測位航法学会 GPS/GNSSシンポジウム2011

マルチGNSS時代における精密測位技術の展望と応用

Precise Positioning Technologies in "Multi-GNSS-Era"

東京海洋大学　高須　知二

Multi-GNSS-Era

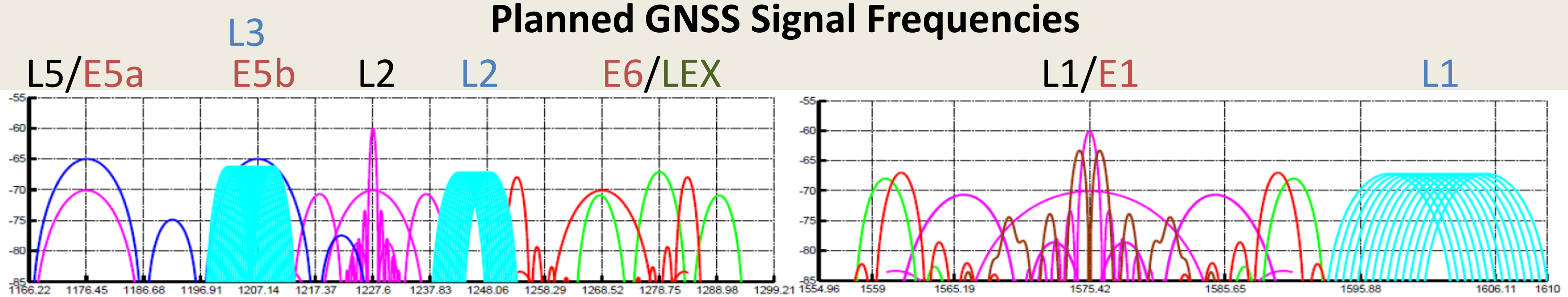
Multi-GNSS-Era

	System	Develop Operation	Satellite Orbit	G/R	Signals		Satellite Launch
					Frequency	MUX	
	GPS	US	MEO	G	L1,L2,L5	CDMA	1978-
	GLONASS	Russia	MEO	G	L1,L2,L3	FDMA CDMA	1985-
	Galileo	EU	MEO	G	E1,E5,E6	CDMA	2011-
	Compass	China	MEO+GEO +IGSO	G	B1,B2,B3,L5	CDMA	2007-
	QZSS	Japan	IGSO	R	L1,L2,L5,LEX	CDMA	2010-
	IRNSS	India	GEO+IGSO	R	L5,S	CDMA	2013-?
	SBAS	US, ...	GEO	R	L1(,L5)	CDMA	-

GNSS Constellation

System	2011	2014	2017	2020
GPS	31 (+1)	32	32	32
GLONASS	24 (+3)	24 (+6)	24 (+6)	24 (+6)
Galileo	0	12	27 (+3)	27 (+3)
Compass	8	12	30	35
QZSS	1	3	4	7
IRNSS	0	7	7	7
SBAS	7	11	11	11
Total	**71**	**101**	**135**	**143**

Planned GNSS Signal Frequencies



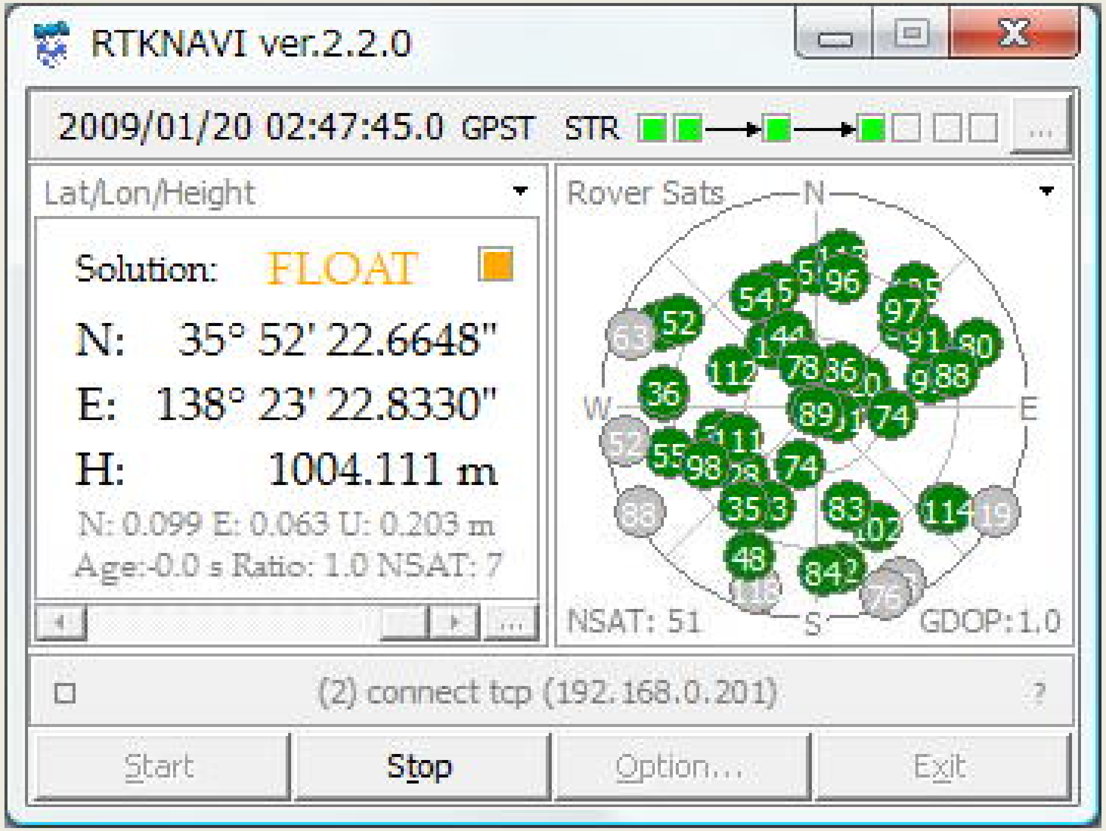
(Y.Yang, COMPASS: View on Compatibility and Interoperability, 2009)

iPhone 4S supports GLONASS !?

Location	• Assisted GPS and GLONASS • Digital compass • Wi-Fi • Cellular

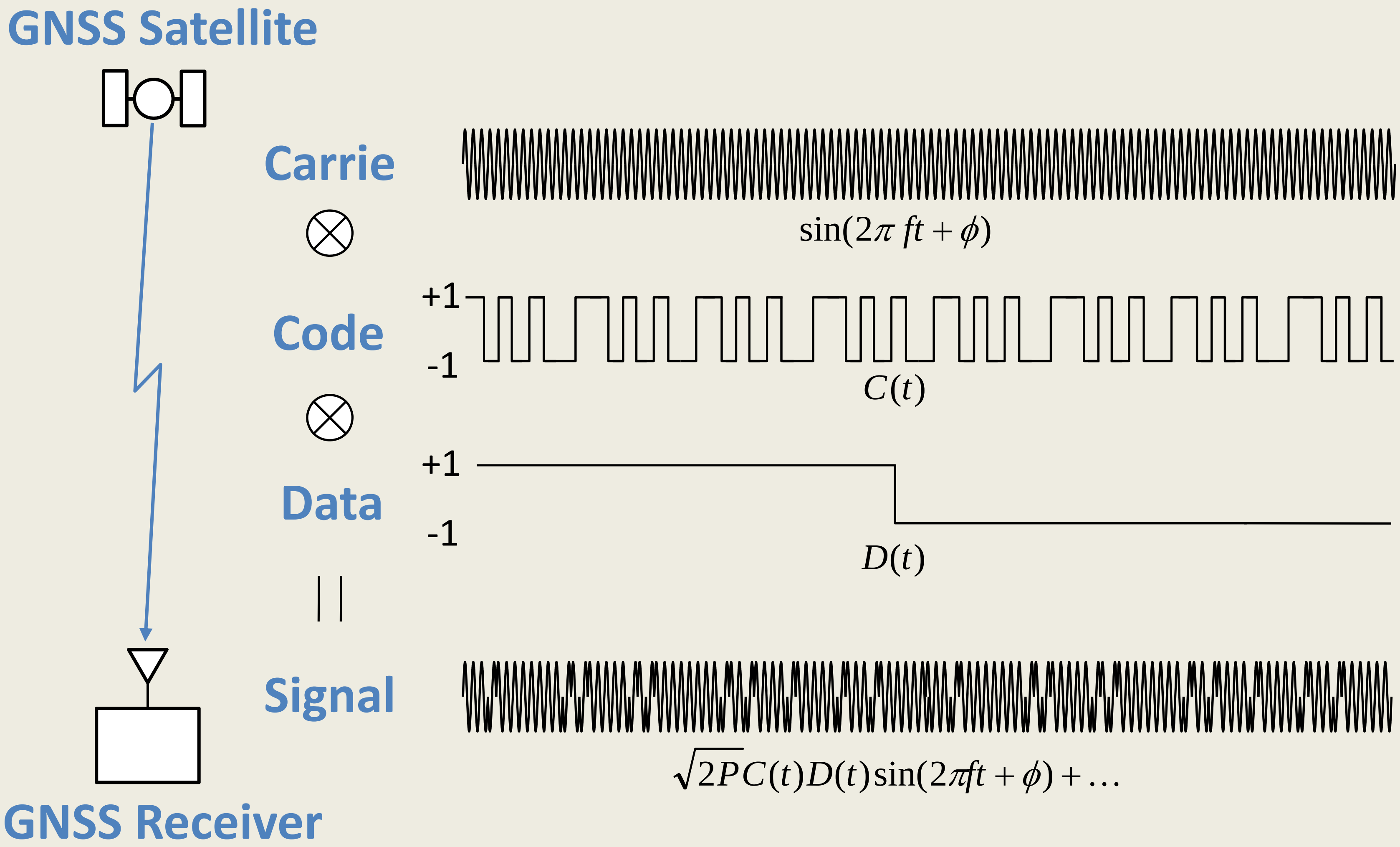
http://www.apple.com

GPS+GLO+Galileo+Compass+QZSS

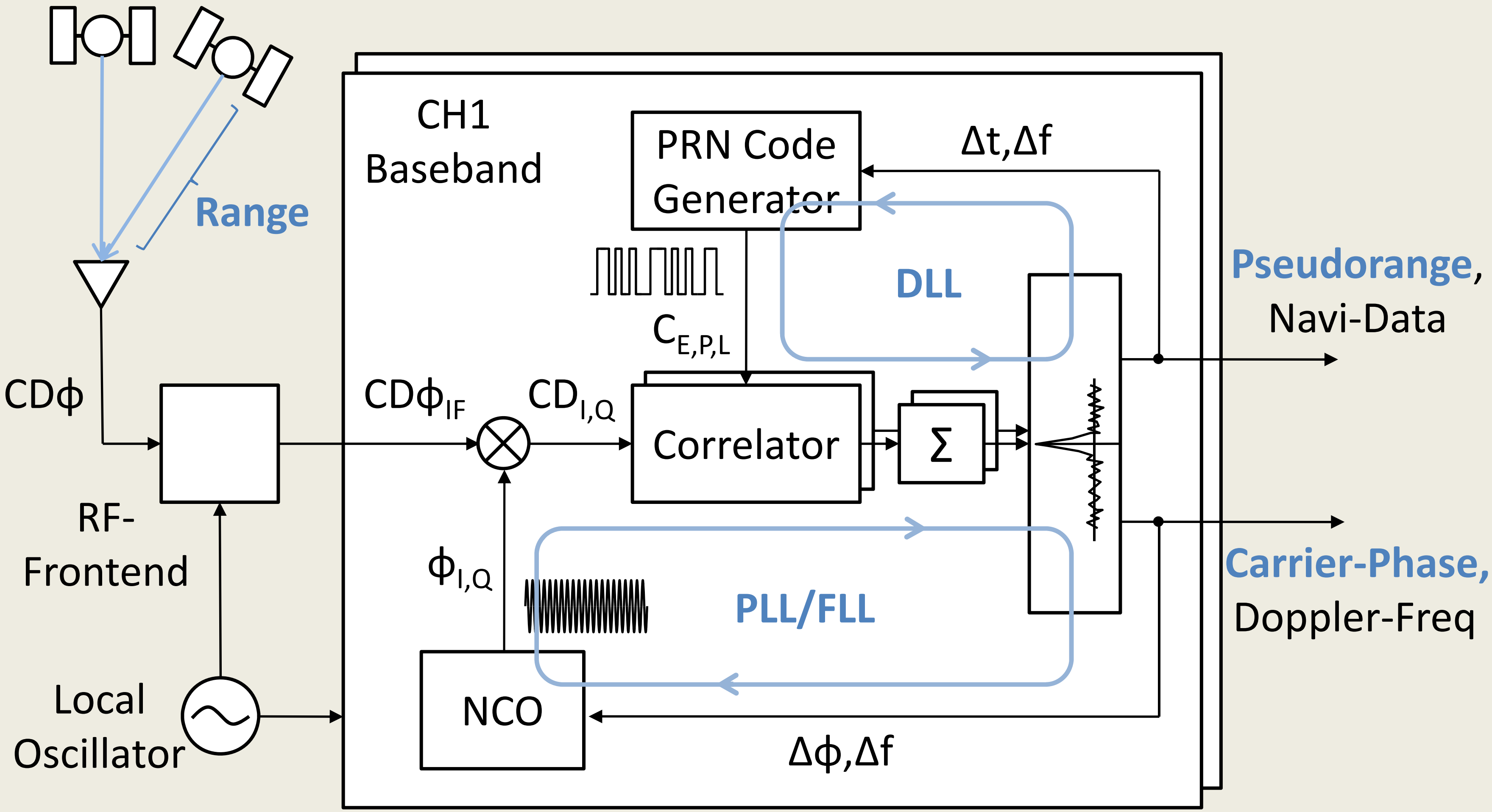


RTK and PPP

GNSS Signal Structure



GNSS Receiver



Code vs Carrier-Based Positioning

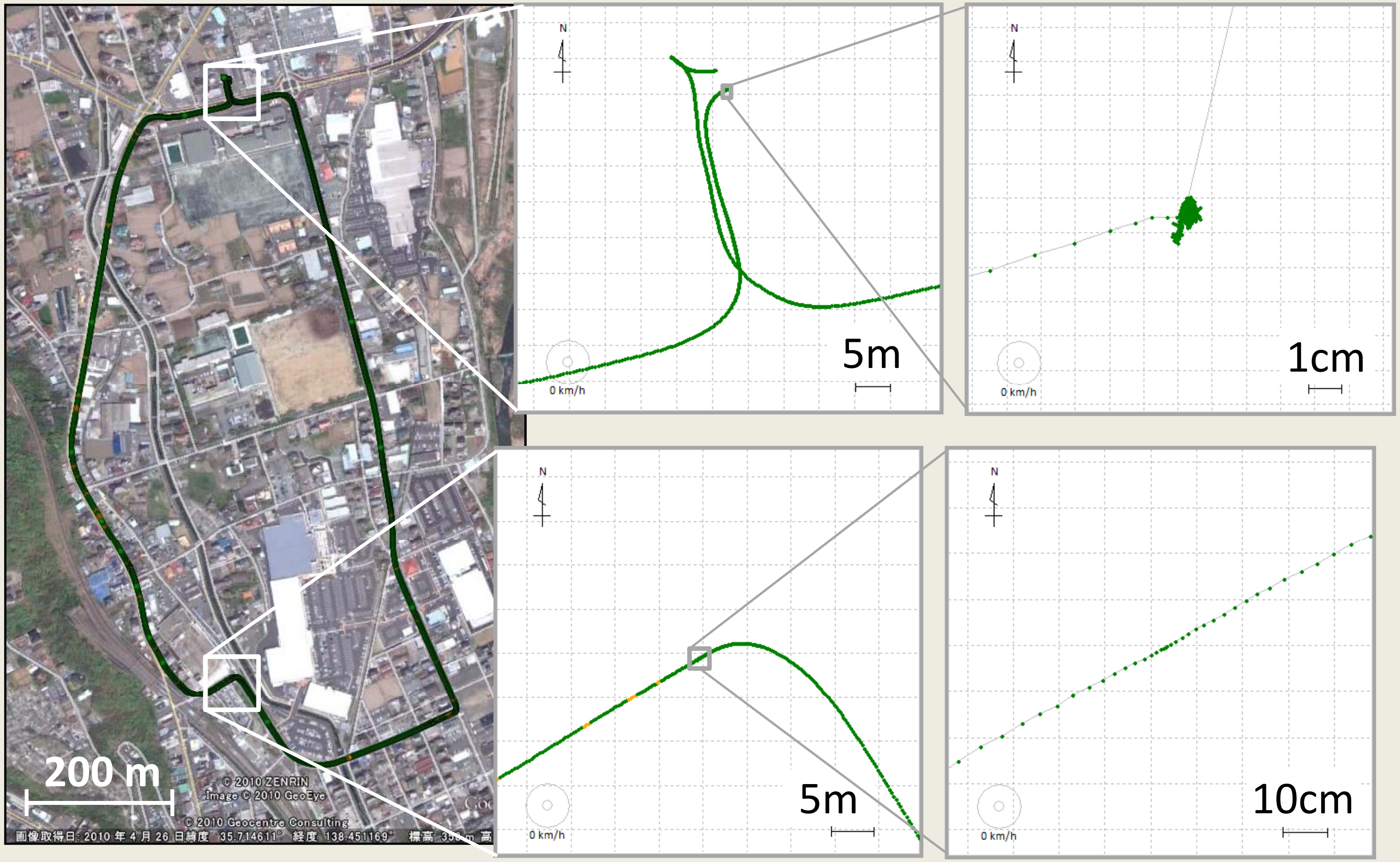
	Code-Based Positioning	Carrier-Based Positioning
Observables	Pseudorange	Carrier-Phase + Pseudorange
Noise	30 cm	3 mm
Multipath	30 cm - 30 m	1 - 3 cm
Sensitivity	High (<20dBHz)	Low (>35dBHz)
Discontinuity	No Slip	Cycle-Slip
Ambiguity	-	Estimated/Resolved
Receiver	Low-Cost ($100)	Expensive ($20,000)
Accuracy (RMS)	3 m (H), 5 m (V) (Single) 1 m (H), 2 m (V) (DGPS)	5 mm (H), 1 cm (V) (Static) 1 cm (H), 2 cm (V) (RTK)
Application	Air/Land/Marine Navigation, LBS, Time Transfer, SAR, ...	Survey, Mapping, Precision Ag, Construction...

RTK: Real-Time Kinematic

- Carrier-Based Relative Positioning
  - cm- level accuracy of moving receiver in real-time
  - Short TTFF by OTF ambiguity resolution (~10 s)
  - Narrow coverage (< 10 km from base)

- Enhancement by Network-RTK
  - Multiple/networked sparse base stations
  - Spatial interpolation of error terms
  - Regional coverage (< 100 km from base)

RTK for Vehicle Tracking



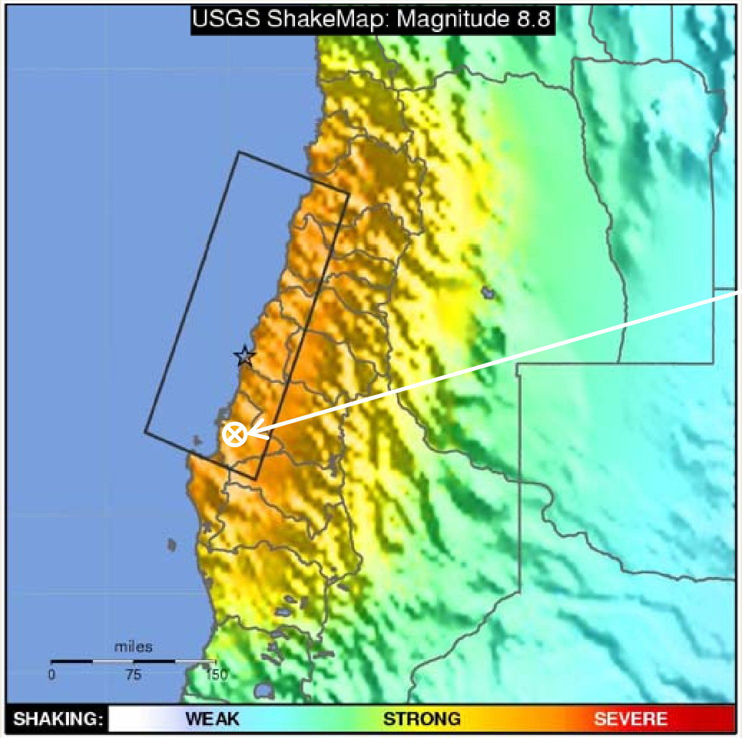
Rover: NovAtel OEMV-3 (L1+L2) + GPS-702, Base Station: NGDS-VRS, 2009/5/15 5:16-25, 20 Hz, RTKNAVI 2.4.0, GPS, Fix rate: 96.7%

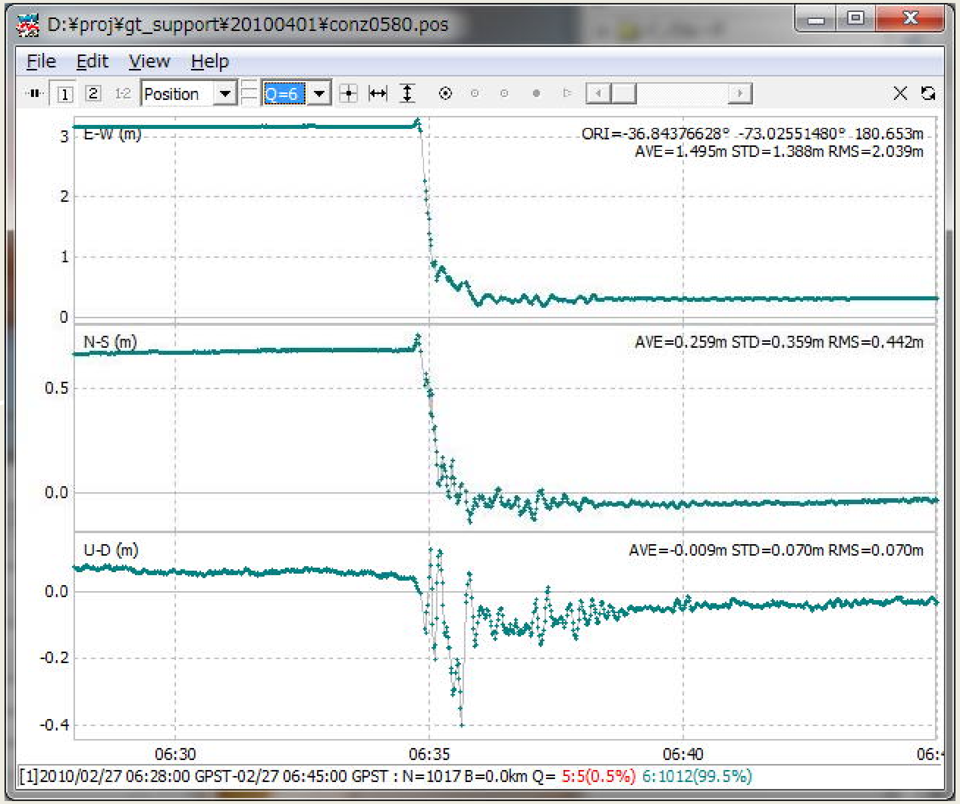
PPP: Precise Point Positioning

- Carrier-based Single Positioning
  - sub-dm - cm-level accuracy by post processing
  - Need precise orbit/clock
  - Need dual-frequency for ionosphere elimination
  - Long TTFF due to float ambiguity (> 30 min)
  - Global coverage world-wide
- Applications
  - Crustal deformation monitor, GPS seismometer
  - GPS meteorology
  - POD of LEO satellite

Displacement by EQ with PPP

2010/1/27 M8.8 Chilean Earthquake





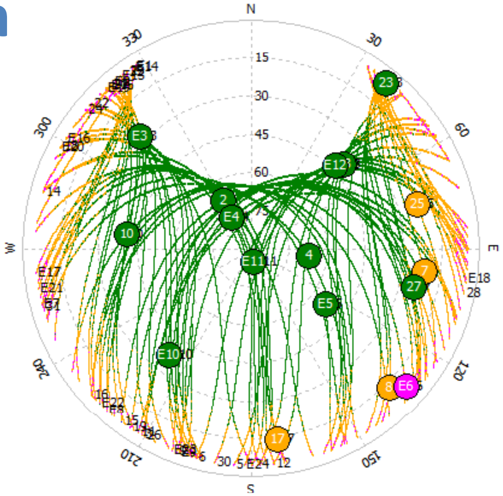
IGS CONZ, Orbit/Clock: CODE/CODE-5 s
2010/2/27 6:28-6:45 1 Hz, RTKNAVI 2.4.0,
Mode: Kinematic PPP + Combined, GPS

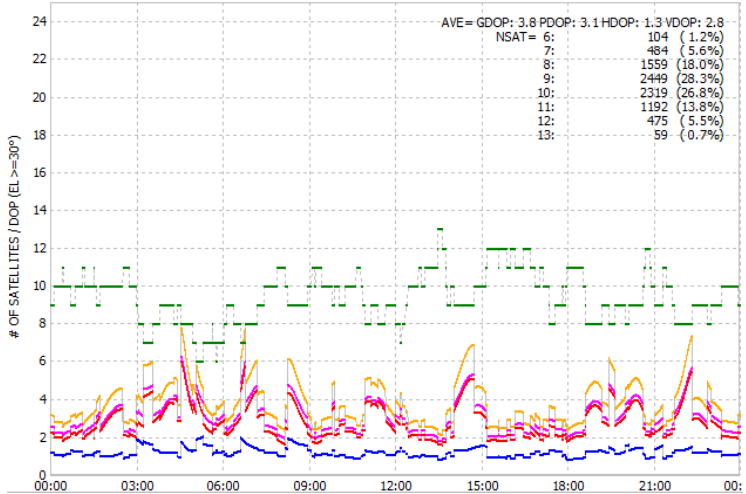
http://earthquake.usgs.gov/earthquakes

Multi-GNSS-RTK

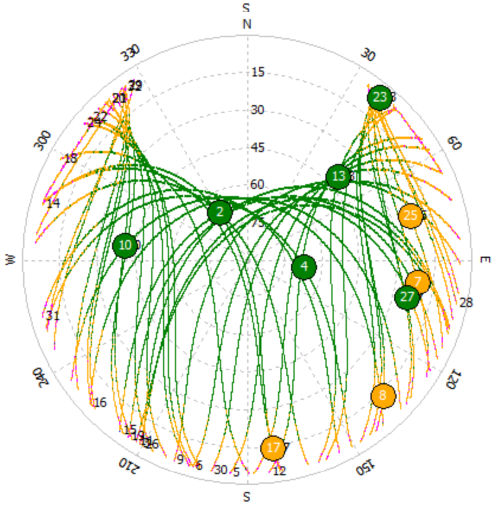
By Simulation

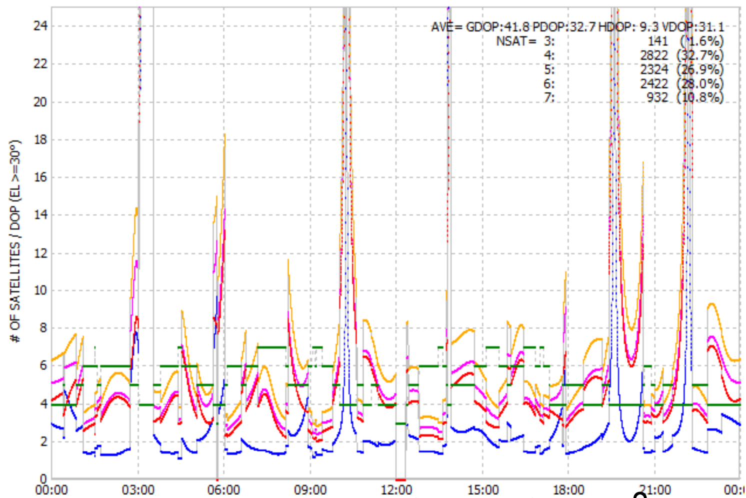
**31GPS+
27 Galileo**





31 GPS





Skyplot

NSAT, DOP: El Mask>30°

GPS vs GPS+Galileo

RTK Performance: Baseline 13.3 km, Instantaneous AR

		El Mask=15°				El Mask=30°			
GPS	Galileo	Fixing Ratio	RMS Error (cm)			Fixing Ratio	RMS Error (cm)		
			E-W	N-S	U-D		E-W	N-S	U-D
L1	-	49.7%	4.6	8.1	19.0	23.3%	71.4	115.0	289
L1,L2	-	99.0%	1.4	1.3	1.9	87.6%	3.4	10.5	15.5
L1,L2,L5	-	99.0%	1.4	1.3	1.9	87.3%	3.4	10.5	15.6
L1	E1	98.8%	1.3	1.2	1.9	90.1%	1.2	2.1	2.7
L1,L2	E1	98.9%	1.4	1.2	1.7	98.7%	1.2	1.0	1.6
L1,L2,L5	E1,E5a, E5b	98.9%	1.5	1.3	2.0	98.9%	1.3	1.1	1.8

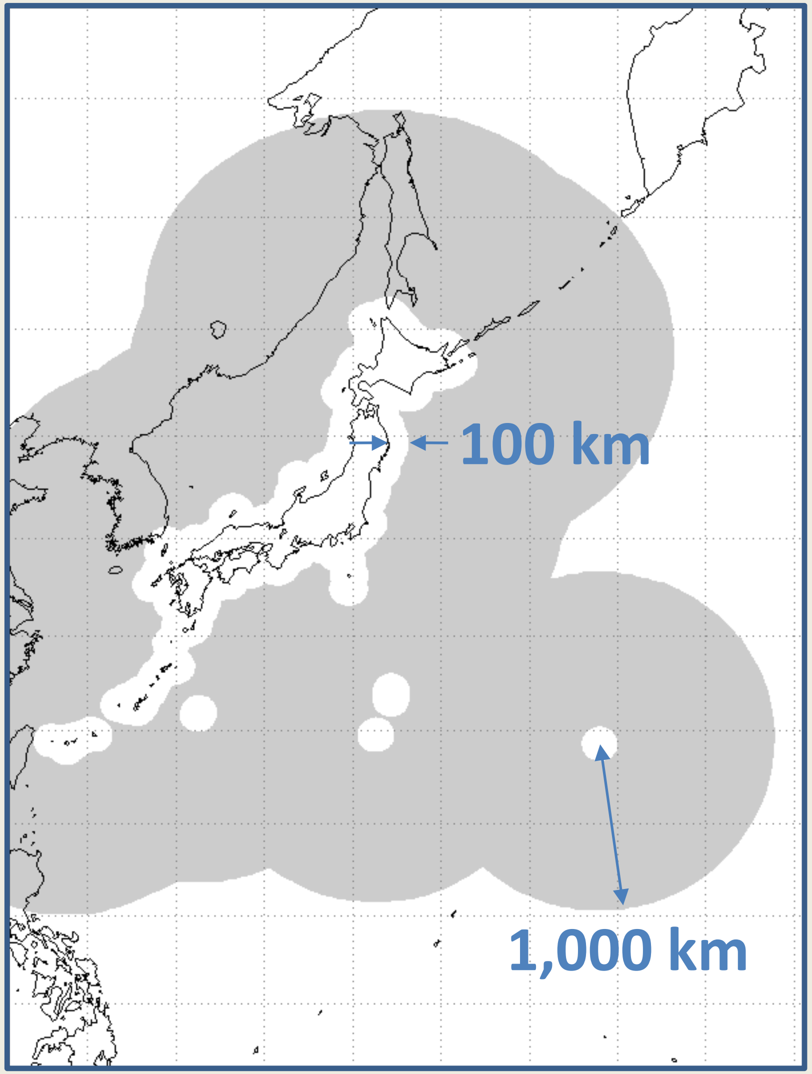
Technology Evolution

Long-range RTK
Real-time PPP
Ambiguity resolution in PPP
Deeply INS/GNSS Integration

Long-Baseline RTK

<table>
<tr><th rowspan="2"></th><th rowspan="2">BL (km)</th><th colspan="4">Error Elimination</th><th rowspan="2">Strategy</th></tr>
<tr><th>Ephem</th><th>Ionos</th><th>Tropos</th><th>Others</th></tr>
<tr><td>S</td><td>0 – 10</td><td>Broadcast</td><td>-</td><td>-</td><td>-</td><td rowspan="2">Conventional RTK</td></tr>
<tr><td rowspan="2">M</td><td rowspan="2">10 – 100</td><td rowspan="2">Broadcast</td><td>Dual-Freq</td><td>-</td><td>-</td></tr>
<tr><td colspan="2">Interpolation</td><td>-</td><td>Network RTK</td></tr>
<tr><td>L</td><td>100 – 1,000</td><td>Real-time Precise (IGU)</td><td>Dual-Freq</td><td>Estimate ZTD + MF</td><td>Earth Tides</td><td>Long-Baseline RTK</td></tr>
<tr><td>VL</td><td>>1,000</td><td>Non-RT Precise (IGR, IGS)</td><td>Dual-Freq</td><td>Estimate ZTD + MF</td><td>Earth Tides, Ph-WU</td><td>Post-Processing or PPP</td></tr>
</table>

Application of Long-Baseline RTK



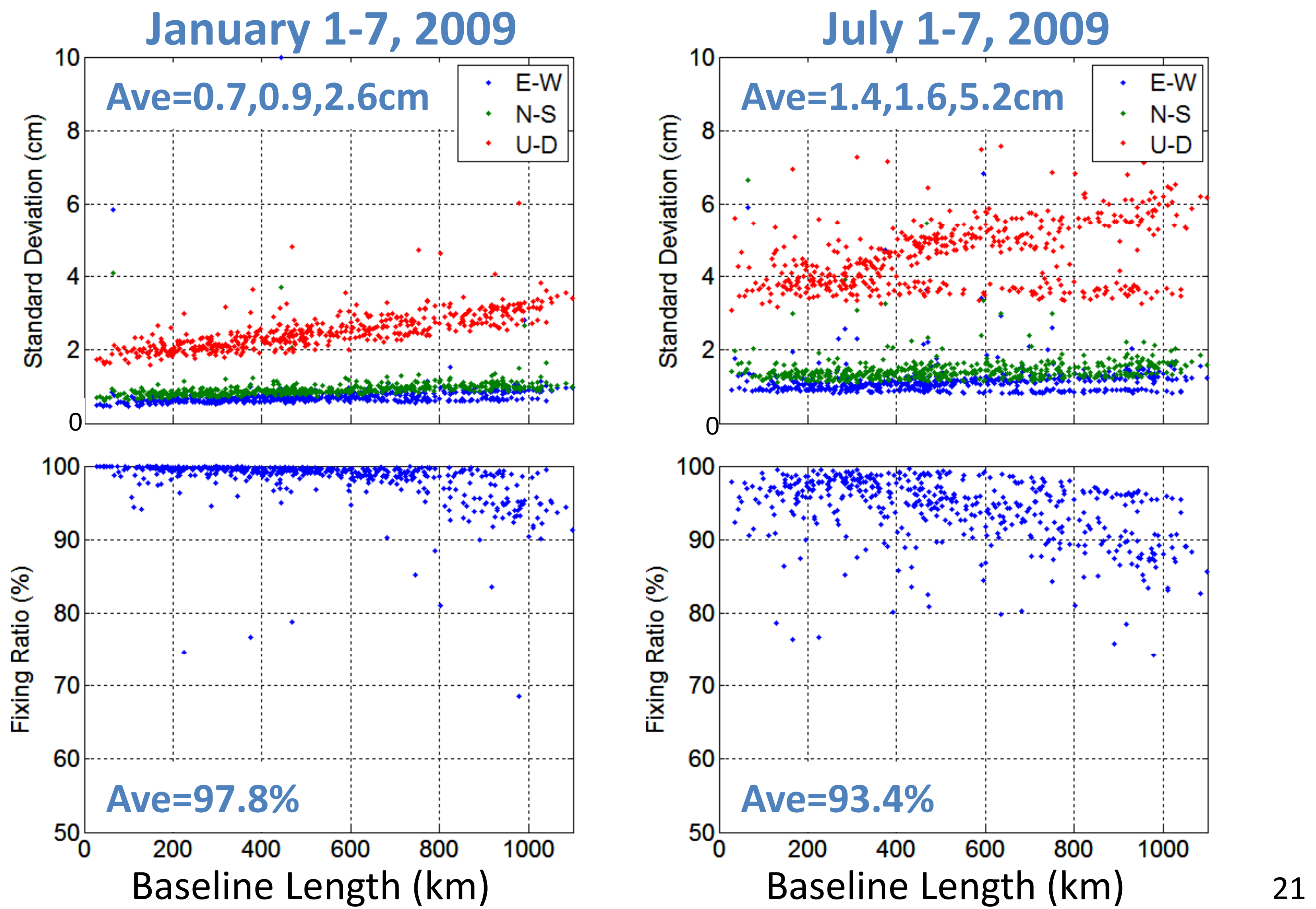
GPS Tsunami Monitoring System (Currently ~15 km off-shore)

http://www.tsunamigps.com

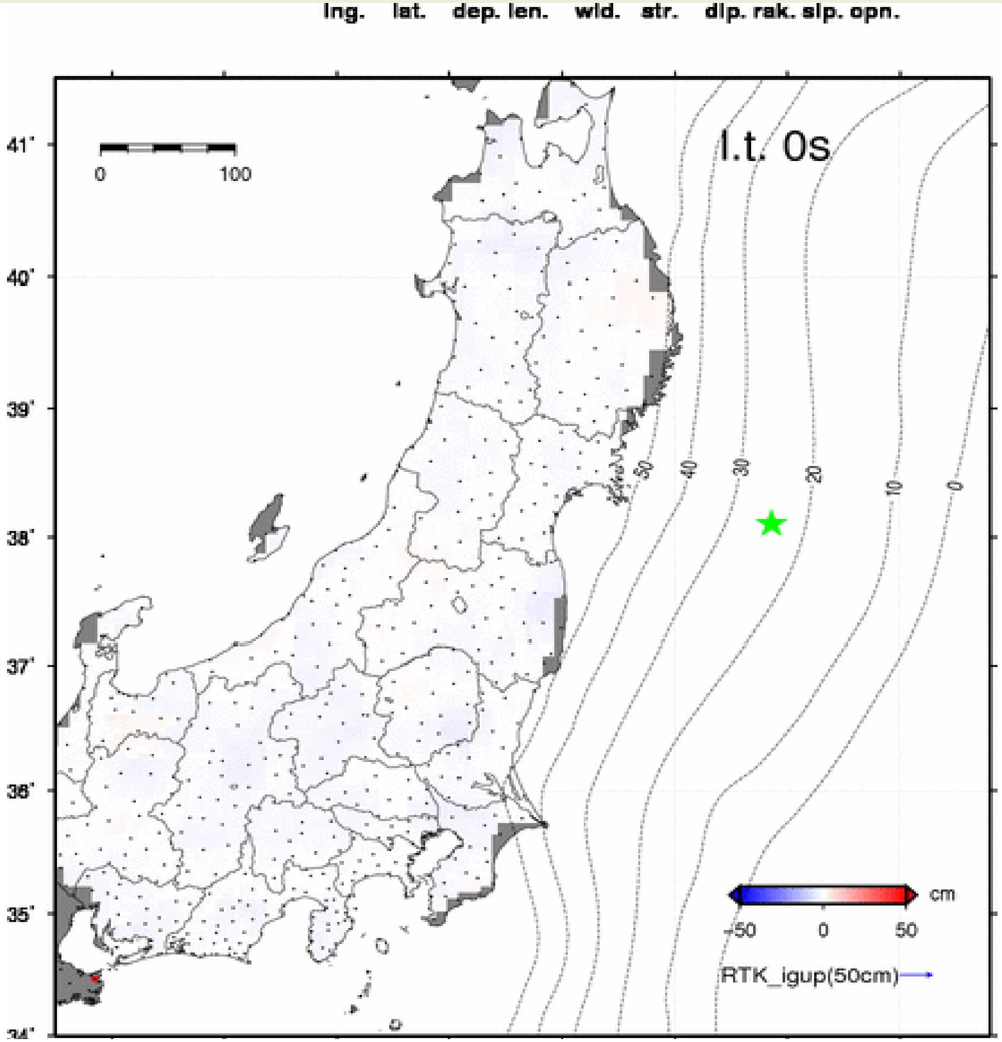
Strategy for Long-Baseline RTK

- EKF-Based Parameter Estimator
  - DD measurement eq. without LC (linear combination)
  - Explicit estimation of ionosphere term
  - Precise correction: troposphere, antenna, earth tides ...
- Precise Orbit:
  - IGU predicted (accuracy ~ 5cm)
- AR Strategy
  - Search under ILS condition (not use rounding)
  - Partial fixing (elevation mask)
  - Tight constraint to once fixed ambiguities

Offline Test Results



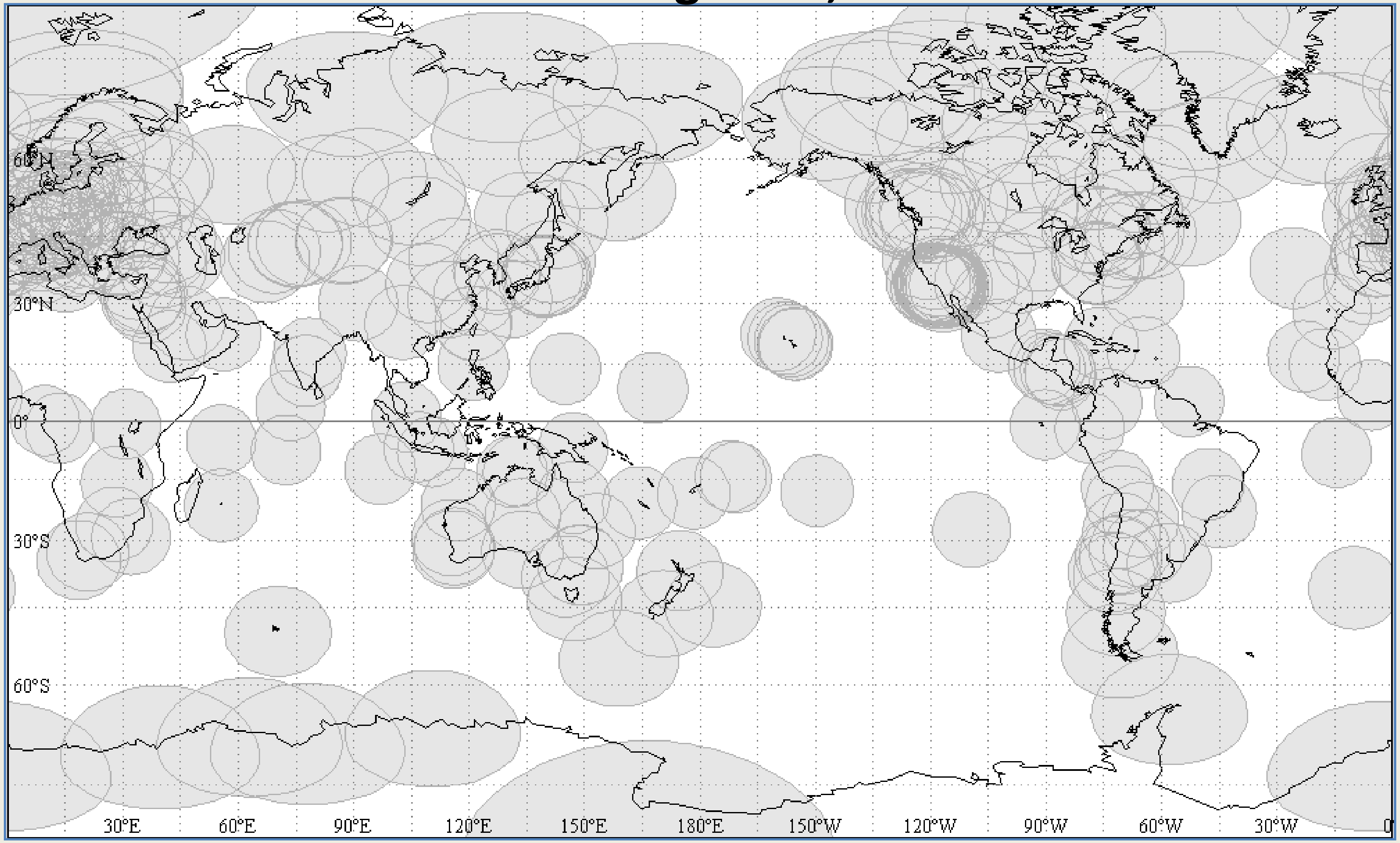
2011 Tohoku-EQ by Long-BL-RTK



Preliminary results of rapid determination of coseismic fault model using RTK-GPS
T.Kobayashi, Y.Ohta and S.Miura, JPGU, 2011

Coverage by Long-BL-RTK

Baseline Length < 1,000 km



Reference Stations = IGS Tracking Network Sites

Real-Time Orbit/Clock for PPP

- Commercial real-time PPP via GEO satellite
  - StarFire, OmniSTAR, Seastar, VERIPOS, CenterPoint RTX
- IGS real-time pilot project (RTPP) via Internet
  - orbit: mostly fixed to IGU (IGS ultra-rapid ephemeris)
  - clock: estimated in real-time with IGS tracking N/W
  - distributed by NTRIP protocol
- PPP experiment via QZSS LEX
  - Conducted by JAXA
  - cm-level orbit/clock determination (2nd-phase)
  - GPS+GLONASS+Galileo+QZSS

Commercial Real-time PPP

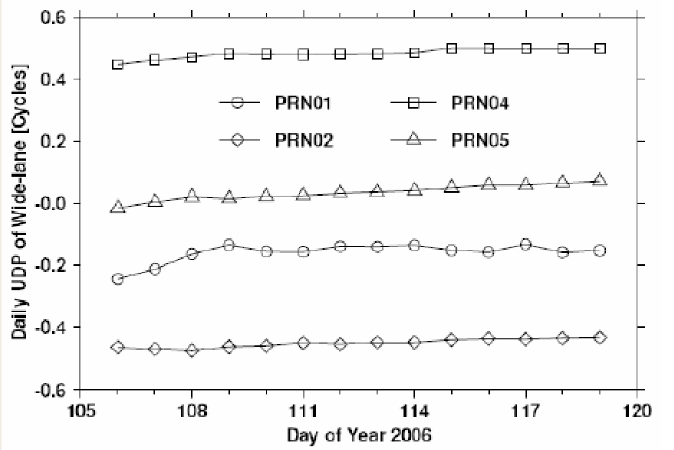
Service	Provider	Coverage	Broad-cast	Ref. Stations	Orbit/ Clock	Engine	Accuracy
StarFire	NavCom	World-wide	3 GEO L-band	60	1 min/ 1-2 s	JPL RTG	<10 cm H <15 cm V (1 sigma)
OmniSTAR XP/HP	Trimble	World-wide (Land)	6 GEO L-band	100	1 min/ 10 s	Omni-STAR	dm-class
SeaSTAR XP/G2	Fugro	World-wide (Sea)	6 GEO L-band	100	1 min/ 10 s	Fuguro/ ESOC (G2)	dm-class
VERIPOS Ultra/Apex	VERIPOS	World-wide	7 GEO L-band	80	30 s/ 30 s	JPL/ ESOC	10 cm H 20 cm V (95%)

Ambiguity Resolution in PPP

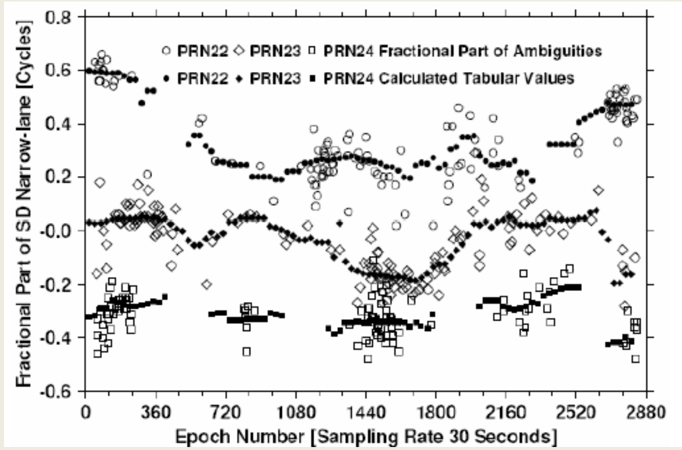
- Typical Strategy
  - Post Processing, Few Research for in Real-Time
  - Use Global Reference Stations Network
  - Fix Narrow-Lane Ambiguity with Iono-Free LC after Fixing Wide-Lane MW LC
  - Estimate Satellite Initial Phase Bias Assuming its Stability
  - PPP with Initial Phase Bias Correction
- Application
  - Precise Network Coordinates by Static-PPP
  - LEO Satellite POD, ...

M.Ge et al., EGU 2007

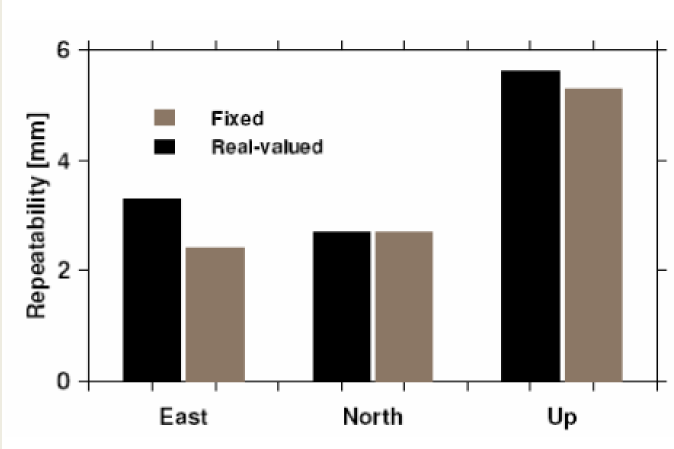
WL Phase Bias Stability



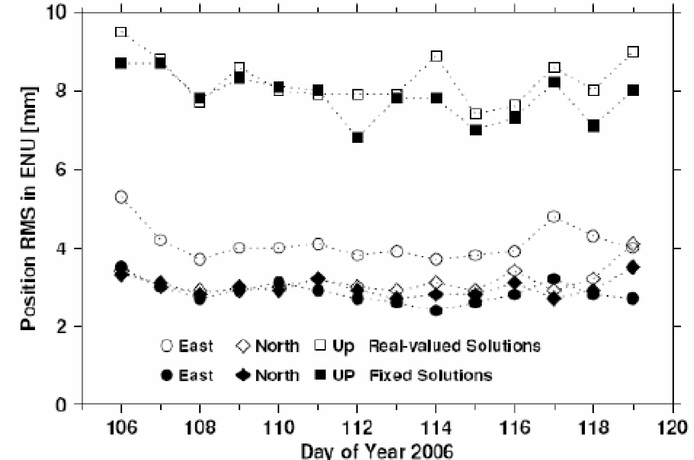
NL Phase Bias Stability



Repeatability of PPP-AR



RMS Error of PPP-AR

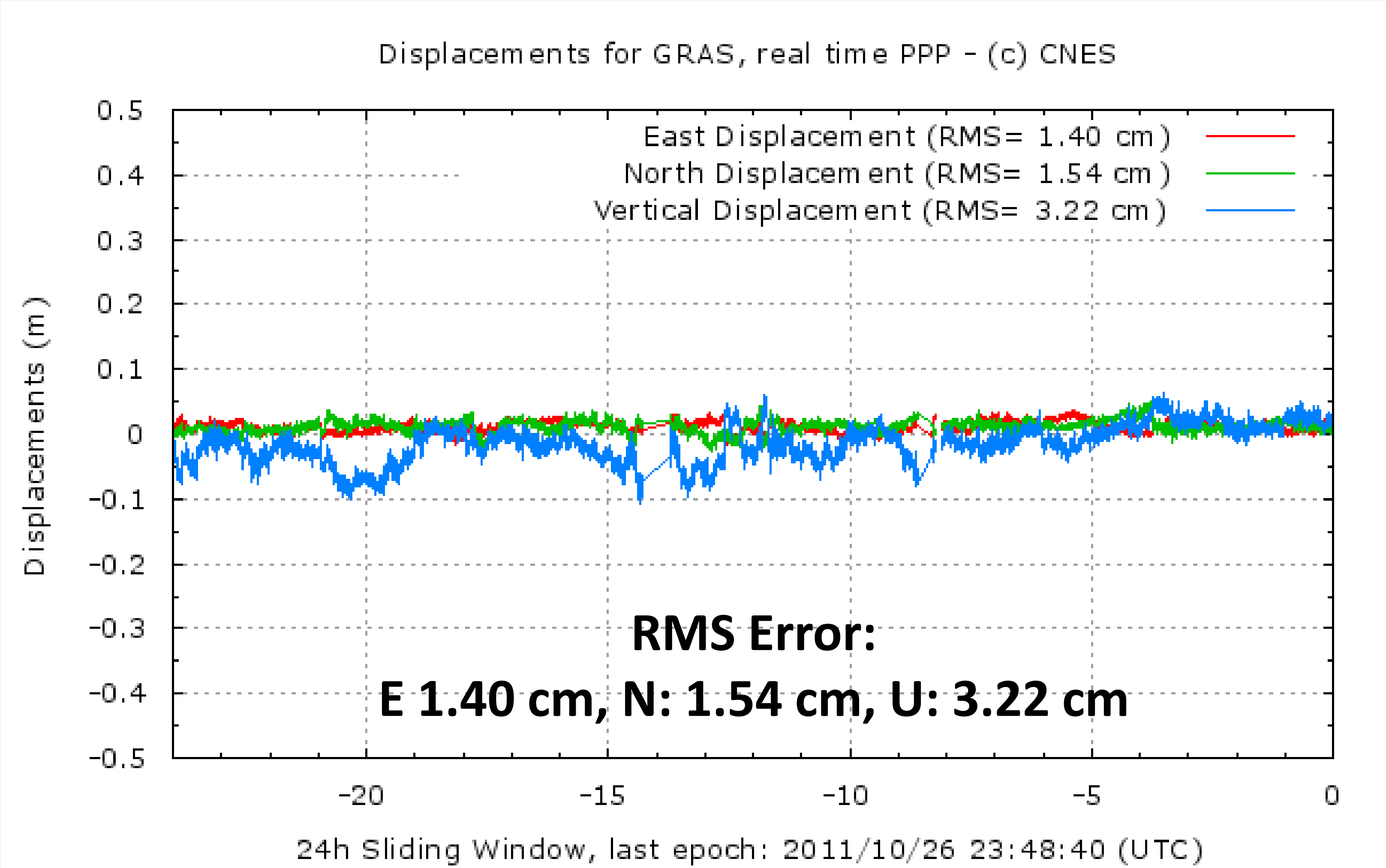


M.Ge et al., Resolution of GPS carrier-phase ambiguity in precise point positioning, EGU Assembly 2007

D.Laurichesse, ION 2010

- Real-Time Implementation of PPP-AR
  - Network WL ambiguity fixing
  - Parameter estimation by EKF with iono-free code/phase: phase-clock, code-phase-bias, ZTD, station position, orbit correction to IGU, phase ambiguity
  - Orbit construction + high-rate clock generation
- Evaluation of Accuracy
  - Orbit: 4cm, code-clock: 5 cm, phase-clock: 1cm
- RT-PPP with AR ("CNES Integer PPP")
  - 1 cm HRMS

PPP-WIZARD by CNES

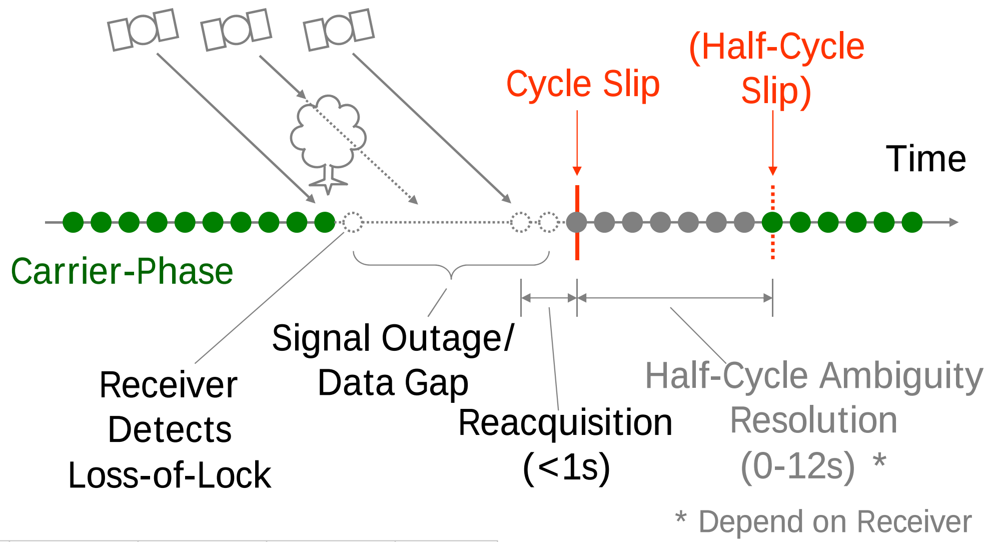


http://www.ppp-wizard.net/ppp.html

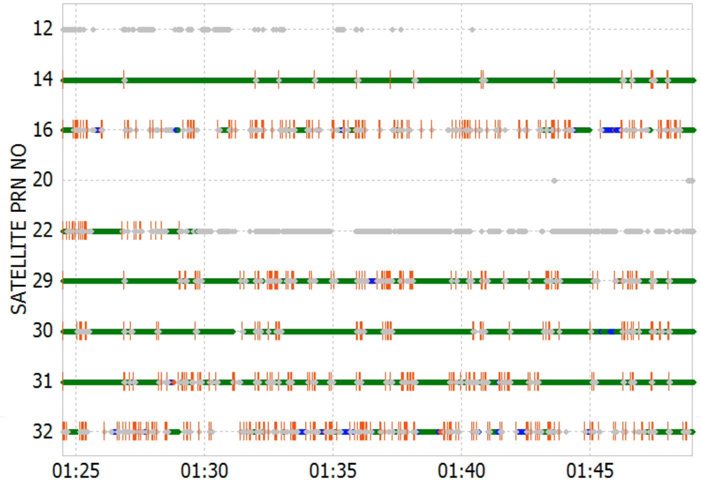
Mobile AP RTK/PPP: Issues

- Cycle Slips
  - Frequent cycle slip with around obstacles
  - Miss-detection of cycle slip
- Low Solution Availability
  - Long acquisition time by weak signal (Low C/N0)
  - Half-cycle ambiguity resolution with Costas PLL
  - Low fixing ratio
- High Noise Level
  - High multipath level in carrier-phase
  - Jamming by RFI

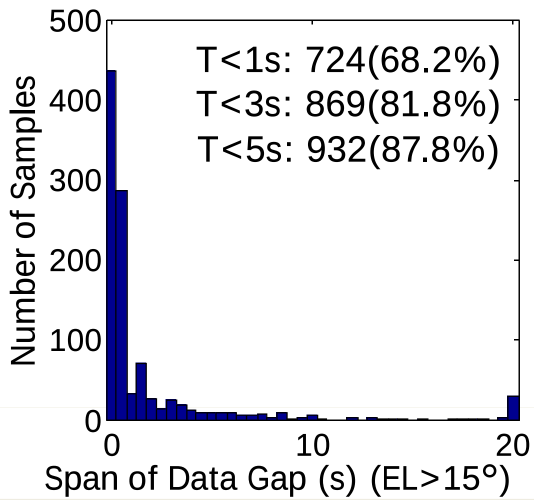
Cycle Slip



Cycle Slip
(Half-Cycle Slip)
Time
Carrier-Phase
Signal Outage/ Data Gap
Receiver Detects Loss-of-Lock
Reacquisition (<1s)
Half-Cycle Ambiguity Resolution (0-12s) *
* Depend on Receiver

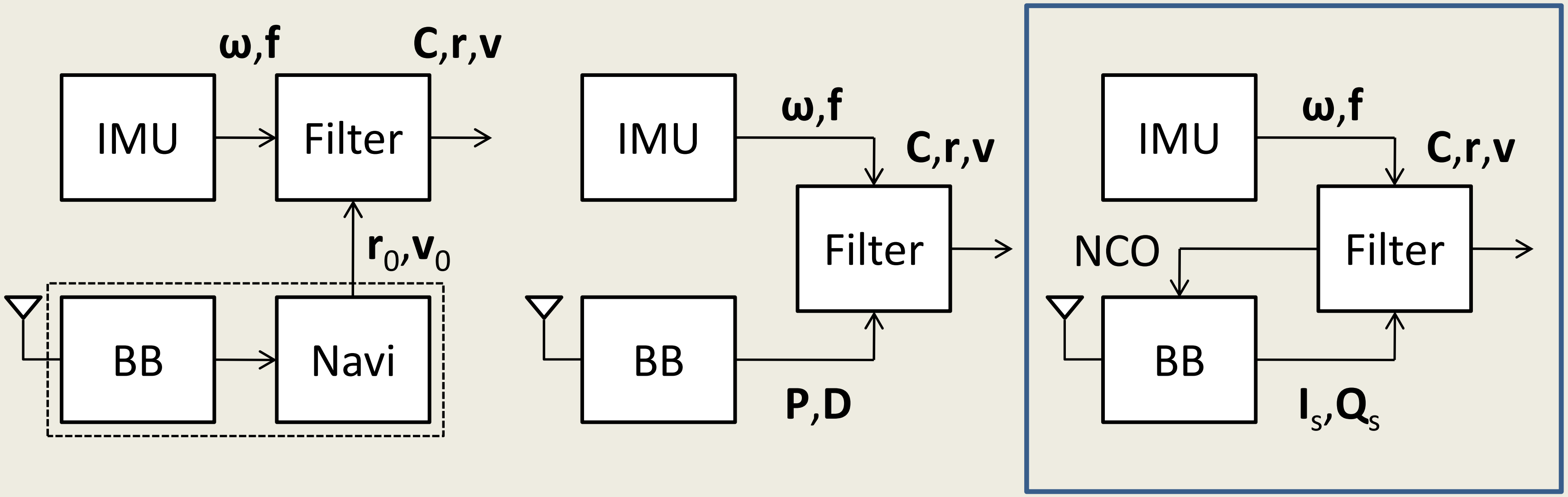


SATELLITE PRN NO
12
14
16
20
22
29
30
31
32
01:25
01:30
01:35
01:40
01:45



T<1s: 724(68.2%)
T<3s: 869(81.8%)
T<5s: 932(87.8%)
Number of Samples
500
400
300
200
100
0
0
10
20
Span of Data Gap (s) (EL>15°)

INS/GNSS Integration



Loosely-Coupled Integration

Tightly-Coupled Integration

Deep Integration (Ultra-Tightly)

High sensitivity
(DLL, PLL)
Slip resistance

"CM-Level Accuracy Anywhere"

Technologies in 2011

	Target Requirement	Conventional Technologies in 2011	
		RTK	PPP
Coverage	Global (world-wide)	<100 km from nearest base	Global (world-wide)
Dynamics	Stationary - Space	Static - Kinematic	Static - Kinematic
Accuracy	1 cm (HRMS) 2 cm (VRMS)	1 cm (HRMS) 2 cm (VRMS)	2 cm (HRMS) 5 cm (VRMS)
Availability	99 % (open sky)	95 % (open sky)	?
	95 % (urban)	30 % (urban)	?
Latency	1 s	1 s	2 days - 2 weeks
TTFF	10 s (land) 1 min (sea)	10 s (dual-freq) 5 min (single-freq)	> 30 min
User Cost	< $100	$20,000 (dual-freq) $2,000 (single-freq)	$20,000 (Dual-freq)

Technologies in 2020

	Requirement	Technologies in 2020
Coverage	Global (world-wide)	RT-Orbit/Clock with AR, Broadcast via Internet + GEO/QZSS Satellite
Dynamics	Stationary - Space	Static - Kinematic
Accuracy	1 cm (HRMS) 2 cm (VRMS)	Local iono/tropos corrections (land) Iono estimation by triple-freq (sea)
Availability	99 % (open sky)	30 sats + triple-freq
	95 % (urban)	30 sats+INS-aided PLL, slip-resistant
Latency	1 s	Real-time corrections
TTFF	10 s (land)	Local iono/tropos corrections
	1 min (sea)	Iono estimation by triple-freq
User Cost	< $100	No patent problem, need killer-AP