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

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

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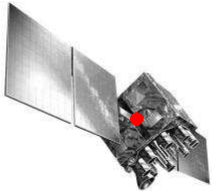

$\vec{x}^k$ position vector of satellite k related to its center of mass

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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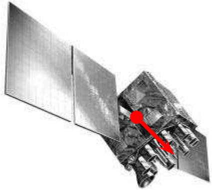

$\vec{x}^k$	position vector of satellite k related to its center of mass
$\Delta\vec{x}^k$, $\Delta\vec{\chi}^k$	vector from the center of mass of the satellite k to the antenna signal emission point for code and phase observations

Observation Equation

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

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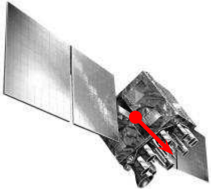

$\vec{x}^k$	position vector of satellite k related to its center of mass
$\Delta\vec{x}^k$, $\Delta\vec{\chi}^k$	vector from the center of mass of the satellite k to the antenna signal emission point for code and phase observations
δ^k	clock correction of the satellite k with respect to GPS time

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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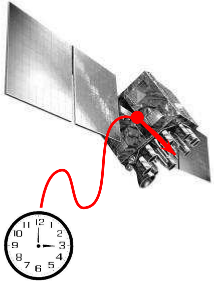

$\vec{x}^k$	position vector of satellite k related to its center of mass
$\Delta\vec{x}^k$, $\Delta\vec{\chi}^k$	vector from the center of mass of the satellite k to the antenna signal emission point for code and phase observations
δ^k	clock correction of the satellite k with respect to GPS time
a^k,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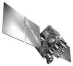

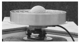

Observation Equation

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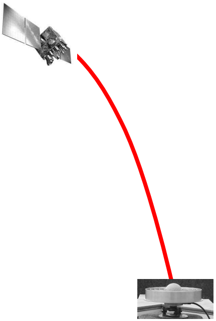

I_i^k signal delay in the ionosphere

Observation Equation

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

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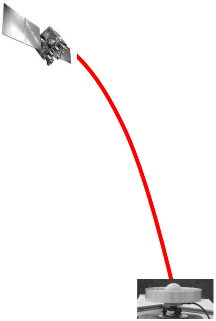

I_i^k signal delay in the ionosphere

${\color{red}T_i^k}$ 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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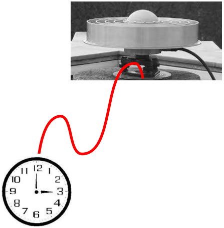

δ_i	clock correction of the receiver at the station i with respect to GPS time
a_i, α_i	hardware delay in the receiver at the station i for code and phase measurements

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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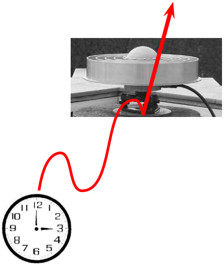

δ_i	clock correction of the receiver at the station i with respect to GPS time
a_i, α_i	hardware delay in the receiver at the station i for code and phase measurements
$\Delta\vec{x}_i$, $\Delta\vec{\chi}_i$	vector from the marker of the station i to the antenna signal reception point for code and phase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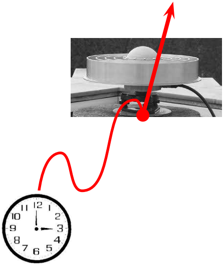

δ_i	clock correction of the receiver at the station i with respect to GPS time
a_i, α_i	hardware delay in the receiver at the station i for code and phase measurements
$\Delta\vec{x}_i$, $\Delta\vec{\chi}_i$	vector from the marker of the station i to the antenna signal reception point for code and phase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

Observation Equation

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

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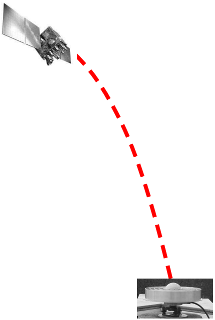

N_i^k phase ambiguity (one and the same for one pass)

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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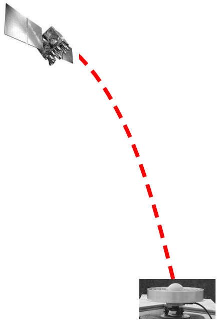

N_i^k	phase ambiguity (one and the same for one pass)
$\Delta\varphi_i^k$	initial phase shift between the oscillators at station i and satellite k

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 ...)

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:

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

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 ...)

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

R. Dach: Biases in Multi-GNSS Processing
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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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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	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$
Phase	$\Delta\vec{\chi}^k$	$\Delta\vec{\chi}_i$

Dependency of the Terms

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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	$\Delta\vec{x}^k$	$\Delta\vec{x}_i$	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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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	
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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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 . . .)					
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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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

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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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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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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

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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	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:

- **DCB: differential code bias**
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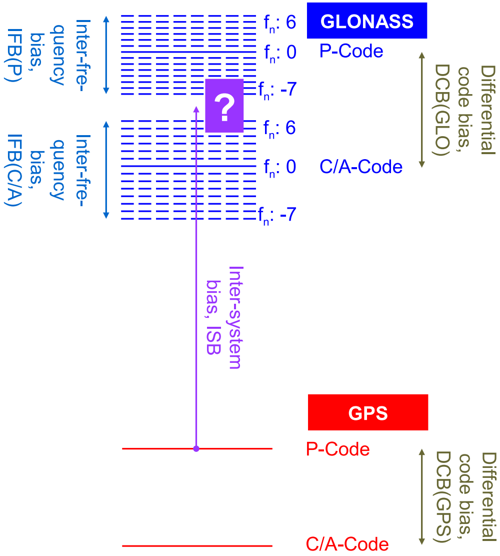
  bias at the receiver and satellite

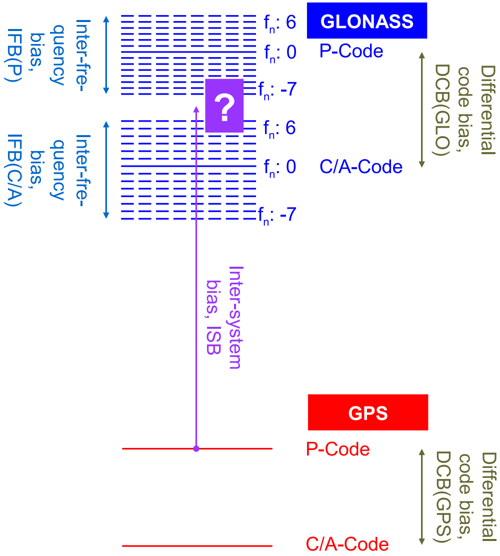
- **ISB: inter-system bias**
  different hardware delays for measurements of different GNSS
  bias only at the receiver

- **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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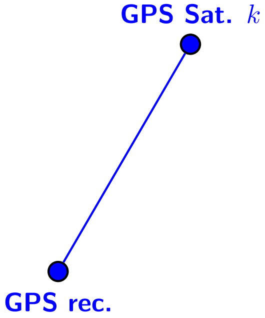

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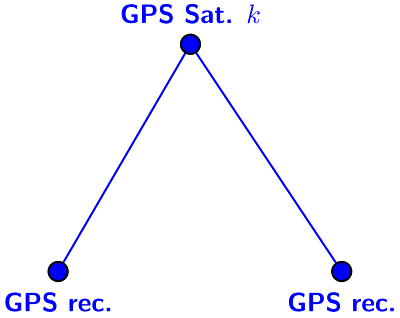

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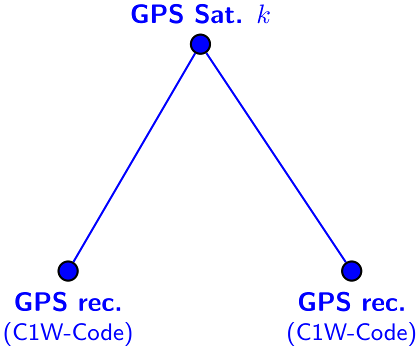

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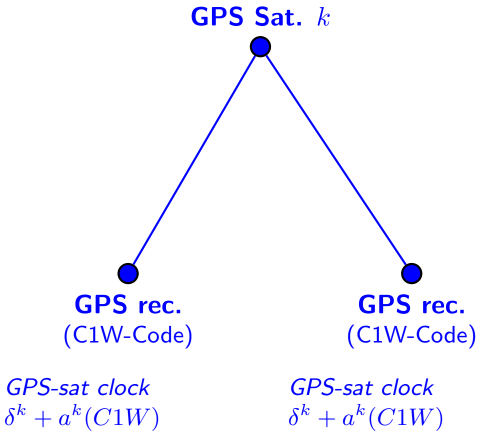

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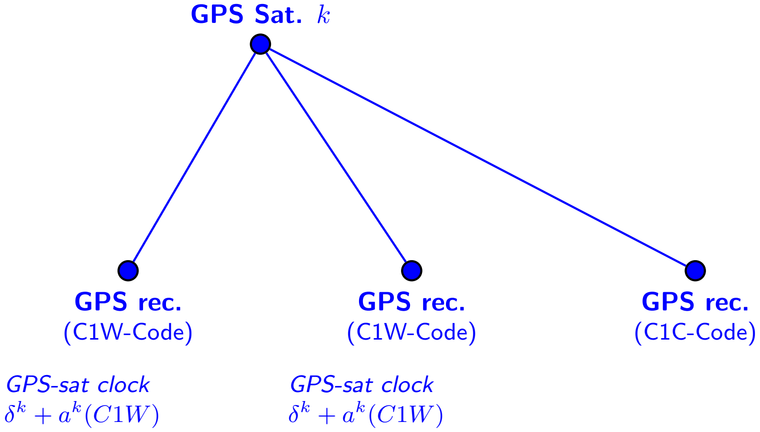

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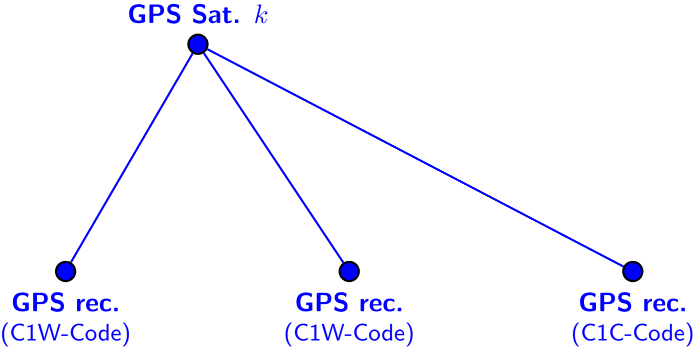
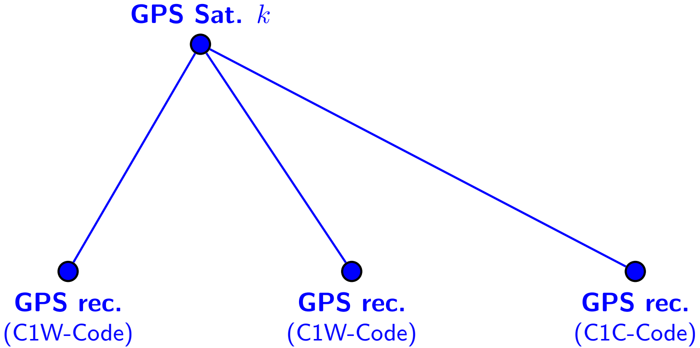


GPS-sat clock
$\delta^k + a^k(C1W)$

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

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

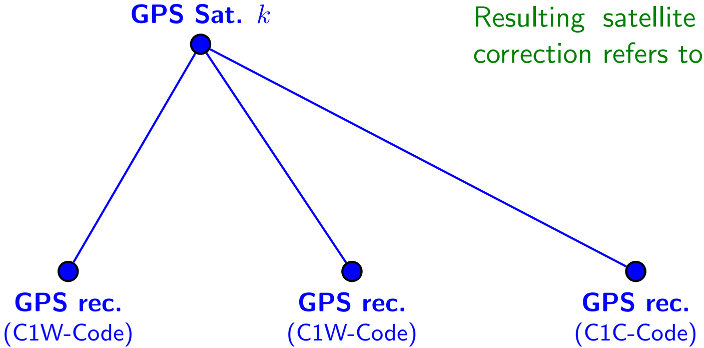
Why do we Need These Biases?



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

Why do we Need These Biases?

Resulting satellite clock correction refers to C1W



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

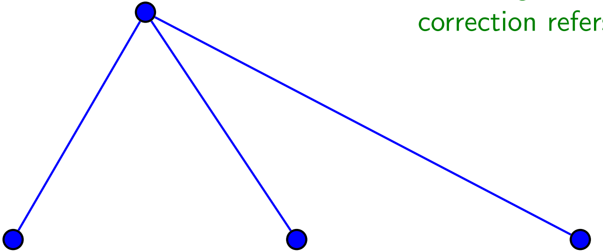
GPS-sat clock
$\delta^k + a^k(C1W)$

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

Why do we Need These Biases?

GPS Sat. k

Resulting satellite clock correction refers to C1C



GPS rec. (C1W-Code)

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

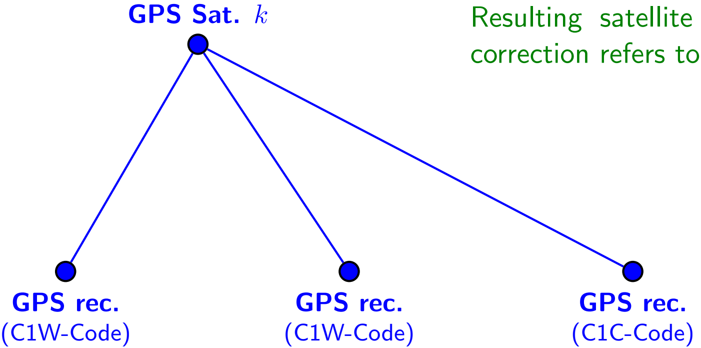
GPS rec. (C1W-Code)

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

GPS rec. (C1C-Code)

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

Why do we Need These Biases?



Resulting satellite clock correction refers to C1C

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

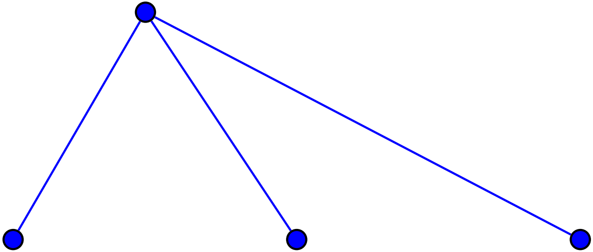
GPS-sat clock
$\delta^k + a^k(C1C)$
$+DCB^k(C1C - C1W)$

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

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. k



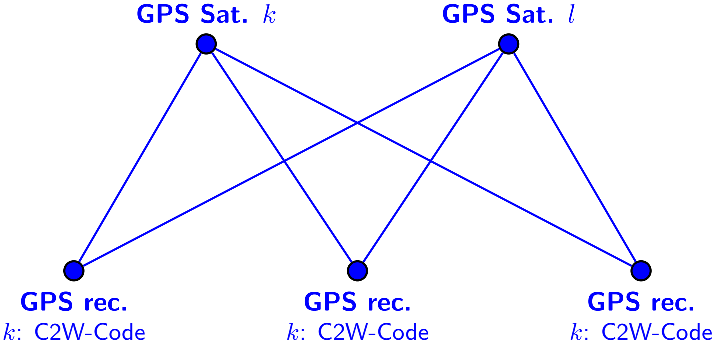
GPS rec.	**GPS rec.**	**GPS rec.**
k: C2W-Code	k: C2W-Code	k: C2W-Code

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

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

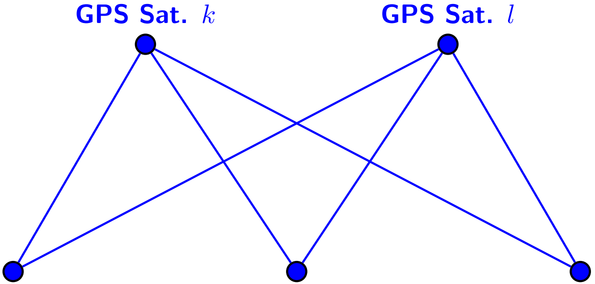
GPS-sat clock
k: $\delta^k + a^k(C2W)$

Why do we Need These Biases?



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

Why do we Need These Biases?



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

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

GPS rec.
k: C2W-Code

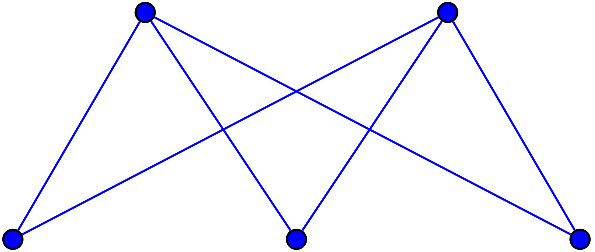
GPS-sat clock
k: $\delta^k + a^k(C2W)$

GPS rec.
k: C2W-Code

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

Why do we Need These Biases?

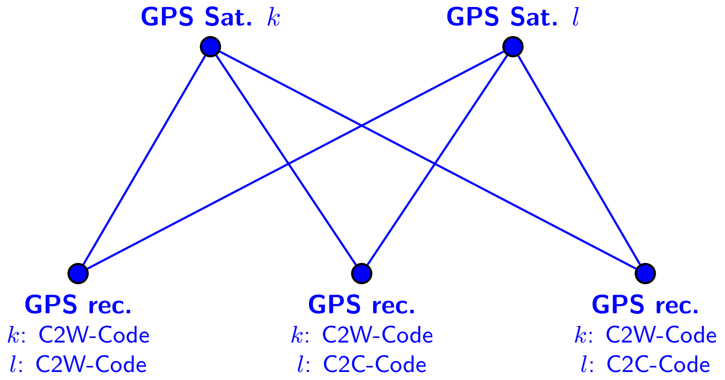
GPS Sat. k GPS Sat. l



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

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

Why do we Need These Biases?

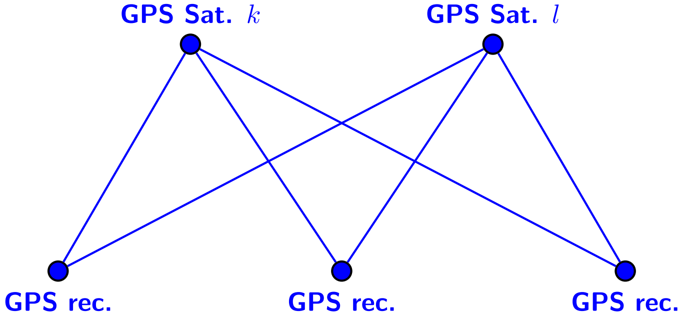


GPS-sat clock
k: $\delta^k + a^k(C2W)$
l: $\delta^l + a^l(C2W)$

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

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

Why do we Need These Biases?



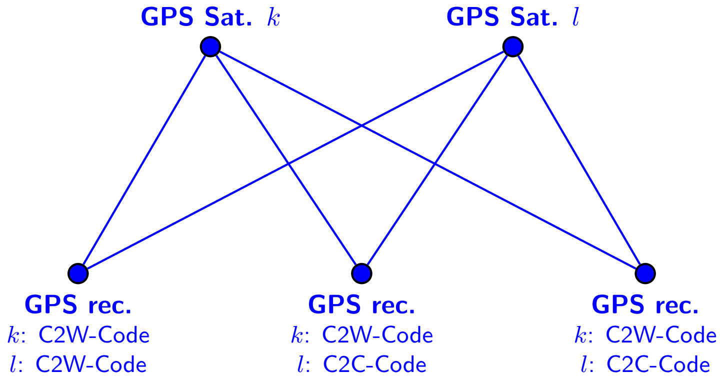
GPS rec.	GPS rec.	GPS rec.
k: C2W-Code	k: C2W-Code	k: C2W-Code
l: C2W-Code	l: C2C-Code	l: C2C-Code

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?



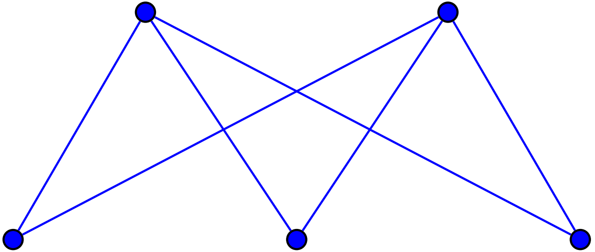
GPS-rec clock
k: $\delta_1 + a_1(C2W)$
l: $\delta_1 + a_1(C2W)$

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?

GPS Sat. k **GPS Sat. l**



GPS rec.	**GPS rec.**	**GPS rec.**
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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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

Code Biases in a GPS Network Solution

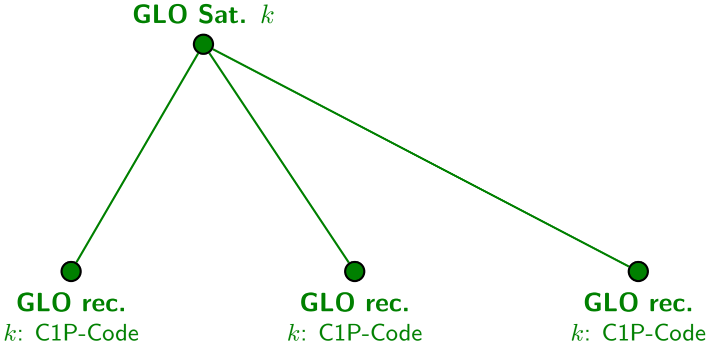
Depending on the code measurements of the individual receivers we can get:

- 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.

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

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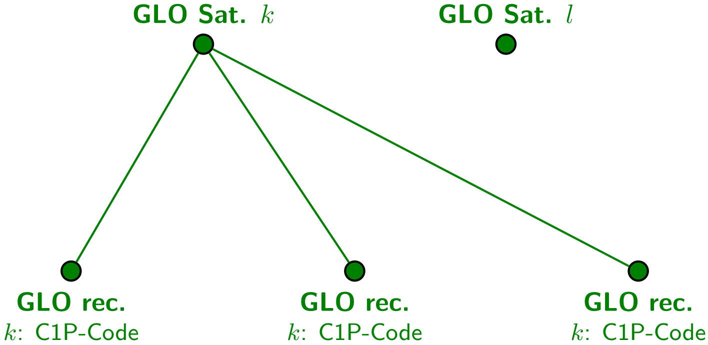

GLO-sat clock	*GLO-sat clock*	*GLO-sat clock*
k: $\delta^k + a^k(C1P)$	*k:* $\delta^k + a^k(C1P)$	*k:* $\delta^k + a^k(C1P)$

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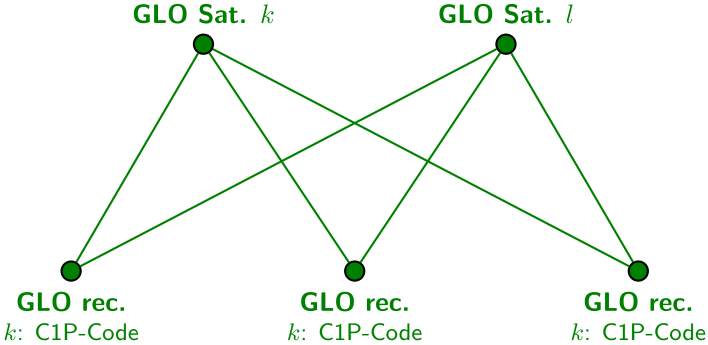
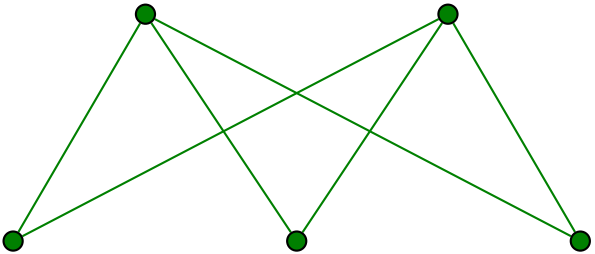


GLO-sat clock	*GLO-sat clock*	*GLO-sat clock*
k: $\delta^k + a^k(C1P)$	*k:* $\delta^k + a^k(C1P)$	*k:* $\delta^k + a^k(C1P)$

Why do we Need These Biases?

GLO Sat. k | **GLO Sat.** l



GLO rec.	**GLO rec.**	**GLO rec.**
k: C1P-Code	k: C1P-Code	k: 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: $\delta^l + a^l(C1P)$		

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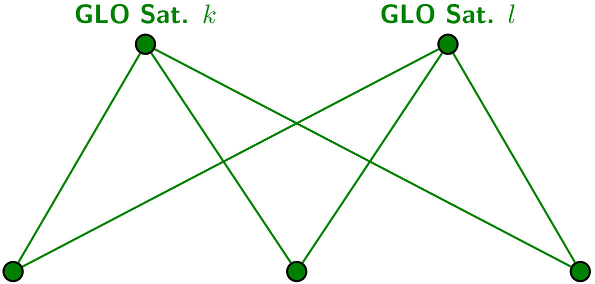

GLO rec.
k: C1P-Code
l: C1P-Code

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

GLO-sat clock
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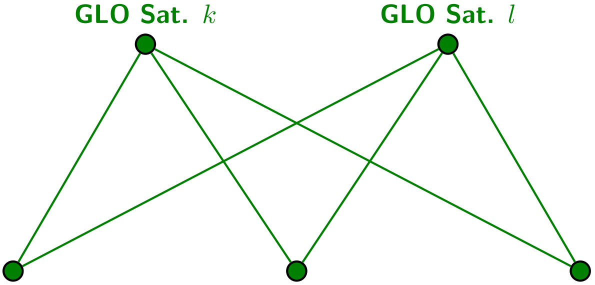

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k: $\delta^k + a^k(C1P)$
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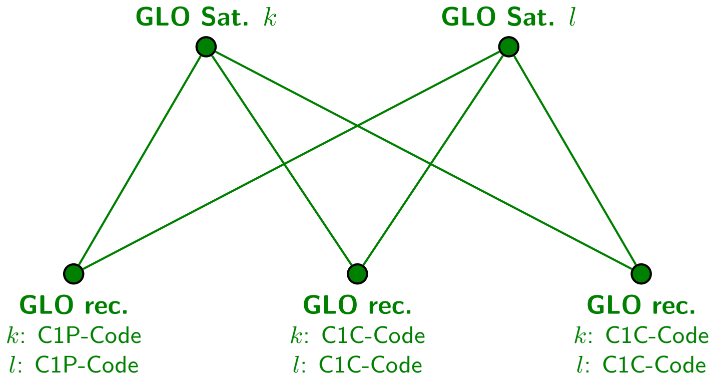
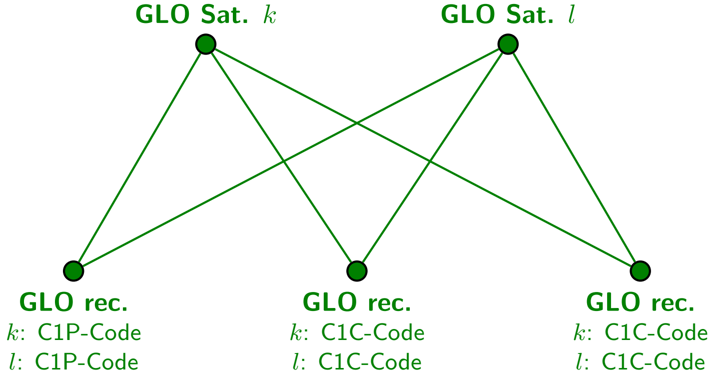


GLO-sat clock
k: $\delta^k + a^k(C1P)$
l: $\delta^l + a^l(C1P)$

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: $\delta^l + a^l(C1C)$

Why do we Need These Biases?



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

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

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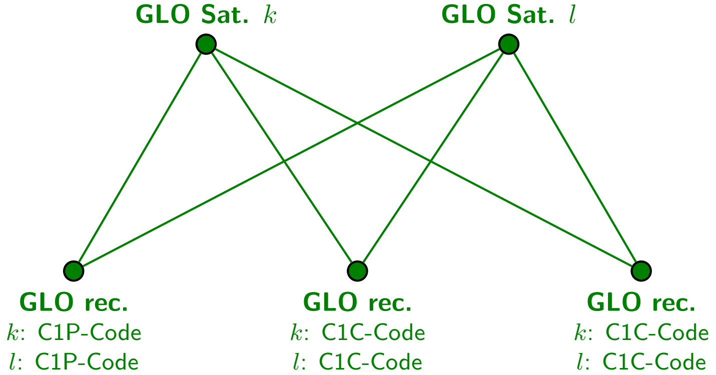
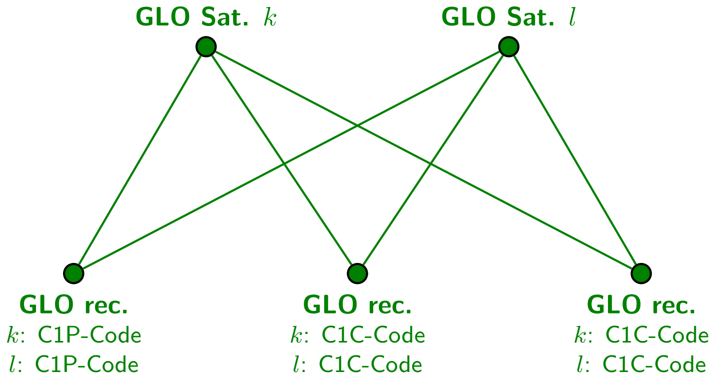


GLO-rec clock
k: $\delta_1 + a_1(C1P)$
l: $\delta_1 + a_1(C1P)$

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: $\delta_3 + a_3(C1C)$

Why do we Need These Biases?

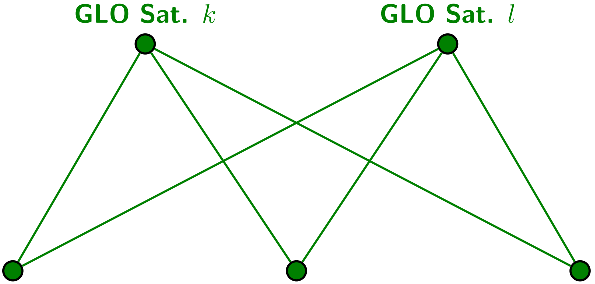


GLO-rec clock
k: $\delta_1 + a_1(C1P)^k$
l: $\delta_1 + a_1(C1P)^l$

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

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

Why do we Need These Biases?



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-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:* $\delta_3 + a_3(C1C)^l$

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

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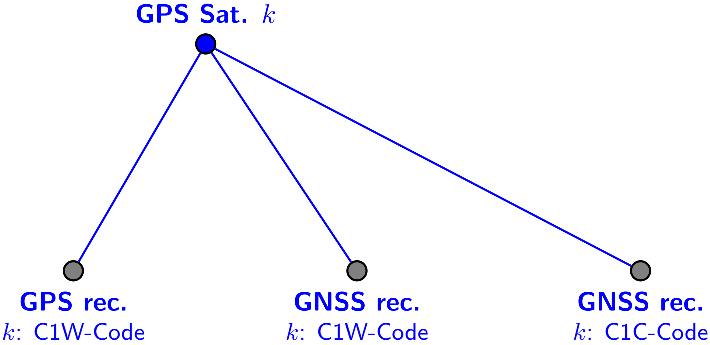
- or to estimate DCB parameters
  P1−C1 and P2−C2: Your reference clock only belongs to either the P- or C-code class – you need an additional reference for the satellite related biases.

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

Why do we Need These Biases?



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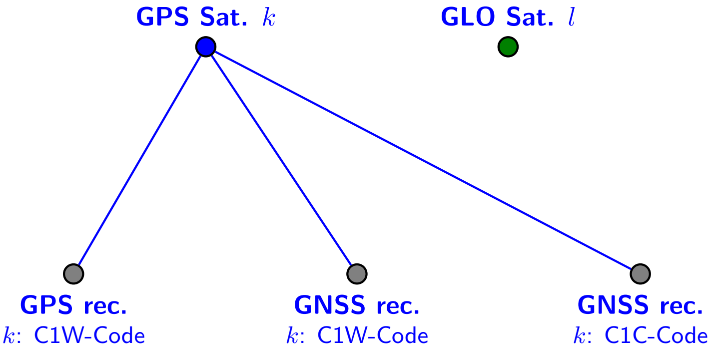

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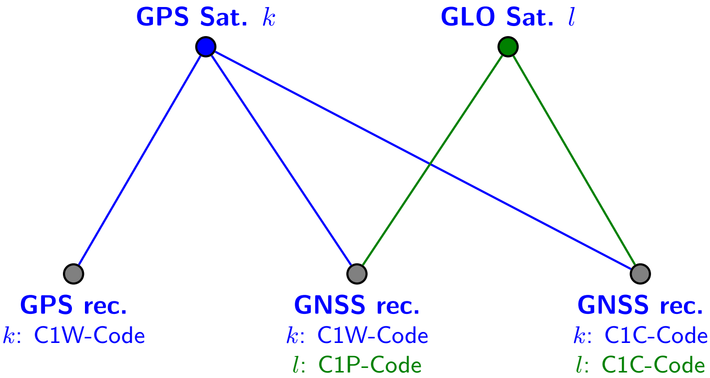

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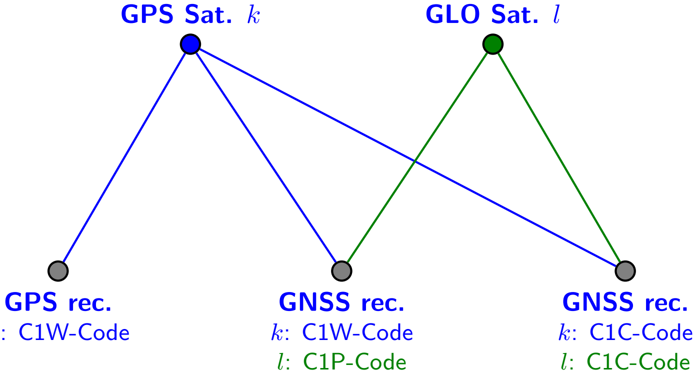
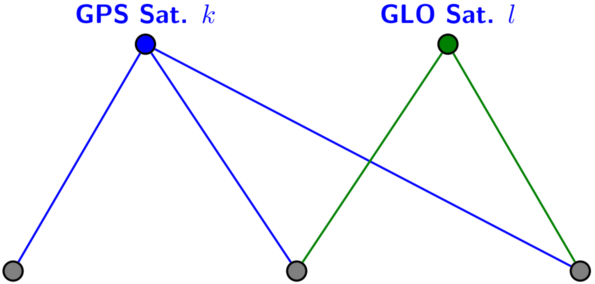


GNSS-sat clock
k: $\delta^k + a^k(C1W)$

GNSS-sat clock
k: $\delta^k + a^k(C1W)$
l: $\delta^k + a^k(C1P)$

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

Why do we Need These Biases?



GPS rec.
k: C1W-Code

GNSS rec.
k: C1W-Code
l: C1P-Code

GNSS rec.
k: C1C-Code
l: C1C-Code

GNSS-sat clock
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GNSS-sat clock
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GNSS-sat clock
k: $\delta^k + a^k(C1W) + DCB^k(C1W - C1C)$
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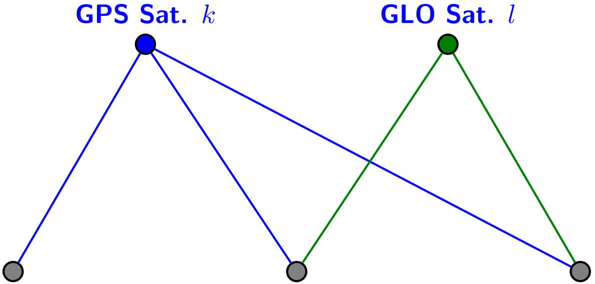
Why do we Need These Biases?



GPS rec.	GNSS rec.	GNSS rec.
k: C1W-Code	k: C1W-Code	k: C1C-Code
	l: C1P-Code	l: C1C-Code

GNSS-rec clock
k: $\delta_1 + a_1(C1W)$

GNSS-rec clock
k: $\delta_2 + a_2(C1W)^{GPS}$
l: $\delta_2 + a_2(C1P)^{GLO}$

GNSS-rec clock
k: $\delta_3 + a_3(C1C)^{GPS}$
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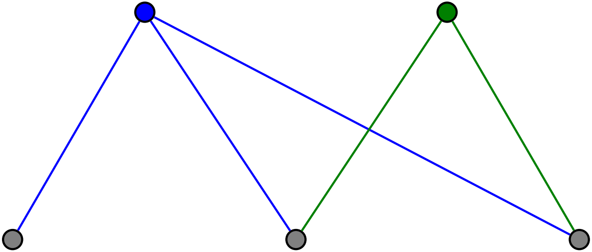
Why do we Need These Biases?

GPS Sat. k **GLO Sat.** l



GPS rec.
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l: C1C-Code

GNSS-rec clock
k: $\delta_1 + a_1(C1W)$

GNSS-rec clock
k: $\delta_2 + a_2(C1W)^{GPS}$
l: $\delta_2 + a_2(C1P)^{GPS} + ISB_2(C1P)^{GPS-GLO}$

GNSS-rec clock
k: $\delta_3 + a_3(C1C)^{GPS}$
l: $\delta_3 + a_3(C1C)^{GPS} + ISB_3(C1C)^{GPS-GLO}$

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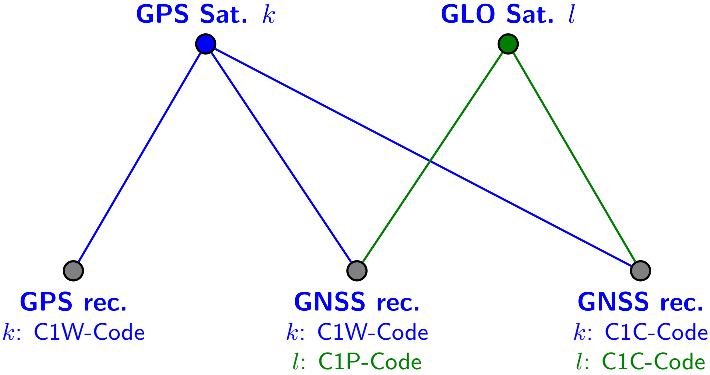

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GNSS-rec clock
k: $\delta_3 + a_3(C1C)^{GPS}$
l: $\delta_3 + a_3(C1C)^{GPS} + ISB_3(C1C)^{GPS-GLO}$

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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All these biases are hardware related (with respect to the satellites or receivers). Consequently we can only assess them as one single parameter $a_i = DCB + IFB + ISB$.

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All these biases are hardware related (with respect to the satellites or receivers). Consequently we can only assess them as one single parameter $a_i = DCB + IFB + ISB$.
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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These biases need to be considered (estimated or corrected) at any time when different types of code measurements are involved.

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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).

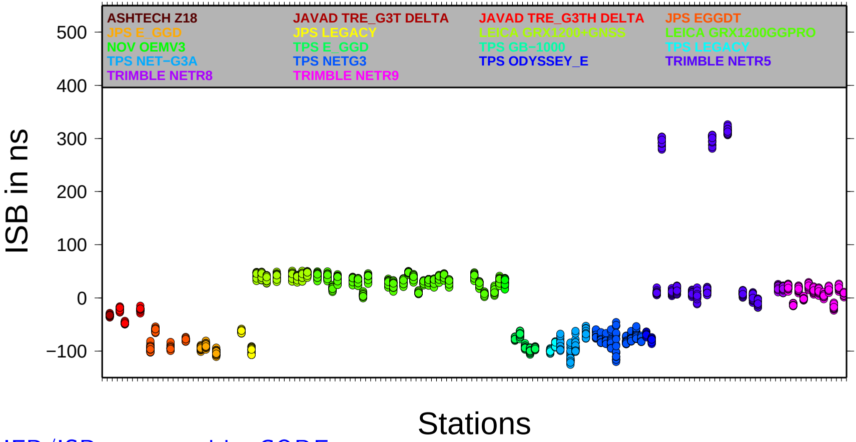
These biases need to be considered (estimated or corrected) at any time when different types of code measurements are involved.

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

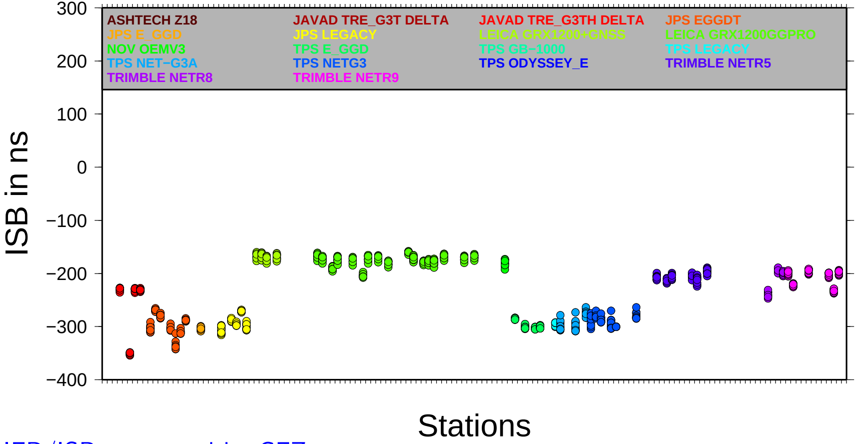


IFB/ISB computed by CODE

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

IFB/ISB Comparisons

ISB characteristic of the receivers

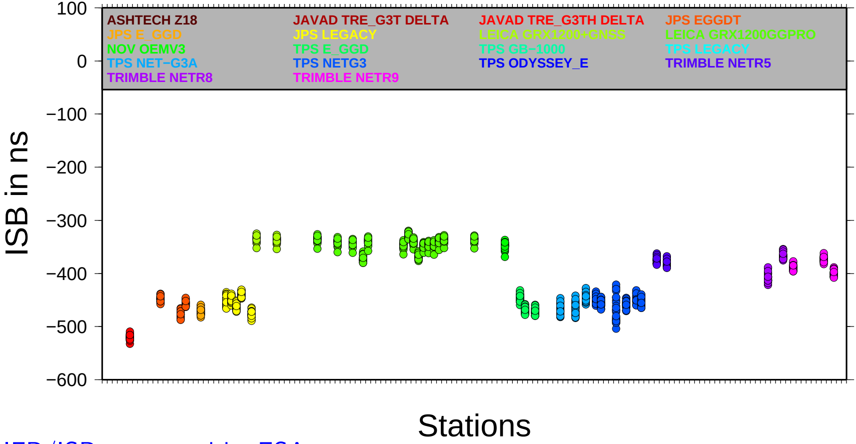


IFB/ISB computed by GFZ

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

IFB/ISB Comparisons

ISB characteristic of the receivers

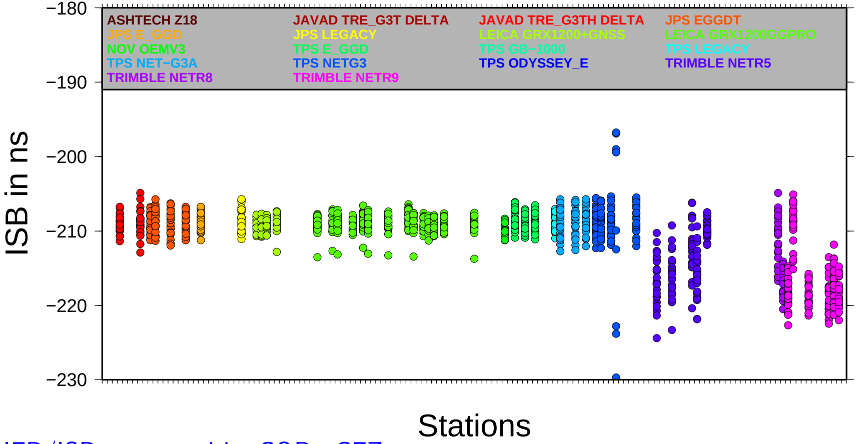


IFB/ISB computed by ESA

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

IFB/ISB Comparisons

Differences between ISB characteristic of the receivers



IFB/ISB computed by COD−GFZ

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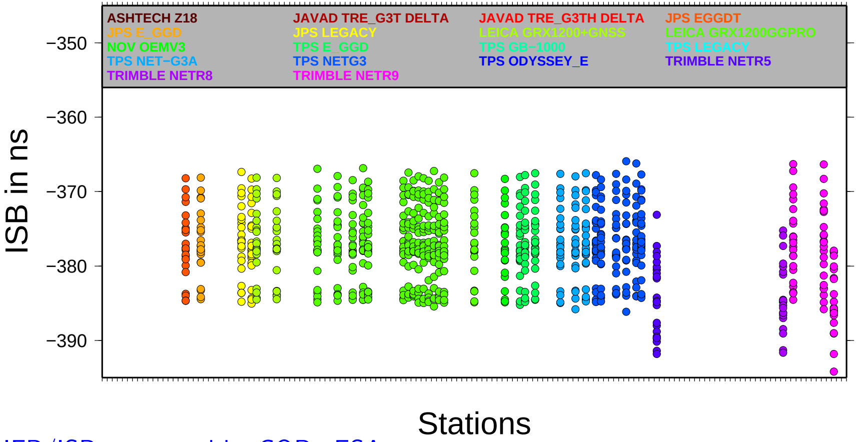
IFB/ISB Comparisons

Differences between ISB characteristic of the receivers



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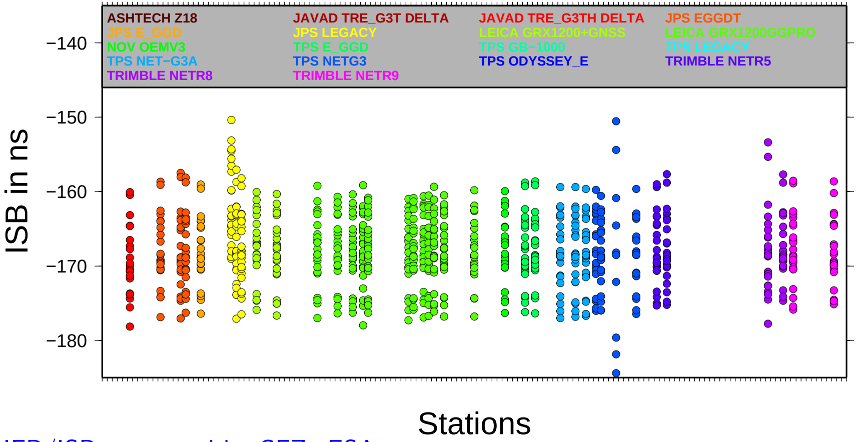

IFB/ISB computed by GFZ−ESA

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

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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- When extracting the ionosphere information by a linear combination, the differences between the hardware delays for P1 and P2 at the receiver and satellite need to be considered as an additional type of DCBs: DCB(P1-P2)

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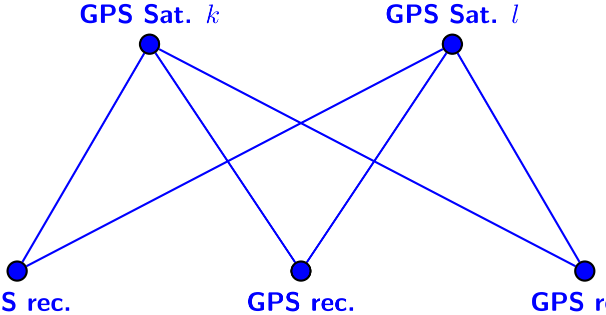
- Alternative factors need to apply when P2 or C2 is not directly tracked (e.g., cross-correlation technique).
- When extracting the ionosphere information by a linear combination, the differences between the hardware delays for P1 and P2 at the receiver and satellite need to be considered as an additional type of DCBs: DCB(P1-P2)
- With more GNSS and their new signals more groups of Code Biases will become relevant (e.g, third frequency for GPS and GLONASS).

Why do we Need These Biases?



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

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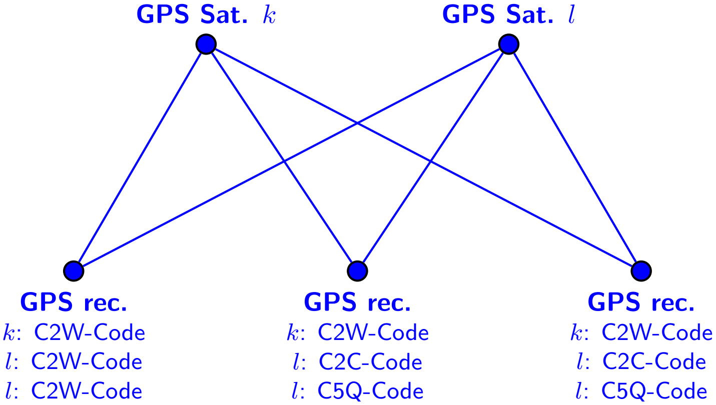

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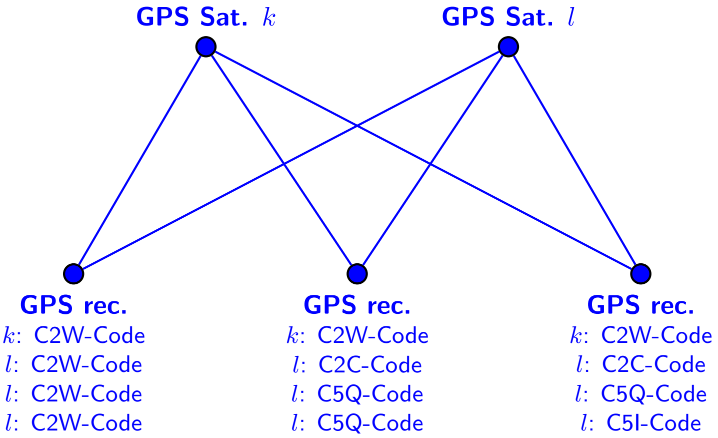

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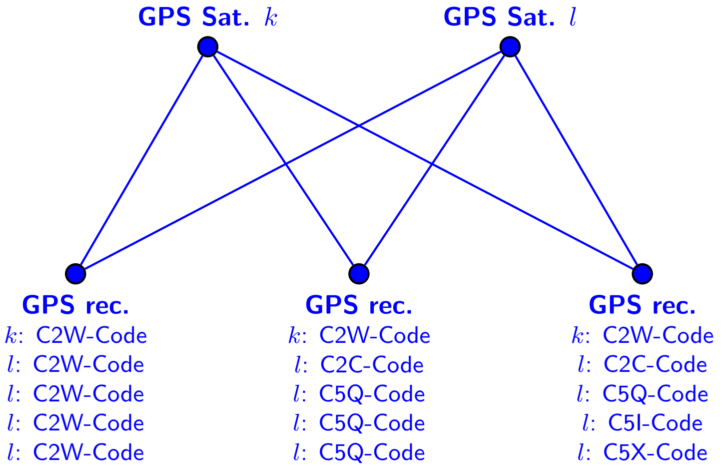
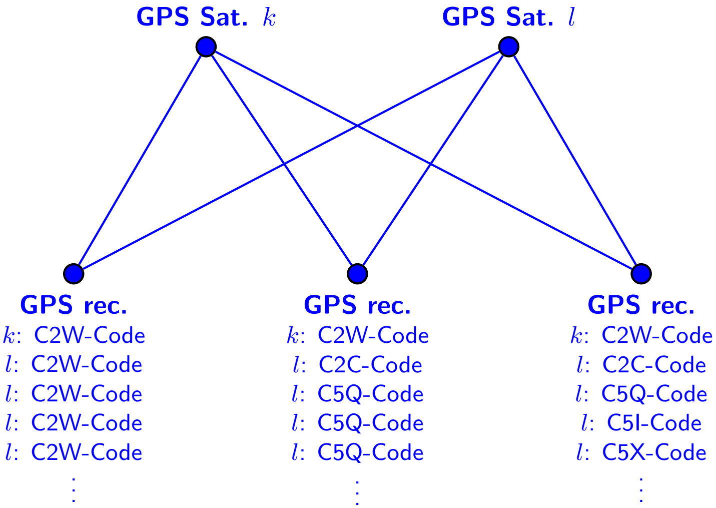


Why do we Need These Biases?



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?).

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Questions/potential problems:

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- Please be reminded that also receiver DCBs may be relevant.
- **It is urgently time to look for an alternative concept!**

Bias Handling in a Multi-GNSS Environment

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

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

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.

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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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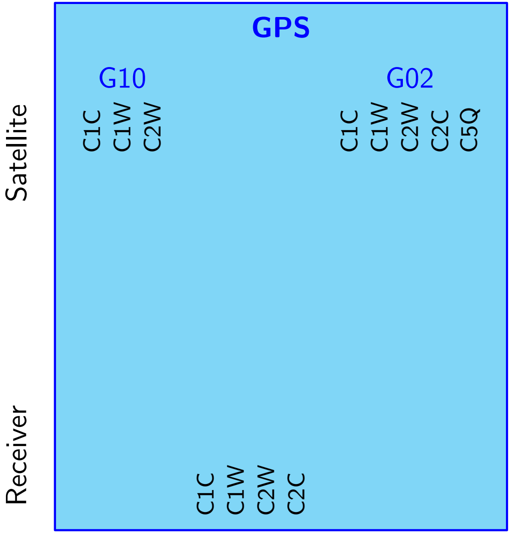
Contributions from these sources can even be combined into one system of OSB parameters.

Pseudo-Absolute Code Biases: CLK



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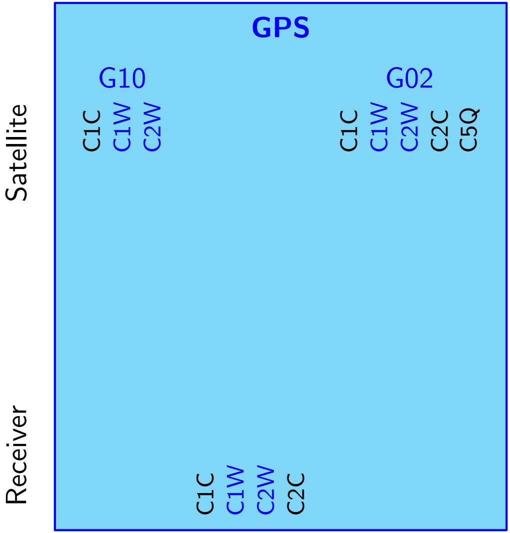

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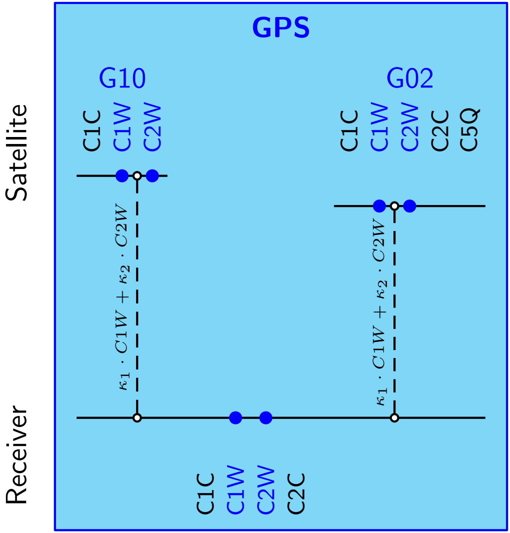

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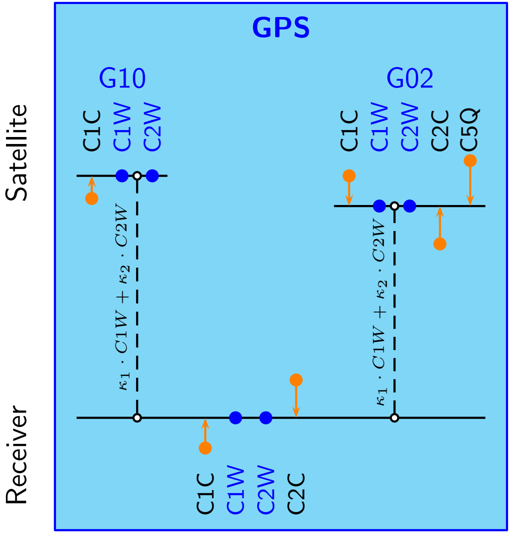

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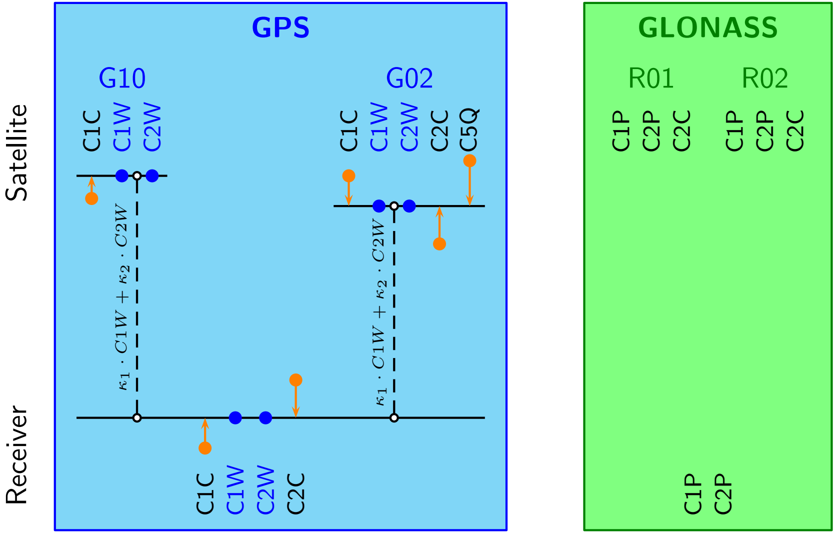

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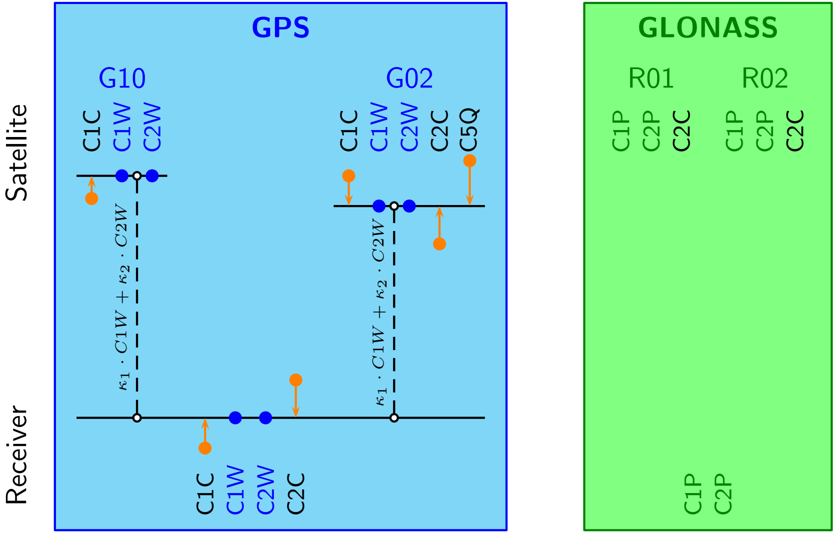

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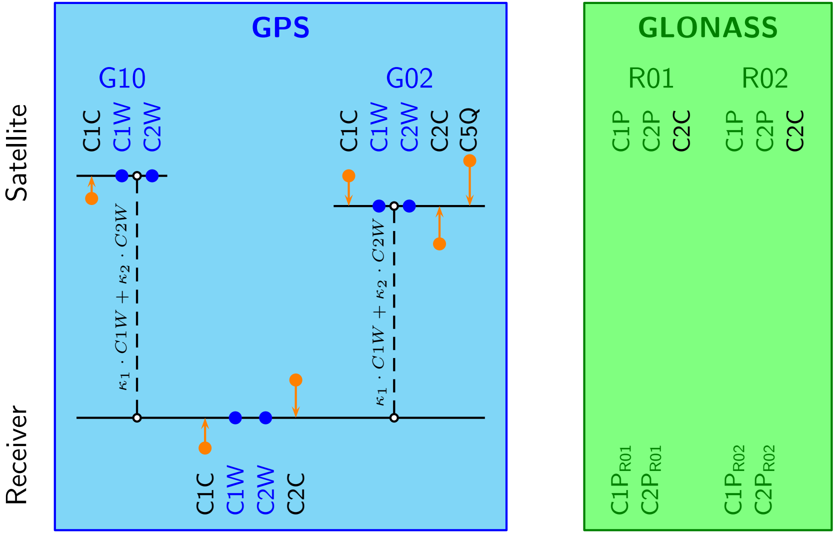

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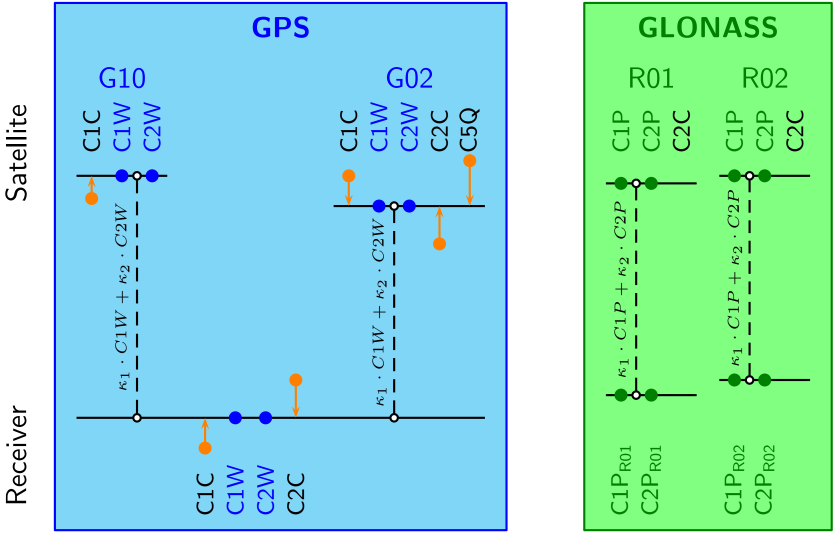

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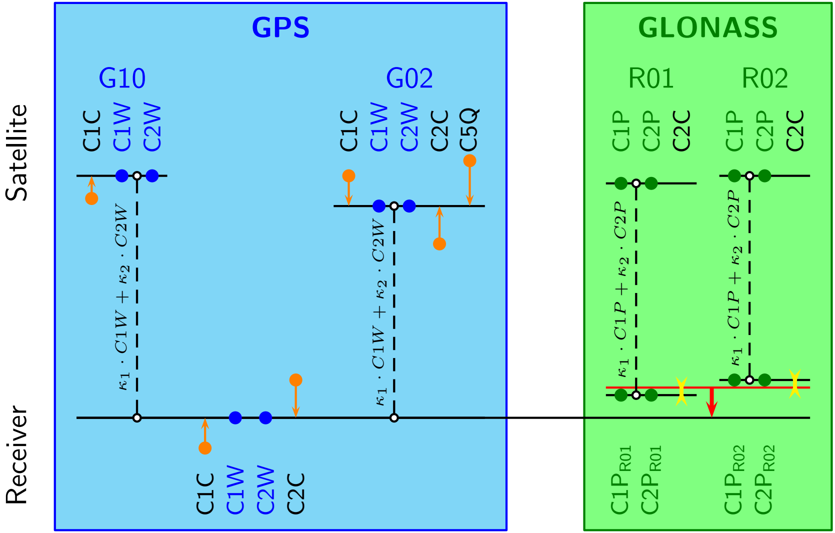

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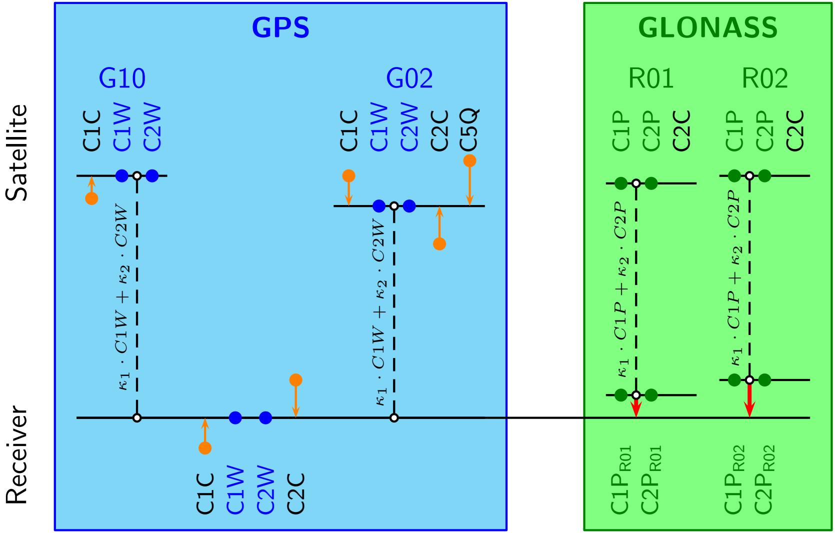

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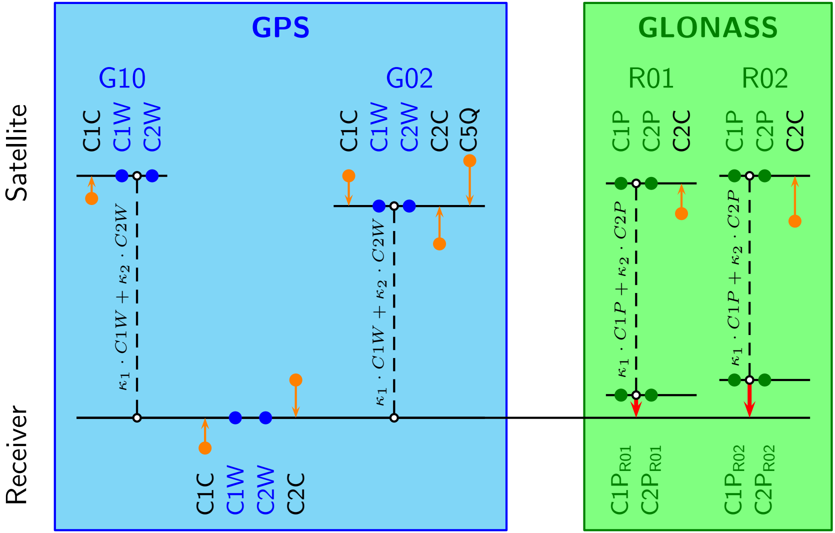
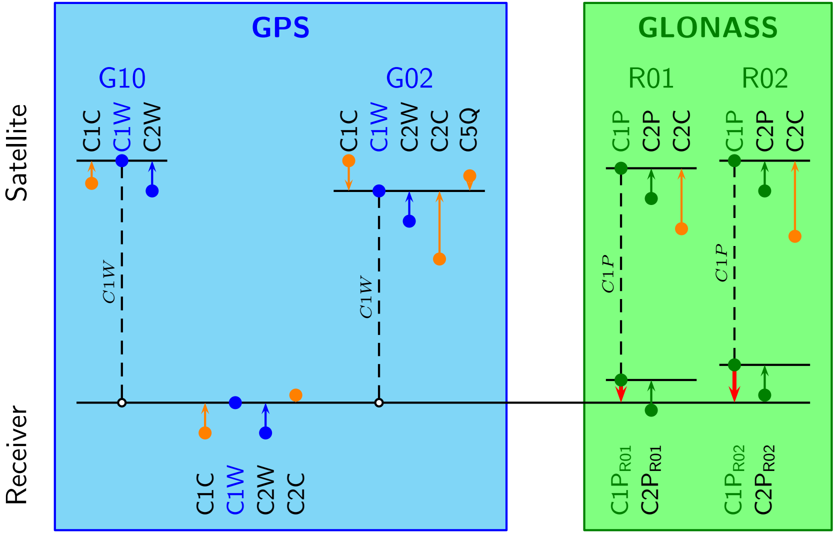
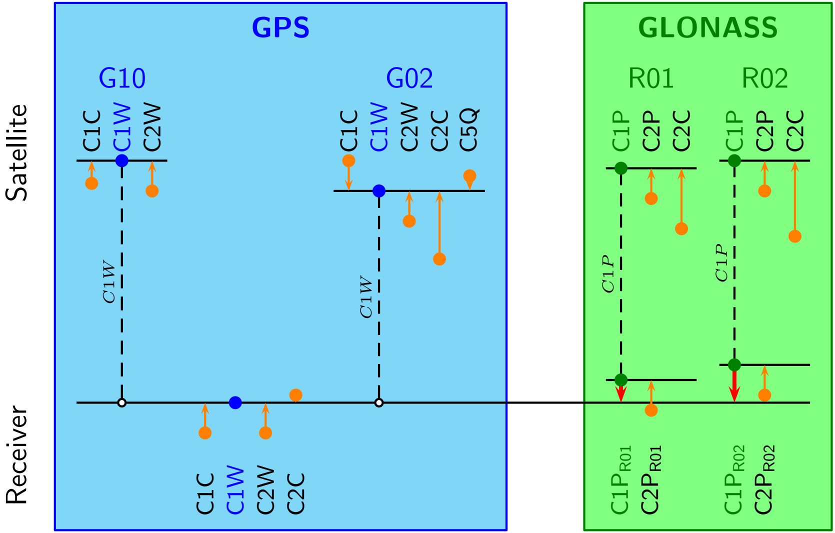


Pseudo-Absolute Code Biases: CLK+ION

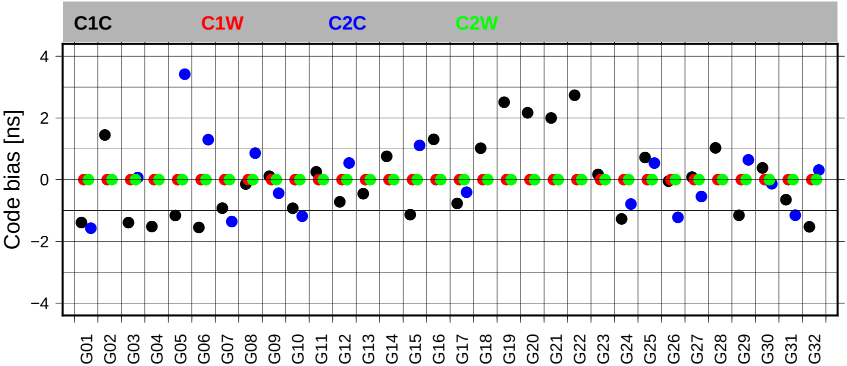


Pseudo-Absolute Code Biases: CLK+ION



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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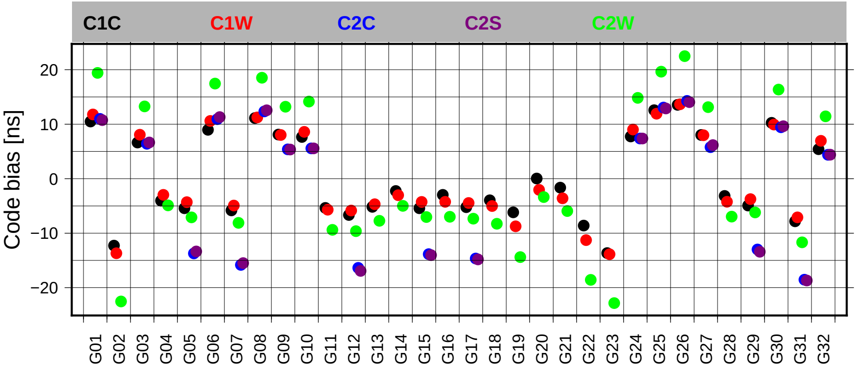

Bias solution for GPS satellites based only on CLK+ION: reference C1W

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

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Astronomical Institute, University of Bern AIUB

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Estimation of Code Biases

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

- Receiver is tracking C1W/C2W:
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- Receiver is tracking C1C/C2W:
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- Receiver is tracking C1C/C2D=L1(C/A)+(P2−P1):
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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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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

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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

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.

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

On the first view, the phase bias parameters $(\alpha_i,\ \alpha^k)$ 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

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

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

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

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

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$$+ \lambda^k \cdot N_j^k + \lambda^k \cdot (\varphi^k(t_0) - \varphi_j(t_0))$$

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

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

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

Forming Differences

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$$+ T_i^k - T_j^k - (I_i^k - I_j^k) - c \cdot (\delta_i - \delta_j - \alpha_i + \alpha_j)$$
$$+ \lambda^k \cdot (N_i^k - N_j^k) - \lambda^k \cdot (\varphi_i(t_0) - \varphi_j(t_0))$$

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

Double differences between two satellites and receivers result in:

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

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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$$- \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_i + \Delta\vec{\chi}_i)\right| + \left|(\vec{x}^l + \Delta\vec{\chi}^l) - (\vec{x}_j + \Delta\vec{\chi}_j)\right|$$
$$+ T_i^k - T_j^k - T_i^l + T_j^l - (I_i^k - I_j^k - I_i^l + I_j^l)$$
$$+ \lambda \cdot (N_i^k - N_j^k - N_i^l + N_j^l)$$

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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  Doubts in the consistency are recommended if
  - the two satellites belong to different GNSS (even if they are using the same frequency: L1 and L5 for GPS and Galileo) because of a potential **Inter-system bias (ISB)**

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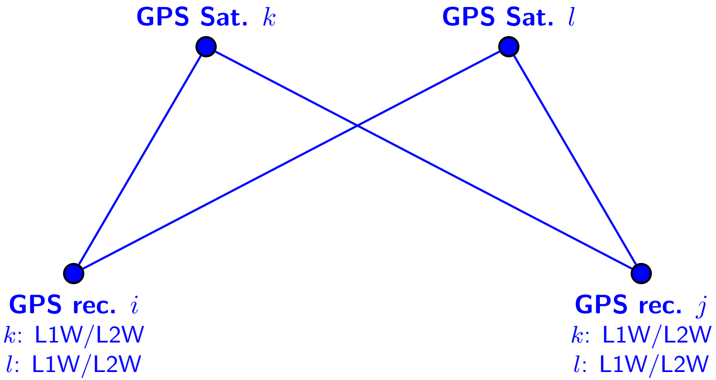
  - the two satellites belong to different GNSS (even if they are using the same frequency: L1 and L5 for GPS and Galileo) because of a potential **Inter-system bias (ISB)**
  - the signals are received on different frequencies because different hardware delays are expected (**Inter-frequency bias, IFB**) (alternatively, the IFB may be calibrated and corrected, e.g., for GLONASS ambiguity resolution).

Compatibility of Phase-Related Hardware Delay



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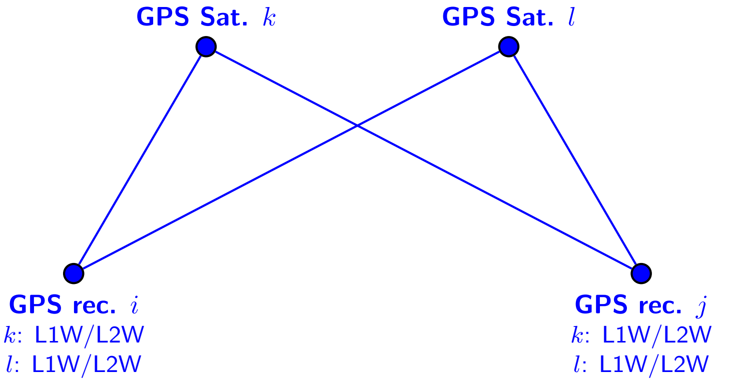
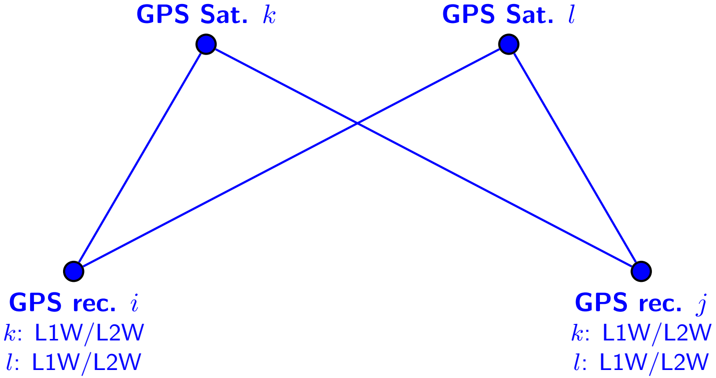


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

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

Compatibility of Phase-Related Hardware Delay

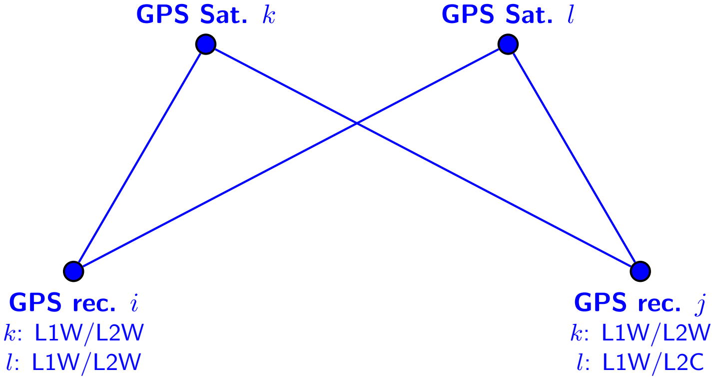


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

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

ambiguity resolution possible

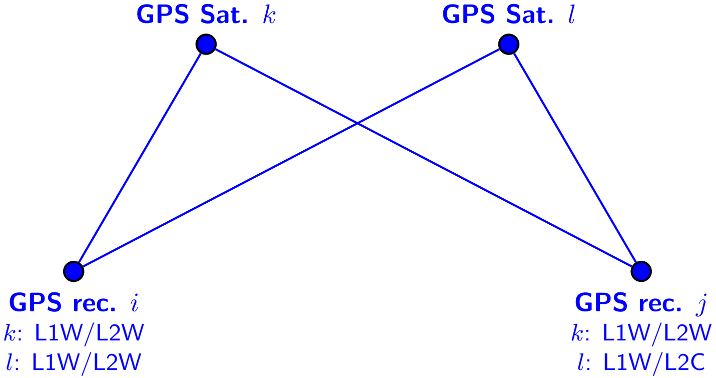
Compatibility of Phase-Related Hardware Delay



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

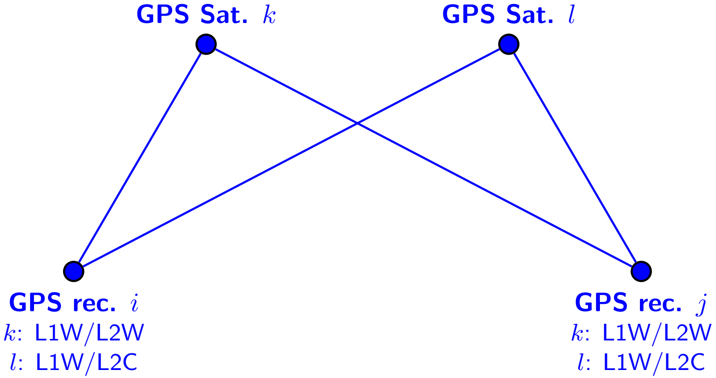


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

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

"quarter cycle problem" – no resolution

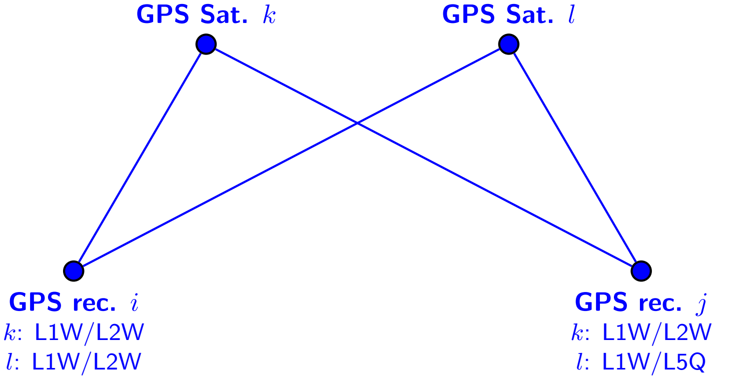
Compatibility of Phase-Related Hardware Delay



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

ambiguity resolution possible

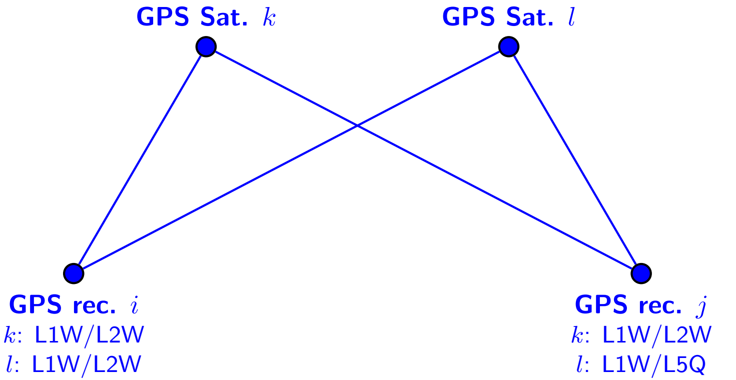
Compatibility of Phase-Related Hardware Delay



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

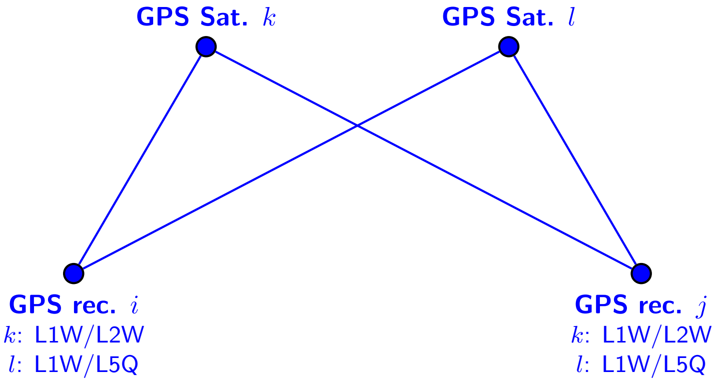


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

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

Incompatible – no resolution

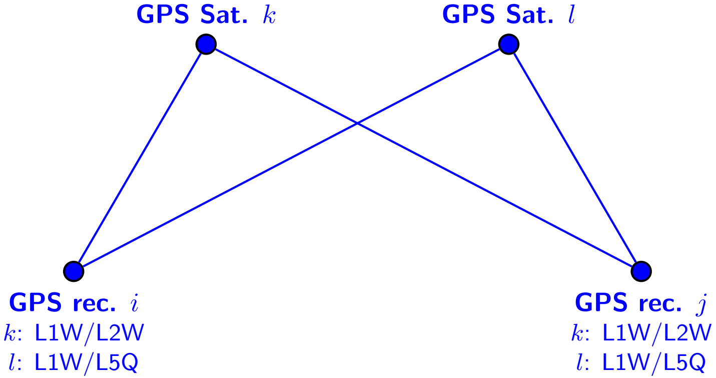
Compatibility of Phase-Related Hardware Delay



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

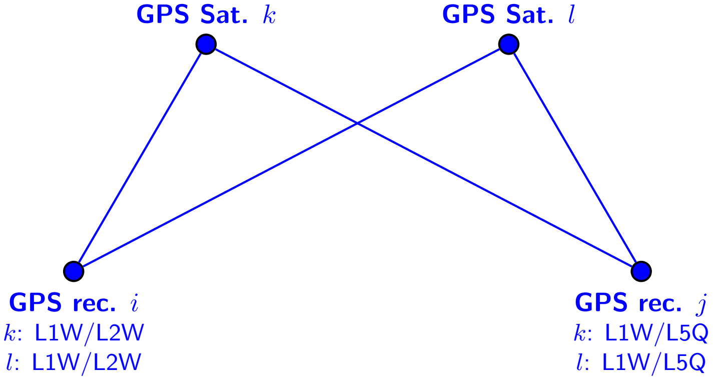


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L5Q)$

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: $\alpha_i(L1W)$ $\alpha_i(L2W)$
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k: $\alpha_j(L1W)$ $\alpha_j(L5Q)$
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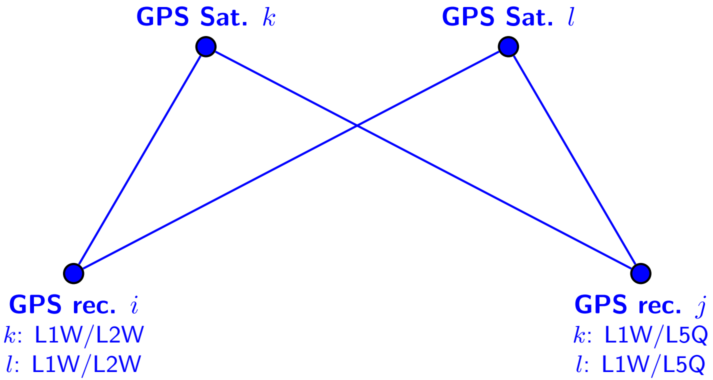
Compatibility of Phase-Related Hardware Delay

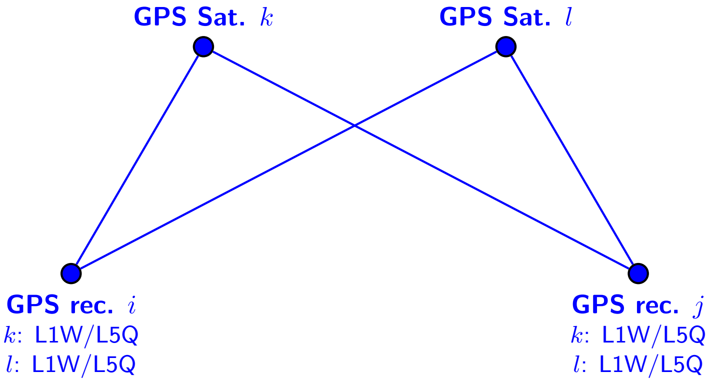


k: $\alpha_i(L1W)$ $\alpha_i(L2W)$
l: $\alpha_i(L1W)$ $\alpha_i(L2W)$

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

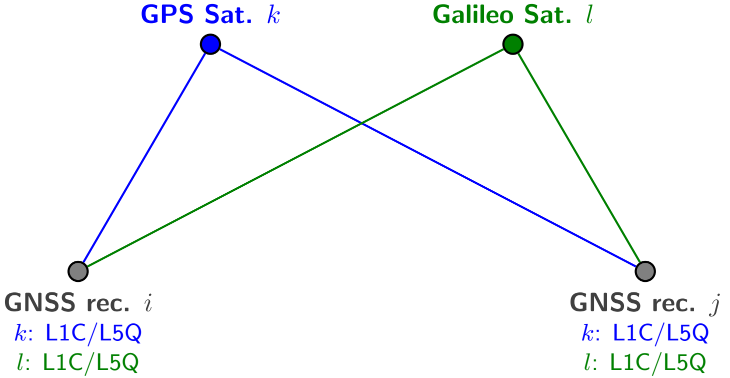


k: $\alpha_i(L1W) \quad \alpha_i(L5Q)$
l: $\alpha_i(L1W) \quad \alpha_i(L5Q)$

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

ambiguity resolution possible

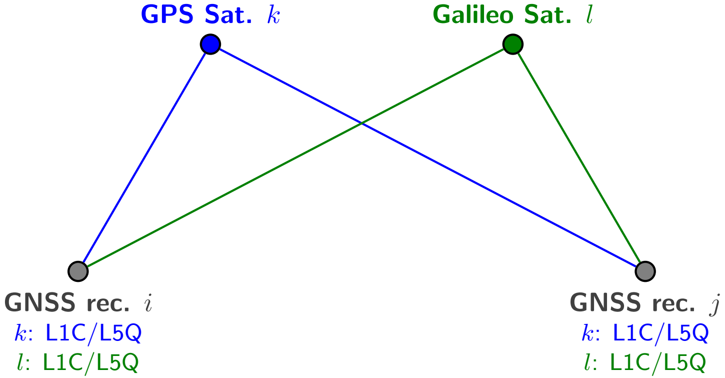
Compatibility of Phase-Related Hardware Delay



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

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

Compatibility of Phase-Related Hardware Delay



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

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

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

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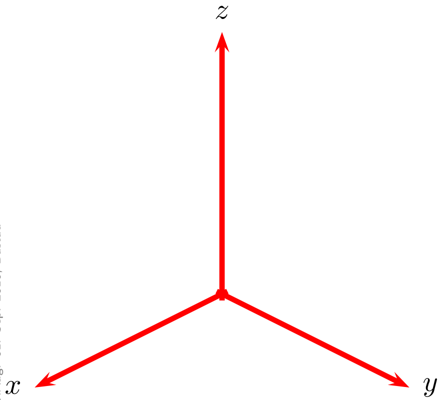
- A related bias parameter was implemented for a background test solution at the CODE analysis center in early 2011.

GPS–GLONASS Antenna Bias: Coordinates



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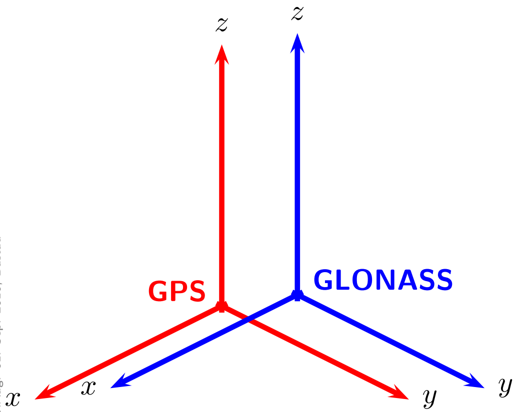

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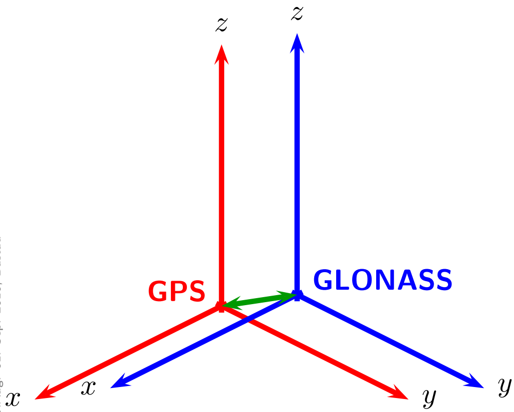

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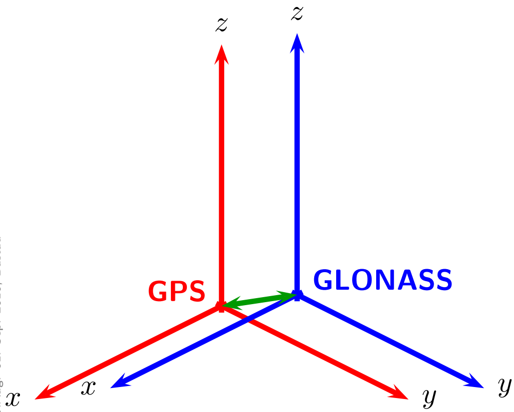

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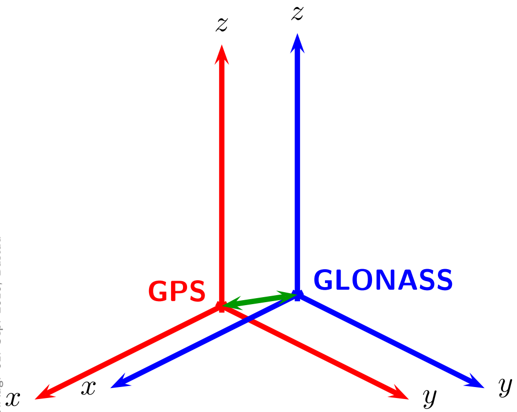

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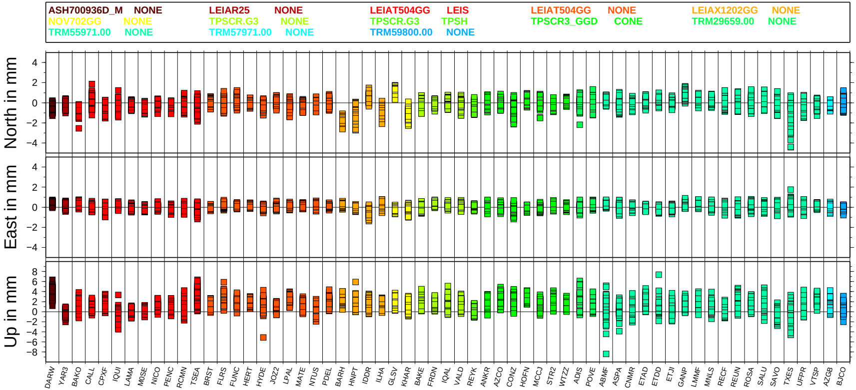
GPS–GLONASS Antenna Bias: Coordinates

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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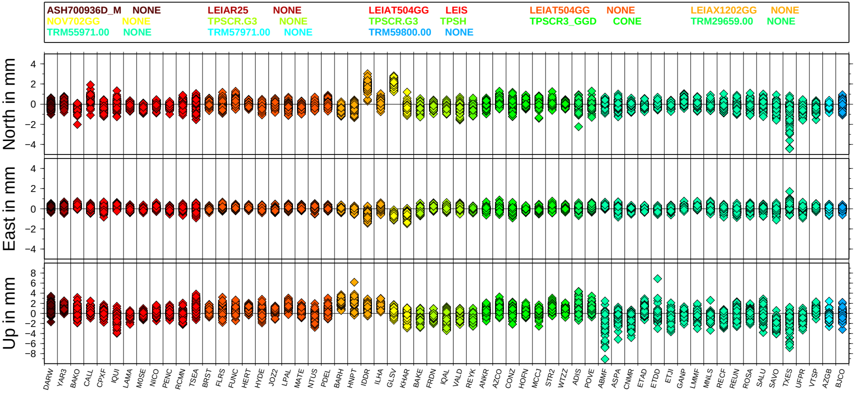

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GPS–GLONASS Antenna Bias: Troposphere

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R. Dach: Biases in Multi-GNSS Processing
NGK Summer School, 29.Aug.–01. Sep. 2016, Båstad

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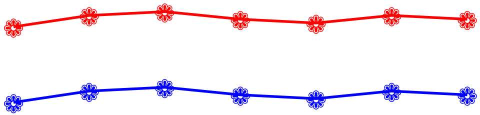

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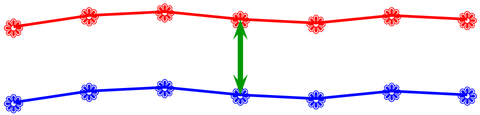

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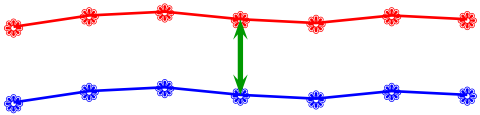

- Troposphere estimates from GPS-only
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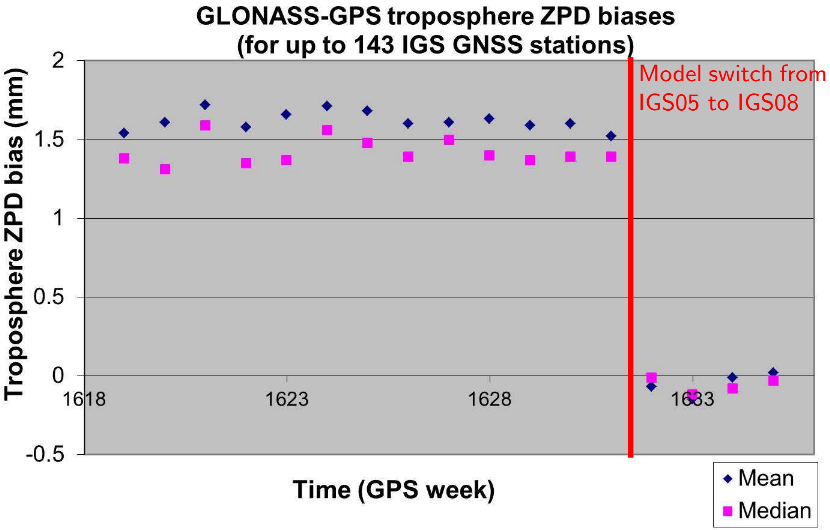
- Difference between GPS– and GLONASS–troposphere series
- No constraints on the GPS–GLONASS–bias are needed

GPS–GLONASS Antenna Bias: Troposphere



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- **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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