Monitoring the ionosphere using new GNSS

R. Warnant[1], C. Deprez[1], G. Wautelet[2], L. Van de Vyvere[3]

[1]University of Liege, Liege, Belgium.

[2]GRGS, Toulouse, France.

[3]M3 System, Wavre, Belgium.

Monitoring TEC for geodetic applications

- For the last 25 years, TEC has been reconstructed from GPS L1/L2 code and phase pseudoranges in order to correct ionospheric effects on positioning applications.
  - Absolute positioning is influenced by absolute TEC and “regular” gradients.
  - Differential and relative positioning are influenced by regular gradients and also local variability in TEC (the latter mainly degrading precise applications).
- GPS-based TEC monitoring data suffers from different shortcomings.

Present shortcomings 1

- Absolute TEC accuracy is limited to 2-5 TECU:
  - Depends on code and phase pseudoranges precision.
  - The use of code levelling to compute phase ambiguities degrades TEC accuracy due to low code precision (main limitation).
- Limited spatial resolution:
  - Depends on the number of satellites in view.
  - In Liege, the number of GPS satellites in view ranges from 8 to 15 (average 11).
  - A proper modeling of local variability in TEC requires increased spatial resolution.

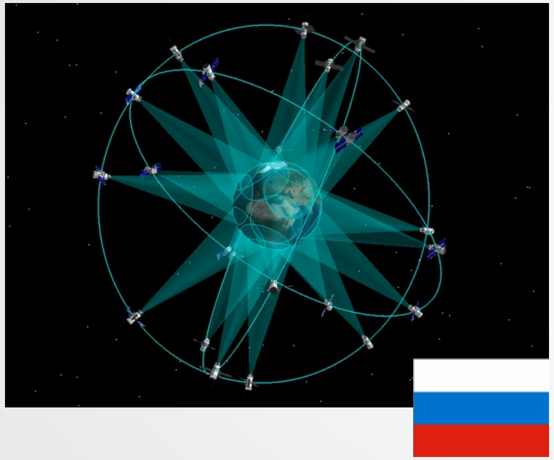
Present shortcomings 2

- Monitoring of local variability in TEC at European mid-latitudes (Belgium):
  - Mainly due Travelling Ionospheric Disturbances.
  - Also detected during geomagnetic storms.
  - Depends on phase pseudorange precision.
  - Requires good spatial resolution.
  - The 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

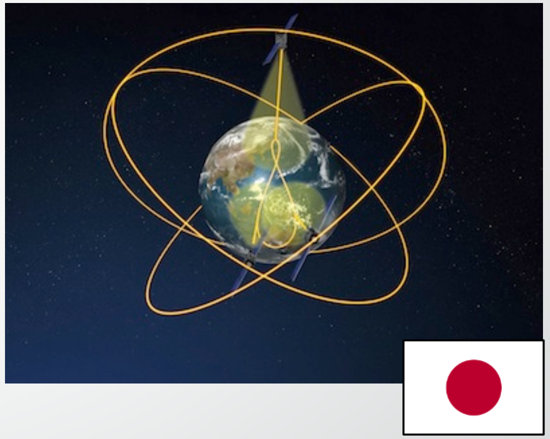
GPS

GLONASS

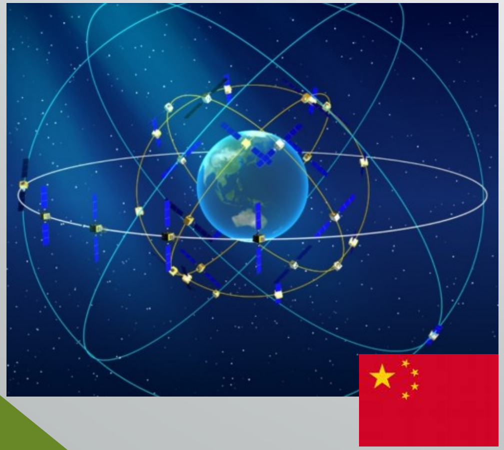


Galileo

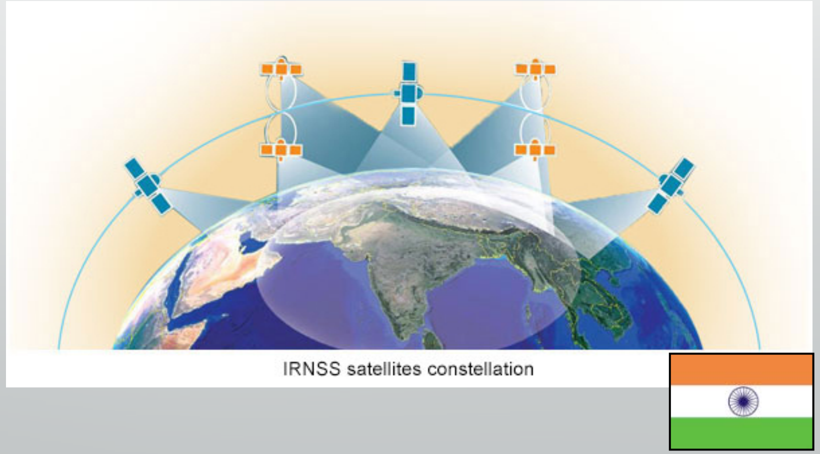
QZSS



Beidou



NAVIC



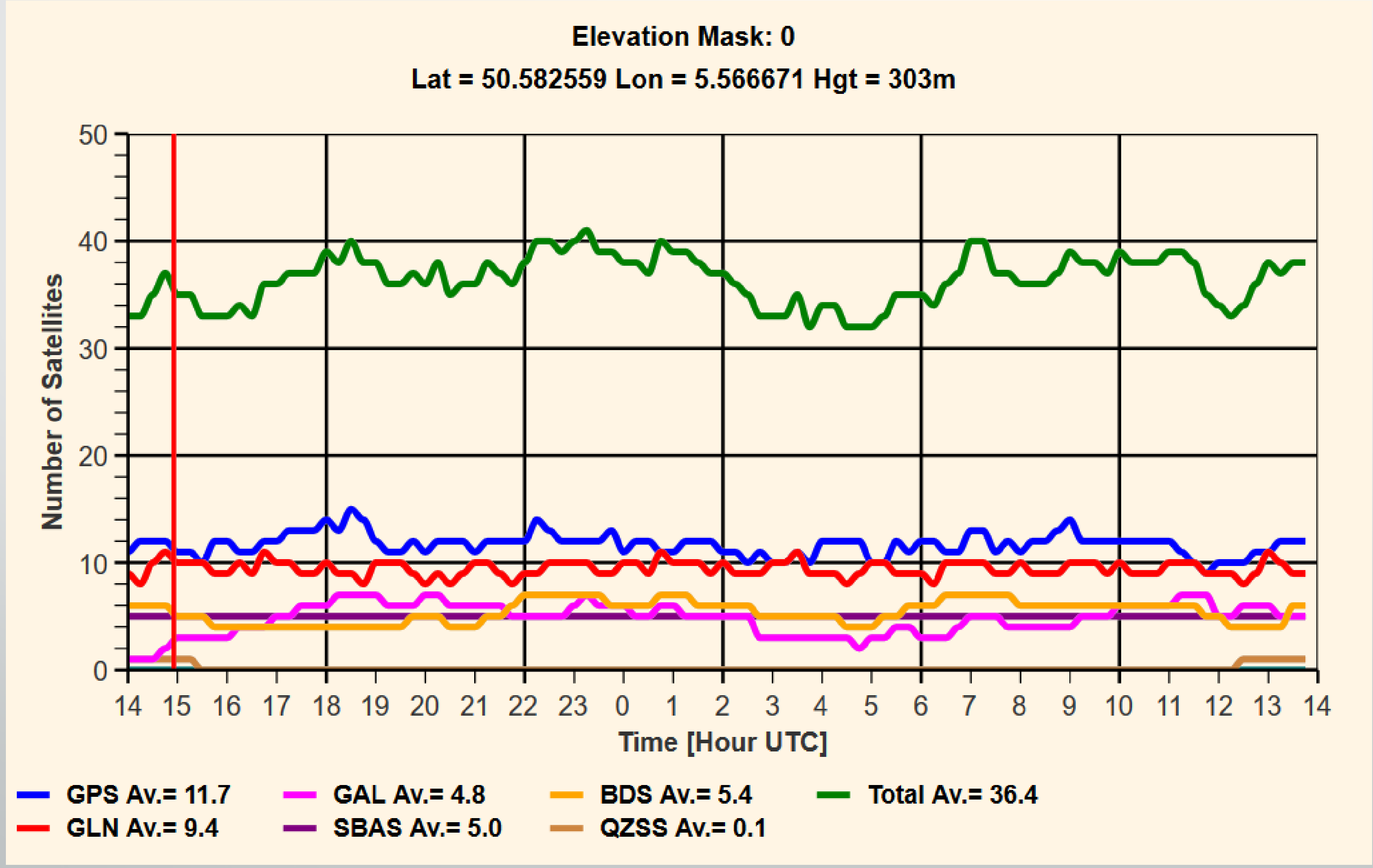
SBAS

New/modernized GNSS 2

- More (than 2) frequencies:
  - Possible to form several frequency pairs to reconstruct TEC
  - Development of improved ambiguity computation (even resolution ?) techniques.
- Improved signals :
  - Better resistance to multipath
  - New modulation techniques allowing to perform more precise code pseudorange measurements.
- More satellites:
  - The combined use of al the available GNSS provides better redundancy and improved spatial resolution.

New/modernized GNSS 3

- Number of GNSS satellites in view (up to 40) in Liege (Belgium)



New/modernized GNSS 4

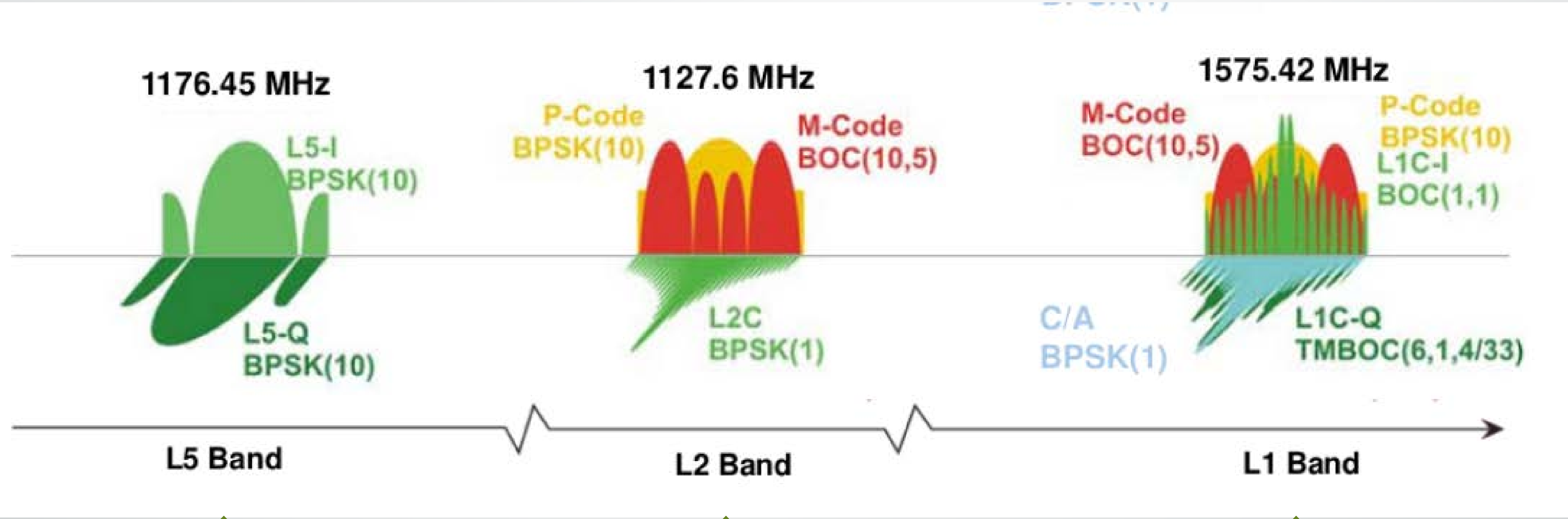
- Different types of orbits:
  - Medium Earth Orbits (MEO)
  - Geostationary Orbits (GEO)
  - Inclined Geosynchronous Orbits (IGSO)
- GEO orbits have a negligible velocity wrt respect to the ionosphere.
- Therefore, GEO satellites have a particular interest for the study of local variability in TEC.

Multi GNSS/multi-frequency TEC precision

GNSS equipment

- Located in Liege (Belgium).
- 2 Trimble GNSS choke ring antenna's 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

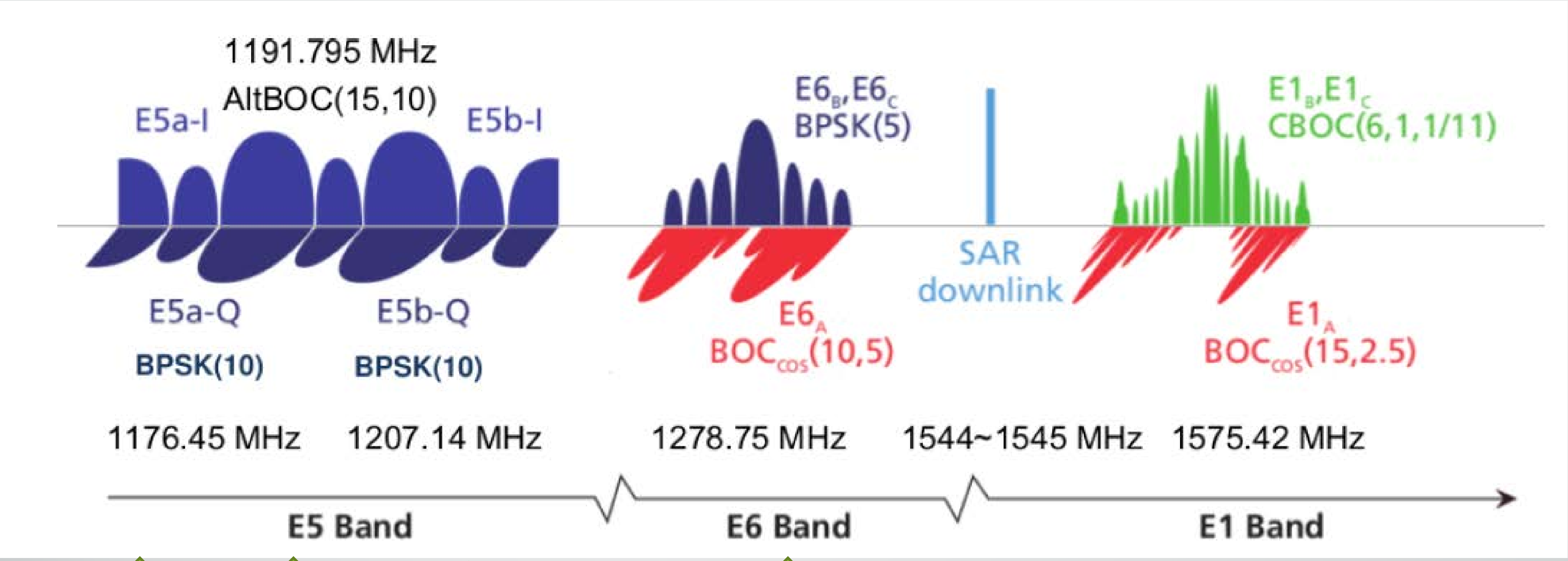


L5

L2

L1

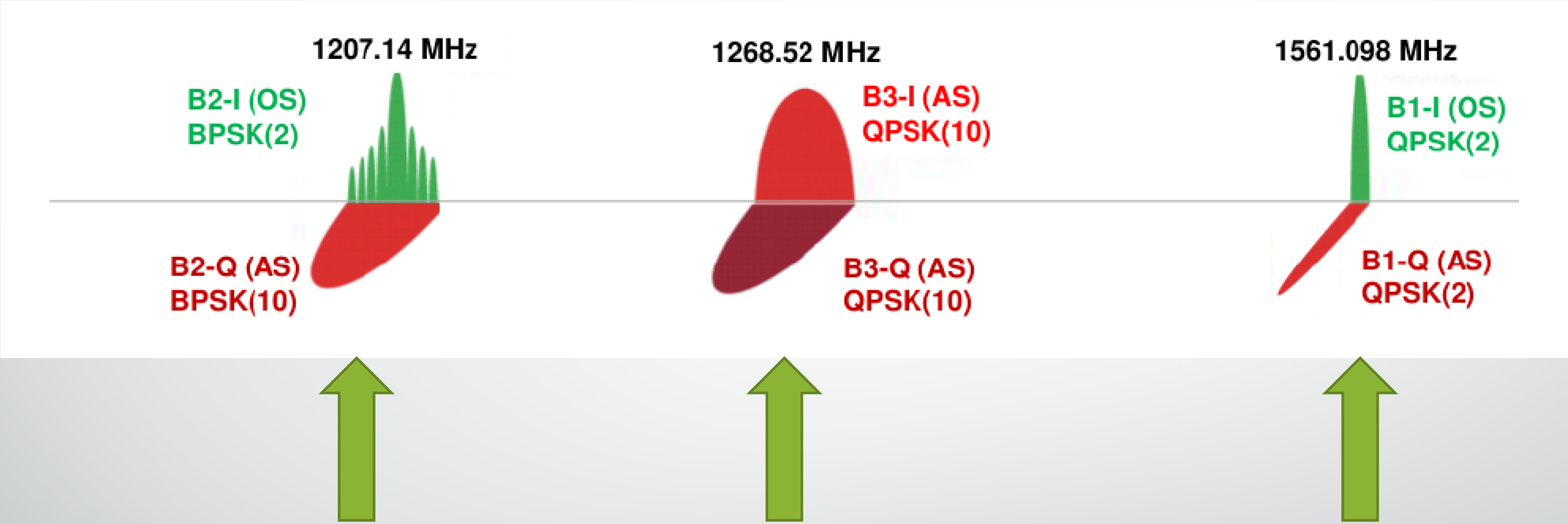
GNSS signals : Galileo



E5a E5 E5b E6 E1

Only available with PolaRx5

GNSS signals : Beidou



B2

B3 → Only available on NetR9 and PolaRx5

B1

Multi-GNSS/frequency TEC precision 1

- For satellite "i" and receiver "p", the code geometry free (GF) combination between frequency f_k and f_l :

$$P^{i}_{p,kl} = P^{i}_{p,k} - P^{i}_{p,l} = \alpha_{kl}\ STEC^{i}_{p,kl} + (d^{i}_{kl} + d_{p,kl}) + M^{i}_{p,kl} + E^{i}_{p,kl}$$

- Codes at frequency f_k and f_l ($P^{i}_{p,k} - P^{i}_{p,l}$)
- Slant TEC ($STEC^{i}_{p,kl}$)
- InterFrequency rec. and sat. biases ($d^{i}_{kl} + d_{p,kl}$)
- Multipath ($M^{i}_{p,kl}$)
- Noise ($E^{i}_{p,kl}$)

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

Multi-GNSS/frequency TEC precision 2

- Reconstructed TEC precision mainly depends on :
  - Code pseudorange (P_k,P_l) precision.
  - Multipath.
  - IF biases variability (one usually assume that they are stable over short time periods).
  - The "TEC coefficient" : α_{kl}^{-1}

$$STEC_{p,kl}^{i} = \frac{(P_{p,k}^{i} - P_{p,l}^{i}) - (d_{kl}^{i} + d_{p,kl}) - M_{p,kl}^{i} - \mathrm{E}_{p,kl}^{i}}{\alpha_{kl}}$$

- Same demonstration can be done for phase pseudoranges which contain an additional term: the phase ambiguity.

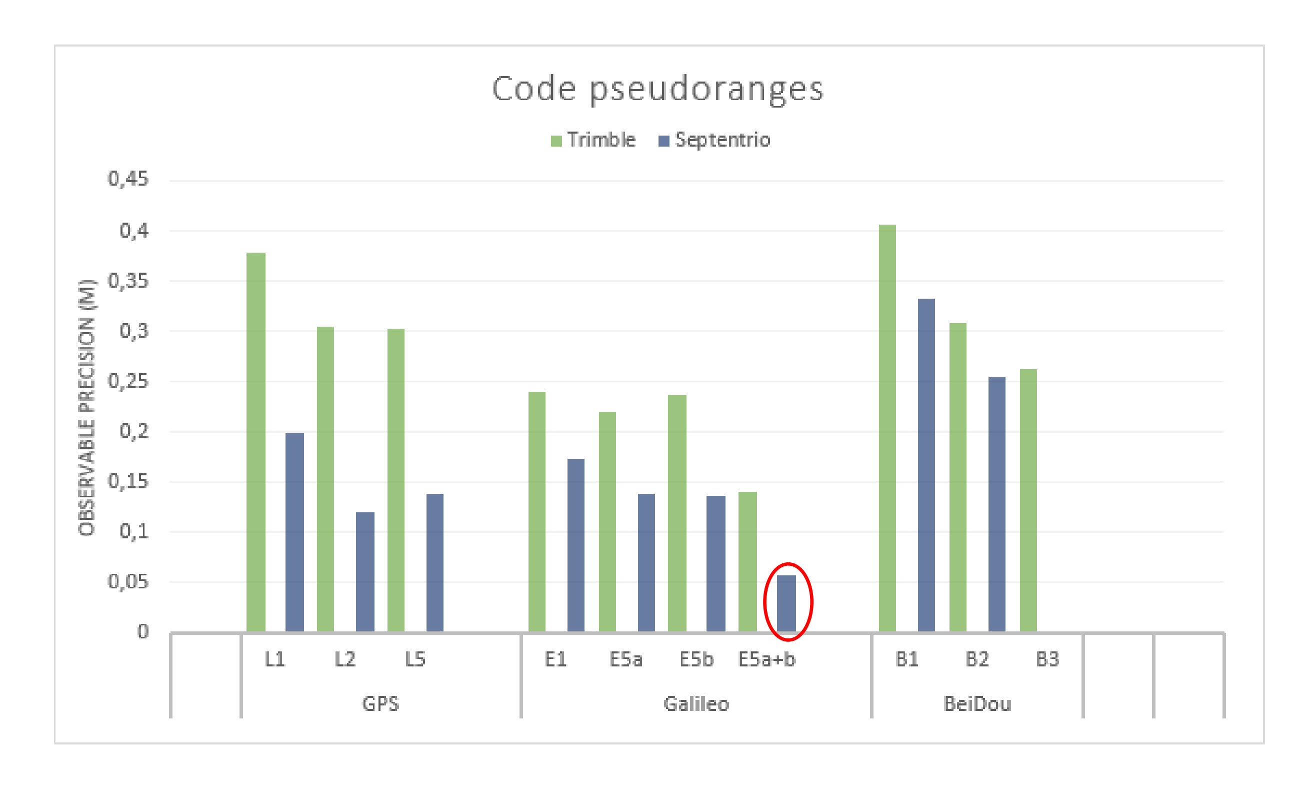
Multi-GNSS/frequency TEC precision 3

- Given the same code 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**

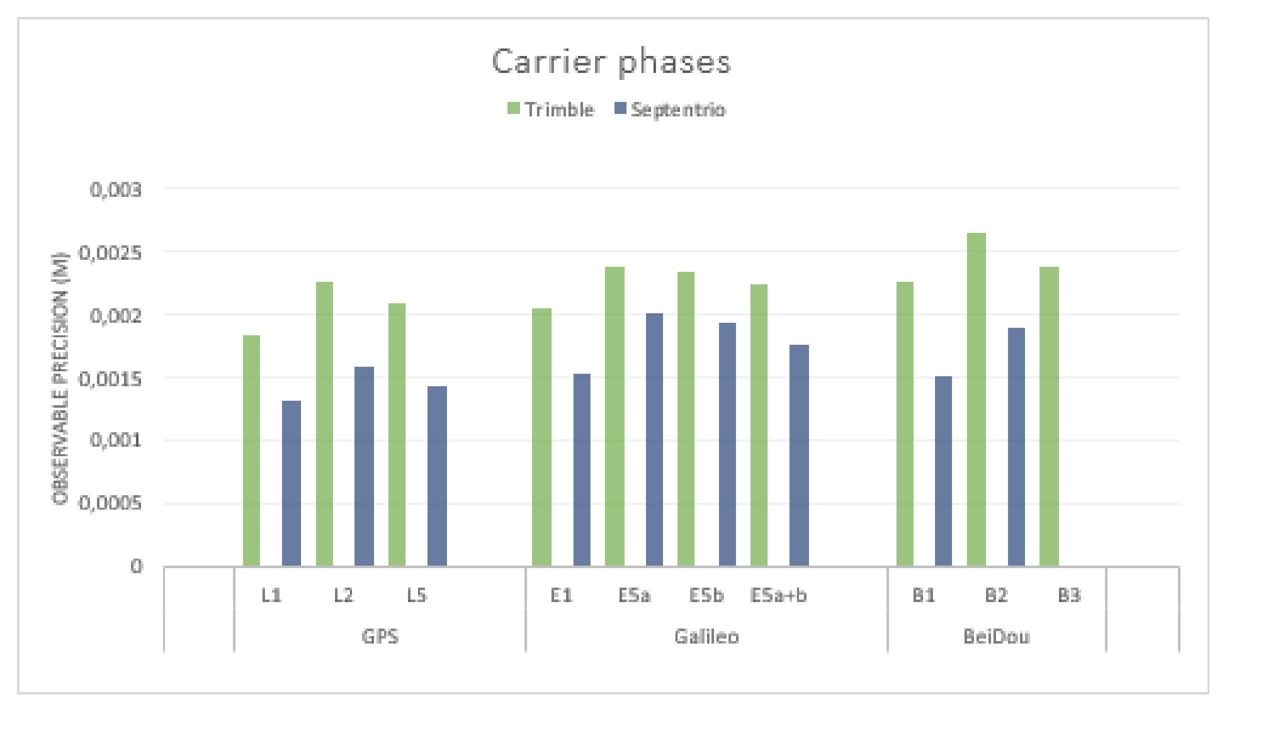
Multi-GNSS/frequency TEC precision 4

- Code pseudorange precision (large differences between frequencies/receivers !)



Multi-GNSS/frequency TEC precision 5

- Phase pseudorange precision: small differences between frequencies/receivers



Methodology to asses TEC precision 1

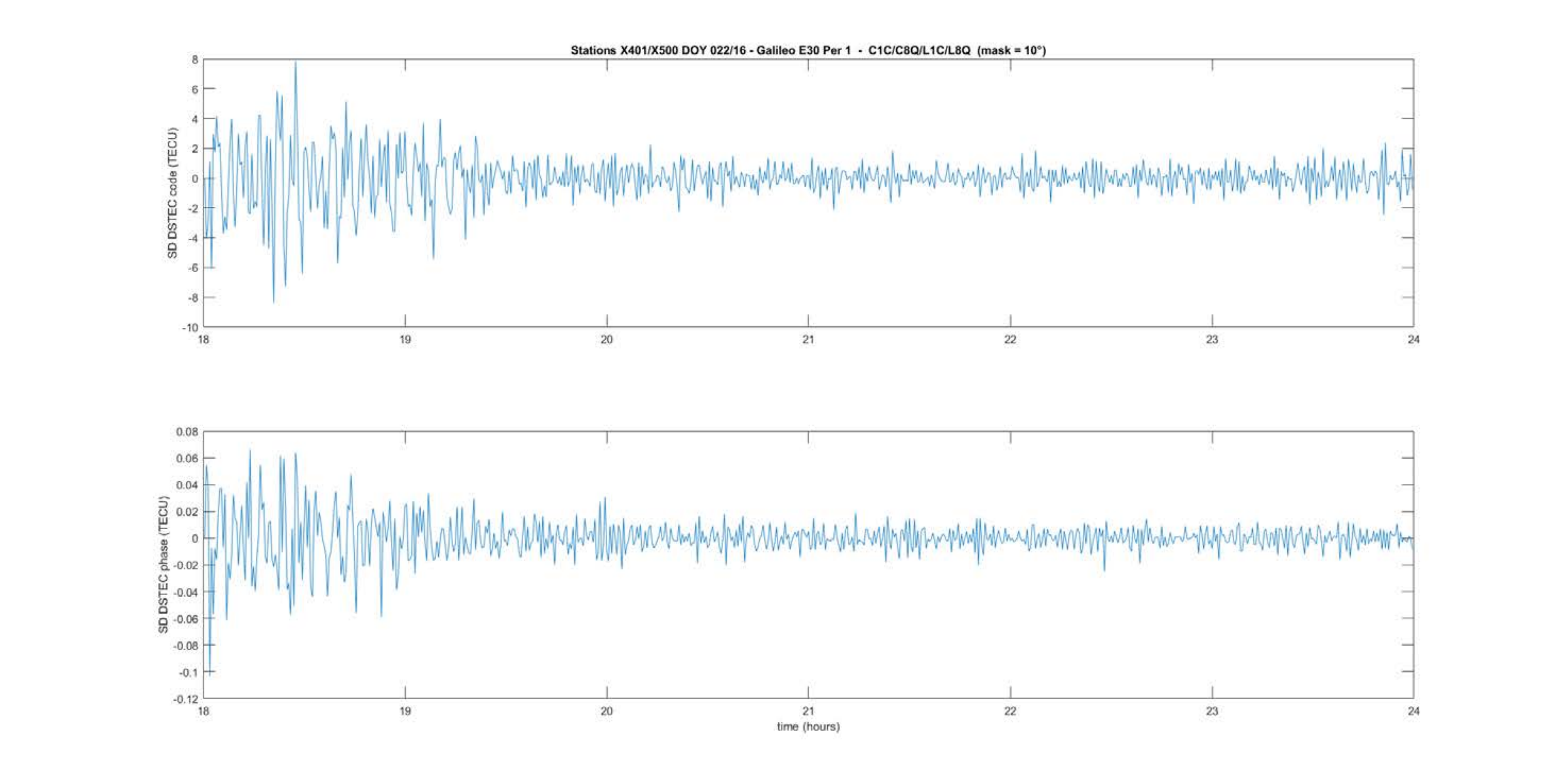
- Compute Slant TEC change from epoch to epoch (30 s interval) without normalization:
  - Removes biases (constant part of IF delays, ambiguities)
  - Still depends on noise and on between epoch variation of TEC and multipath

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

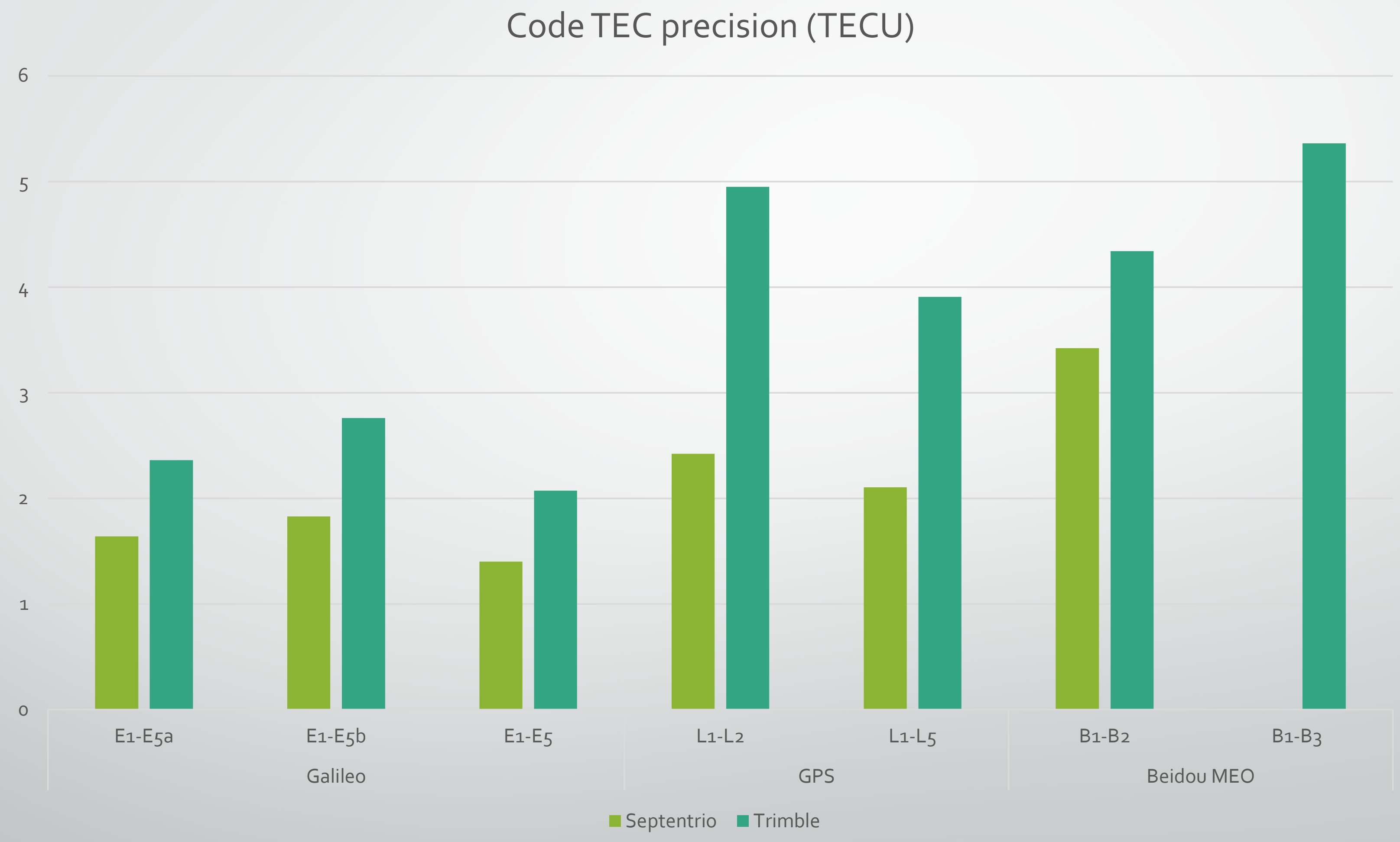
- Form single (between receiver) differences of $\Delta STEC(t_k)$ on ULg short baseline (5,352 m):
  - Completely removes TEC (same ionosphere).
  - Still contains multipath and noise.

Methodology to asses TEC precision 2

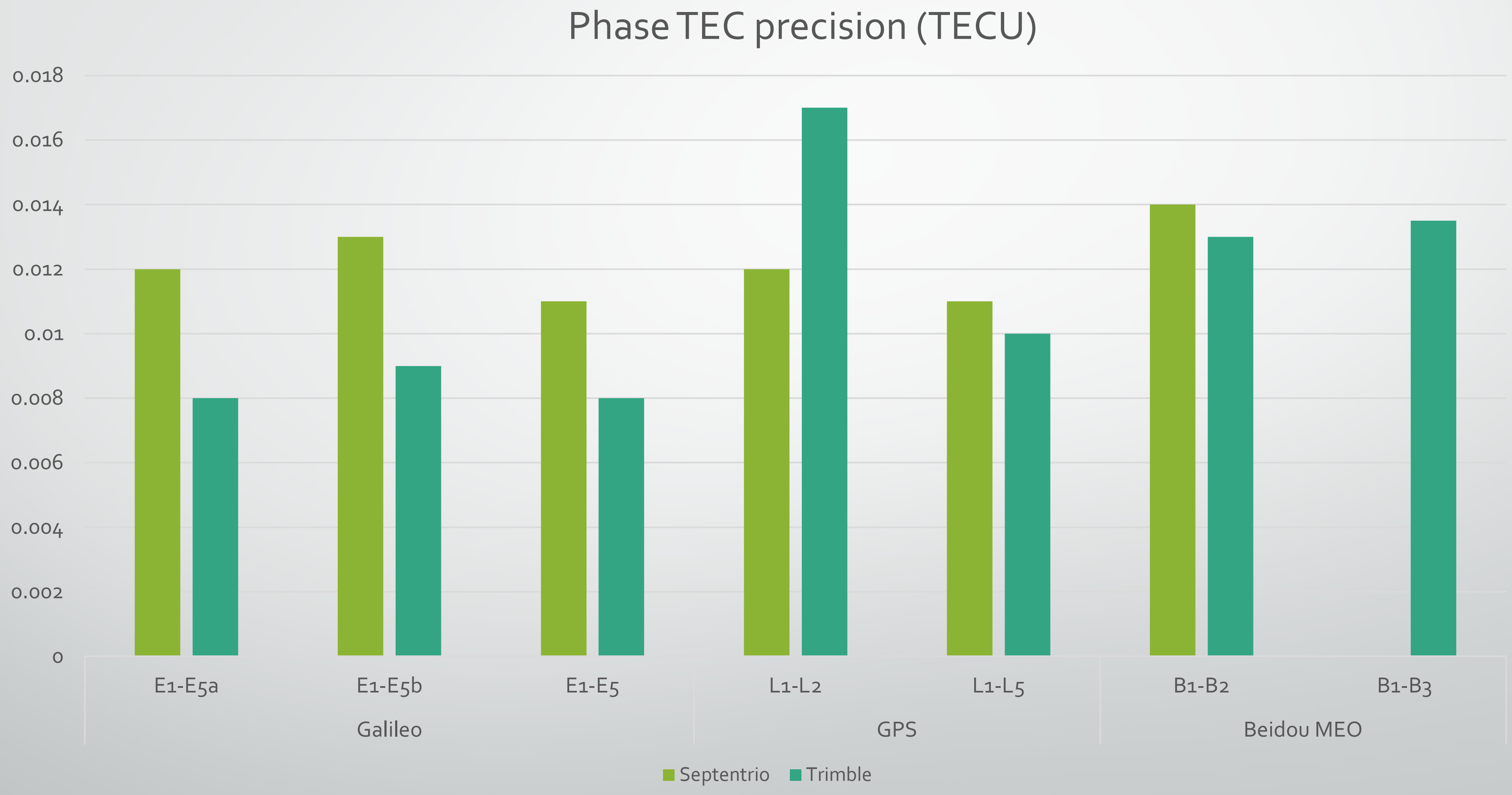
- TEC precision is estimated by computing the standard deviation of single differences of $\Delta STEC(t_k)$ and by dividing them by 2 (error propagation).



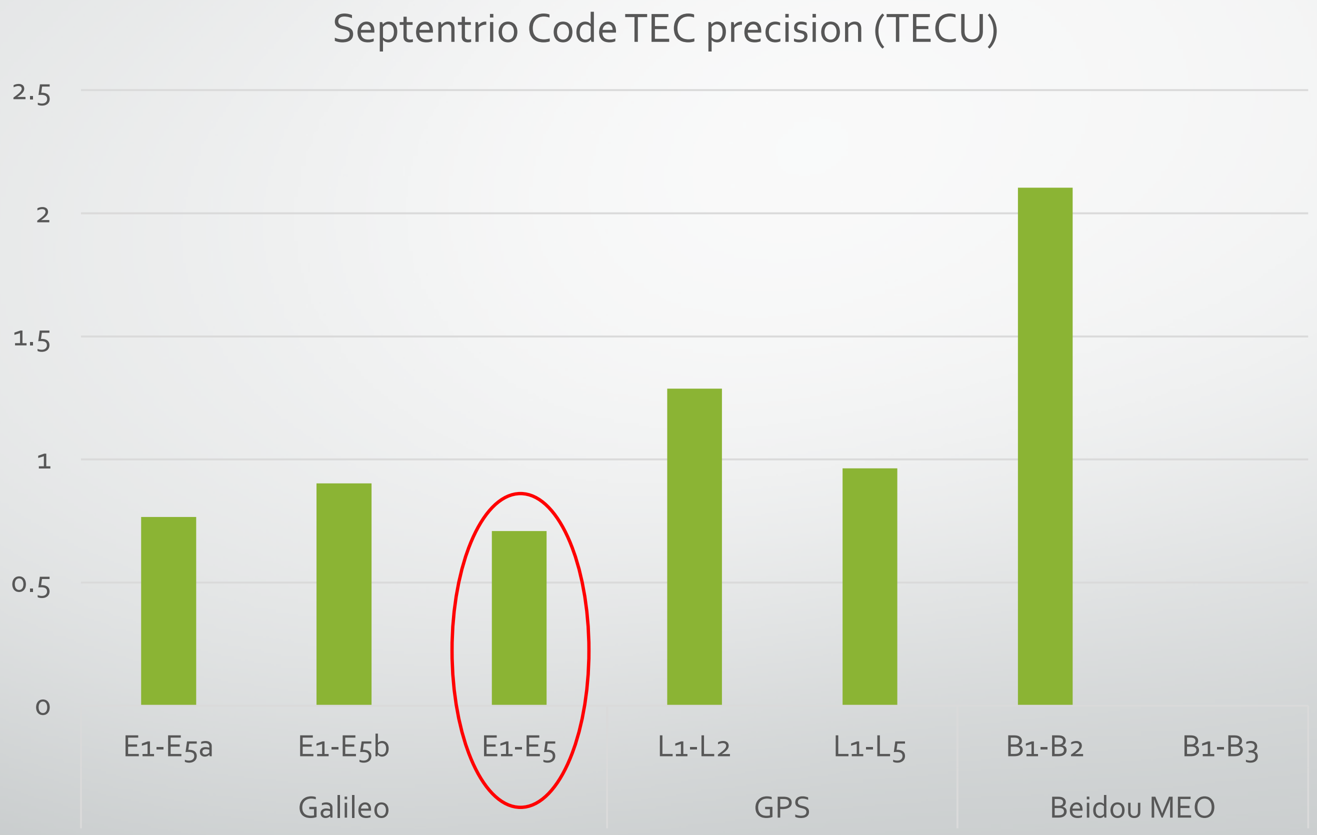
Results: code (multipath filter off - mask 10°)



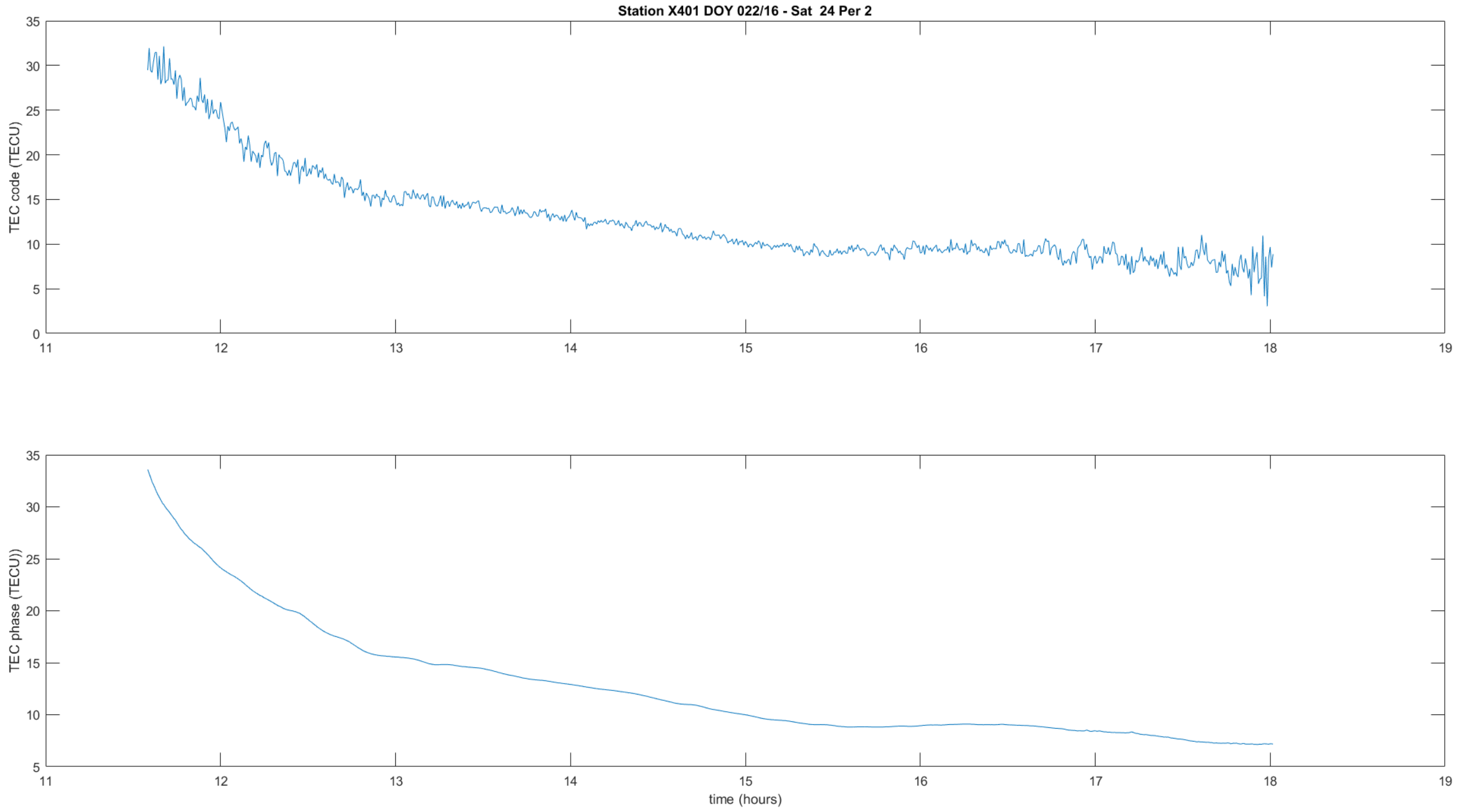
Results: Phase (multipath filter off - mask 10°)



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



Slant TEC Galileo E1-E5 code versus phase



Multi-GNSS/frequency TEC: Summary 1

- Strong improvement in code TEC precision with Galileo wrt the "standard" GPS L1/L2.
  - Galileo E1/E5 combination has a precision better than 1 TECU above 20° elevation (Septentrio PolaRx4).
  - This will bring improvement in code-phase leveling.

    ➔ Better TEC accuracy.
  - Depending on application requirement, TEC could directly be obtained from code measurements.

    ➔ No phase ambiguity to compute

    ➔ No problem with cycle slips, in particular during disturbed ionosphere conditions.

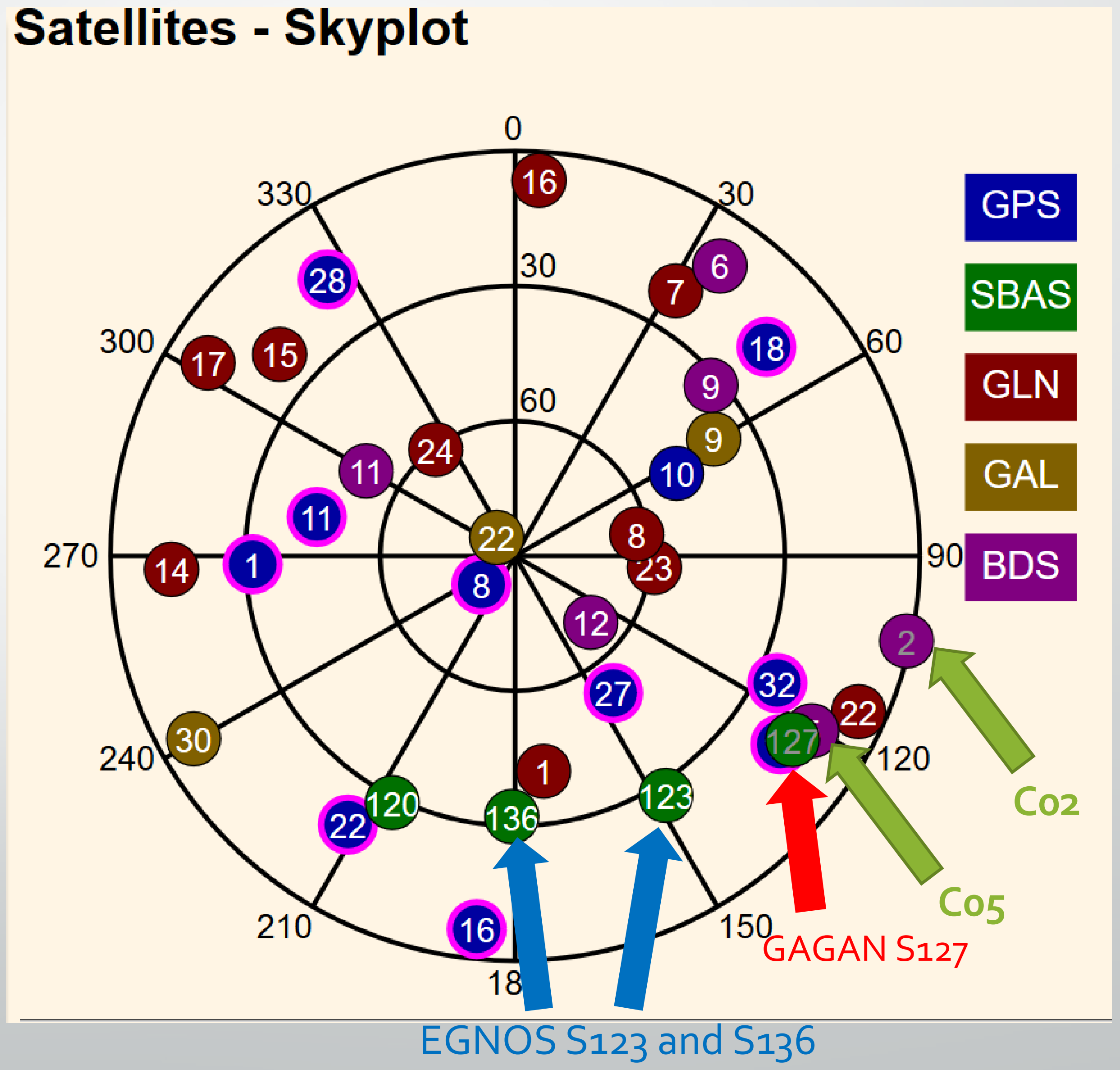
Multi-GNSS/frequency TEC: Summary 2

- As far as phase TEC accuracy is concerned, for Septentrio receivers, TEC precision has similar accuracy levels of about 0,012 TECU (mask 10°) for the different combinations/GNSS.
- For Trimble receivers, Galileo provides the best accuracy (0,008 TECU).

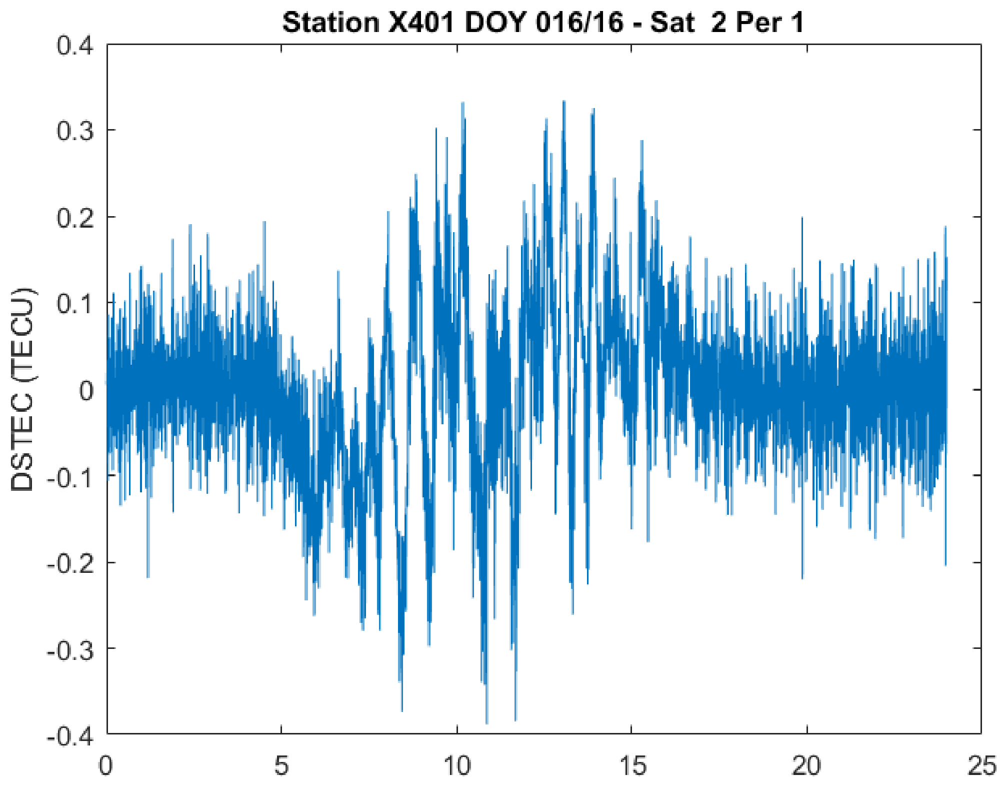
GEO satellites for ionosphere monitoring

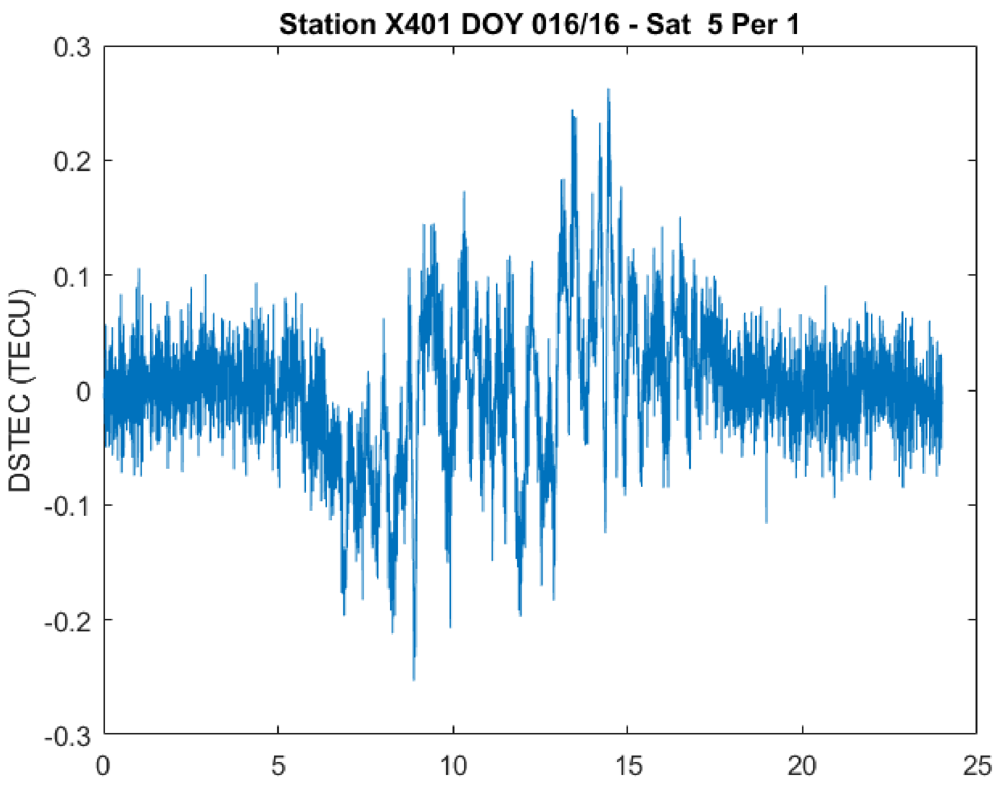
GEO at European mid-latitude (Liège, Belgium)

- **Beidou**
  - C02 (1°-2°)
  - C05 (15°)
- SBAS
  - **GAGAN (India)**
    - S127 (16°)
  - **EGNOS (Europe)**
    - S123 (27°)
    - S136 (32°)
- NAVIC
  - I06 (29°)
  - Only single frequency available yet (with PolaRx5).

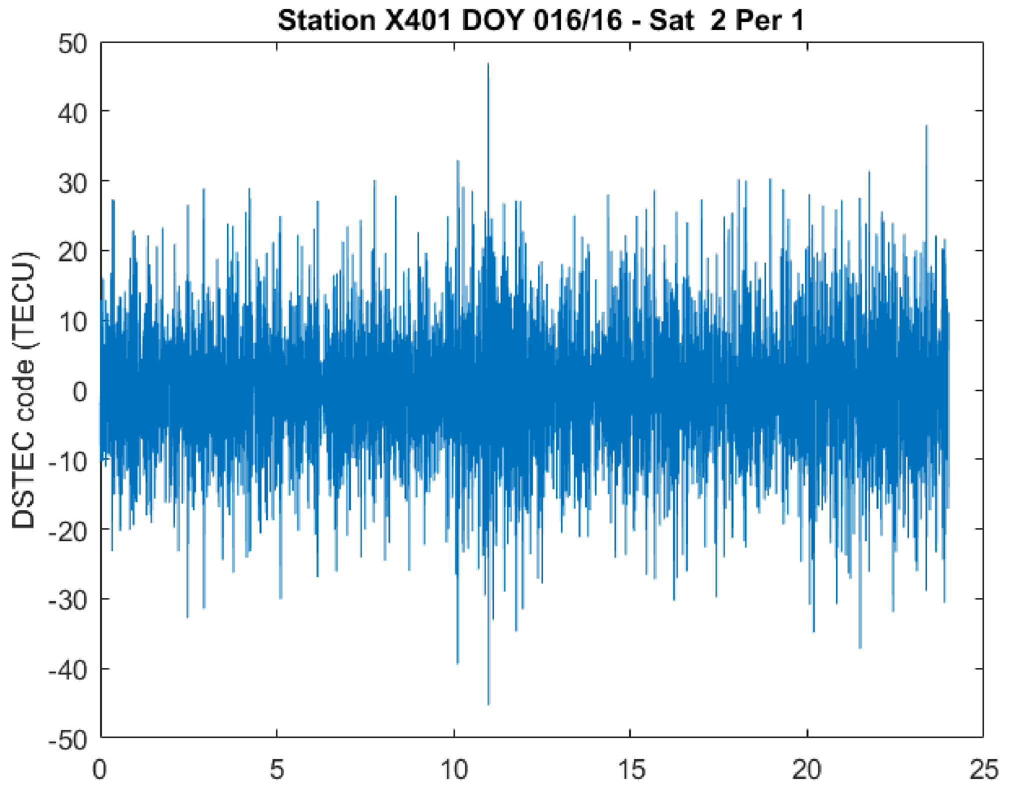


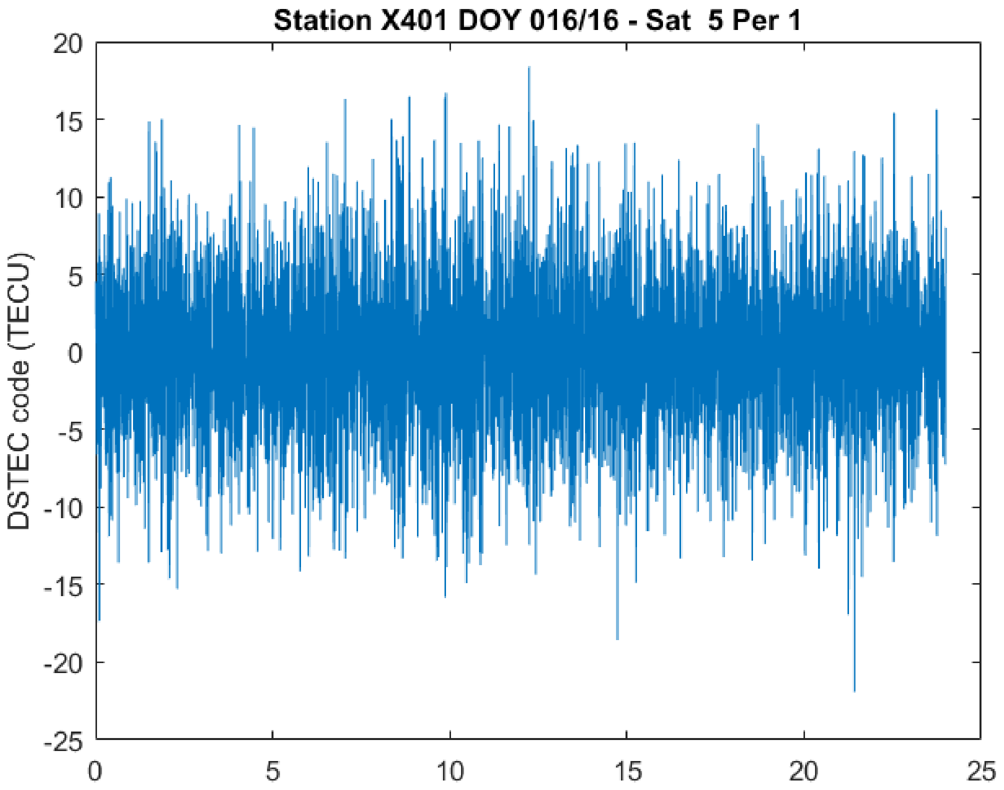
Beidou GEO : $\Delta STEC$ Phase



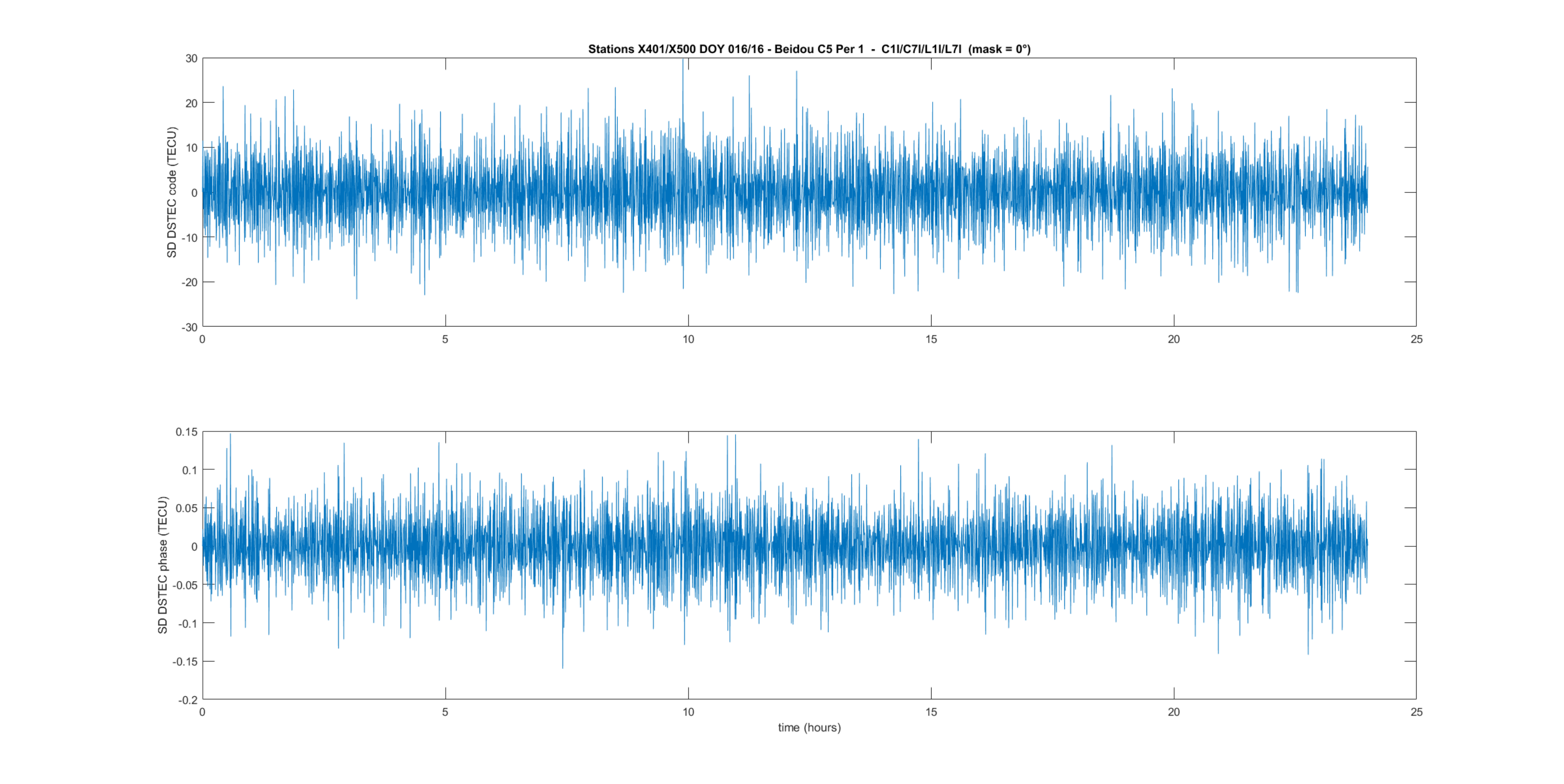


Beidou GEO : $\Delta STEC$ Code

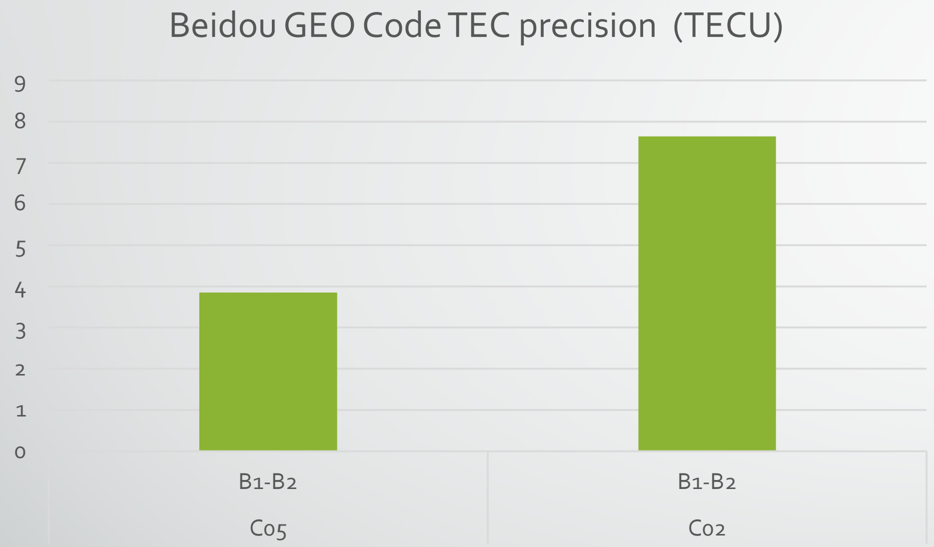


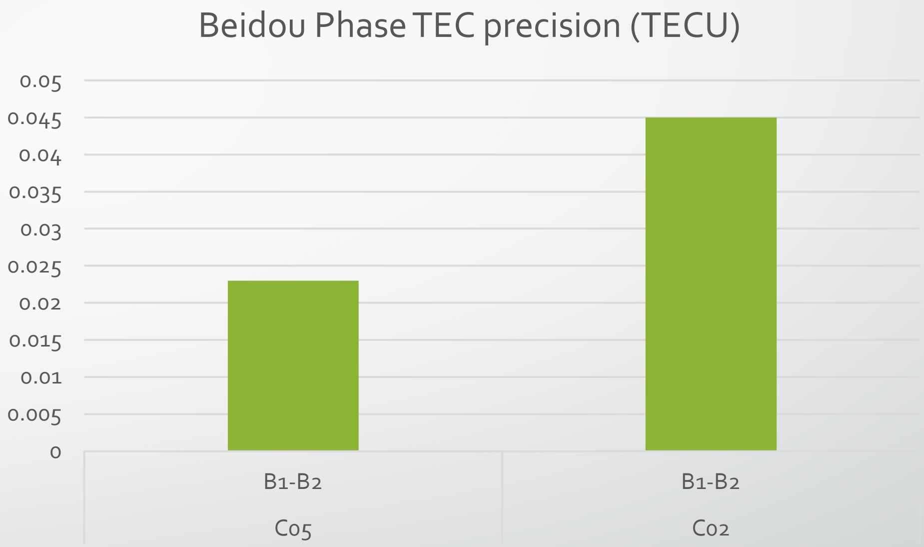


Beidou GEO: SD of $\Delta STEC$ (C05)

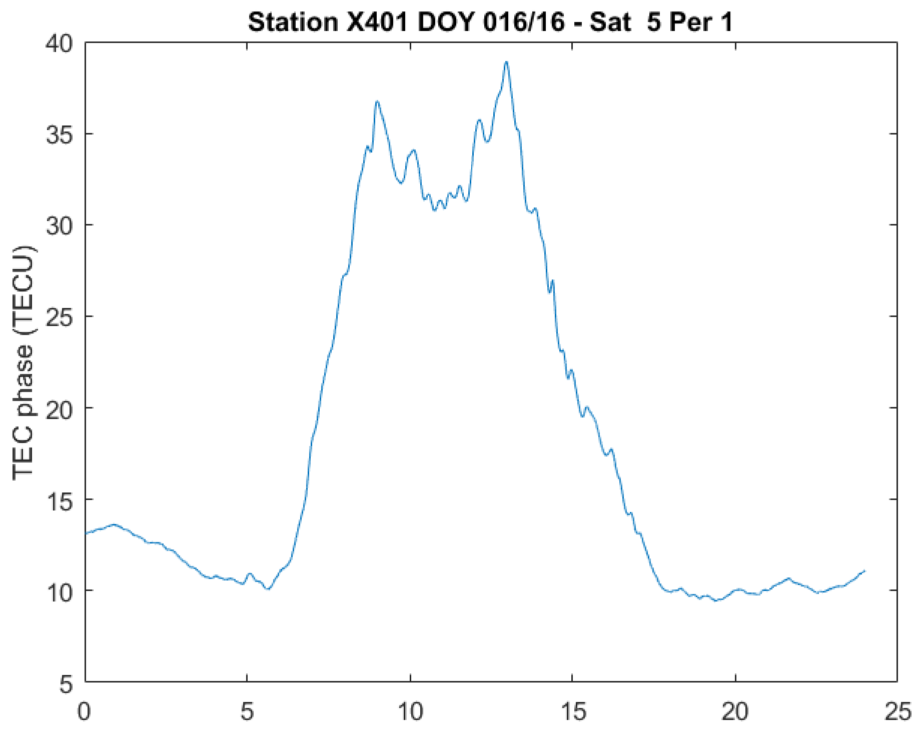


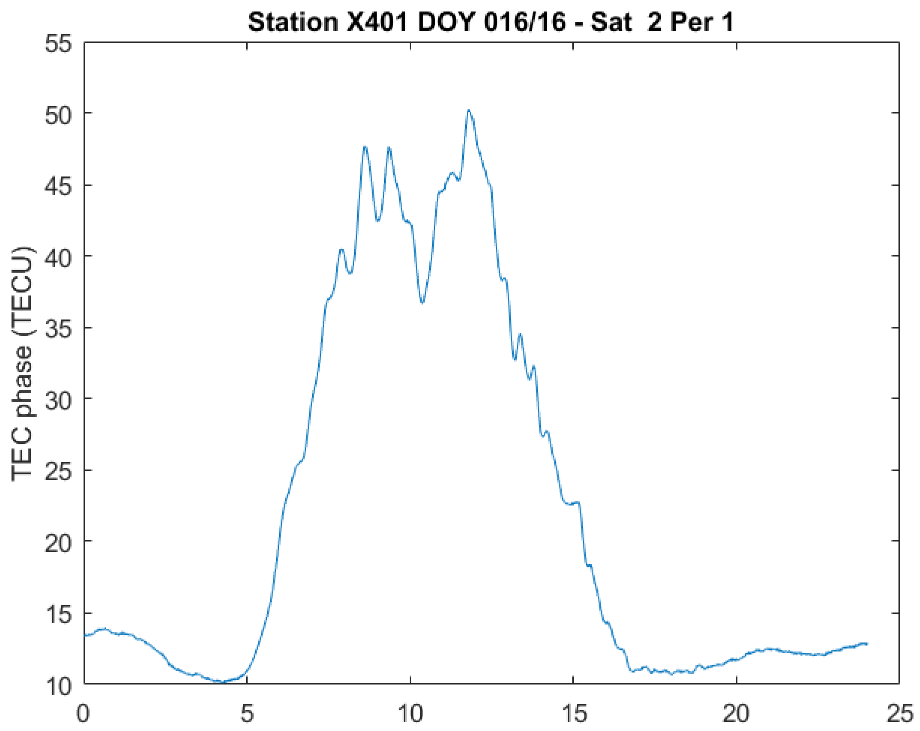
Beidou GEO: accuracy





Beidou GEO: Slant phase TEC





Beidou GEO: Summary 1

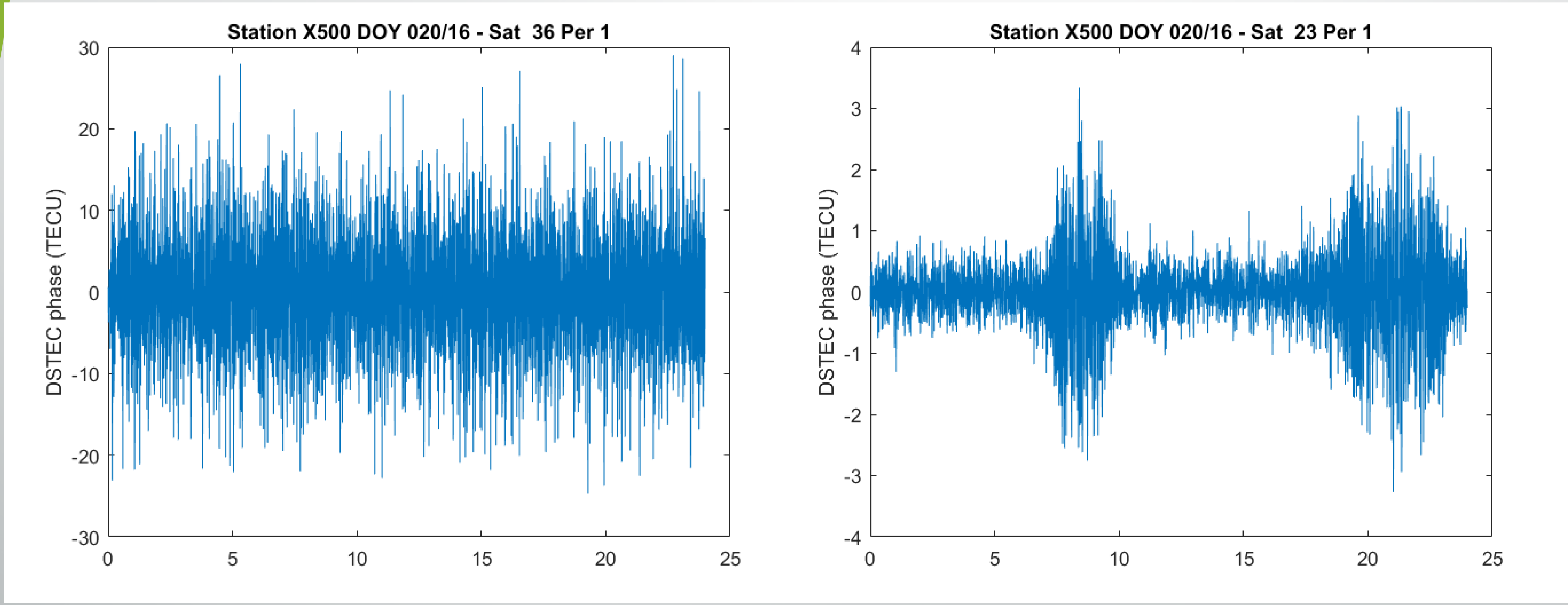
- In Liege (Belgium), Beidou GEO satellites C05 (15°) and C02 (1-2°) can be tracked by all Septentrio receivers.
- C05 data are continuous (in average less than 1 cycle slip a day).
  - ➔ Phase ambiguity often remains the same during several days.
- C02 data are usually continuous during several hours (up to 24 hours).
- Given phase TEC accuracy (C05: 0,023 TECU) and (C02: 0,045 TECU), both satellites could be used to monitor TEC or local variability in TEC.

Beidou GEO: Summary 2

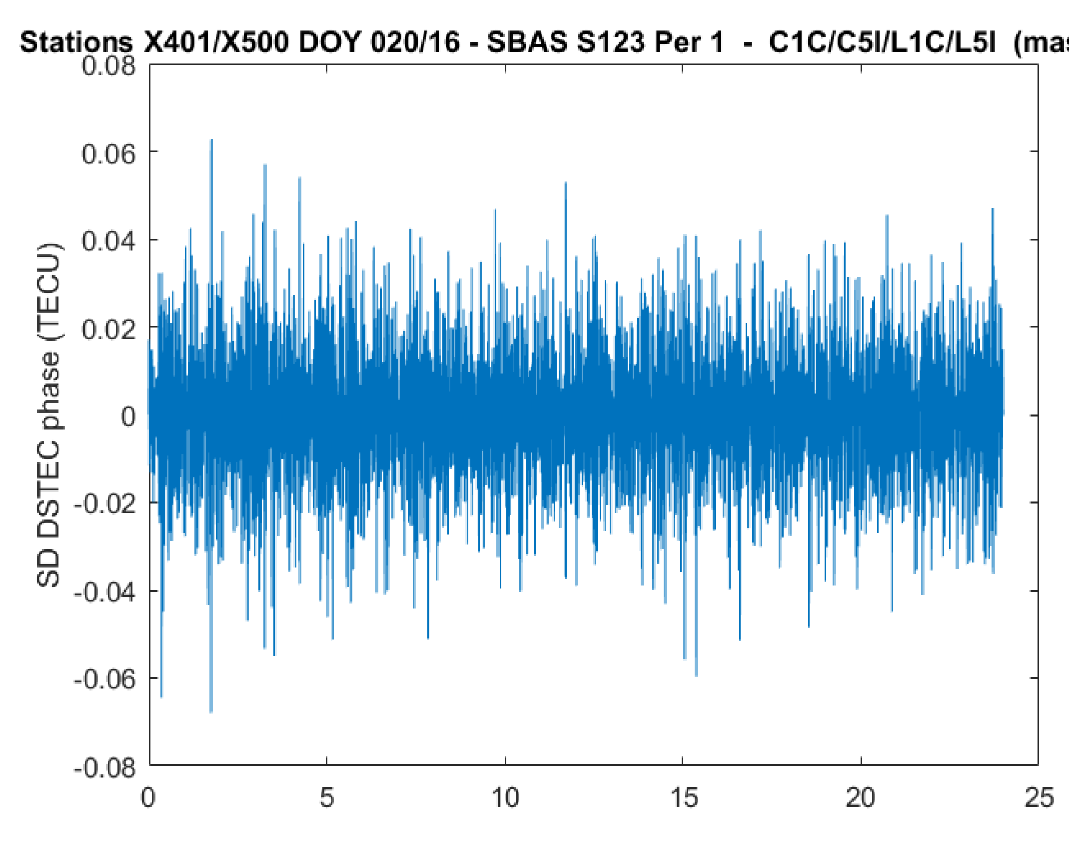
- Code leveling could be degraded by code noise but ambiguities are usually computed on much longer time periods.
- Further investigations are necessary to interpret the variability observed in $\Delta STEC$
  - Multipath, Ionosphere, variability in IF biases.
- Our Trimble NetR9 receivers only track C05 but data are unusable due to cycle slips.

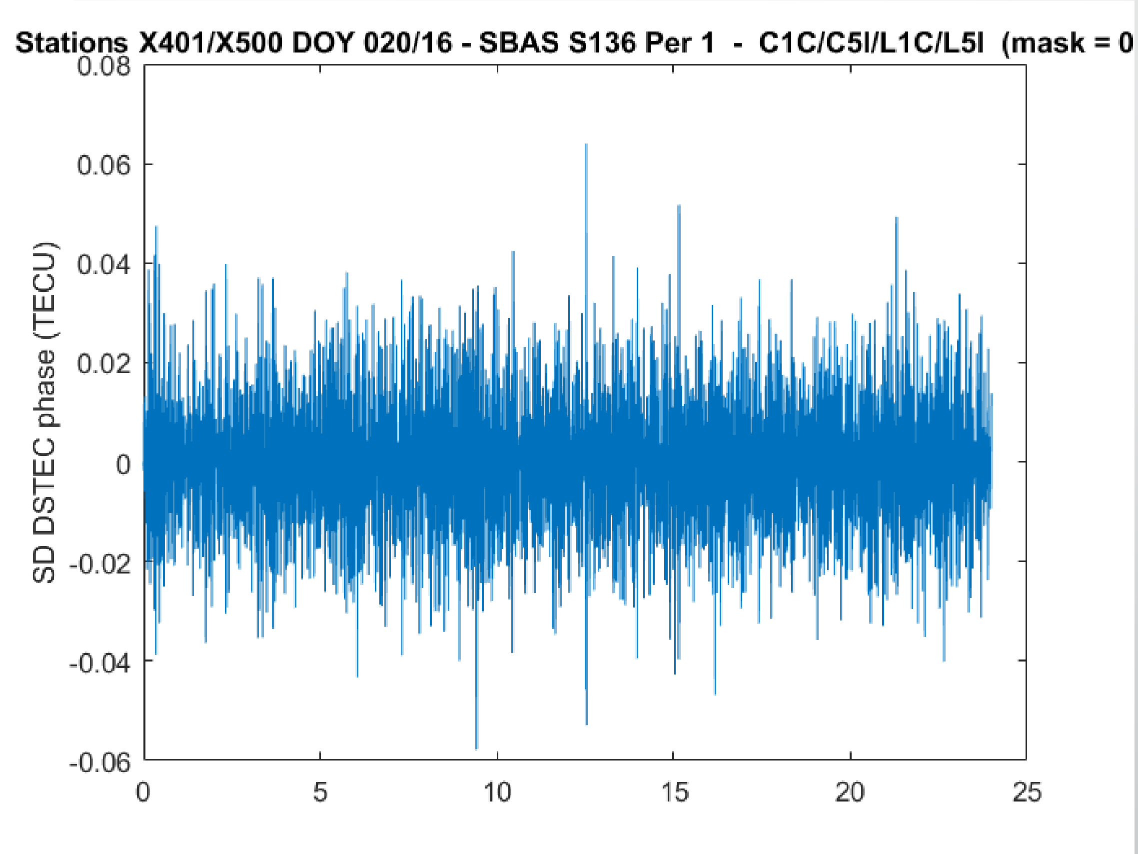
Thanks for your attention !

EGNOS: $\Delta STEC$

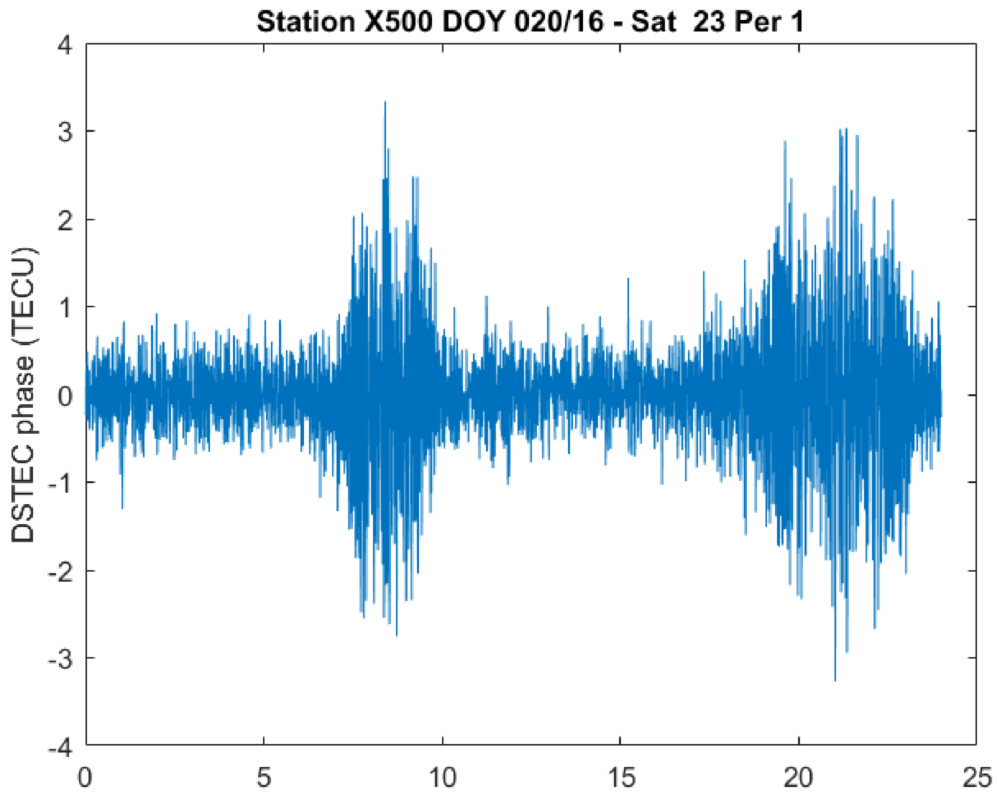


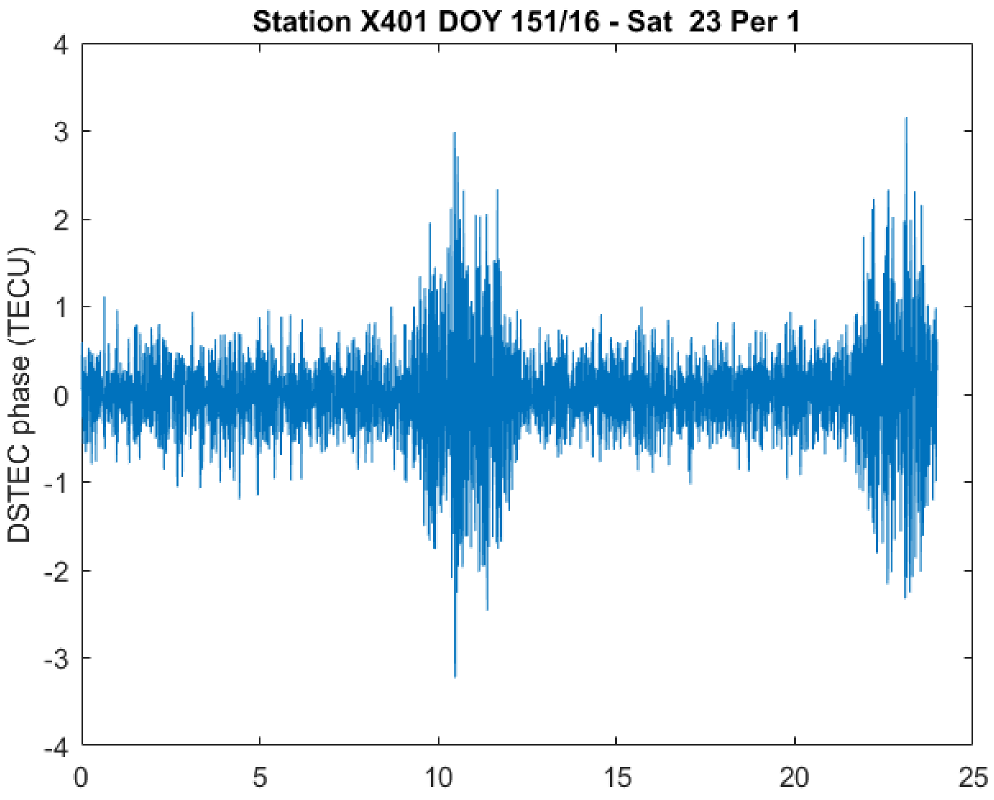
EGNOS: SD of $\Delta STEC$



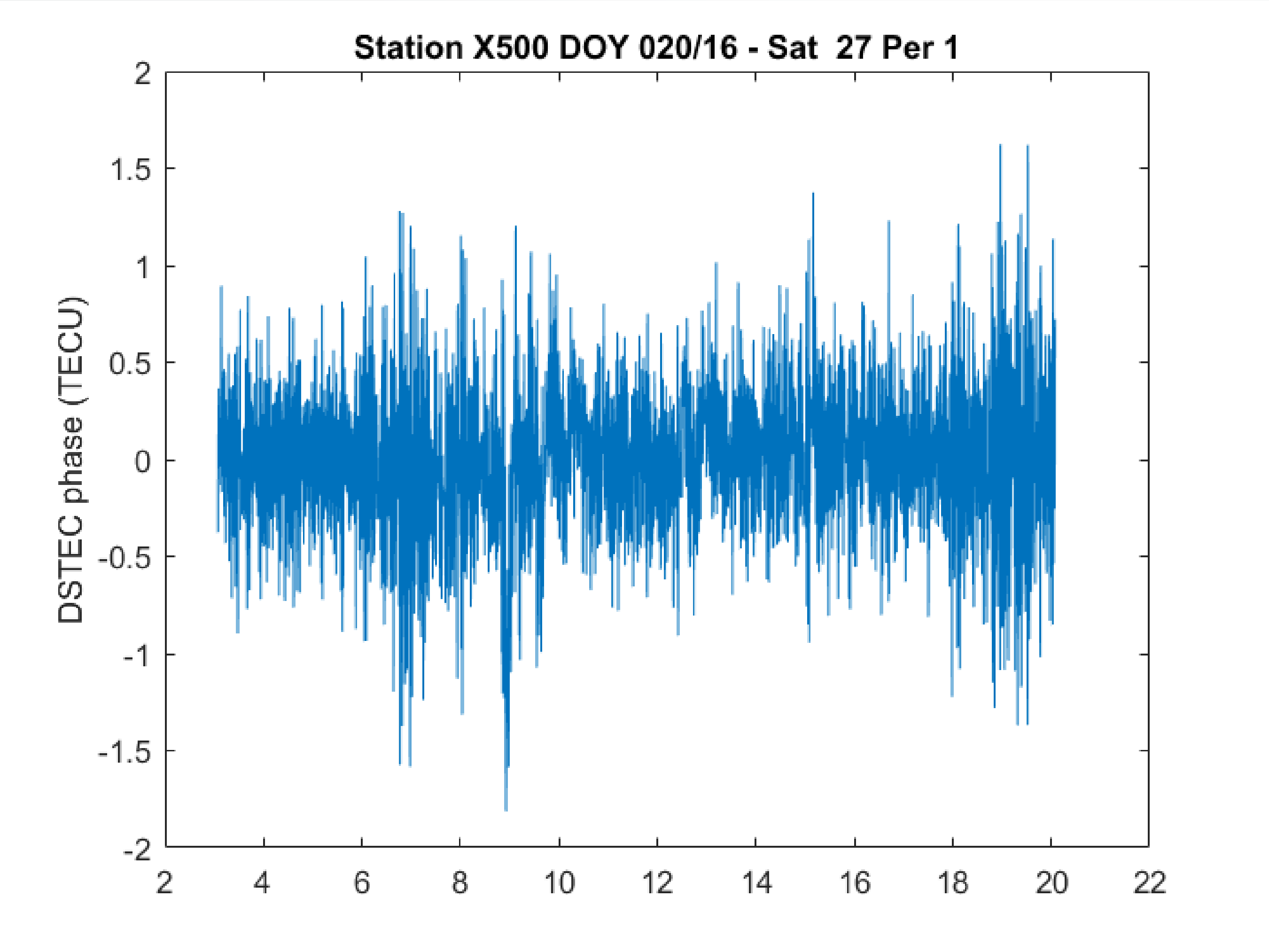


EGNOS S123: multipath ?





GAGAN: $\Delta STEC$



SBAS code precision