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Precise Geospatial Positioning with current multi-GNSS constellations

Dr. Octavian Andrei

Department of Survey Engineering, Chulalongkorn University, Thailand

NAC2015: 11th NSTDA Annual Conference
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Agenda

- Why GNSS?
- How precise is GNSS?
- What enables Precision GNSS?
- Practical examples
- Conclusions

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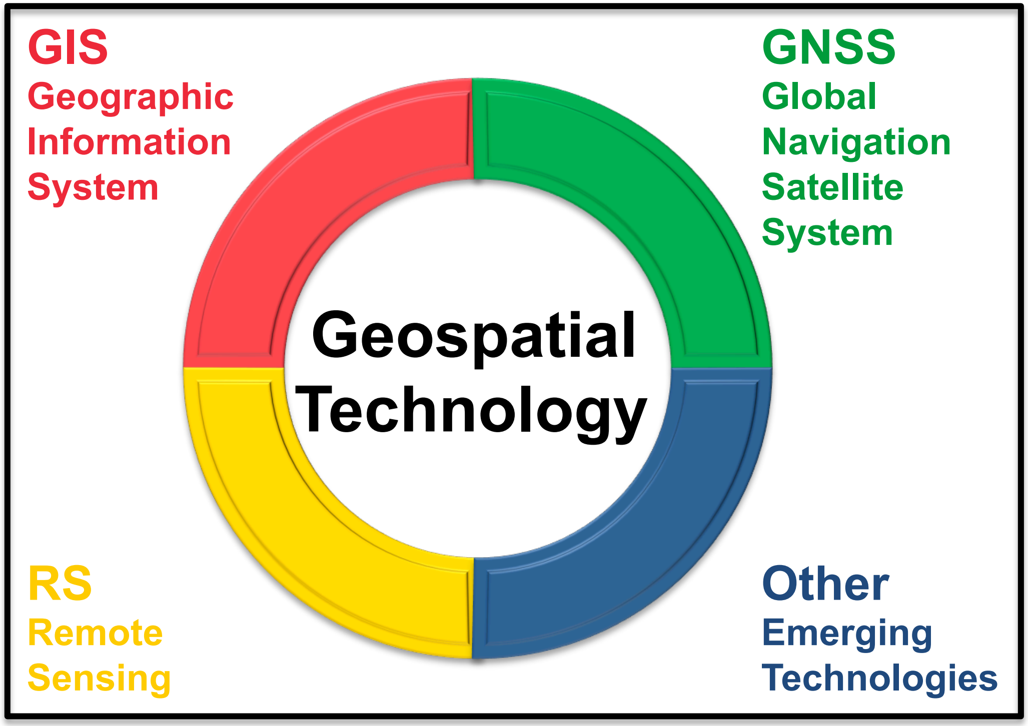
Geospatial is not special but pervasive and/or ubiquitous



GIS
Geographic Information System

GNSS
Global Navigation Satellite System

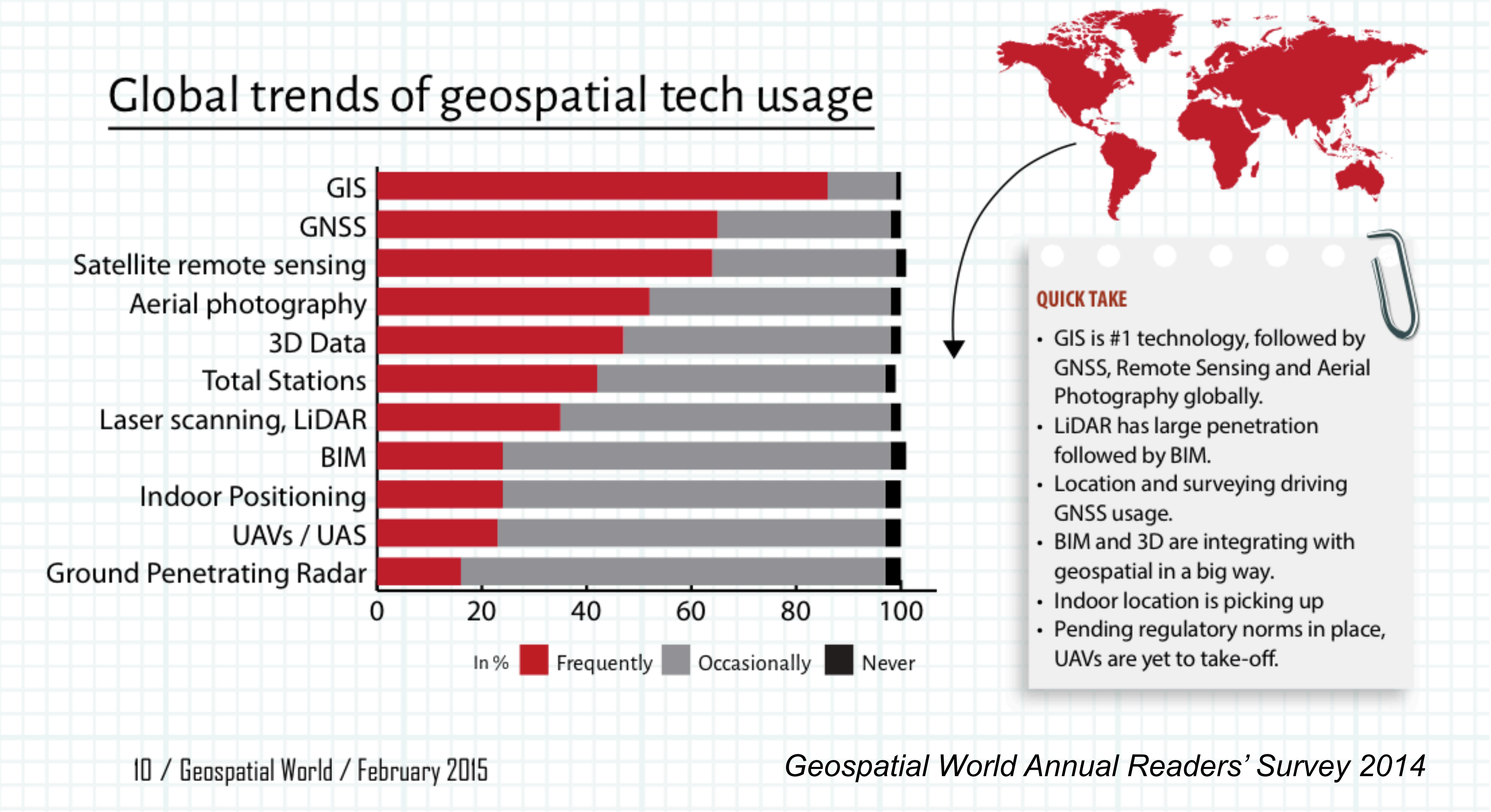
Geospatial Technology

RS
Remote Sensing

Other
Emerging Technologies

GNSS provides geospatial positioning with global coverage.

Geospatial World Annual Survey



Global trends of geospatial tech usage

QUICK TAKE

- GIS is #1 technology, followed by GNSS, Remote Sensing and Aerial Photography globally.
- LiDAR has large penetration followed by BIM.
- Location and surveying driving GNSS usage.
- BIM and 3D are integrating with geospatial in a big way.
- Indoor location is picking up
- Pending regulatory norms in place, UAVs are yet to take-off.

10 / Geospatial World / February 2015

Geospatial World Annual Readers' Survey 2014

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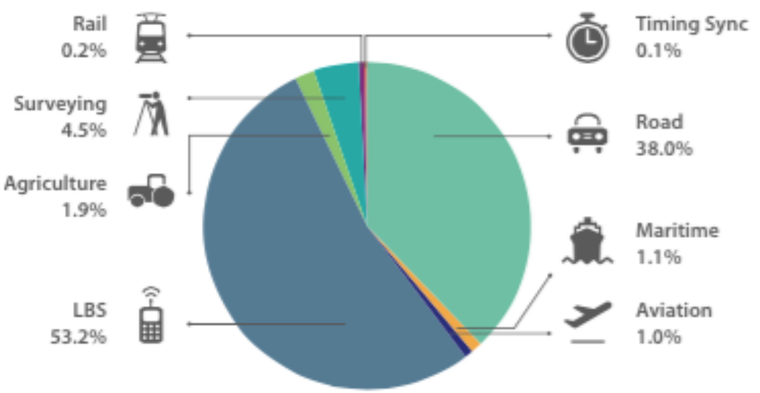
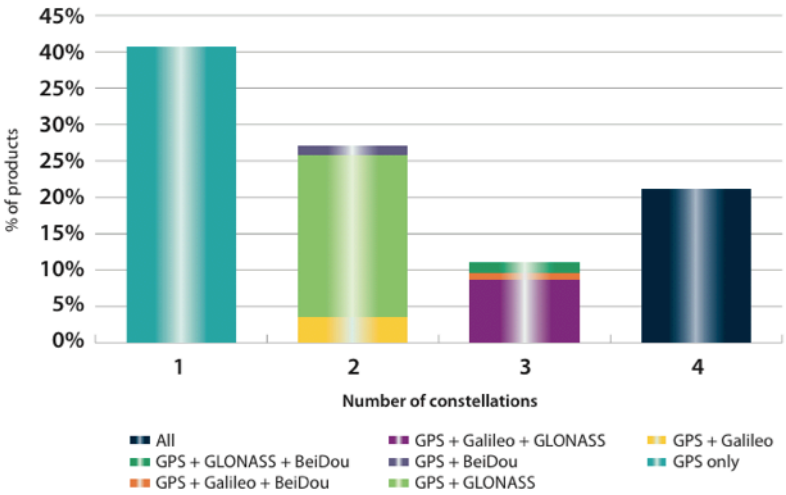
GSA GNSS Market Report

- By 2019, there will be over **7 bln devices** – for an average of one device per person on the planet.
- **LBS and Road dominate** cumulative GNSS revenues
- The primary region of global market growth will be **Asia-Pacific**.
- Almost 60% of all available receivers, chipsets and modules are supporting a minimum of **two constellations**.

Cumulative core revenue 2013-2023



Supported constellations by receivers – All segments



GNSS Market Report | Issue 4, March 2015

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Satellite Navigation Champions League

March 25, 2015

GPS IIF-9 Successfully Lifts Off from Cape Canaveral

The U.S. Air Force's ninth GPS Block IIF satellite (GPS IIF-9) launched on time Wednesday at 2:36 p.m. EDT (1836 GMT) from Space Launch Complex 37 at Cape Canaveral Air Force Station, Fla. The GPS satellite has been deployed by the Delta IV rocket. read more

March 27, 2015

Two Galileo Satellites Launched for Europe's Navigation Constellation

UPDATE: The two Galileo satellites are confirmed separated from their Soyuz Fregat upper stage into 22,522 altitude orbit right on schedule, according to ESA. Both are in their planned orbits. Two more Galileo satellites were successfully launched... read more

March 28, 2015

India's IRNSS-1D Launched into Orbit

The fourth satellite of IRNSS satellite navigation constellation, IRNSS-1D, was launched onboard PSLV-C27 on Saturday, March 28, according to the Indian Space Research Organization (ISRO). The Polar Satellite Launch Vehicle blasted off at 11:49 GMT (7:49... read more

March 30, 2015

China Launches First of Next-Gen BeiDou Satellites

UPDATE (3/31/15): The BeiDou satellite is being targeted for an IGSO orbit, not a MEO orbit as previously speculated. The two images below make this clear. Below is a CCTV (China Central Television) news story covering the launch. ... read more

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Current status as of April 2015

US: GPS

(Global Positioning System)

System:
32 MEO satellites (29 operational)
Baseline constellation: 24+3

Russia: GLONASS

(Global Navigation Satellite System)

System:
28 MEO satellites (24 operational)
Baseline constellation: 24

EU: Galileo

System:
8 MEO satellites (unavailable until 2015-04-20)
Baseline constellation: 27+3

China: BeiDou

System:
5 GEO + 5 GSO + 4 MEO
Baseline constellation: 35

Japan: QZSS

(Quasi Zenith Satellite System)

System:
1 GSO satellite operational
Baseline constellation: 4 GSO + 3 GEO

India: IRNSS

(Indian Regional Navigation Satellite System)

System:
1 GEO + 3 GSO satellite (development)
Baseline constellation: 3 GEO + 4 GSO

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GNSS SEA hotspot

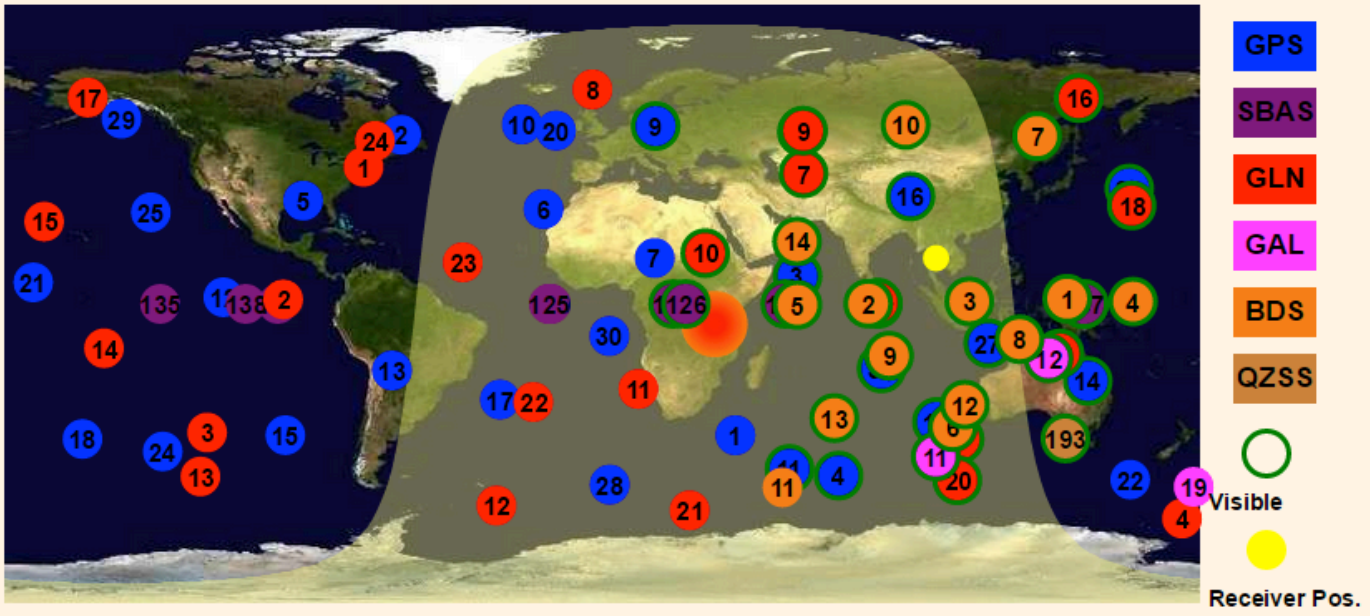
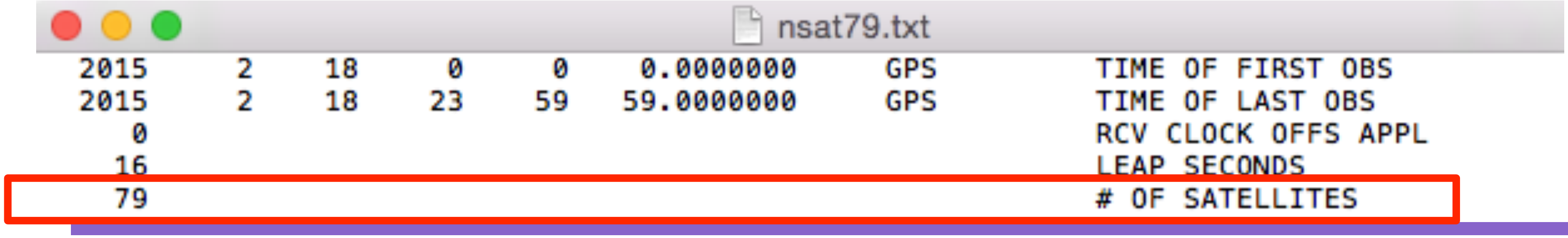


Image Courtesy NASA's Visible Earth Project



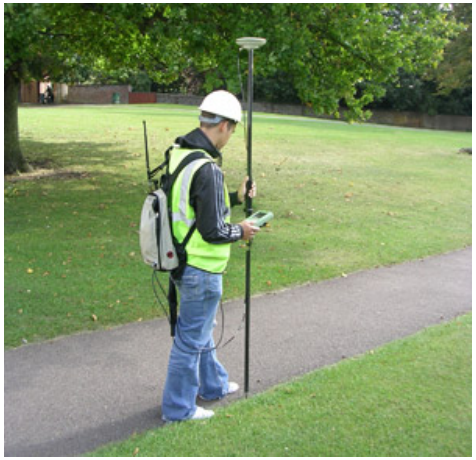
```
   2015       2      18       0       0   0.0000000     GPS         TIME OF FIRST OBS
   2015       2      18      23      59  59.0000000     GPS         TIME OF LAST OBS
      0                                                             RCV CLOCK OFFS APPL
     16                                                             LEAP SECONDS
     79                                                             # OF SATELLITES
```

How precise is GNSS?

10 m

1 m

1 cm



1 mm

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02-Apr-2015

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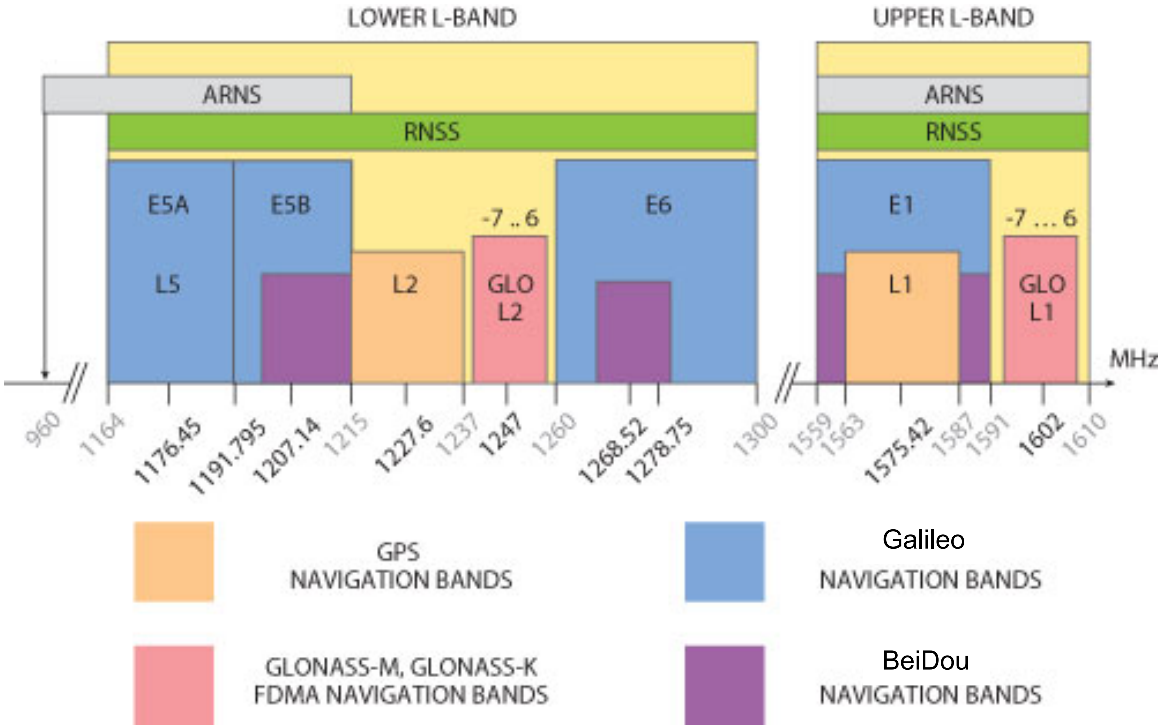
GNSS Signals



- **Carrier**
- **Code**
- **Data**
- **Multiple frequencies**
- **Multiple channels**
- Data carried:
  - CDMA vs. FDMA
  - PRN codes: C/A, P(Y), L2C, L5C (I/Q), L1C, E5a+5b, E6, LEX, etc
  - Almanac – approximate location
  - Ephemeris – precise location, unique data
  - NAVDATA – time, date, and health

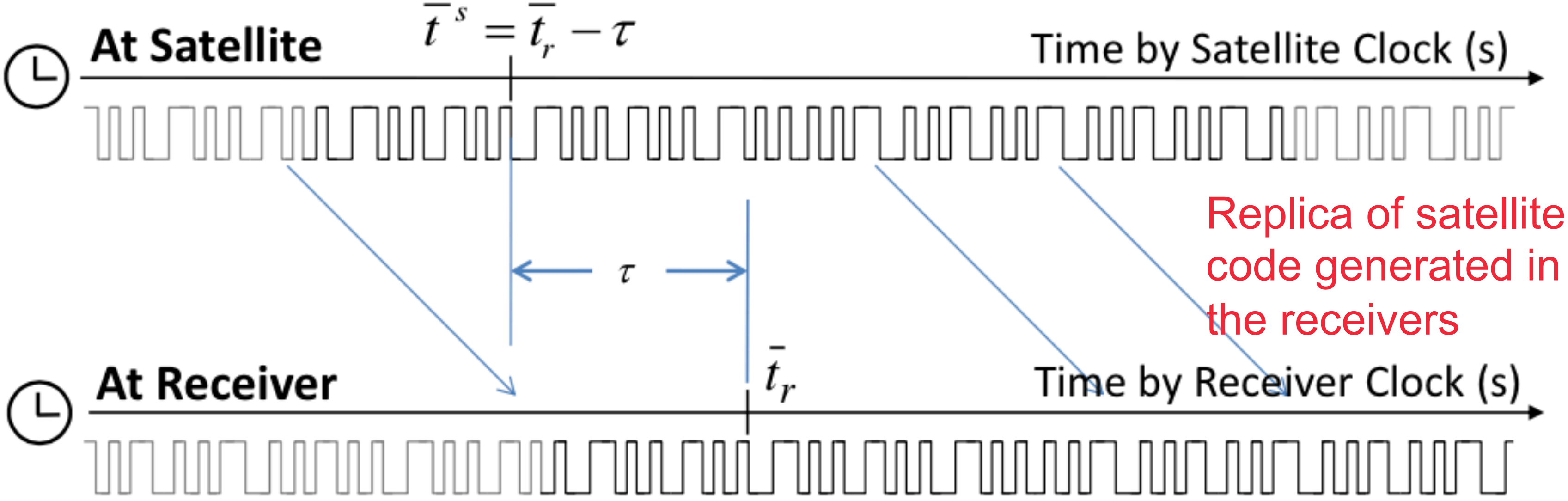
Pseudorange

Definition:

$$P_r^s \equiv c\tau = c(\bar{t}_r - \bar{t}^s)$$

(m)

> *"The pseudorange (code) measurement is defined to be equivalent to the difference of the time of reception (expressed in the time frame of the receiver) and the time of transmission (expressed in the time frame of the satellite) of a distinct satellite signal."* (RINEX 2.10)



Transmitted code from satellite

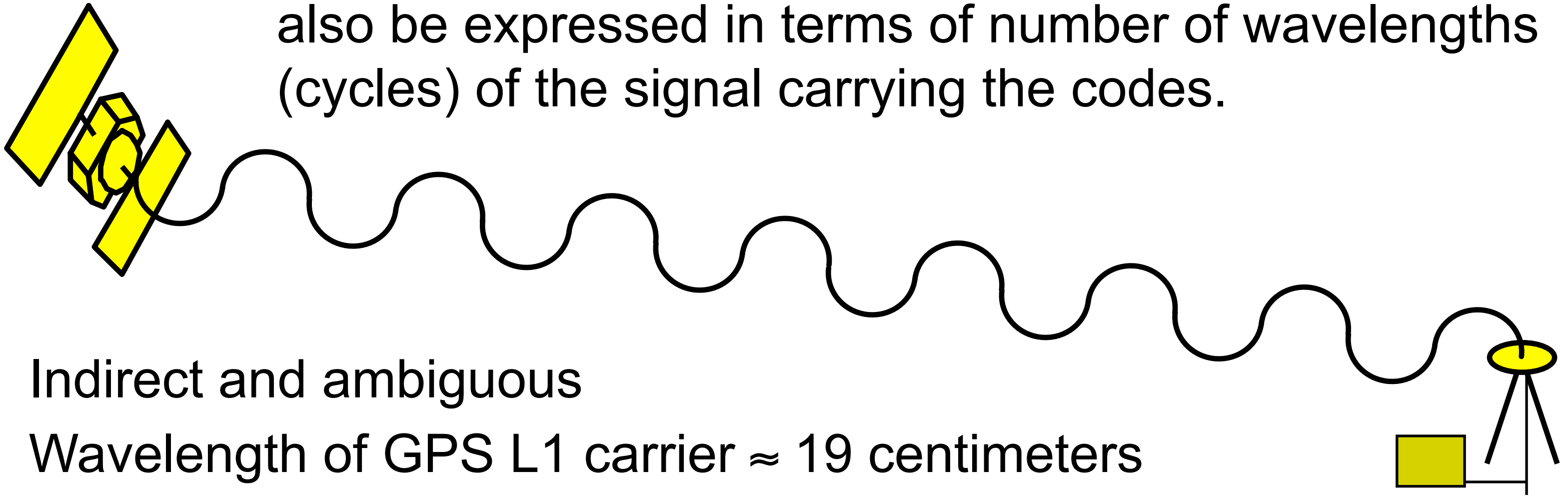
Replica of satellite code generated in the receivers

Source: www.rtklib.com/prog/manual_2.4.2.pdf

Carrier phase

> *"The carrier-phase measurement is a measurement on the beat frequency between the received carrier of the satellite signal and a receiver-generated reference frequency."* (RINEX 2.10)

- Distance from the satellite to the user's antenna can also be expressed in terms of number of wavelengths (cycles) of the signal carrying the codes.



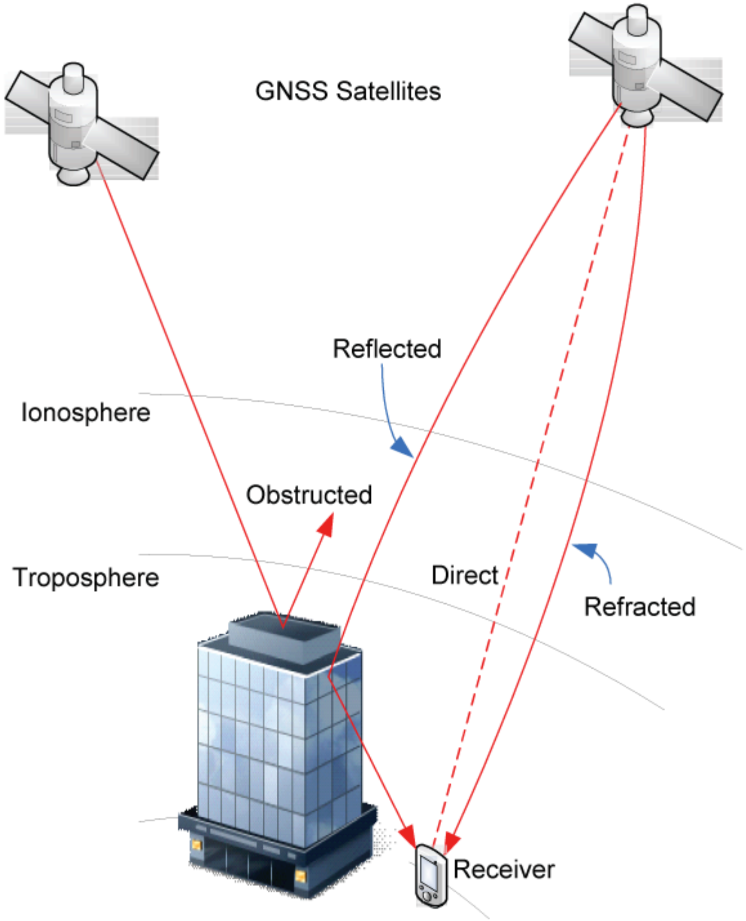
- Indirect and ambiguous
- Wavelength of GPS L1 carrier ≈ 19 centimeters
- Fractional part ("phase") of a given wavelength can be measured to 1/100 of a wavelength ~ resolution of 2 mm
- Enables position relative to a known point with centimeter accuracy

Code vs. carrier-based positioning

Feature	Code-based (Standard Positioning)	Carrier-based (Precise Positioning)
Observables	Pseudorange (code)	**Carrier-Phase + Pseudorange**
Receiver noise	3 m / 30 cm	3 cm
Multipath	30 cm – 30 m	1 – 3 cm
Sensitivity	High (< 20 dBHz)	Low (> 35 dBHz)
Discontinuity	No Slip	Cycle-Slip
Ambiguity	-	Estimated / Resolved
Receiver cost	Low (€100+)	**Expensive (€10k+)**
Accuracy (RMS)	3 m (H), 5 m (V) Single 1 m (H), 2 m (V) DGNSS	**5 mm (H), 1 cm (V) Static** **1 cm (H), 2 cm (V) RTK**
Applications	General navigation, Fleet management, Geocaching, Timing, SAR, LBS, …	Surveying (land, sea and air), Machine Guidance, Deformation Monitoring, Datum Monitoring, Precise Engineering, etc.

Sources of error in GNSS

- **Satellite-dependent**
  - Orbit errors, clock errors
  - Phase wind-up, PCO, PCV, biases
- **Signal-dependent**
  - Ionospheric & tropospheric delays
  - Multipath
  - Cycle slips
- **Receiver/site-dependent**
  - Receiver clock error, noise
  - Antennae, biases *… lots of them*



Source: http://www.novatel.com/

Error mitigation

- By using **theoretical and empirical models**
  - e.g., Point Positioning

- By using **differentiation principle**
  - e.g., DGNSS, RTK, NRTK

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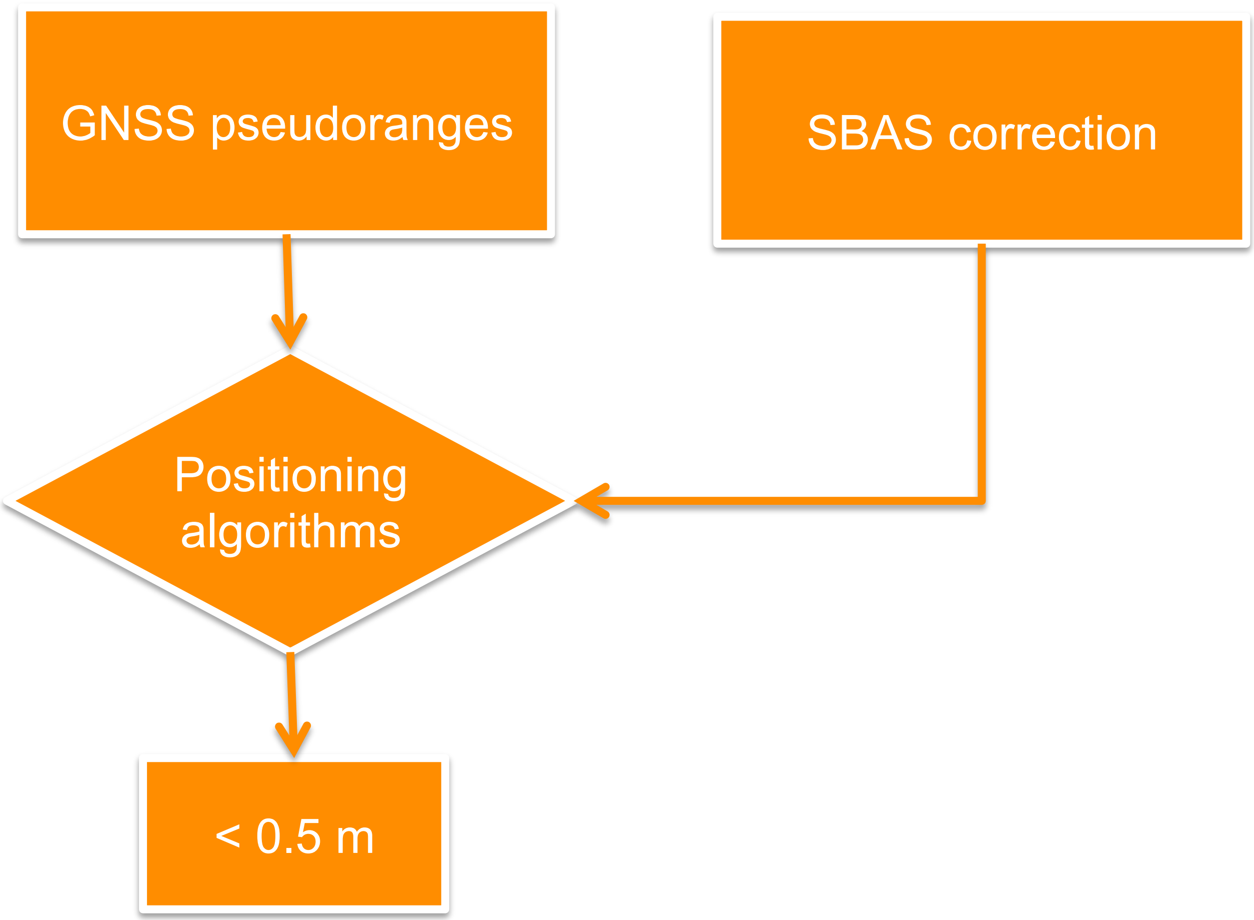
General Standalone GNSS positioning



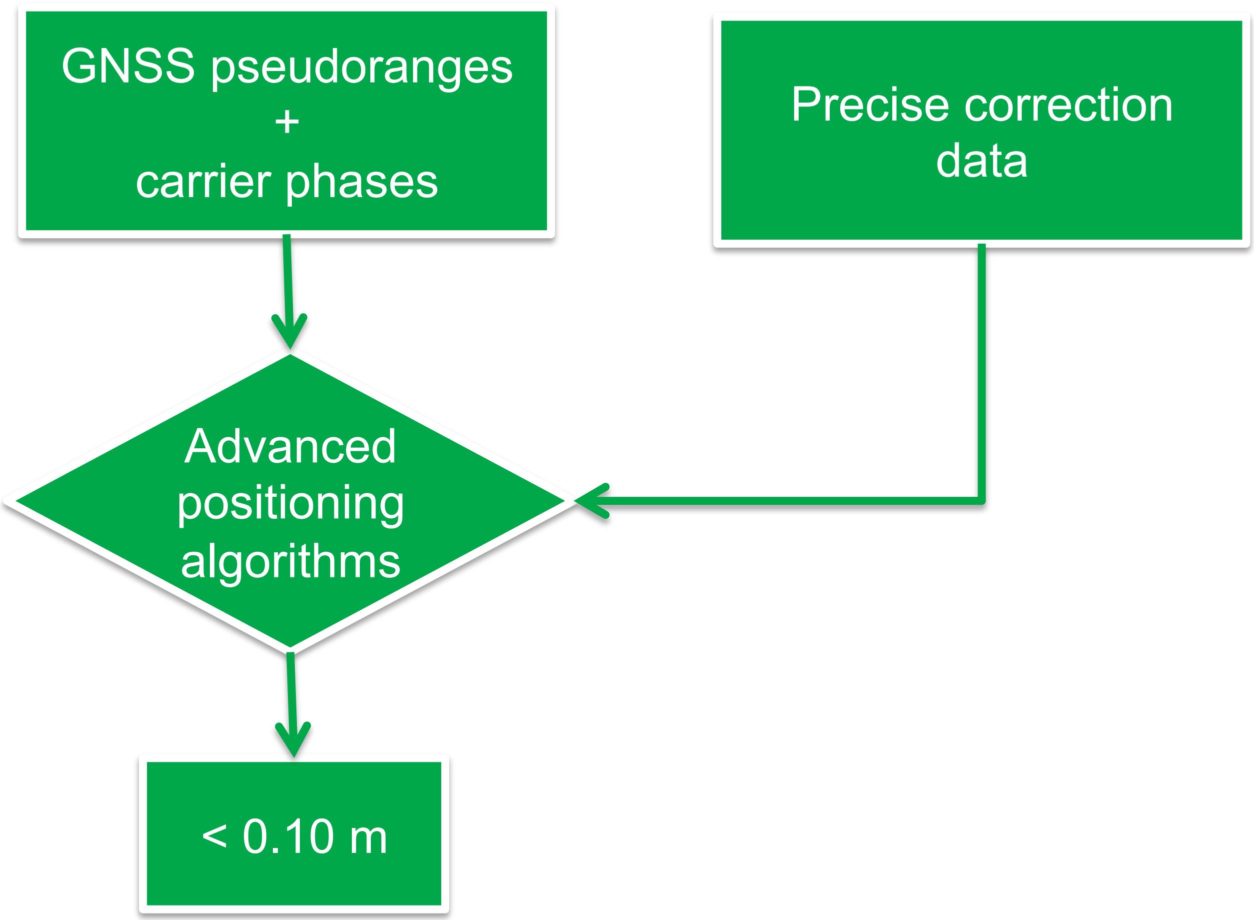
GNSS pseudoranges

SBAS correction

Positioning algorithms

< 0.5 m

Precise GNSS positioning



GNSS pseudoranges
+
carrier phases

Precise correction data

Advanced positioning algorithms

< 0.10 m

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What enables precise positioning?

- Cm-level accuracy has been possible for more than 10 years!
- The enablers
  - Easily accessible correction data
  - Advanced positioning algorithms

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Correction data

Before

- Your own base receiver
- Radio link (limited to 3 km, affected by terrain)
- Availability of radio channels
- Long delays for precise orbits and clocks

Now

- RTK correction services development, broadcast over cellular frequencies
- Base station data available 24/7 via CORS network
- Rapid precise orbits and clock corrections
- Increased quality of corrections delivered over L-band / SSR / MSM

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Advanced positioning algorithms

Real-Time Kinematic (RTK)

- User determines the position of an unknown point (rover) with respect to a known point (base)
    - At least a **pair** of receivers
- Simultaneous observations
    - Time-tagged GNSS measurements are transmitted from the base
    - The differentiation process takes place at the rover
- Baseline and position at rover
- Faster fixes over longer baselines
- Single base or Network RTK

Precise Point Positioning (PPP)

- **Precise orbits** and satellite **clocks**
- **Carrier phase** observations
- **Single** (dual-Frequency) receiver
- Iono-free data combinations ()
- Significant improvements in the last decade
- Post-processing (popular)
- Real-time (now)
- Cm-level accuracy in kinematic, real-time achievable

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Drivers for GNSS performance

- **Quality and type of measurements**
  - antenna + receiver
- **Error modelling**
  - Comprehensive & long list (especially for PPP)
- **Positioning mode**
  - Point (SPP, PPP) vs. Relative (DGNSS, RTK, NRTK)

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Practical examples

- **SPP**
  - Single- vs. multi-system solution
- **PPP static**
  - Single- vs- multi-system solution
- **PPP kinematic**
  - Boat-mounted mapping system trajectory

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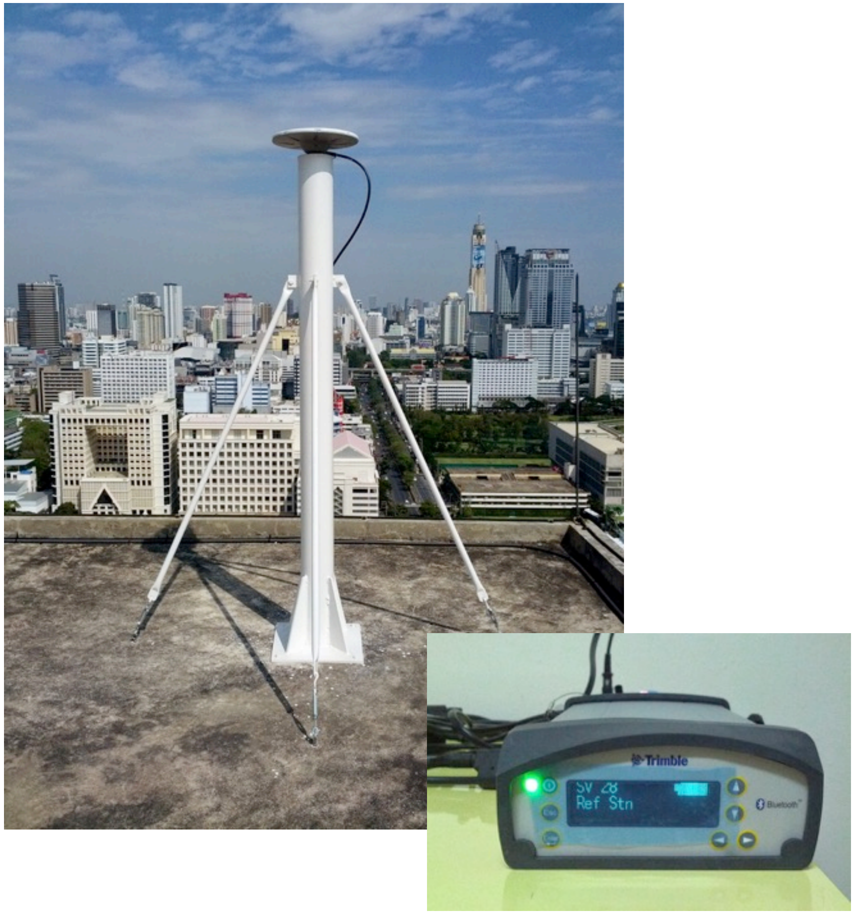
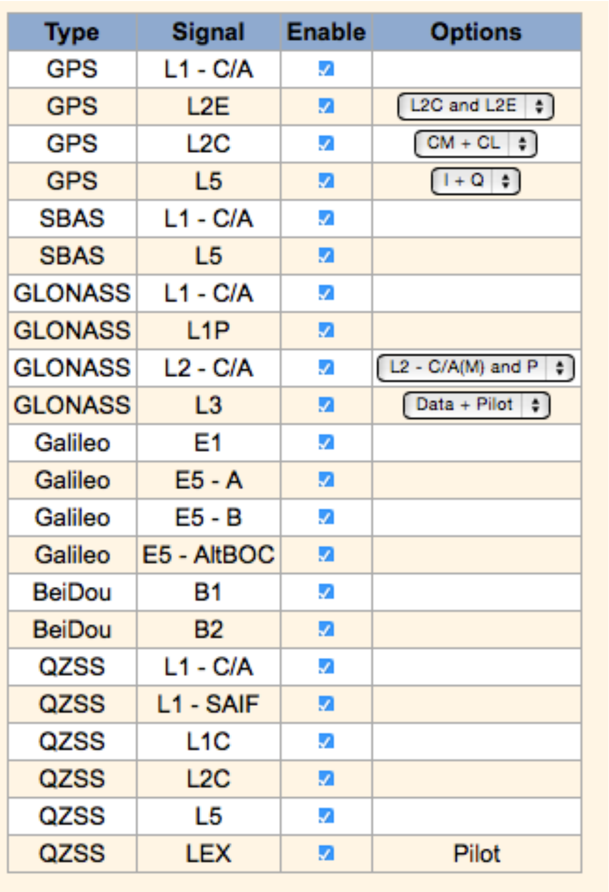
CUUT: Multi-GNSS CORS @Chula





Type	Signal	Enable	Options
GPS	L1 - C/A	☑	
GPS	L2E	☑	L2C and L2E
GPS	L2C	☑	CM + CL
GPS	L5	☑	I + Q
SBAS	L1 - C/A	☑	
SBAS	L5	☑	
GLONASS	L1 - C/A	☑	
GLONASS	L1P	☑	
GLONASS	L2 - C/A	☑	L2 - C/A(M) and P
GLONASS	L3	☑	Data + Pilot
Galileo	E1	☑	
Galileo	E5 - A	☑	
Galileo	E5 - B	☑	
Galileo	E5 - AltBOC	☑	
BeiDou	B1	☑	
BeiDou	B2	☑	
QZSS	L1 - C/A	☑	
QZSS	L1 - SAIF	☑	
QZSS	L1C	☑	
QZSS	L2C	☑	
QZSS	L5	☑	
QZSS	LEX	☑	Pilot

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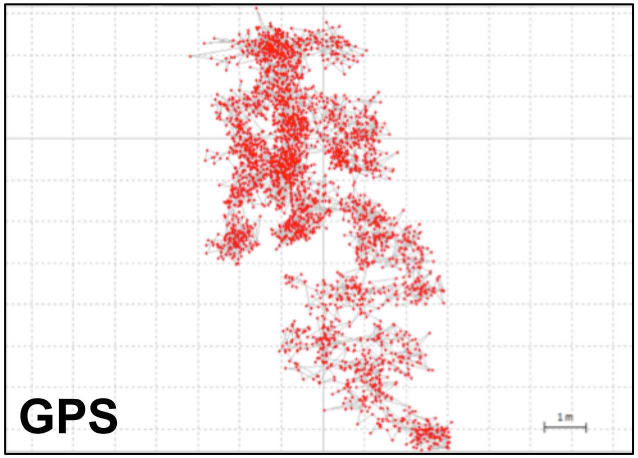
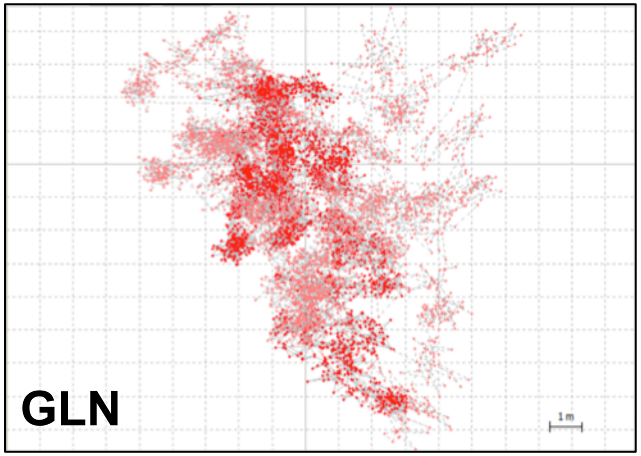
Single Point Positioning (CUUT, 2015/02/01)

24 hr, 30 sec rate, 5 deg elevation cut-off



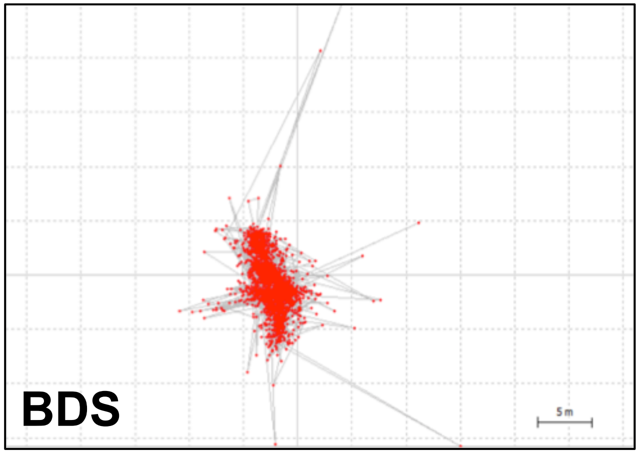
GPS

RMS
U: 7.00m
2D: 6.33m



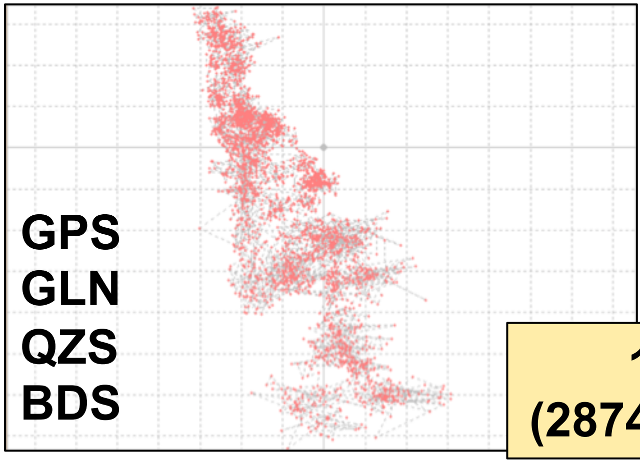
GLN

RMS
U: 9.15m
2D: 7.69m



BDS

RMS
U: 6.65m
2D: 7.52m



GPS
GLN
QZS
BDS

RMS
U: 6.60m
2D: 6.47m

100%
(2874 epochs)

SPP (different elevation cut-offs)

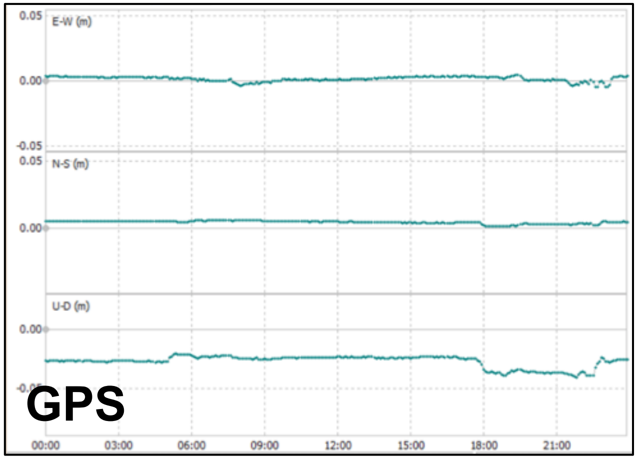
GNSS constellation	Elevation cut-off **5 deg** RMS			Elevation cut-off **30 deg** RMS			Elevation cut-off **45 deg** RMS		
	U	2D	Availability	U	2D	Availability	U	2D	Availability
G	7,00	6,33	**100,0**	7,53	5,93	94,22	11,37	6,49	10,96
R	9,16	7,69	99,4	27,97	19,08	33,75	70,38	13,50	0,17
C	6,65	7,52	99,4	10,98	8,92	97,70	14,69	8,99	61,20
GR	6,56	6,42	**100,0**	6,60	5,09	**100,00**	114,75	57,03	36,64
GJ	6,53	6,76	**100,0**	6,42	6,14	96,42	11,23	6,18	20,15
GC	6,89	6,46	**100,0**	8,00	6,60	**100,00**	15,92	9,66	89,60
GRJ	6,20	6,68	**100,0**	5,97	4,88	**100,00**	68,85	24,69	47,81
GRC	6,70	6,40	**100,0**	7,57	6,09	**100,00**	69,16	52,92	94,08
GJC				7,48	6,05	**100,00**	11,36	8,68	91,96
GRJC	6,60	6,47	**100,0**	7,13	5,58	**100,00**	68,39	52,45	95,06

G= GPS, R=GLONASS, C=BeiDou, J=QZSS

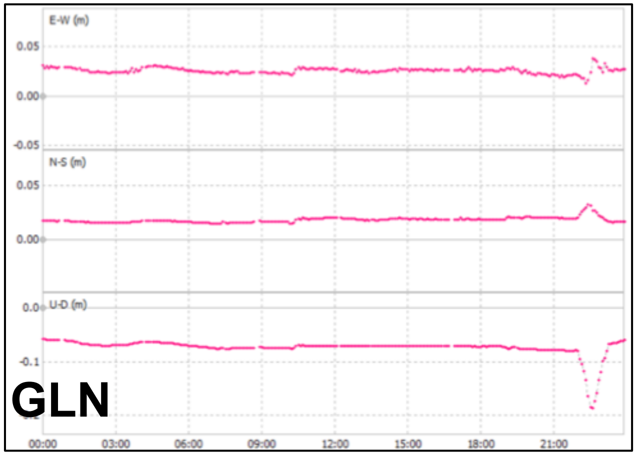
Multi-GNSS means increased availability, continuity, integrity and accuracy.

Precise Point Positioning

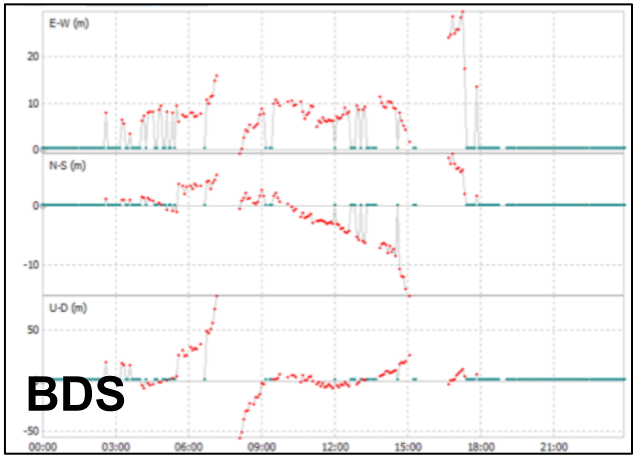
Static mode, FW-BW, 24 hr, 5-min rate, 15 deg elevation cut-off



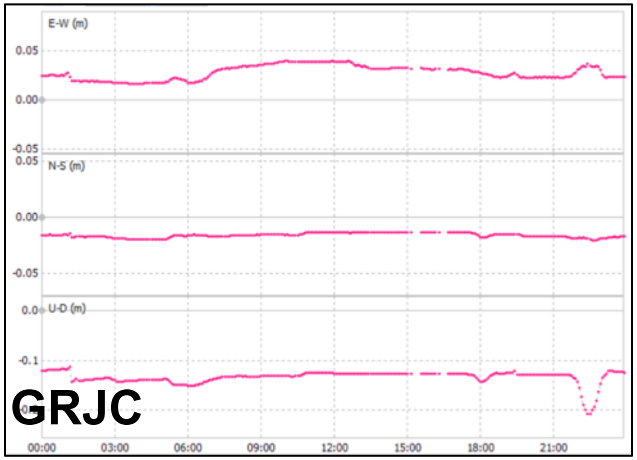
RMS
U: 0.028m
2D: 0.011m



RMS
U: 0.076m
2D: 0.063m



RMS
U: 13.83m
2D: 15.44m



RMS
U: 0.135m
2D: 0.065m

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PPP (15 deg) vs. PPP (30 deg)

GNSS constellation	Elevation cut-off **15 deg** RMS			Elevation cut-off **30 deg** RMS		
	U	2D	Availability	U	2D	Availability
G	0,028	0,011	**100,0**	0,065	0,010	94,79
R	0,076	0,063	97,2	0,435	0,406	31,60
C	13,837	15,436	50,3	19,288	12,556	26,74
GR	0,035	0,013	**100,0**	0,067	0,006	**100,00**
GJ	0,040	0,051	**100,0**	0,117	0,111	96,88
GC	0,189	0,064	**100,0**	0,516	0,099	**100,00**
GRJ	0,043	0,051	**100,0**	0,112	0,118	**100,00**
GRC	0,130	0,034	**100,0**	0,422	0,076	99,65
GRJC	0,135	0,065	**100,0**	0,411	0,268	**100,00**

Why?

G= GPS, R=GLONASS, C=BeiDou, J=QZSS

Multi-GNSS precise positioning means also complex error models to account for biases between signals, frequencies, and different systems.

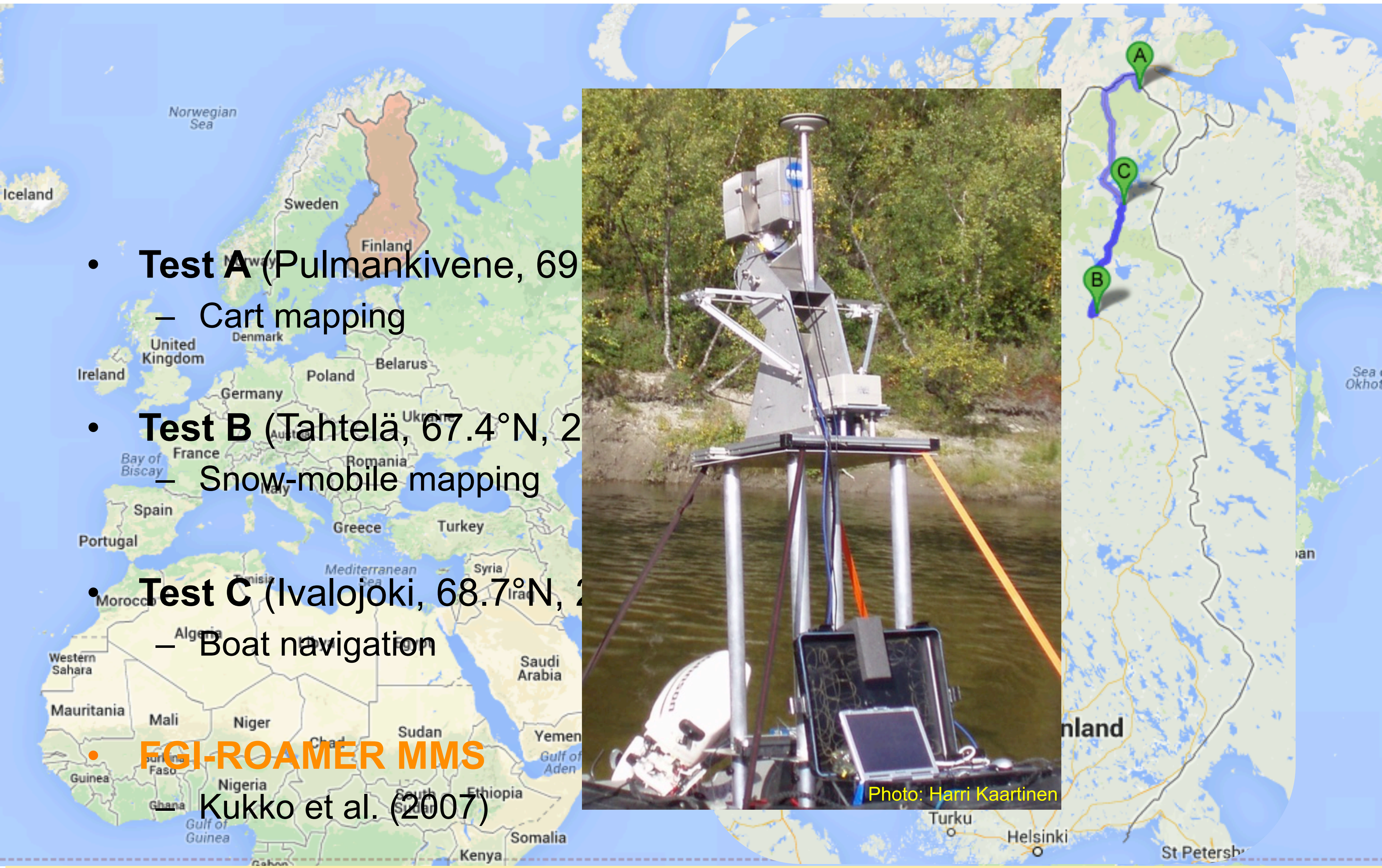

Photo: Harri Kaartinen

- **Test A** (Pulmankivene, 69
  - Cart mapping
- **Test B** (Tahtelä, 67.4°N, 2
  - Snow-mobile mapping
- **Test C** (Ivalojoki, 68.7°N, 2
  - Boat navigation
- **FGI-ROAMER MMS**
  - Kukko et al. (2007)

Kukko, A., **Andrei, C-O.**, Salminen, V.M., Kaartinen, H., Chen, Y., Rönnholm, P., Hyyppä, H., Hyyppä, J., Chen, R., Haggren, H., Kosonen, I., Capek, K. (**2007**). *Road environment mapping system of the Finnish Geodetic Institute - FGI ROAMER*. International Archives of Photogrammetry, Remote Sensing and Spatial Information Sciences, Volume XXXVI, Part 3/W52, pp.241-248, ISSN 1682-1777

PPP algorithm requires complex error modelling

- Precise orbits (*.sp3)
- Precise clocks (*.clk_05s)
- Absolute antenna phase center variations (igs05.atx)
- Differential code biases (P1C1 DCB)
- Ocean Loading (*.BLQ)
- Pole displacements (*.ERP)
- Phase wind-up
- Elevation cut-off: 10 deg

- Stochastic model
  - Random walk: E, N, H, tropo
  - White noise: rx_clk
- Standard deviation
  - Code: 4 m
  - Phase: 0.2 m
- Coordinates
  - Uncertainty: 100 m
  - Test A: 2 m/s (Hz), 0.5 m/s (Vert)
  - Test B: 5 m/s (Hz), 0.5 m/s (Vert)
  - Test C: 10 m/s (Hz), 0.5 m/s (Vert)
- Tropo: $3x10^{-8}$ m^2/s

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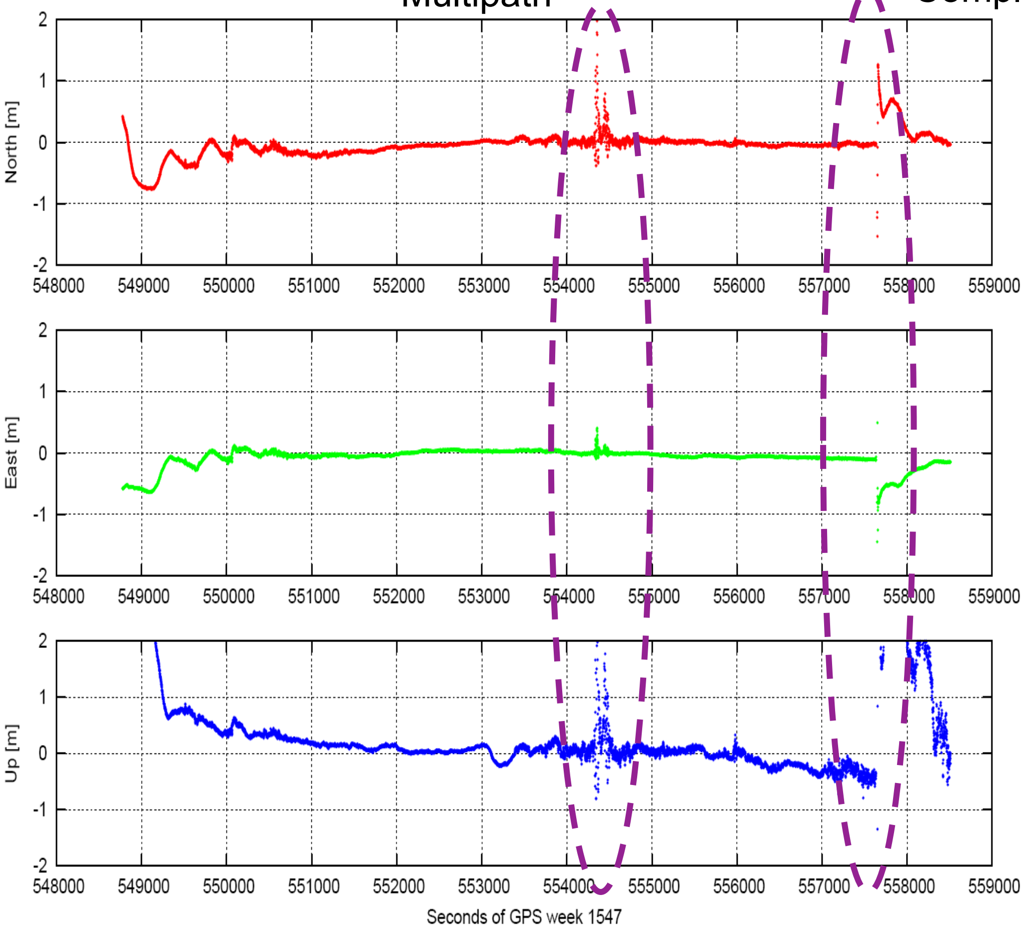
Post-Processing: PPP Kinematic Forward


Multipath

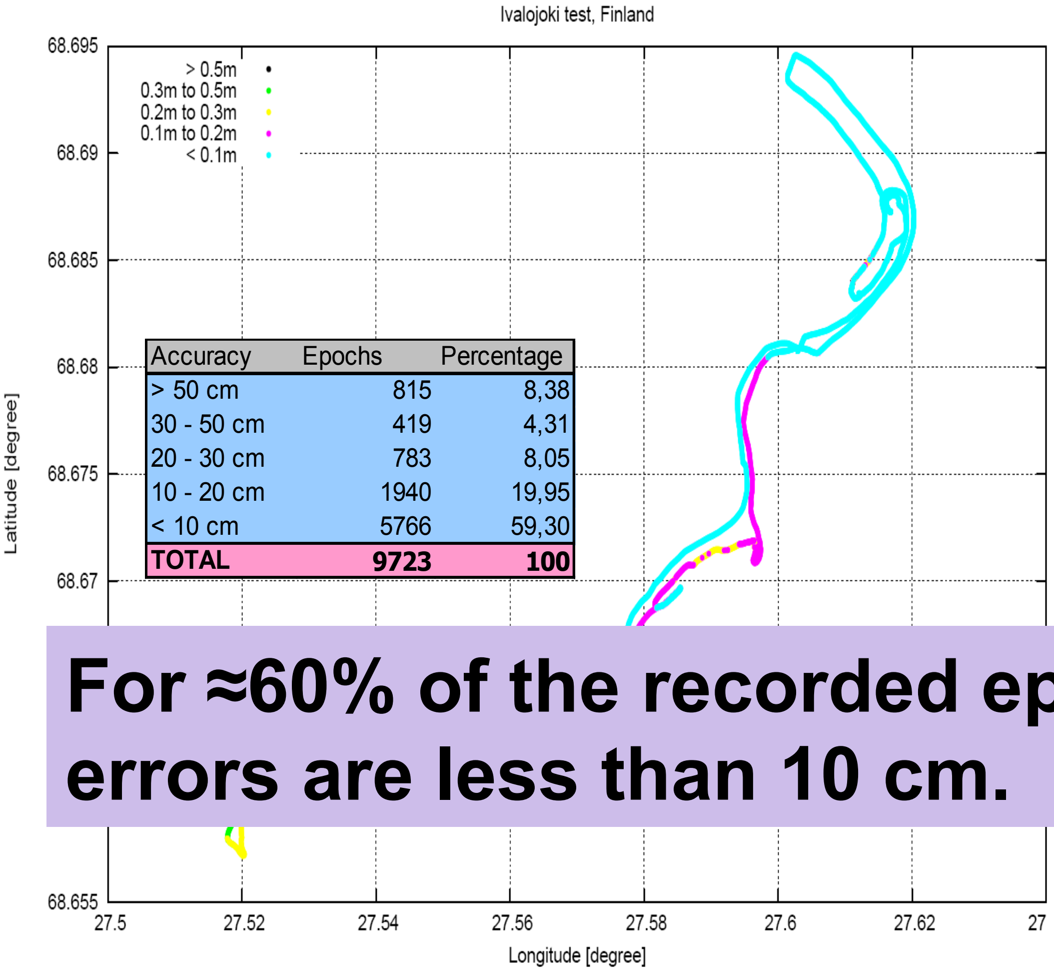
Complete loss-of-lock

Statistics	North (m)	East (m)	Up (m)	2D (m)
Mean	-0,035	-0,067	0,293	0,151
RMS	0,194	0,167	0,837	0,256

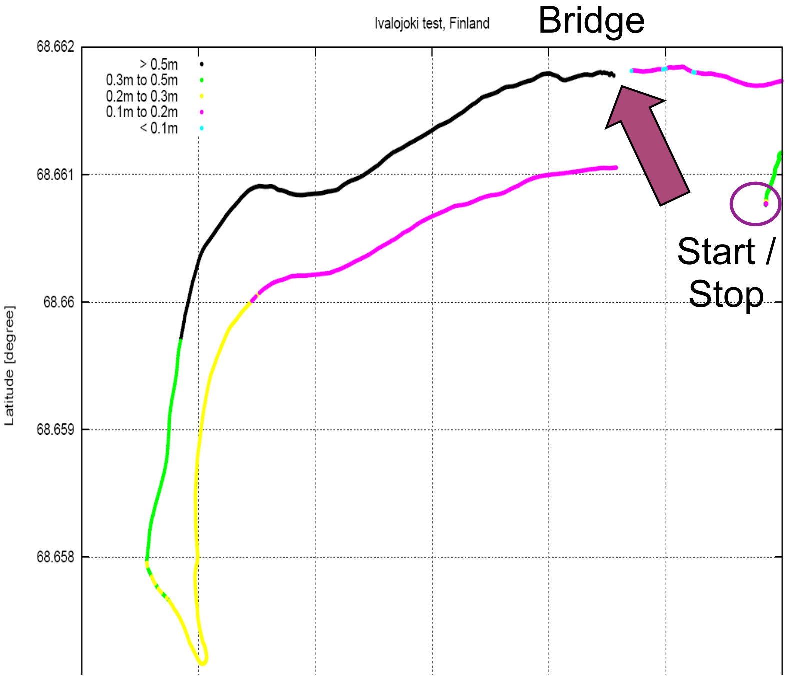
Photo: Erkka Taivainen

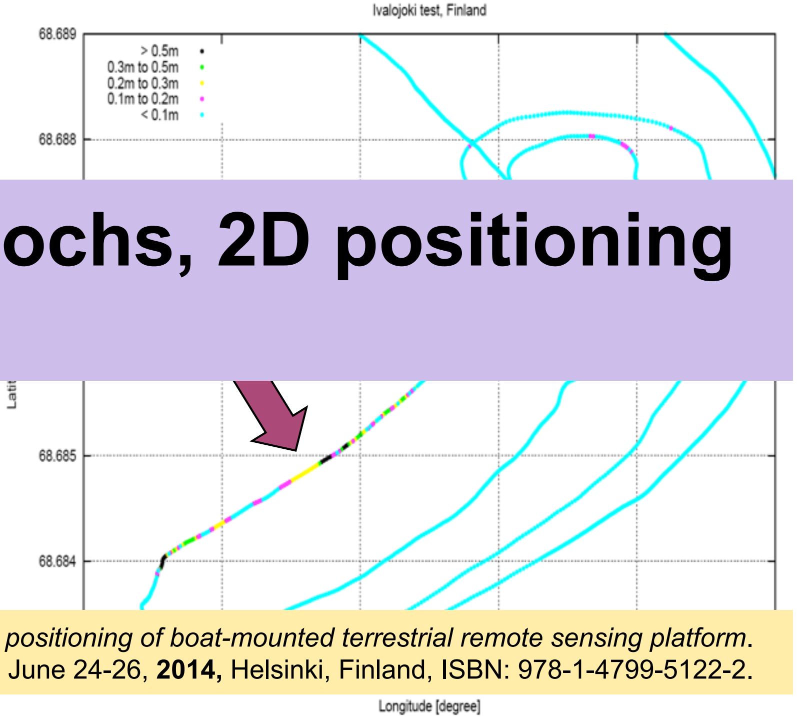
Ground truth: TC GPS/INS combined solution

PPP Kinematic (cont')



Accuracy	Epochs	Percentage
> 50 cm	815	8,38
30 - 50 cm	419	4,31
20 - 30 cm	783	8,05
10 - 20 cm	1940	19,95
< 10 cm	5766	59,30
TOTAL	**9723**	**100**





For ≈60% of the recorded epochs, 2D positioning errors are less than 10 cm.

Andrei, C-O., Kaartinen, H., Kukko, A., Satirapod, C. *Precise carrier phase-based point positioning of boat-mounted terrestrial remote sensing platform*. Localization and GNSS (ICL-GNSS) 2014, IEEE Conference Publications, IEEE Xplore, June 24-26, **2014,** Helsinki, Finland, ISBN: 978-1-4799-5122-2.

Conclusions

- It is no longer just about GPS!
- But multiple constellations, frequencies, signals
- Multi-GNSS means increased availability, continuity, integrity and accuracy
  - Also more challenges to be solved (e.g., IFB, ISB, AR, etc.)
- Precise positioning becomes more available because of correction data and advanced positioning algorithms

Octavian.A@chula.ac.th

Thank you for Your attention!

http://www.sv.eng.chula.ac.th

Chulalongkorn University
Phayathai Road, Pathumwan,
Bangkok 10330,
Thailand