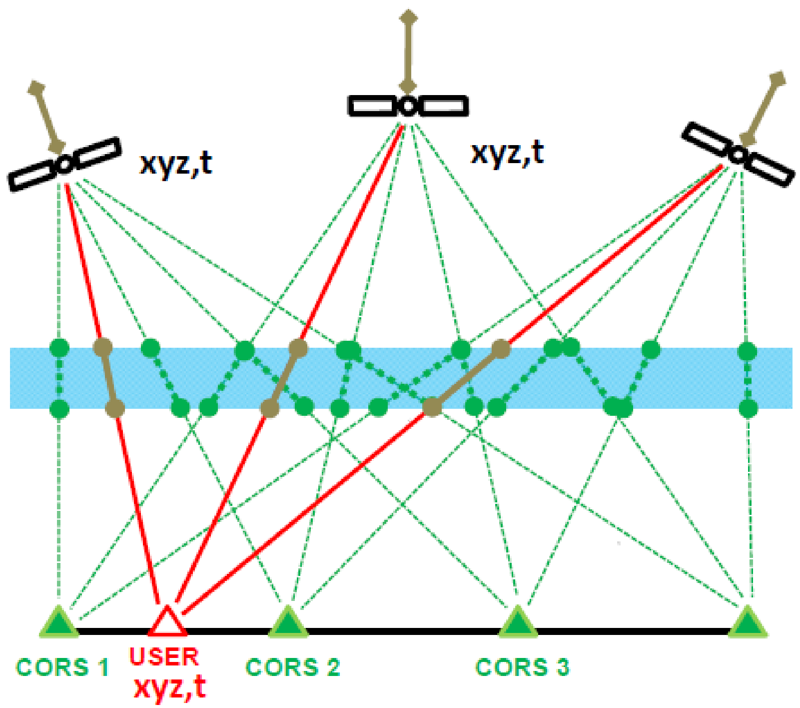





PPP-RTK:

Multi-GNSS with Mixed Receivers

(Peter Teunisen)





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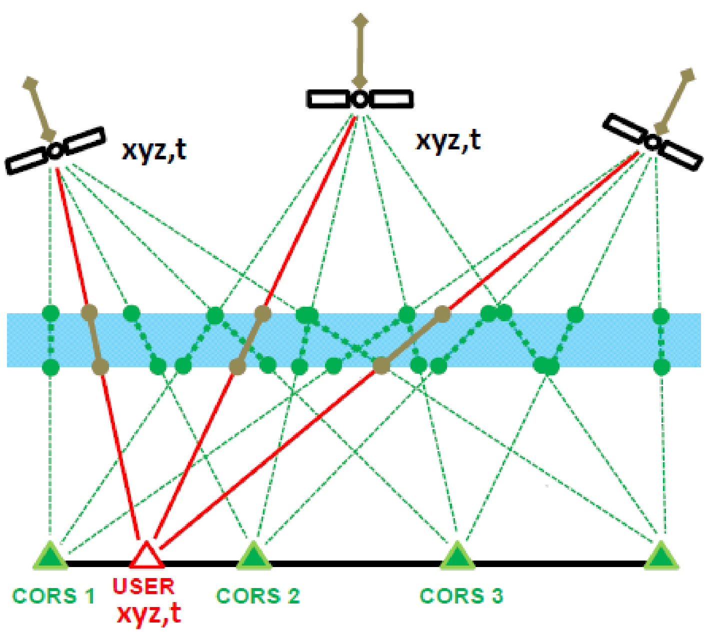

PPP-RTK Corrections:

- Orbits
- Satellite clock
- Satellite phase bias
- Ionospheric delays

Orbits, Satellite clock: PPP

Orbits, Satellite clock, Satellite phase bias: PPP-AR

Orbits, Satellite clock, Satellite phase bias, Ionospheric delays: PPP-RTK

PPP-RTK:

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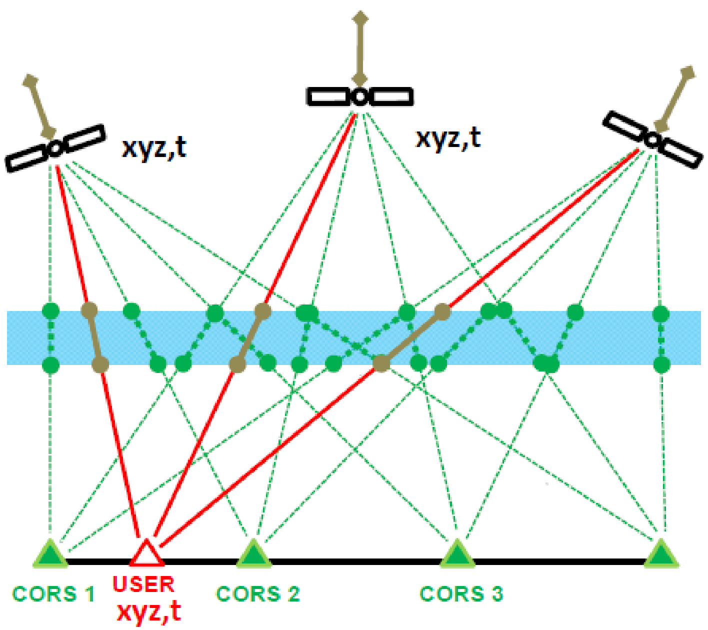
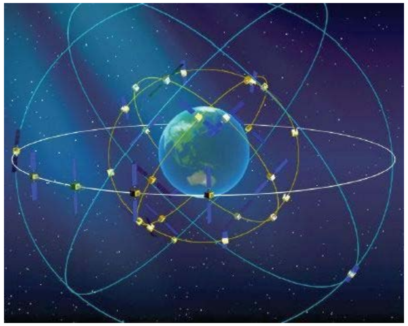


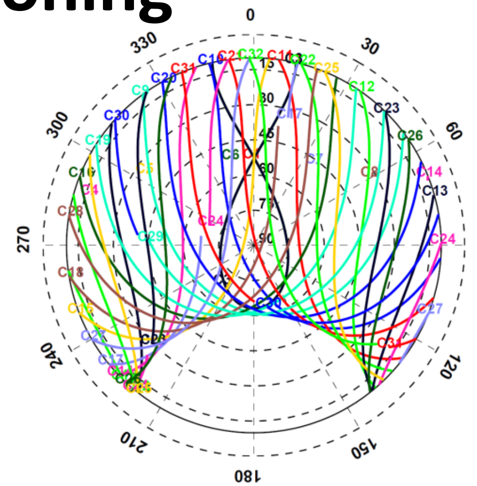
Mixed-receiver precise positioning

Mixed-Receiver BeiDou Positioning



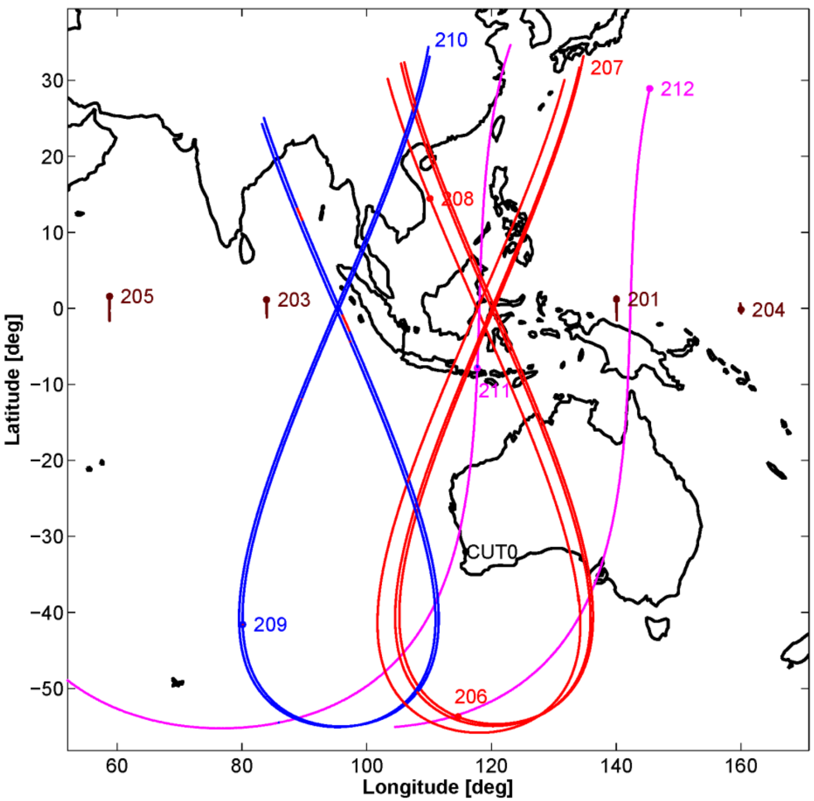
BeiDou 2020:

5 GEO, 3 IGSO, 27 MEO



(c) Skyplot (BeiDou)

Constellation used for positioning:



BeiDou 2013:

5 GEO, 5 IGSO, 4 MEO

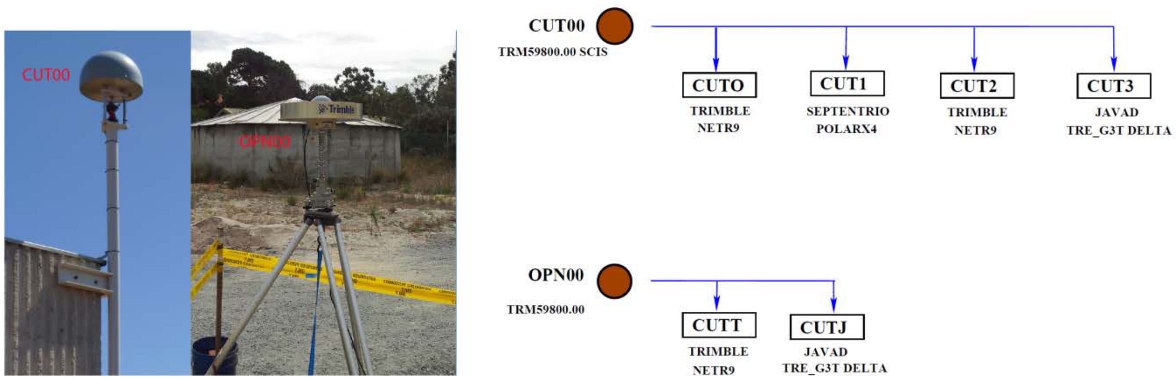
B1:	1561.098 MHz	19.20 cm
B2:	1207.140 MHz	24.83 cm
B3:	1268.520 MHz	23.63 cm

Compare to GPS:

L1:	1575.420 MHz	19.03 cm
L2:	1227.600 MHz	24.42 cm
L5:	1176.450 MHz	25.48 cm

Mixed-receiver BeiDou RTK Positioning

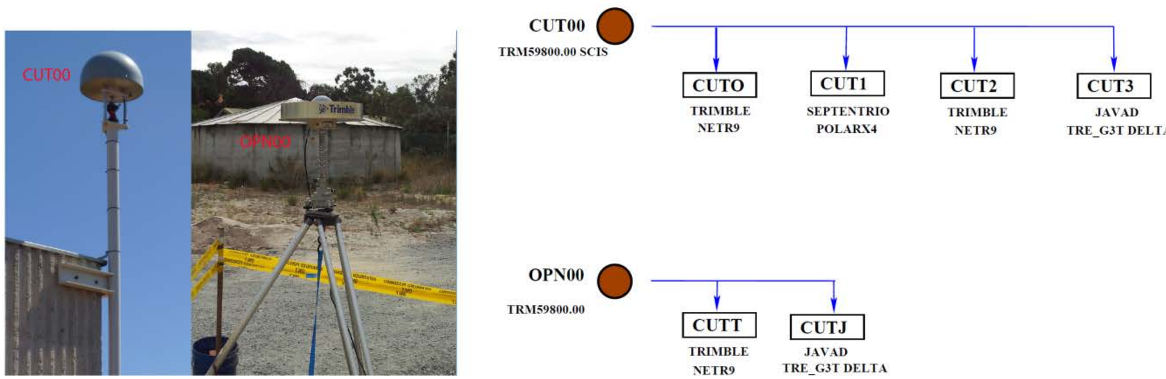
[Receivers A-B-C]



(a) Antenna setup (b) Receiver-antenna connectivity

Figure 1. Curtin GNSS antennas and receivers used for the 1 km baseline experiment

Mixed-receiver BeiDou RTK Positioning

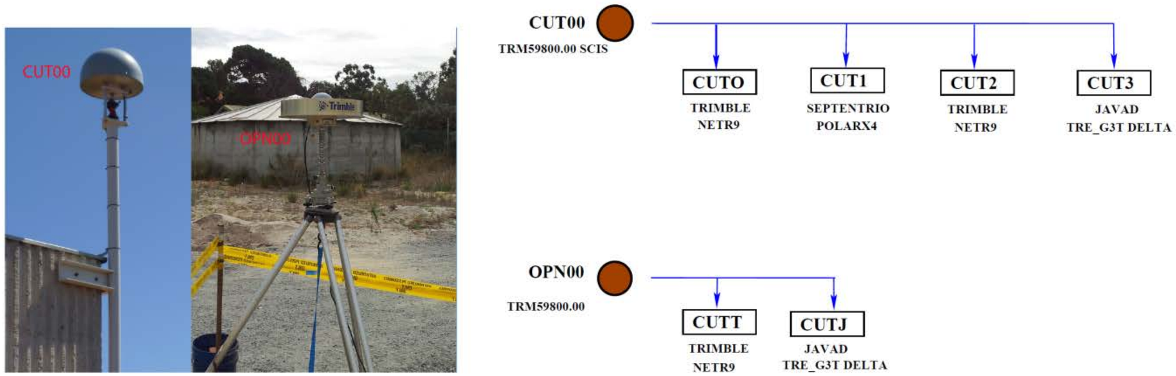


(a) Antenna setup (b) Receiver-antenna connectivity

Figure 1. Curtin GNSS antennas and receivers used for the 1 km baseline experiment

1 km Baseline	B1 Ambiguity Success-Rate
CUT0-CUTT (Rx **A** – Rx **A**)	0.93
CUT3-CUTJ (Rx **B** – Rx **B**)	0.93
CUT1-CUTT (Rx **C** – Rx **A**)	0.95

Mixed-receiver BeiDou RTK Positioning



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CUT1-CUTT (Rx **C** – Rx **A**)	0.95
CUT0-CUTJ (Rx **A** – Rx **B**)	0.0
CUT1-CUTJ (Rx **C** – Rx **B**)	0.0

Existence of mixed-receiver phase-ISTB

(Inter-Satellite-Type-Bias)

Experiment	Receiver Pair	Freq	IGSO-GEO	IGSO-MEO	GEO-MEO
Curtin Exp. 20-29 July 2013 (10 day data)	CUT0-CUT1 (Rx **A** – Rx **C**)	B1 B2	-0.50		+0.50
	CUT0-CUT2 (Rx **A** – Rx **A**)	B1 B2			
	CUT0-CUT3 (Rx **A** – Rx **B**)	B1 B2	-0.50		+0.49

Existence of mixed-receiver phase-ISTB

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Experiment	Receiver Pair	Freq	IGSO-GEO	IGSO-MEO	GEO-MEO
Curtin Exp. 20-29 July 2013 (10 day data)	CUT0-CUT1 (Rx **A** – Rx **C**)	B1			
		B2	-0.50		+0.50
	CUT0-CUT2 (Rx **A** – Rx **A**)	B1			
		B2			
	CUT0-CUT3 (Rx **A** – Rx **B**)	B1	-0.50		+0.49
		B2			

Frequency	A	C	B
B1	− **0.5**	− **0.5**	0
B2	0	**0.5**	0

Table 1. Differential phase ISTB [cyc] between GEO and IGSO/MEO satellites with B the pivot receiver [1]

Mixed-receiver BeiDou ISTB is stable over time

Experiment	Receiver Pair	Freq	IGSO-GEO	IGSO-MEO	GEO-MEO
Curtin Exp. 20-29 July 2013	CUT0-CUT1 (Rx **A** – Rx **C**)	B1 B2	-0.50		+0.50
	CUT0-CUT2 (Rx **A** – Rx **A**)	B1 B2			
	CUT0-CUT3 (Rx **A** – Rx **B**)	B1 B2	-0.50		+0.49
IGS M-GEX 23-29 Sept 2013	UNX2-UNX3 (Rx **B** – Rx **C**)	B1	+0.50		-0.50
Curtin Exp. 17-26 Dec 2013	CUT0-CUT1 (Rx **A** – Rx **C**)	B1 B2	-0.50		+0.50
	CUT0-CUT2 (Rx **A** – Rx **A**)	B1 B2			
	CUT0-CUT3 (Rx **A** – Rx **B**)	B1 B2	-0.50		+0.50
	SPA5-SPA7 (Rx **A** – Rx **B**)	B1 B2	-0.50		+0.50

Phase-ISTB is stable and can be calibrated

1 km Baseline	B1 Single-epoch Ambiguity Success-Rate		
	Ignore ISTB	Estimate ISTB	Correct for ISTB
CUT0-CUTT (Rx **A** – Rx **A**)	0.93	0.73	0.93
CUT3-CUTJ (Rx **B** – Rx **B**)	0.93	0.73	0.93
CUT1-CUTT (Rx **C** – Rx **A**)	0.95	0.79	0.95
CUT0-CUTJ (Rx **A** – Rx **B**)	0.0	0.68	0.91
CUT1-CUTJ (Rx **C** – Rx **B**)	0.0	0.74	0.94

Phase-ISTB is stable and can be calibrated

1 km Baseline	B1 Single-epoch Ambiguity Success-Rate		
	Ignore ISTB	Estimate ISTB	Correct for ISTB
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CUT0-CUTJ (Rx **A** – Rx **B**)	0.0	0.68	0.91
CUT1-CUTJ (Rx **C** – Rx **B**)	0.0	0.74	0.94

Frequency	A	C	B
B1	− **0.5**	0	0
B2	0	0	0

Table 1. Differential phase ISTB [cyc] between GEO and IGSO/MEO satellites with B the pivot receiver [1]

Mixed-receiver Pos & Nav:

- Inter Satellite Type Bias
- Inter System Biases

Definition of Inter-System Bias (ISB)

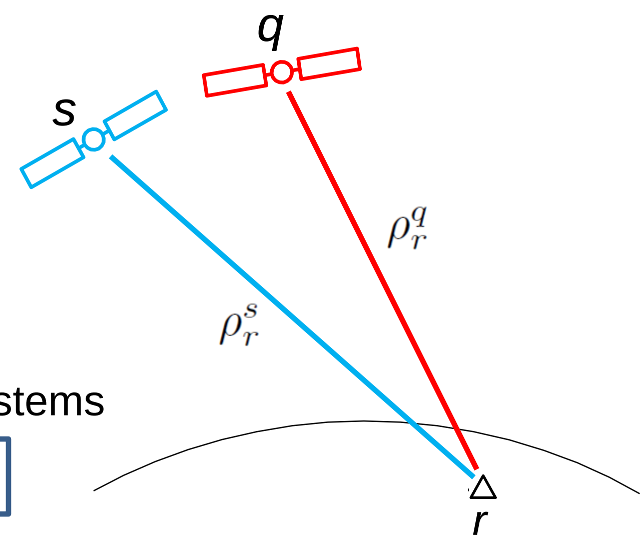
Code observation equations for multi-GNSS receiver *r*:

$$E(p_r^s) = \rho_r^s + \underbrace{(cdt_r + d_r^A)}_{cdt_r^A} - (cdt^s + d^s)$$

$$E(p_r^q) = \rho_r^q + \underbrace{(cdt_r + d_r^B - ct_{AB})}_{cdt_r^B} - (cdt^q + d^q)$$

time offset between systems

Receiver hardware delay is system dependent: $d_r^A \neq d_r^B$



Constellation A & B

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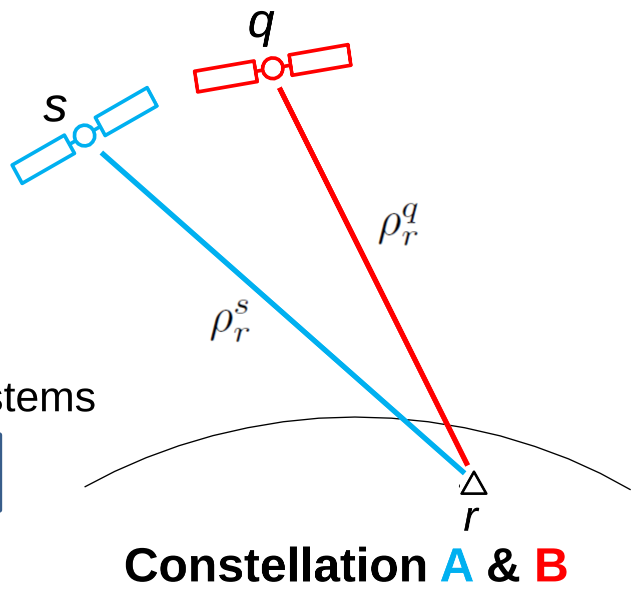
$$E(p_r^s) = \rho_r^s + \underbrace{(cdt_r + d_r^A)}_{cdt_r^A} - (cdt^s + d^s)$$

$$E(p_r^q) = \rho_r^q + \underbrace{(cdt_r + d_r^B - ct_{AB})}_{cdt_r^B} - (cdt^q + d^q)$$

time offset between systems



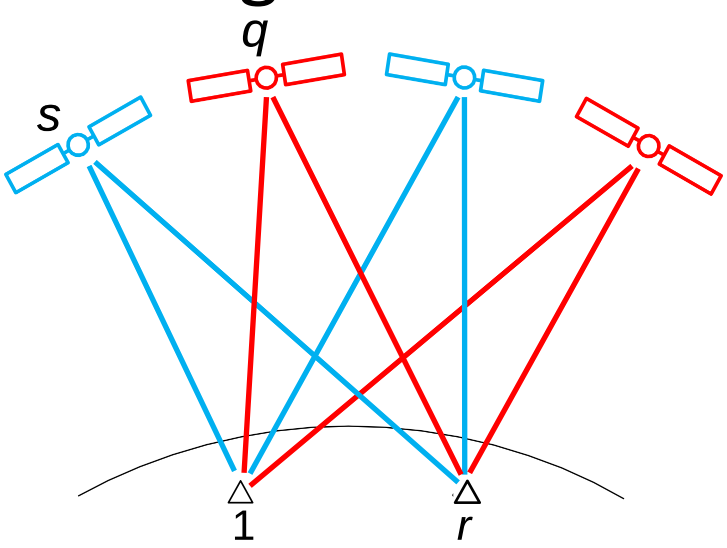
Receiver hardware delay is system dependent: $d_r^A \neq d_r^B$

(Absolute) code ISB is defined as the <u>difference of receiver clock A and receiver clock B</u>:

$$ISB_{p,r}^{AB} = cdt_r^B - cdt_r^A = d_r^B - d_r^A - ct_{AB} \quad \text{(meter)}$$

ISB = RECEIVER HARDWARE BIAS DIFFERENCE + SYSTEM TIME OFFSET

Differential ISBs in relative positioning model



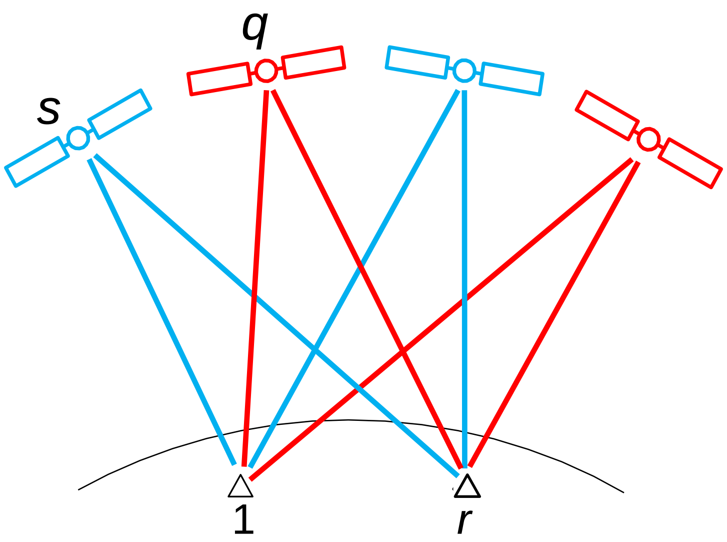
Constellation A & B

Differential code ISB (DISB) is the difference of the absolute ISBs between receiver 1 and *r*:

$$
\begin{aligned}
ISB_{p,1r}^{AB} &= ISB_{p,r}^{AB} - ISB_{p,1}^{AB} \\
&= (d_r^B - d_1^B) - (d_r^A - d_1^A) \quad \text{(meter)}
\end{aligned}
$$

DISB = DOUBLE DIFFERENCE OF RECEIVER HARDWARE BIASES
(NOTE: SYSTEM TIME OFFSET IS ELIMINATED)

Differential ISBs in relative positioning model



Constellation A & B

Differential phase ISB (DISB) is the difference of the absolute ISBs between receiver 1 and *r*:

$$ISB^{AB}_{\phi,1r} \quad = \quad ISB^{AB}_{\phi,r} - ISB^{AB}_{\phi,1} \quad = \quad (\delta^B_r - \delta^B_1) - (\delta^A_r - \delta^A_1) \quad \text{(cycle)}$$

Estimable DISB for phase: $\overline{ISB}^{AB}_{\phi,1r} = \Delta ISB^{AB}_{\phi,1r} + \overline{a}^{sq}_{1r}$

↑ fractional phase DISB ↑ arbitrary integer

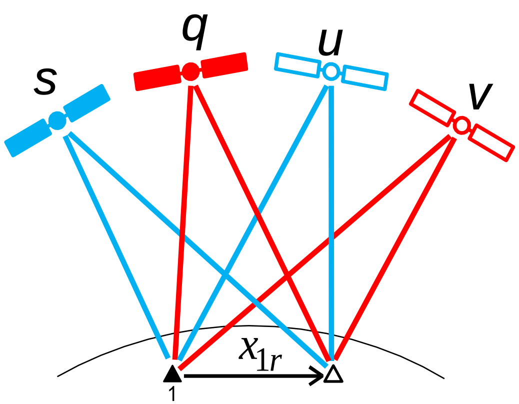
Mixed double-differenced observation model

Double-differencing w.r.t. pivot satellite per constellation:

$$
\begin{aligned}
E(\phi^{su}_{1r}) &= \rho^{su}_{1r} + \lambda a^{su}_{1r} \\
E(\phi^{qv}_{1r}) &= \rho^{qv}_{1r} + \lambda a^{qv}_{1r} \\
E(p^{su}_{1r}) &= \rho^{su}_{1r} \\
E(p^{qv}_{1r}) &= \rho^{qv}_{1r}
\end{aligned}
$$

Double-differencing with estimation of unknown DISBs:

$$
\begin{aligned}
E(\phi^{su}_{1r}) &= \rho^{su}_{1r} + \lambda a^{su}_{1r} \\
E(\phi^{sq}_{1r}) &= \rho^{sq}_{1r} + \lambda \overline{ISB}^{AB}_{\phi,1r} \\
E(\phi^{sv}_{1r}) &= \rho^{sv}_{1r} + \lambda a^{qv}_{1r} + \lambda \overline{ISB}^{AB}_{\phi,1r} \\
E(p^{su}_{1r}) &= \rho^{su}_{1r} \\
E(p^{sq}_{1r}) &= \rho^{sq}_{1r} + ISB^{AB}_{p,1r} \\
E(p^{sv}_{1r}) &= \rho^{sv}_{1r} + ISB^{AB}_{p,1r}
\end{aligned}
$$



Constellation A & B

MODELS HAVE EXACTLY THE SAME PERFORMANCE, IN TERMS OF AMBIGUITY RESOLUTION & POSITIONING !

Consequence of calibrating the DISBs…

"Traditional" double-differencing:

$$
\begin{aligned}
E(\phi^{su}_{1r}) &= \rho^{su}_{1r} + \lambda a^{su}_{1r}\\
E(\phi^{qv}_{1r}) &= \rho^{qv}_{1r} + \lambda a^{qv}_{1r}\\
E(p^{su}_{1r}) &= \rho^{su}_{1r}\\
E(p^{qv}_{1r}) &= \rho^{qv}_{1r}
\end{aligned}
$$

Two pivot satellites (s & q)

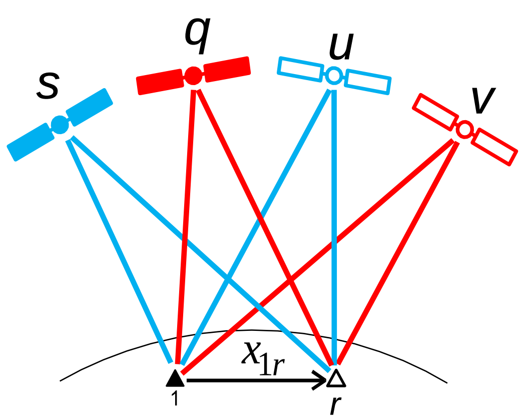
"Inter-system" double-differencing:

$$
\begin{aligned}
E(\phi^{su}_{1r}) &= \rho^{su}_{1r} + \lambda a^{su}_{1r}\\
E(\phi^{sq}_{1r} - \lambda \Delta ISB^{AB}_{\phi,1r}) &= \rho^{sq}_{1r} + \lambda \bar{a}^{sq}_{1r}\\
E(\phi^{sv}_{1r} - \lambda \Delta ISB^{AB}_{\phi,1r}) &= \rho^{sv}_{1r} + \lambda \bar{a}^{sv}_{1r}\\
E(p^{su}_{1r}) &= \rho^{su}_{1r}\\
E(p^{sq}_{1r} - ISB^{AB}_{p,1r}) &= \rho^{sq}_{1r}\\
E(p^{sv}_{1r} - ISB^{AB}_{p,1r}) &= \rho^{sv}_{1r}
\end{aligned}
$$

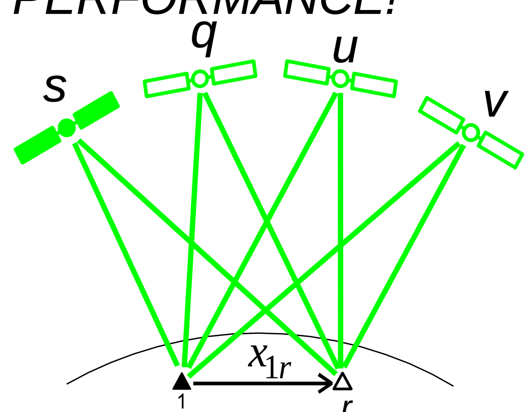
One pivot satellite; with $\bar{a}^{sv}_{1r} = a^{qv}_{1r} + \bar{a}^{sq}_{1r}$

Having an additional satellite,

BETTER PERFORMANCE!



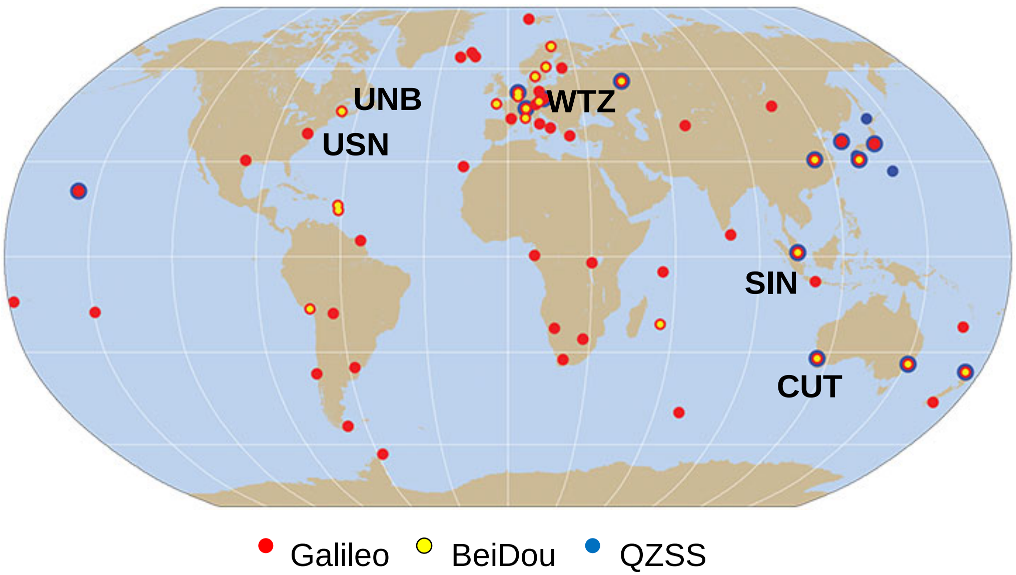
Constellation A & B



"As if one constellation"

Selected multi-GNSS datasets

IGS MGEX network (June 2013)



Co-located MGEX/CUT stations used for our DISB estimation:

Station ID	Receiver type	G	E	C	J
CUT0	Trimble NetR9	Y	Y	Y	Y
CUT1	Septentrio PolaRx4	Y	Y	Y	N
CUT2	Trimble NetR9	Y	Y	Y	Y
CUT3	Javad TRE-G3TH	Y	Y	Y	Y
USN4	Septentrio PolaRx4	Y	Y	N	N
USN5	Novatel OEM6	Y	Y	N	N
SIN1	Trimble NetR9	Y	Y	Y	Y
SIN0	Javad TRE-G3TH	Y	Y	N	Y
UNB3	Trimble NetR9	Y	Y	Y	N
UNBD	Javad TRE-G2T	Y	Y	N	N
UNBS	Septentrio PolaRxS	Y	Y	Y	N
WTZ2	Leica GR25	Y	Y	N	N
WTZ3	Javad TRE-G3TH	Y	Y	N	N
WTZR	Leica GRX1200+GNSS	Y	Y	N	N

G=GPS; E=Galileo; C=BeiDou; J=QZSS

All *zero* baselines (ZB), except:

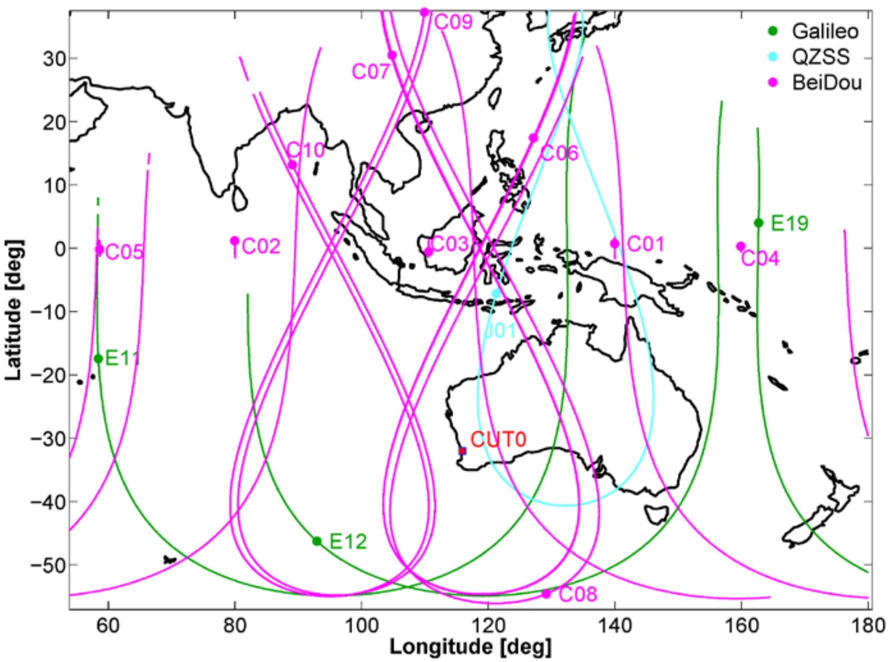
- UNB3-UNBD/UNBS: 20 m
- WTZ2-WTZ3: 70 m

which are short baselines (SB)

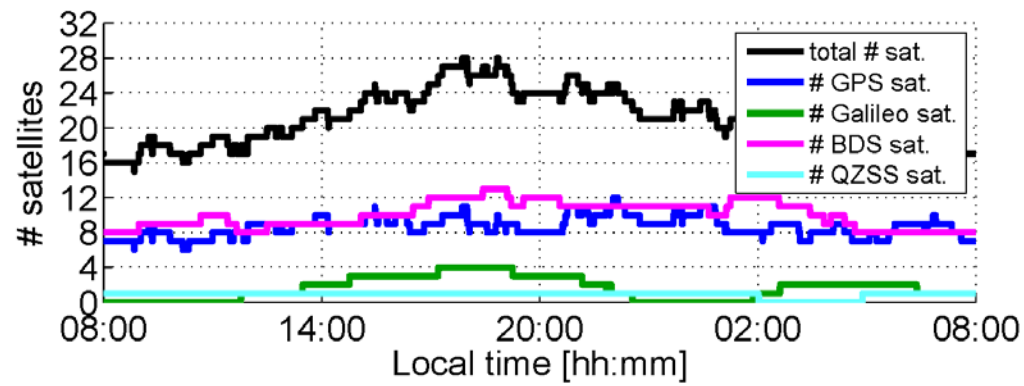
Estimation of phase and code DISBs:

Zero baseline: $\rho_{1r}^{sq} = 0$. Short baseline: ρ_{1r}^{sq} = known.

BDS+QZSS
+Galileo



BDS+Galileo+QZSS+GPS



Perth (April 20, 2013): # of satellites for *10°* elevation cut-off angle

Single-Epoch, single-freq. success rates

Same Receiver A (CUT0-CUTT) empirical ILS success rate, full ambiguity resolution ISBs-fixed/assumed zero (ISBs-float). **4 days of real data**, April 19-20, April 29-30, 2013

System/ Frequency Trimble -Trimble	Empirical ILS **Success rate %** for cut-off [deg.]					
	10	20	25	30	35	40
BDS B1:	96.4	85.4	81.2	63.4	46.7	20.8
GPS L1:	81.6	53.9	32.4	17.7	7.5	3.3
Galileo+GPS E1+L1:	90.3 (86.0)	72.6 (63.9)	53.9 (43.8)	39.8 (29.3)	27.5 (16.7)	19.1 (8.2)
BDS+GPS B1+L1:	98.3	100	100	99.4	96.5	81.7
BDS+ Galileo+ QZSS+GPS:	98.3 (98.3)	100 (100)	100 (100)	100 (99.5)	99.5 (96.7)	91.7 (83.1)

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System/ Frequency Rx **A** – Rx **A**	**Empirical ILS** **Success rate %** for cut-off [deg.]					
	10	20	25	30	35	40
BDS B1:	96.4	85.4	81.2	63.4	46.7	20.8
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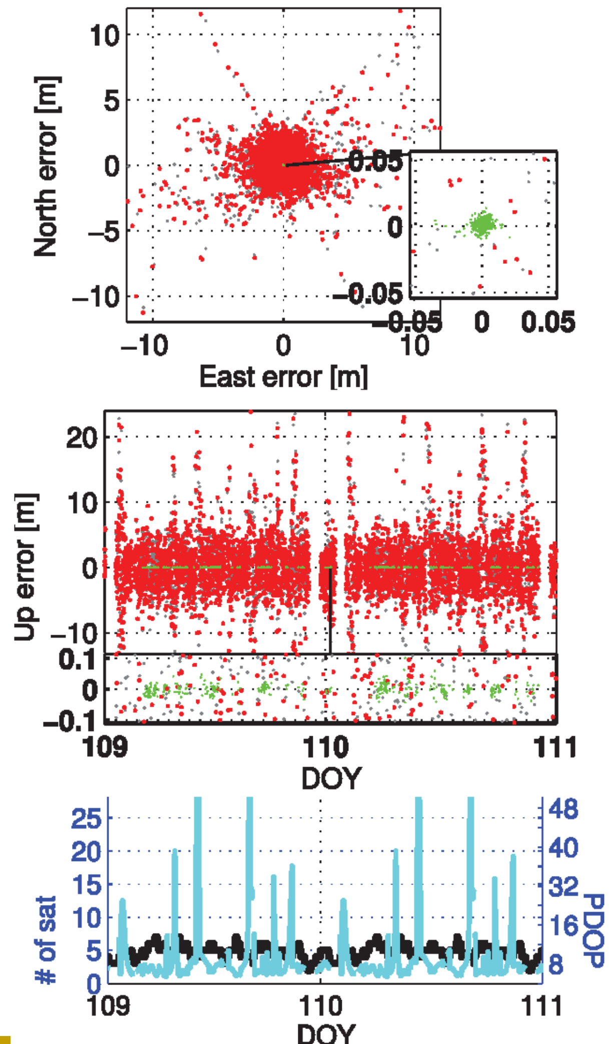
BDS+GPS B1+L1:	98.3	100	100	99.4	96.5	81.7
BDS+ **Galileo+** **QZSS+GPS:**	98.3 (98.3)	100 (100)	100 (100)	100 (99.5)	99.5 (96.7)	91.7 (83.1)

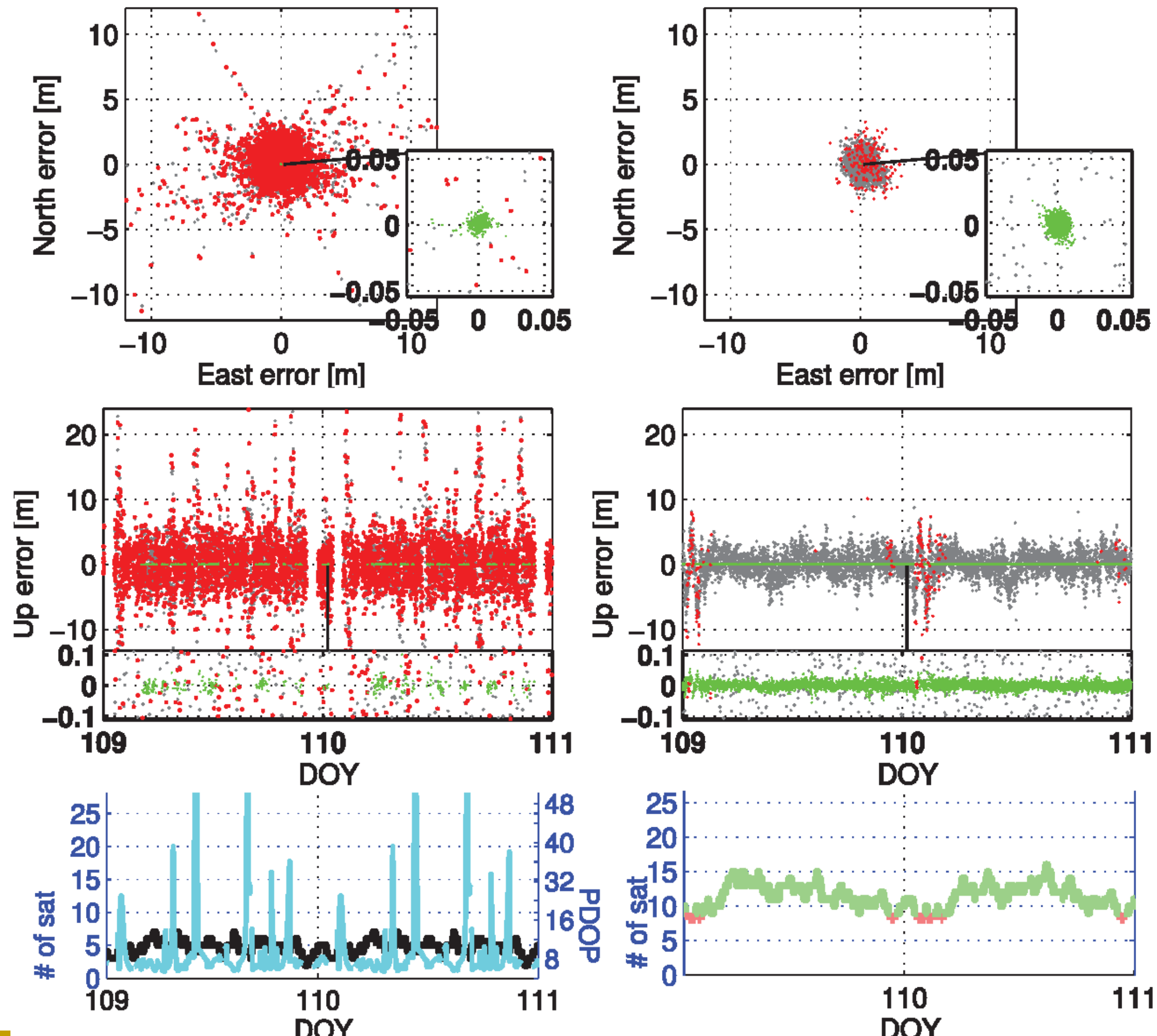
Instantaneous RTK float and fixed (correct & incorrect solutions), elevation cut-off angle 35 deg.

L1 GPS
(7.5% ILS SR)



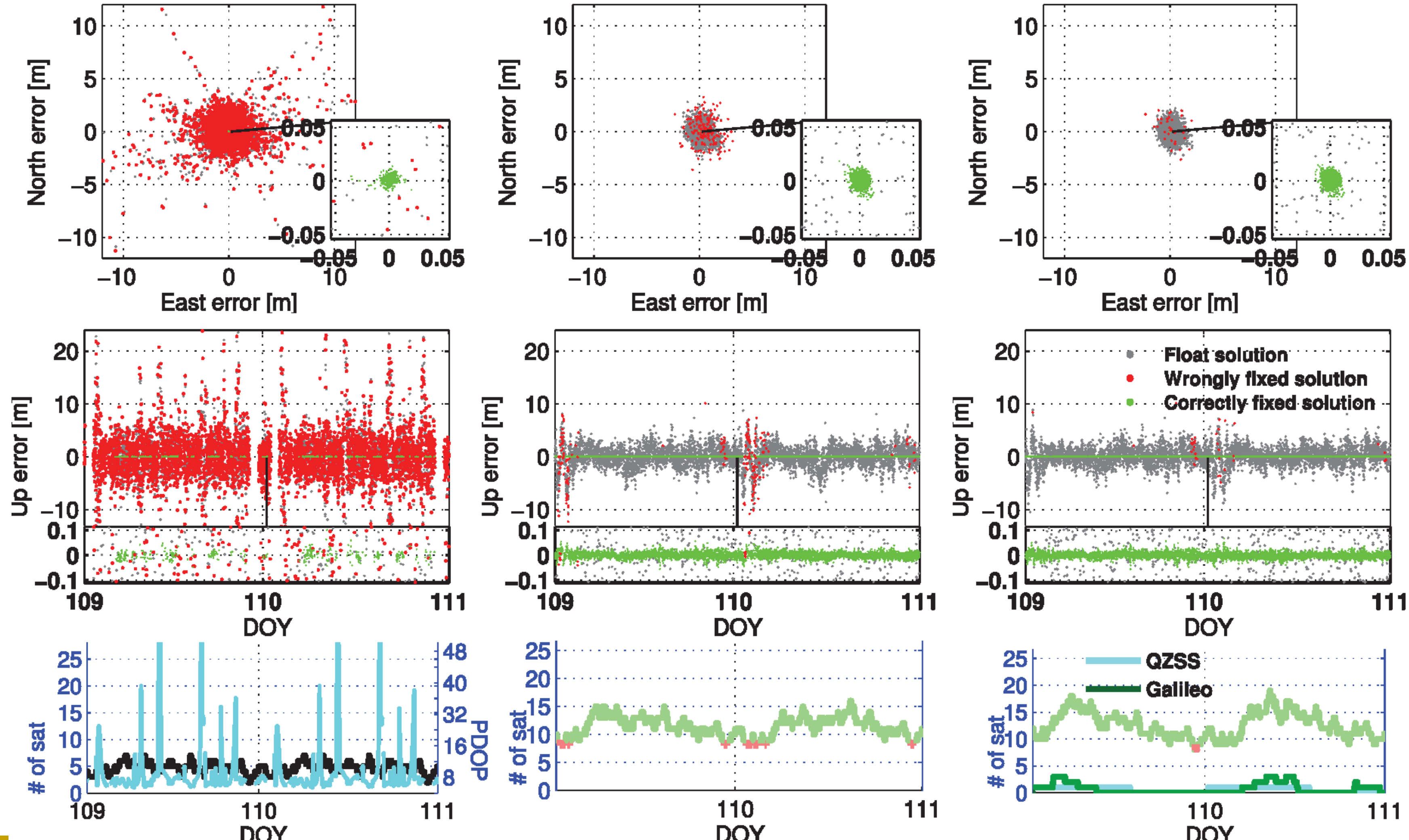
Instantaneous RTK float and fixed (correct & incorrect solutions), elevation cut-off angle 35 deg.

L1 GPS (7.5% ILS SR) | B1+L1 BDS+GPS (96.5% ILS SR)



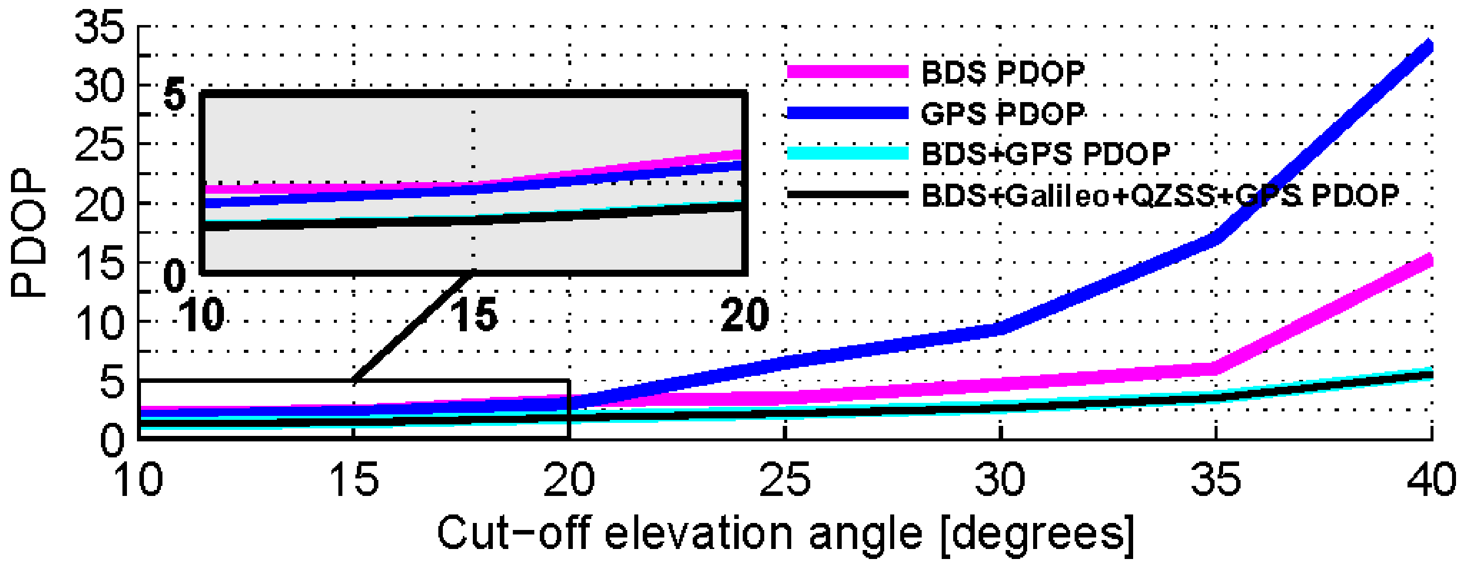
Instantaneous RTK float and fixed (correct & incorrect solutions), elevation cut-off angle 35 deg.

L1 GPS	B1+L1 BDS+GPS	B1+E1+L1+L1 ISBs-fixed
(7.5% ILS SR)	(96.5% ILS SR)	(99.5% ILS SR)



Positional dilution of precision (PDOP) for different elevation cut-off angles

Mean of the single-epoch PDOP over 4days (April 19-20 and April 29-30, 2013).



Single-Epoch, single-freq. success rates

Mixed Receiver C - A (CUT1-CUTT) empirical ILS success rate, full ambiguity resolution ISBs-fixed (ISBs-float), red=ISBs ignored. **2 days**

System/ Frequency Trimble -Septentrio	**Empirical ILS Success rate %** for cut-off [deg.]					
	10	20	25	30	35	40
BDS B1:	93.0	80.8	77.0	57.8	44.7	19.3
GPS L1:	84.5	60.9	40.3	24.5	11.0	4.1
Galileo+GPS E1+L1:	92.7 (88.9) 37.4	78.2 (70.3) 29.9	60.8 (50.8) 20.7	46.2 (35.5) 12.9	31.4 (20.3) 5.7	22.6 (10.3) 2.4
BDS+GPS B1+L1:	98.4	100	100	96.8	91.9	79.9
BDS+ Galileo+ QZSS+GPS:	98.4 (98.4) 97.7	100 (100) 93.6	100 (100) 88.8	99.8 (97.7) 78.9	98.7 (93.3) 71.3	89.1 (81.1) 55.8

Single-Epoch, single-freq. success rates

Mixed Receiver C - A (CUT1-CUTT) empirical ILS success rate, full ambiguity resolution ISBs-fixed (ISBs-float), red=ISBs ignored. **2 days**

System/ Frequency Rx **C** – Rx **A**	**Empirical ILS Success rate %** for cut-off [deg.] 10	20	25	30	35	40
BDS B1:	93.0	80.8	77.0	57.8	44.7	19.3
GPS L1:	84.5	60.9	40.3	24.5	11.0	4.1
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	(88.9)	(70.3)	(50.8)	(35.5)	(20.3)	(10.3)
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	(98.4)	(100)	(100)	(97.7)	(93.3)	(81.1)
	97.7	93.6	88.8	78.9	71.3	55.8

Single-Epoch, single-freq. success rates

Mixed Receiver C - A (CUT1-CUTT) empirical ILS success rate, full ambiguity resolution ISBs-fixed (ISBs-float), red=ISBs ignored. **2 days**

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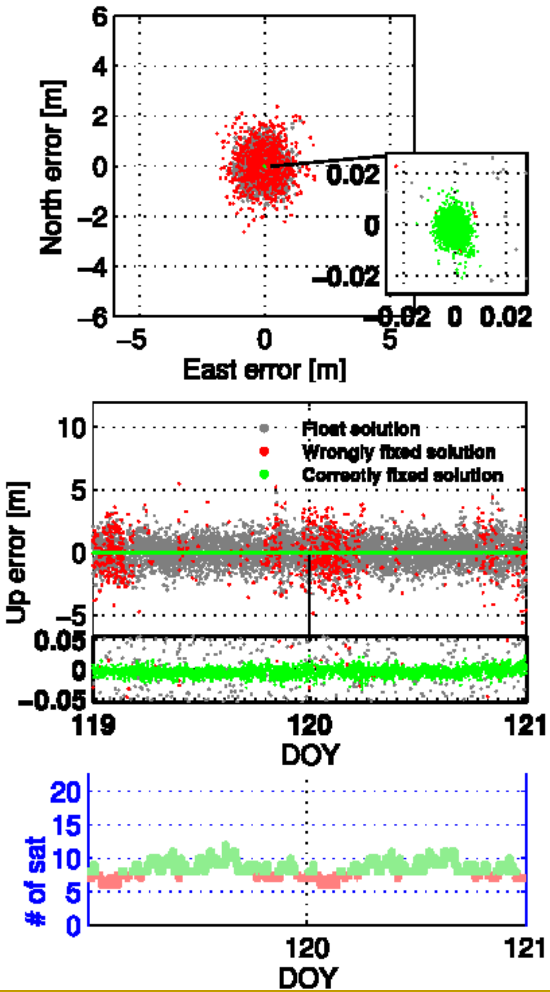
	(98.4)	(100)	(100)	(97.7)	(93.3)	(81.1)
	97.7	93.6	88.8	78.9	71.3	55.8

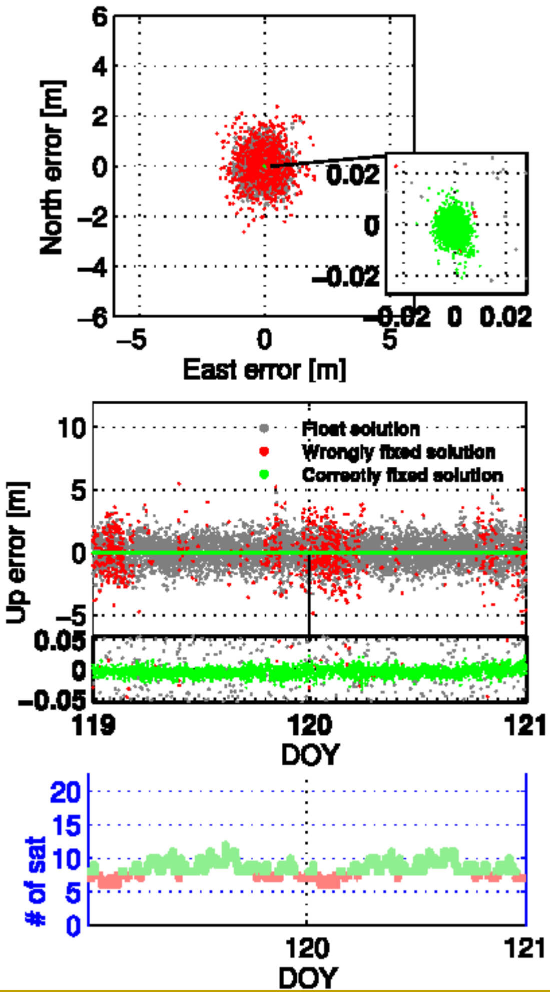
Mixed receiver types: elevation cut-off angle 10 deg.

L1 GPS
(84.5% ILS SR)

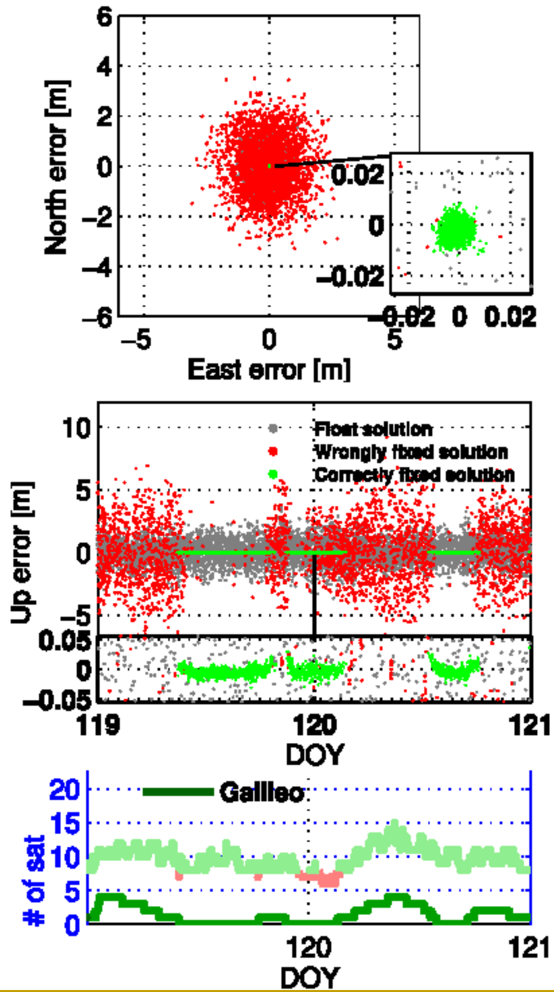


Mixed receiver types: elevation cut-off angle 10 deg.

L1 GPS
(84.5% ILS SR)

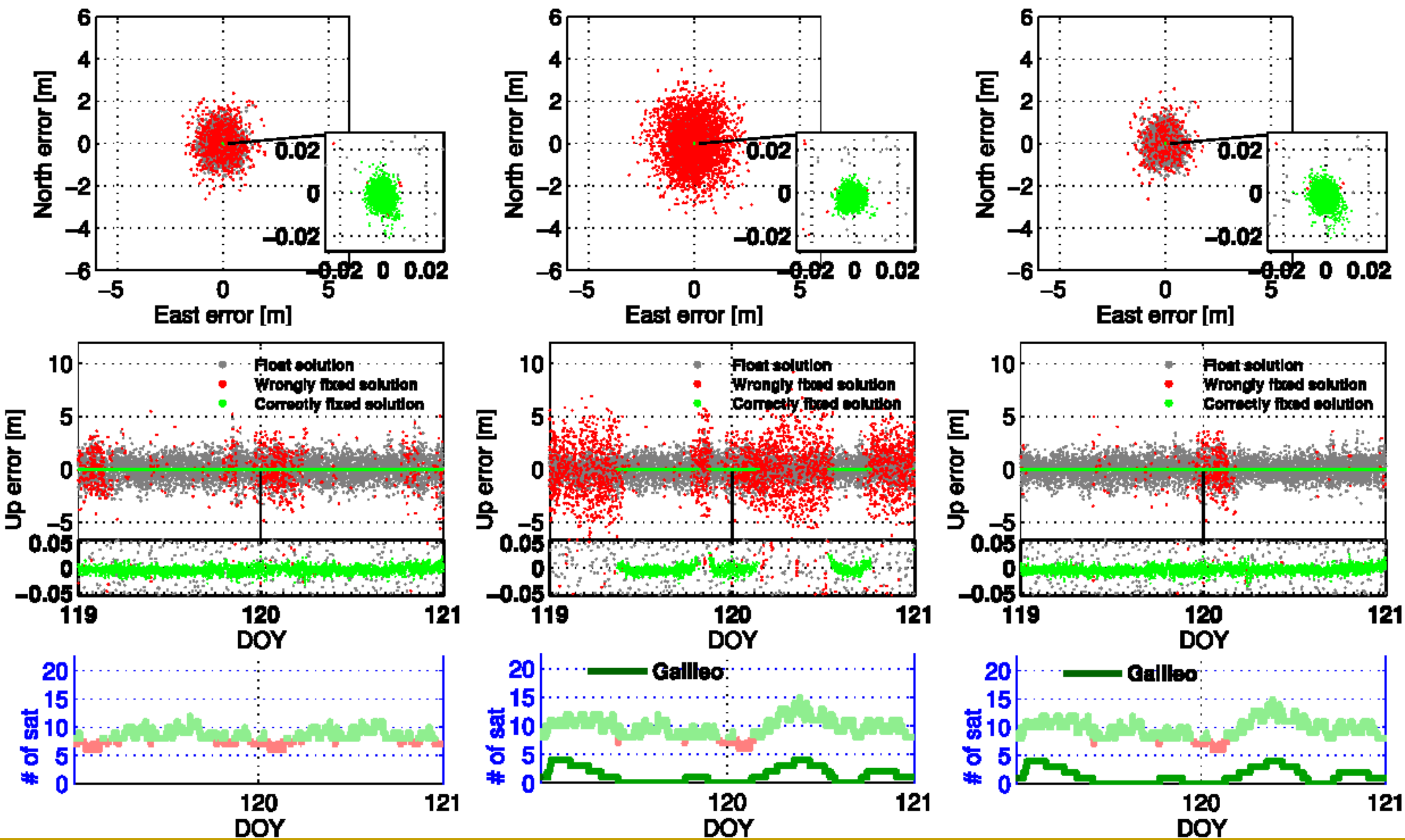


E1+L1 Galileo+GPS
ISBs-ignored
(37.4% ILS SR)



Mixed receiver types: elevation cut-off angle 10 deg.

L1 GPS	E1+L1 Galileo+GPS	E1+L1 Galileo+GPS
	ISBs-ignored	ISBs-fixed
(84.5% ILS SR)	(37.4% ILS SR)	(92.7% ILS SR)



Conclusions
Multi-GNSS Mixed-Receiver Positioning

- Excellent Multi-GNSS precise positioning performance with ISBs known (high cut-off elevations)
- ISBs seem always to be **zero** for receivers of **same manufacturer**
- IBSs of **mixed receiver combinations** may not be zero, but if non- zero they are **very stable in time**
- Developed a **mixed-receiver ISB Calibration Table**
- **Mixed-receiver, multi-GNSS precise positioning impossible** without ISB estimation/calibration