PPP: PPP

Precise Point Positioning:
Processing, Performance and Potential

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Outline

- GNSS fundamentals
- PPP theory
- High-quality data
- Low-cost data
- Potential

GNSS fundamentals, PPP theory: Processing

High-quality data, Low-cost data: Performance

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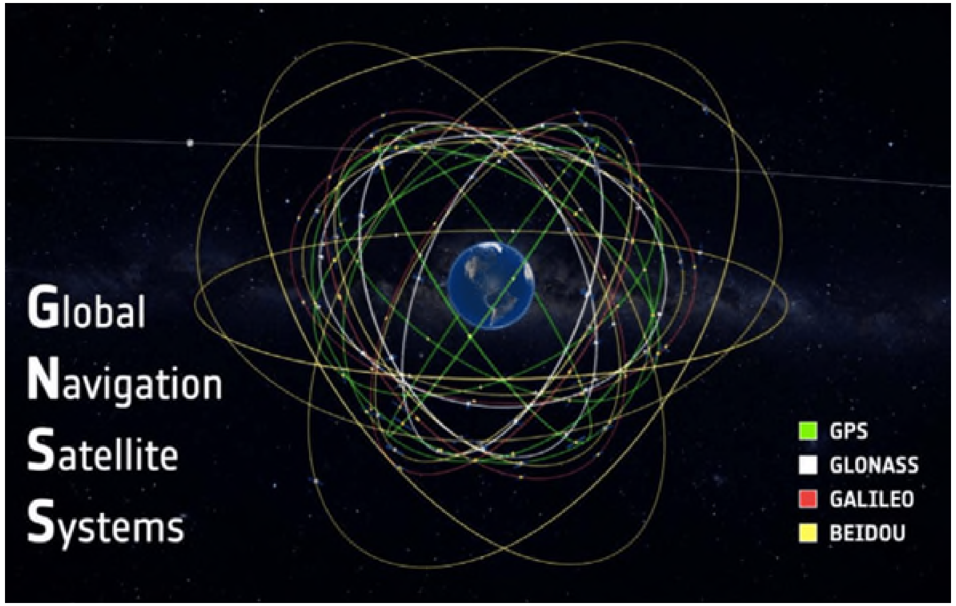
GNSS

- Four major Global Navigation Satellite Systems: GPS, GLONASS, Galileo, BeiDou
- Satellite constellations emitting signals
- Enable worldwide positioning and navigation service



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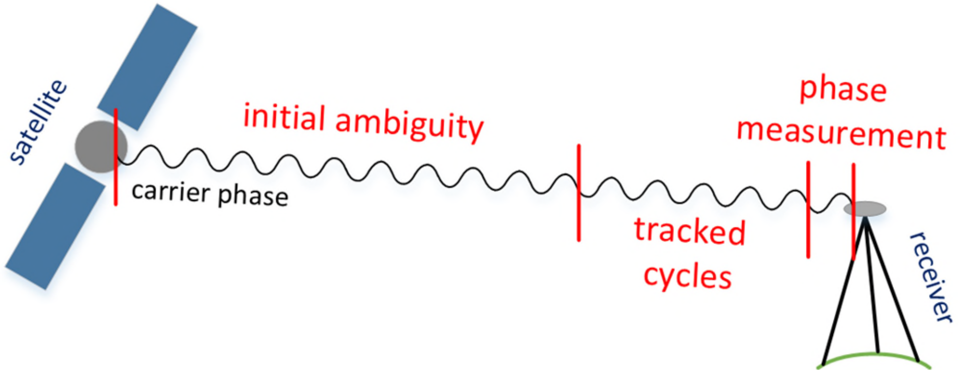
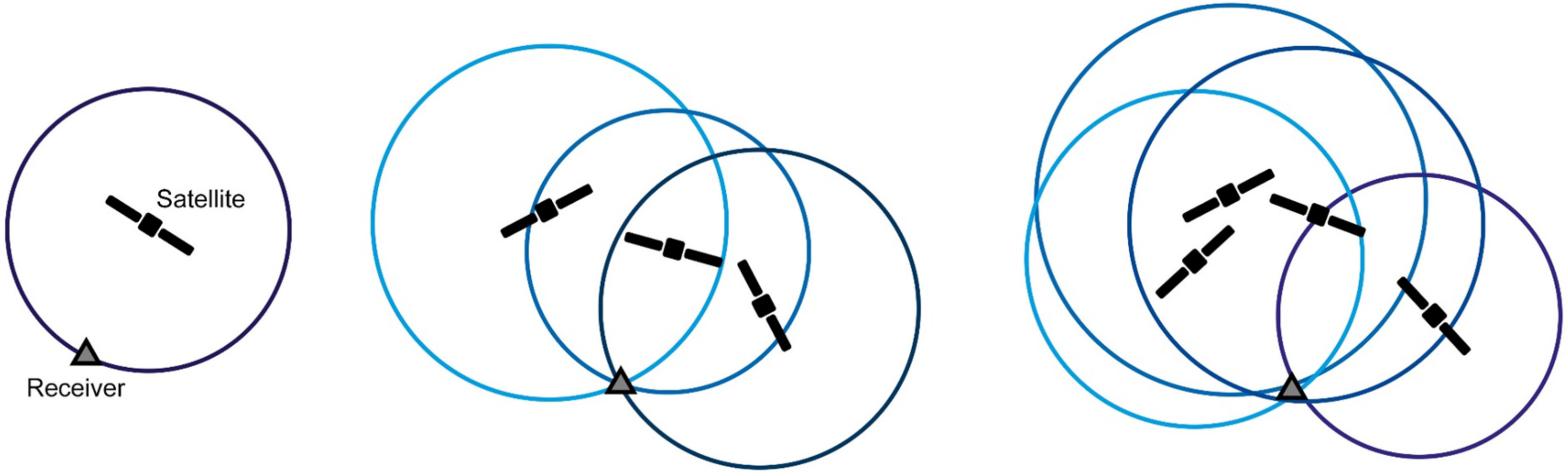
GNSS Positioning

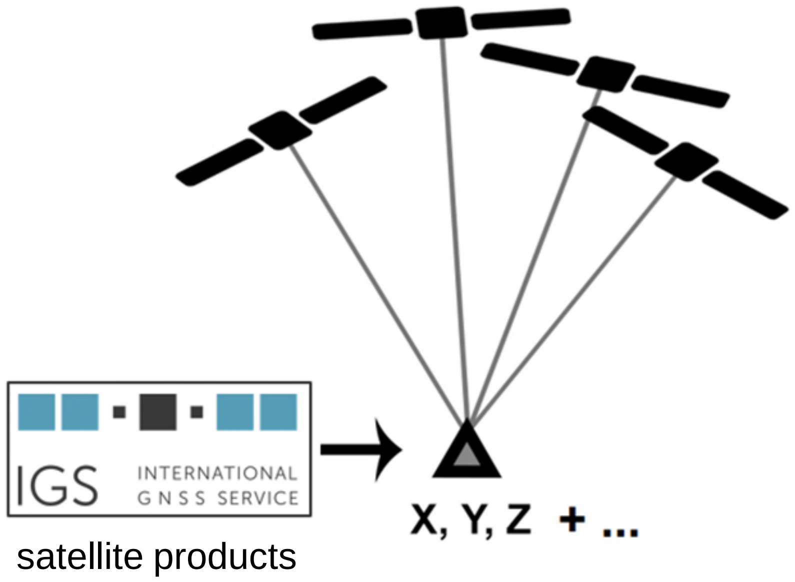
- Code
- Phase
- Signal-to-Noise ratio
- Doppler





Precise Point Positioning

- PPP relies on precise satellite products: satellite orbits, clocks and biases
- Complex models and algorithms
- Position accuracy: cm, or even mm
- Major drawback: convergence time



multi-GNSS

multi-frequency

modern satellite products

new PPP models

reduce convergence time

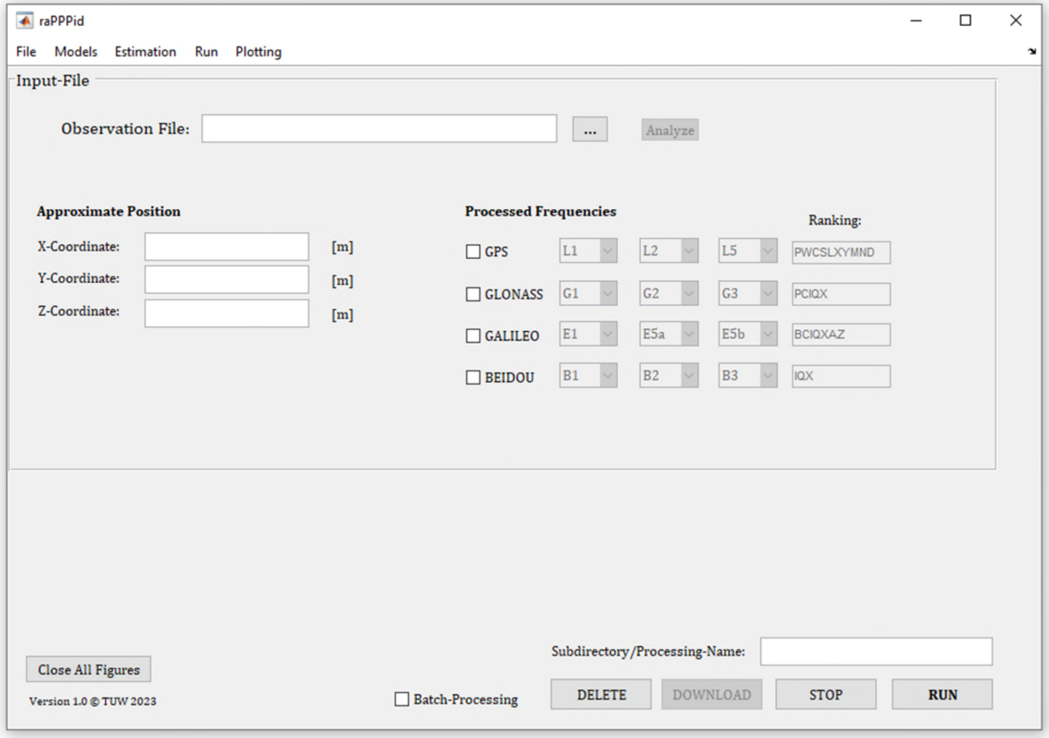
integer ambiguity fixing

accurate error models

TU WIEN ViеVS Vienna VLBI and Satellite Software

raPPPid

- State-of-the-art PPP software
- Self-developed
- PPP module of VieVS
- GitHub:
  https://github.com/TUW-VieVS/raPPPid
- Documentation:
  https://vievswiki.geo.tuwien.ac.at/en/raPPPid



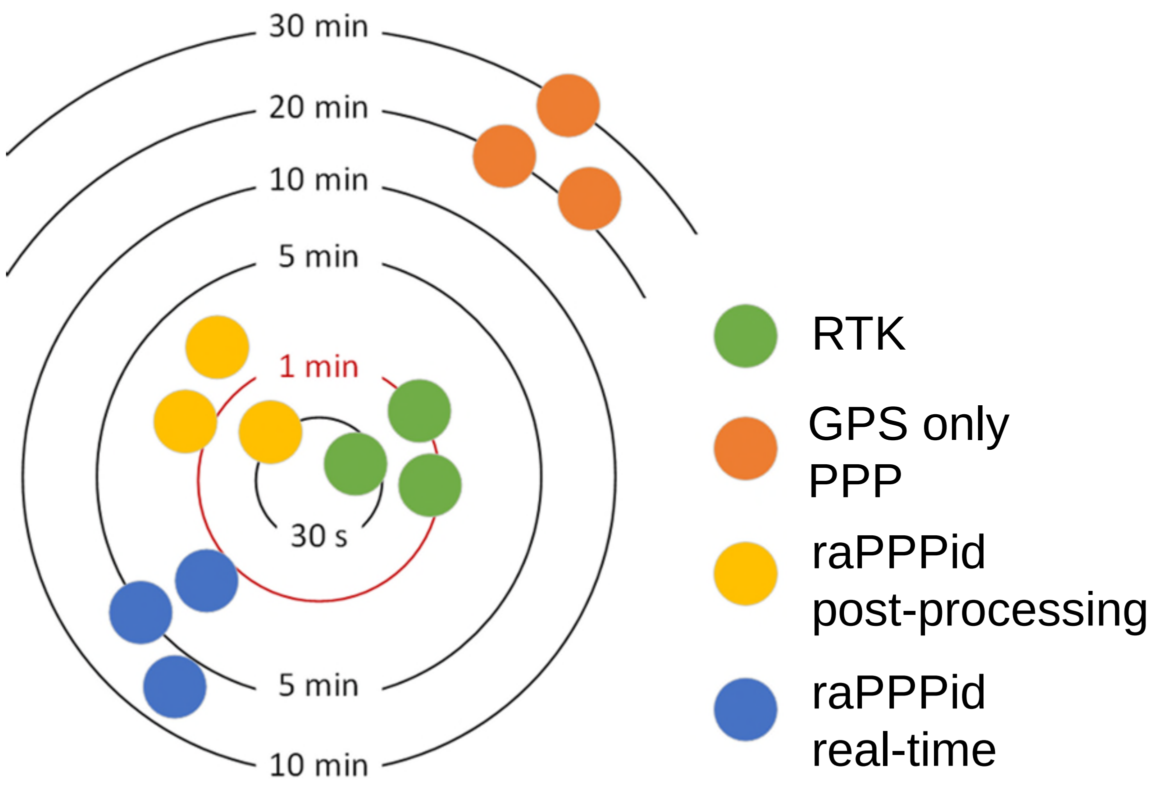
raPPPid

→ Convergence:

- Float (2D < 10 cm): several minutes
- Fixed (2D < 5 cm): 1 min or below

→ Accuracy: cm-level or below

→ Comparable to RTK



(static reference stations)

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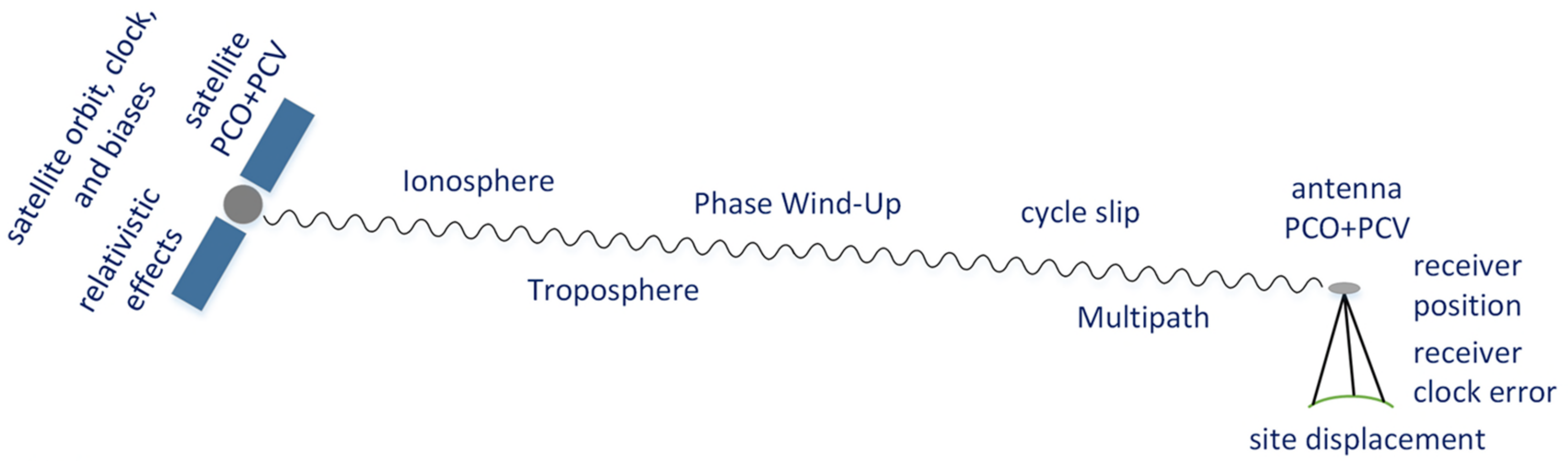
Error sources

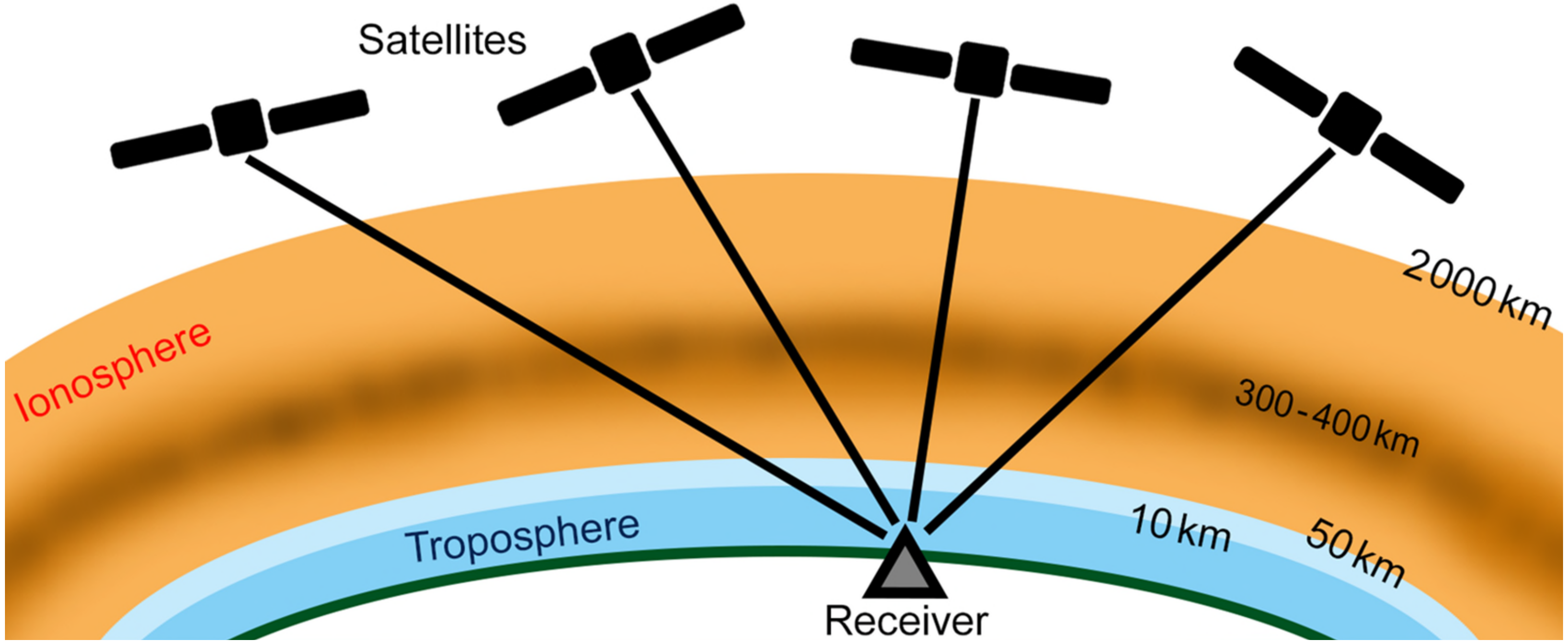


$$L_i^{model} = \rho - c \cdot dt^S - dt_{rel} + c(dt_R^{GPS} + \delta t^g) - DCB_{1i} - \frac{f_1^2}{f_i^2} \cdot dIono_1 + dTrop + dTrop_{residual}^{wet} - \delta\rho_{solid} - \delta\rho_{ocean\,loading} - \delta\rho_R^{PCO_i,PCV_i} + \delta\rho_R^{ARP_i} + \delta\rho_{PCO_i,PCV_i}^S + \delta\rho_{Wind-Up_i} + \lambda_i N_i$$

$$P_i^{model} = \rho - c \cdot dt^S - dt_{rel} + c(dt_R^{GPS} + \delta t^g) - DCB_{1i} + \frac{f_1^2}{f_i^2} \cdot dIono_1 + dTrop + dTrop_{residual}^{wet} - \delta\rho_{solid} - \delta\rho_{ocean\,loading} + \delta\rho_{GDV_i} - \delta\rho_R^{PCO_i,PCV_i} + \delta\rho_R^{ARP_i} + \delta\rho_{PCO_i,PCV_i}^S$$

→ many to consider

Atmosphere



Ionospheric delay

- Major error source
- Strong fluctuations
- Challenging

Tropospheric delay

- Hydrostatic and wet part
- ~90% and ~10%
- Model and estimate

Error sources

Symbol	Description	Magnitude
ρ	Theoretical distance	10^7 m
~~dt^S~~	~~Satellite clock error~~	~~μs-ns~~
~~dt_{rel}~~	~~Relativistic effects~~	~~10 ns~~
dt_R^{GPS}	Receiver clock error	ns-ms
δt^g	Receiver offset GNSS	ns
~~DCB_{Π}~~	~~Receiver DCB~~	~~ns~~
~~$dIono_1$~~	~~Ionospheric delay~~	~~1-20 m~~
~~$dTrop$~~	~~Tropospheric delay~~	~~1-15 m~~
$dTrop^{wet}_{residual}$	Residual wet delay	mm-dm
~~$\delta\rho_{solid}$~~	~~Solid Earth tides~~	~~cm~~
~~$\delta\rho_{GDV_i}$~~	~~Group Delay Variations~~	~~mm-1 m~~
~~$\delta\rho_{oceanloading}$~~	~~Ocean loading~~	~~mm-cm~~
~~$\delta\rho^S_{PCO_i,PCV_i}$~~	~~Satellite PCO and PCV~~	~~1 m, mm-cm~~
~~$\delta\rho_R^{PCO_i,PCV_i}$~~	~~Receiver PCO and PCV~~	~~cm-dm, mm-cm~~
~~$\delta\rho_R^{ARP_i}$~~	~~Receiver ARP (height)~~	~~cm-1 m~~
~~$\delta\rho_{wind-up_i}$~~	~~Phase Wind Up~~	~~cm-dm~~
N_i	Phase Ambiguity	-

(includes satellite and user position)

→ remaining are estimated as parameters

PPP models

Conventional

- Ionosphere-free linear combination
- 1st order ionospheric delay eliminated
- Well-established and convenient
- Only for two frequencies

IF

Uncombined

- Raw observations are processed
- Ionospheric delay is estimated
- Modern approach
- Any number of frequencies

UC

$$P_{IF} = \rho + c(dt_R^{GNSS_1} + \delta t_R^g) + dTrop^{wet} + \varepsilon$$

$$L_{IF} = \rho + c(dt_R^{GNSS_1} + \delta t_R^g) + dTrop^{wet} + \underbrace{\lambda_{IF} N_{IF}}_{\text{float}} + \varepsilon$$

Conventional model

Uncombined model

$$P_i = \rho + c(dt_R^{GNSS_1} + \delta t^g) - DCB_{1i} + dTrop^{wet} + \gamma_{1i} \cdot dIono_1 + \varepsilon$$

$$L_i = \rho + c(dt_R^{GNSS_1} + \delta t^g) - DCB_{1i} + dTrop^{wet} - \gamma_{1i} \cdot dIono_1 + \underbrace{\lambda_i N_i}_{\text{float}} + \varepsilon$$

\+ ionospheric pseudo-observations

$$dIono_{pseudo} = dIono_1 + \varepsilon$$

→ uncombined model with ionospheric constraint

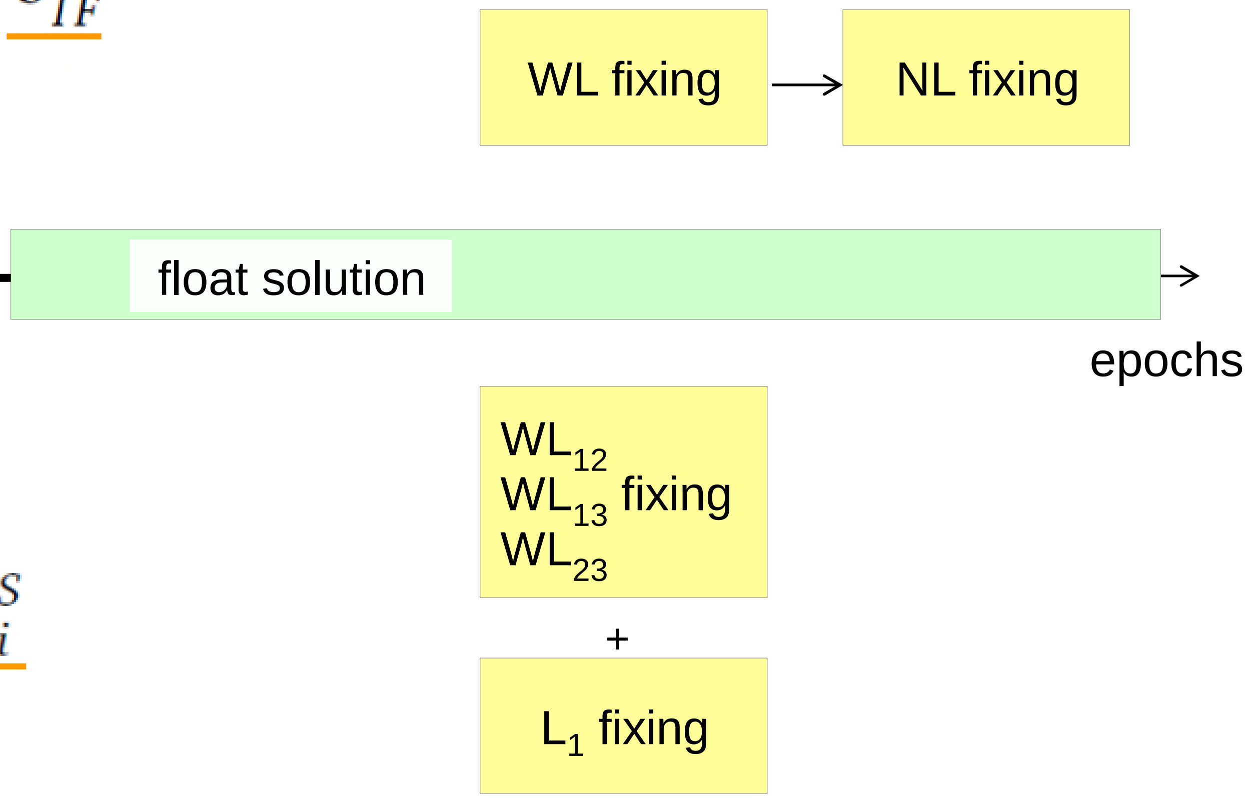
Ambiguity Fixing

float = integer + eliminate - correct

$$\underline{N_{IF}} = \underline{\overline{N}_{IF}} + \underline{b_{R,IF}} - \underline{b_{IF}^{S}}$$

Conventional

Uncombined



$$\underline{N_i} = \underline{\overline{N}_i} + \underline{b_{R,i}} - \underline{b_i^{S}}$$

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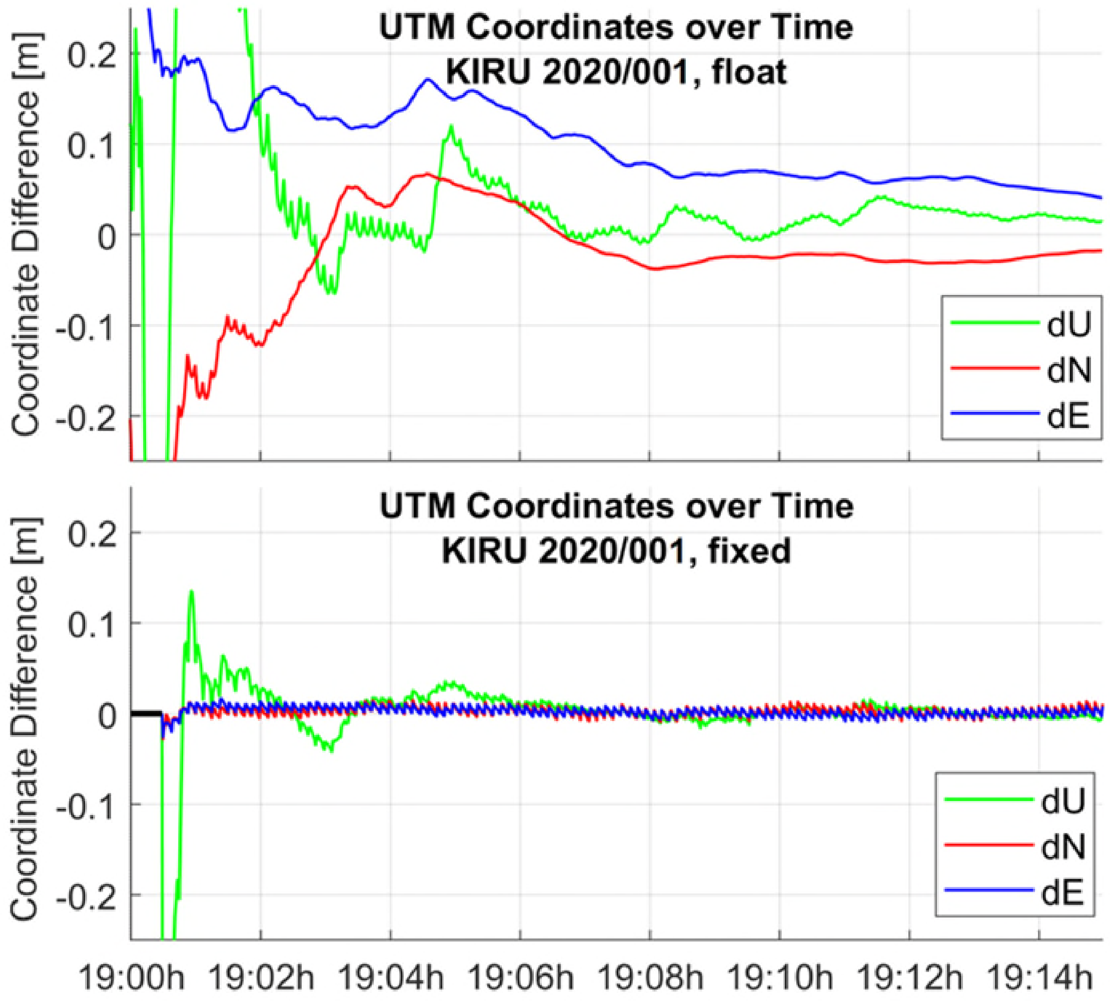
Float solution

- Extended Kalman Filter

Fixed solution

- Fixed ambiguities are introduced as pseudo-observations
- Least-Square-Adjustment



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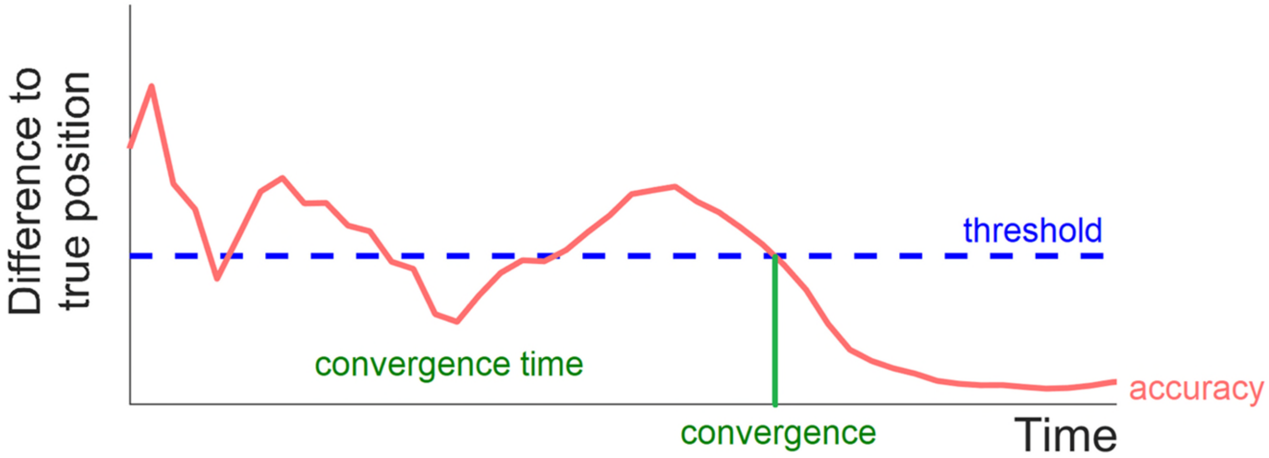
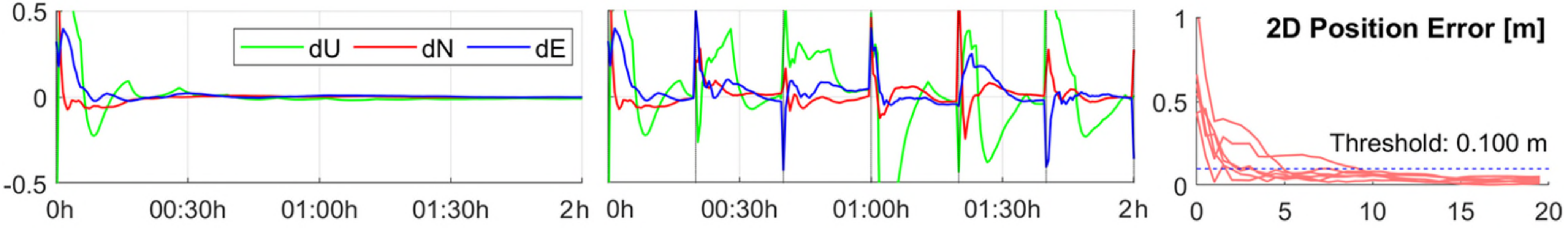
Convergence and accuracy



Coordinate convergence is achieved when the position difference reaches a specific level of accuracy and does not exceed this level after reaching it.

Performance

How to study the performance of PPP:



+ reference values (e.g., coordinates)

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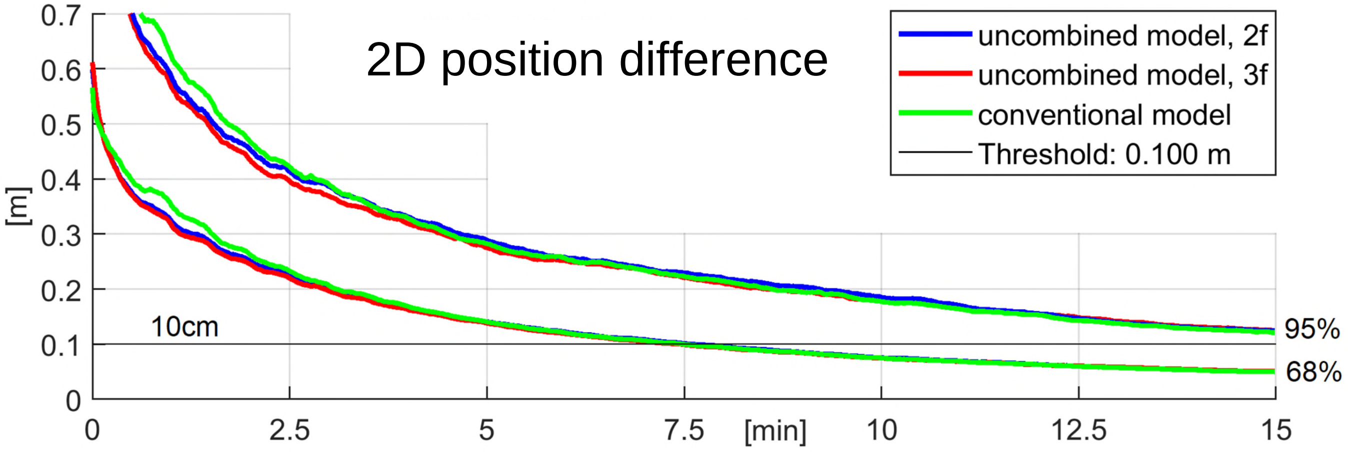
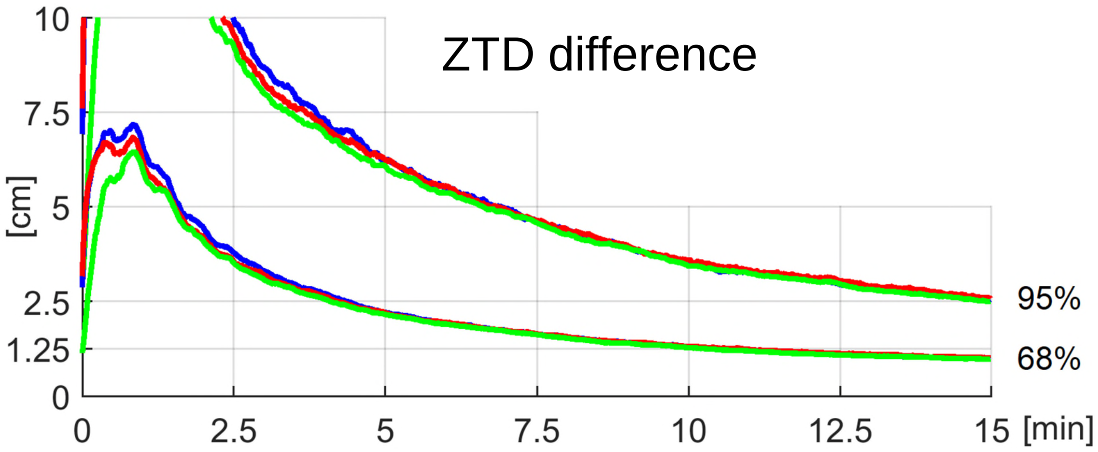
Float convergence

- Typical convergence time (2D < 10 cm): 7 min
- UC vs. IF:
  - First minutes
  - Difference vanishes
  - Accuracy similar

Coordinates



Tropospheric delay



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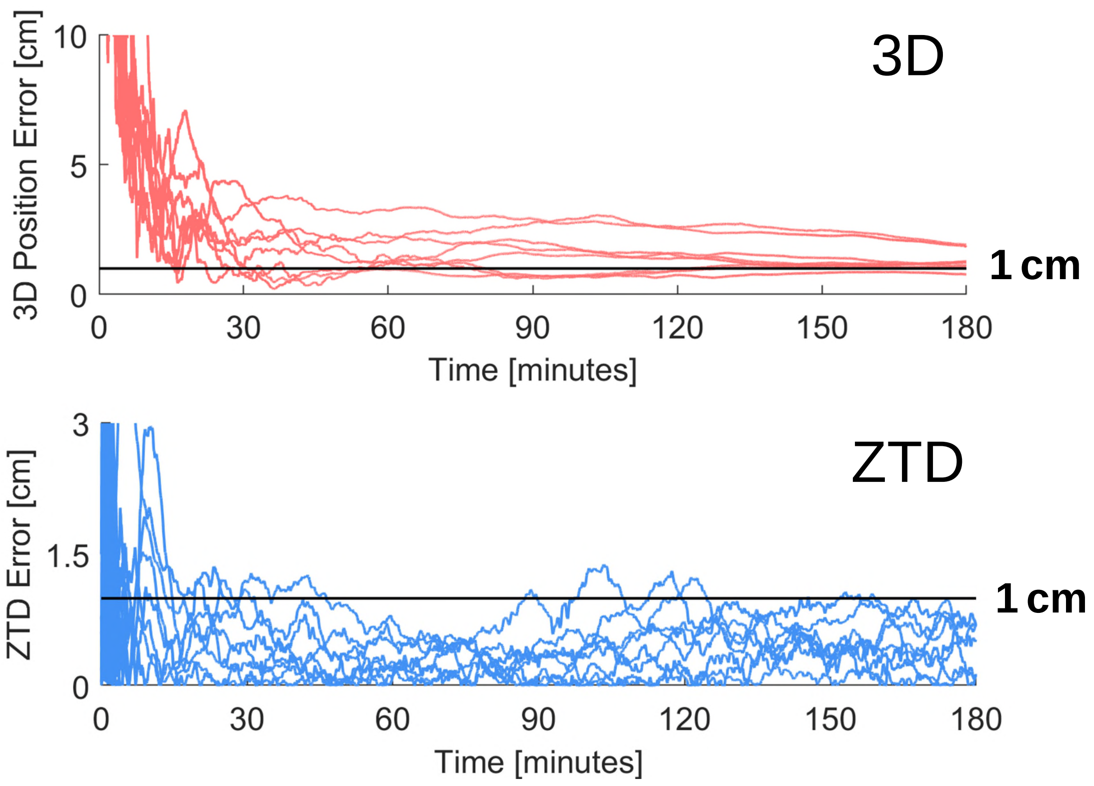
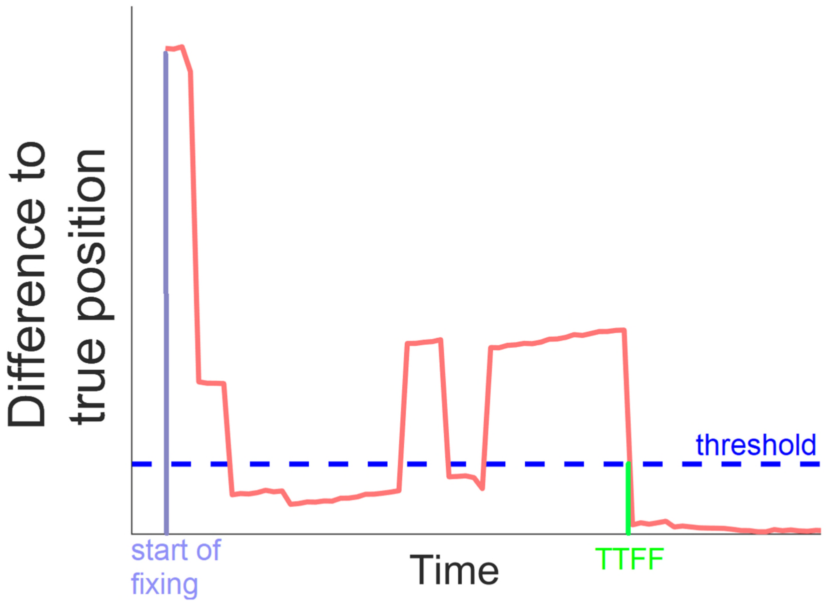
Long-term performance

- Float coordinates and tropospheric delay
- At or below one-cm-level
- On the edge of the physical limits of GNSS



Arequipa, Peru Aug 1, 2022

Time to first fix



The time to first fix time (TTFF) is achieved when the fixed position reaches a specific level of accuracy and does not exceed this level afterwards (2D < 5 cm).

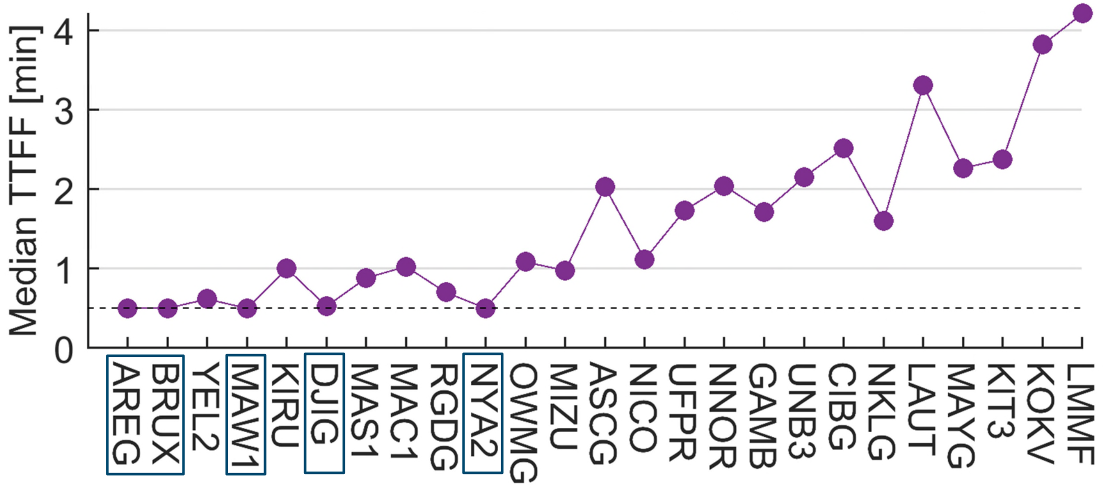
Median TTFF

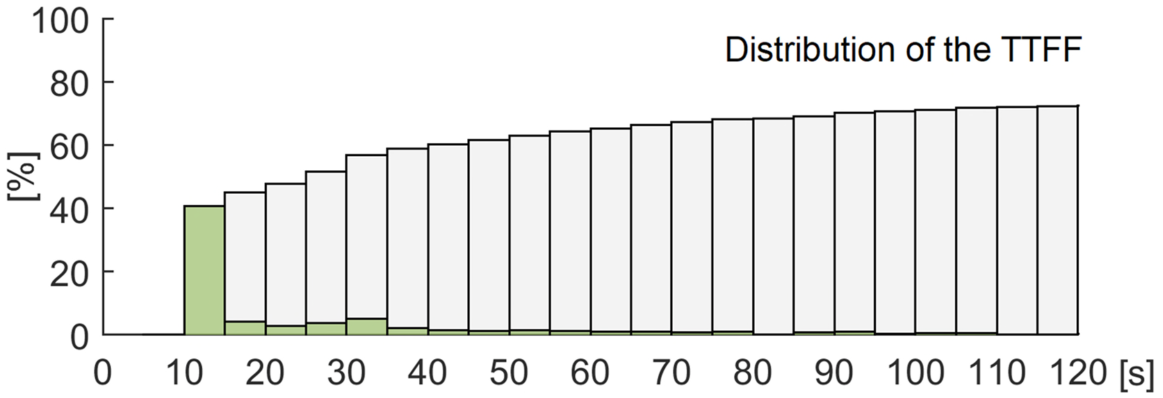
Global test case

- Fixing starts after 30 sec
- Stations perform differently
- Median TTFF: 30 sec to 4 min

Five best stations

- All operating a Septentrio PolaRx5 receiver
- Fixing starts after 10 sec → “instantaneous”





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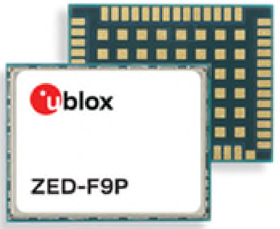
Low-cost equipment

~200$



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+

~100$

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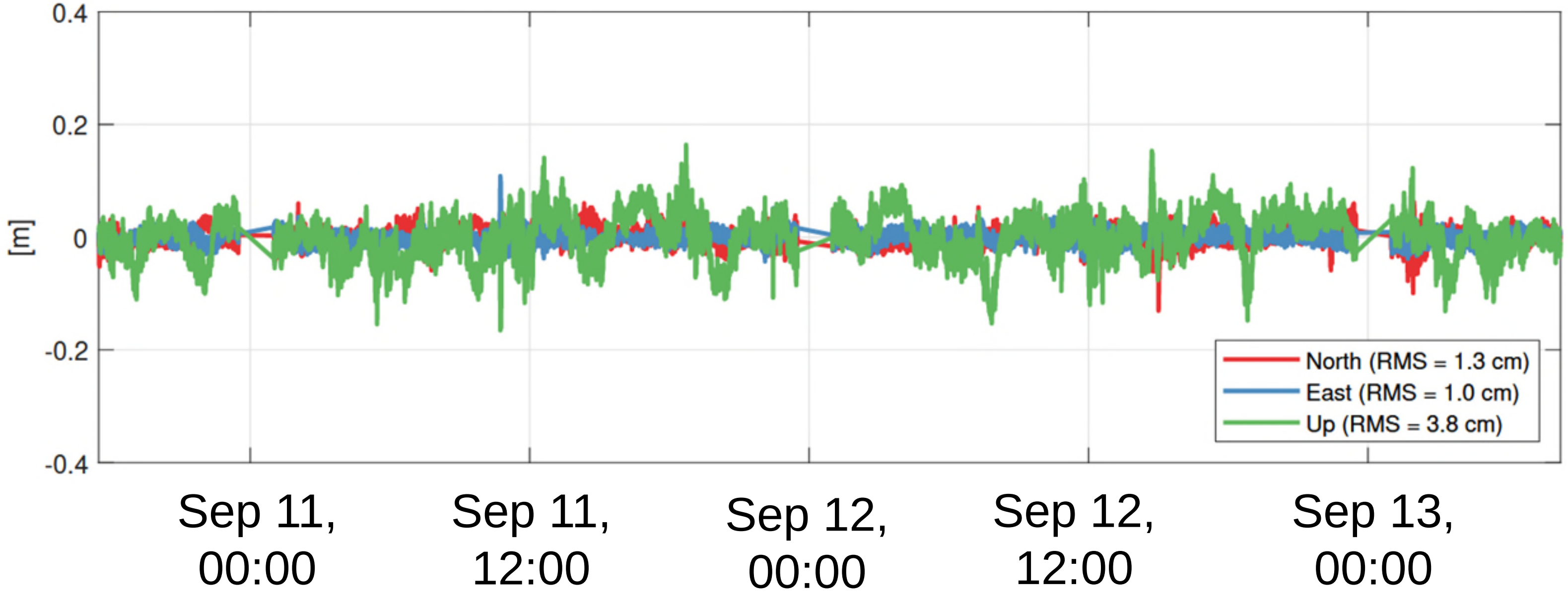
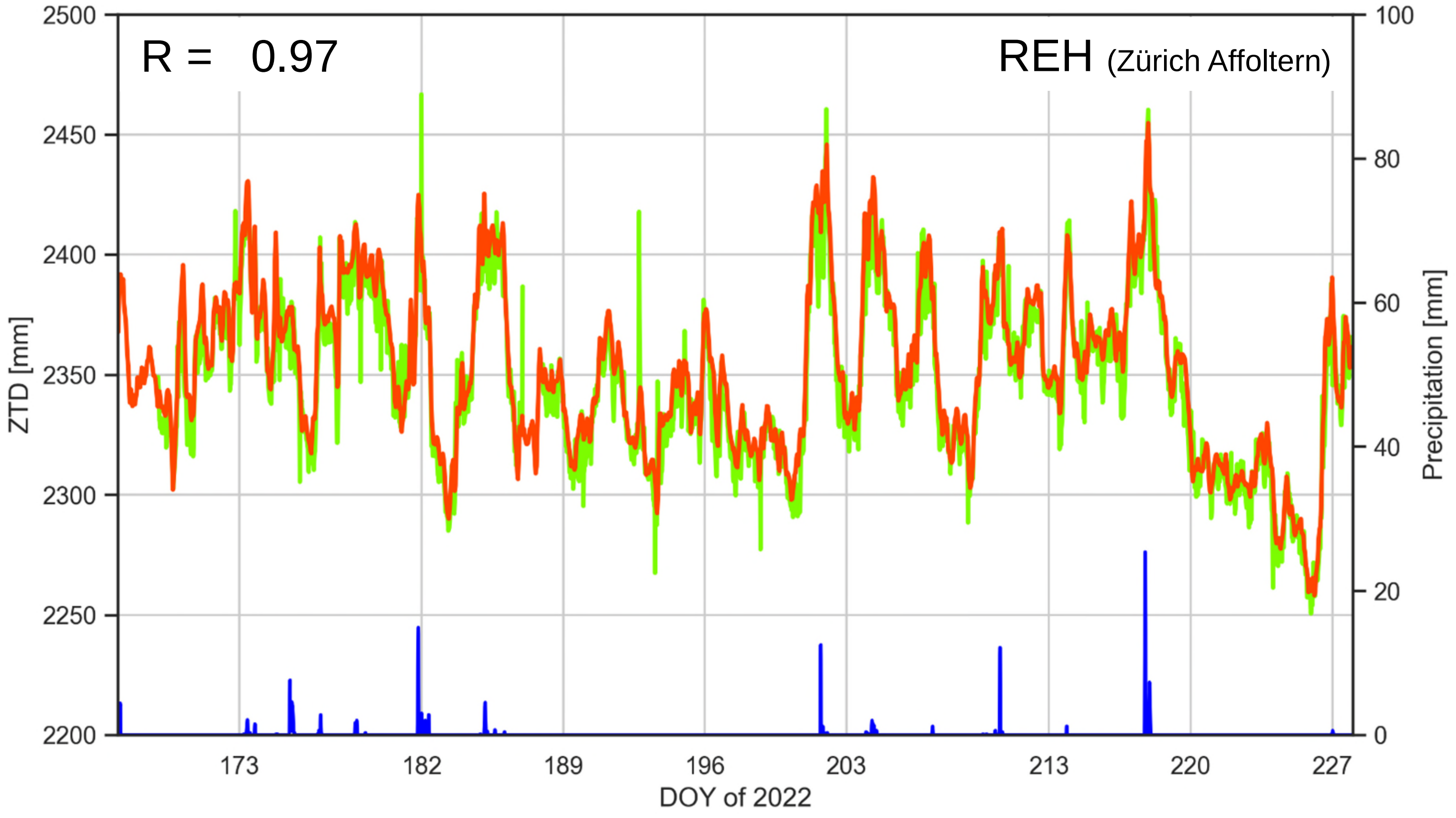


→ stable cm-level position with real-time settings

2021

ZTD estimation



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raPPPid vs. Bernese

rms = 10.61
bias = 5.06 [mm]
std = 9.33

raPPPid (real-time settings)
Bernese (post-processing)
Precipitation (measured)

Smartphone + GNSS

- Since 2016, Android allows accessing raw GNSS measurements
- Enables self-developed GNSS algorithms
- Log GNSS measurements
- PPP processing with raPPPid

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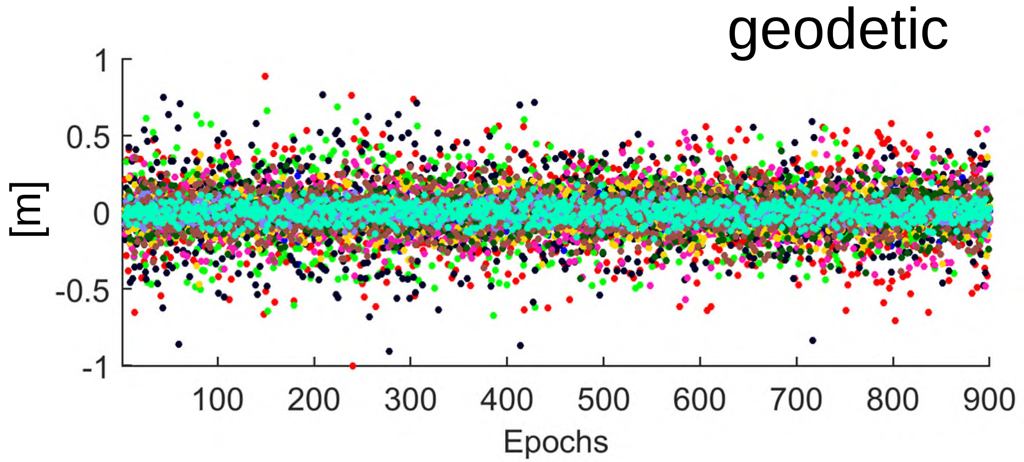
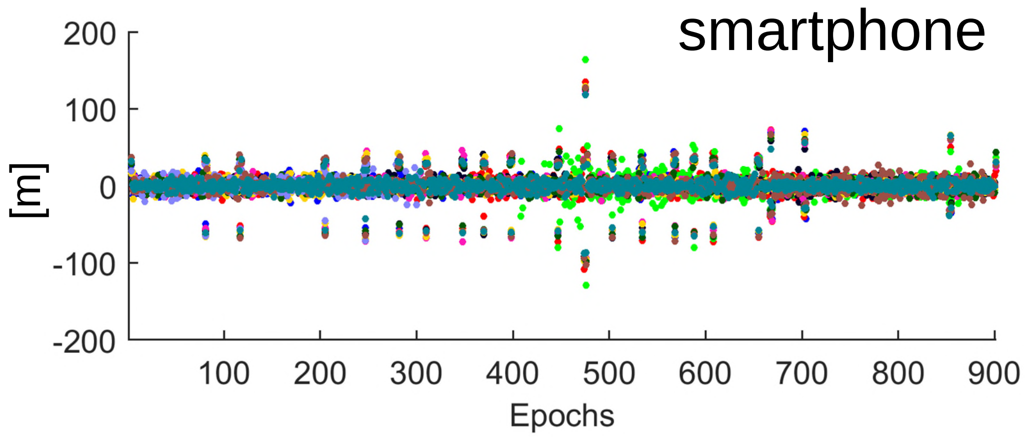
Observation quality

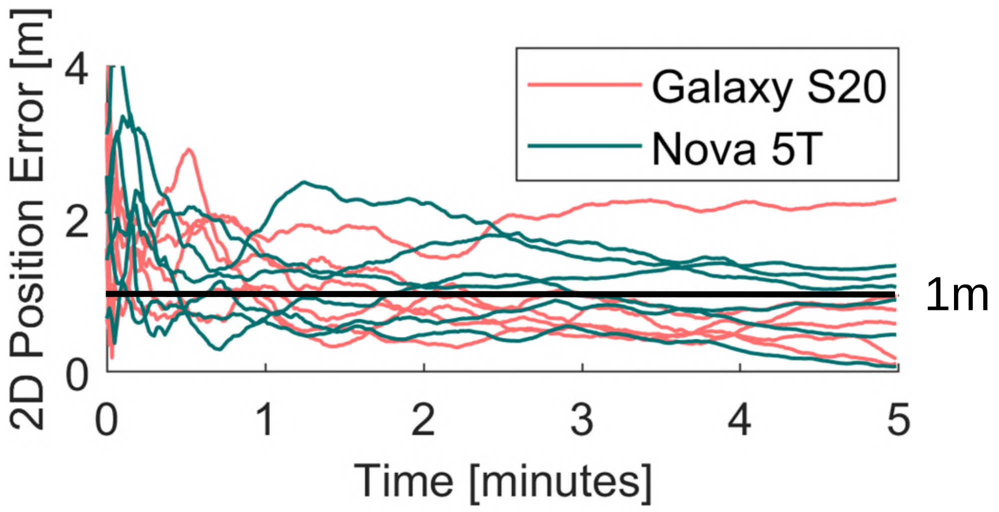
- Code observations
- 1 sec observation interval
- Build triple difference
- Just one of many examples…





Convergence

- Code only
- Few minutes
- 2D position error < 1 m



Samsung Galaxy S20 FE, Huawei Nova 5T

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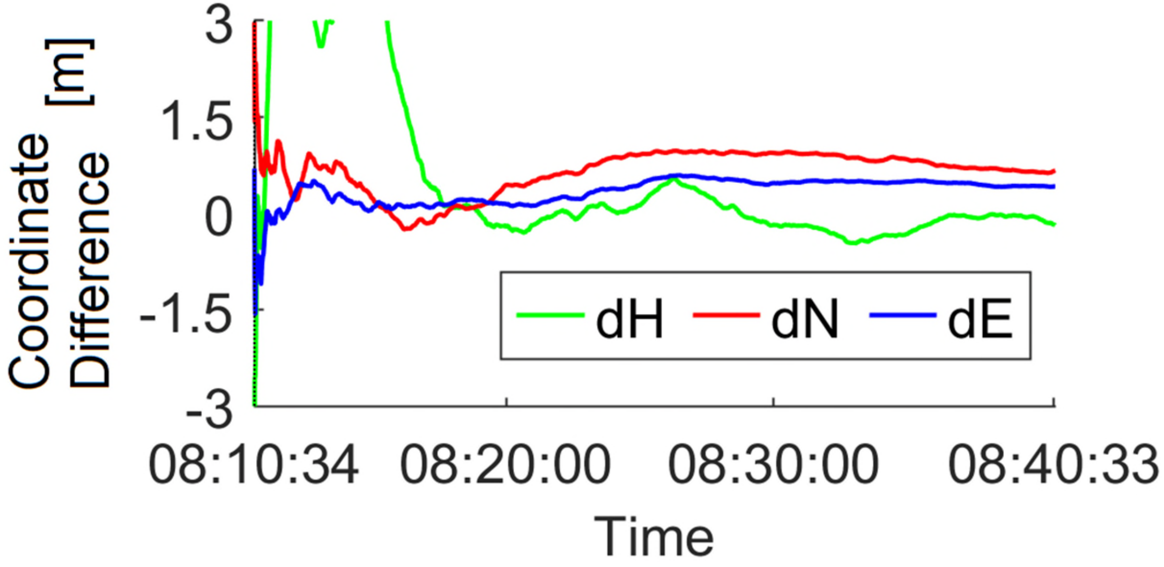
Long-term stability

- Samsung Galaxy S20 FE
- 30 min period
- Stable decimeter-level accuracy

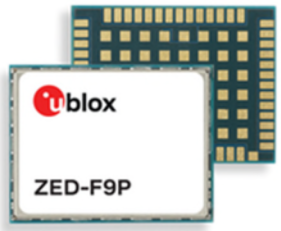
RMS [m]: 0.22, 0.73, 0.40



Performance

Low-cost

- Encouraging results
- Comparable to geodetic equipment



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Smartphone

- Various challenges
- Big potential (e.g., phase)
- $< 1\,m$ is possible

→ FFG-project: APPP

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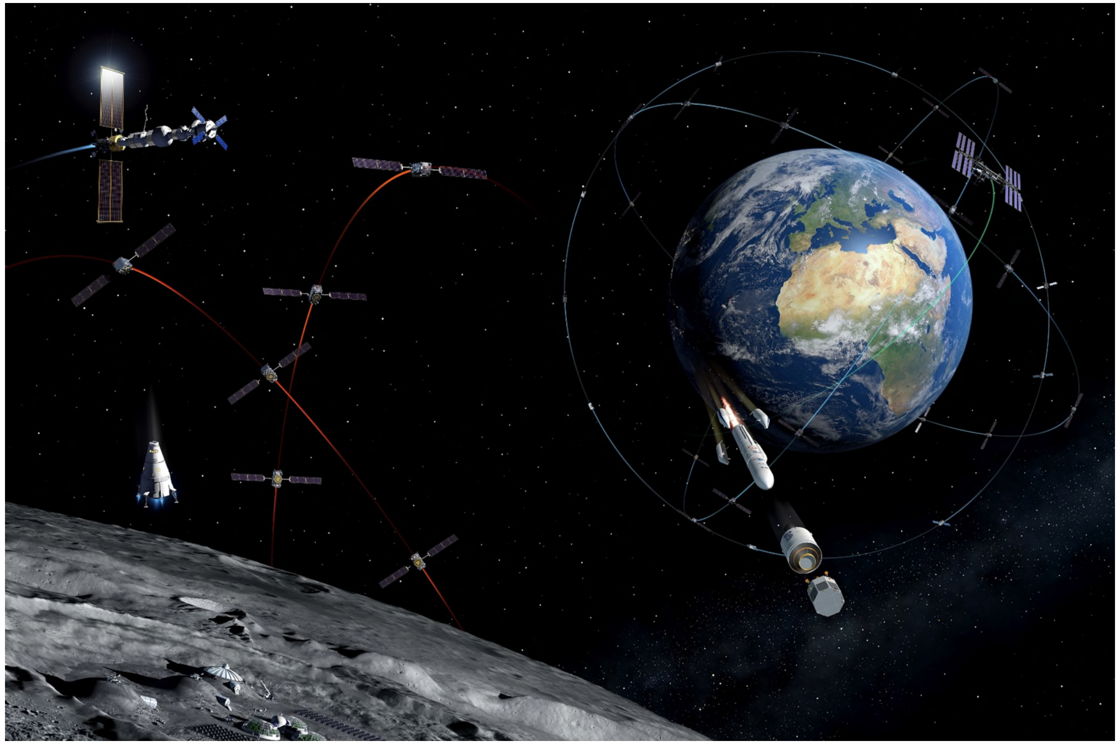
Potential

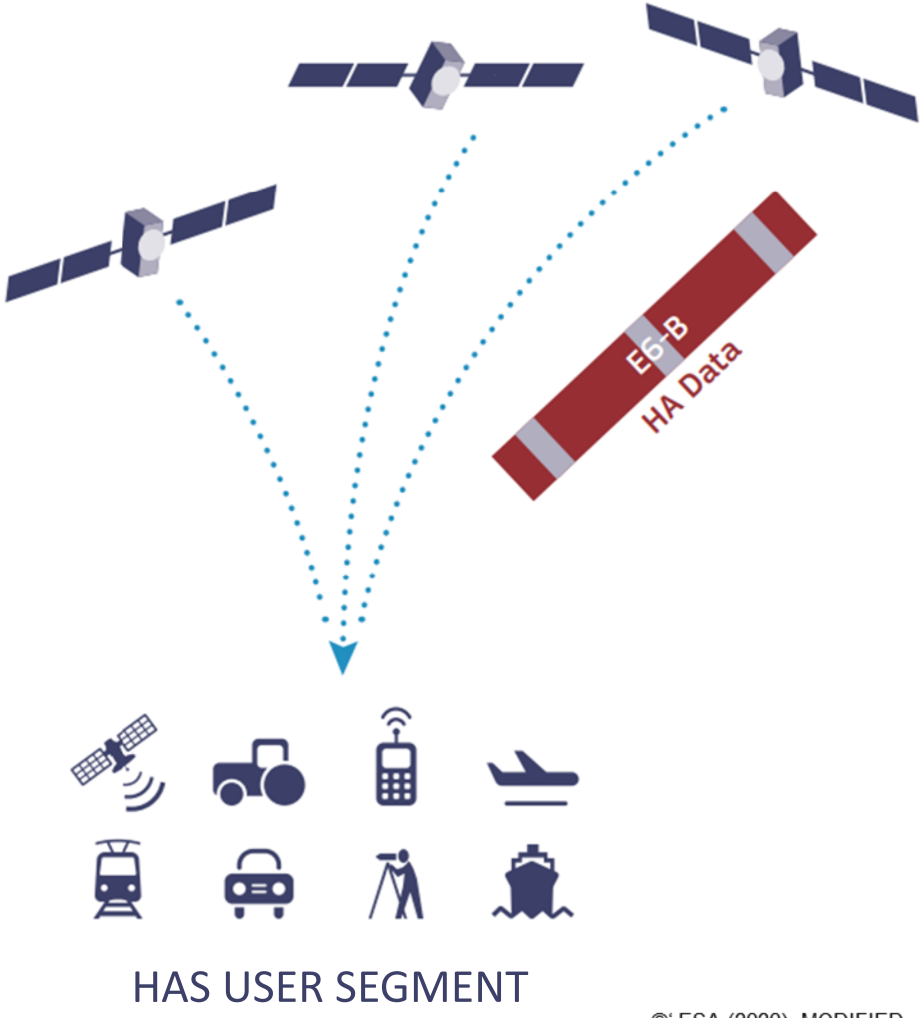
- Challenge well-established relative positioning methods like RTK
- Low-cost, low-quality, kinematic
- Combination and cooperation with other…
  - Techniques: reverse PPP,…
  - Sensors: accelerometer,…



Outlook

PPP is an upcoming positioning method:

- More available satellites and frequencies
- Advancing satellite products (e.g., Kepler)
- Instantaneous convergence?
- Galileo HAS



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Thank you
for your attention!

References

- Drotek (2021). Improve your GNSS position thanks to multi-constellation and multi-frequency. Retrieved February 7, 2021, from https://electronics.drotek.com/?p=6201
- ESA (2022). Galileo: Europas Unabhängigkeit und Kooperation. Retrieved September 22, 2022, from https://www.esa.int/Space_in_Member_States/Germany/Galileo_Europas_Unabhaengigkeit_und_Kooperation
- u-blox (2023). ZED-F9P module. Retrieved January 17, 2023, from https://www.u-blox.com/en/product/zed-f9p-module
- Ardusimple (2023). Calibrated Survey GNSS Multiband antenna (IP67). Retrieved January 17, 2023, from https://www.ardusimple.com/product/calibrated-survey-gnss-multiband-antenna-ip67/
- ESA (2020). Galileo High Accuracy Service. doi:10.2878/581340. Retrieved January 17, 2023, from https://www.gsc-europa.eu/sites/default/files/sites/all/files/Galileo_HAS_Info_Note.pdf
- ESA (2020). Lunar satellites. Retrieved January 29, 2023, from https://www.esa.int/ESA_Multimedia/Images/2020/07/Moonlight_logo
- ESA (2021). Extending satnav to the Moon. Retrieved January 29, 2023, from https://www.esa.int/ESA_Multimedia/Images/2021/03/Extending_satnav_to_the_Moon

References

- Hohensinn R, Stauffer R, Glaner MF, Herrera Pinzón ID, Vuadens E, Rossi Y, Clinton J, Rothacher M (2022). Low-Cost GNSS and Real-Time PPP: Assessing the Precision of the u-blox ZED-F9P for Kinematic Monitoring Applications. Remote Sensing 14(20):5100. https://doi.org/10.3390/rs14205100
- Aichinger-Rosenberger M, Wolf A, Senn C, Hohensinn R, Glaner MF, Moeller G, Soja B, Rothacher M (under review) MPG-NET: A low-cost, multi-purpose GNSS collocation station network for environmental monitoring