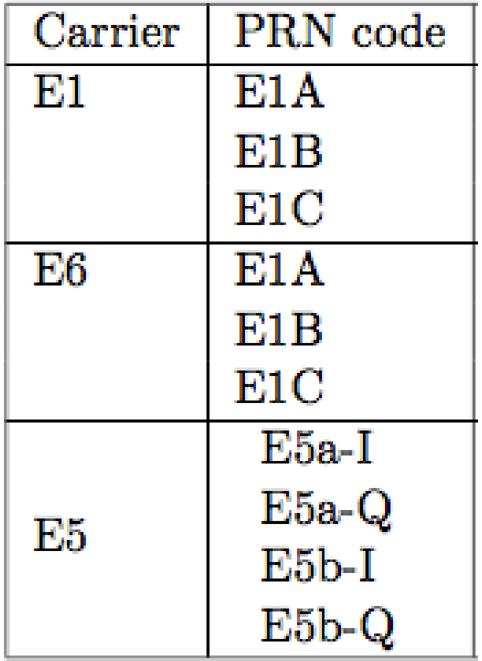


Carrier	PRN Code
L1	C/A P L1C
L2	P L2C
L5	L5C (L5I L5Q)

3. Global Navigation Satellite Systems

Galileo

- European GNSS
- Project initialized in 1999
- Altitude of 23 222 kilometres
- Satellites:
  - Prototypes GIOVE-A and GIOVE-B decommissioned in 2012
  - IOV[1] generation: 3 satellites available
  - FOC[2] generation: 4 satellites under commissioning
- 4 carrier frequencies (E1, E5a, E5b, E6) and 10 codes
- E5a+b obtained with the AltBOC modulation of E5a an E5b



Carrier	PRN code
E1	E1A
	E1B
	E1C
E6	E1A
	E1B
	E1C
E5	E5a-I
	E5a-Q
	E5b-I
	E5b-Q

[1]: In orbit Validation phase

[2]: Full Operational Capability phase

4. Hypothesis

Hypothesis:

Galileo E5a+b outperforms other GPS and Galileo signals [Caelen, 2014]:

- lower observation noise
- better multipath mitigation

Assumption: Precision on positioning should be better with Galileo E5a+b than with other signals

Constraints:

- First constraint: solution based on the **code-only observable** (non ambiguous) to reach decimetre precision on position estimation.
- Second constraint: **single-frequency** solution, the most common for public applications

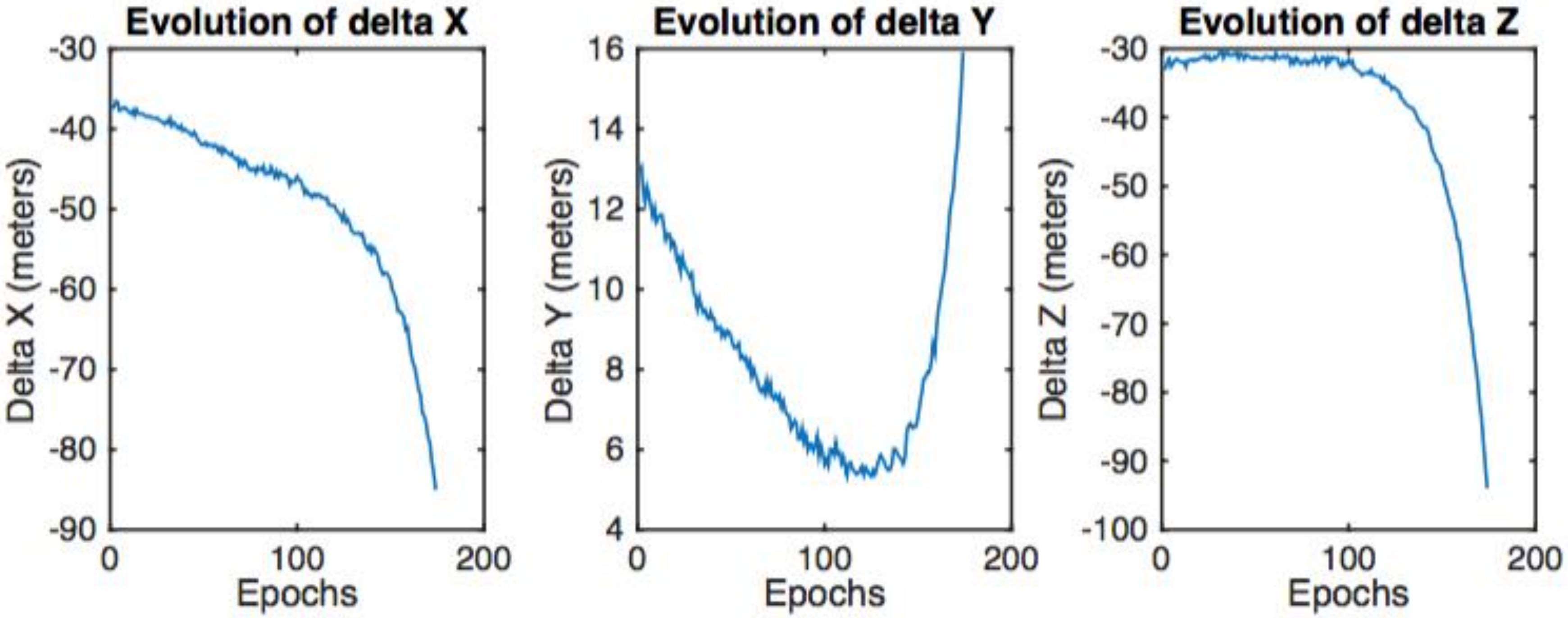
Research question:

Could Galileo E5 AltBOC single-frequency code-only measurements be used to reach decimetre-level accuracy on satellite-based position estimations?

5. Methods

Single-frequency code-only methods:

- Single point positioning:

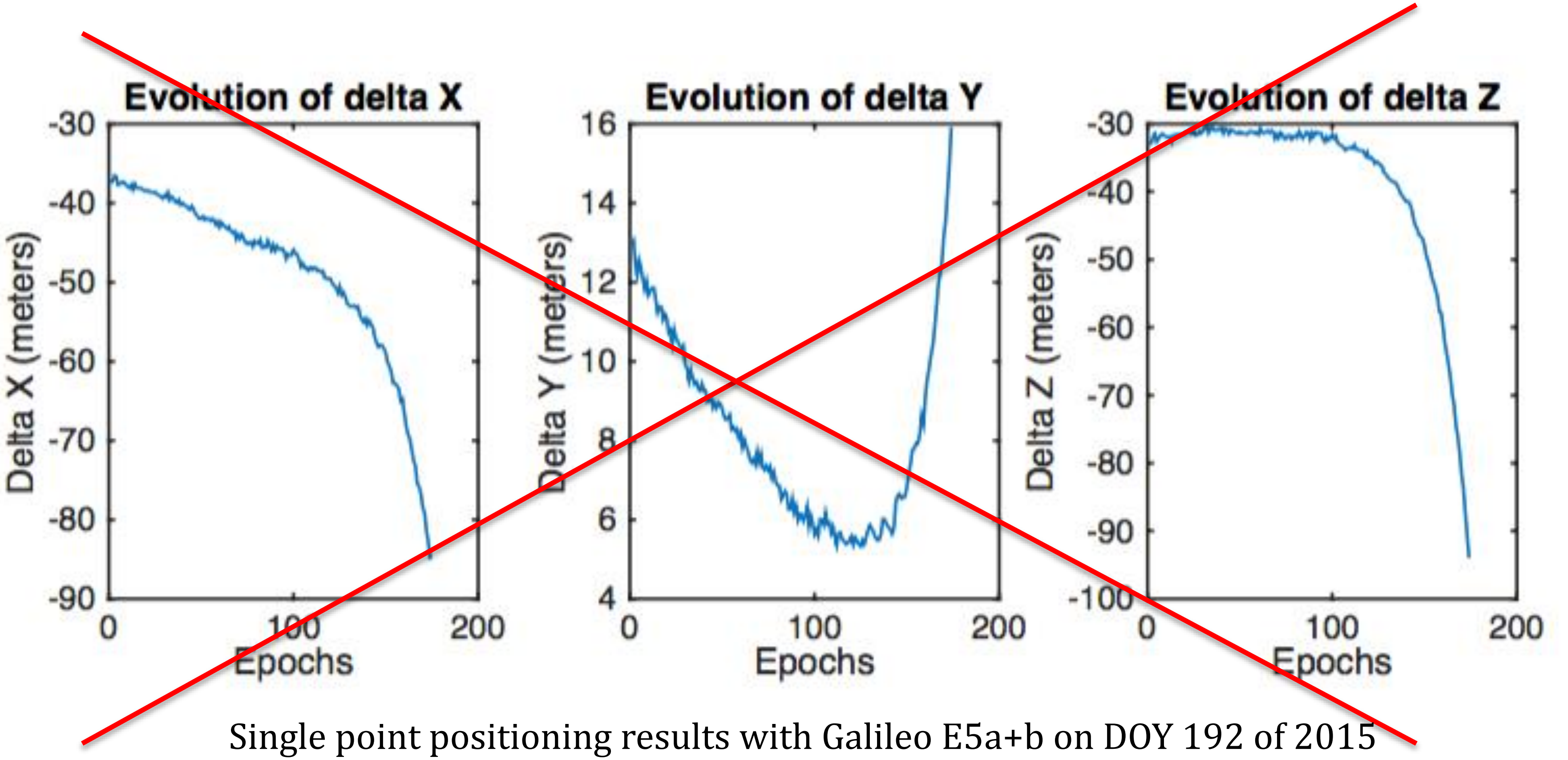


Single point positioning results with Galileo E5a+b on DOY 192 of 2015 obtained with a Trimble receiver

5. Methods

Single-frequency code-only methods:

- Single point positioning:



Single point positioning results with Galileo E5a+b on DOY 192 of 2015 obtained with a Trimble receiver

5. Methods

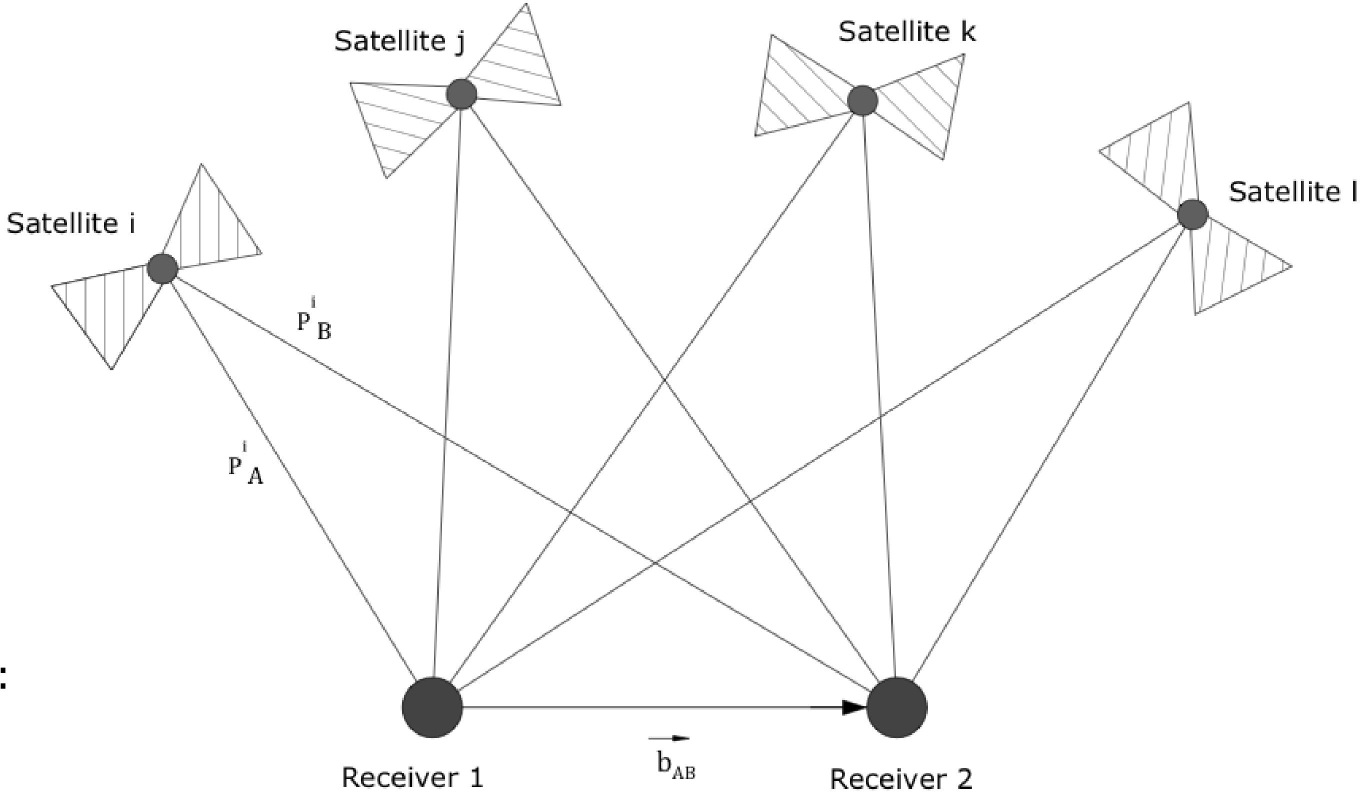
Single-frequency code-only methods:

- Relative positioning:

Principle: Two receivers **simultaneously** observe the same satellites.

Single difference: Difference between two receiver observations of the same satellite

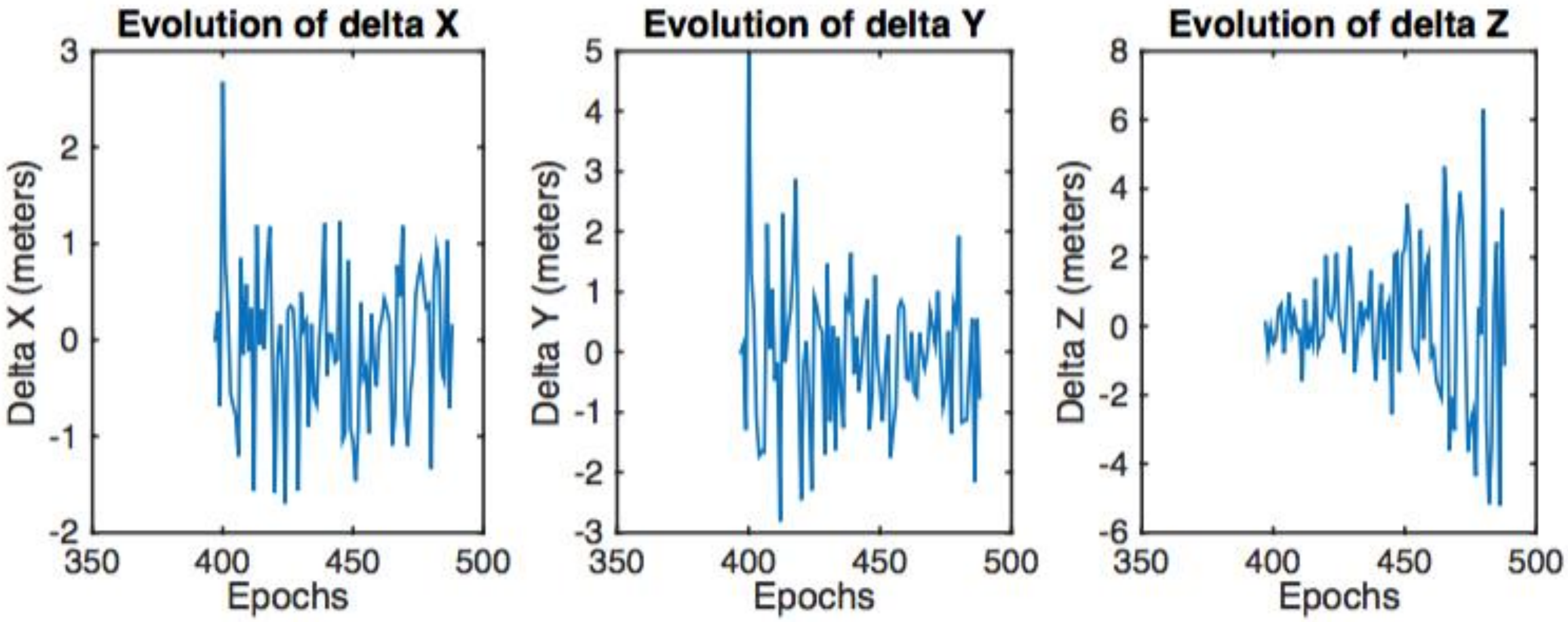
Double difference: Difference between two receiver observations of the two same satellites.



5. Methods

Single-frequency code-only methods:

- Single difference:

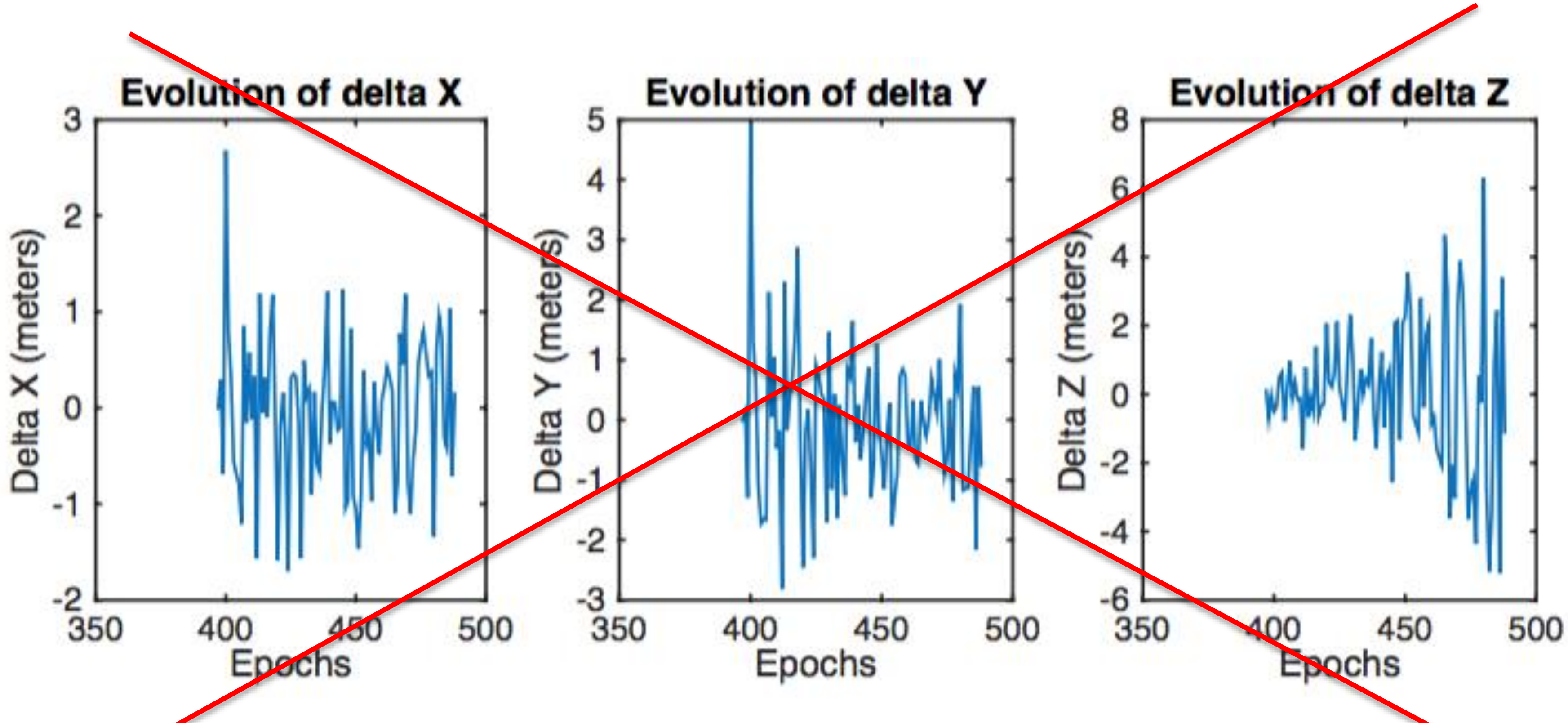


Single difference results with Galileo E5a+b on DOY 345 of 2014 obtained with two Trimble receivers

5. Methods

Single-frequency code-only methods:

- Single difference:



Single difference results with Galileo E5a+b on DOY 345 of 2014 obtained with two Trimble receivers

5. Methods

Single-frequency code-only methods:

- Double difference : configurations

Zero baseline

- ~~Receiver clock bias~~
- ~~Satellite clock bias~~
- ~~Atmospheric errors~~
  - ~~Tropospheric errors~~
  - ~~Ionospheric errors~~
- ~~Multipath~~
- Part of the observation
- noise e_{12}^{ij}
- ~~Satellite hardware delays~~
- ~~Receiver hardware delays~~

Position equation:

$$P_{12}^{ij} = D_{12}^{ij} + e_{12}^{ij}$$

Short baseline

- ~~Receiver clock bias~~
- ~~Satellite clock bias~~
- ~~Atmospheric errors~~
  - ~~Tropospheric errors~~
  - ~~Ionospheric errors~~
- Multipath
- Observation noise
- ~~Satellite hardware delays~~
- ~~Receiver hardware delays~~

Position equation:

$$P_{12}^{ij} = D_{12}^{ij} + M_{12,k,m}^{ij} + e_{12,k,m}^{ij}$$

Medium baseline

- ~~Receiver clock bias~~
- ~~Satellite clock bias~~
- Atmospheric errors
  - Tropospheric errors
  - Ionospheric errors
- Multipath
- Observation noise
- ~~Satellite hardware delays~~
- ~~Receiver hardware delays~~

Position equation:

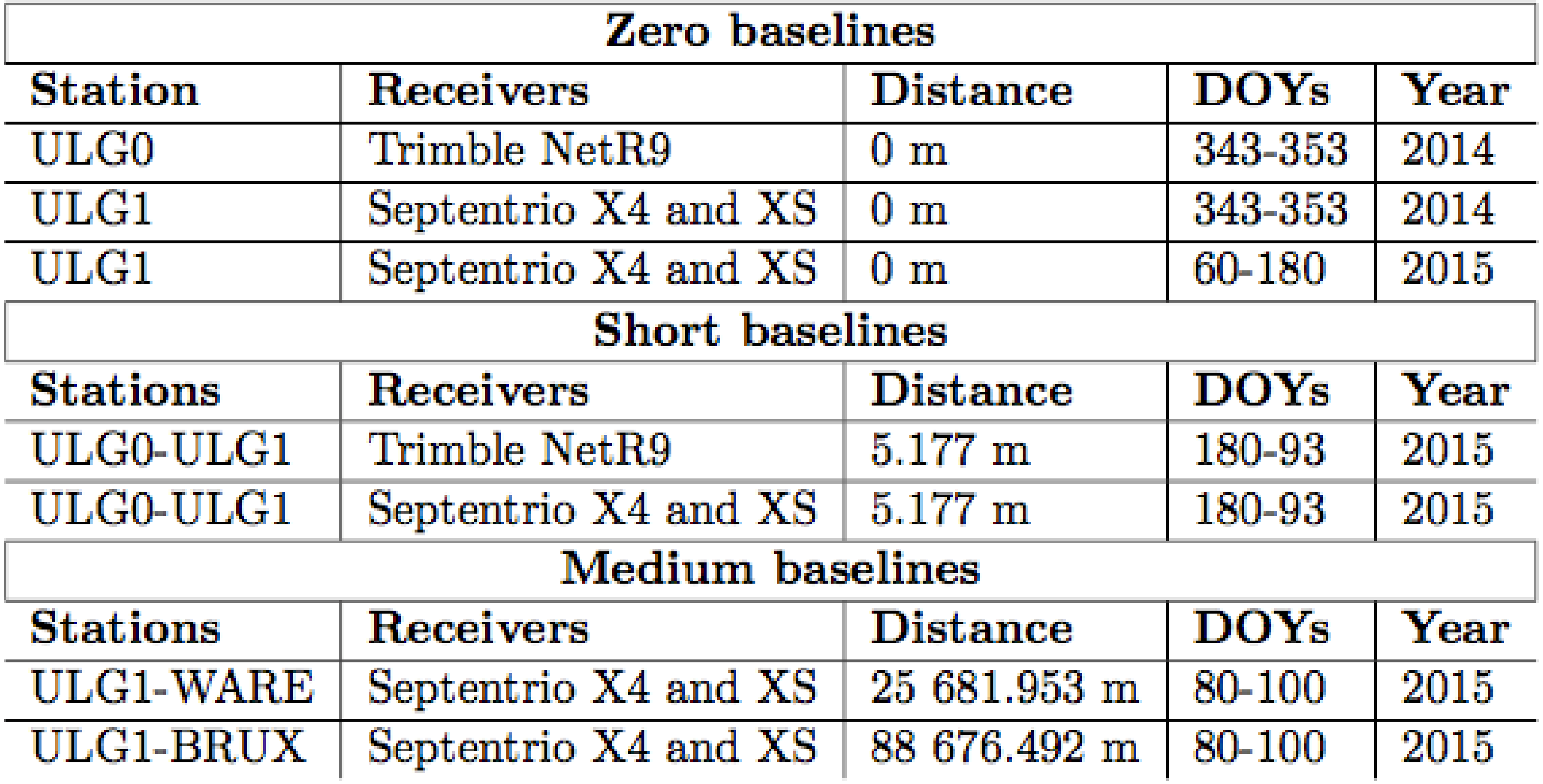
$$P_{12}^{ij} = D_{12}^{ij} + T_{12}^{ij} + I_{12,k}^{ij} + M_{12,k,m}^{ij} + e_{12,k,m}^{ij}$$

6. Results

- Least Square Adjustment
- Fixed precise coordinates

- MATLAB program
- Real Time

- Configuration details:

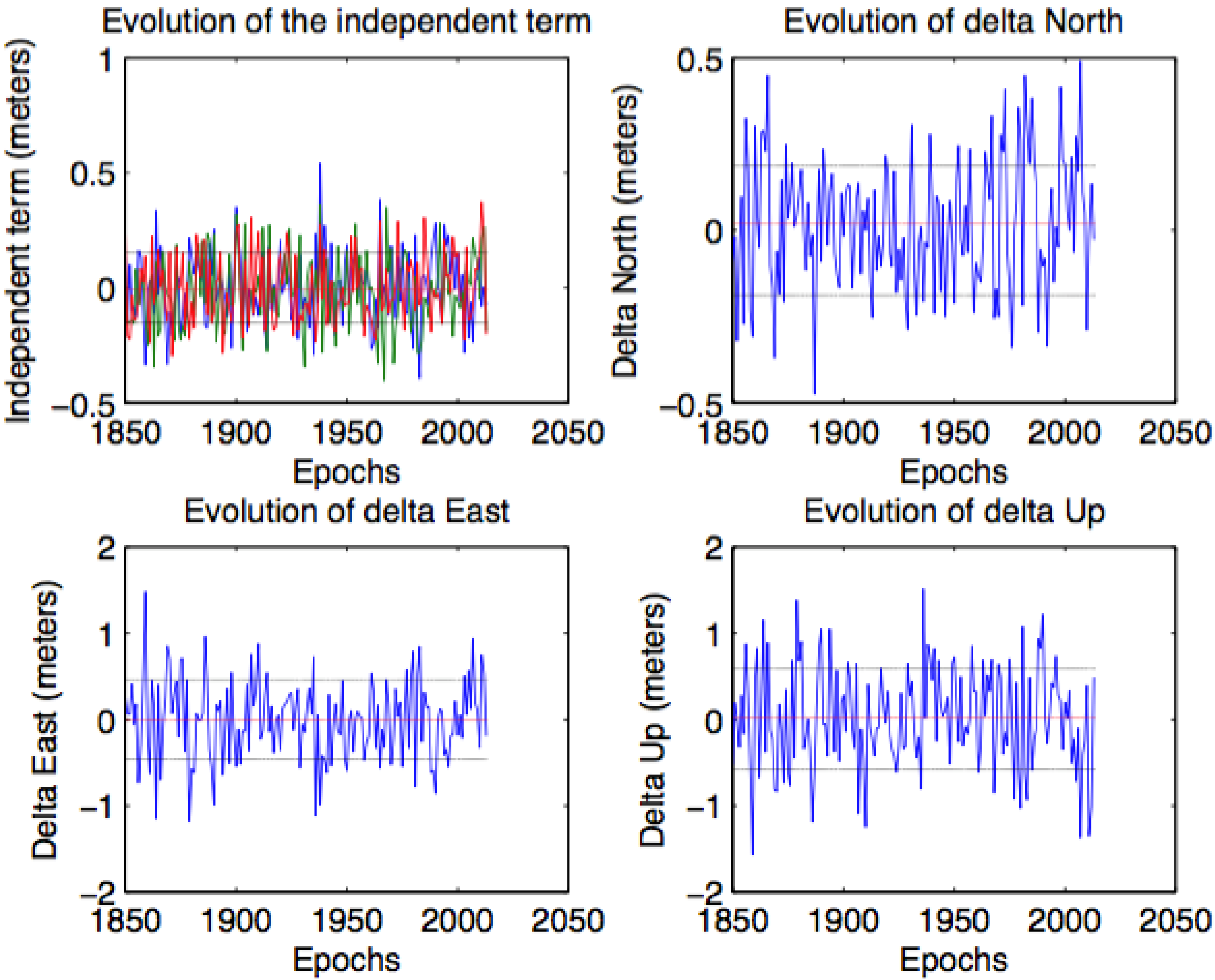


Station	Receivers	Distance	DOYs	Year
Zero baselines				
Station	**Receivers**	**Distance**	**DOYs**	**Year**
ULG0	Trimble NetR9	0 m	343-353	2014
ULG1	Septentrio X4 and XS	0 m	343-353	2014
ULG1	Septentrio X4 and XS	0 m	60-180	2015
Short baselines				
Stations	**Receivers**	**Distance**	**DOYs**	**Year**
ULG0-ULG1	Trimble NetR9	5.177 m	180-93	2015
ULG0-ULG1	Septentrio X4 and XS	5.177 m	180-93	2015
Medium baselines				
Stations	**Receivers**	**Distance**	**DOYs**	**Year**
ULG1-WARE	Septentrio X4 and XS	25 681.953 m	80-100	2015
ULG1-BRUX	Septentrio X4 and XS	88 676.492 m	80-100	2015

6. Results

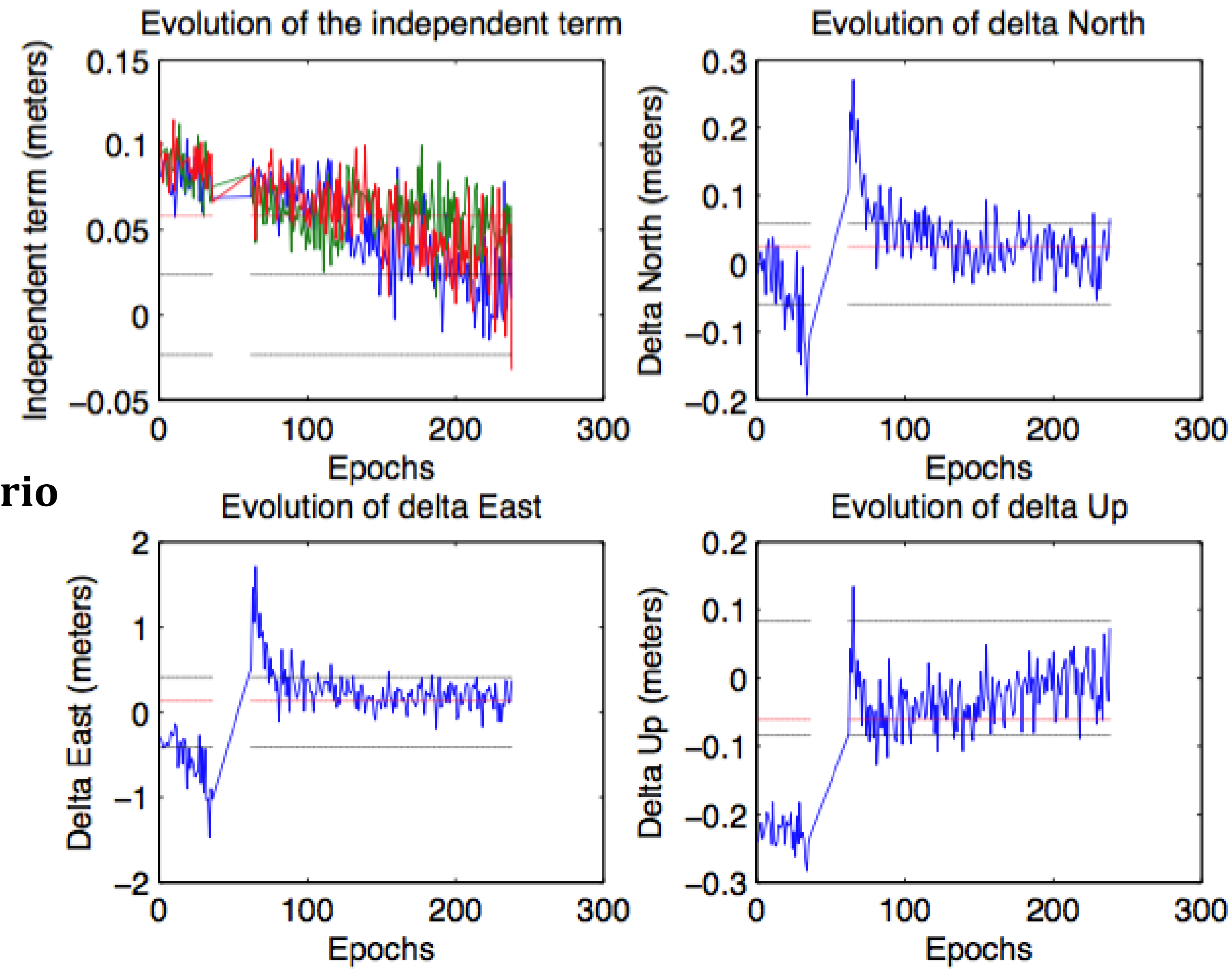
Very different results obtained with the two types of receivers:

Trimble



6. Results

Very different results obtained with the two types of receivers:



Septentrio

6. Results

- Trimble receivers: less precise than the Septentrio's receivers (higher observation noise)

- Septentrio receivers: non simultaneity of the observations
  - Observation precision as computed by our software might be altered
  - Values of position precision are lower

- Three main parameters affect the position precision:
  - PDOP: Position Dilution Of Precision
  - The elevations of the satellites observed
  - The number of visible satellites

- GPS results are compared to Galileo results:
  - Galileo is more affected by PDOP and low elevation satellites
  - Galileo E5 shows the best observation precision
  - Comparison with GPS constellation reduced to 4 satellites: Galileo E5 shows the best position precision

7. Conclusion

Trimble in zero baseline mode:

- Decimetres precision obtained on **observations** with Galileo E1, E5a and E5b signals (correspond to results obtained by [Springer et al., 2013])
- A few centimetres precision on **observations** with Galileo E5 (correspond to expected values with Galileo full constellation [Colomina et al., 2012], [Silva et al., 2012], [Lopes et al., 2012])
- Metres precision on **position** with all Galileo signals and decimetres precision when PDOP is low (also reached by [ESA, 2014], [Langley et al., 2012], [Steigneberger & Hauschild, 2015] with real data)

Septentrio in zero, short and medium baselines:

- A few centimetres precision on **observations** with all the Galileo signals ([Colomina et al., 2012], [Silva et al., 2012], [Lopes et al., 2012])
- A few decimetres precision on **position** with all the Galileo signals
- When Brussels medium baseline is considered (80 kilometres), the decimetres precision can only be reached when PDOP values are low

8. Prospects

- As high PDOP values were encountered with Galileo signals (due to their reduced constellation), the same study should be undertaken when more satellites will be available
- Issues due to the non simultaneity of the Septentrio receivers should be solved
- Statistics based on more observation days
- Similar study on carrier phase observable
- Combine GPS and Galileo observations

I thank you for your attention