The added value of new GNSS to monitor the ionosphere

R. Warnant[1], C. Deprez[1], L. Van de Vyvere[2]

[1]University of Liege, Liege, Belgium.

[2]M3 System, Wavre, Belgium.

Monitoring TEC for geodetic applications

- For the last 25 years, GPS L1/L2 code and phase pseudoranges have been used to monitor the ionosphere Total Electron Content (TEC).
- Both absolute TEC and Rate of TEC change are crucial parameters for the mitigation of the ionospheric effects on GNSS applications.
- Nevertheless, GPS L1/L2 TEC reconstruction suffers from different shortcomings.
- We investigate if new/modernized GNSS can bring improvements in:
  - Reconstructed TEC precision (not accuracy).
  - The monitoring of local variability in TEC (Travelling Ionospheric Disturbances)

Absolute TEC 1

- Absolute Slant TEC can be reconstructed from code and/or phase geometry-free combinations :

$$STEC^i_{p,kl} = \alpha_{kl}^{-1}\left[(P^i_{p,k} - P^i_{p,l}) - (d^i_{kl} + d_{p,kl}) - M^i_{p,kl} - E^i_{p,kl}\right]$$

Slant TEC

Code/phase GF at frequencies f_k and f_l

InterFrequency rec. and sat. biases

Multipath

Noise

Phase ambiguity

$$STEC^i_{p,kl} = -\alpha_{kl}^{-1}\left[(\Phi^i_{p,k} - \Phi^i_{p,l}) - (\delta^i_{kl} + \delta_{p,kl}) - m^i_{p,kl} - \varepsilon^i_{p,kl} - (\lambda_k N^i_{p,k} - \lambda_l N^i_{p,l})\right]$$

$$\alpha_{kl} = 40.3\left(\frac{1}{f_k^2} - \frac{1}{f_l^2}\right)$$

Absolute TEC 2

- Absolute TEC precision/accuracy mainly depends on :
  - Code and/or phase pseudorange precision (noise).
  - The "TEC coefficient" α_{kl}^{-1} which depends on the considered frequency pair (should be as small as possible ➔ large frequency difference)
  - Residual errors : multipath, IF biases
  - Ambiguities when phase observables are used (main influence on accuracy)

Rate of TEC change 1

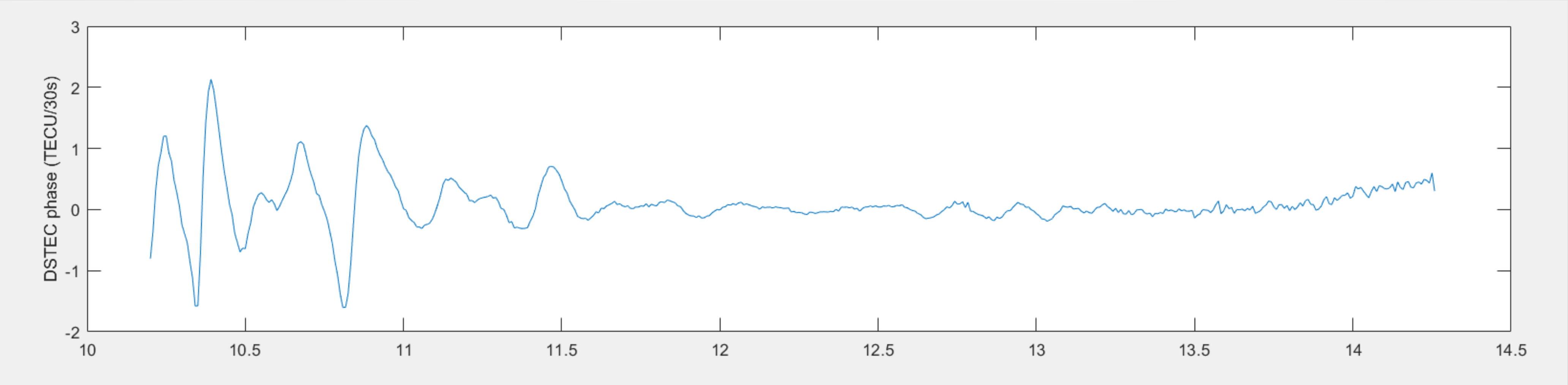
- Between epoch change in slant TEC can be used to monitor local variability in TEC due to moving structures.

$$\Delta STEC^{i}_{p,kl}(t_k) = STEC^{i}_{p,kl}(t_k) - STEC^{i}_{p,kl}(t_{k-1})$$

- Can be mapped to vertical and/or normalized (to 1 minute interval).
- This combination removes biases (constant part of IF delays, ambiguities) but it still depends on noise and on between epoch variation of TEC, multipath and IF biases (usually considered as negligible).

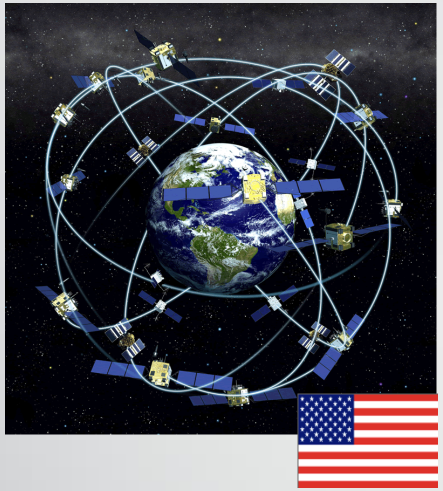
Rate of TEC change 2

- Local variability in TEC at European mid-latitudes (Belgium):
  - Mainly due Travelling Ionospheric Disturbances (affect precise positioning).
  - GPS-based detection of moving structures (TIDs) is « biased » by the fact that ionospheric points have a velocity wrt the ionosphere due to satellite orbital motion.

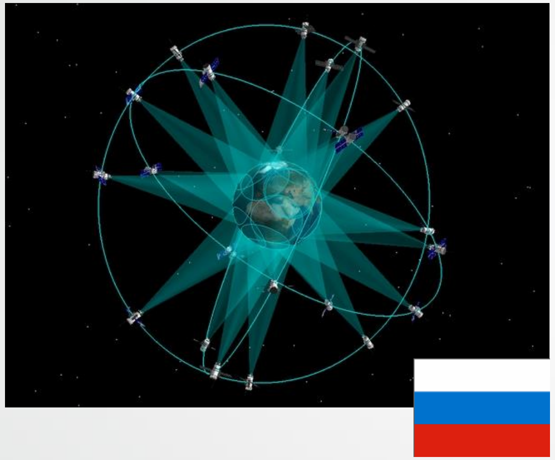


New/modernized GNSS 1

GPS

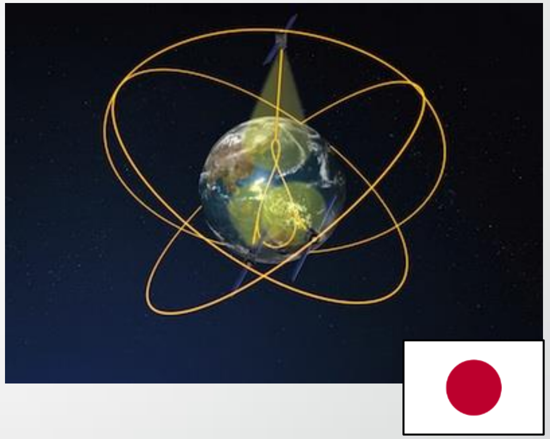


GLONASS

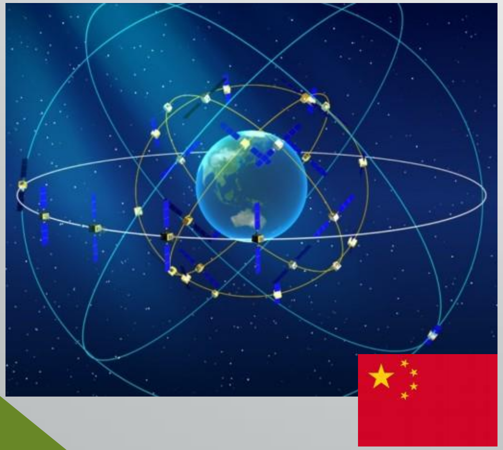


Galileo

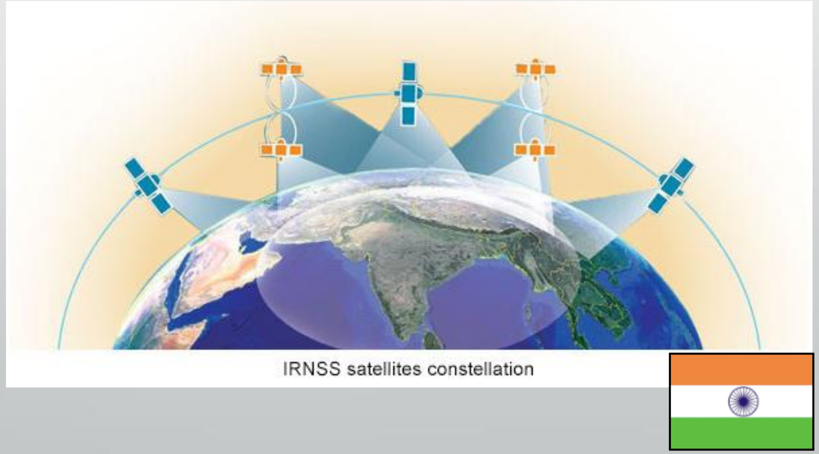
QZSS



Beidou



NAVIC



SBAS

New/modernized GNSS 2

- More (than 2) frequencies:
  - Possible to form several frequency pairs to reconstruct TEC (influence on α_{kl}^{-1})
- Improved signals :
  - Better resistance to multipath
  - New modulation techniques allowing to perform more precise code pseudorange measurements.

New/modernized GNSS 3

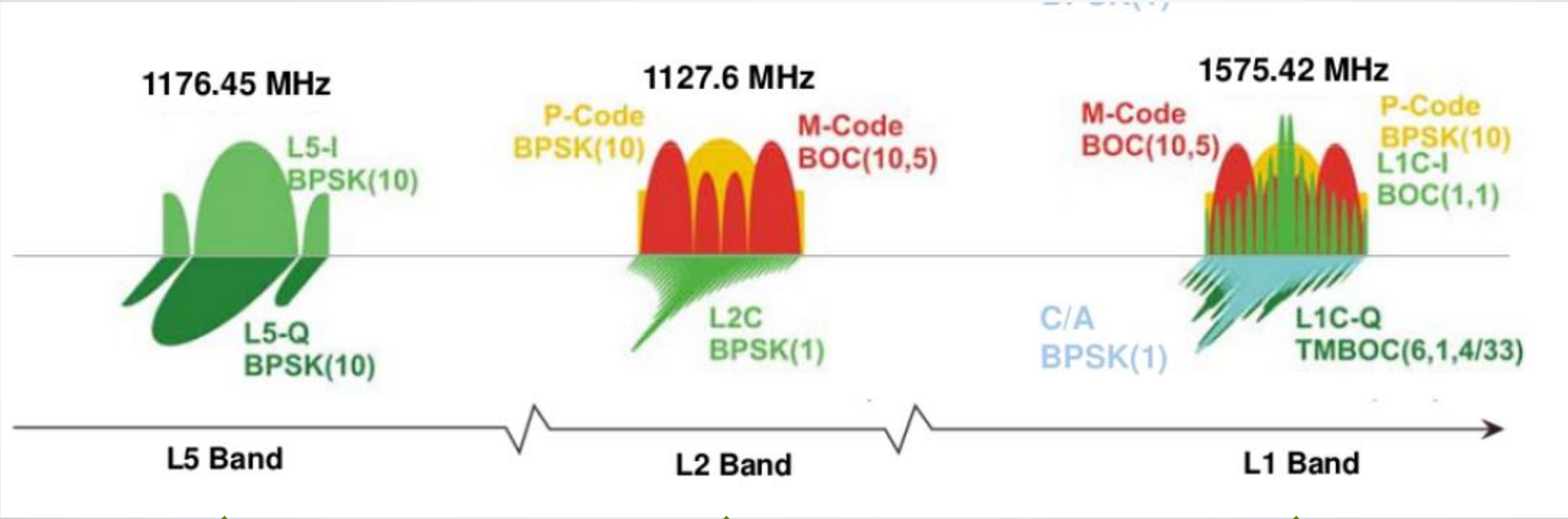
- Availability of (dual or triple frequency) geostationary navigation satellites
  - SBAS (2F): EGNOS, GAGAN, WAAS.
  - Beidou (3F): C01 to C05.
- As GEO satellites have a negligible velocity wrt respect to the ionosphere, they could be interesting for the study of local variability in TEC.
- Availability of new generation receivers and antennas which already bring improvement in the "standard" GPS L1/L2 case.

Multi GNSS/multi-frequency TEC precision

GNSS equipment

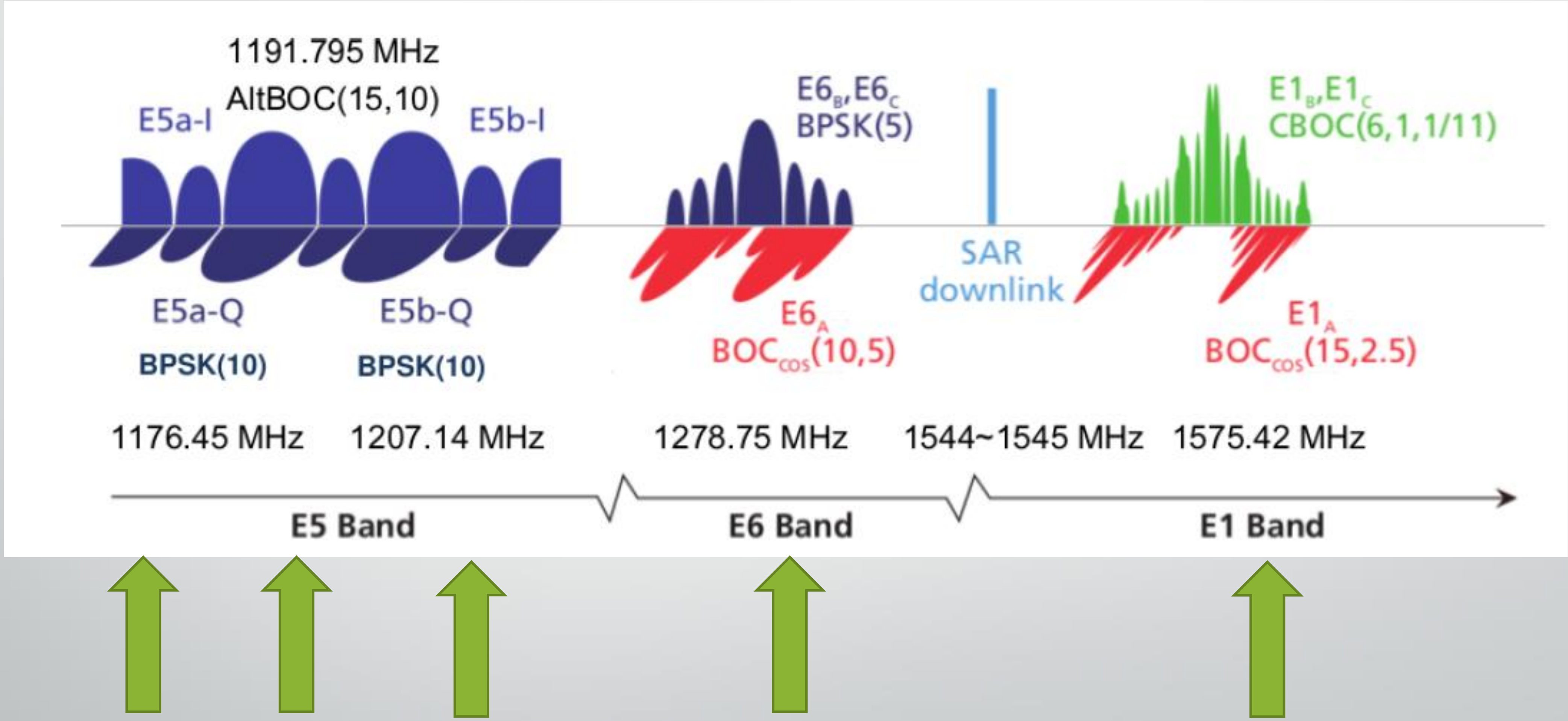
- Located in Liege (Belgium).
- 2 Trimble GNSS choke ring antennas on a short baseline (5,352 m).
- 6 multi-GNSS/multi-frequency receivers :
  - 2 Trimble NetR9 receivers
  - 2 Septentrio PolaRx4 receivers
  - 1 Septentrio PolaRxS scintillation receiver
  - 1 Septentrio PolaRx5 (new model).
- Equipment used to perform zero and short baseline tests for positioning and ionosphere monitoring.

GNSS signals : GPS



L5 L2 L1

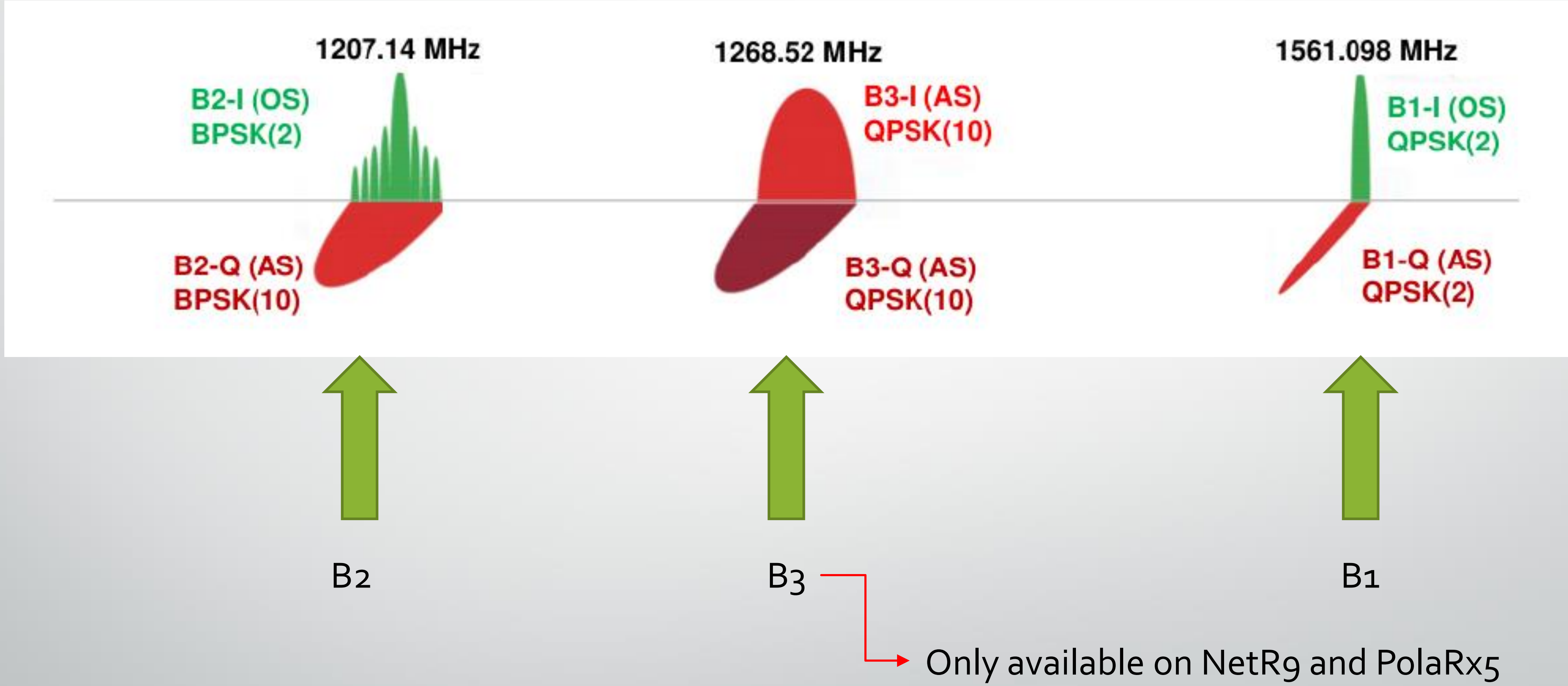
GNSS signals : Galileo



E5a E5 E5b E6 E1

Only available with PolaRx5

GNSS signals : Beidou (phase II)



Different TEC coefficients

- Given the same code/phase precision, a larger frequency difference gives a smaller TEC coefficient and therefore a better TEC precision.

TEC coefficients								
Galileo				GPS			Beidou	
E1-E5a	E1-E5b	E1-E5	E1-E6	L1-L2	L1-L5	L2-L5	B1-B2	B1-B3
7,764	8,757	8,24	**11,893**	9,52	**7,764**	**42,089**	8,993	**11,754**

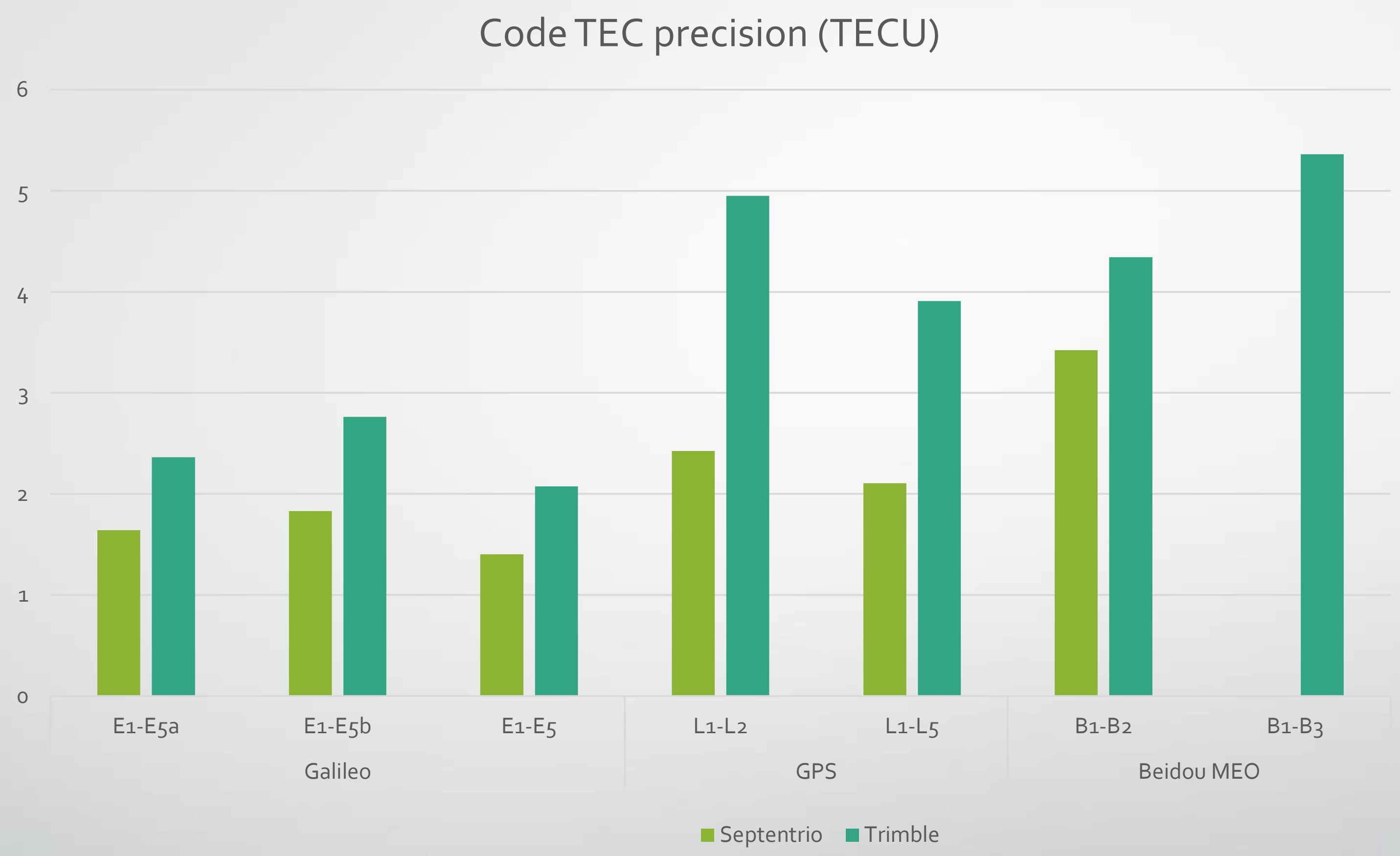
Methodology to asses TEC precision

- Compute Slant TEC change from epoch to epoch (30 s interval)

$$\Delta STEC^{i}_{p,kl}(t_k) = STEC^{i}_{p,kl}(t_k) - STEC^{i}_{p,kl}(t_{k-1})$$

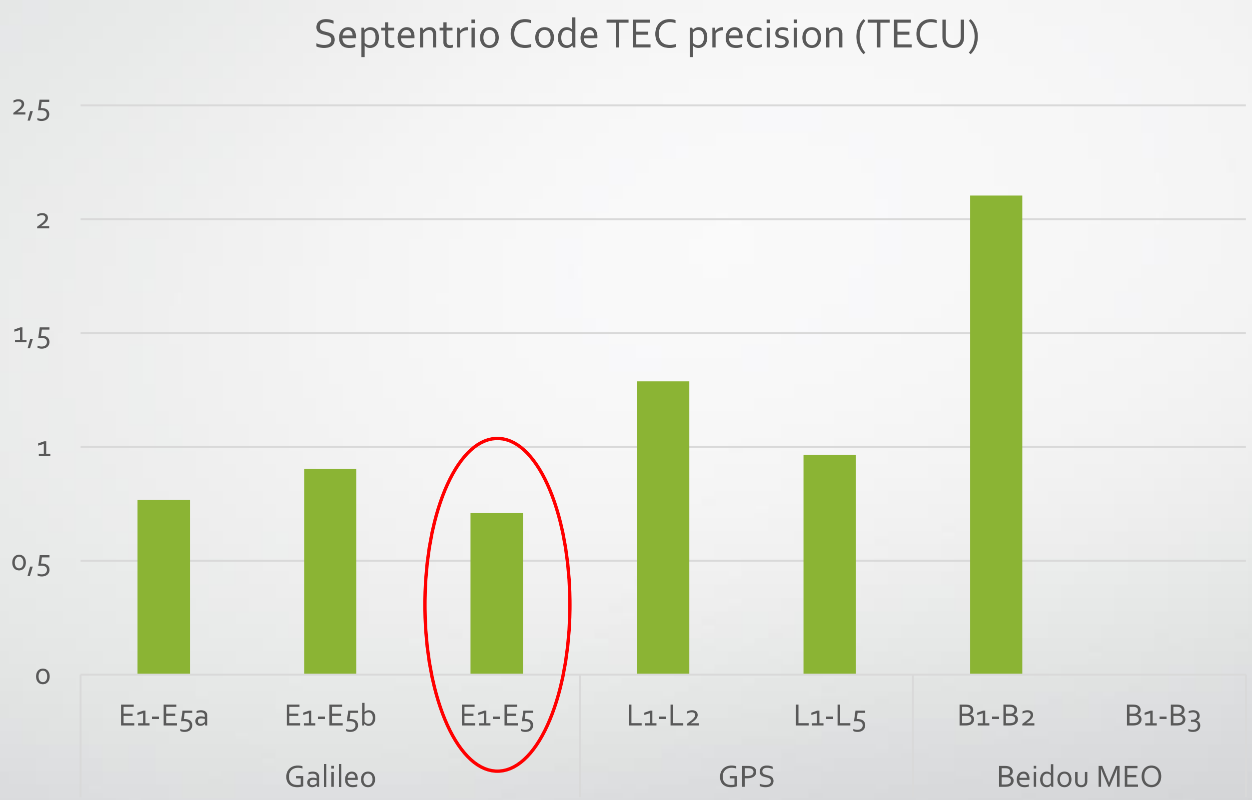
- Form single (between receiver) differences of $\Delta STEC(t_k)$ on ULg short baseline (5,352 m):
  - Completely removes TEC (same ionosphere).
  - Still contains multipath and noise.
- TEC precision is estimated by computing the standard deviation of single differences of $\Delta STEC(t_k)$ (10 day period) and by dividing them by 2 (error propagation).

Results: code (multipath filter off - mask 10°)



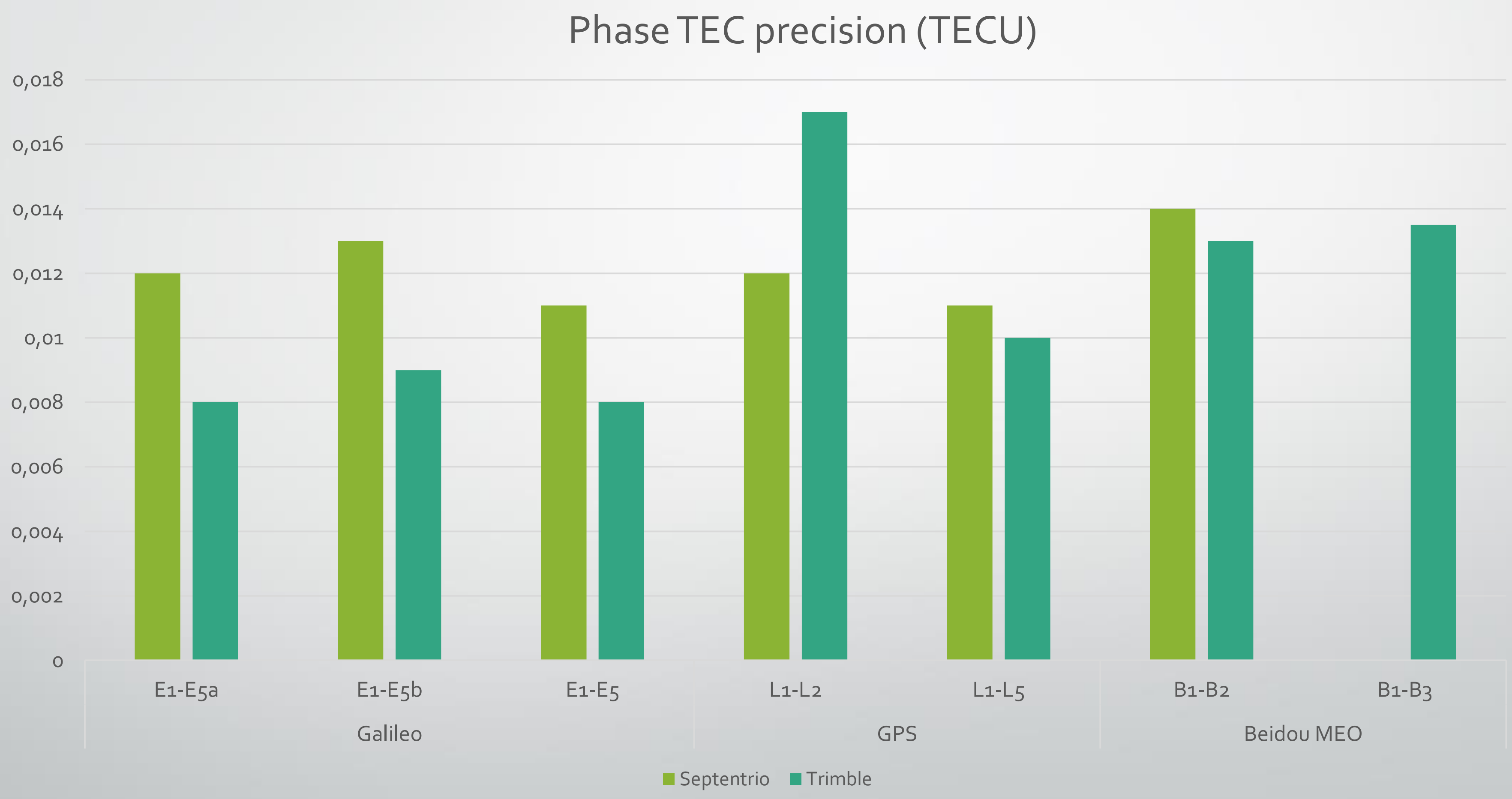
- Strong improvement in code TEC precision with Galileo (in particular E1/E5) wrt the "standard" GPS L1/L2.

Results: code (multipath filter on - mask 20°)



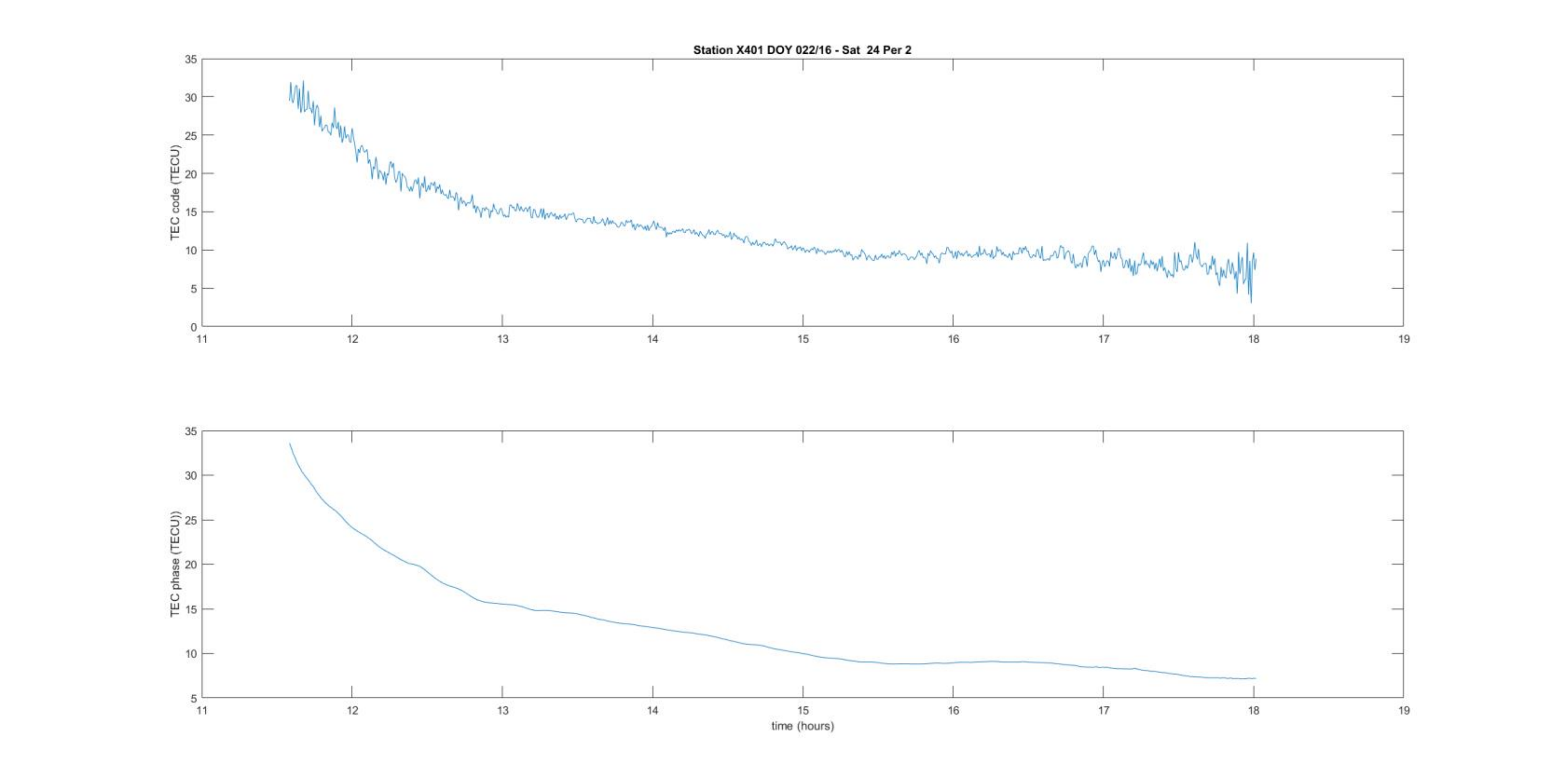
- Galileo E1/E5 combination has a precision better than 1 TECU above 20° elevation (Septentrio PolaRx4).

Results: Phase (multipath filter off - mask 10°)



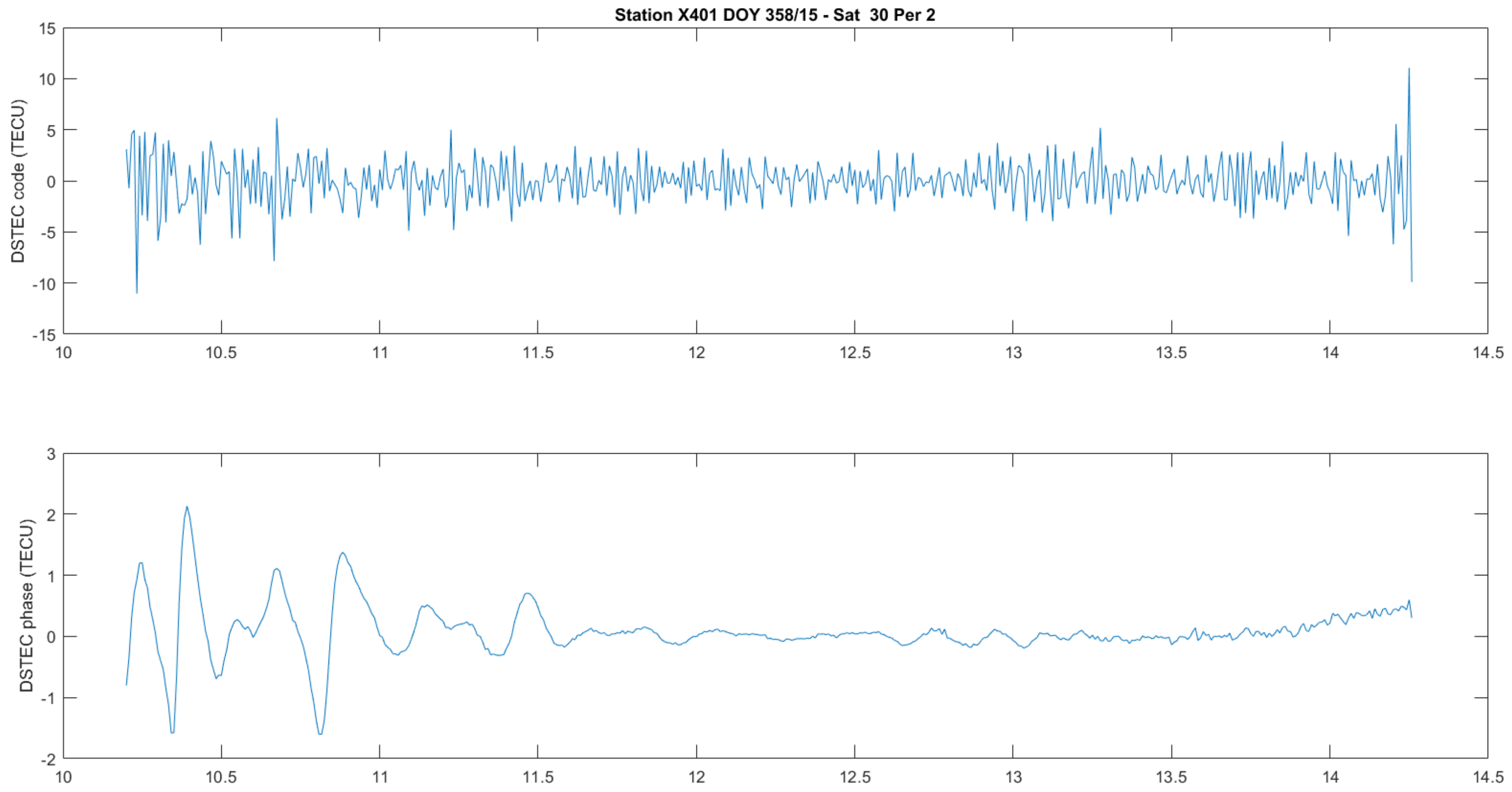
Galileo E1-E5 Slant TEC (code versus phase)

- TEC could directly be obtained from code measurements :
  - No phase ambiguity to compute.
  - No problem with cycle slips, in particular during disturbed ionosphere conditions.



Galileo E1-E5 RoTEC (code versus phase)

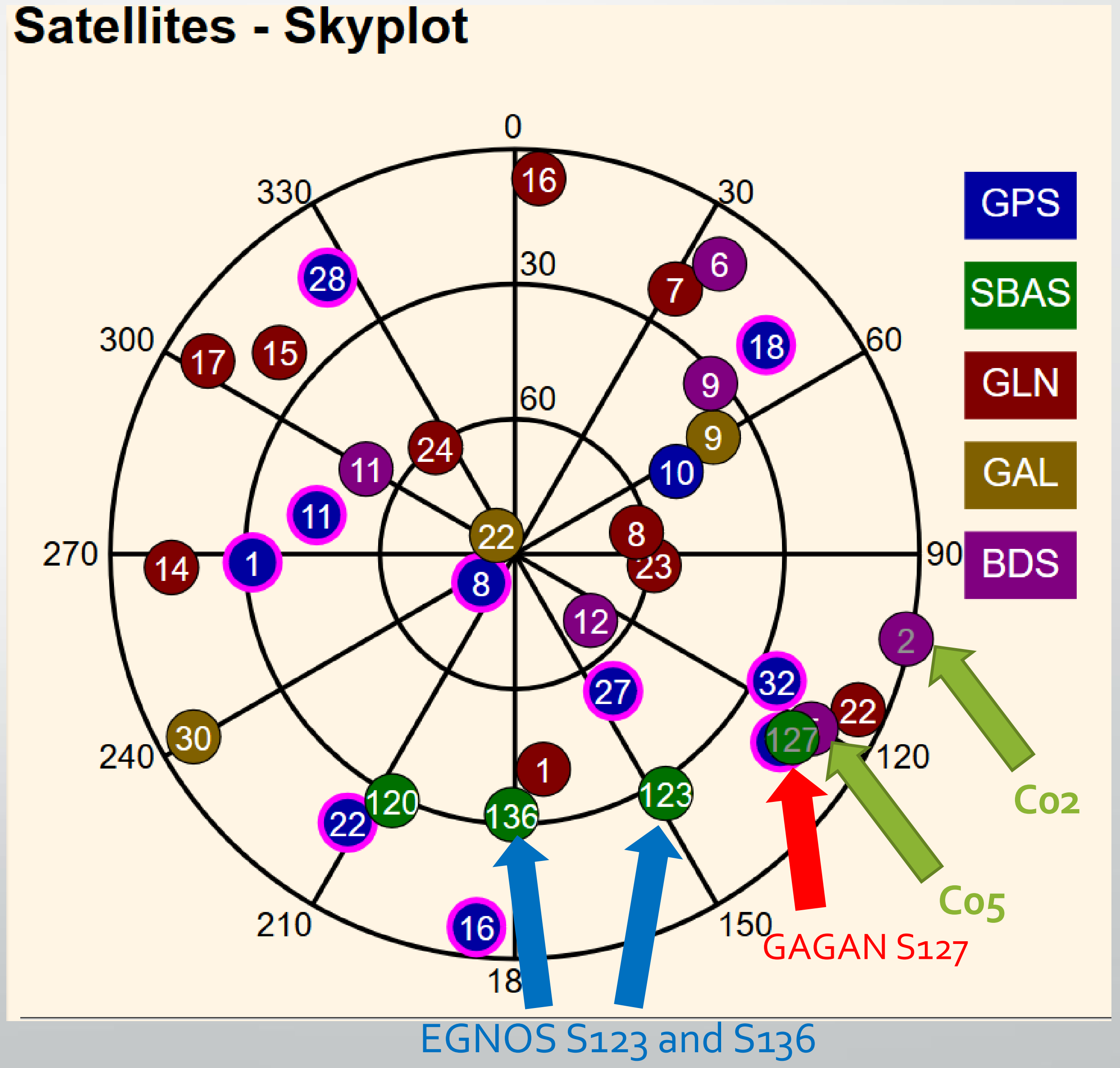
- Nevertheless, a strong TID cannot be extracted from code noise.



GEO satellites for ionosphere monitoring

GEO at European mid-latitude (Liege, Belgium)

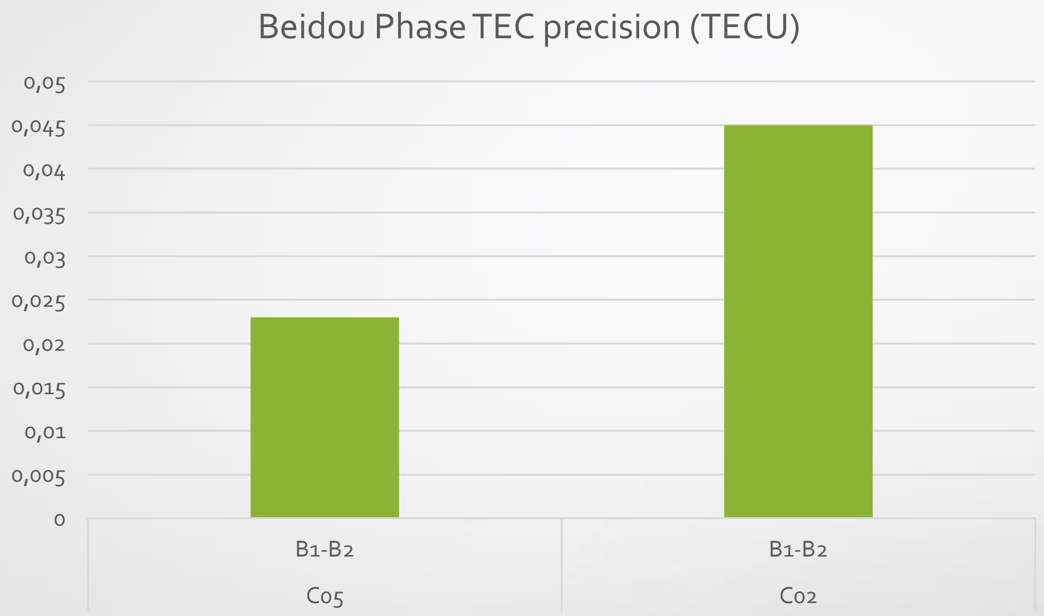
- **Beidou**
  - C02 (1°-2°)
  - C05 (15°)
- SBAS
  - **GAGAN (India)**
    - S127 (16°)
  - **EGNOS (Europe)**
    - S123 (27°)
    - S136 (32°)



Beidou GEO

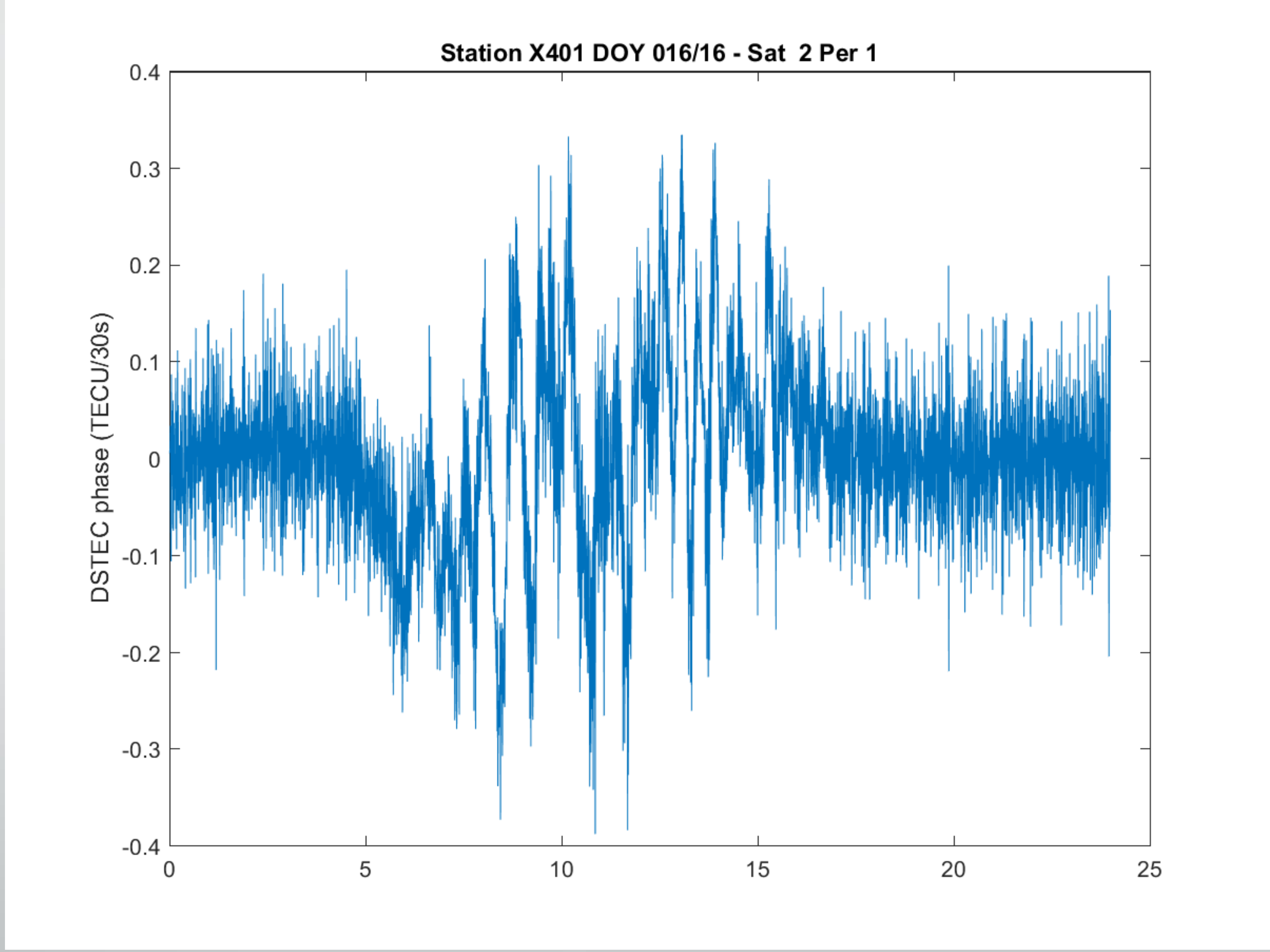
- In Liege (Belgium), Beidou GEO satellites C05 (15°) and C02 (1-2°) can be tracked by all Septentrio receivers.
- C05 data are continuous (in average less than 1 cycle slip a day).
  - ➔ Phase ambiguity often remains the same during several days.
- C02 data are usually continuous during several hours (up to 24 hours).
- Our Trimble NetR9 receivers only track C05 but data are unusable due to many cycle slips.

Beidou GEO (Liege): Precision (phase)



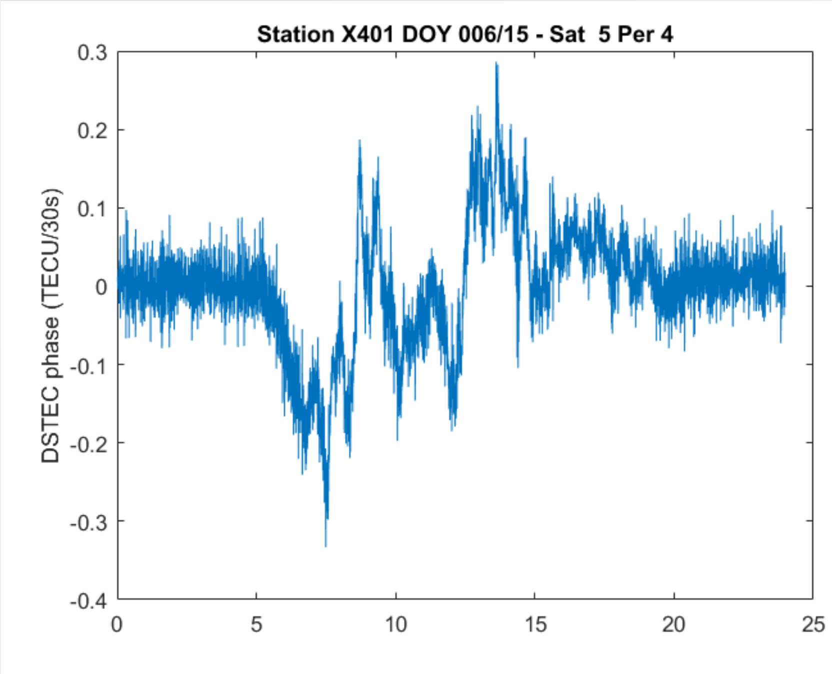
- Given phase TEC accuracy (C05: 0,023 TECU) and (C02: 0,045 TECU), both satellites can be used to monitor slant TEC or local variability in TEC.

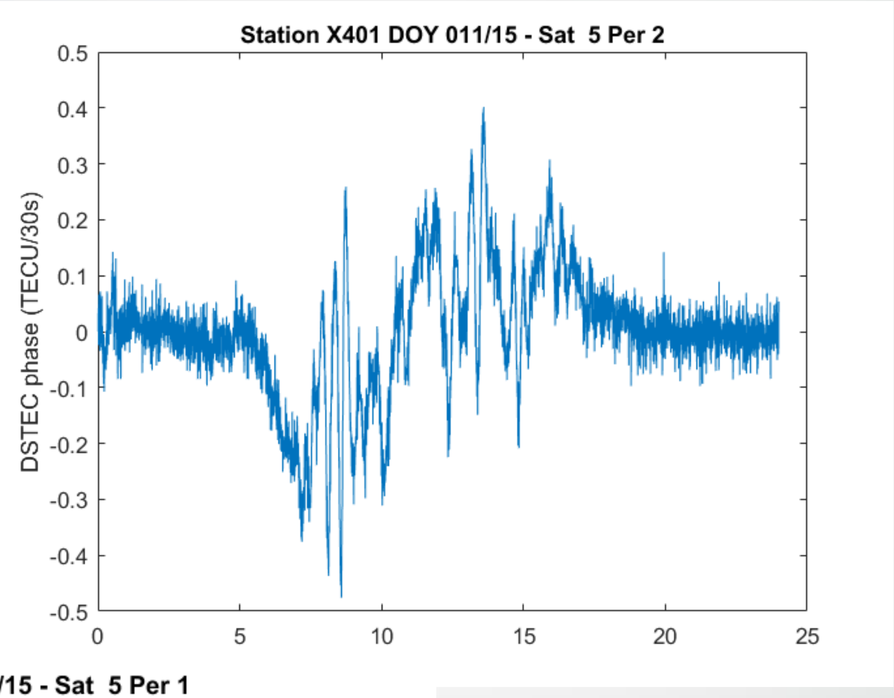
Beidou GEO : $\Delta STEC$ Phase 1

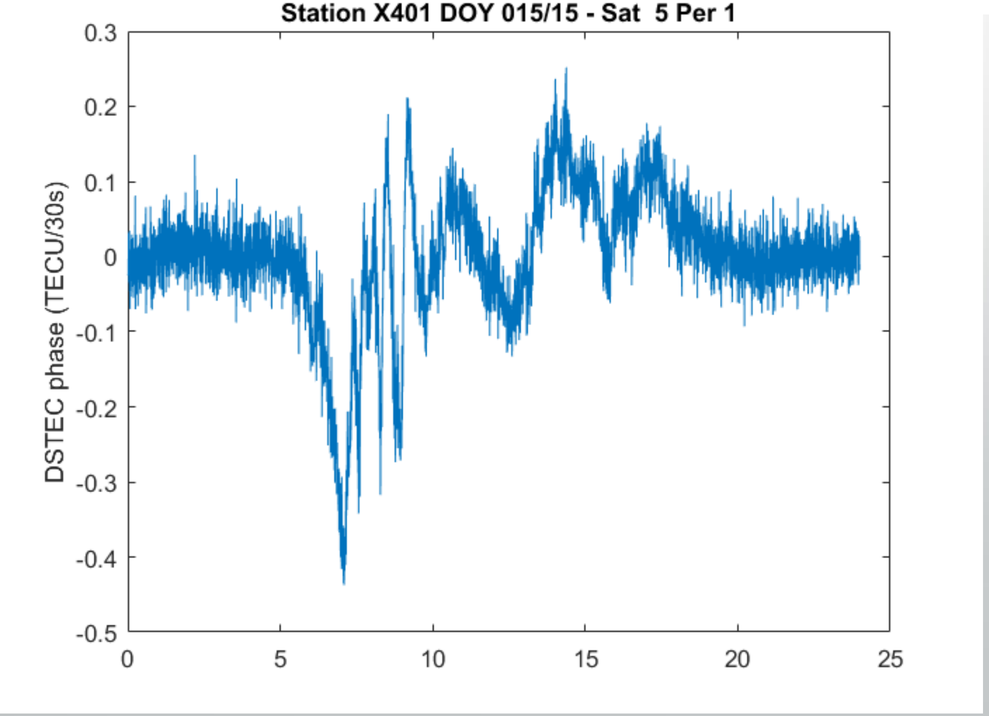


Beidou GEO : $\Delta STEC$ Phase 2

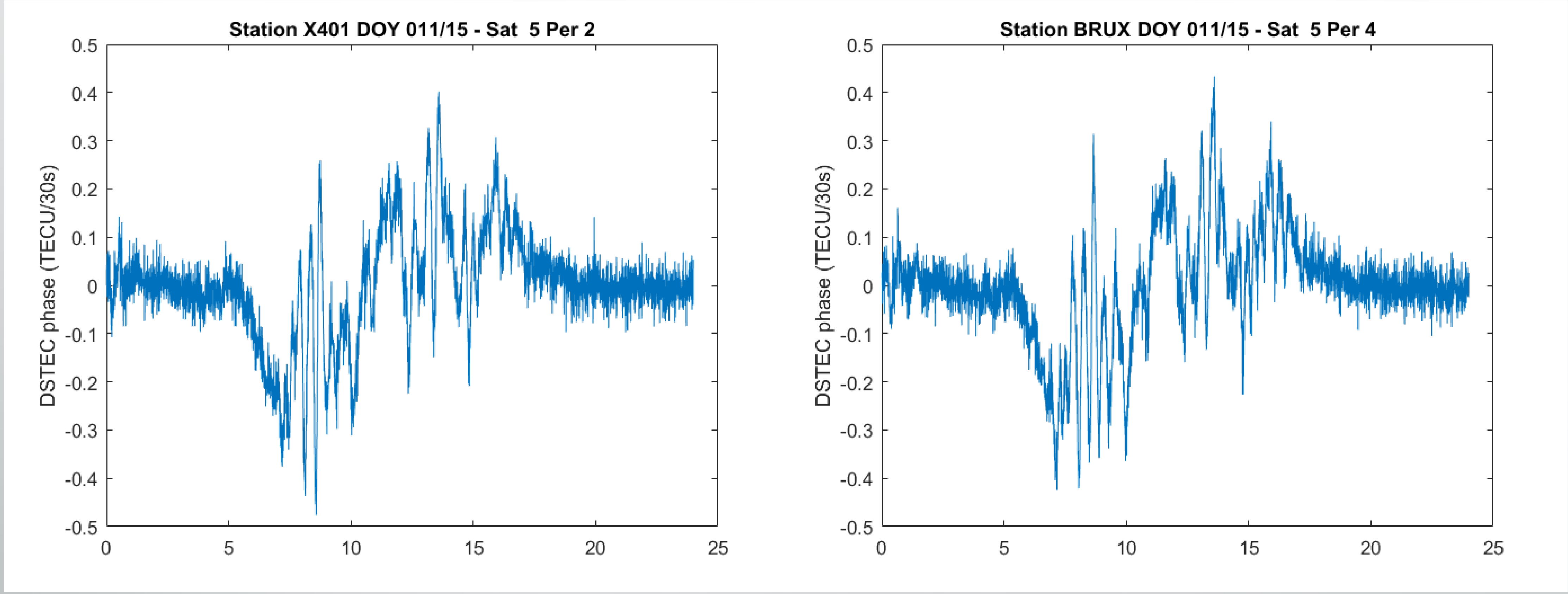
- The variability observed in $\Delta STEC$ could be due to between epoch variation of :
  - TEC
  - Multipath (at the station or at the satellite)
  - IF biases (should be very small if any).
- For GEO satellites, multipath is expected to have :
  - A repeatability of 1 sidereal day.
  - A low frequency due to the slow variation of the geometry.





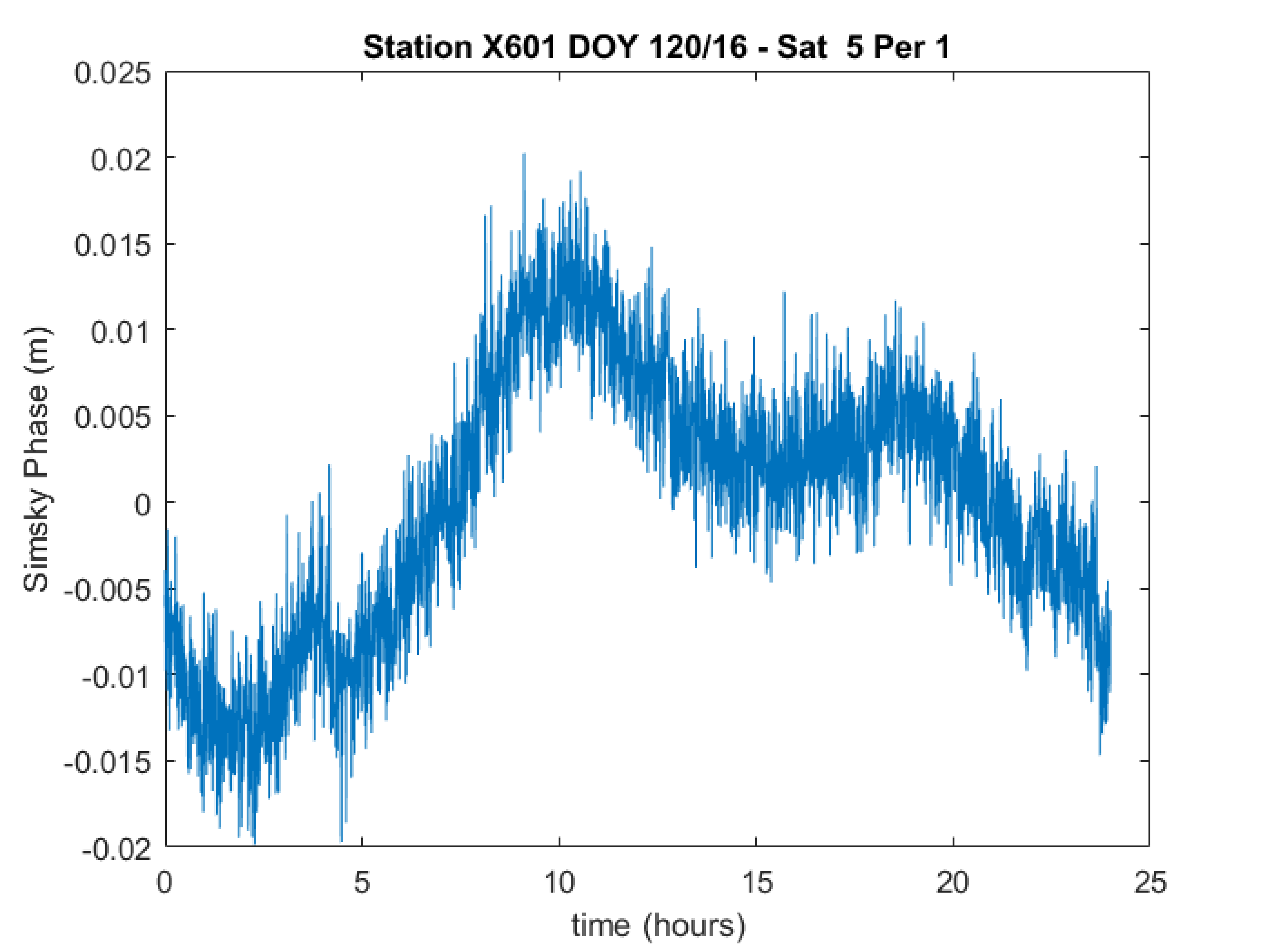


No daily repeatability



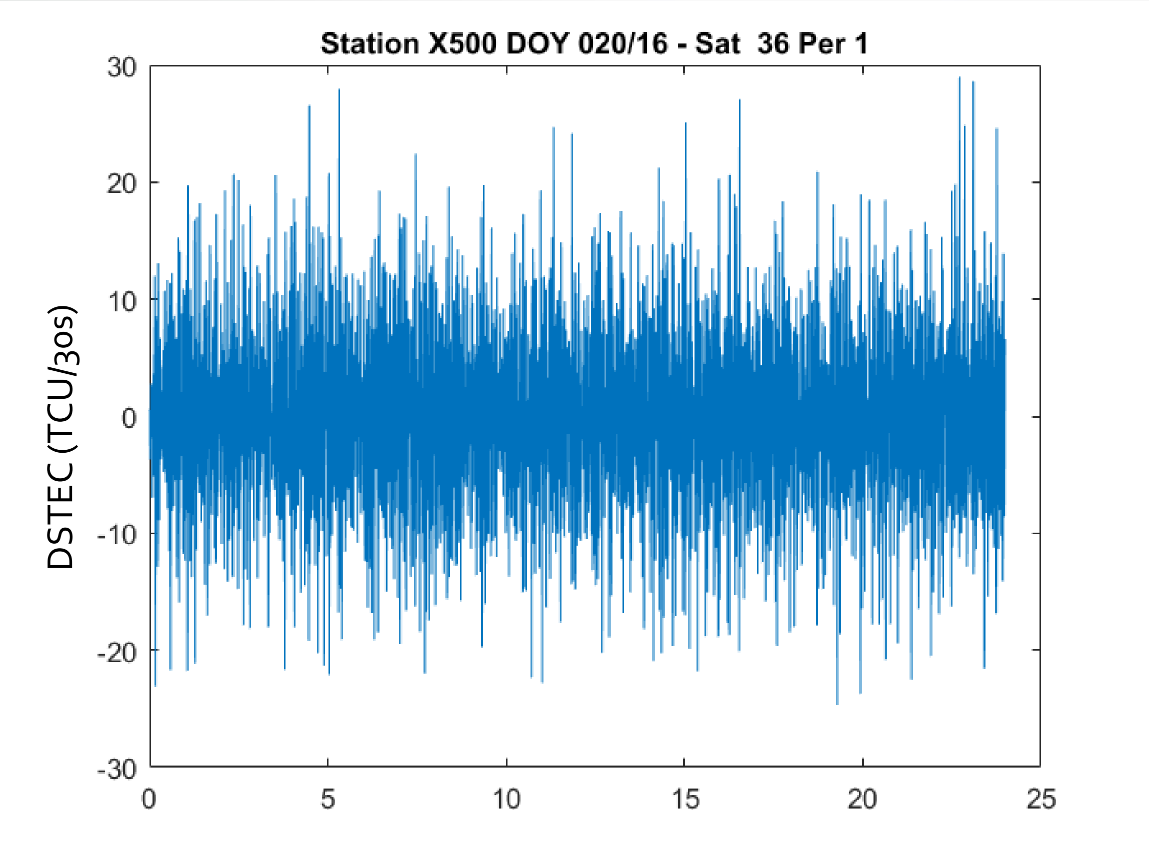
Similar signal for Liege and Brussels (about 100 km baseline)

Simsky 3F combination



SBAS (Liege)

- First results show that $\Delta STEC$ (phase) reconstructed from SBAS available in Liege is NOT precise enough to monitor TIDs (to be confirmed by further investigation).



Conclusions

- New/modernized GNSS combined with last generation receivers/antennas bring improvement in code and phase TEC accuracy (larger frequency difference, more precise code and phase observables more resistant to multipath).
- In particular, Code TEC precision is better than 1 TECU (above 20° elevation, multipath filter on, Septentrio PolaRx4) when using Galileo E1 and E5.
  - Code only TEC reconstruction becomes an option.
  - Not possible to detect even strong TIDs.
- In Liege, TEC reconstructed with
  - Available SBAS is NOT precise enough to study local variability in TEC (to be confirmed);
  - Beidou GEO provide a valuable tool to study “moving structures” in TEC.

Thanks for your attention !