Enhancement of Total Electron Content Monitoring Using Triple Frequency GNSS Data

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Outline

Introduction

Context

GPS and Galileo systems emit signals on three civil frequencies

- two common frequencies L1/L5
- Galileo L2/L5 closer

Signal	Frequency [MHz]	
	GPS	Galileo
L1	1575.42	1575.42
L2	1227.60	1207.14
L5	1176.45	1176.45

Context

New signals...

- new linear combinations
  - elimination or mitigation of several error sources (ionosphere, multipath, noise...)
  - ambiguity resolution (widelane combinations)
  - TEC reconstruction (Geometric-Free combination)
- signal structure of Galileo
  - increased power, new modulation schemes
  - reduction of code multipath delays and measurement noise in regards with GPS L1/L2

TEC reconstruction

The Total Electron Content (TEC) is the integral of the electron density along the satellite-to-receiver path. It is expressed in TECU, with 1 TECU $= 10^{16}\,\mathrm{electrons/m^2}$.

- The free electrons of the ionosphere (dispersive medium) affect the propagation of GNSS signals (refraction)
- TEC can be reconstructed by using dual frequency GPS measurements
  - accuracy limited to a few TECU
- development of a new method
  - using triple frequency GNSS measurements
  - improving the accuracy of TEC values

Background

GNSS measurements

observable = geometric distance + error sources

- basic observables: code/phase
- phase more precise but ambiguous (integer ambiguity N)
- error sources divided into 3 groups: satellite/signal/receiver
- frequency-dependent vs frequency-independent errors

GNSS measurements

Source	Error
Satellite	Orbital bias Clock bias Relativistic effects Earth rotation effect Hardware delays Antenna phase center offset and variations
Signal	Ionospheric delays Troposheric delays Multipath delays
Receiver	Clock bias Hardware delays Antenna phase center offset and variations Measurement noise Phase wind-up effect

GNSS measurements

When using Geometric-Free combinations for TEC reconstruction frequency-dependent errors do not cancel out

1. ionospheric delays (TEC)
2. hardware delays
   - generated by the electronic of the satellites and receivers
3. multipath delays (mean ~ 0)
   - reflection on objects near the receiver
   - direct and indirect (reflected) signals interfere at the receiver
4. measurement noise (mean$=0$)
   - random measurement errors caused by disturbances in the antenna, cables and receiver (measurement resolution)

GNSS measurements

Standard deviation of code and phase multipath delays

Signal	$\sigma_{M_{g,k}}$ [m]		$\sigma_{M_{\Phi,k}}$ [mm]	
	GPS	Galileo	GPS	Galileo
L1	0.6	0.4	3	3
L2	0.6	0.2	3	3
L5	0.2	0.2	3	3

- code delays on L1/L2: smaller on Galileo than on GPS
- code delays on L5: similar
- phase delays: similar

GNSS measurements

Standard deviation of code and phase measurement noise

Signal	$\sigma_{\varepsilon_{g,k}}$ [m]		$\sigma_{\varepsilon_{\Phi,k}}$ [mm]	
	GPS	Galileo	GPS	Galileo
L1	0.25	0.18	0.5	0.5
L2	0.25	0.05	0.7	0.7
L5	0.07	0.05	0.7	0.7

- code delays on L1/L2: smaller on Galileo than on GPS
- code delays on L5: similar
- phase delays: similar

Extracting TEC with dual frequency GNSS

Geometric-Free (GF) phase combination on L1/L2

$$\begin{aligned} \Phi_{GF,12}\,[\mathrm{m}] &= \Phi_{\mathrm{L2}} - \Phi_{\mathrm{L1}} \\ &= \alpha_{12}\, TEC + IFB_{\Phi,12} + E_{\Phi,12} - \lambda_k\, N_{GF,12} \end{aligned}$$

- all frequency-dependent effects remain
  - phase hardware delays $IFB_{\Phi,km}$
  - phase multipath delays/measurement noise grouped in $E_{\Phi,km}$
- extracting TEC relies on the resolution of the GF ambiguity
- several approaches exist...

Extracting TEC with dual frequency GNSS

Resolution of the GF ambiguity $N_{GF,12}$

- Carrier-to-code levelling process
  - satellite-by-satellite
  - use GF code combination $(P_{\mathrm{L2}} - P_{\mathrm{L1}})$
    $\longrightarrow$ **levelling errors** ε_l
  - needs STEC modeling (mathematical expansion + MF)
    $\longrightarrow$ **model errors** ε_{model}
- Unlevelled carrier phase process
  - arc-by-arc
  - needs STEC modeling (mathematical expansion + MF)
    $\longrightarrow$ **model errors** ε_{model}

Extracting TEC with dual frequency GNSS

Precision and accuracy of TEC [1]

precision determined by $E_{\Phi,km}$ and ~ 0.1 TECU

accuracy determined by model errors (ε_{model}) and levelling errors (ε_l)

Accuracy	$TEC_{c,l}$		$TEC_{c,u}$	
[TECU]	mid-lat	low-lat	mid-lat	low-lat
ε_l	$[-1.6, 1.6]$	$[-0.5, 0.5]$	$[-]$	$[-]$
ε_{model}	$[-3.0, 2.0]$	$[-5.0, 4.5]$	$[-2.5, 2.5]$	$[-5.5, 7.5]$
$\varepsilon_l + \varepsilon_{model}$	$[-4.6, 3.6]$	$[-5.5, 5.0]$	$[-2.5, 2.5]$	$[-5.5, 7.5]$

Triple frequency TEC reconstruction

Principles

- undifferenced code/phase measurements on L1,L2,L5
- resolution of the original ambiguities on L1,L2,L5
  $\rightarrow$ GF ambiguity $\rightarrow$ TEC with GF phase combination
- using adequate linear combinations
  - widelane-narrowlane combinations
    - code/phase
    - elimination of the geometry and of the ionosphere
    - larger wavelength, easier ambiguity resolution
  - triple frequency phase multipath combination
    - phase only
    - elimination of the geometry and of the ionosphere
- tested on simulated and real data

Ambiguity resolution

Widelane combinations

$$
\begin{aligned}
c_{EWL}\,[\text{cycles}] &= \varphi_{\mathrm{L2}} - \varphi_{\mathrm{L5}} - \frac{f_{\mathrm{L2}} - f_{\mathrm{L5}}}{f_{\mathrm{L2}} + f_{\mathrm{L5}}} \left(\frac{f_{\mathrm{L2}}}{c} P_{\mathrm{L2}} + \frac{f_{\mathrm{L5}}}{c} P_{\mathrm{L5}} \right) \\
&= N_{EWL} + \Delta\, c_{EWL}
\end{aligned}
$$

$$
\begin{aligned}
c_{WL}\,[\text{cycles}] &= \varphi_{\mathrm{L1}} - \varphi_{\mathrm{L2}} - \frac{f_{\mathrm{L1}} - f_{\mathrm{L2}}}{f_{\mathrm{L1}} + f_{\mathrm{L2}}} \left(\frac{f_{\mathrm{L1}}}{c} P_{\mathrm{L1}} + \frac{f_{\mathrm{L2}}}{c} P_{\mathrm{L2}} \right) \\
&= N_{WL} + \Delta\, c_{WL}
\end{aligned}
$$

$$
\begin{aligned}
c_{ML}\,[\text{cycles}] &= \varphi_{\mathrm{L1}} - \varphi_{\mathrm{L5}} - \frac{f_{\mathrm{L1}} - f_{\mathrm{L5}}}{f_{\mathrm{L1}} + f_{\mathrm{L5}}} \left(\frac{f_{\mathrm{L1}}}{c} P_{\mathrm{L1}} + \frac{f_{\mathrm{L5}}}{c} P_{\mathrm{L5}} \right) \\
&= N_{ML} + \Delta\, c_{ML}
\end{aligned}
$$

Ambiguity resolution

Widelane combinations

c_{EWL}, c_{WL}, c_{ML} are the widelane-narrowlane combinations used to resolve the EWL, WL, ML ambiguities

- GF and IF $\longrightarrow$ residual term Δ
  - frequency-dependent errors (multipath/noise/hardware)
  - code/phase
- resolution possible if $\Delta < \frac{1}{2}$ [cycle] or $\frac{\lambda}{2}$ [m]

LC	λ [m]	
	GPS	Galileo
EWL	5.861	9.768
WL	0.862	0.814
ML	0.751	0.751

Ambiguity resolution

Widelane combinations

Resolution of the widelane ambiguities

- Considering multipath delays and measurement noise as Gaussian white noise gives for GPS/Galileo [cycles]:

$$\begin{aligned} \Delta\, c_{EWL} &< 0.16/0.05 \\ \Delta\, c_{WL} &< 1.39/0.83 \\ \Delta\, c_{ML} &< 1.31/0.91 \end{aligned}$$

- $+$ influence of hardware delays
  $\rightarrow$ Δ mainly depends on code hardware delays

$\rightarrow$ EWL ambiguities can be resolved
$\rightarrow$ WL and ML ambiguities can not be resolved

Ambiguity resolution

Widelane combinations

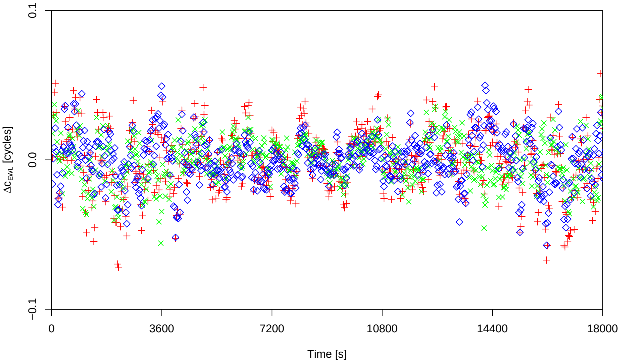

Figure: Influence of multipath delays and measurement noise on Galileo EWLNL combination (red = total, green = codes only, blue = phases only).

Ambiguity resolution

Widelane combinations

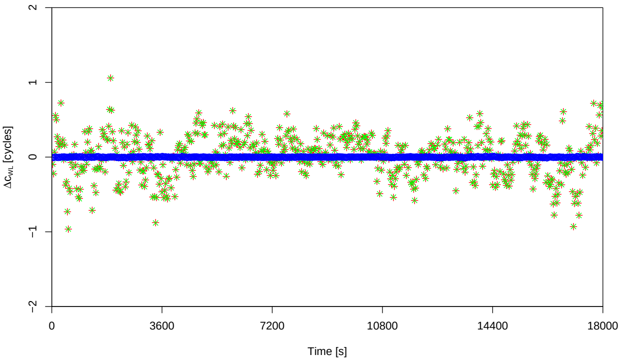

Figure: Influence of multipath delays and measurement noise on Galileo WLNL combination (red = total, green = codes only, blue = phases only).

Ambiguity resolution

Widelane combinations

$$\begin{aligned}\varphi_{DWL}\,[\text{cycles}] &= \varphi_{\mathrm{L1}} - \varphi_{\mathrm{L2}} - (\varphi_{\mathrm{L2}} - \varphi_{\mathrm{L5}} - N_{EWL})\,\frac{\lambda_{EWL}}{\lambda_{WL}} \\ &= \varphi_{WL} - (\varphi_{EWL} - N_{EWL})\,\frac{\lambda_{EWL}}{\lambda_{WL}}\end{aligned}$$

φ_{DWL} is differenced widelane combination [2]
$\rightarrow$ uses EWL ambiguities (N_{EWL}) to resolve WL ambiguities (N_{WL})
N.B. similar combination to resolve ML ambiguities (N_{ML})

- GF but NOT IF $\rightarrow$ residual term Δ
  - Δ = multipath/noise/hardware + ionosphere
  - phase only
- resolution possible if $\Delta < \frac{1}{2}$ [cycle]

Ambiguity resolution

Widelane combinations

Resolution of the widelane ambiguities

Influence of phase multipath/noise for GPS/Galileo [cycles]

$$\Delta \varphi_{DWL} < 0.33/0.56$$

- use of an average filter $\langle x_t \rangle = \langle x_{t-1} \rangle + \frac{1}{t} (x_t - \langle x_{t-1} \rangle)$
  $\rightarrow$ phase multipath/noise average down to ~ 0

Influence of ionospheric delays [cycles]

$$I_{\varphi_{DWL}} = \kappa \cdot \mathrm{TEC}$$

- $I_{\varphi_{DWL}} > \frac{1}{2}$ if $\mathrm{TEC} > \frac{1}{2} \cdot \kappa^{-1}$ (6 TECU)
- $I_{\varphi_{DWL}}$ can be estimated by using dual frequency TEC values
  $\rightarrow$ accurate enough if $\Delta\mathrm{TEC} < \frac{1}{2} \cdot \kappa^{-1}$ (6 TECU)

Ambiguity resolution

Widelane combinations

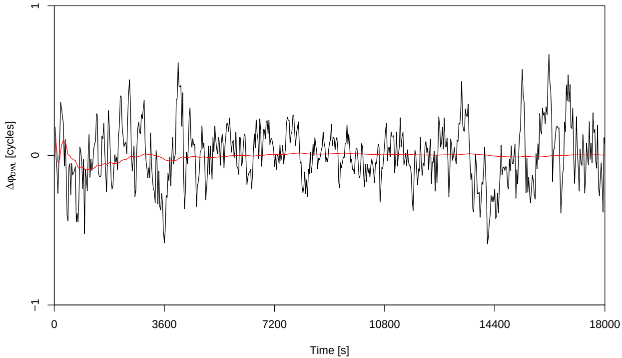

Figure: Influence of multipath delays and measurement noise on Galileo DWL combination (red = running average).

Ambiguity resolution

Widelane combinations

Resolution of the widelane ambiguities

In total

- WL ambiguities can be resolved
  - using an average filter (not in real time)
  - using a dual frequency estimation of TEC
- same conclusions reached for the ML ambiguities

Ambiguity resolution

Triple frequency phase multipath combination

$$
\begin{aligned}
\Phi_{M,125}\,[\mathrm{cycles}] &= \frac{(\lambda_{\mathrm{L5}}^2 - \lambda_{\mathrm{L2}}^2)}{(\lambda_{\mathrm{L2}}^2 - \lambda_{\mathrm{L1}}^2)}\,\Phi_{\mathrm{L1}} + \frac{(\lambda_{\mathrm{L1}}^2 - \lambda_{\mathrm{L5}}^2)}{(\lambda_{\mathrm{L2}}^2 - \lambda_{\mathrm{L1}}^2)}\,\Phi_{\mathrm{L2}} + \Phi_{\mathrm{L5}} \\
&= d\,\Phi_{\mathrm{L1}} + e\,\Phi_{\mathrm{L2}} + f\,\Phi_{\mathrm{L5}} \\
&= -d\,\lambda_{\mathrm{L1}}\,N_{\mathrm{L1}} - e\,\lambda_{\mathrm{L2}}\,N_{\mathrm{L2}} - f\,\lambda_{\mathrm{L5}}\,N_{\mathrm{L5}} \\
&\quad + \Delta\,\Phi_{M,125}
\end{aligned}
$$

Ambiguity resolution

Triple frequency phase multipath combination

$\Phi_{M,125}$ is the triple frequency phase multipath combination

- GF and IF $\longrightarrow$ residual term Δ
  - frequency-dependent errors (multipath/noise/hardware)
  - phase only
- can be used for [3]:
  - mitigation of phase multipath delays
  - multi-frequency ambiguity resolution algorithms
- used to resolve the original ambiguities on L1,L2,L5
  - if we introduce the EWL and WL ambiguities in $\Phi_{M,125}$ $\longrightarrow$ N_{L2} is the only unknown
  - influence of Δ on N_{L2} !

Ambiguity resolution

Triple frequency phase multipath combination

Resolution of the N_{L2} ambiguity

Influence of phase multipath/noise [cycles]

$$\Delta N_{\mathrm{L2}} < 8.05/12.61$$

- average filter $\rightarrow$ phase multipath/noise ~ 0

Influence of phase hardware delays [cycles]

$$\Delta N_{\mathrm{L2}} < 1.43/2.24 \rightarrow \pm\ 2 \text{ cycles}$$

- $\pm$ 2 cycles on N_{L2} (N_{L1}, N_{L5}) $\rightarrow \pm$ 1 TECU on TEC

TEC reconstruction

Geometric-Free ambiguity reconstruction

$$N_{GF,km} = -N^i_{p,k} + \frac{f_k}{f_m} N^i_{p,m}$$

TEC reconstruction

$$\begin{aligned} \mathrm{TEC_r} &= \frac{1}{\alpha_{km}} \left(\Phi_{GF,km} + \lambda_k N_{GF,km} \right) \\ &= \mathrm{TEC} + \frac{1}{\alpha_{km}} \left(IFB_{\Phi,km} + \Delta N_{GF,km} + E_{\Phi,km} \right) \end{aligned}$$

- Triple frequency $\rightarrow k, m \in \{\mathrm{L1}, \mathrm{L2}, \mathrm{L5}\}$
  - $\alpha_{25} << \alpha_{12}, \alpha_{15}$
  - reconstruct TEC with L1/L2 or L1/L5

TEC reconstruction

$$\mathrm{TEC_r} = \mathrm{TEC} + \frac{1}{\alpha_{km}} \left(IFB_{\Phi,km} + \Delta N_{GF,km} + E_{\Phi,km} \right)$$

Precision and accuracy of TEC_r

precision phase multipath/noise ($E_{\Phi,km}$) $\sim$ 0.1 TECU

accuracy determined by phase hardware delays

- $IFB_{\Phi,km}$ $\pm$ 0.02 TECU
- error on N_{L2} ($\Delta N_{GF,km}$) $\pm$ 1 TECU

Conclusions

Conclusions

Triple frequency TEC reconstruction

- new linear combinations → resolution of the original ambiguities

1. EWL ambiguities resolved using the EWLNL combination
2. WL ambiguities resolved using the differenced widelane combination (+ML)
3. The N_{L2} ambiguities resolved by introducing EWL/WL ambiguities in the triple frequency phase multipath combination

- accuracy
  - dependent on phase hardware delays and about $\pm$ 1 TECU
  - improved in regards with the dual frequency TEC reconstruction

Bibliography

C. Brunini and F. Azpilicueta.
Accuracy assessment of the GPS-based slant total electron content.
Journal of Geodesy, 83(8):773–785, 2009.

R Hatch, J. Jung, P. Enge, and B. Pervan.
Civilian GPS: The Benefits of Three Frequencies.
GPS Solutions, 3(4):1–9, 2000.

A. Simsky.
Three's the Charm - Triple frequency Combinations in Future GNSS.
Inside GNSS, 1(5):38–41, 2006.

Thank you for your attention !

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