Biases in Multi-GNSS Processing

R. Dach
and the Satellite Geodesy research group

Astronomical Institute, University of Bern, Switzerland

NGK Summer School
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Overview

Observation Equation

GNSS Code Biases

GNSS Phase Biases

Inter-System Antenna Bias

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c\cdot(\delta_i - \alpha_i) - c\cdot(\delta^k - \alpha^k) + \lambda^k\cdot N_i^k + \lambda^k\cdot\Delta\varphi_i^k$$

Observation Equation

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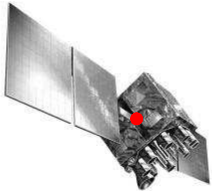

$\vec{x}^k$ position vector of satellite k related to its center of mass

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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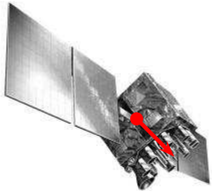
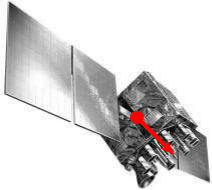


$\vec{x}^k$	position vector of satellite k related to its center of mass
$\Delta\vec{x}^k$, $\Delta\vec{\chi}^k$	vector from the center of mass of the satellite k to the antenna signal emission point for code and phase observations

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot ({\color{red}\delta^k} - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot ({\color{red}\delta^k} - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$



$\vec{x}^k$	position vector of satellite k related to its center of mass
$\Delta\vec{x}^k$, $\Delta\vec{\chi}^k$	vector from the center of mass of the satellite k to the antenna signal emission point for code and phase observations
δ^k	clock correction of the satellite k with respect to GPS time

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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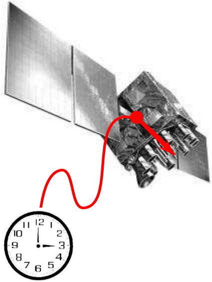

$\vec{x}^k$	position vector of satellite k related to its center of mass
$\Delta\vec{x}^k$, $\Delta\vec{\chi}^k$	vector from the center of mass of the satellite k to the antenna signal emission point for code and phase observations
δ^k	clock correction of the satellite k with respect to GPS time
a^k, α^k	hardware delay in the satellite k for code and phase measurements

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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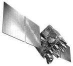

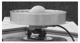

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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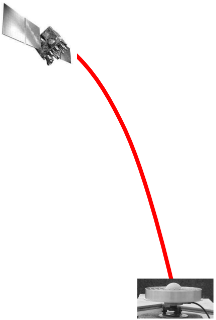

I_i^k signal delay in the ionosphere

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

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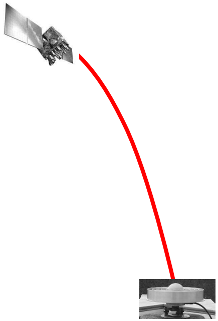

I_i^k signal delay in the ionosphere
T_i^k signal delay in the troposphere

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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δ_i clock correction of the receiver at the station i with respect to GPS time

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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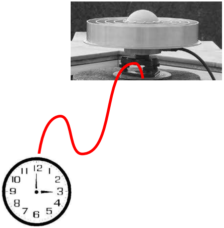

δ_i	clock correction of the receiver at the station i with respect to GPS time
a_i, α_i	hardware delay in the receiver at the station i for code and phase measurements

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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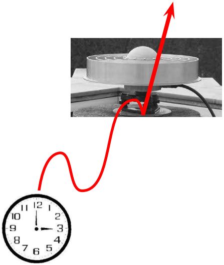

δ_i	clock correction of the receiver at the station i with respect to GPS time
a_i, α_i	hardware delay in the receiver at the station i for code and phase measurements
$\Delta\vec{x}_i$, $\Delta\vec{\chi}_i$	vector from the marker of the station i to the antenna signal reception point for code and phase observations

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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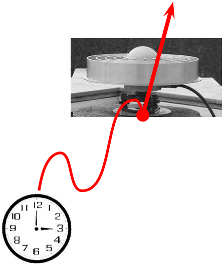
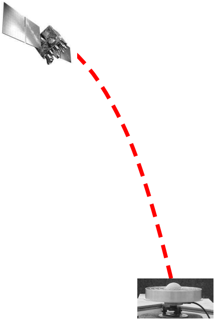


δ_i	clock correction of the receiver at the station i with respect to GPS time
a_i, α_i	hardware delay in the receiver at the station i for code and phase measurements
$\Delta\vec{x}_i$, $\Delta\vec{\chi}_i$	vector from the marker of the station i to the antenna signal reception point for code and phase observations
$\vec{x}_i$	position vector of marker at station i

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

$$\begin{aligned} L_i^k = &\left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c\cdot(\delta_i - \alpha_i) - c\cdot(\delta^k - \alpha^k) \\ &+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k \end{aligned}$$



N_i^k phase ambiguity (one and the same for one pass)

Observation Equation

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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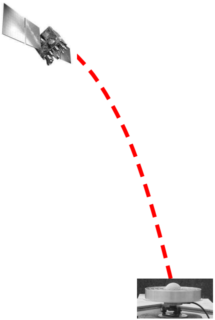

N_i^k	phase ambiguity (one and the same for one pass)
$\Delta\varphi_i^k$	initial phase shift between the oscillators at station i and satellite k

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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The following parameters depend on:

GNSS: (GPS or GLONASS or ...)

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Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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The following parameters depend on:

GNSS:	(GPS or GLONASS or ...)
Code	$\Delta\vec{x}_i$
Phase	$\Delta\vec{\chi}_i$

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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The following parameters depend on:

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Code	$\Delta\vec{x}_i$	a_i
Phase	$\Delta\vec{\chi}_i$	α_i

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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The following parameters depend on:

GNSS:	(GPS or GLONASS or ...)		
Code	$\Delta\vec{x}_i$	a_i	δ^k
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GNSS: (GPS or GLONASS or ...)

Code	$\Delta\vec{x}_i$	a_i	δ^k
Phase	$\Delta\vec{\chi}_i$	α_i	δ^k

ISB: Inter-System Bias

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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The following parameters depend on:

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Code	$\Delta\vec{x}_i$	a_i	δ^k
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ISB: Inter-System Bias

Frequency: (f1 or f2 or fn for GLONASS or ...)

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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Code	$\Delta\vec{x}_i$	a_i	δ^k	ISB: Inter-System Bias
Phase	$\Delta\vec{\chi}_i$	α_i	δ^k	

Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$
Phase	$\Delta\vec{\chi}^k$

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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GNSS: (GPS or GLONASS or ...)

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Phase	$\Delta\vec{\chi}_i$	α_i	δ^k

ISB: Inter-System Bias

Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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GNSS:	(GPS or GLONASS or ...)				
Code		$\Delta\vec{x}_i$	a_i	δ^k	ISB: Inter-System Bias
Phase		$\Delta\vec{\chi}_i$	α_i	δ^k	
Frequency:	(f1 or f2 or fn for GLONASS or ...)				
Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i		
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i		

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$

The following parameters depend on:

GNSS: (GPS or GLONASS or ...)

Code		$\Delta\vec{x}_i$	a_i		δ^k
Phase		$\Delta\vec{\chi}_i$	α_i		δ^k

ISB: Inter-System Bias

Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k	
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k	

IFB: Inter-Frequency Bias

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c\cdot(\delta_i - \alpha_i) - c\cdot(\delta^k - \alpha^k) + \lambda^k\cdot N_i^k + \lambda^k\cdot\Delta\varphi_i^k$$

The following parameters depend on:

GNSS: (GPS or GLONASS or ...)

Code		$\Delta\vec{x}_i$	a_i	δ^k	ISB: Inter-System Bias
Phase		$\Delta\vec{\chi}_i$	α_i	δ^k	

Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k	IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k	

Signal type: (C1W/C or C2W/C or L2W/C or ...)

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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Code		$\Delta\vec{x}_i$	a_i	δ^k	ISB: Inter-System Bias
Phase		$\Delta\vec{\chi}_i$	α_i	δ^k	
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Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k	IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k	
Signal type: (C1W/C or C2W/C or L2W/C or . . .)					
Code			a_i		

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k	IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k	

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Phase		$\Delta\vec{\chi}_i$	α_i		δ^k	

Frequency: (f1 or f2 or fn for GLONASS or ...)

Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k	IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k	

Signal type: (C1W/C or C2W/C or L2W/C or ...)

Code	a_i	a^k	DCB: Differential Code Bias

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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GNSS:	(GPS or GLONASS or ...)					
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Frequency:	(f1 or f2 or fn for GLONASS or ...)					
Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k		IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k		
Signal type:	(C1W/C or C2W/C or L2W/C or ...)					
Code			a_i	a^k		DCB: Differential Code Bias
Phase			α_i	α^k		(Quarter cycle problem)

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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Phase		$\Delta\vec{\chi}_i$	α_i		δ^k	
Frequency:	(f1 or f2 or fn for GLONASS or ...)					
Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k		IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k		
Signal type:	(C1W/C or C2W/C or L2W/C or ...)					
Code			a_i	a^k		DCB: Differential Code Bias

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$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

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	Antenna		Hardware			
GNSS:						
Code		$\Delta\vec{x}_i$	a_i		δ^k	ISB: Inter-System Bias
Phase		$\Delta\vec{\chi}_i$	α_i		δ^k	
Frequency:						
Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k		IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k		
Signal type:						
Code			a_i	a^k		DCB: Differential Code Bias

GNSS Code Biases: Overview

If we focus on processing code measurements we have to consider:

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If we focus on processing code measurements we have to consider:

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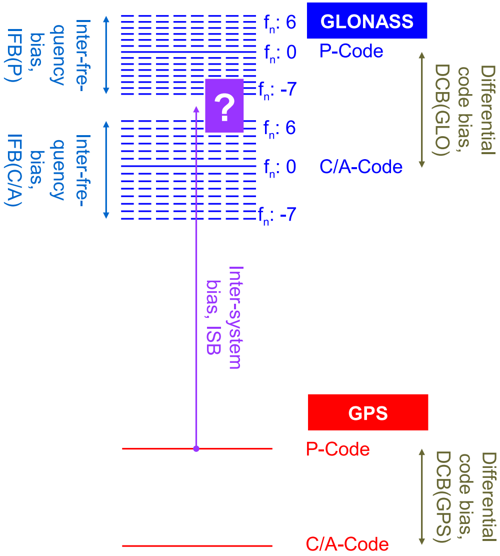
  bias at the receiver and satellite

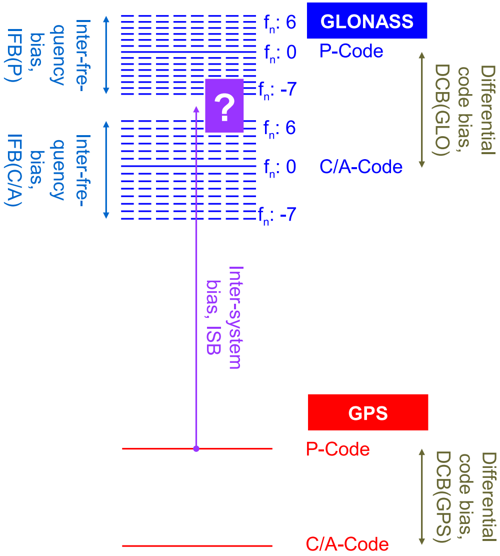
- **ISB: inter-system bias**
  different hardware delays for measurements of different GNSS
  bias only at the receiver

- **IFB: inter-frequency bias**
  frequency-dependent hardware delays for the different GLONASS-signals
  bias at the receiver
  (also at the satellite when frequency is changed)

GNSS Code Biases: Overview



GNSS Code Biases: Overview



We can only extract the sum of delays from a GPS/GLONASS data processing.

Why do we Need These Biases?

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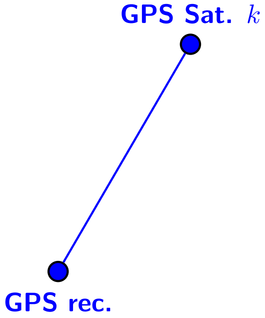

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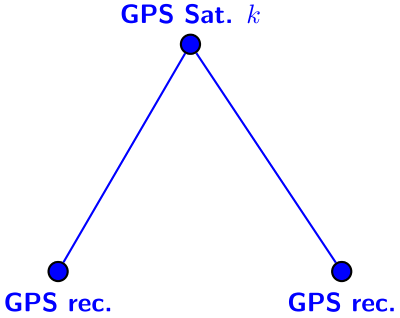

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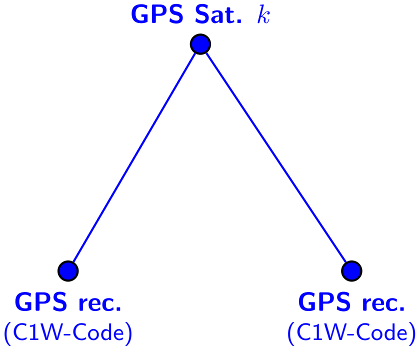

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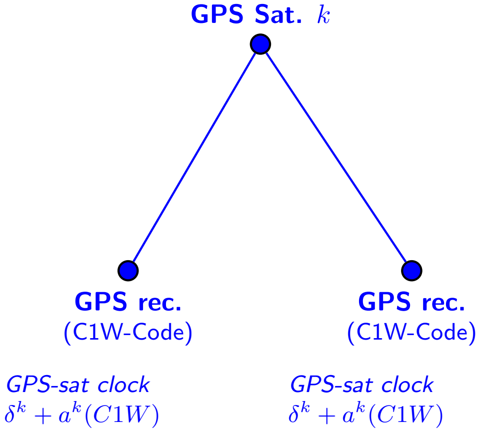

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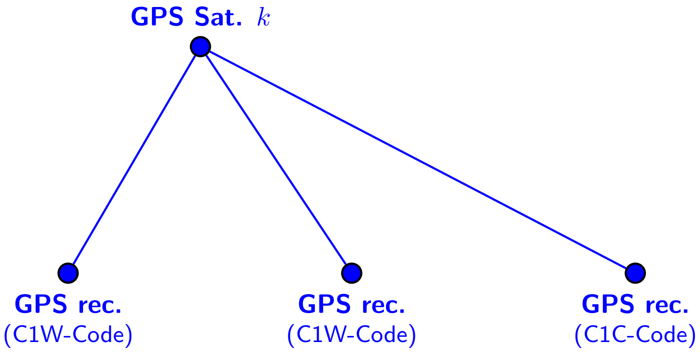

GPS-sat clock
$\delta^k + a^k(C1W)$

GPS-sat clock
$\delta^k + a^k(C1W)$

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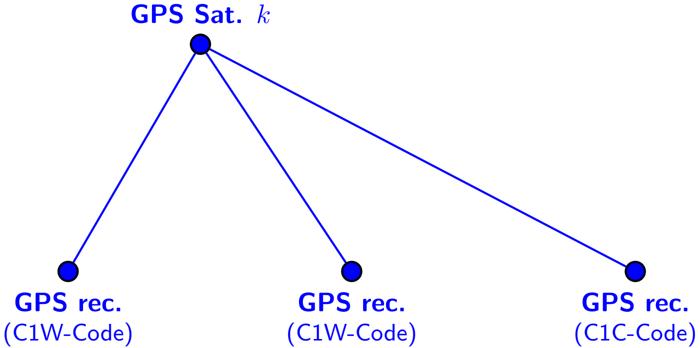
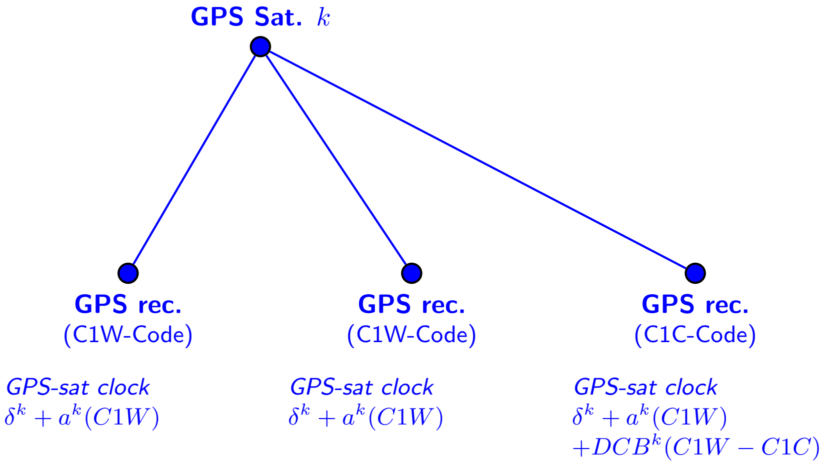


GPS-sat clock	*GPS-sat clock*	*GPS-sat clock*
$\delta^k + a^k(C1W)$	$\delta^k + a^k(C1W)$	$\delta^k + a^k(C1C)$

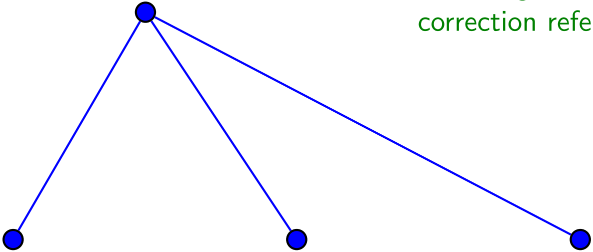
Why do we Need These Biases?



Why do we Need These Biases?

Resulting satellite clock correction refers to C1W

GPS Sat. k



GPS rec. (C1W-Code)

GPS-sat clock
$\delta^k + a^k(C1W)$

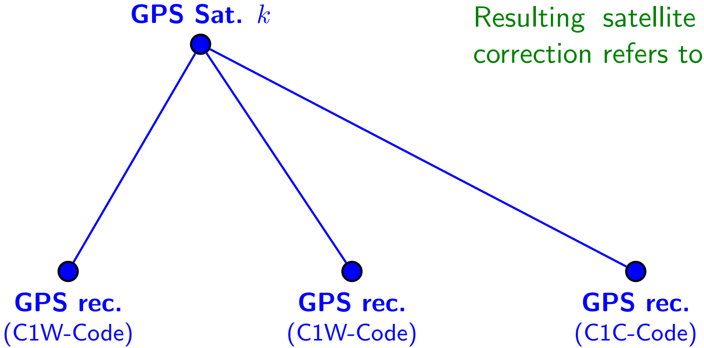
GPS rec. (C1W-Code)

GPS-sat clock
$\delta^k + a^k(C1W)$

GPS rec. (C1C-Code)

GPS-sat clock
$\delta^k + a^k(C1W)$
$+DCB^k(C1W - C1C)$

Why do we Need These Biases?



Resulting satellite clock correction refers to C1C

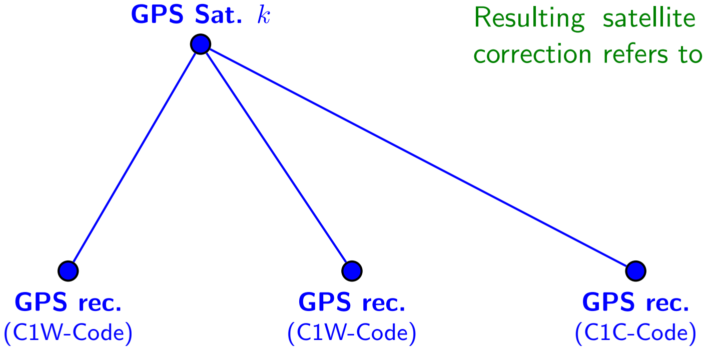
GPS-sat clock
$\delta^k + a^k(C1C)$
$+DCB^k(C1C - C1W)$

GPS-sat clock
$\delta^k + a^k(C1C)$
$+DCB^k(C1C - C1W)$

GPS-sat clock
$\delta^k + a^k(C1C)$

Why do we Need These Biases?

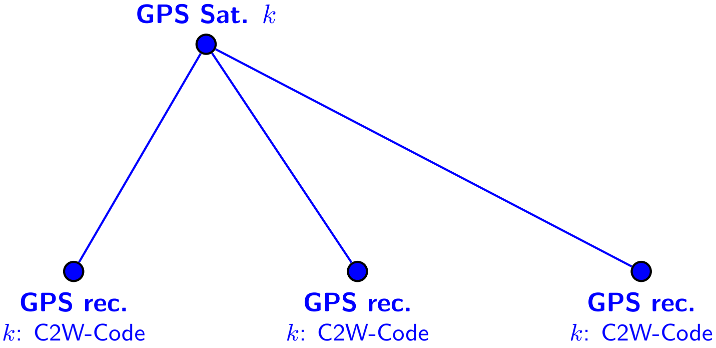
Resulting satellite clock correction refers to C1C



GPS rec. (C1W-Code)	GPS rec. (C1W-Code)	GPS rec. (C1C-Code)
GPS-sat clock $\delta^k + a^k(C1C)$ $+DCB^k(C1C-C1W)$	*GPS-sat clock* $\delta^k + a^k(C1C)$ $+DCB^k(C1C-C1W)$	*GPS-sat clock* $\delta^k + a^k(C1C)$

Whether choosing C1W or C1C as reference is fully equivalent.
Choosing C1C or C1W for the satellite clock is purely conventional.
The IGS products refer to the P-Code for the satellite clocks.

Why do we Need These Biases?



GPS-sat clock
k: $\delta^k + a^k(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$

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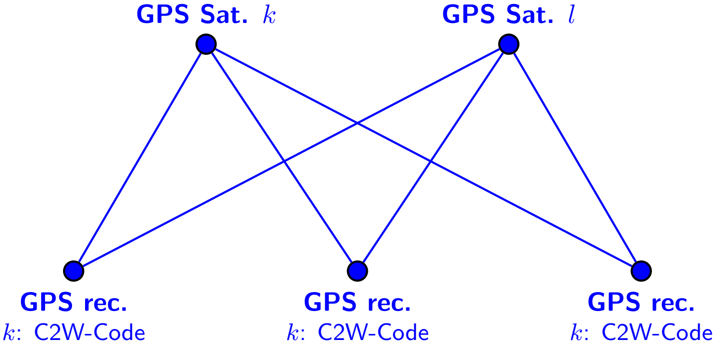

GPS-sat clock
k: $\delta^k + a^k(C2W)$

GPS-sat clock
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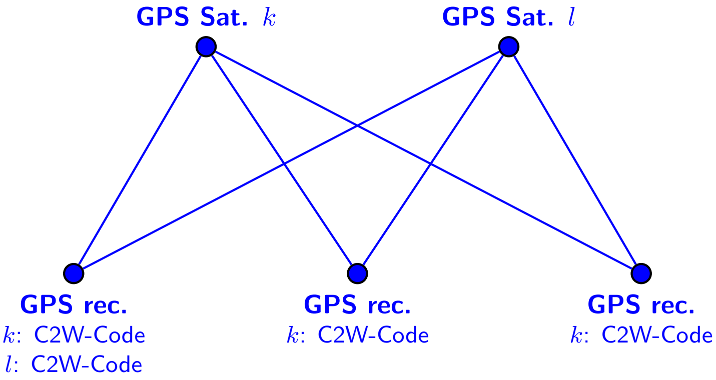

GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$

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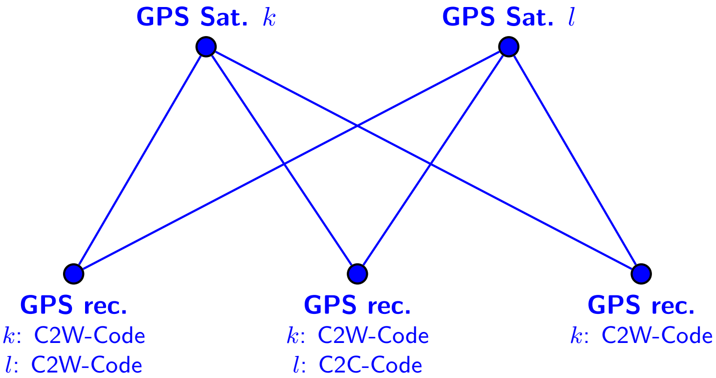
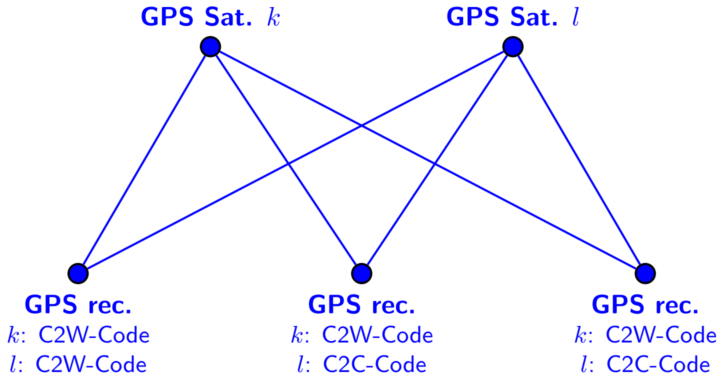


GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2C)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$

Why do we Need These Biases?



GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2C)$

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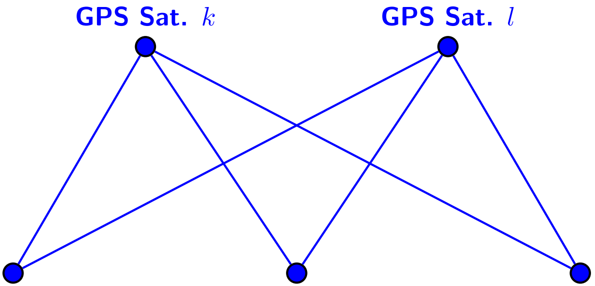


GPS rec.
k: C2W-Code
l: C2W-Code

GPS rec.
k: C2W-Code
l: C2C-Code

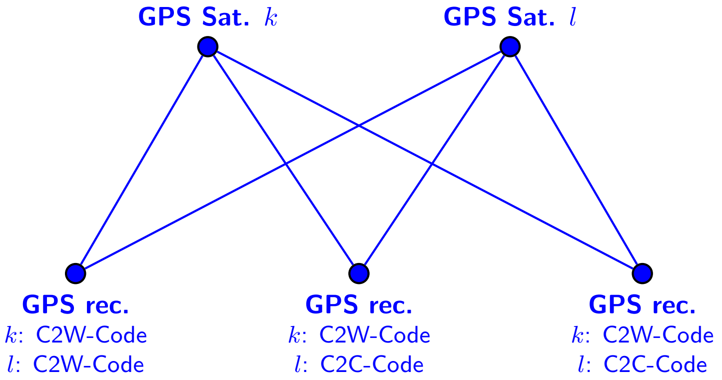
GPS rec.
k: C2W-Code
l: C2C-Code

GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W) + DCB^l(C2W - C2C)$

GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W) + DCB^l(C2W - C2C)$

Why do we Need These Biases?

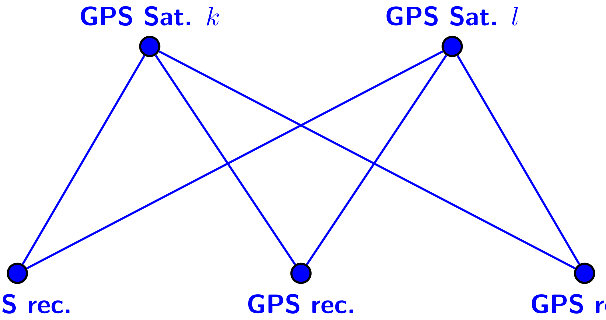


GPS-rec clock
k: $\delta_1 + a_1(C2W)$
l: $\delta_1 + a_1(C2W)$

GPS-rec clock
k: $\delta_2 + a_2(C2W)$
l: $\delta_2 + a_2(C2C)$

GPS-rec clock
k: $\delta_3 + a_3(C2W)$
l: $\delta_3 + a_3(C2C)$

Why do we Need These Biases?



k: C2W-Code	k: C2W-Code	k: C2W-Code
l: C2W-Code	l: C2C-Code	l: C2C-Code

GPS-rec clock	*GPS-rec clock*	*GPS-rec clock*
k: $\delta_1 + a_1(C2W)$	*k:* $\delta_2 + a_2(C2W)$	*k:* $\delta_3 + a_3(C2W)$
l: $\delta_1 + a_1(C2W)$	*l:* $\delta_2 + a_2(C2W) + DCB_2(C2W - C2C)$	*l:* $\delta_3 + a_3(C2W) + DCB_3(C2W - C2C)$

Code Biases in a GPS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1W-C1C or P1−C1 DCBs for all GPS satellites,
- C2W-C2C or P2−C2 DCBs for Block IIR-M (or later) satellites,
- C2W-C2C or P2−C2 DCBs for receivers if it tracks GPS satellites with P- and C-code on the second frequency at the same time.

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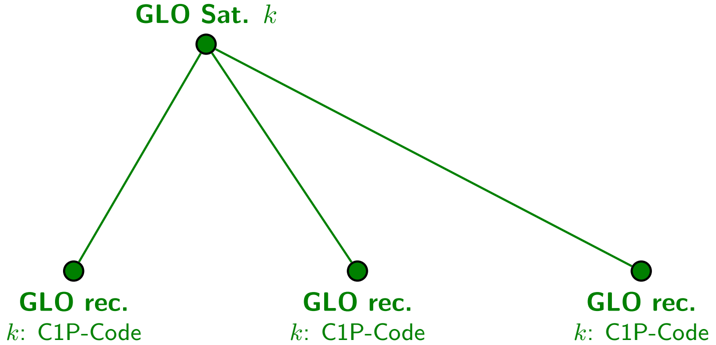
- C2W-C2C or P2−C2 DCBs for receivers if it tracks GPS satellites with P- and C-code on the second frequency at the same time.

As soon as we get a mixture between all these observation types in one network solution we need

- either to correct the DCBs in the data processing
- or to estimate DCB parameters
  P1−C1: Your reference clock only belongs to either the P- or C/A-code class – you need an additional reference for the satellite related biases.
  P2−C2: You have these DCBs at the satellites and receivers at the same time – you need additional references for the satellite and receiver related biases.

Why do we Need These Biases?



GLO-sat clock
k: $\delta^k + a^k(C1P)$

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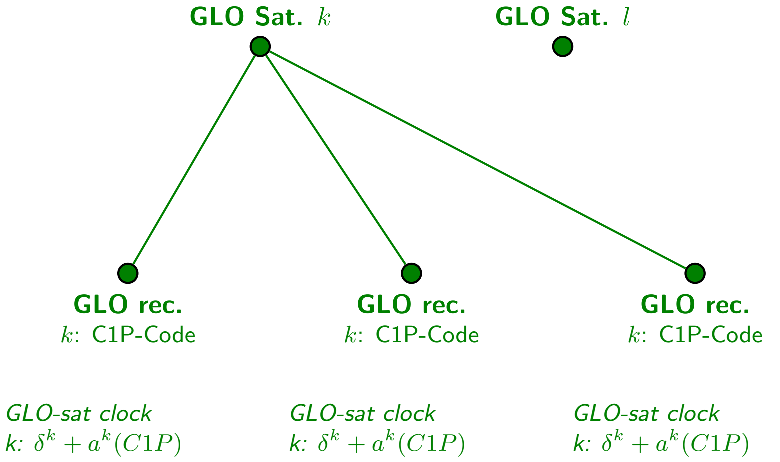

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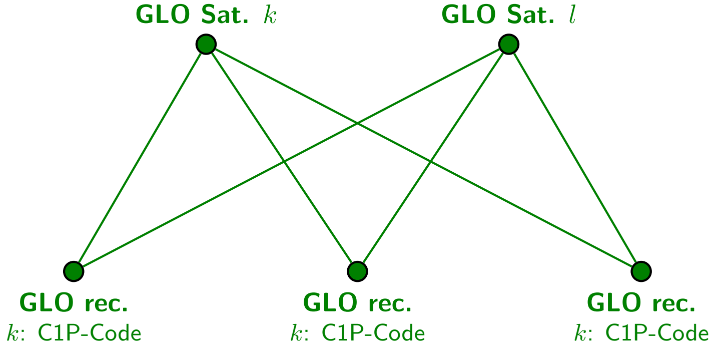

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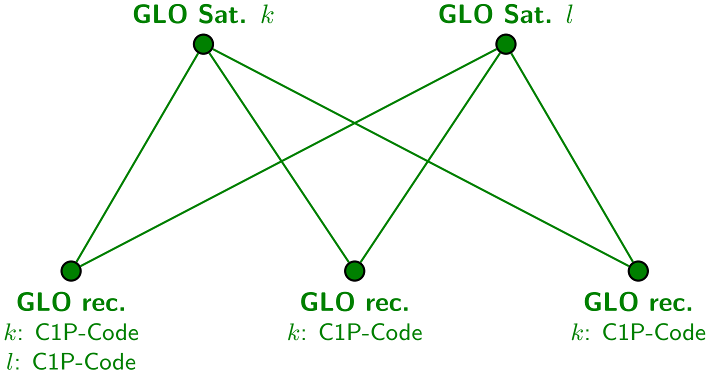

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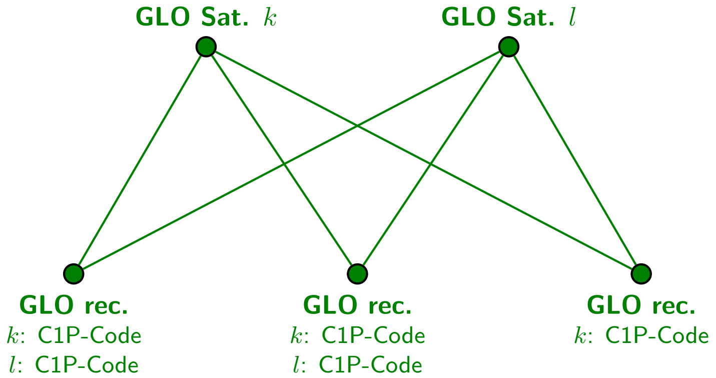

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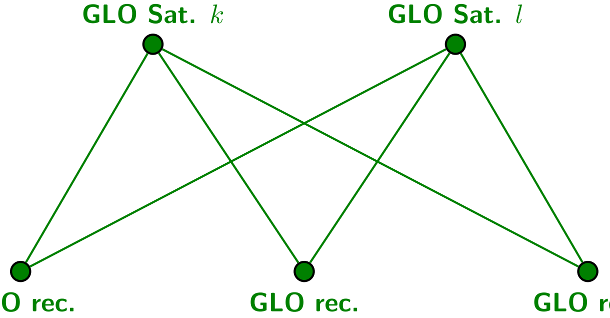

GLO rec.	GLO rec.	GLO rec.
k: C1P-Code	k: C1P-Code	k: C1P-Code
l: C1P-Code	l: C1P-Code	l: C1P-Code

GLO-sat clock	GLO-sat clock	GLO-sat clock
k: $\delta^k + a^k(C1P)$	k: $\delta^k + a^k(C1P)$	k: $\delta^k + a^k(C1P)$
l: $\delta^l + a^l(C1P)$	l: $\delta^l + a^l(C1P)$	l: $\delta^l + a^l(C1P)$

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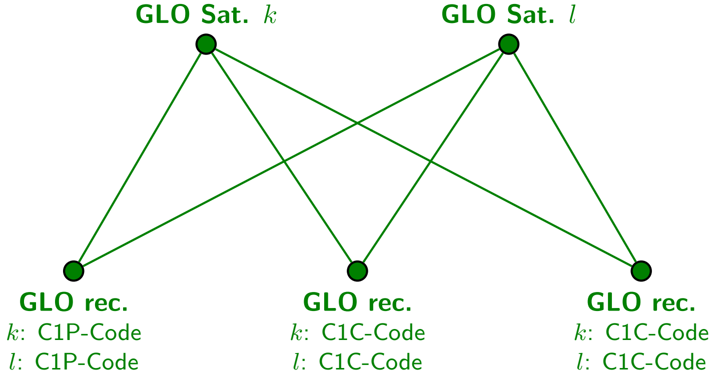

GLO-sat clock
k: $\delta^k + a^k(C1P)$
l: $\delta^l + a^l(C1P)$

GLO-sat clock
k: $\delta^k + a^k(C1C)$
l: $\delta^l + a^l(C1C)$

GLO-sat clock
k: $\delta^k + a^k(C1C)$
l: $\delta^l + a^l(C1C)$

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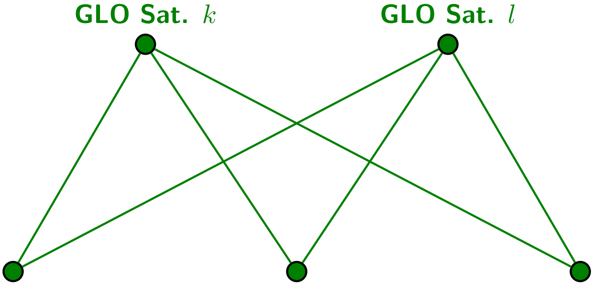

GLO rec.	GLO rec.	GLO rec.
k: C1P-Code	k: C1C-Code	k: C1C-Code
l: C1P-Code	l: C1C-Code	l: C1C-Code

GLO-sat clock	*GLO-sat clock*	*GLO-sat clock*
k: $\delta^k + a^k(C1P)$	*k:* $\delta^k + a^k(C1P) + DCB^k(C1P - C1C)$	*k:* $\delta^k + a^k(C1P) + DCB^k(C1P - C1C)$
l: $\delta^l + a^l(C1P)$	*l:* $\delta^l + a^l(C1P) + DCB^l(C1P - C1C)$	*l:* $\delta^l + a^l(C1P) + DCB^l(C1P - C1C)$

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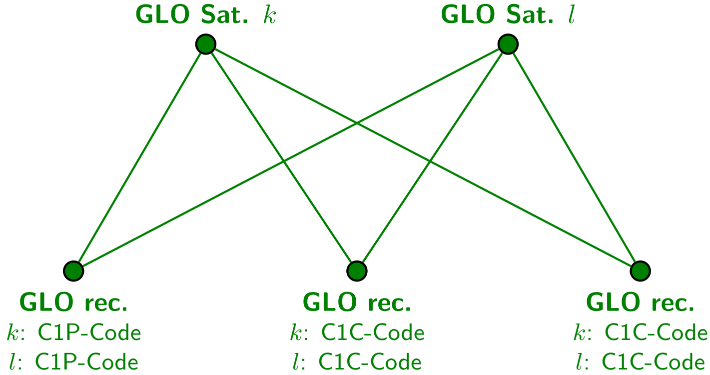

GLO-rec clock
k: $\delta_1 + a_1(C1P)$
l: $\delta_1 + a_1(C1P)$

GLO-rec clock
k: $\delta_2 + a_2(C1C)$
l: $\delta_2 + a_2(C1C)$

GLO-rec clock
k: $\delta_3 + a_3(C1C)$
l: $\delta_3 + a_3(C1C)$

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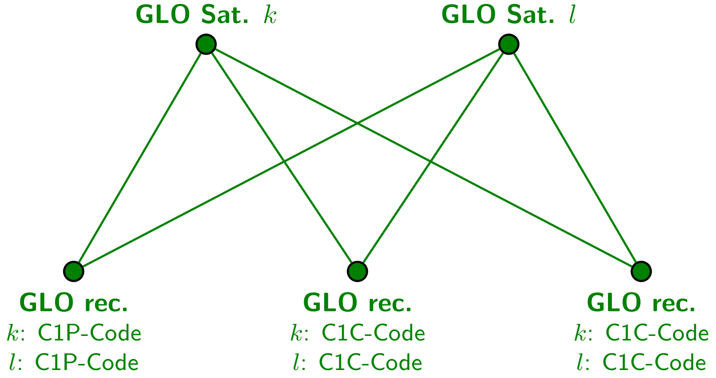

GLO-rec clock	*GLO-rec clock*	*GLO-rec clock*
k: $\delta_1 + a_1(C1P)^k$	*k:* $\delta_2 + a_2(C1C)^k$	*k:* $\delta_3 + a_3(C1C)^k$
l: $\delta_1 + a_1(C1P)^l$	*l:* $\delta_2 + a_2(C1C)^l$	*l:* $\delta_3 + a_3(C1C)^l$

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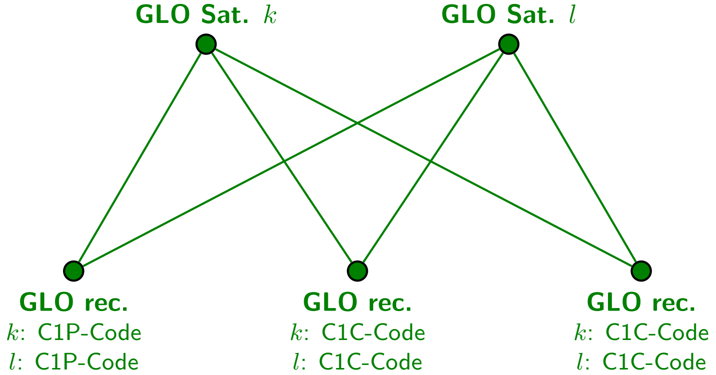

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l: $\delta_2 + a_2(C1C)^l$

GLO-rec clock
k: $\delta_3 + a_3(C1C)^k$
l: $\delta_3 + a_3(C1C)^l$

Because each GLONASS satellite emits the signal on ist own frequency the receiver hardware delays become (satellite-)frequency-dependent.

Code Biases in a GLONASS Network Solution

Depending on the code measurements of the individual receivers we can get:

- C1P−C1C or P1−C1 DCBs for all GLONASS satellites,
- C2P−C2C or P2−C2 DCBs for all GLONASS satellites.

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As soon as we get a mixture between all these observation types in one network solution we need

- either to correct the DCBs in the data processing
- or to estimate DCB parameters
  P1−C1 and P2−C2: Your reference clock only belongs to either the P- or C-code class – you need an additional reference for the satellite related biases.

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We also need to consider in addition an inter-frequency bias (IFB) because each GLONASS satellite emits the signal on another frequency.

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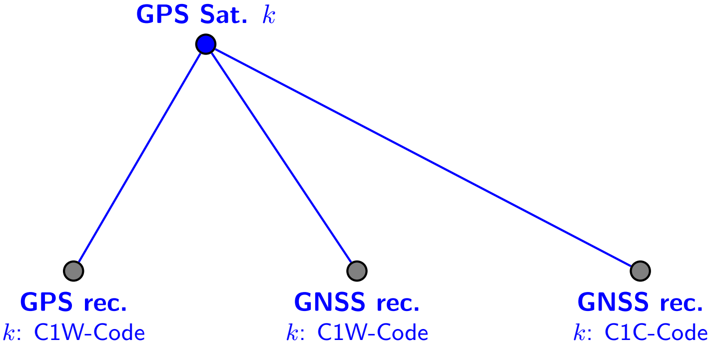

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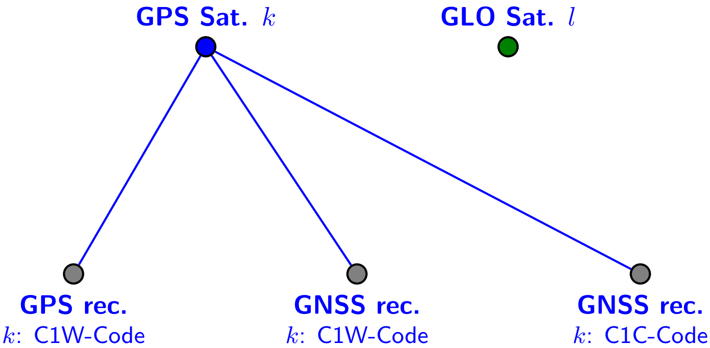

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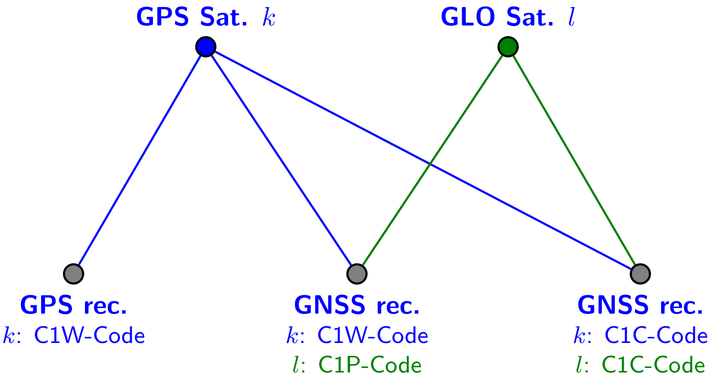

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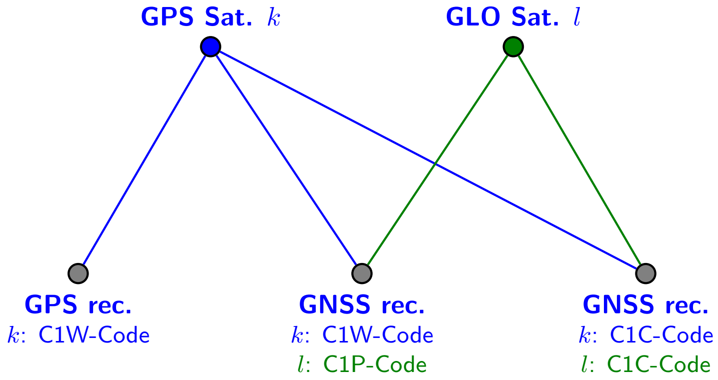

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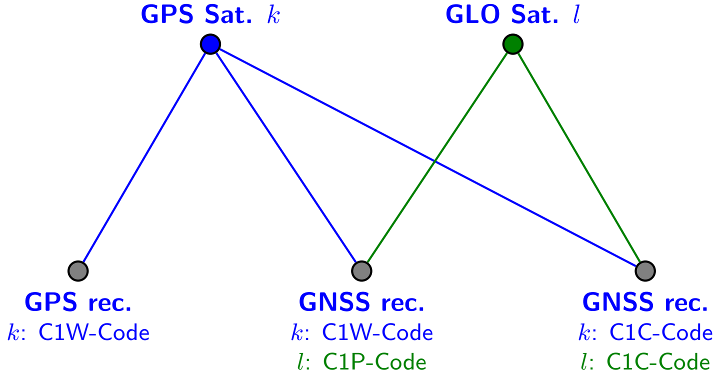

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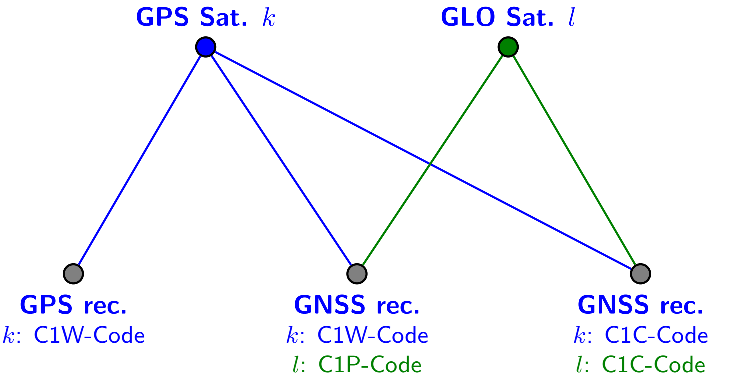

GNSS-rec clock
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GNSS-rec clock
k: $\delta_2 + a_2(C1W)^{GPS}$
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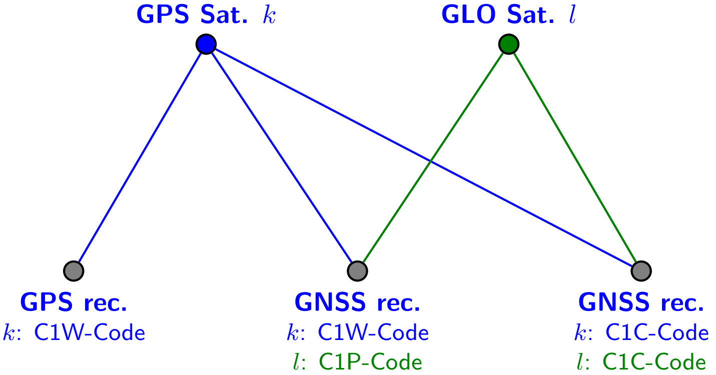

GNSS-rec clock
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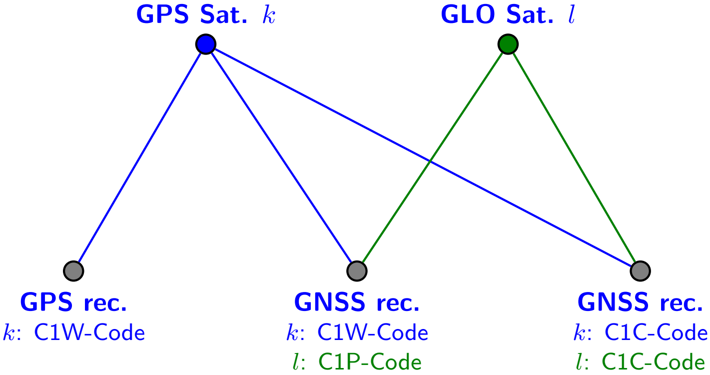

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Biases in a GPS/GLONASS Network Solution

We can see all DCBs from a GPS and GLONASS network solution and the GLONASS IFB in a combine GPS/GLONASS network solution.

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References are needed for

- P1-C1 DCB for GPS satellites,
- P2-C2 DCB for GPS satellites and GPS receivers tracking C2C,
- ISB for combined GPS/GLONASS tracking receivers,
- IFB for GLONASS tracking receivers.

Biases in a GPS/GLONASS Network Solution

In consequence the estimated biases depend on the realization of the reference (e.g., selection of a reference or list of stations in case of zero-mean conditions).

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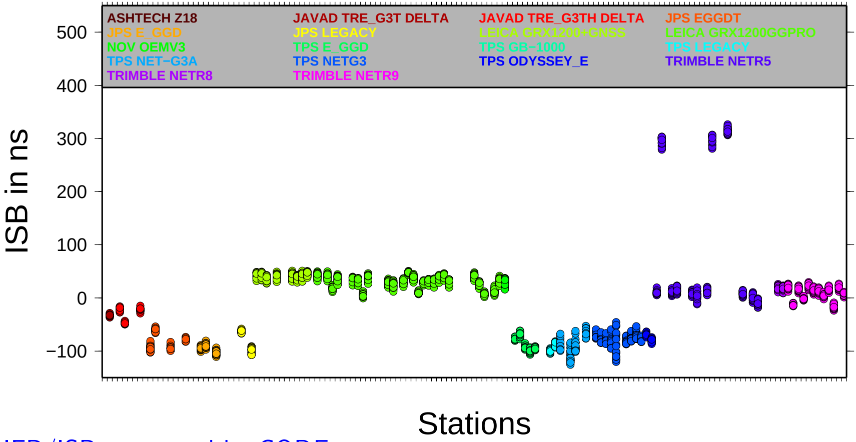
Typical examples are:

- Receiver/satellite clock estimation in a zero-difference network solution.
- Melbourne-Wübbena linear combination for ambiguity resolution (even in the double-difference analysis).

IFB/ISB Comparisons

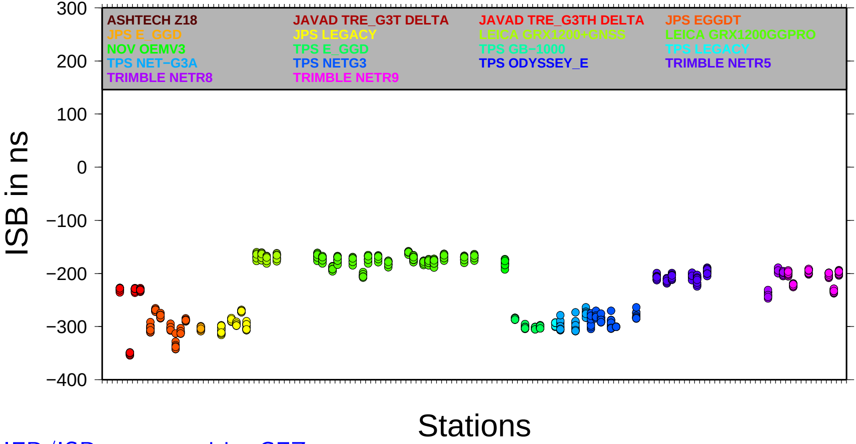
ISB characteristic of the receivers



IFB/ISB computed by CODE

Test solution submitted to the IGS workshop on GNSS biases in January 2012

ISB characteristic of the receivers



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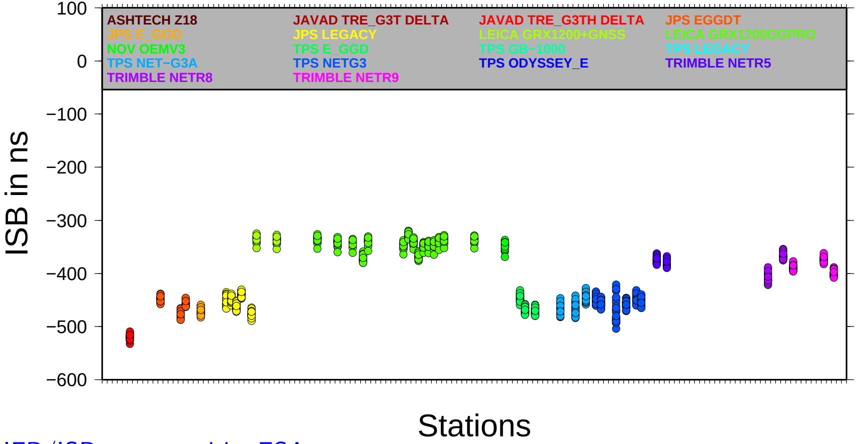

IFB/ISB computed by ESA

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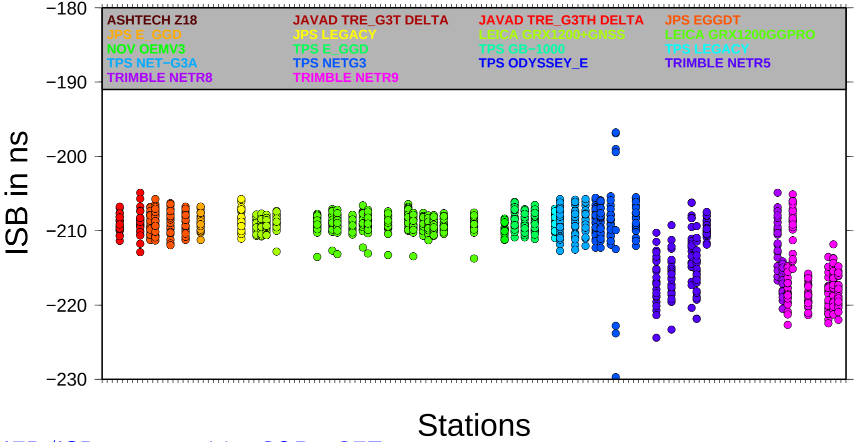
IFB/ISB Comparisons

Differences between ISB characteristic of the receivers



IFB/ISB computed by COD−GFZ

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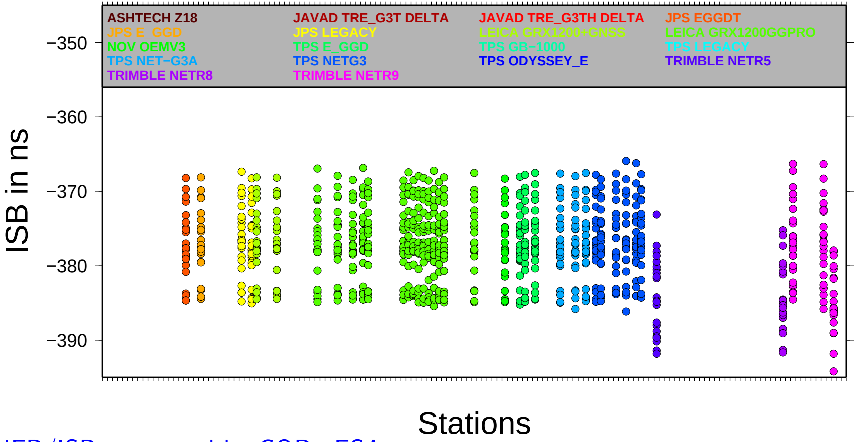

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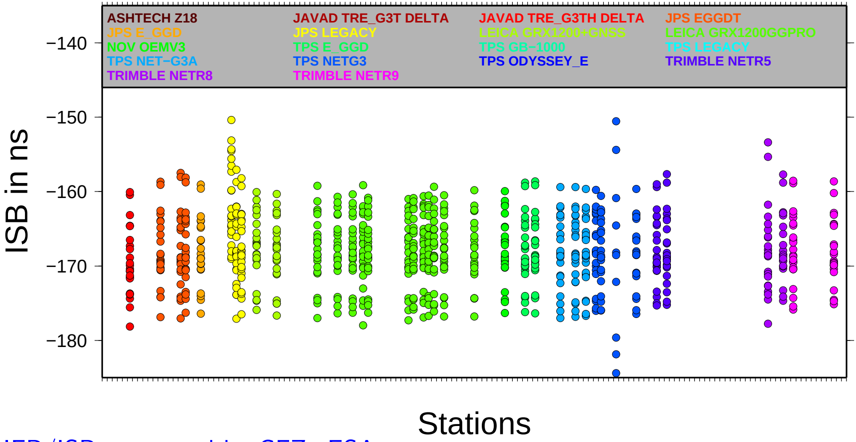

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IFB/ISB Comparisons

Differences between ISB characteristic of the receivers

Difference	Num. of Stations	Mean in ns	Median in ns	RMS in ns
CODE – GFZ	52	−210.6	−209.4	4.9
CODE – ESA	39	−377.5	−377.6	5.1
GFZ – ESA	36	−167.7	−168.2	6.1
CODE – GRGS	50	−371.9	−372.2	18.7
GFZ – GRGS	46	−162.1	−163.0	19.2
ESA – GRGS	34	6.1	5.8	20.6

- High consistency (low RMS) with a proper IFB–handling (enough weight for the code measurements?)
- Test whether the ACs select the same type of code observations (CODE differs from ESA and GFZ)

Further Code Biases

- When forming linear combinations from the P1 and P2 measurements

$$LC = \kappa_1 \cdot P_1 + \kappa_2 \cdot P_2$$

  the original P1−C1, P2−C2 DCB values have to be applied with the corresponding coefficients:

$$DCB(LC) = \kappa_1 \cdot DCB(P1 - C1) + \kappa_2 \cdot DCB(P2 - C2)$$

- Alternative factors need to apply when P2 or C2 is not directly tracked (e.g., cross-correlation technique).

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- With more GNSS and their new signals more groups of Code Biases will become relevant (e.g, third frequency for GPS and GLONASS).

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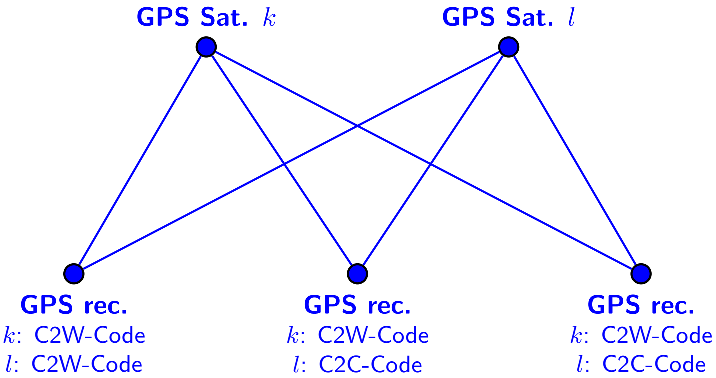

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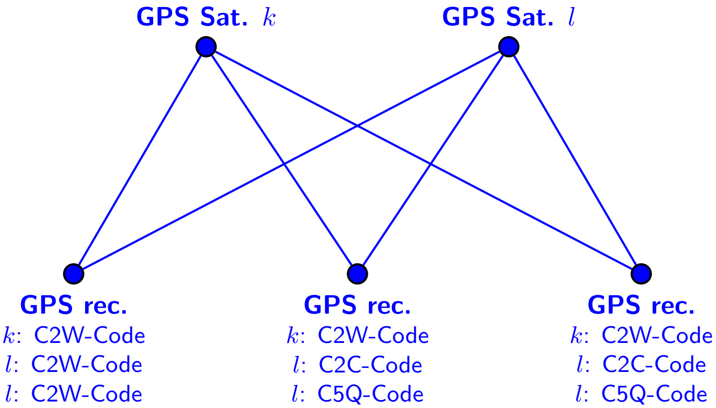

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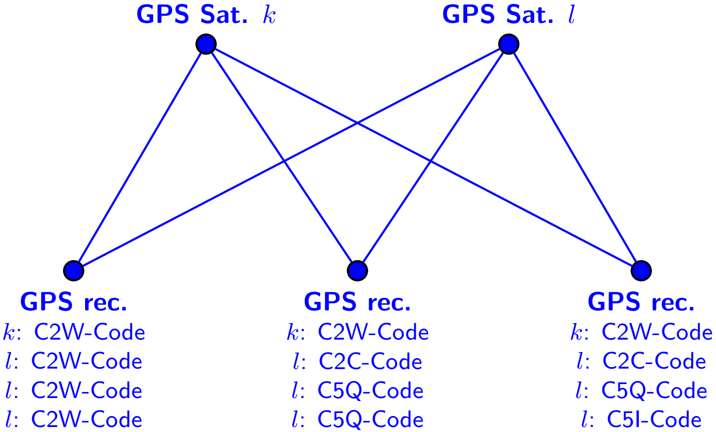

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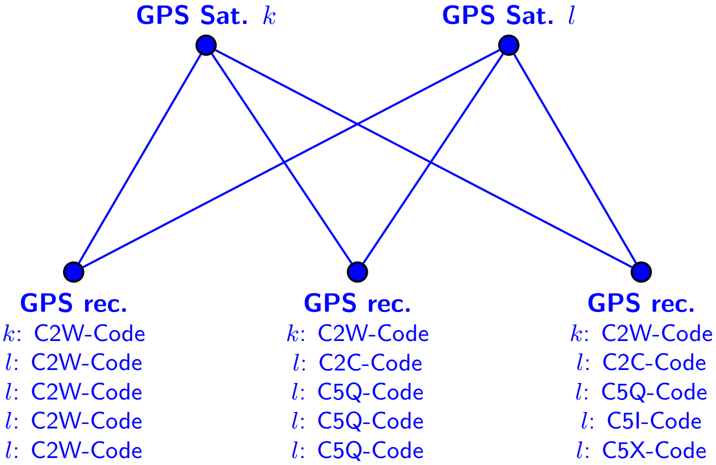

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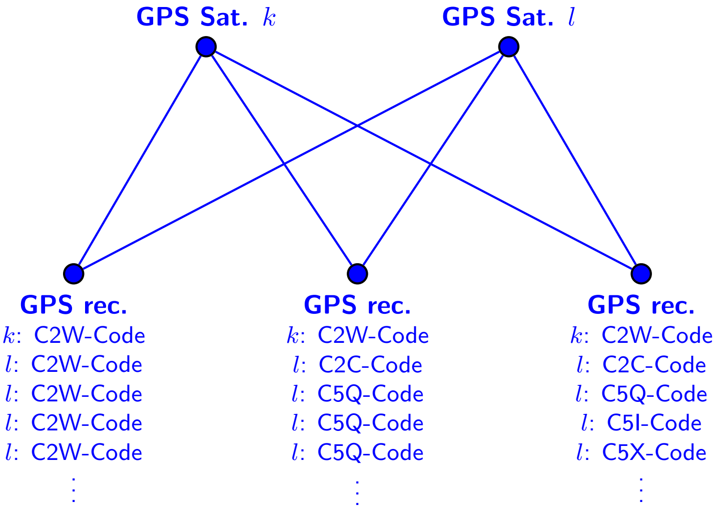

Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

$DCB^l(C2C - C2W)$, $DCB^l(C5Q - C2W)$,
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- C5X is a mixture of C5Q- and C5I-signal that is not further specified by the manufacturers.
  It must be expected that it is different for receivers from different manufacturers (firmware?).

Bias Handling in a Multi-GNSS Environment

If you simply follow the recipe from the classical examples you will end up with a long list of DCBs:

$DCB^l(C2C - C2W)$, $DCB^l(C5Q - C2W)$,
$DCB^l(C5I - C2W)$, $DCB^l(C5X - C2W)$, $\ldots$

Questions/potential problems:

- What to do if C2W is not tracked by any station in the network?

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- **It is urgently time to look for an alternative concept!**

Bias Handling in a Multi-GNSS Environment

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

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Each code measurement P_i^k refers to two hardware delay terms: a_i for the receiver and a^k for the satellite.

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They can directly be setup as pseudo-absolute code biases (OSB) parameter.

When processing linear combinations of the original observations each observation contributes to four OSB parameters.

Pseudo-Absolute Code Biases

Pseudo-absolute code biases parameter can be derived in all processing steps where also classical DCB parameters can be obtained:

- GNSS clock estimation
- GNSS ionosphere model generation

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  - if either redundant measurements (e.g., C1W and C1C) are provided, or
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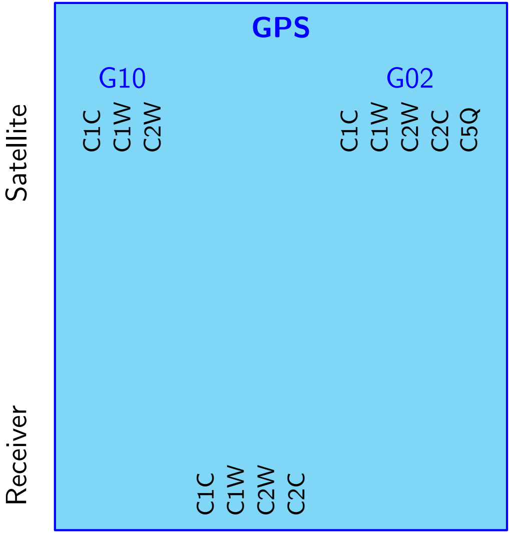
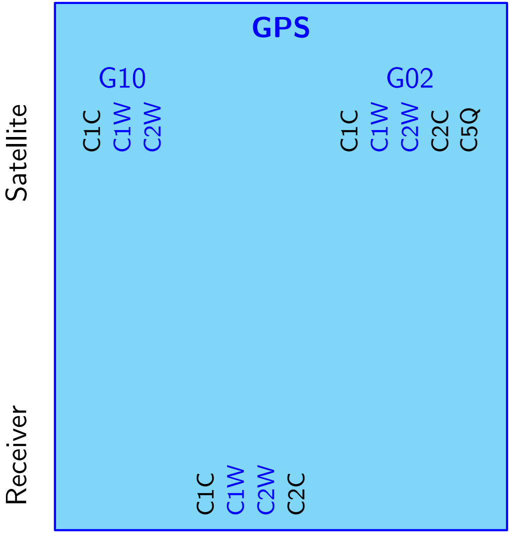
Contributions from these sources can even be combined into one system of OSB parameters.

Pseudo-Absolute Code Biases: CLK



Pseudo-Absolute Code Biases: CLK



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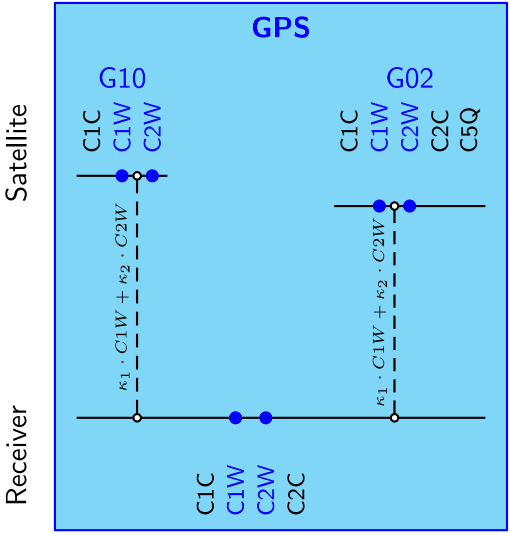

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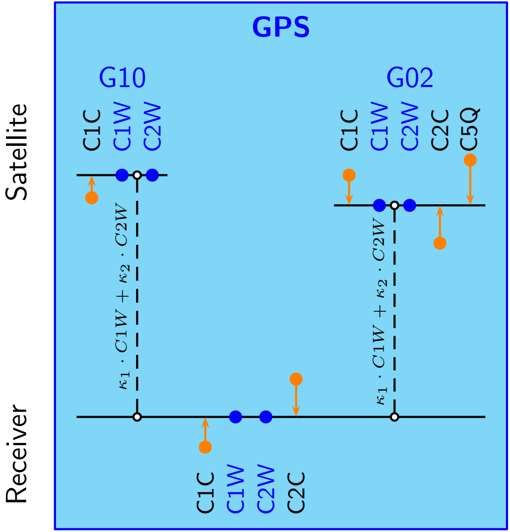

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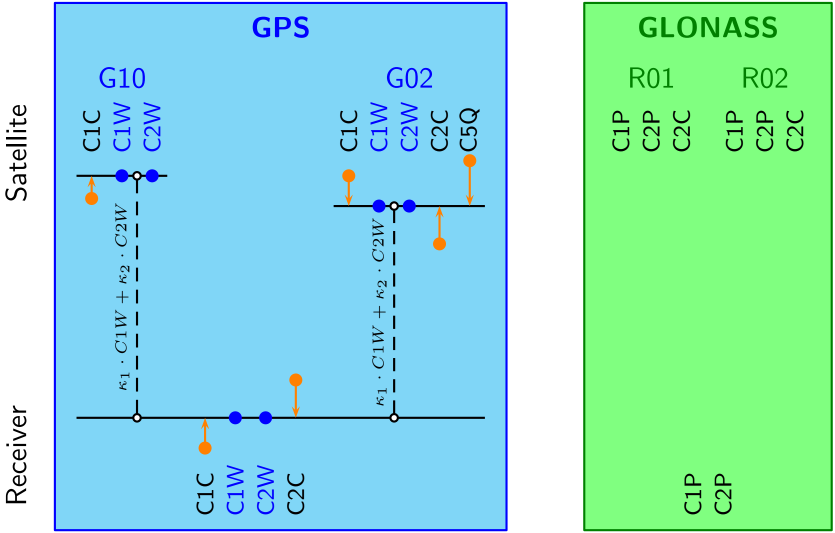

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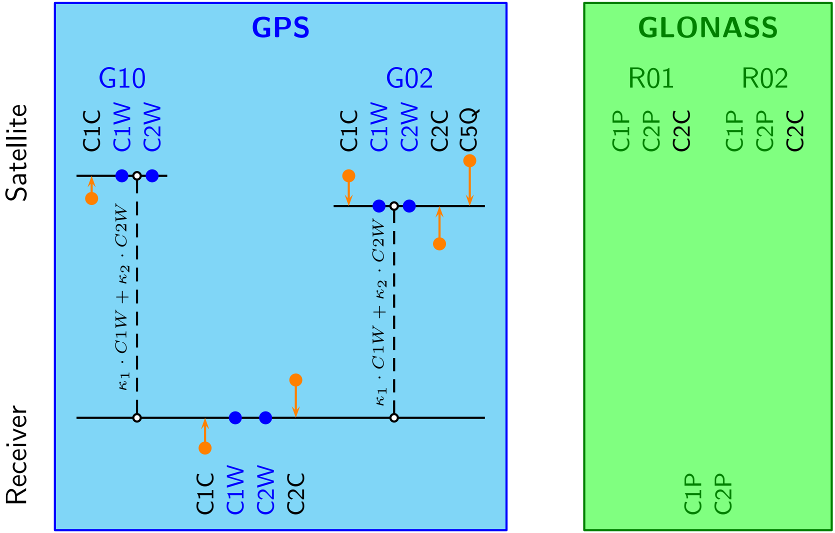

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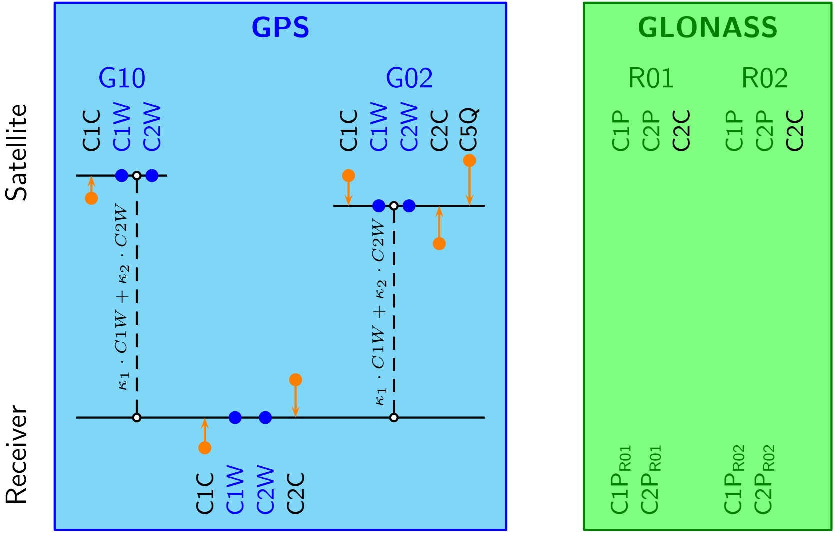

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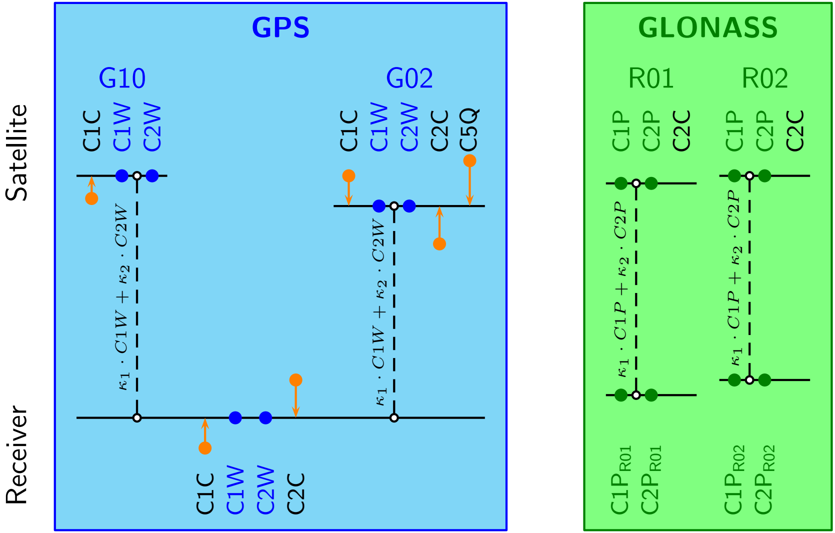

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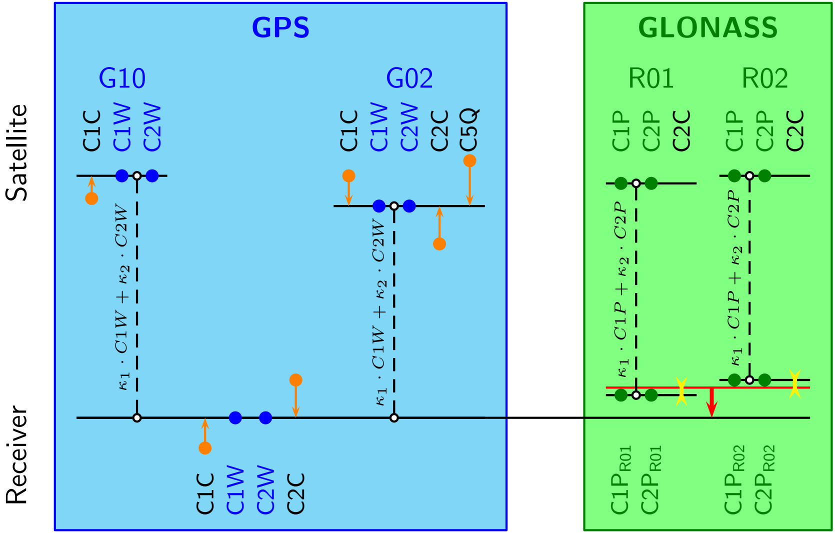

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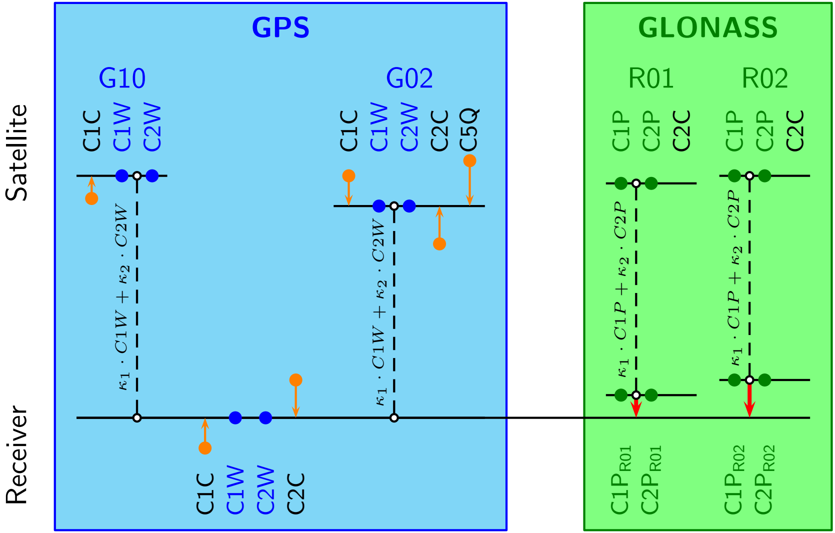

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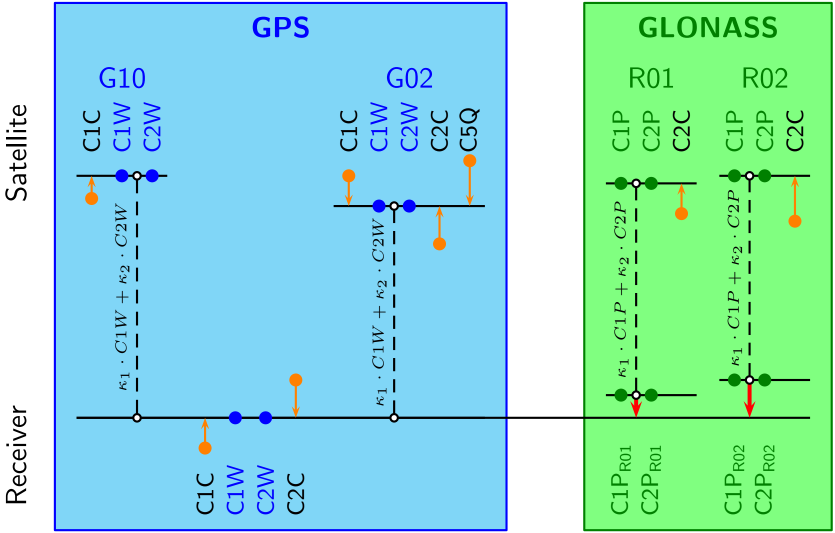
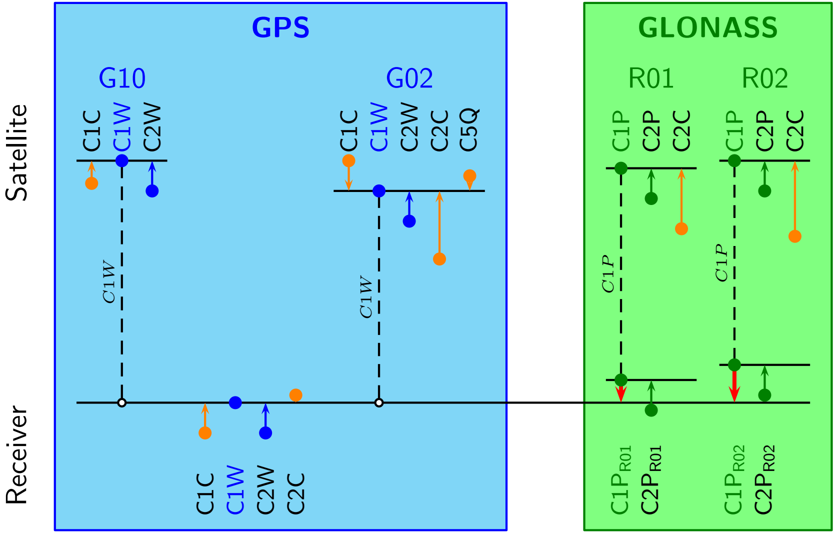


Pseudo-Absolute Code Biases: CLK+ION



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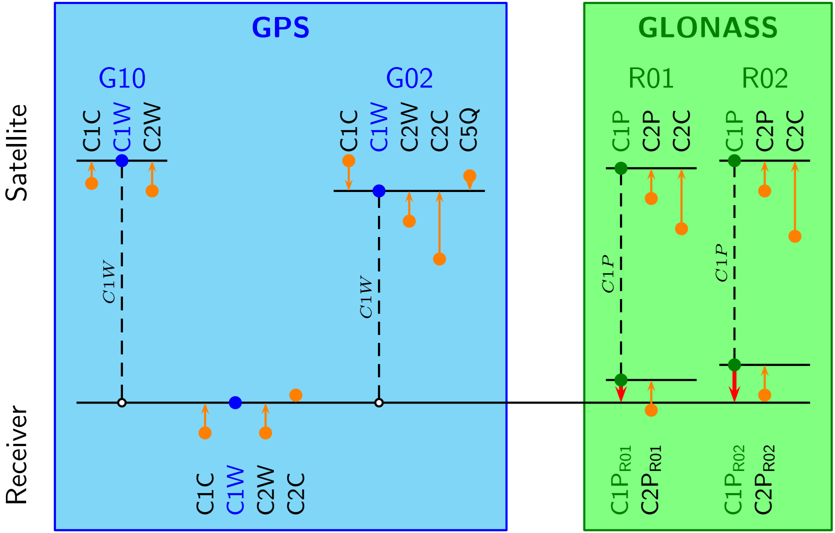
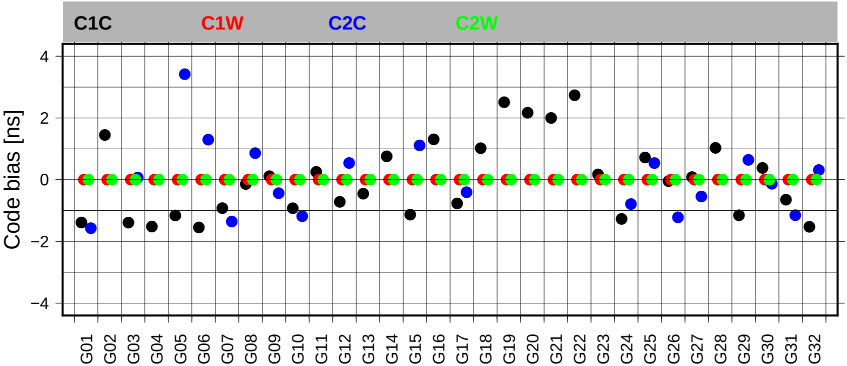


Pseudo-Absolute Code Biases

Estimated bias parameters from the CODE MGEX solution



Bias solution for GPS satellites based only on CLK:

reference ionosphere-free linear combination from C1W/C2W

(only biases for the satellites have been estimtated)

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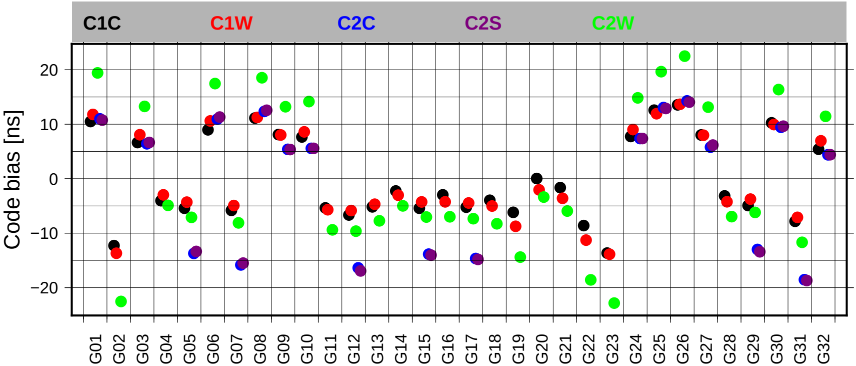
Estimated bias parameters from the CODE MGEX solution



Bias solution for GPS satellites based only on CLK+ION: reference C1W

(also biases for all stations are estimtated)

Estimation of Code Biases

The Reference signal for IGS products is defined by:

$$a(LC_{ion-free}) = \kappa_1 \cdot a(P1 - Code) + \kappa_2 \cdot a(P2 - Code)$$

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Examples:

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- Receiver is tracking C1C/C2W: DCB(P1−C1) need to be applied

$$\kappa_1 \cdot DCB(P1 - C1) = \frac{f_1^2}{f_1^2 - f_2^2} \cdot DCB(P1 - C1)$$

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$$\kappa_1 \cdot DCB(P1 - C1) + \kappa_2 \cdot DCB(P1 - C1) = DCB(P1 - C1)$$

Estimation of Code Biases

When estimating DCBs the receiver classes must be distinguished as derived before:

- Receiver is tracking C1W/C2W:
  $0 \cdot DCB(P1 - C1)$
- Receiver is tracking C1C/C2W:
  $\kappa_1 \cdot DCB(P1 - C1)$
- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
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- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
  $1 \cdot DCB(P1 - C1)$

In order to estimate the DCB(P1−C1), the factors are used as partial derivatives in the least squares adjustment process.

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  $1 \cdot DCB(P1 - C1)$

If the DCB(P1−C1) is known the pre-factor can be estimated and the tracking technology of the receiver can be detected/verified.

Estimation of Code Biases

Station		Estimated factor	Sigma	Related tracking	Receiver	Receiver tracking	
GANP	11515M001	2.826	0.021	C1/P2	TRIMBLE NETR8	C1/P2	OK
HERT	13212M010	2.503	0.019	C1/P2	LEICA GRX1200GGPRO	C1/P2	OK
JOZ2	12204M002	2.489	0.024	C1/P2	LEICA GRX1200GGPRO	C1/P2	OK
LAMA	12209M001	2.546	0.020	C1/P2	LEICA GRX1200GGPRO	C1/P2	OK
MATE	12734M008	2.454	0.025	C1/P2	LEICA GRX1200GGPRO	C1/P2	OK
ONSA	10402M004	0.317	0.023	P1/P2	JPS E_GGD	P1/P2	OK
PTBB	14234M001	-0.096	0.027	P1/P2	ASHTECH Z-XII3T	P1/P2	OK
TLSE	10003M009	2.851	0.023	C1/P2	TRIMBLE NETR5	C1/P2	OK
WSRT	13506M005	-0.091	0.022	P1/P2	AOA SNR-12 ACT	P1/P2	OK
WTZR	14201M010	2.503	0.030	C1/P2	LEICA GRX1200GGPRO	C1/P2	OK
WTZZ	14201M014	0.335	0.023	?1/?2	TPS E_GGD	P1/P2	
ZIM2	14001M008	2.891	0.025	C1/P2	TRIMBLE NETR5	C1/P2	OK
ZIMM	14001M004	2.608	0.021	C1/P2	TRIMBLE NETRS	C1/P2	OK

Estimation of Code Biases

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PTBB 14234M001	-0.096	0.027	P1/P2	ASHTECH Z-XII3T	P1/P2	OK
TLSE 10003M009	2.851	0.023	C1/P2	TRIMBLE NETR5	C1/P2	OK
WSRT 13506M005	-0.091	0.022	P1/P2	AOA SNR-12 ACT	P1/P2	OK
WTZR 14201M010	2.503	0.030	C1/P2	LEICA GRX1200GGPRO	C1/P2	OK
WTZZ 14201M014	0.335	0.023	?1/?2	TPS E_GGD	P1/P2	
ZIM2 14001M008	2.891	0.025	C1/P2	TRIMBLE NETR5	C1/P2	OK
ZIMM 14001M004	2.608	0.021	C1/P2	TRIMBLE NETRS	C1/P2	OK

With the same technology the signal reported in the RINEX3 files for the MGEX stations can be verified and potentially the reference for the "X-signal" for each receiver type (and firmware) determined.

GNSS Phase Biases

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$

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On the first view, the phase bias parameters (α_i, α^k) seems to be easily manageable in the GNSS processing because the ambiguity term (N_i^k) is fully correlated and can absorb all effects.

GNSS Phase Biases

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c \cdot (\delta_i - a_i) - c \cdot (\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$

On the first view, the phase bias parameters (α_i, α^k) seems to be easily manageable in the GNSS processing because the ambiguity term (N_i^k) is fully correlated and can absorb all effects.

This is only true as long as the ambiguities are not resolved to their integer values.

Forming Differences

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c \cdot (\delta_i - \alpha_i) - c \cdot (\delta^k - \alpha^k)$$
$$+ \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$

$$L_j^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| + T_j^k - I_j^k + c \cdot (\delta_j - \alpha_j) - c \cdot (\delta^k - \alpha^k)$$
$$+ \lambda^k \cdot N_j^k + \lambda^k \cdot \Delta\varphi_j^k$$

Forming Differences

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c\cdot(\delta_i - \alpha_i) - c\cdot(\delta^k - \alpha^k)$$
$$+ \lambda^k \cdot N_i^k + \lambda^k \cdot (\varphi^k(t_0) - \varphi_i(t_0))$$

$$L_j^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| + T_j^k - I_j^k + c\cdot(\delta_j - \alpha_j) - c\cdot(\delta^k - \alpha^k)$$
$$+ \lambda^k \cdot N_j^k + \lambda^k \cdot (\varphi^k(t_0) - \varphi_j(t_0))$$

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$$L_j^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| + T_j^k - I_j^k + c\cdot(\delta_j - \alpha_j) - c\cdot(\delta^k - \alpha^k)$$
$$+ \lambda^k \cdot N_j^k + \lambda^k \cdot (\varphi^k(t_0) - \varphi_j(t_0))$$

Forming single differences between two stations we obtain:

$$\begin{aligned}\Delta L_{ij}^k =& L_i^k - L_j^k \\ =& \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ &+ T_i^k - T_j^k - (I_i^k - I_j^k) - c\cdot(\delta_i - \delta_j - \alpha_i + \alpha_j) \\ &+ \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0))\end{aligned}$$

Forming Differences

$$\begin{aligned}\Delta L_{ij}^k = & \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ & + T_i^k - T_j^k - (I_i^k - I_j^k) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \\ & + \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0))\end{aligned}$$

$$\begin{aligned}\Delta L_{ij}^l = & \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ & + T_i^l - T_j^l - (I_i^l - I_j^l) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j) \\ & + \lambda^l \cdot (N_i^l - N_j^l) - \lambda^l \cdot (\varphi_i(t_0) - \varphi_j(t_0))\end{aligned}$$

Forming Differences

$$\Delta L_{ij}^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right|$$
$$+ T_i^k - T_j^k - (I_i^k - I_j^k) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j)$$
$$+ \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0))$$

$$\Delta L_{ij}^l = \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_j + \Delta\vec{\chi}_j)\right|$$
$$+ T_i^l - T_j^l - (I_i^l - I_j^l) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j)$$
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Forming Differences

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Double differences between two satellites and receivers result in:

$$\begin{aligned}\nabla\Delta L_{ij}^{kl} =& L_{ij}^k - L_{ij}^l \\ =& \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ &- \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ &+ T_i^k - T_j^k - T_i^l + T_j^l - (I_i^k - I_j^k - I_i^l + I_j^l) \\ &+ \lambda^k \cdot (N_i^k - N_j^k) - \lambda^l \cdot (N_i^l - N_j^l) - (\lambda^k - \lambda^l)\cdot(\varphi_i(t_0) - \varphi_j(t_0))\end{aligned}$$

Forming Differences

$$\begin{aligned}\Delta L_{ij}^{k} = &\left|(\vec{x}^{k} + \Delta\vec{\chi}^{k}) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^{k} + \Delta\vec{\chi}^{k}) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ &+ T_i^k - T_j^k - (I_i^k - I_j^k) - c\cdot(\delta_i - \delta_j - \alpha_i + \alpha_j) \\ &+ \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0))\end{aligned}$$

$$\begin{aligned}\Delta L_{ij}^{l} = &\left|(\vec{x}^{l} + \Delta\vec{\chi}^{l}) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| - \left|(\vec{x}^{l} + \Delta\vec{\chi}^{l}) - (\vec{x}_j + \Delta\vec{\chi}_j)\right| \\ &+ T_i^l - T_j^l - (I_i^l - I_j^l) - c\cdot(\delta_i - \delta_j - \alpha_i + \alpha_j) \\ &+ \lambda^l \cdot (N_i^l - N_j^l) - \lambda^l \cdot (\varphi_i(t_0) - \varphi_j(t_0))\end{aligned}$$

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GNSS Phase Biases

- The ambiguity resolution in the zero difference processing does also only use double differences to get access to the integer ambiguities.

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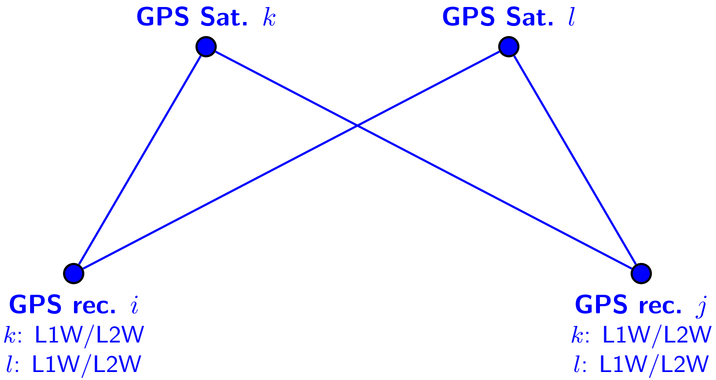
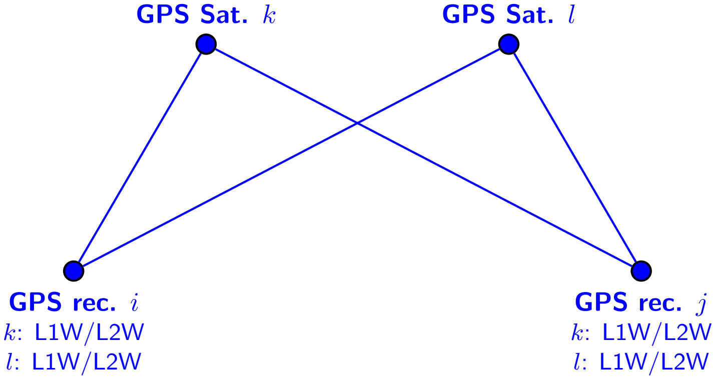
  - the signals are received on different frequencies because different hardware delays are expected (**Inter-frequency bias, IFB**) (alternatively, the IFB may be calibrated and corrected, e.g., for GLONASS ambiguity resolution).

Compatibility of Phase-Related Hardware Delay

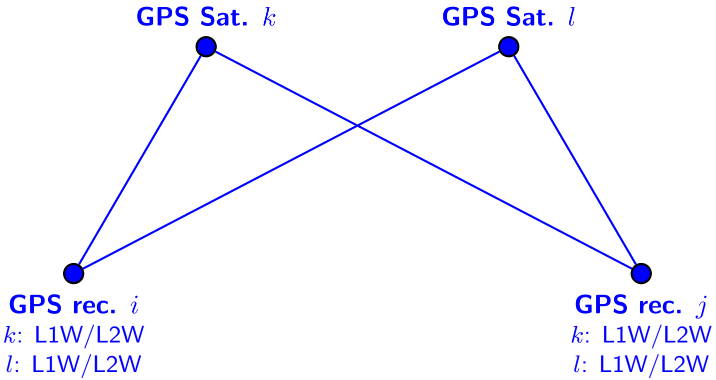


Compatibility of Phase-Related Hardware Delay



k: $\alpha_i(L1W)$	$\alpha_i(L2W)$		k: $\alpha_j(L1W)$	$\alpha_j(L2W)$
l: $\alpha_i(L1W)$	$\alpha_i(L2W)$		l: $\alpha_j(L1W)$	$\alpha_j(L2W)$

Compatibility of Phase-Related Hardware Delay

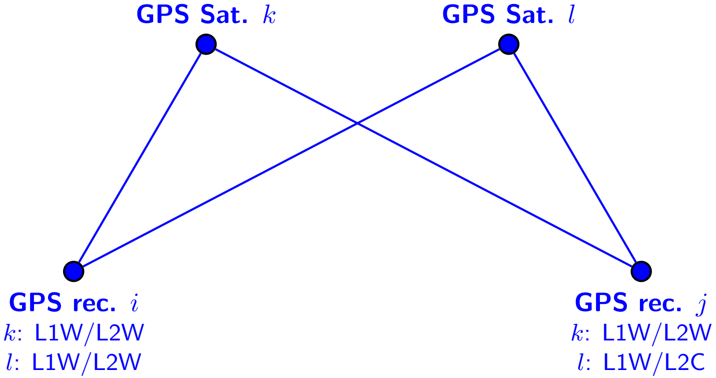


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

k: $\alpha_j(L1W)$ $\alpha_j(L2W)$
l: $\alpha_j(L1W)$ $\alpha_j(L2W)$

ambiguity resolution possible

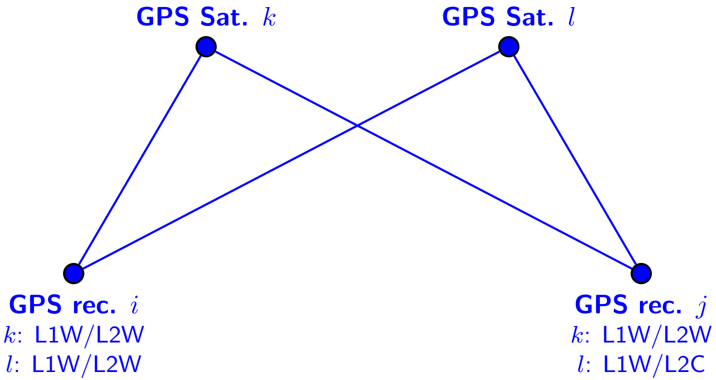
Compatibility of Phase-Related Hardware Delay



k:	$\alpha_i(L1W)$	$\alpha_i(L2W)$
l:	$\alpha_i(L1W)$	$\alpha_i(L2W)$

k:	$\alpha_j(L1W)$	$\alpha_j(L2W)$
l:	$\alpha_j(L1W)$	$\alpha_j(L2C)$

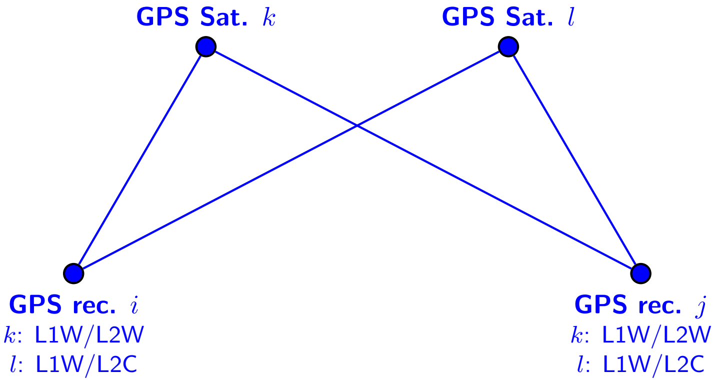
Compatibility of Phase-Related Hardware Delay



k:	$\alpha_i(L1W)$	$\alpha_i(L2W)$	*k:*	$\alpha_j(L1W)$	$\alpha_j(L2W)$
l:	$\alpha_i(L1W)$	$\alpha_i(L2W)$	*l:*	$\alpha_j(L1W)$	$\alpha_j(L2C)$

"quarter cycle problem" – no resolution

Compatibility of Phase-Related Hardware Delay

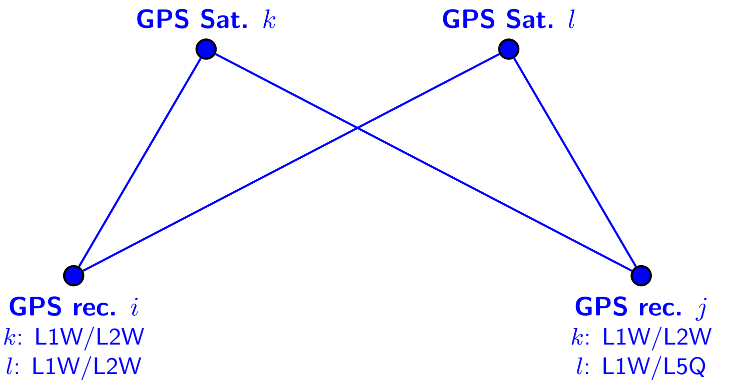


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2C)$

k: $\alpha_j(L1W)$ $\alpha_j(L2W)$
l: $\alpha_j(L1W)$ $\alpha_j(L2C)$

ambiguity resolution possible

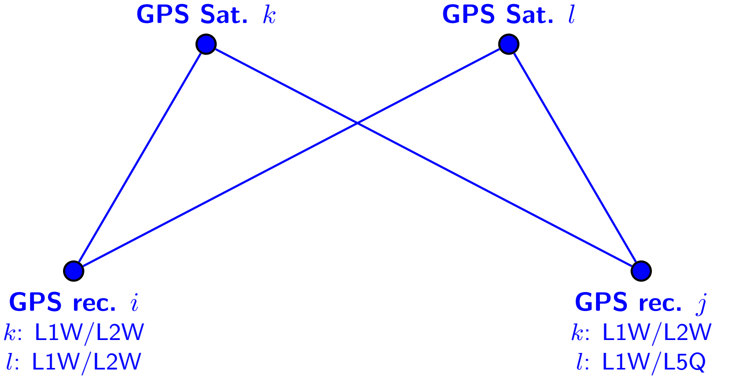
Compatibility of Phase-Related Hardware Delay



k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

k: $\alpha_j(L1W)$ $\alpha_j(L2W)$
l: $\alpha_j(L1W)$ $\alpha_j(L5Q)$

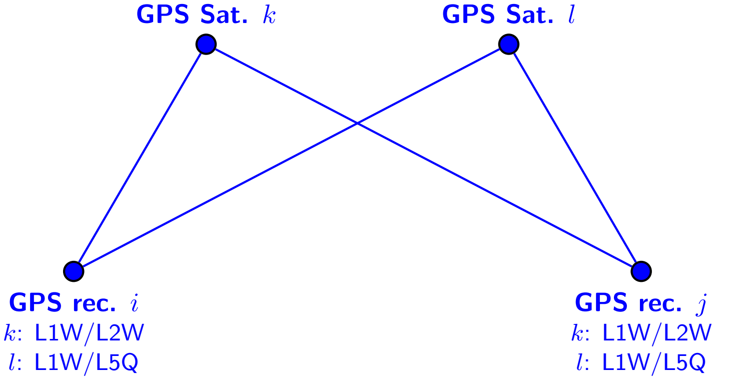
Compatibility of Phase-Related Hardware Delay



k: $\alpha_i(L1W)$	$\alpha_i(L2W)$	k: $\alpha_j(L1W)$	$\alpha_j(L2W)$
l: $\alpha_i(L1W)$	$\alpha_i(L2W)$	l: $\alpha_j(L1W)$	$\alpha_j(L5Q)$

Incompatible – no resolution

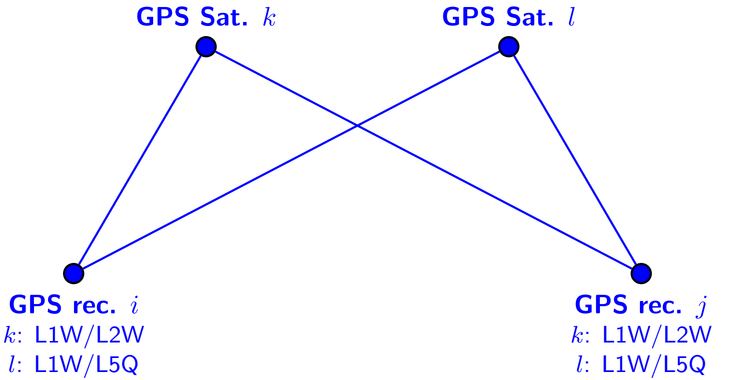
Compatibility of Phase-Related Hardware Delay



k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L5Q)$

k: $\alpha_j(L1W)$ $\alpha_j(L2W)$
l: $\alpha_j(L1W)$ $\alpha_j(L5Q)$

Compatibility of Phase-Related Hardware Delay



k: $\alpha_i(L1W)$ $\alpha_i(L2W)$

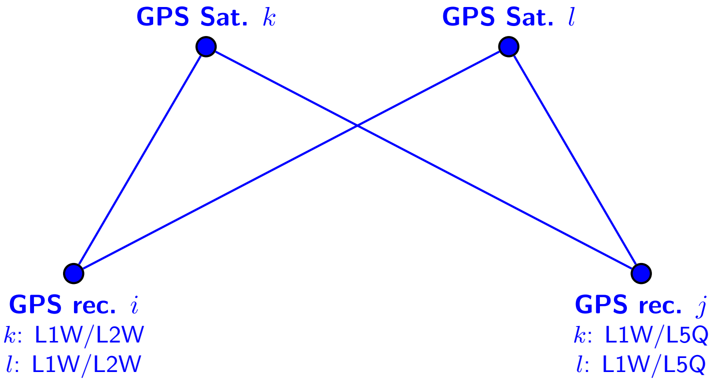
l: $\alpha_i(L1W)$ $\alpha_i(L5Q)$

k: $\alpha_j(L1W)$ $\alpha_j(L2W)$

l: $\alpha_j(L1W)$ $\alpha_j(L5Q)$

Be careful: $\alpha_i(L5Q) - \alpha_i(L2W) \stackrel{?}{=} \alpha_j(L5Q) - \alpha_j(L2W)$

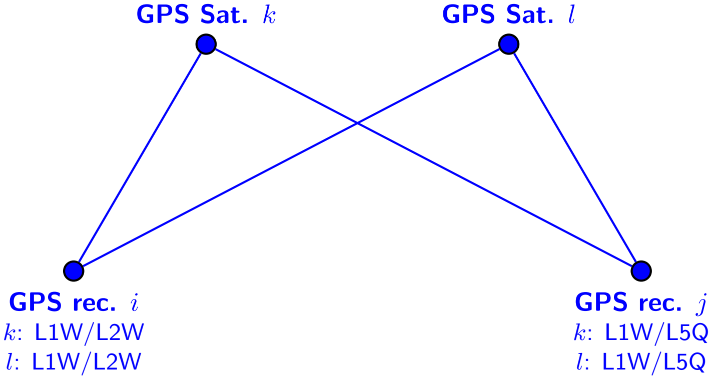
Compatibility of Phase-Related Hardware Delay



k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

k: $\alpha_j(L1W)$ $\alpha_j(L5Q)$
l: $\alpha_j(L1W)$ $\alpha_j(L5Q)$

Compatibility of Phase-Related Hardware Delay

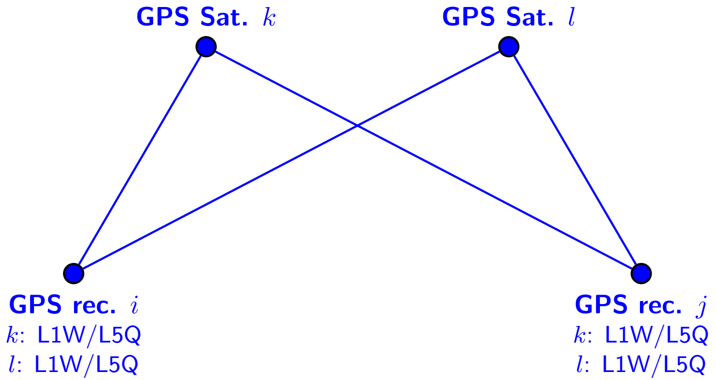


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

k: $\alpha_j(L1W)$ $\alpha_j(L5Q)$
l: $\alpha_j(L1W)$ $\alpha_j(L5Q)$

Be careful: $\alpha^k(L5Q) - \alpha^k(L2W) \stackrel{?}{=} \alpha^l(L5Q) - \alpha^l(L2W)$

Compatibility of Phase-Related Hardware Delay

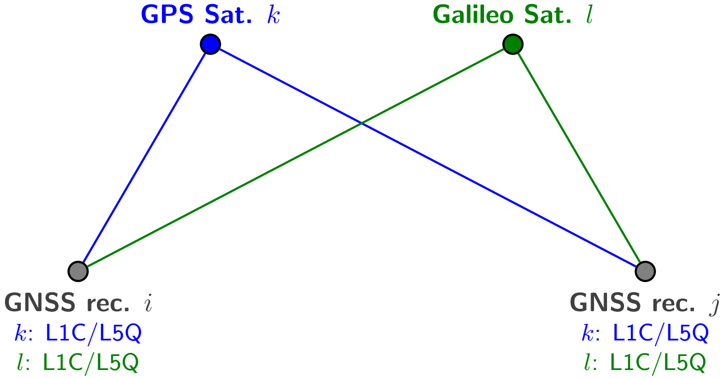


k: $\alpha_i(L1W)$ $\alpha_i(L5Q)$
l: $\alpha_i(L1W)$ $\alpha_i(L5Q)$

k: $\alpha_j(L1W)$ $\alpha_j(L5Q)$
l: $\alpha_j(L1W)$ $\alpha_j(L5Q)$

ambiguity resolution possible

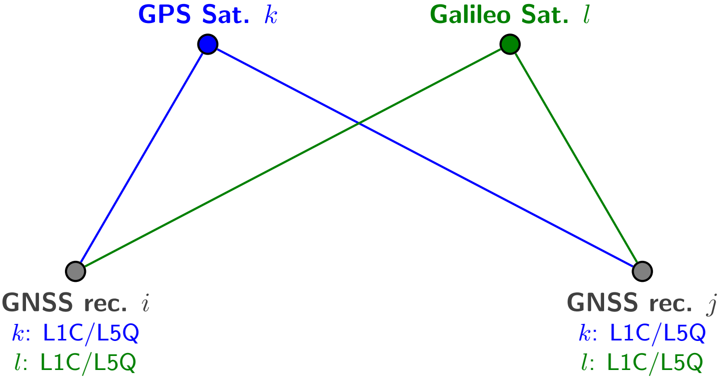
Compatibility of Phase-Related Hardware Delay



$\alpha_i(L1C)^{GPS}$ $\alpha_i(L5Q)^{GPS}$
$\alpha_i(L1C)^{GAL}$ $\alpha_i(L5Q)^{GAL}$

$\alpha_j(L1C)^{GPS}$ $\alpha_j(L5Q)^{GPS}$
$\alpha_j(L1C)^{GAL}$ $\alpha_j(L5Q)^{GAL}$

Compatibility of Phase-Related Hardware Delay



$\alpha_i(L1C)^{GPS}$ $\alpha_i(L5Q)^{GPS}$
$\alpha_i(L1C)^{GAL}$ $\alpha_i(L5Q)^{GAL}$

$\alpha_j(L1C)^{GPS}$ $\alpha_j(L5Q)^{GPS}$
$\alpha_j(L1C)^{GAL}$ $\alpha_j(L5Q)^{GAL}$

Be careful: $ISB_i(L1C, L5Q) \stackrel{?}{=} ISB_j(L1C, L5Q)$

Dependency of the Terms

$$P_i^k = \left|(\vec{x}^k + \Delta\vec{x}^k) - (\vec{x}_i + \Delta\vec{x}_i)\right| + T_i^k + I_i^k + c\cdot(\delta_i - a_i) - c\cdot(\delta^k - a^k)$$

$$L_i^k = \left|(\vec{x}^k + \Delta\vec{\chi}^k) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + T_i^k - I_i^k + c\cdot(\delta_i - \alpha_i) - c\cdot(\delta^k - \alpha^k) + \lambda^k \cdot N_i^k + \lambda^k \cdot \Delta\varphi_i^k$$

	Antenna		Hardware			
GNSS:						
Code		$\Delta\vec{x}_i$	a_i		δ^k	ISB: Inter-System Bias
Phase		$\Delta\vec{\chi}_i$	α_i		δ^k	
Frequency:						
Code	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	a_i	a^k		IFB: Inter-Frequency Bias
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$	α_i	α^k		
Signal type:						
Code			a_i	a^k		DCB: Differential Code Bias

GPS–GLONASS Antenna Bias: Coordinates

- A GNSS antenna should be individually calibrated for each GNSS to consider the system-dependency of the $\Delta\vec{\chi}_i$ term.

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- The coordinate GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center offset.

GPS–GLONASS Antenna Bias: Coordinates

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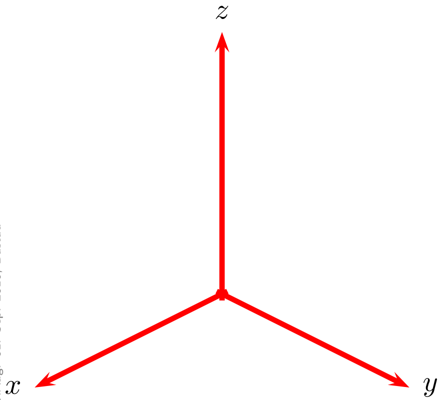
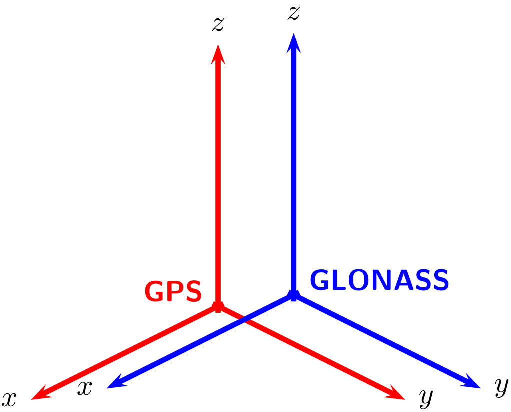
- The coordinate GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center offset.

- A related bias parameter was implemented for a background test solution at the CODE analysis center in early 2011.

GPS–GLONASS Antenna Bias: Coordinates

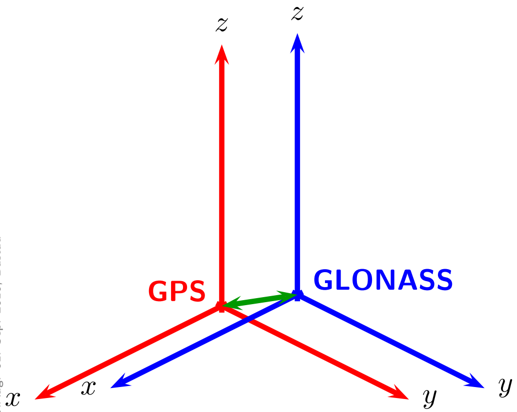


GPS–GLONASS Antenna Bias: Coordinates



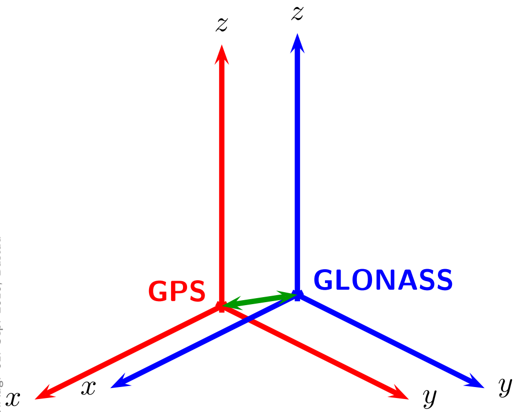
- Station coordinate from GPS-only
- Station coordinate from GLONASS-only

GPS–GLONASS Antenna Bias: Coordinates



- Station coordinate from GPS-only
- Station coordinate from GLONASS-only
- Vector between GPS– and GLONASS–coordinates

GPS–GLONASS Antenna Bias: Coordinates



- Station coordinate from GPS-only
- Station coordinate from GLONASS-only
- Vector between GPS– and GLONASS–coordinates
- two independent networks with independent datum definition

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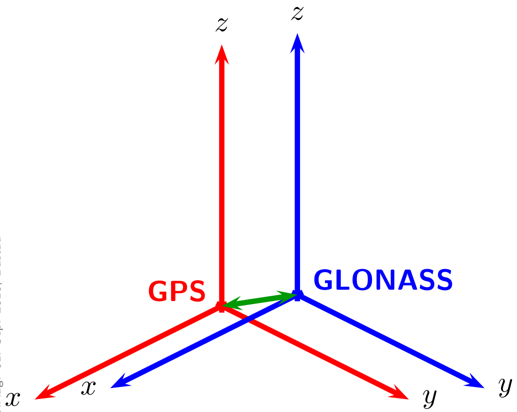

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- Vector between GPS– and GLONASS–coordinates
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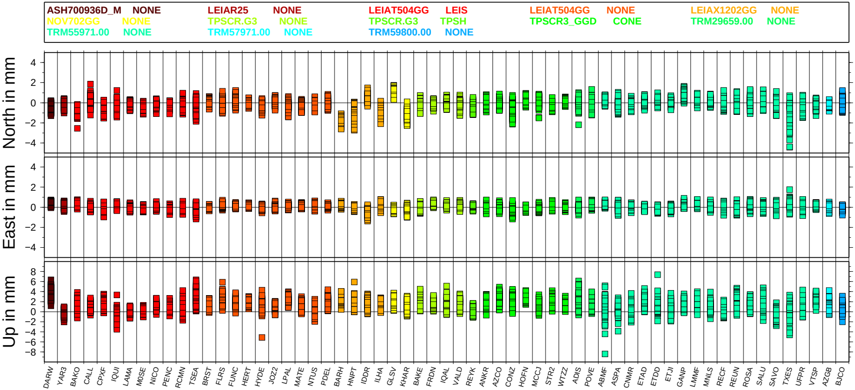
- zero–mean condition over all GPS–GLONASS–bias in xyz

GPS–GLONASS Antenna Bias: Coordinates

Differences between weekly coordinate solutions for GPS/GLONASS stations with and without estimating GLONASS-GPS translation biases:



GPS–GLONASS–Bias for the coordinates using `IGS05.atx`–antenna phase center corrections from weekly solutions of the years 2009 and 2010.

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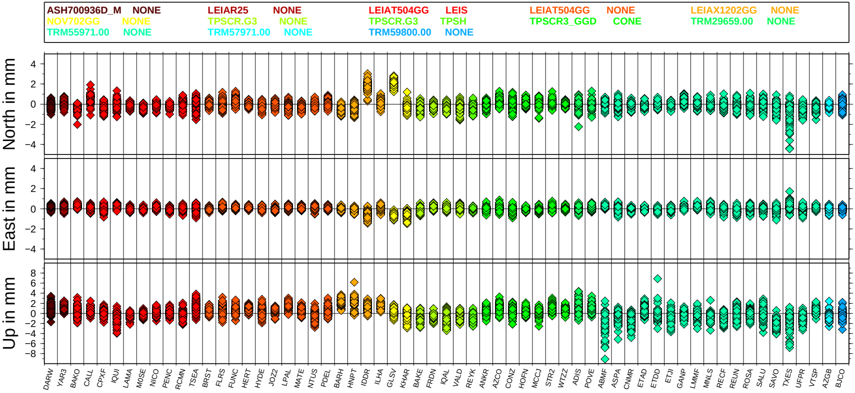

GPS–GLONASS–Bias for the coordinates using `IGS08.atx`–antenna phase center corrections from weekly solutions of the years 2009 and 2010.

GPS–GLONASS Antenna Bias: Troposphere

The troposphere GLONASS-GPS translation bias shall compensate for a potential deficiency in the GNSS-specific calibration of the antenna phase center variation.

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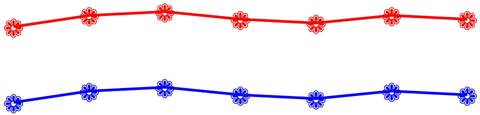

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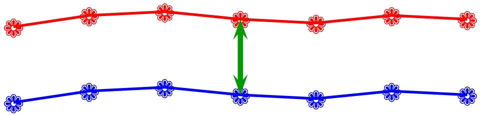

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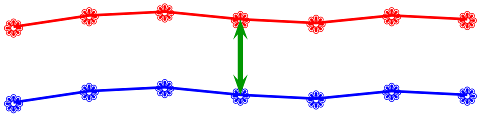
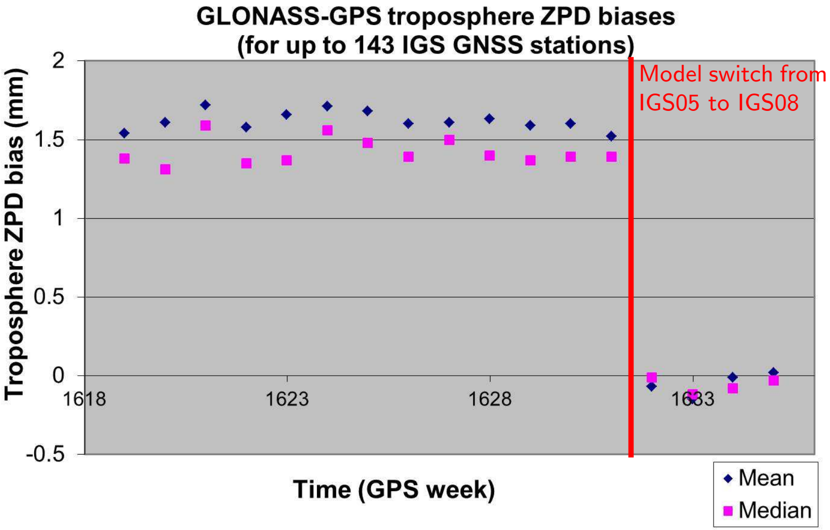


- Troposphere estimates from GPS-only
- Troposphere estimates from GLONASS-only
- Difference between GPS– and GLONASS–troposphere series
- No constraints on the GPS–GLONASS–bias are needed

GPS–GLONASS Antenna Bias: Troposphere



Inter-System Antenna Bias

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- The currently used `IGS08.atx` and `IGS14.atx` sets of corrections provide sufficient calibration for legacy GPS and GLONASS measurements.
- **The missing receiver antenna calibration values are a significant problem in the current status of multi-GNSS processing.**
- With the proposed method the influence of the deficiency on the results may be limited given that a sufficient amount of data are available.

THANK YOU
for your attention

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