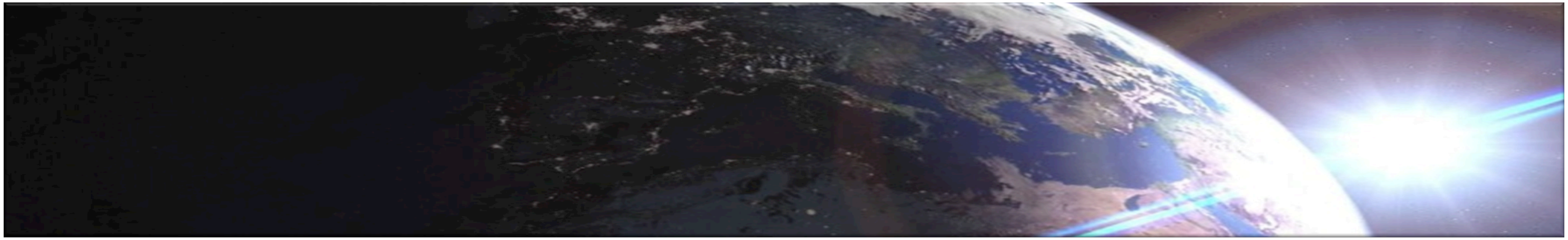

How Multi-GNSS Brings Benefits to SEA

A Technical Point of View

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NAVIS Centre, HUST, Vietnam

Beyond GPS Session

Bangkok, Thailand, 2 April 2014

navis International Collaboration Centre

for R&D on Satellite Navigation Technology in South East Asia

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ISMB Istituto Superiore Mario Boella

Work Motivation

- South East Asia (SEA) region is covered by:
  - All 4 GNSSes (GPS, Galileo, GLONASS, Beidou); and
  - 1 RNSS (QZSS).
- Now: GPS-standalone solution still dominates, but
- Future is multi-GNSS + RNSS;

→ Verification of the advantages of Multi-GNSS over stand-alone solutions in SEA by real data collected from all system constellations.

Content

1. **Multi-GNSS Environment**
   – Challenges of Multi-GNSS Environment
   – Advantages of Multi-GNSS Environment
2. **Multi-GNSS Signal Processing Chain**
   – Experiment Result
3. **QZSS augmentation services:**
   – Sub-meter class: L1-SAIF;
   – Centimeter class: L6-LEX.
4. **Conclusions**

Content

- **Multi-GNSS Environment**
  - Challenges of Multi-GNSS Environment
  - Advantages of Multi-GNSS Environment
- **Multi-GNSS Signal Processing Chain**
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- **QZSS augmentation services:**
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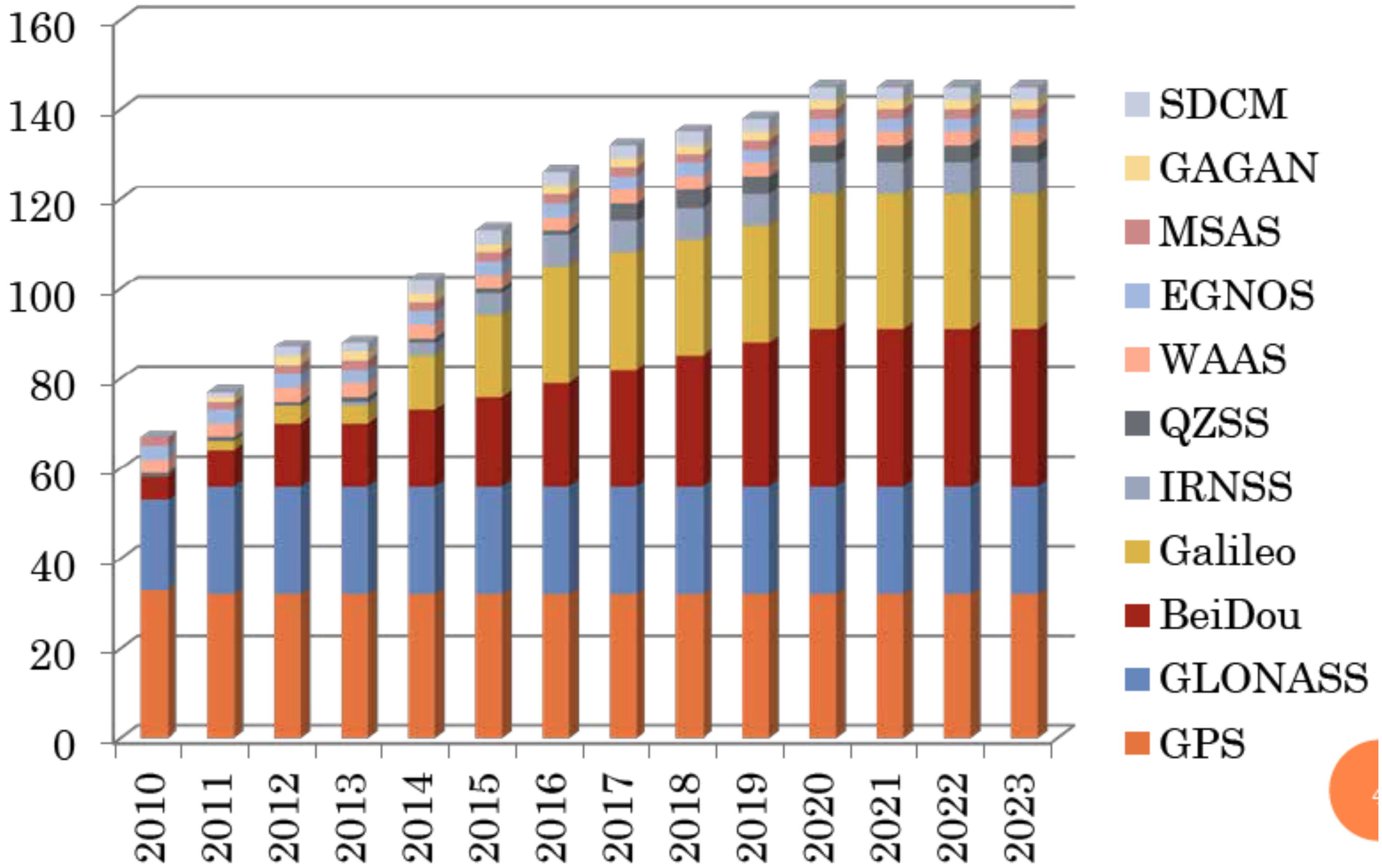
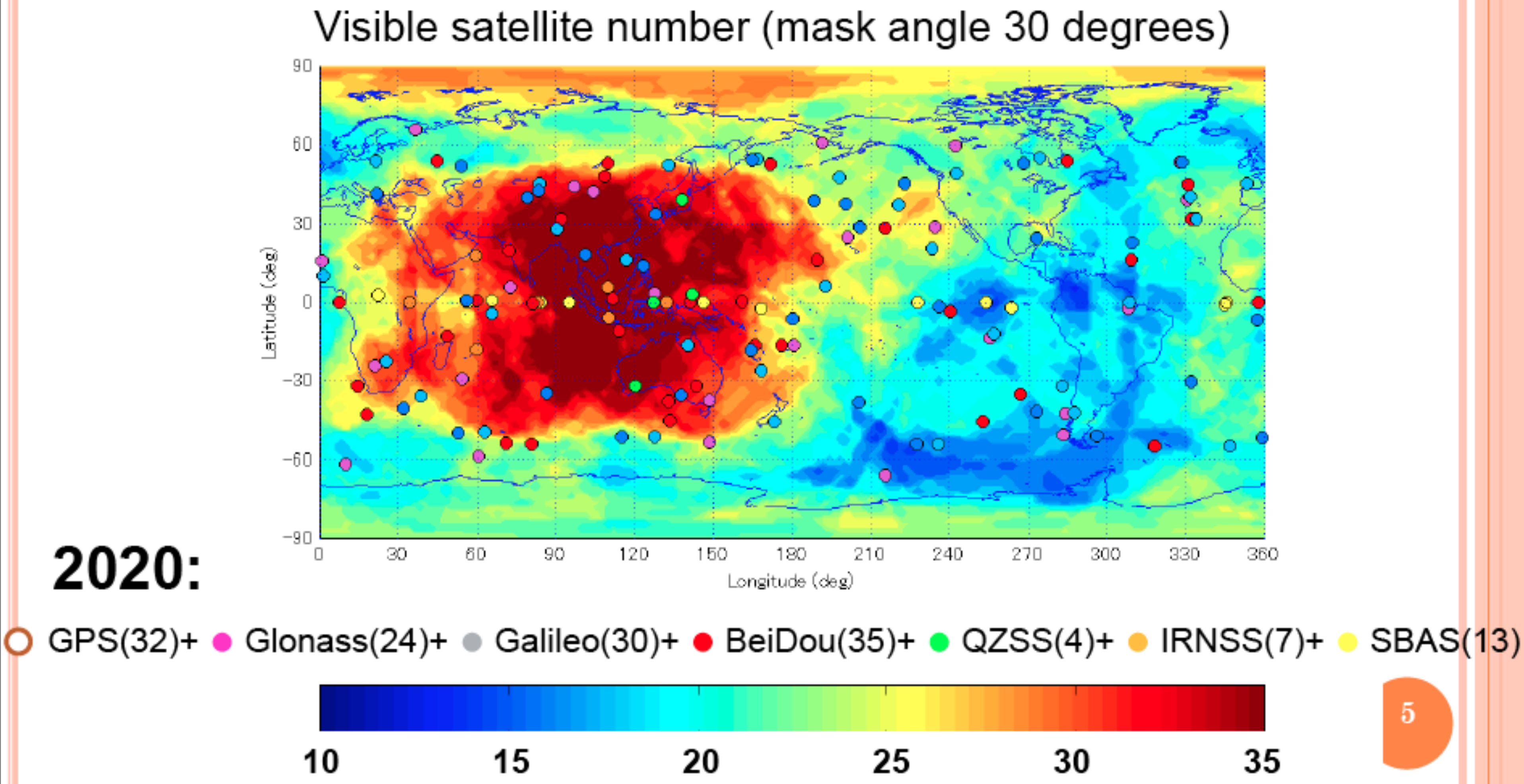
- **Conclusions**

Multi-GNSS Environment



Multi-GNSS Environment



2020:

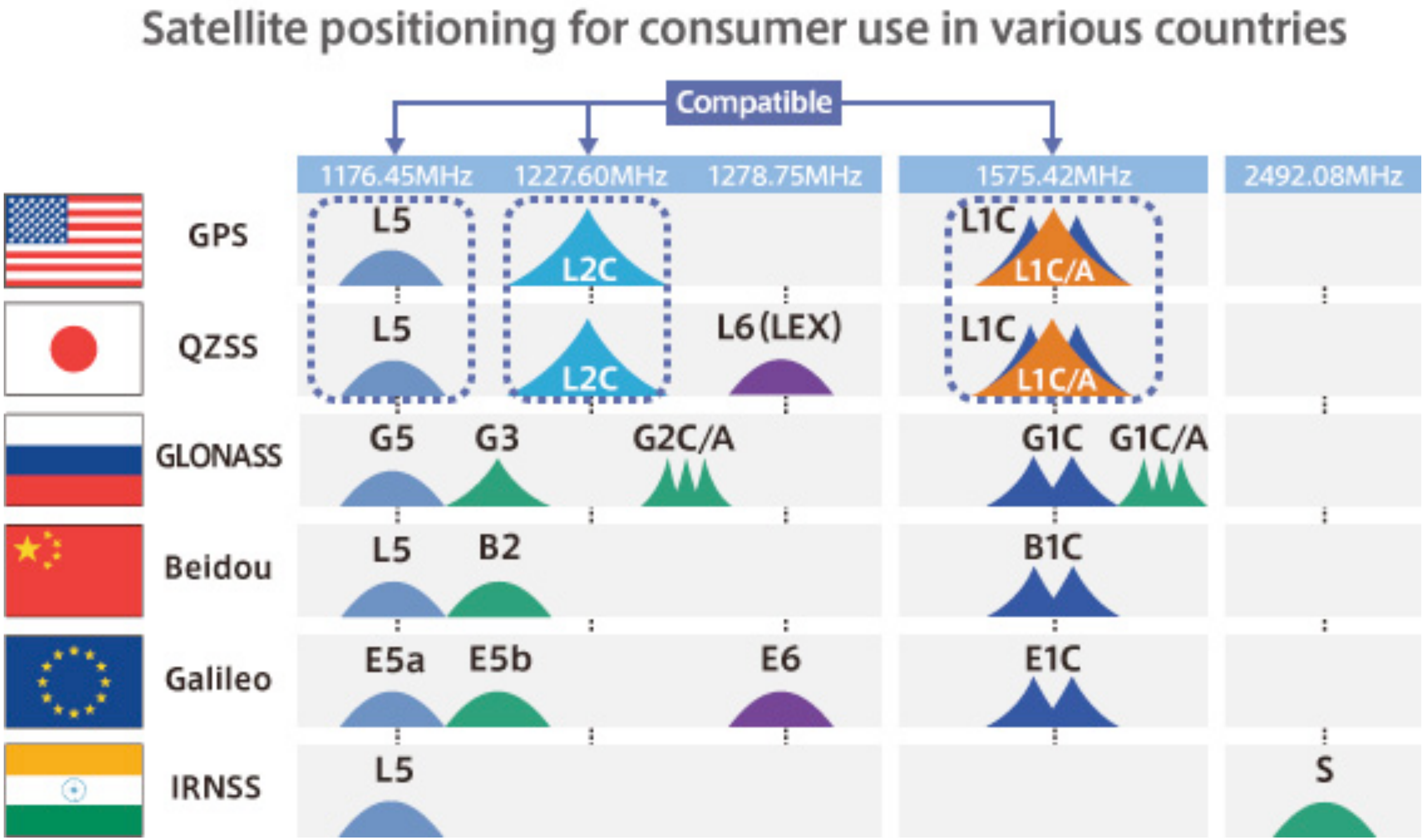
Challenges of Multi-GNSS Environment

- Inter-system interference: GNSSes broadcast navigation signals in overlapped frequency bands → Inter-system interference.
- Complexity increase:
  - Analog part: operate with multiple systems, multiple frequency bands at larger signal bandwidths → Increase complexity and receiver cost.
  - Digital part: More advanced and complex algorithms, more channels for more satellites → Increase the computational complexity, the resource capability requirements and receiver cost.
- Different Coordinate Reference System: each GNSS uses its own coordinate reference systems

System	GPS	GLONASS	Galileo	Beidou
Satellite position	Kepler param.	ECEF	Kepler param.	Kepler param.
Coordinate reference system	WGS-84	PZ-90.02	GTRF	CGCS2000

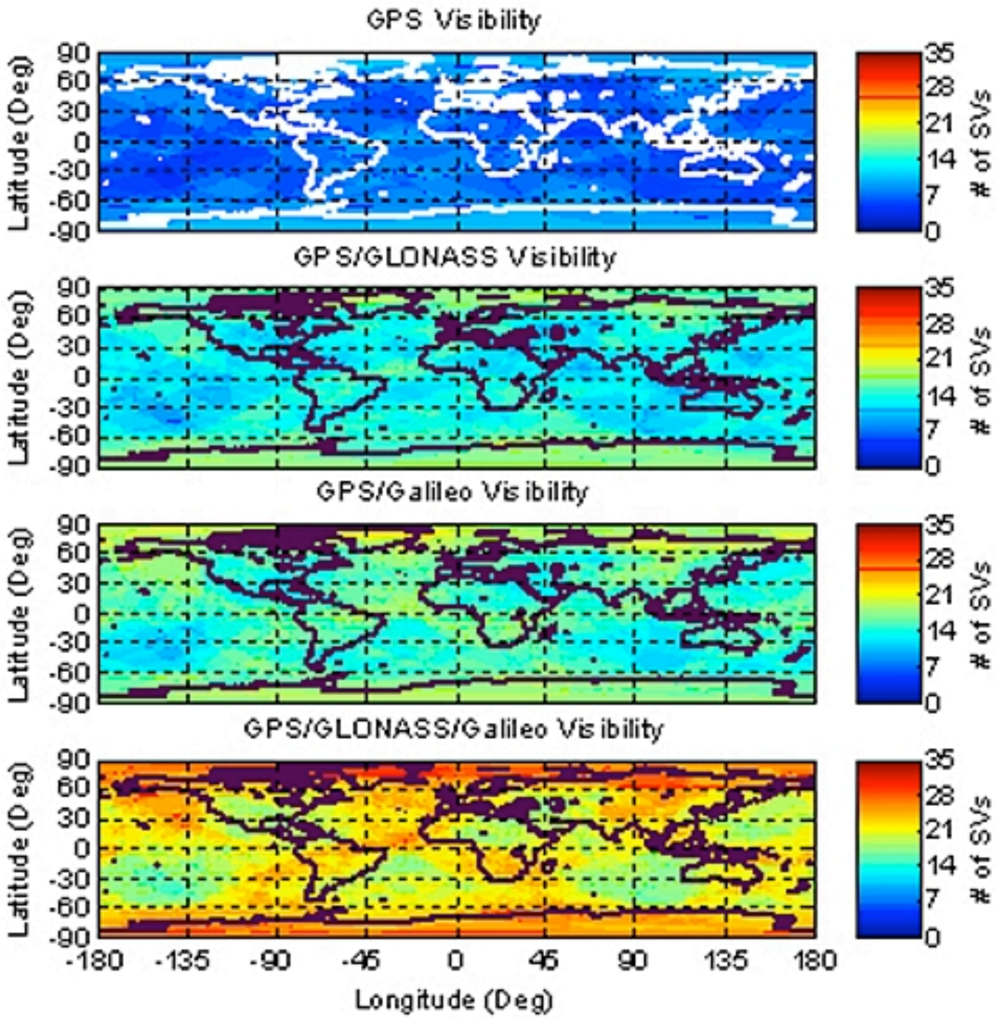
Advantages of Multi-GNSS environment

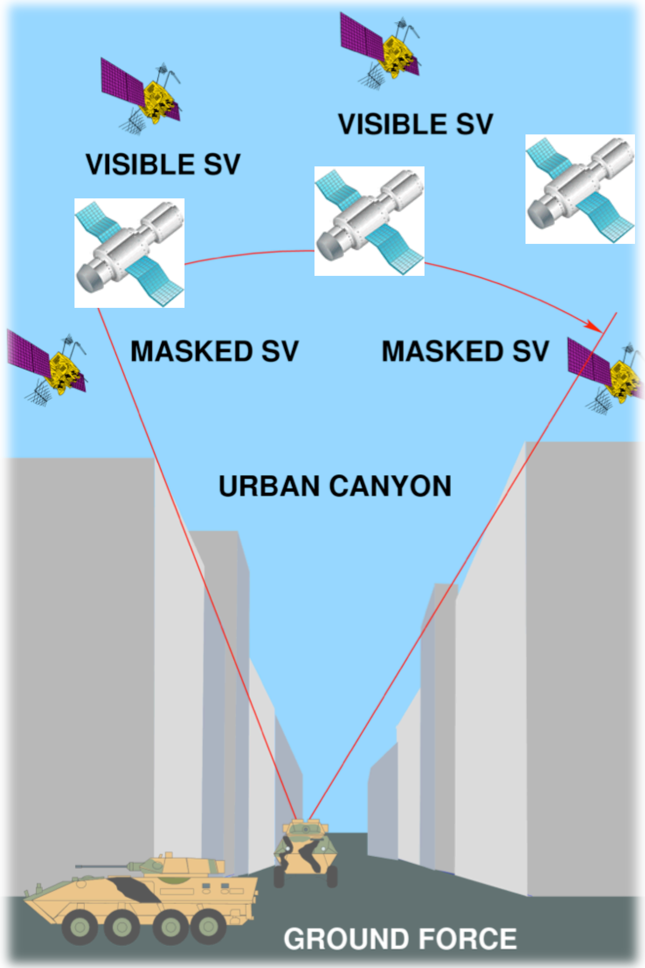
- More signals, more services => more options



Source: qzs.jp

- Increase in availability and coverage:

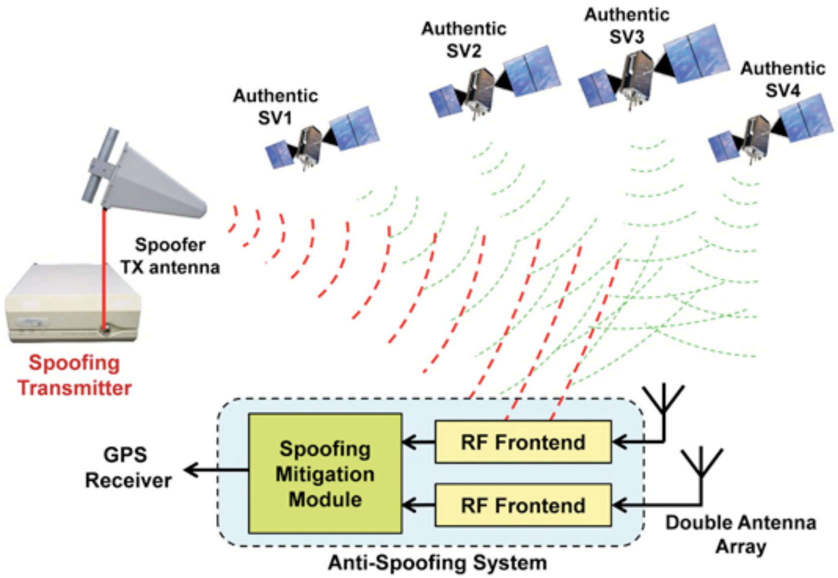




Urban canyon problem

- More robust and reliable services:
  - Reliable services: Integrity information is provided by SBAS or GNSSes;
  - Robustness positioning:
    - New advanced signals
    - The redundancy of multi-systems and multi-bands;

    => more difficult to be jammed and spoofed;



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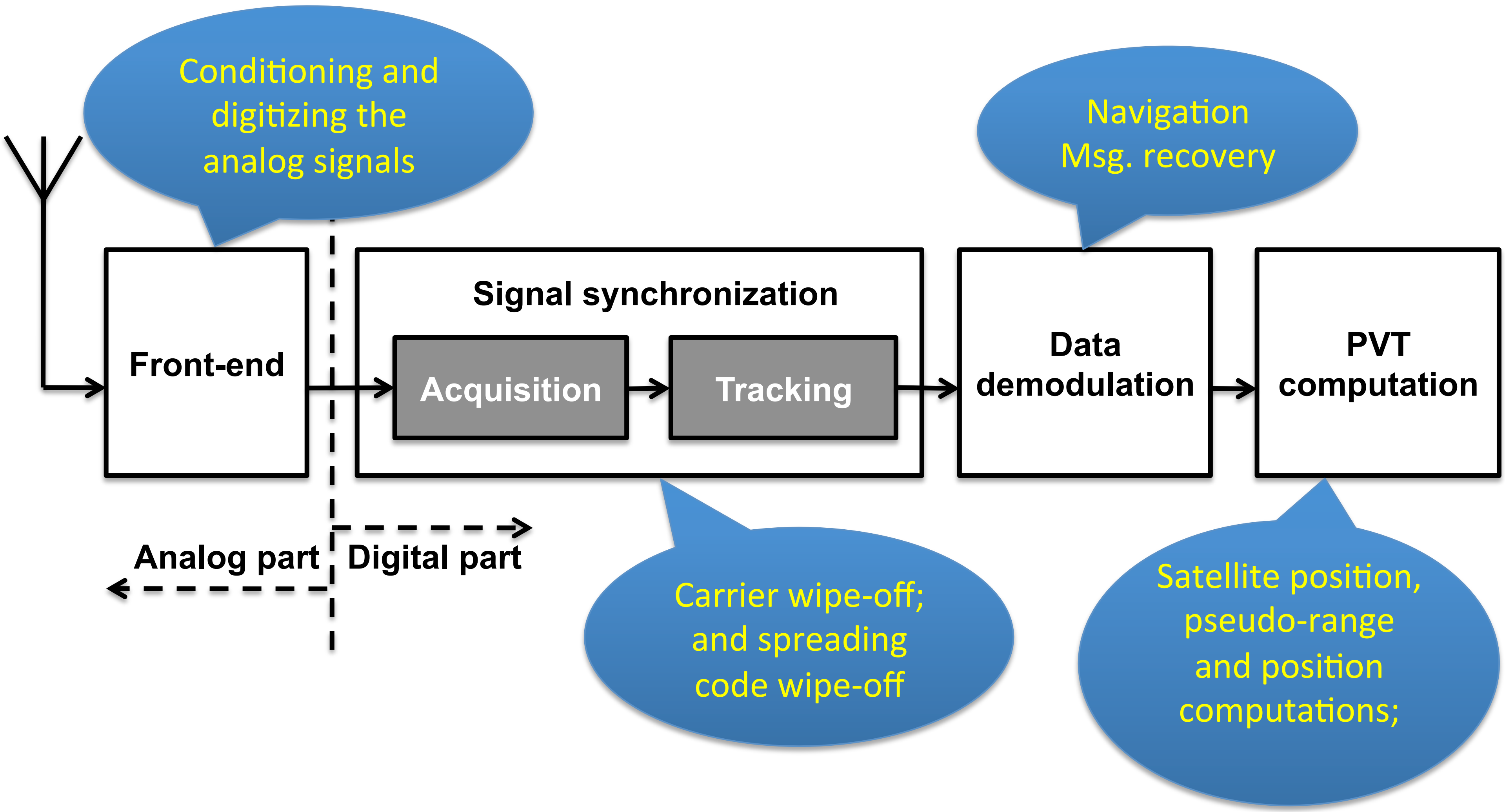
GNSS Signal Processing Chain



- Signals in concerns: open and free signals of the 5 systems, namely:

Signals	Carrier (MHz)	PRN code	Code Length	Code rate	Data rate
GPS L1-C/A	1575.42	Gold	1023	1.023	50
Galileo E1	1575.42	Memory	4092	1.023	250
Beidou B1	1561.098	Gold	2046	2.046	
Glonass L1-OF	1602+ k×0.5625	Maximal length	511	0.511	50

Note: GLONASS L1-OF is the only FDMA signal; the others are CDMA ones

Adaptations to Multi-GNSS:

Analog parts (1/2): (Antenna & Front-end)

- Antenna requirements:
  - Capable of receiving all 4 signals;
  - Aero Antenna Choke Ring AT1675-120: [1525 ÷1615] MHz

Adaptations to Multi-GNSS:

Analog parts (2/2): (Antenna & Front-end)

- Front-end:
  - Functionalities: conditioning and digitizing analog signals
  - Chosen front-end: MAX2769

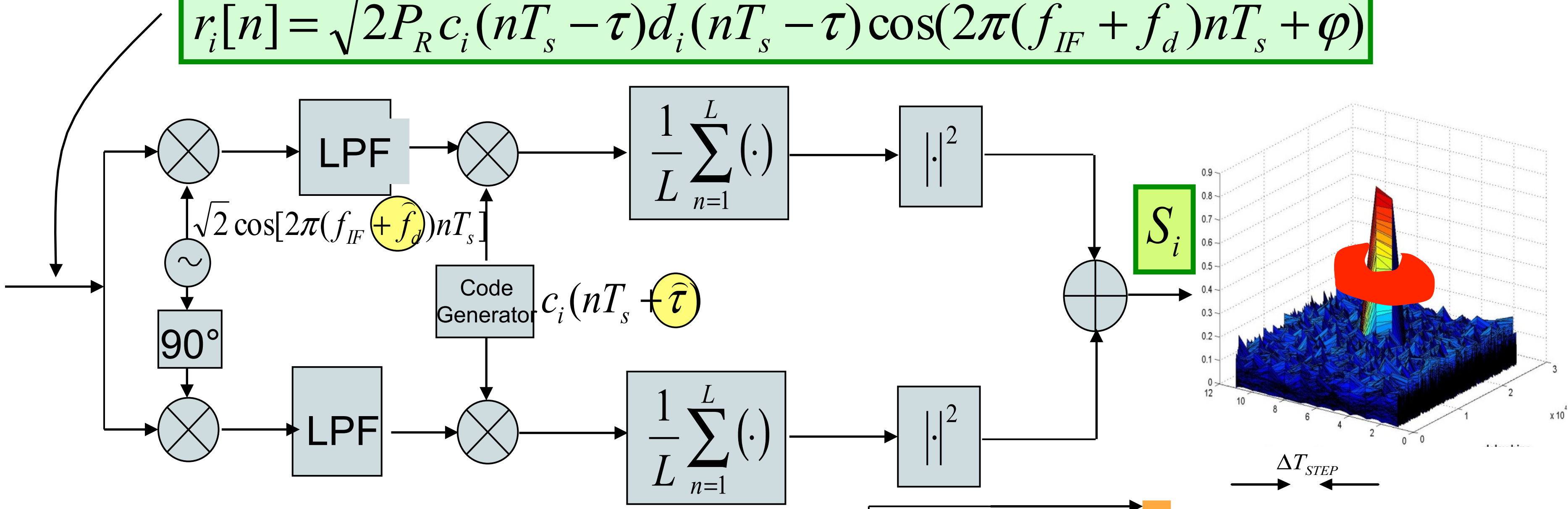
Table 1: MAX 2769 front-end configuration

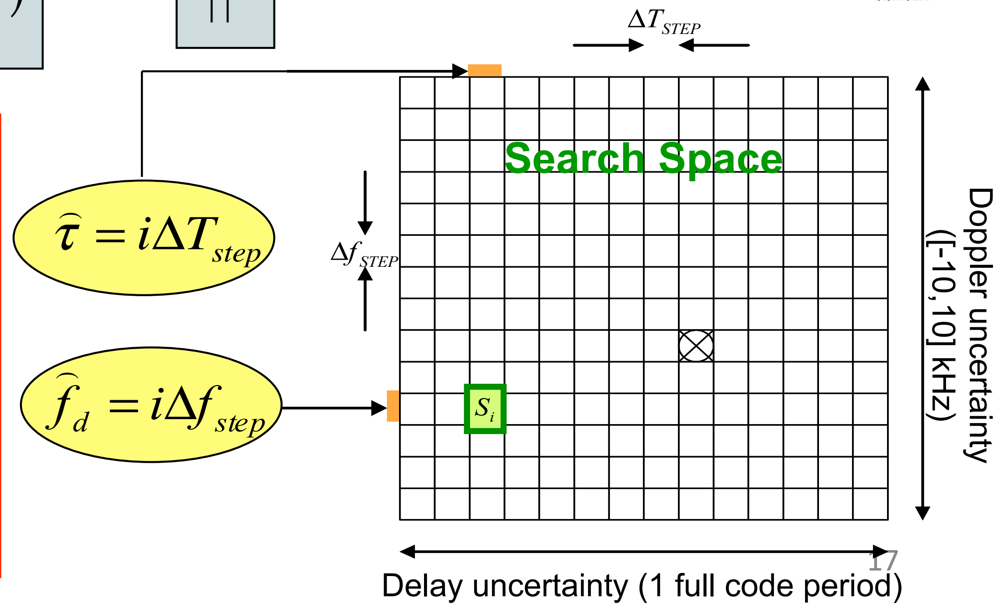
Sampling frequency	F_S = 16.368 MHz
Intermediate frequency	F_{IF1} = 4.092 MHz (for L1-C/A, E1 and B1) F_{IF2} = -16 kHz (for L1-OF)
Bandwidth	B_{w1} = 4.2 MHz (for L1-C/A, E1 and B1) B_{w2} = 8 MHz (for L1-OF)
Number of quantization bits	2 bits

Adaptations to Multi-GNSS:

Signal Acquisition Process

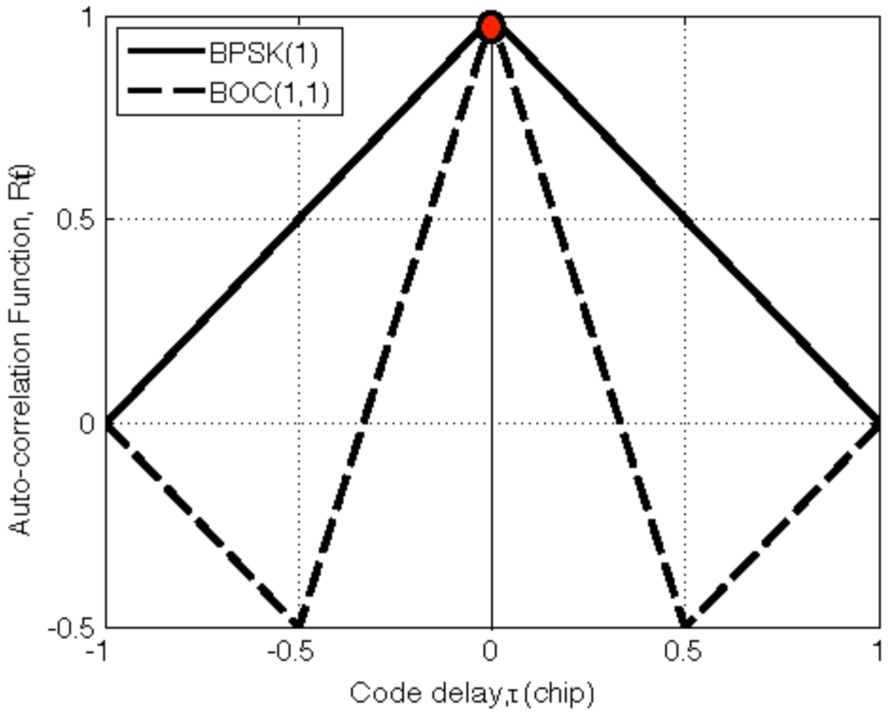
$$r_i[n] = \sqrt{2P_R}\, c_i(nT_s - \tau)\, d_i(nT_s - \tau) \cos(2\pi(f_{IF} + f_d)nT_s + \varphi)$$

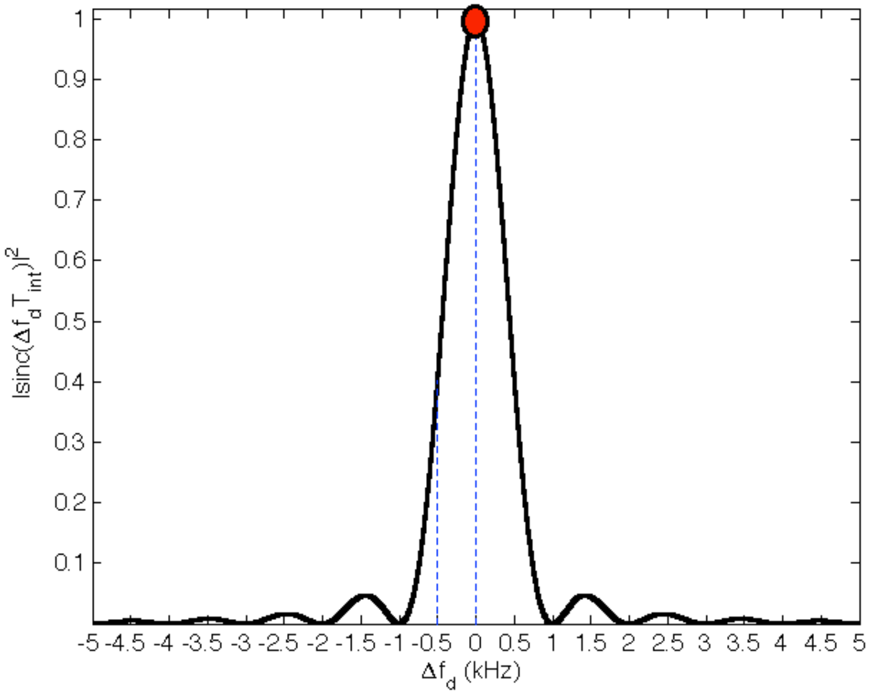




- **Detection**: detect the *i*-th satellite (if present)
- **Estimation**: roughly estimate the parameters of the detected satellites, which are:
  - Arrival time $(\hat{\tau})$
  - Doppler shift $(\hat{f}_d)$

- Choice of the step sizes of Doppler and code delay estimations:





As for BPSK signals (except Galileo)

$$\Delta T_{step} = 0.5 \text{ (chip)}$$

As for BOC signal (only Galileo)

$$\Delta T_{step} = 0.25 \text{ (chip)}$$

$$\Delta f_{step} = \frac{1}{2LTs}$$

Signal	***i*** or ***k***	$\bar{\theta}$ **(chip)**	$\Delta\bar{\theta}$ **(chip)**	$\bar{f}_d$ **(kHz)**	$\Delta\bar{f}_d$ **(kHz)**
L1-C/A	[1,32]	[0,1022]	0.5	[-10,10]	0.5
E1	[1,36]	[0,4095]	0.25		0.125
B1	[1,37]	[0,2045]	0.5		0.5
L1-OF	[-7,6]	[0,510]	0.5		0.5

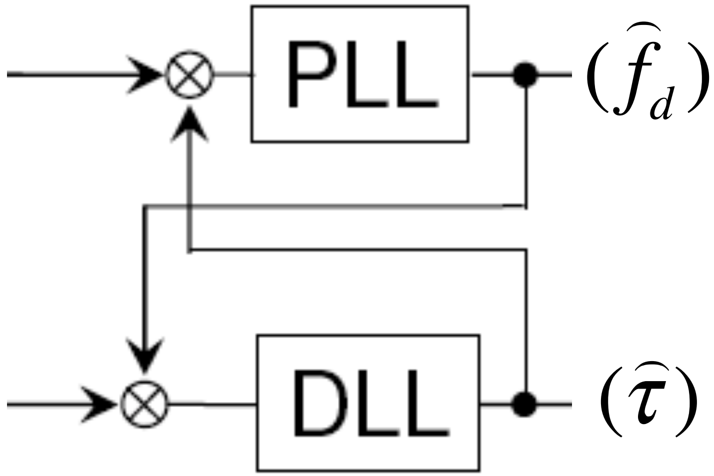
Adaptations to Multi-GNSS:

Signal Tracking Process

- Refine the acquisition results (rough estimations of $(\widehat{\tau}, \widehat{f}_d)$);
- Estimate continuously (follow dynamically – track) the values of (τ, f_d)

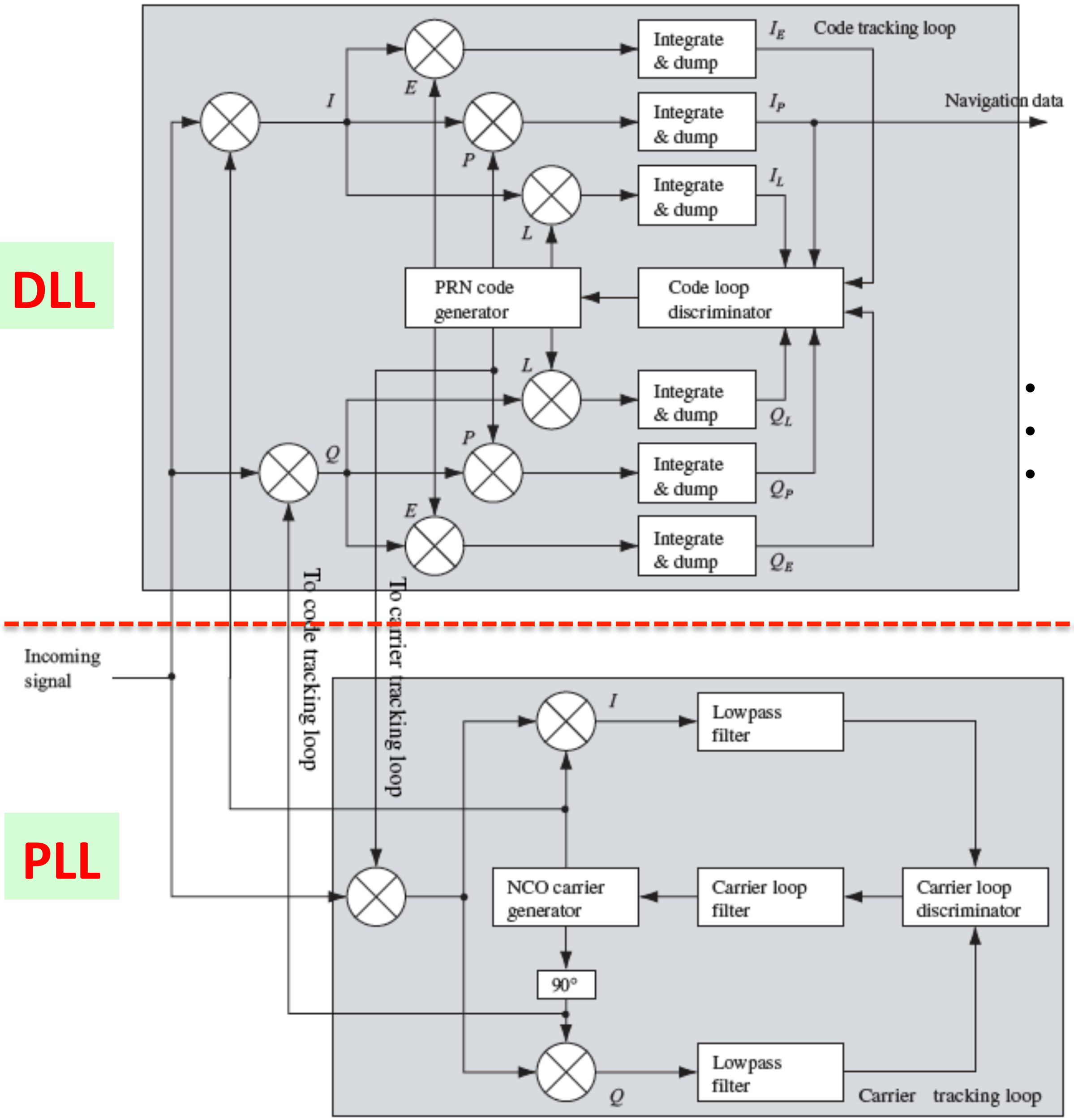
For Carrier wipe-off and Code wipe-off;

- Carrier wipe-off: Phase Lock Loop (PLL);
- Code wipe-off: Delay Lock Loop (DLL)

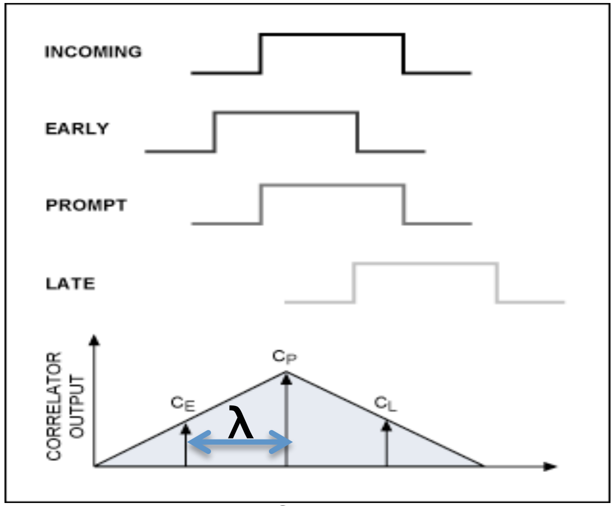


DLL & PLL are strictly interrelated, and work in a concatenated way

DLL



PLL



- λ = 0.5 (chip) for L1C/A, B1, L1OF
- λ = 0.25 (chip) for E1 (BOC(1,1))
- Discrimination Function

$$D = \frac{(I_E^2 + Q_E^2) - (I_L^2 + Q_L^2)}{(I_E^2 + Q_E^2) + (I_L^2 + Q_L^2)},$$

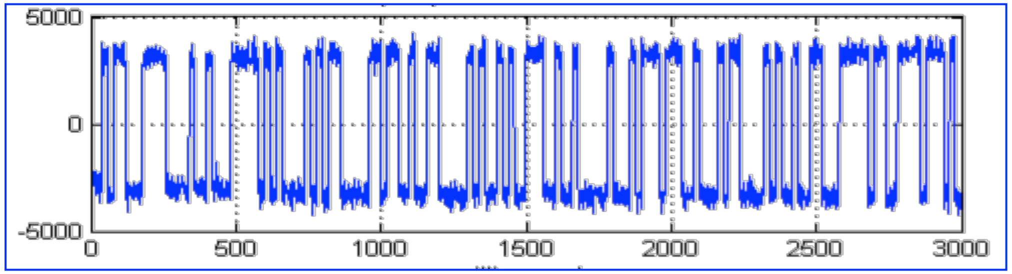
- 2nd order Costas Loop
- Discrimination Function

$$D = \arctan\left(\frac{Q^k}{I^k}\right)$$

Adaptations to Multi-GNSS:

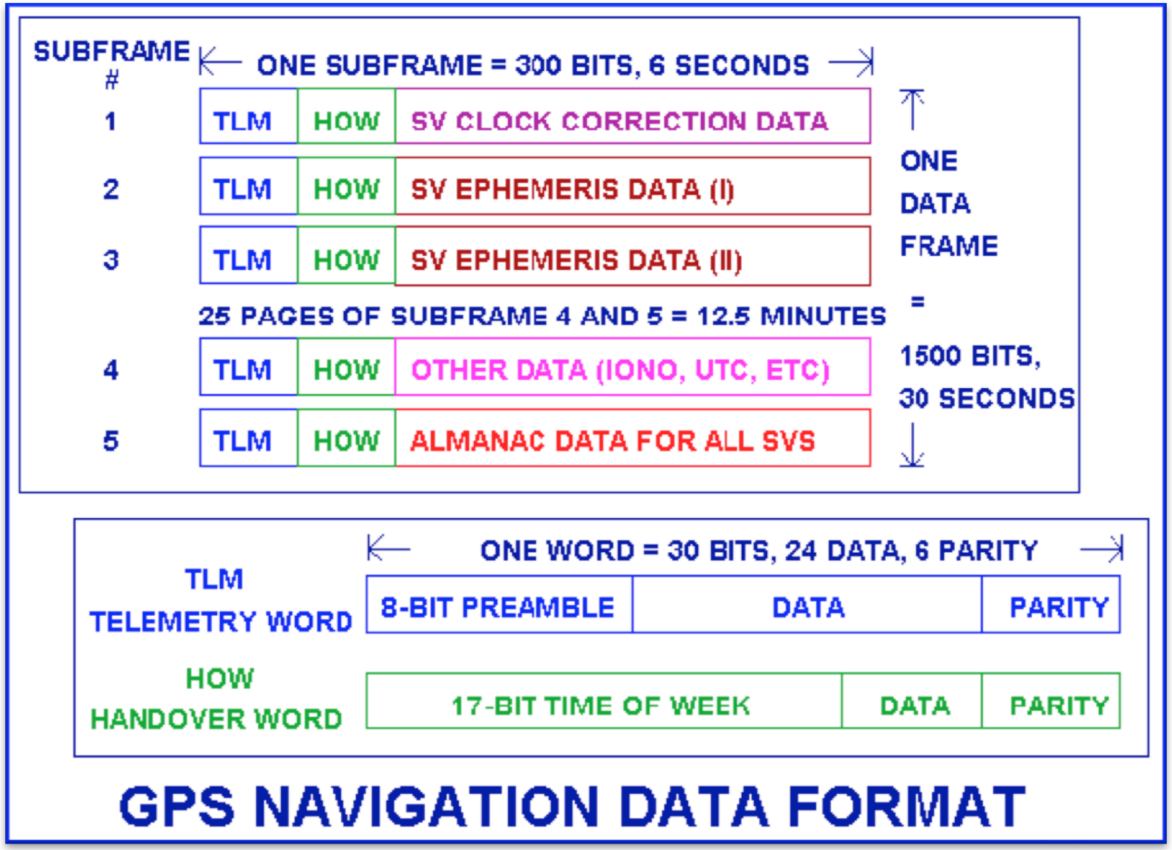
Data demodulation

The tracking output: bit stream



- Sub-frame synchronization;
- Data validation;
- Message content re-organization/recovery

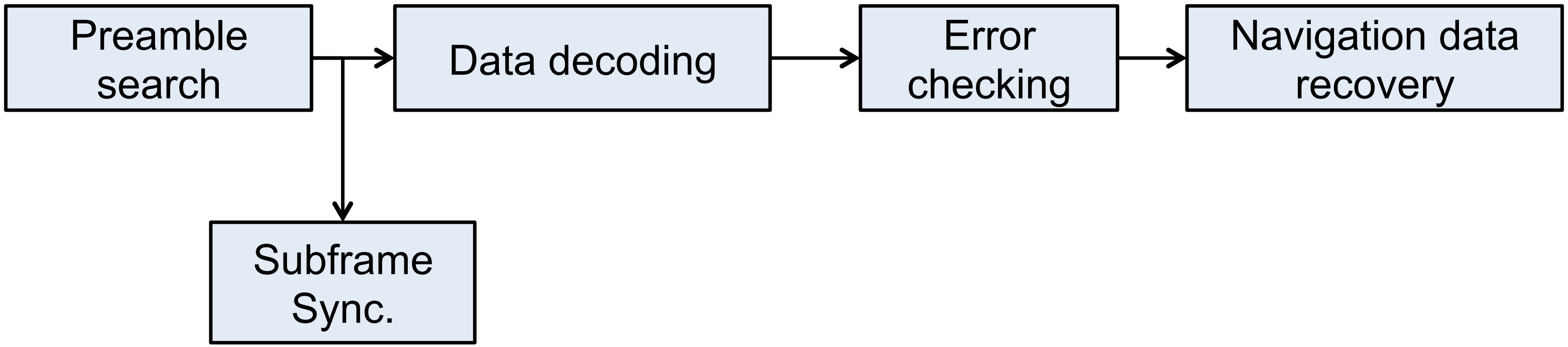
Time, clock, ephemeris, almanac information.



- Navigation data format of GNSSes

Signals	GPS L1 C/A	GLONASS L1 OF	Galileo E1	BeiDou B1 (D1)	BeiDou B1 (D2)
Preamble	8b×20ms	30b×10ms	10b×4ms	11b×20ms	11b×2ms
Subframe	300b×20ms	200b×10ms	250b×4ms	300b×20ms	300b×2ms
Data	292b×20ms	85b×20ms	120b×8ms	19b×20ms	19b×2ms
Error checking	Parity	Hamming	CRC	BCH(15, 11, 1)	

- Data demodulation procedure:

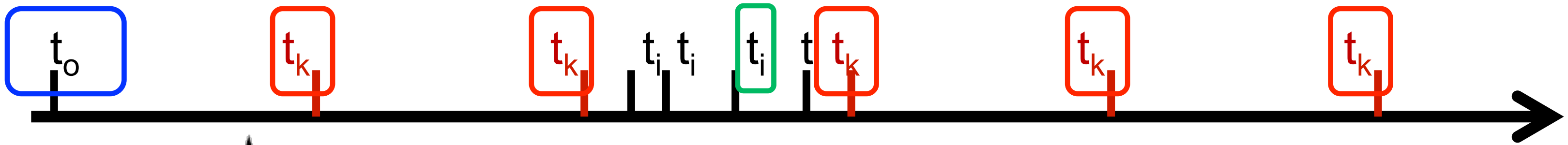


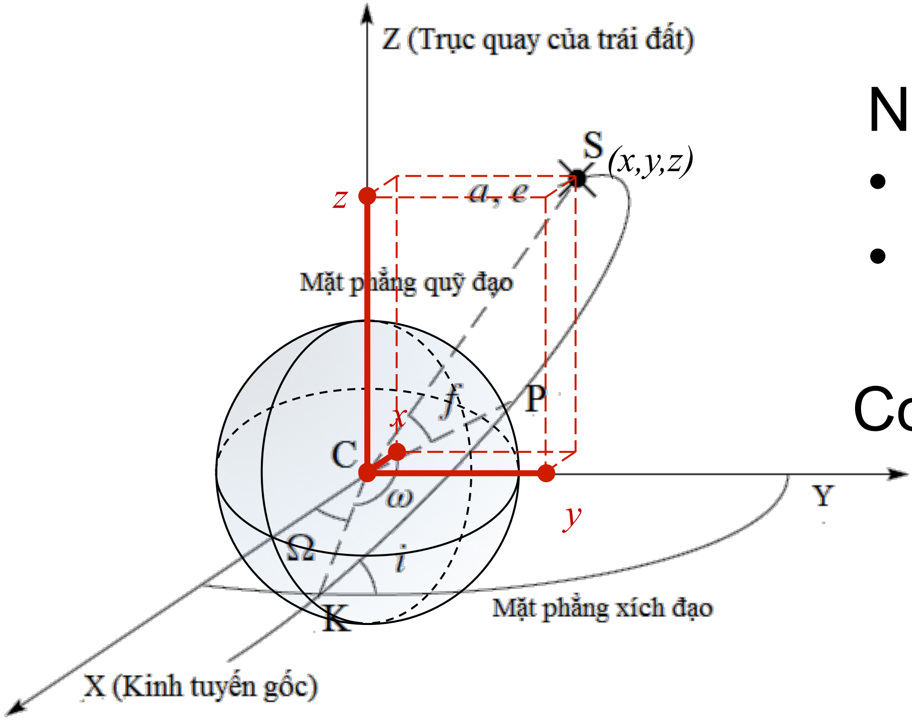
- Note: Sub-frame synchronization is important for pseudo-range measurements

Adaptations to Multi-GNSS:

Satellite Position Computation

Signal	GPS L1 C/A	GLONASS L1 OF	Galileo E1	BeiDou B1 (D1)	BeiDou B1 (D2)
Orbital Parameter *(provided by NAV. Msg)*	Kepler	ECEF	Kepler	Kepler	
Coordinate system	WGS-84	PZ-90.02	GTRF	CGCS2000	





Navigation message provides:

- Satellite positions at t_0;
- Sub-frame starting time t_k;

Computation of satellite positions at t_i

Adaptations to Multi-GNSS:

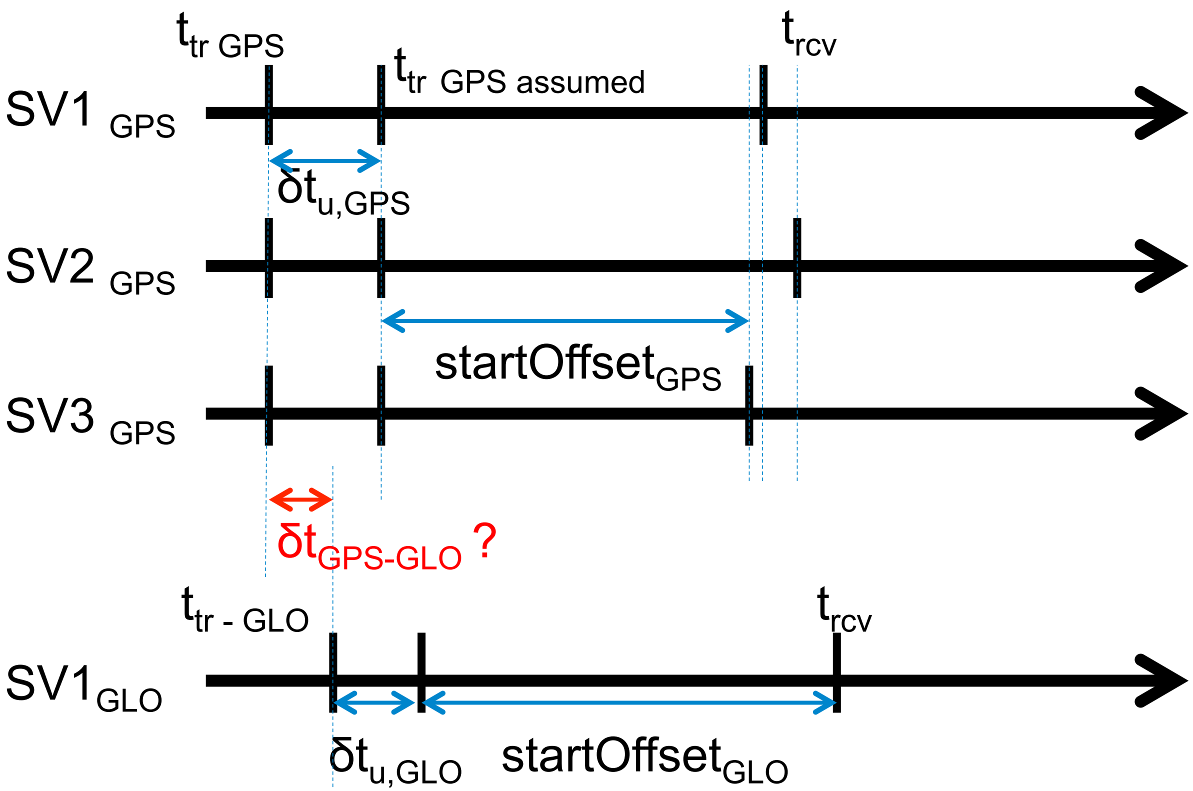
Pseudo-range Computation (1/2)

System	GPS	GLONASS	Galileo	BeiDou	
Time system	GPST	GLONASST	GST	BDT	
Orbit	MEO	MEO	MEO	MEO	GEO, IGSO
Altitude	20180 km	19140 km	23222 km	21528 km	35786 km
Approx. travel time	70 ms	66,53 ms	80,15 ms	74,5 ms	122,06 ms

- Facts:
  - Ranges are computed via estimated travel time;
  - In fact, only pseudo-ranges are derived because of bias between satellite and receiver clocks;
  - Different GNSSes use different time systems.
  - In a GNSS, all satellites are synchronized to a common time system;

Adaptations to Multi-GNSS:

Pseudo-range Computation (2/2)



- t_{tr}: real transmit time of GPS;
- $t_{tr\ assumed}$: assumed transmit time;
- startOffset: assumed shortest travel time;
- $\delta t_{GPS-GLO}$: different between GPS and GLONASS time systems

Adaptations to Multi-GNSS:

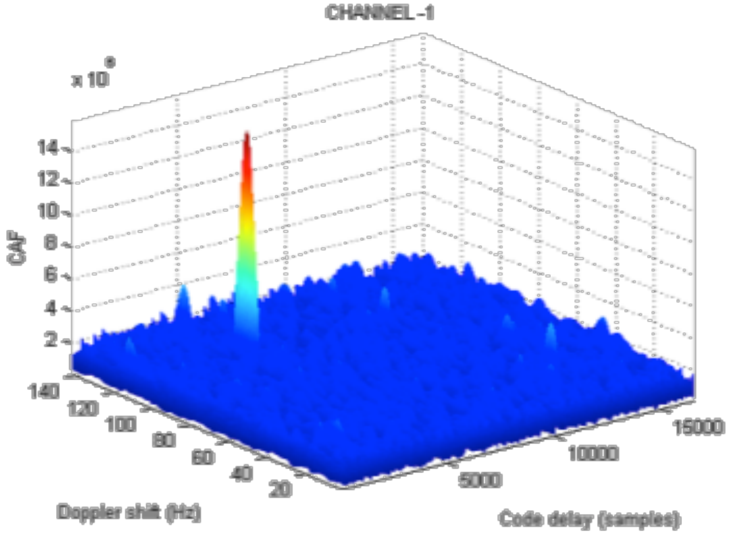
PVT Computation: Navigation equations

- Stand-alone GNSS:
  - 4 equations needs 4 satellites
- Multi-GNSSes:
  - Each system has its own time system;
  - Extra unknowns for these differences; or
  - Use the time system offsets broadcasted by GNSSes, e.g. GPS-Galileo offset; GPS-Beidou offset…

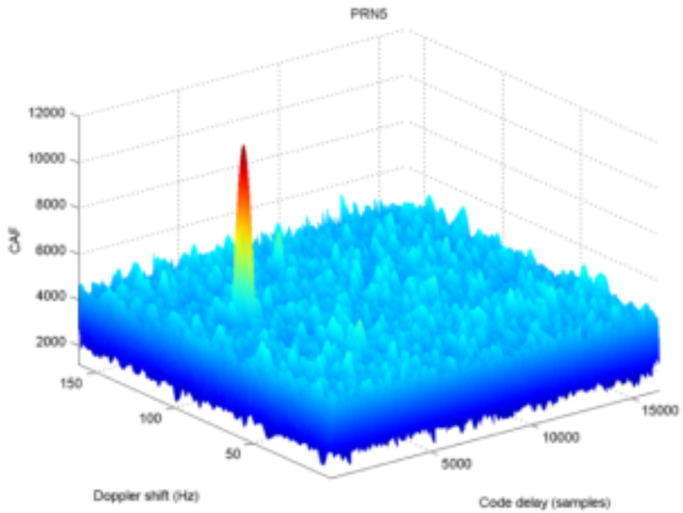
$$
\begin{cases}
\rho_{1,GPS} = \sqrt{(x_{1,GPS} - x_u)^2 + (y_{1,GPS} - y_u)^2 + (z_{1,GPS} - z_u)^2} + ct_{GPS} \\
\rho_{2,GPS} = \sqrt{(x_{2,GPS} - x_u)^2 + (y_{2,GPS} - y_u)^2 + (z_{2,GPS} - z_u)^2} + ct_{GPS} \\
\vdots \\
\rho_{i,GPS} = \sqrt{(x_{i,GPS} - x_u)^2 + (y_{i,GPS} - y_u)^2 + (z_{i,GPS} - z_u)^2} + ct_{GPS} \\
\vdots \\
\rho_{i,Gal} = \sqrt{(x_{i,Gal} - x_u)^2 + (y_{i,Gal} - y_u)^2 + (z_{i,Gal} - z_u)^2} + ct_{Gal} \\
\vdots \\
\rho_{i,Glo} = \sqrt{(x_{i,Glo} - x_u)^2 + (y_{i,Glo} - y_u)^2 + (z_{i,Glo} - z_u)^2} + ct_{Glo} \\
\vdots \\
\rho_{i,Bei} = \sqrt{(x_{i,Bei} - x_u)^2 + (y_{i,Bei} - y_u)^2 + (z_{i,Bei} - z_u)^2} + ct_{Bei} \\
\vdots
\end{cases}
\quad (1)
$$

Result Analyses: Acquisition

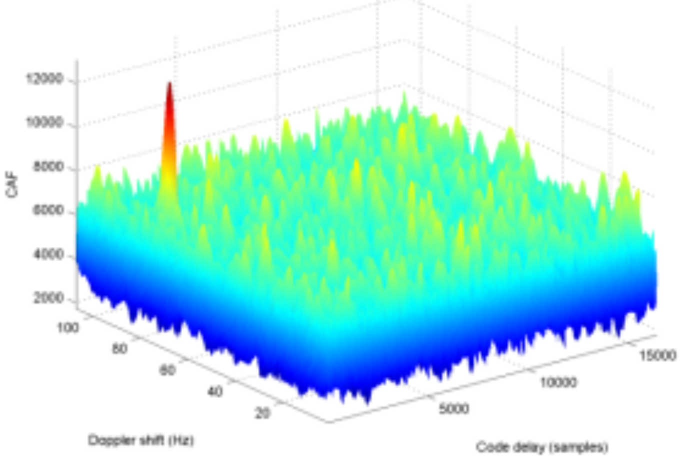
GLONASS PRN 1



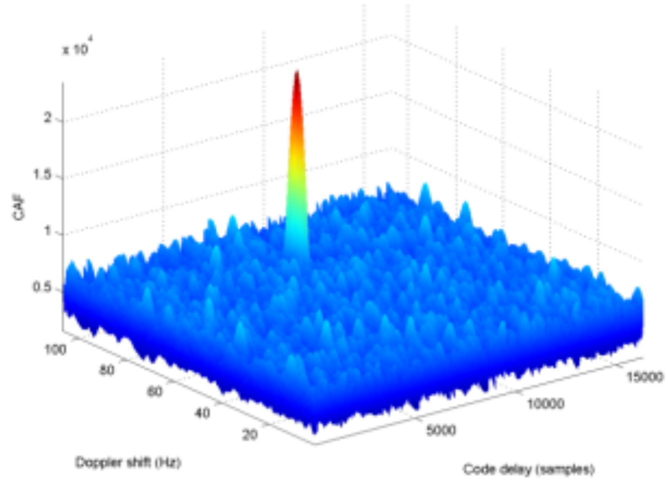
Beidou PRN 5



Galileo PRN 20

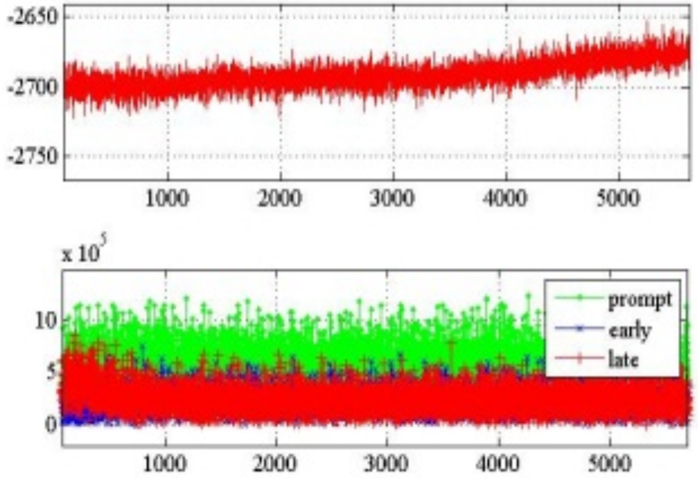


GPS PRN 22



Result Analyses: Tracking

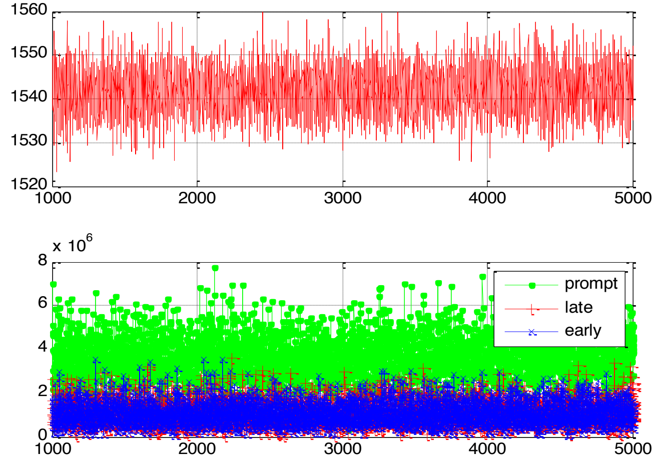
GLONASS PRN 1



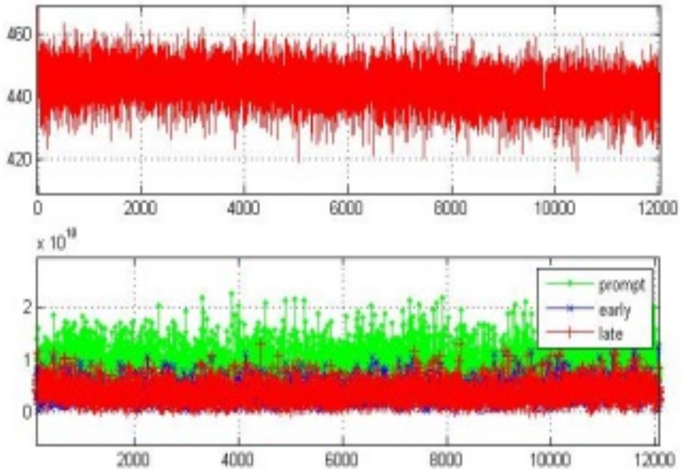
PLL output

DLL output

Beidou PRN 5



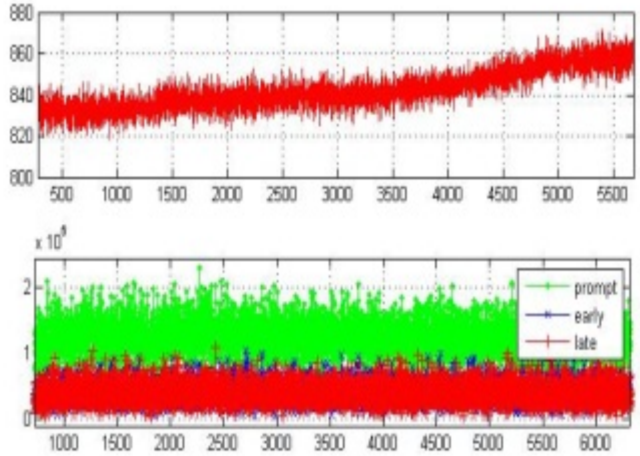
Galileo PRN 20



PLL output

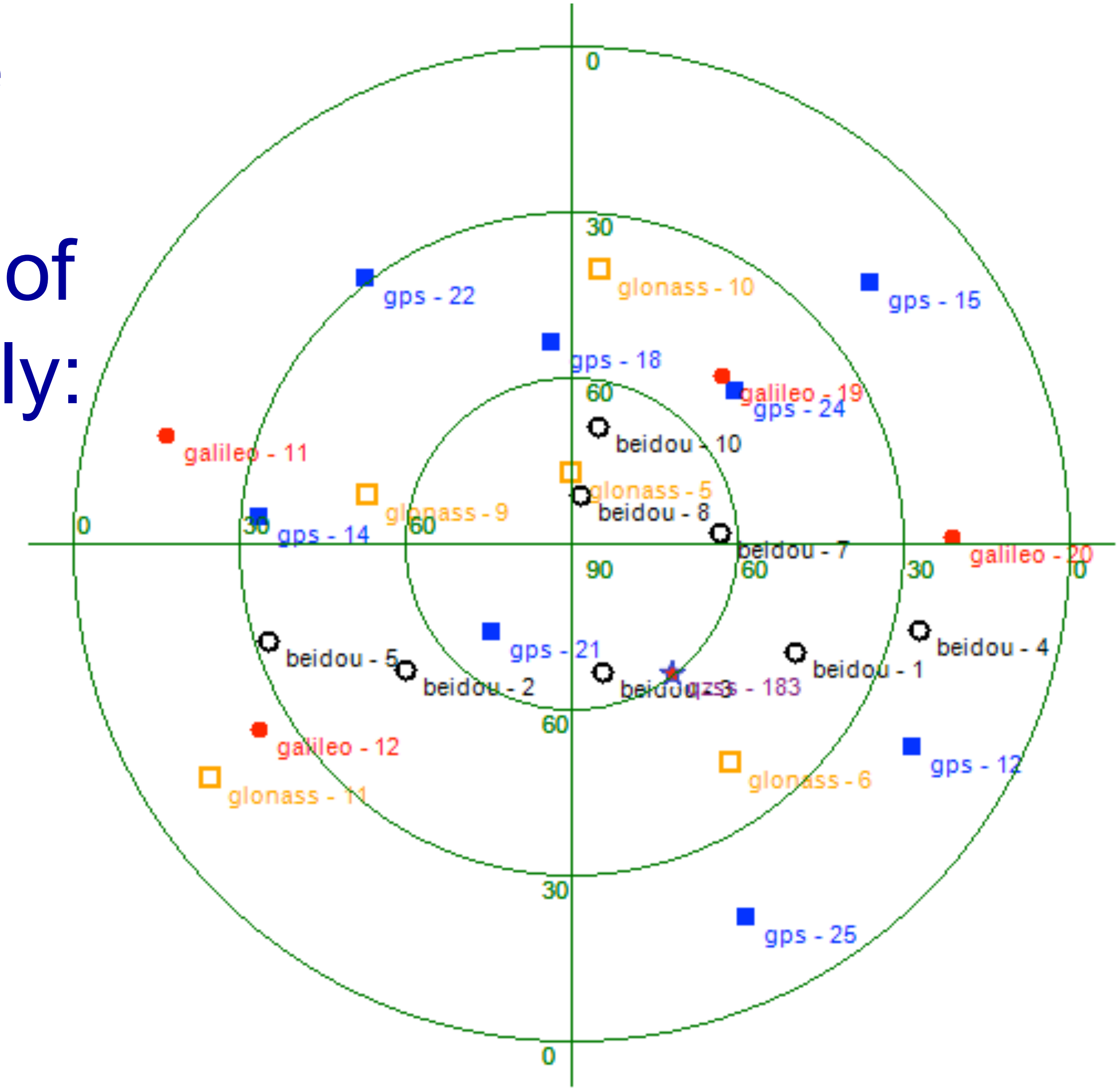
DLL output

GPS PRN 22



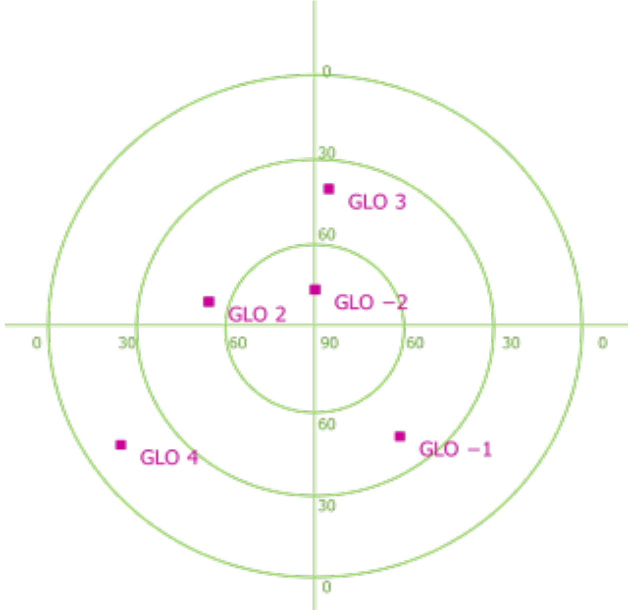
Result Analyses: Data demodulation

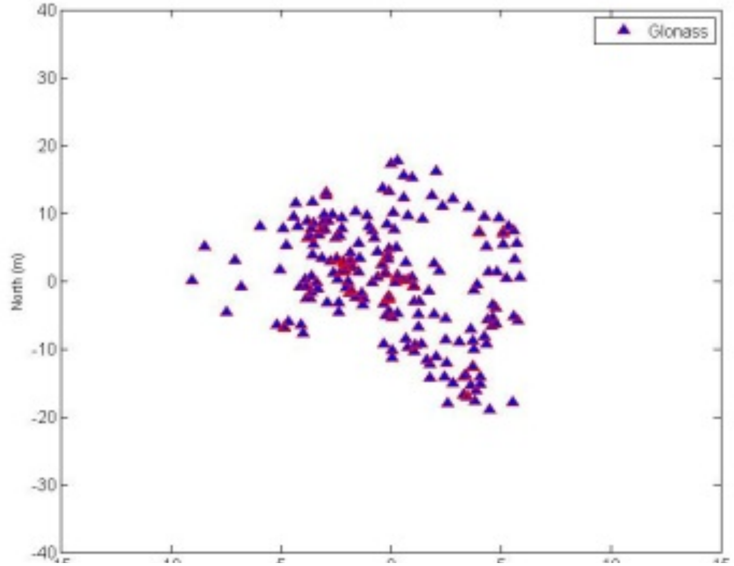
- Sky-plot (satellite positions): 26 satellites-in-view of 5 systems, namely:
  - 8 GPS;
  - 4 Galileo;
  - 5 GLONASS;
  - 8 Beidou;
  - 1 QZSS.



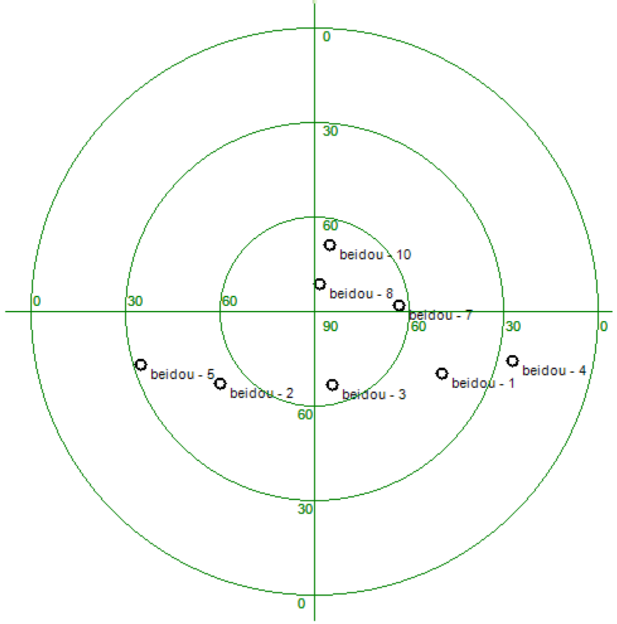
Result Analyses: Stand-alone Positioning (1/3)

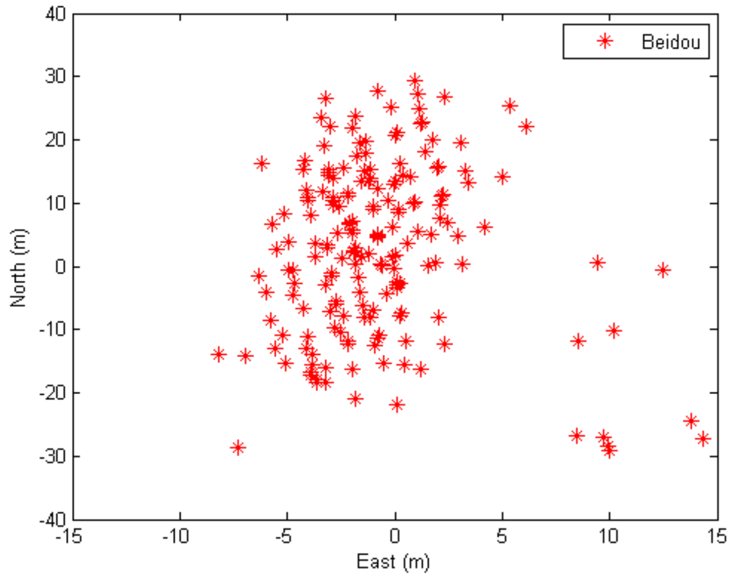
GLONASS





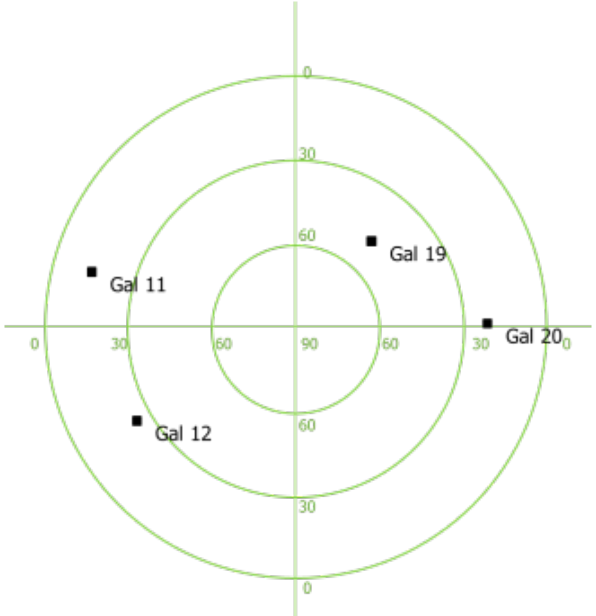
Beidou

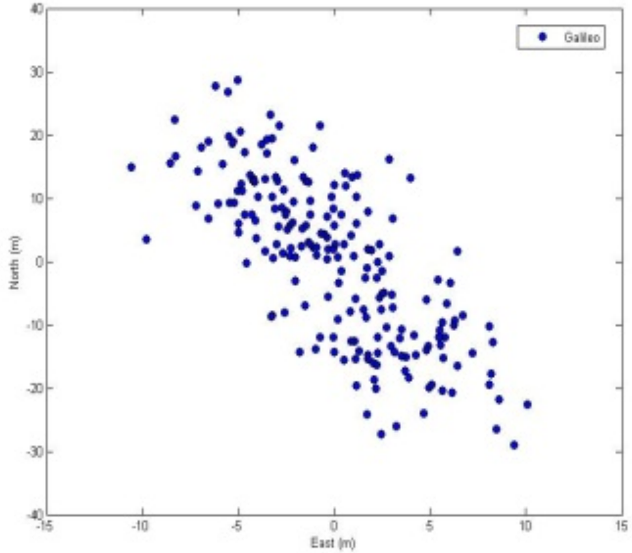




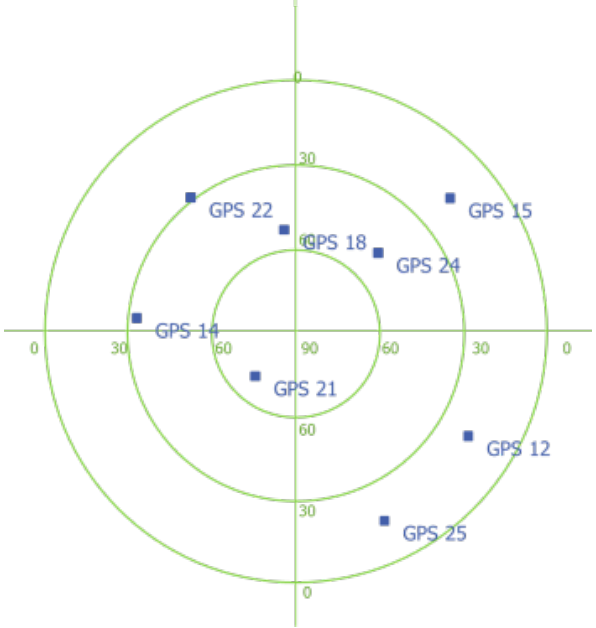
Result Analyses: Stand-alone Positioning (2/3)

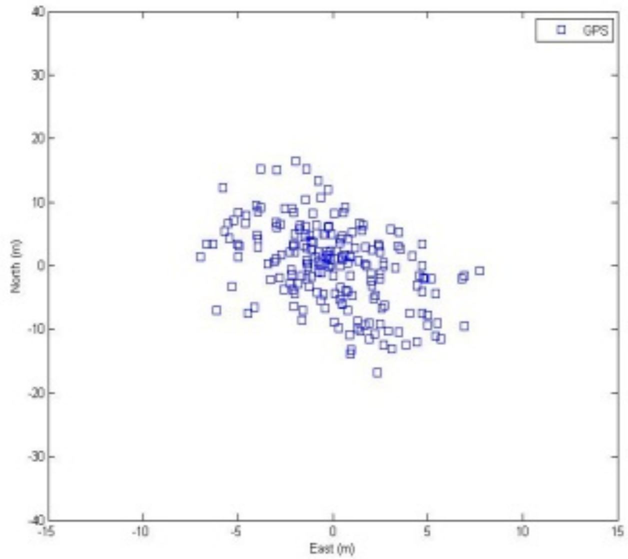
Galileo





GPS



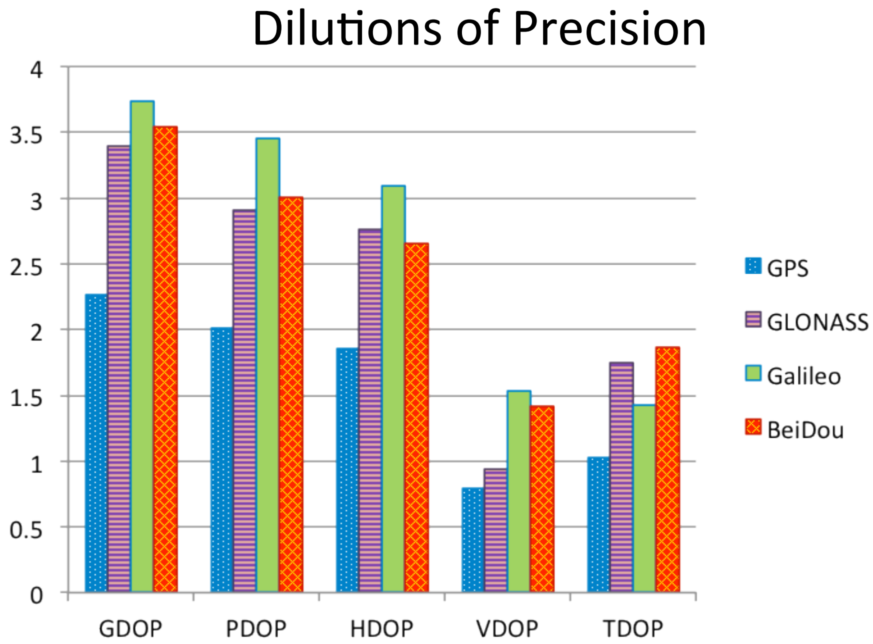


Result Analyses: Stand-alone Positioning (2/3)

- Accuracy of GNSSes at the campaign

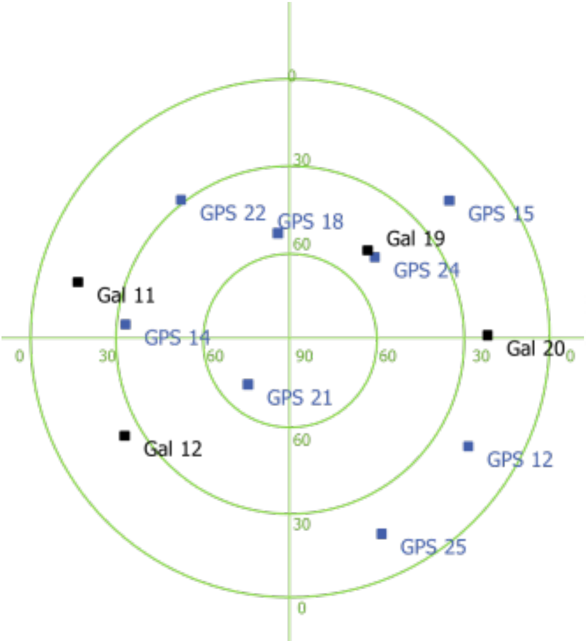
Horizontal Errors

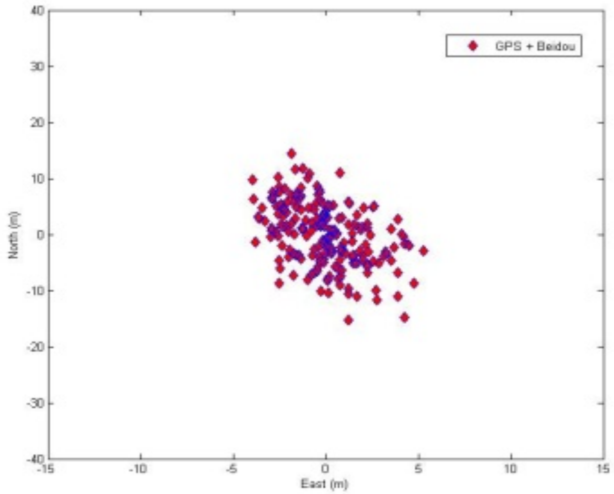
System	δ_{East} (m)	δ_{North} (m)
Glonass	3.2584	8.1746
Beidou	3.7629	13.4952
Galileo	4.0887	12.8882
GPS	2.9859	6.3924



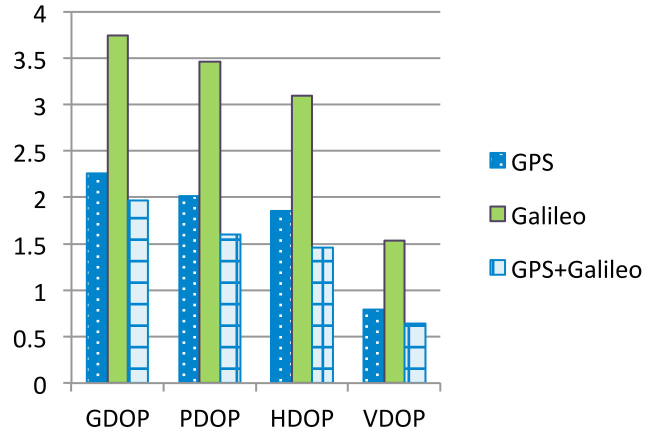
Result Analyses: Multi-GNSS Positioning

GPS+Galileo





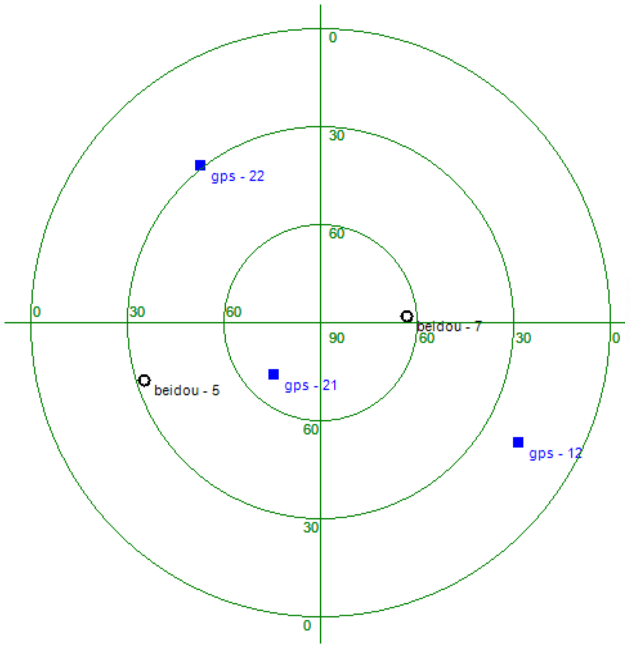
δ_{East} = 2.4029 m δ_{North} = 5.8056 m

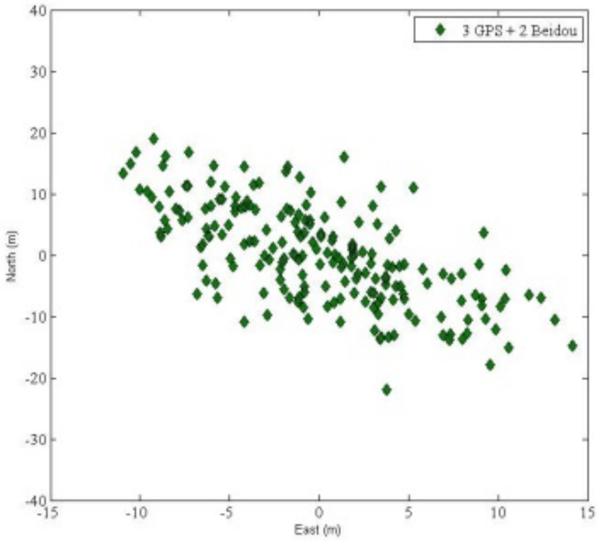


- GPS L1 C/A and Galileo BOC(1,1) are two interoperability signals:
  - Common carrier frequency;
  - Mutual interference mitigation (BOC modulation).

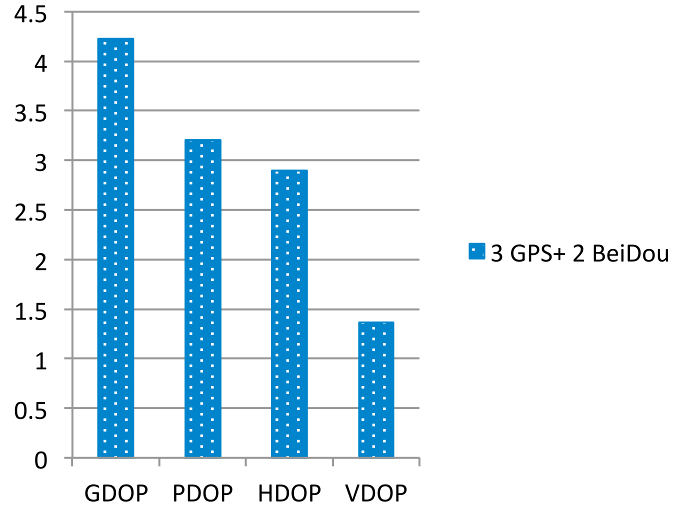
Suitable for combined positioning

Result Analyses: Multi-GNSS Positioning
3 GPS + 2 Beidou



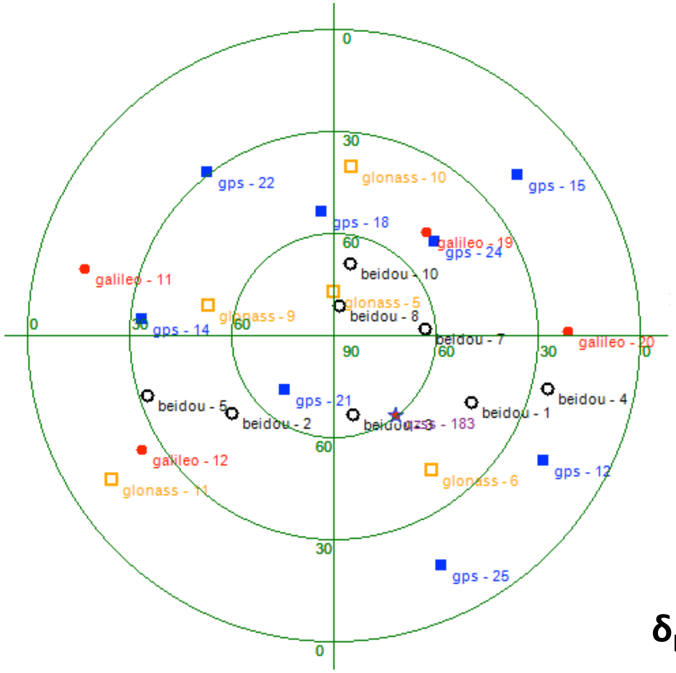


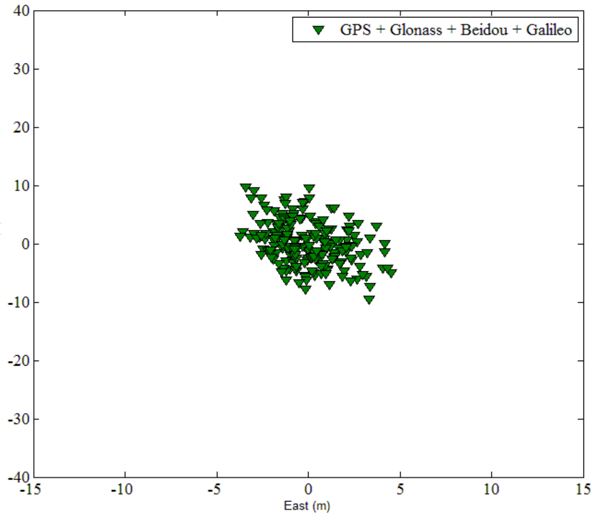
δ_{East} = 5.4983 m δ_{North} = 8.0544 m

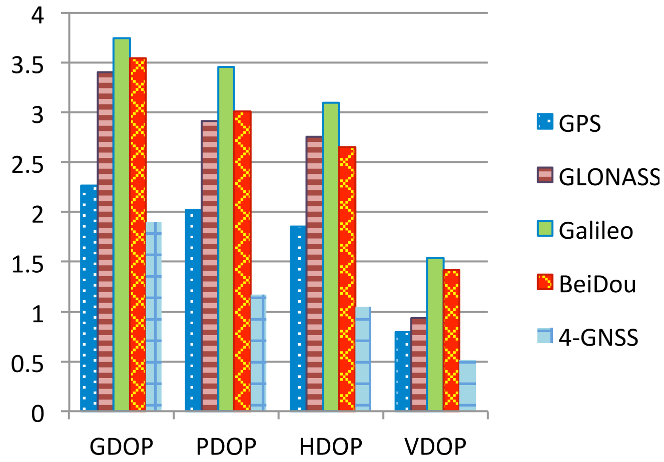


- Geostationary SVs of Beidou always visible at high elevation in SEA

Result Analyses: Multi-GNSS Positioning
All GNSSes + QZSS







δ_{East} = 1.7582 m δ_{North} = 3.7840 m

- GPS/GLONASS/Galileo/Beidou/QZSS: 26 satellites are involved
- Better accuracy in comparison with any stand-alone
- But complexity increase

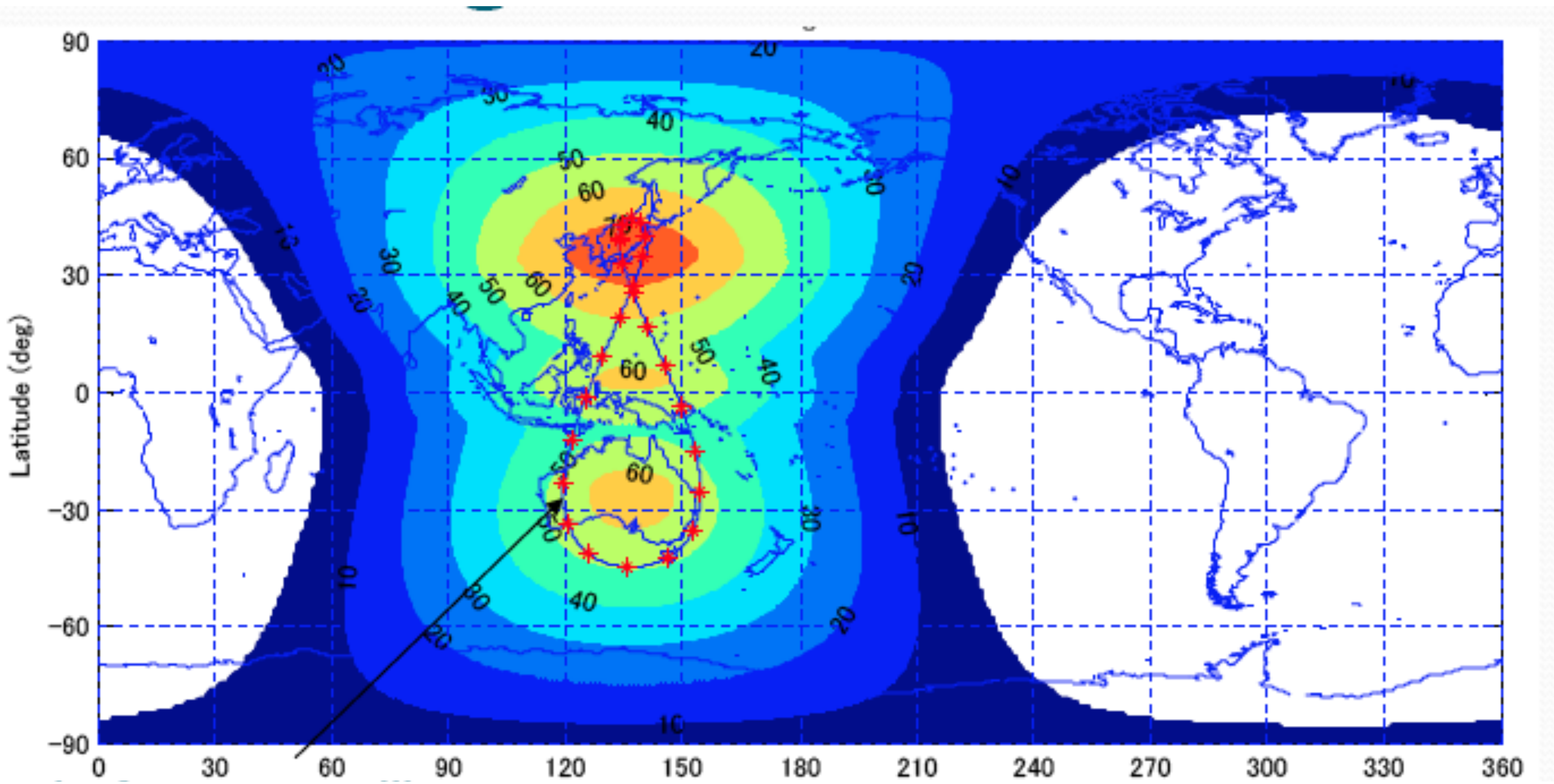
Content

1. **Multi-GNSS Environment**
   – Challenges of Multi-GNSS Environment
   – Advantages of Multi-GNSS Environment
2. **Multi-GNSS Signal Processing Chain**
   – Experiment Result
3. **QZSS augmentation services:**
   – Sub-meter class: L1-SAIF;
   – Centimeter class: L6-LEX.
4. **Conclusions**

Overview of QZSS

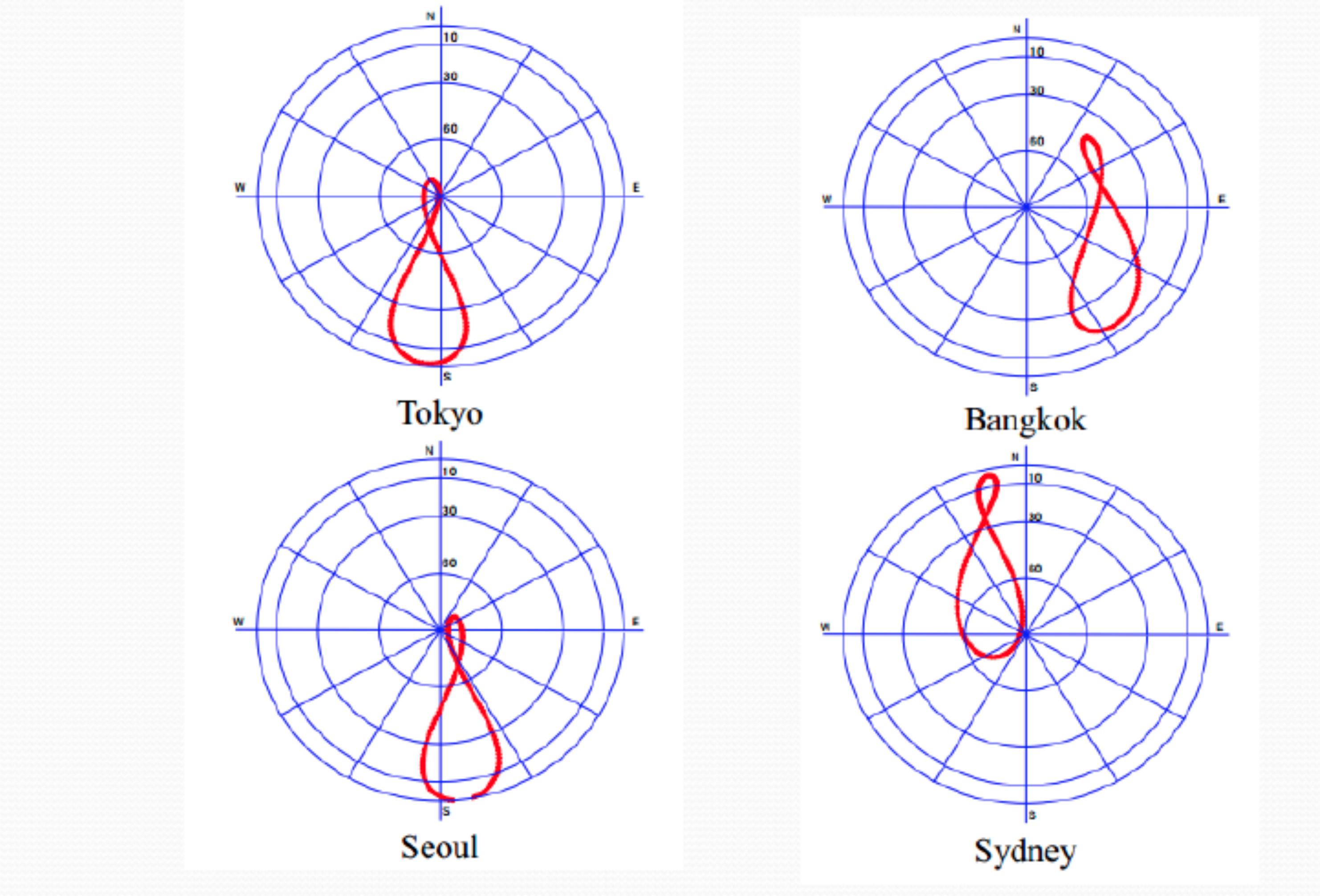
- The Quasi-Zenith Satellite System (QZSS) is a RNSS of Japan.
- Functional Capability:
  - GNSS Complementary
  - GNSS Augmentation:
    - Sub-metter class
    - Centimeter class
  - Messaging Service
- Signals:
  - L1C/A, L1C, L2C and L5
  - L1S (L1-SAIF)
  - L6 (LEX)
- 2018: provide services by 4 SVs

- Coverage: East Asia and Pacific Region



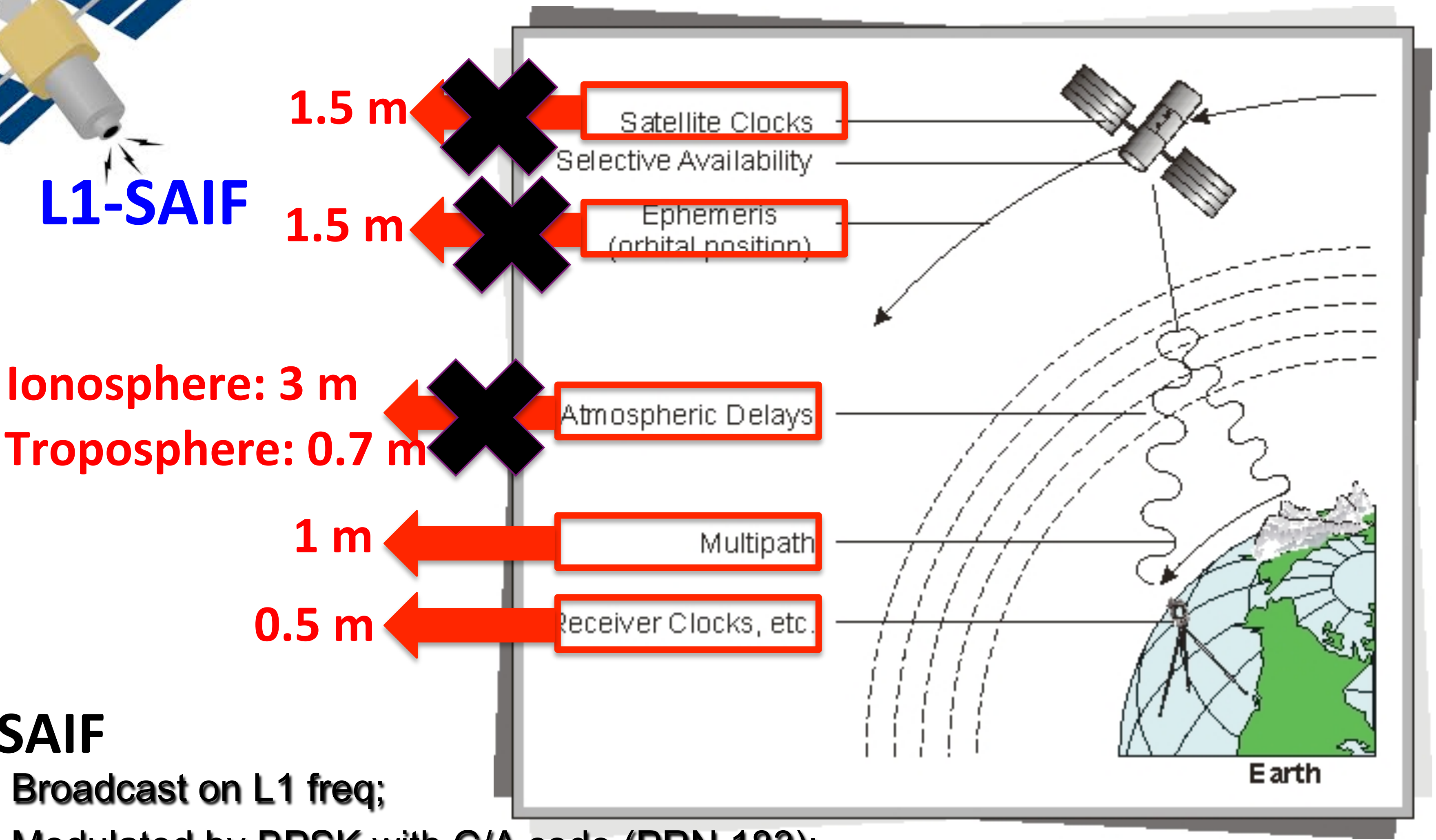
Ground Track of a QZSS satellite

- Elevation and Azimuth of the 1st SV: Michibiki



Elevation and Azimuthal angles for each city (Observation EPOCH = 2009/Dec/26/12:00 UTC)

Sub-meter class: L1-SAIF



L1-SAIF

– Broadcast on L1 freq;
– Modulated by BPSK with C/A code (PRN 183);
– 250 bps data rate with 1/2 FEC; message structure is identical with SBAS;
– Differences from GPS L1C/A: Large Doppler and additional messages.

L1-SAIF Error Correction Algorithm

- Clock and Orbit error correction (Long-term correction):

$$\Delta t_{SV,i}^{corrected} = \Delta t_{SV,i} + \delta\Delta t_{SV,i}$$

Clock Error Correction parameter

$$\begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{corrected} = \begin{bmatrix} x_i \\ y_i \\ z_i \end{bmatrix}_{ephemeris} + \begin{bmatrix} \delta x_i \\ \delta y_i \\ \delta z_i \end{bmatrix}$$

the x-, y- and z- Orbital Position Error Correction parameters

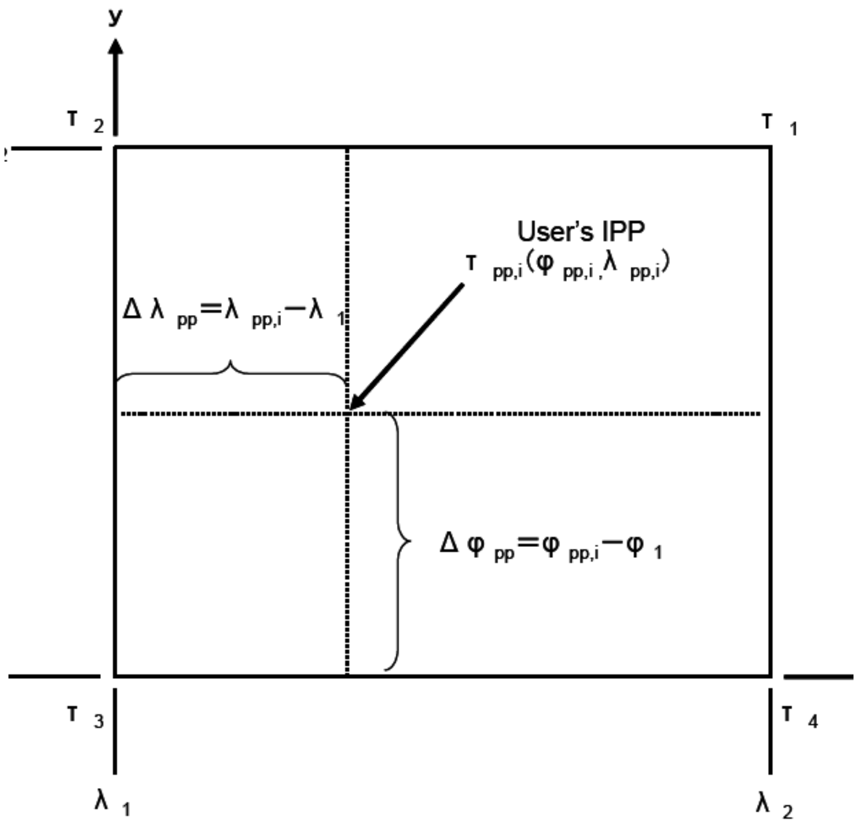
- Fast Correction and Atmospheric Delay Correction

$$PR_i^{corrected} = PR_i^{measured} + FC_i + IC_i + TC_i$$

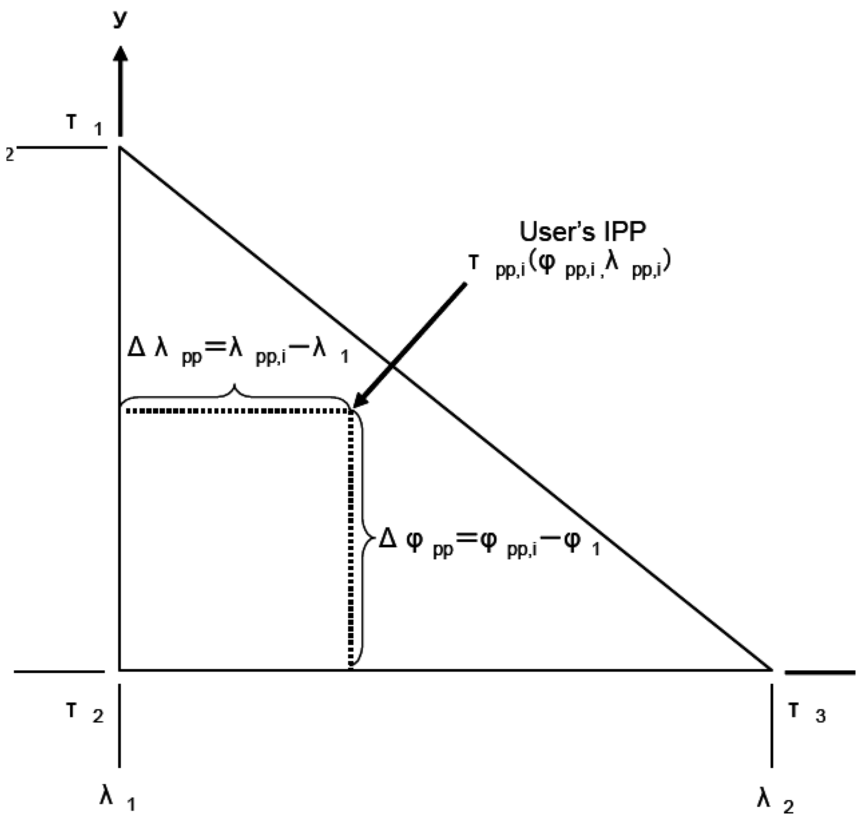
correction of SV onboard clock variation (FC) **Ionospheric delay** (IC) **Tropospheric delay** (TC)

- Ionospheric delay correction:
  - ✓ Step 1: Determination of Ionospheric Pierce Point (IPP) based on 4 surrounding Ionospheric Grid Points
  - ✓ Step 2: Computation of Ionospheric Correction

Case a: 4 surrounding IGPs

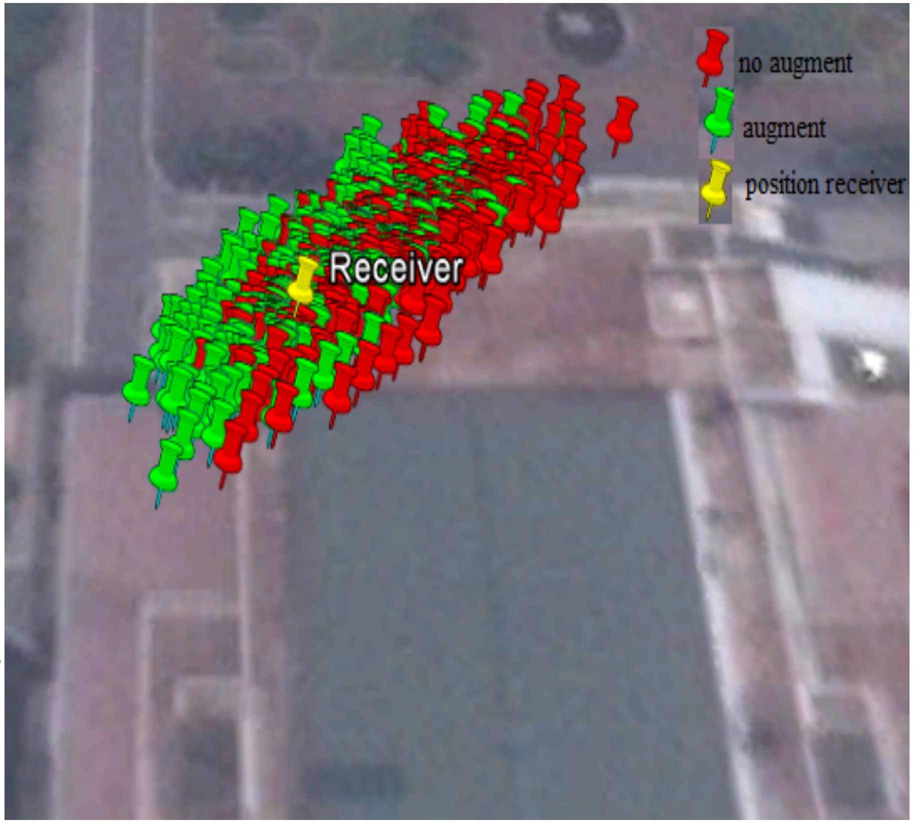


Case b: 3 surrounding IGPs



Experiment Results with L1-SAIF

- Long term correction and Fast Correction are available
- However, ionospheric correction is not available since the there are not enough IGPs (often 2 points only)
- Therefore, the correction is not as expected at least during many campaigns, which we have done so far



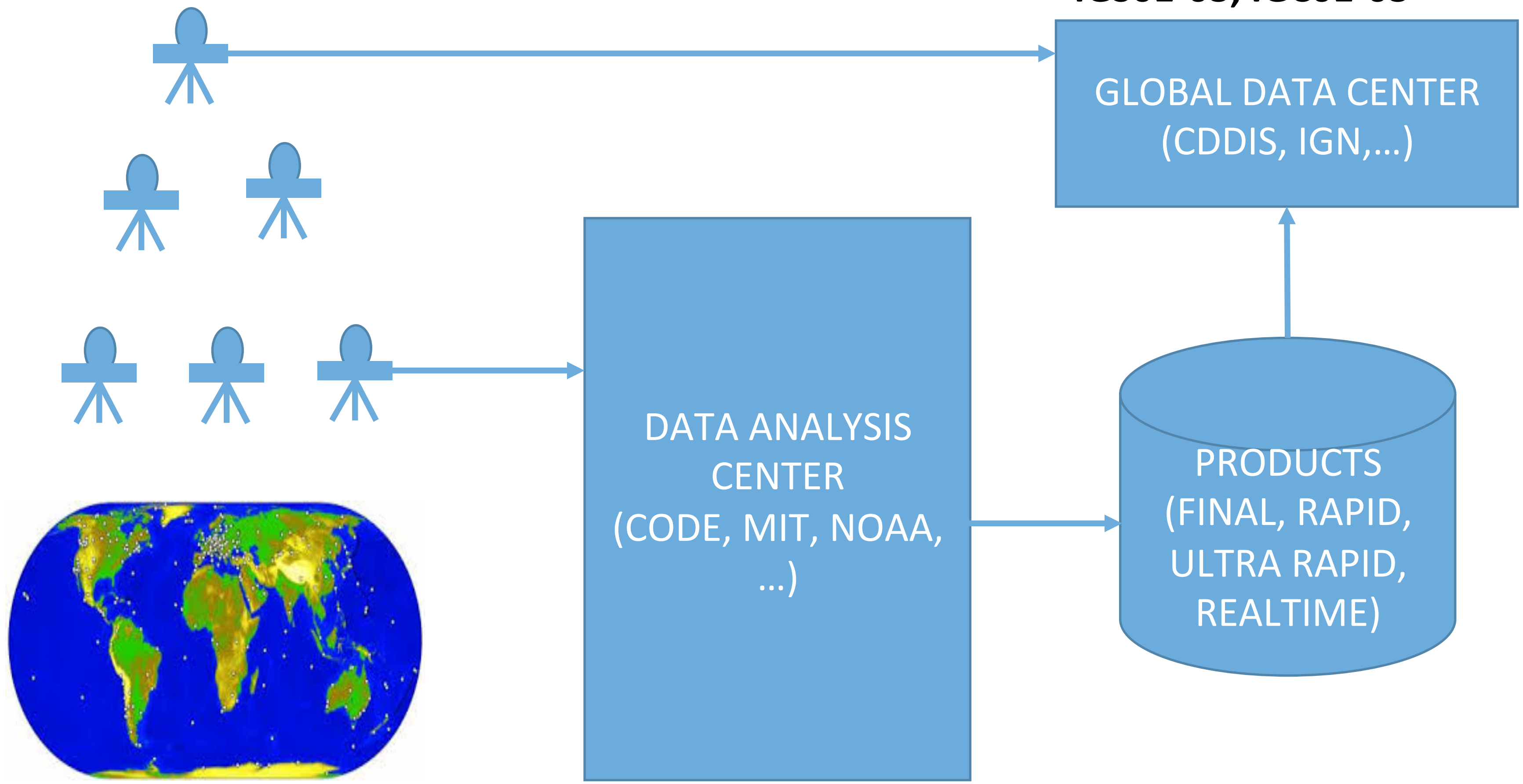
IGP No.	Long	Lat	Ionospheric delay [m]
67	110	15	-
42	105	15	3.5
41	105	10	4.125
66	110	10	-

QZSS – LEX: Centimeter Service

- Based on Precise Point Positioning (PPP) Technology:
- With single receiver (no reference station)
- Conventionally post-processing
- With recent services such as: IGS Realtime, QZSS LEX it is possible to have realtime PPP
- Need satellite orbit and clock
  - Post-processing (IGS final) or real-time (IGS RT, QZSS LEX)
  - Require observation data of tracking stations world-wide
  - Vietnam does not have any IGS station, NAVIS is the first one in MGA
  - Data format:
    - SP3 for orbit (ECEF positions of satellite mass center)
    - CLK for clock biases

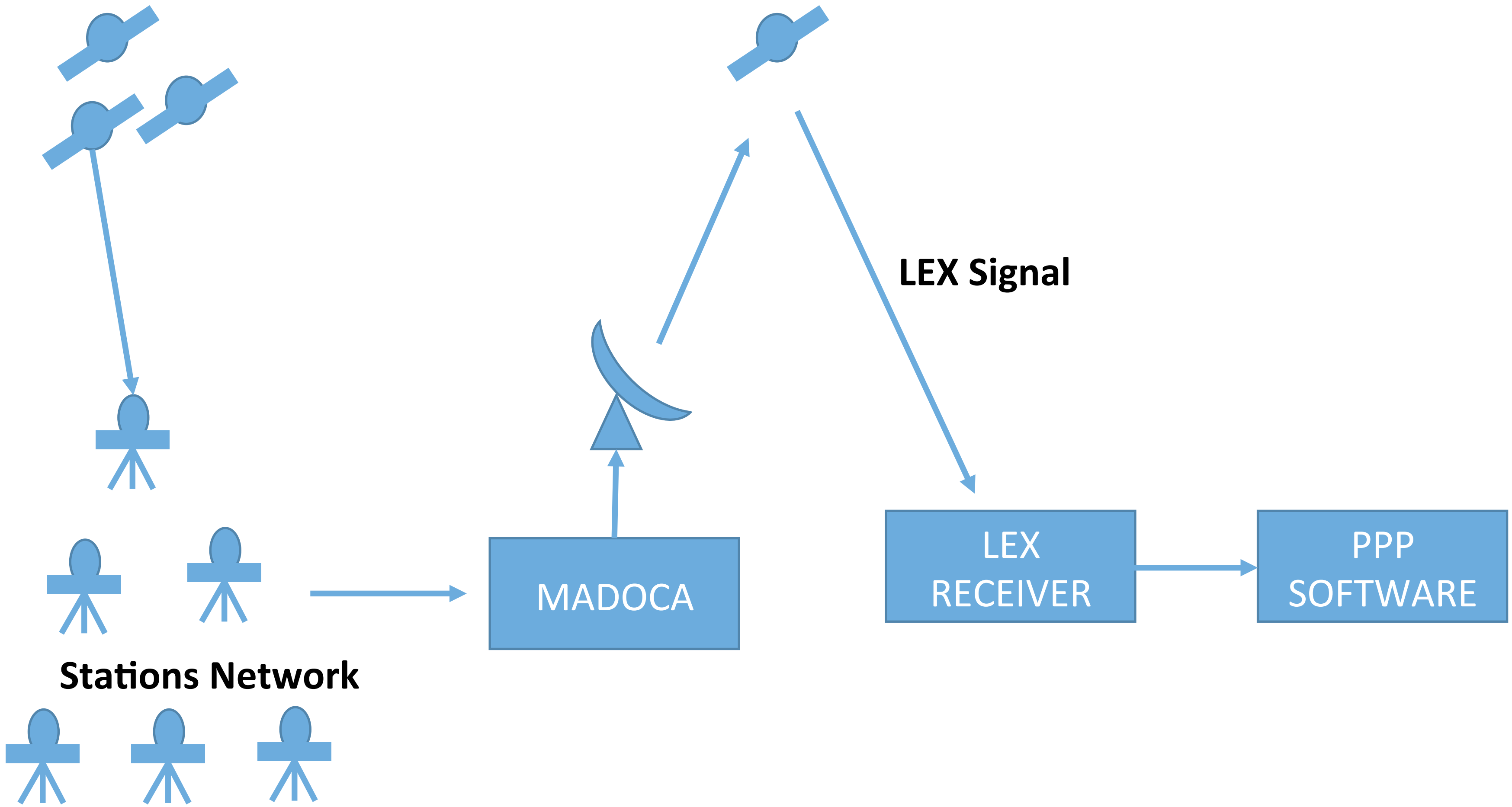
Precise Point Positioning – IGS Products

Sample IGS Realtime services:
products.igs-ip.net, mountpoint
IGS01-03, IGC01-03

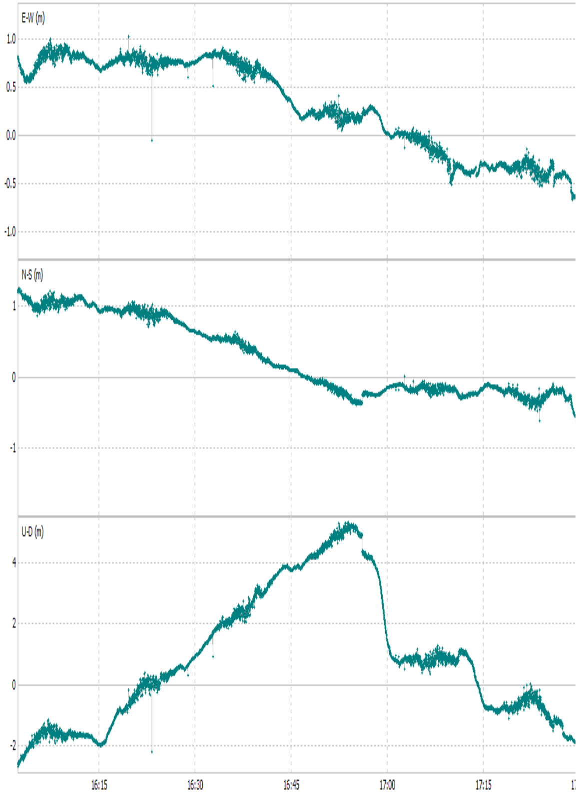


IGS Station Network

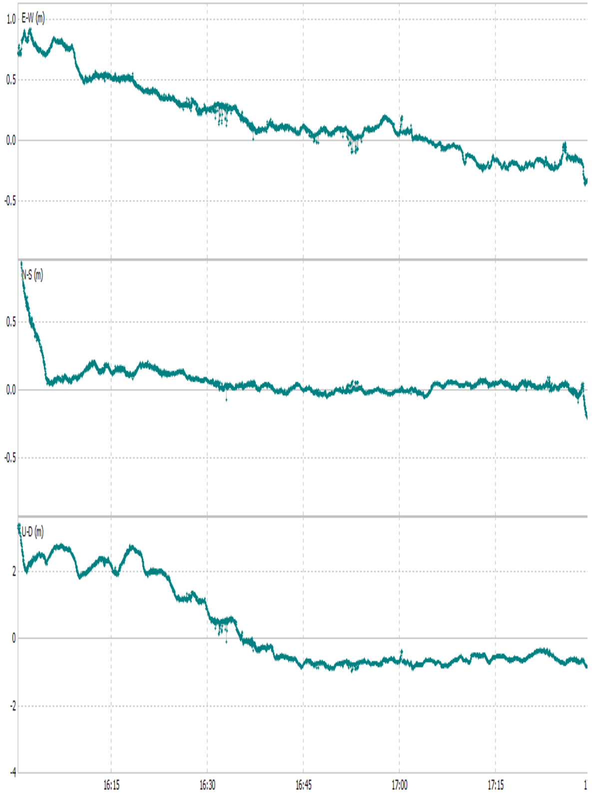
Precise Point Positioning – QZSS LEX



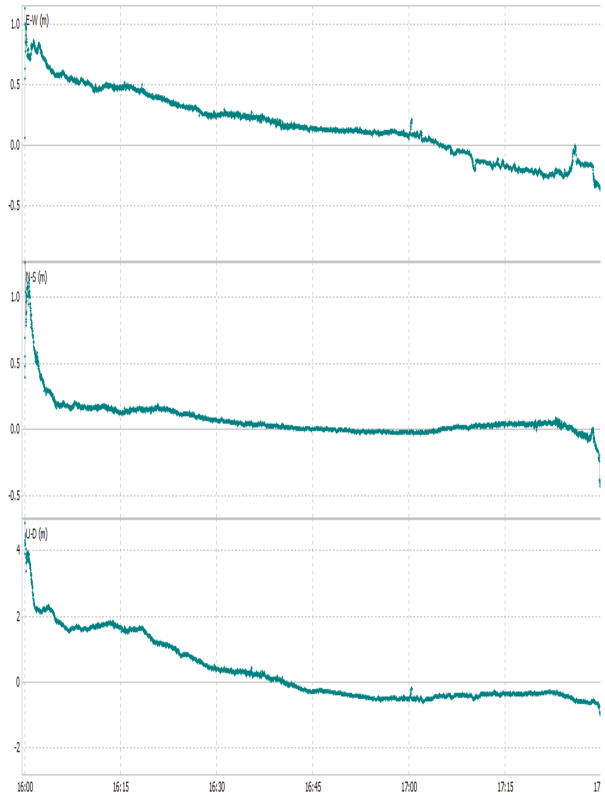
Precise Point Positioning – Some Results



Kinematic – IGS Ultra Rapid



Kinematic – IGS Rapid



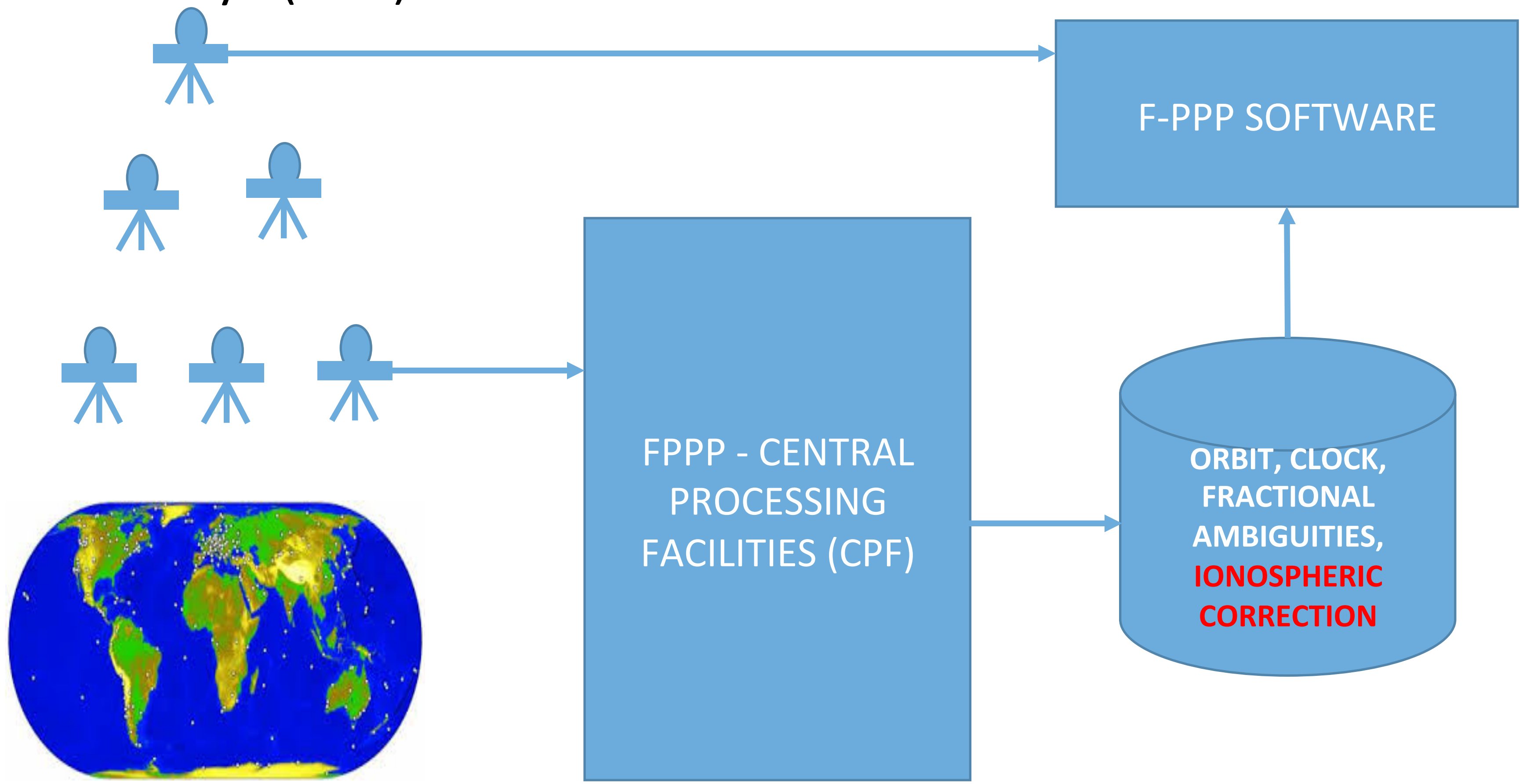
Kinematic – QZSS LEX

- LEX Realtime positioning is possible (almost as good as IGS Rapid product)
- Convergence time is still a problem (30-60 minutes to reach decimeter level in kinematic mode)

Fast Precise Point Positioning (FPPP)

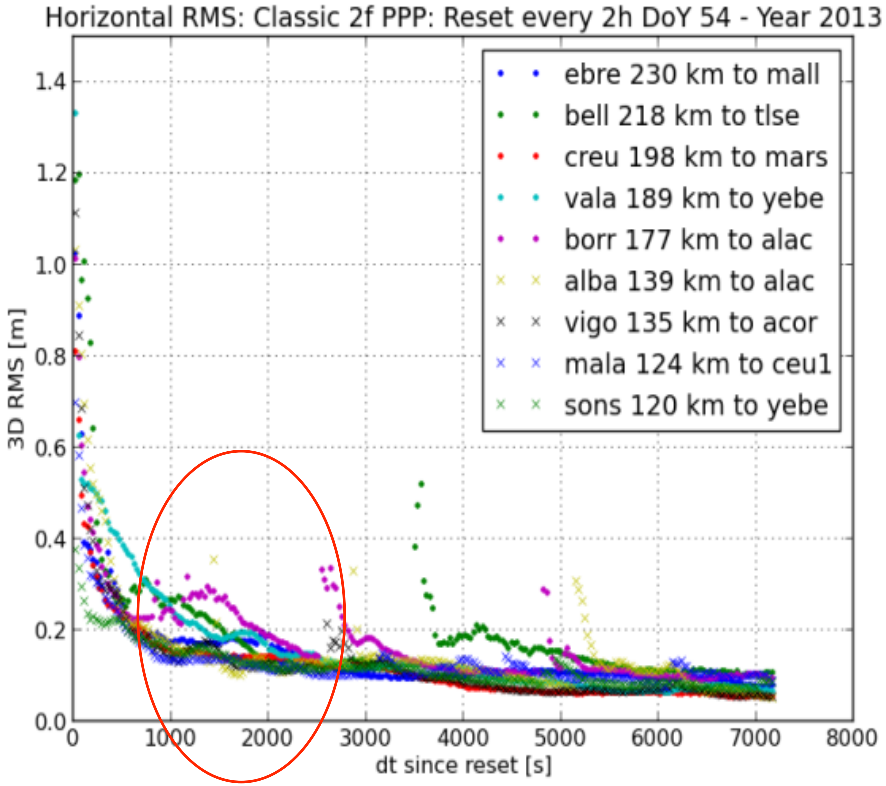
- Proposed by Research group of Astronomy and GEomatics (gAGE), Universitat Politècnica de Catalunya (UPC)

IONOSPHERIC CORRECTION will be used to fasten the convergence process of the PPP filter

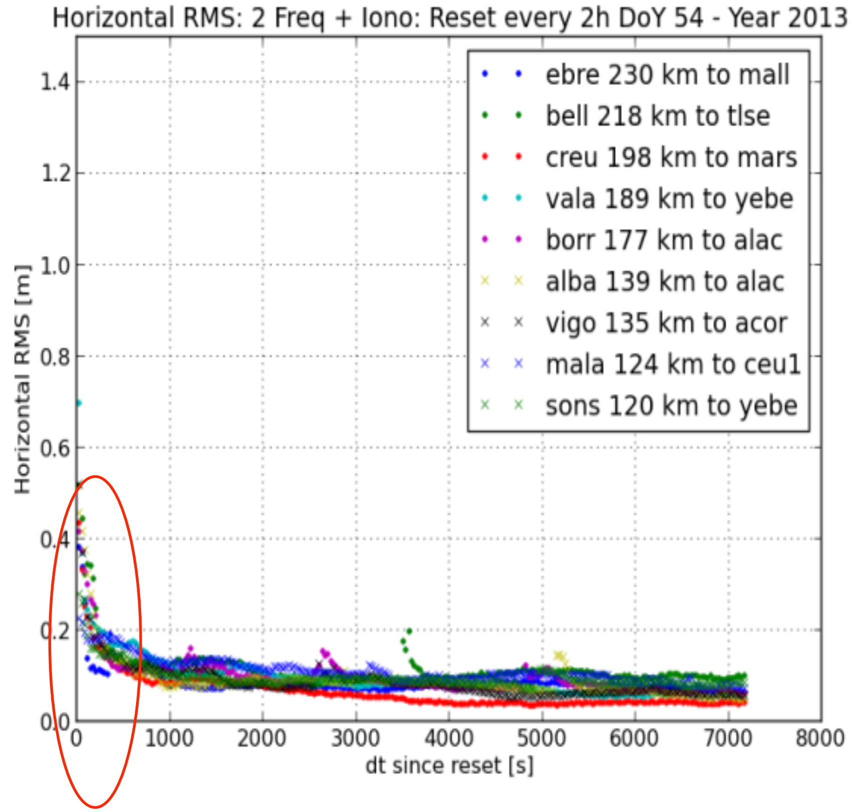


IGS Station Network

Precise Point Positioning – FPPP



Classic PPP with IGS Final



Fast PPP

Conclusions

- Multi-GNSS environment increases: availability, reliability and accuracy of the navigation services
- South-East Asia is covered by the largest number of systems (GNSSes + RNSSes) => interesting region for GNSS research
- Multi-GNSS positioning solutions are validated in South-East Asia, with results showing the advantages of multi-GNSS solutions
- QZSS-LEX is a good solution for precise positioning (no local infrastructure required, good performance…)
- … but just the beginning, exhaustive research on “smart” combinations of G(R)NSSes (with complexity & cost concerns) must be done.

Thank you very much for your attention!

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