NAVITEC 2022

Real-Time Multi-GNSS Precise Point Positioning with Instant Convergence for Inland Waterway Navigation

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Gefördert durch:

Bundesministerium für Wirtschaft und Energie

aufgrund eines Beschlusses des Deutschen Bundestages

Outline

- **1. Introduction of SCIPPPER Project**
- **2. PPP Mathematical Model**
- **3. Measurement Campaign and PPP Validation**
  - 4.1 Measurement Campaign
  - 4.2 PPP Validation over the Waterway Lock
  - 4.3 PPP Validation over the Bridges
- **4. Conclusion and Outlook**

Introduction of SCIPPPER Project

Project SciPPPer:

Lock Maneuvering Assistance System Based on PPP and VDES for Inland Vessels

Funding:

German Federal Ministry for Economic Affairs and Energy

Duration:

11/2018 – 02/2022

Partners:

Argonics GmbH
Argonav GmbH
Alberding GmbH
German Aerospace Center (DLR)
WSV(Traffic Technologies Center)
BAW(Federal Waterways Engineering and Research Institute)

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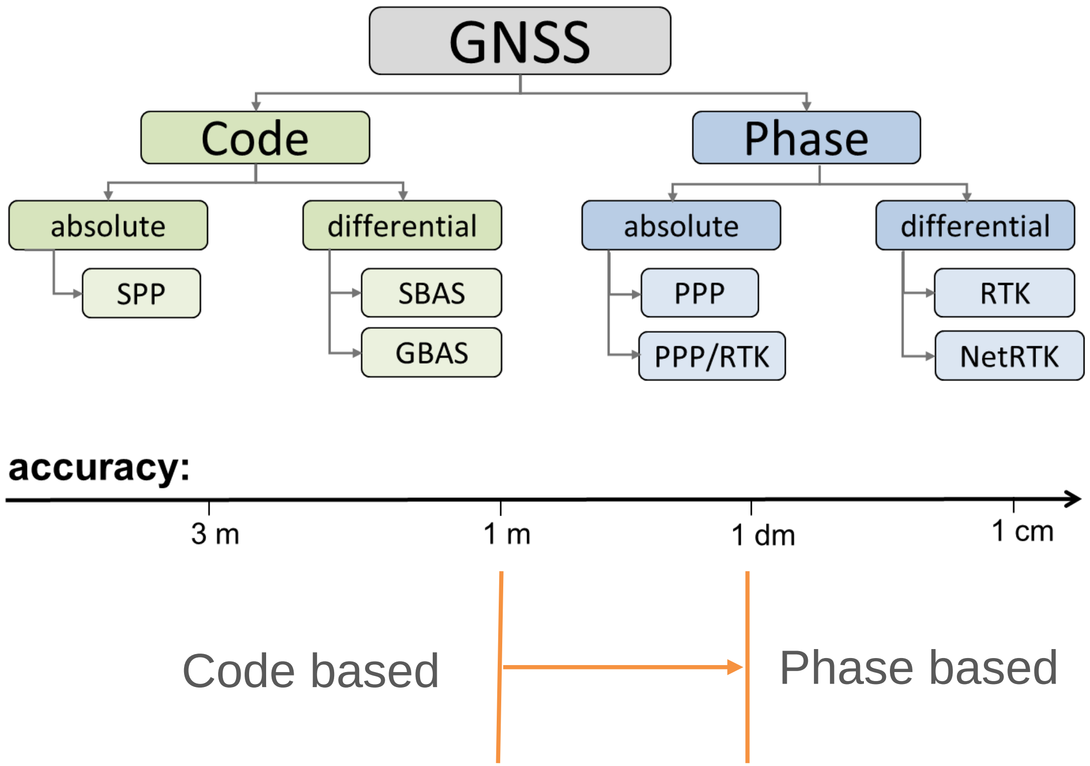
Introduction of SCIPPPER Project



RTK/ NetRTK

1. Based on a network of reference stations
2. Two way communication
3. Use obs & corrections from RTK network
4. Mass data transfer

PPP/ PPP-RTK

1. Based on a global or regional network
2. One way communication
3. Rover uses state space information
4. Less data transfer

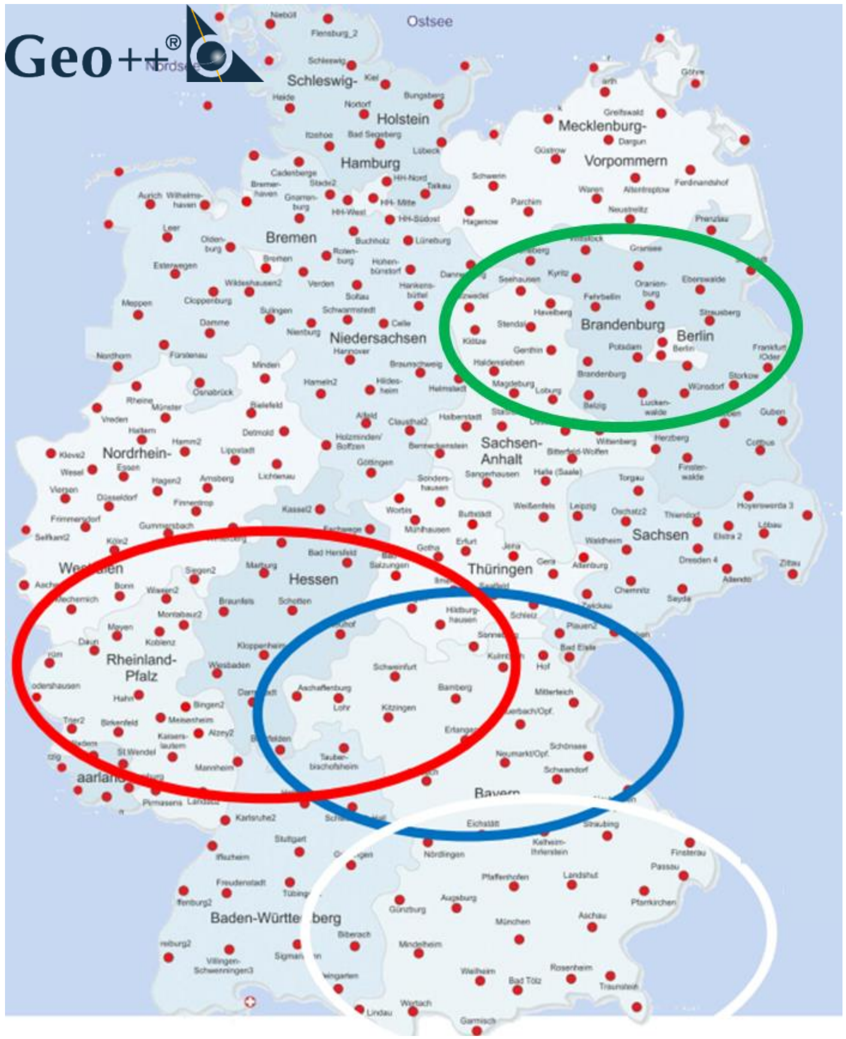
Introduction of SCIPPPER Project

State Space Representation (SSR) for PPP

Low rate (30s)

- Satellite corrections
  - Satellite orbit correction
  - Satellite clock correction
  - Satellite code bias
  - Satellite phase bias
- Atmospheric corrections
  - Ionospheric correction
  - Tropospheric correction

High rate (5s) → Satellite clock correction



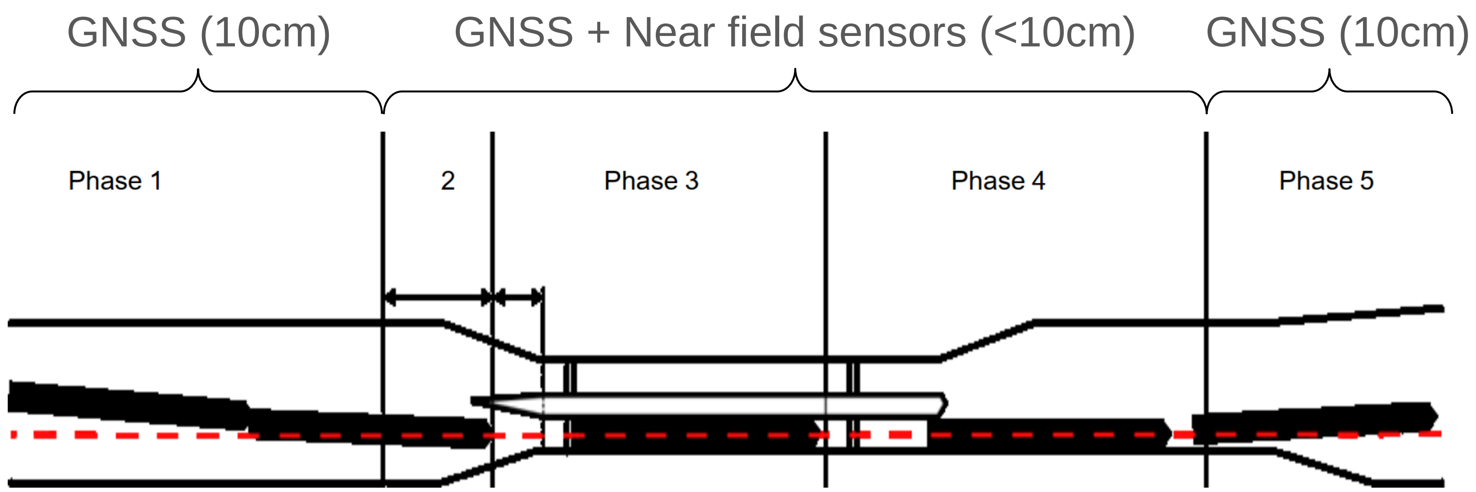
Satellite Positioning Service of the German Land Survey (SAPOS)

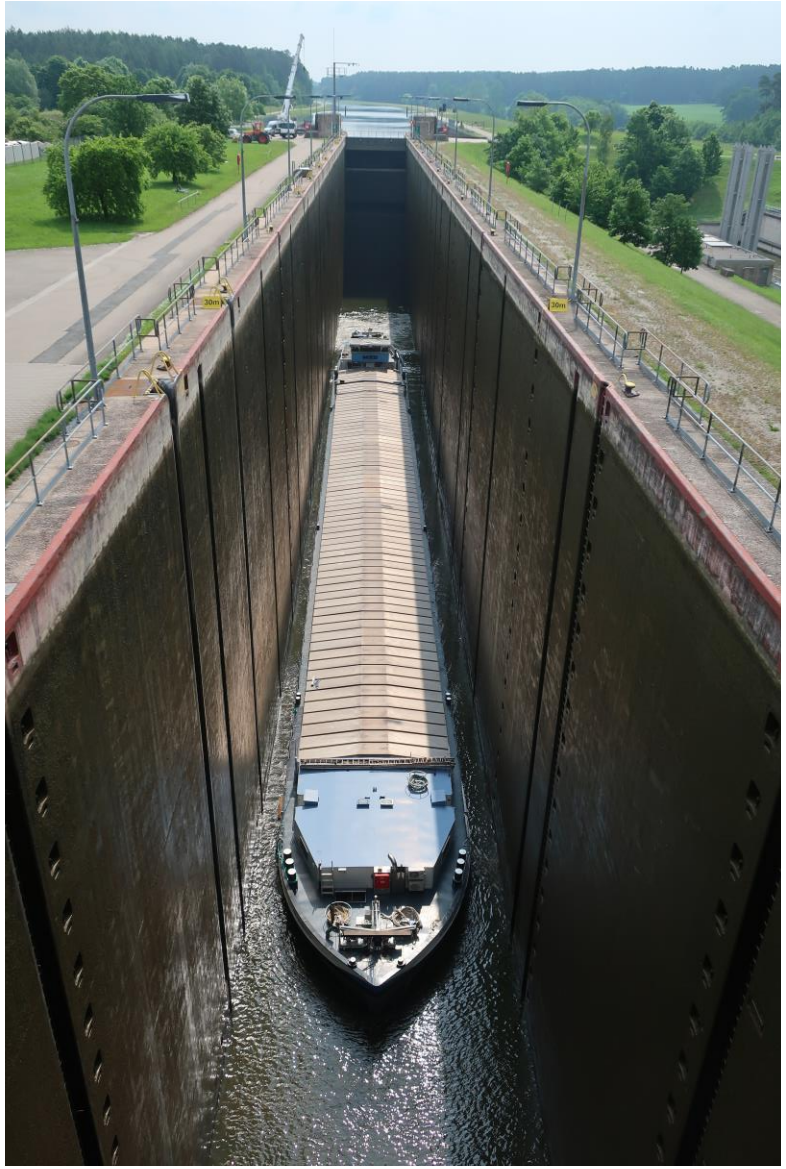
Introduction of SCIPPPER Project

Navigation Information of the Vessel

- Position
- Velocity
- Rate of Turn
- Heading
- …

Phases	Positioning accuracy (Horizontal)
Phase 1,5	10cm
Phase 2	1cm (Bow), 10cm (Stern)
Phase 3,4	1cm





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PPP Mathematical Model

GNSS Single-differenced Observation Equation between Satellites i and j:

Code Obs

$$\begin{cases} P_{s,1}^{ij} = \rho_0^{ij} + C_x^{ij} dx + C_y^{ij} dy + C_z^{ij} dz - dt^{ij} + m^{ij}T + I^{ij} - \delta B^{ij,1} + \varepsilon(P_{s,1}^{ij}) \\ P_{s,2}^{ij} = \rho_0^{ij} + C_x^{ij} dx + C_y^{ij} dy + C_z^{ij} dz - dt^{ij} + m^{ij}T + g_{s,2} I^{ij} - \delta B^{ij,2} + \varepsilon(P_{s,2}^{ij}) \end{cases}$$

Phase Obs

$$\begin{cases} L_{s,1}^{ij} = \rho_0^{ij} + C_x^{ij} dx + C_y^{ij} dy + C_z^{ij} dz - dt^{ij} + m^{ij}T - I^{ij} - \delta H^{ij,1} + \lambda_{s,1} N_{s,1}^{ij} + \varepsilon(L_{s,1}^{ij}) \\ L_{s,2}^{ij} = \rho_0^{ij} + C_x^{ij} dx + C_y^{ij} dy + C_z^{ij} dz - dt^{ij} + m^{ij}T - g_{s,2} I^{ij} - \delta H^{ij,2} + \lambda_{s,2} N_{s,1}^{ij} + \lambda_{s,2} N_{s,wl}^{ij} + \varepsilon(L_{s,2}^{ij}) \end{cases}$$

Estimated XYZ | Sat Clock | Trop & Iono Delay | Sat Bias | Narrow & Wide-Lane Amb. | Obs. Noise

SSR Tropospheric and Ionospheric Pseudo-observations

Troposphere: $SSR_T^{ij} = m^{ij}T + \varepsilon(SSR_T^{ij})$

Ionosphere: $SSR_I^{ij} = I^{ij} + \varepsilon(SSR_T^{ij})$

SSR Trop and Iono Obs. Noise

PPP Mathematical Model

Velocity Computation:

Time Differenced phase observation between two epochs:

$$\begin{cases} \Delta L^{ij}_{s,1} = \Delta\rho^{ij}_0 + \Delta C^{ij}_x vx + \Delta C^{ij}_y vy + \Delta C^{ij}_z vz - \Delta dt^{ij} + \Delta m^{ij} T - \Delta I^{ij} - \Delta\delta H^{ij,1} + \Delta\lambda_{s,1} N^{ij}_{s,1} + \varepsilon(\Delta L^{ij}_{s,1}) \\ \Delta L^{ij}_{s,2} = \Delta\rho^{ij}_0 + \Delta C^{ij}_x vx + \Delta C^{ij}_y vy + \Delta C^{ij}_z vz - \Delta dt^{ij} + \Delta m^{ij} T - \Delta g_{s,2} I^{ij} - \Delta\delta H^{ij,2} + \Delta\lambda_{s,2} N^{ij}_{s,1} + \Delta\lambda_{s,2} N^{ij}_{s,wl} + \varepsilon(\Delta L^{ij}_{s,2}) \end{cases}$$

Sat Clock | Trop & Iono Delay | Sat Bias | Narrow & Wide-Lane Amb. | Obs. Noise

Corrected and removed (Sat Clock, Trop & Iono Delay, Sat Bias)

Removed if no cycle slip detected (Narrow & Wide-Lane Amb.)

$$\begin{cases} \Delta L^{ij}_{s,1} = \Delta\rho^{ij}_0 + \Delta C^{ij}_x vx + \Delta C^{ij}_y vy + C^{ij}_z vz + \varepsilon(\Delta L^{ij}_{s,1}) \\ \Delta L^{ij}_{s,2} = \Delta\rho^{ij}_0 + \Delta C^{ij}_x vx + \Delta C^{ij}_y vy + C^{ij}_z vz + \varepsilon(\Delta L^{ij}_{s,2}) \end{cases}$$

Estimated Vx Vy Vz

PPP Mathematical Model

Kalman Filter for PPP:

Assuming there are totally l single-differenced satellite-pairs:

$$\boldsymbol{X}_{k|k-1} = \boldsymbol{F}_k \boldsymbol{X}_{k-1|k-1} + \boldsymbol{W}_k \text{ , with } \boldsymbol{X} = \begin{bmatrix} \boldsymbol{a} \\ \dot{\boldsymbol{a}} \\ \boldsymbol{b} \\ \boldsymbol{n} \end{bmatrix}, \boldsymbol{F}_k = \begin{bmatrix} \boldsymbol{I}_{3\times3} & \boldsymbol{I}_{3\times3} & & \\ & \boldsymbol{I}_{3\times3} & & \\ & & \boldsymbol{I}_{(l+1)\times(l+1)} & \\ & & & \boldsymbol{I}_{2l\times2l} \end{bmatrix},$$

$$\boldsymbol{Position}: \ \boldsymbol{a} = [dx, dy, dz]^T, \boldsymbol{Cov}: \ \boldsymbol{P_{aa}}$$

$$\boldsymbol{Velocity}: \ \dot{\boldsymbol{a}} = \left[dv_x, dv_y, dv_z\right]^T, \boldsymbol{Cov}: \ \boldsymbol{P_{\dot{a}\dot{a}}}$$

$$\boldsymbol{Trop.and\ Iono.delays}: \ \boldsymbol{b} = [T, I^{1p}, \dots, I^{mp}, I^{1q}, \dots, I^{nq}]^T, \boldsymbol{Cov}: \ \boldsymbol{P_{bb}}$$

$$\boldsymbol{Ambiguities}: \ \boldsymbol{n} = \left[N_{G,1}^{1p}, \dots, N_{G,1}^{mp}, N_{E,1}^{1q}, \dots, N_{E,1}^{nq}, N_{G,wl}^{1p}, \dots, N_{G,wl}^{mp}, N_{E,wl}^{1q}, \dots, N_{E,wl}^{nq}\right], \boldsymbol{Cov}: \ \boldsymbol{P_{nn}}$$

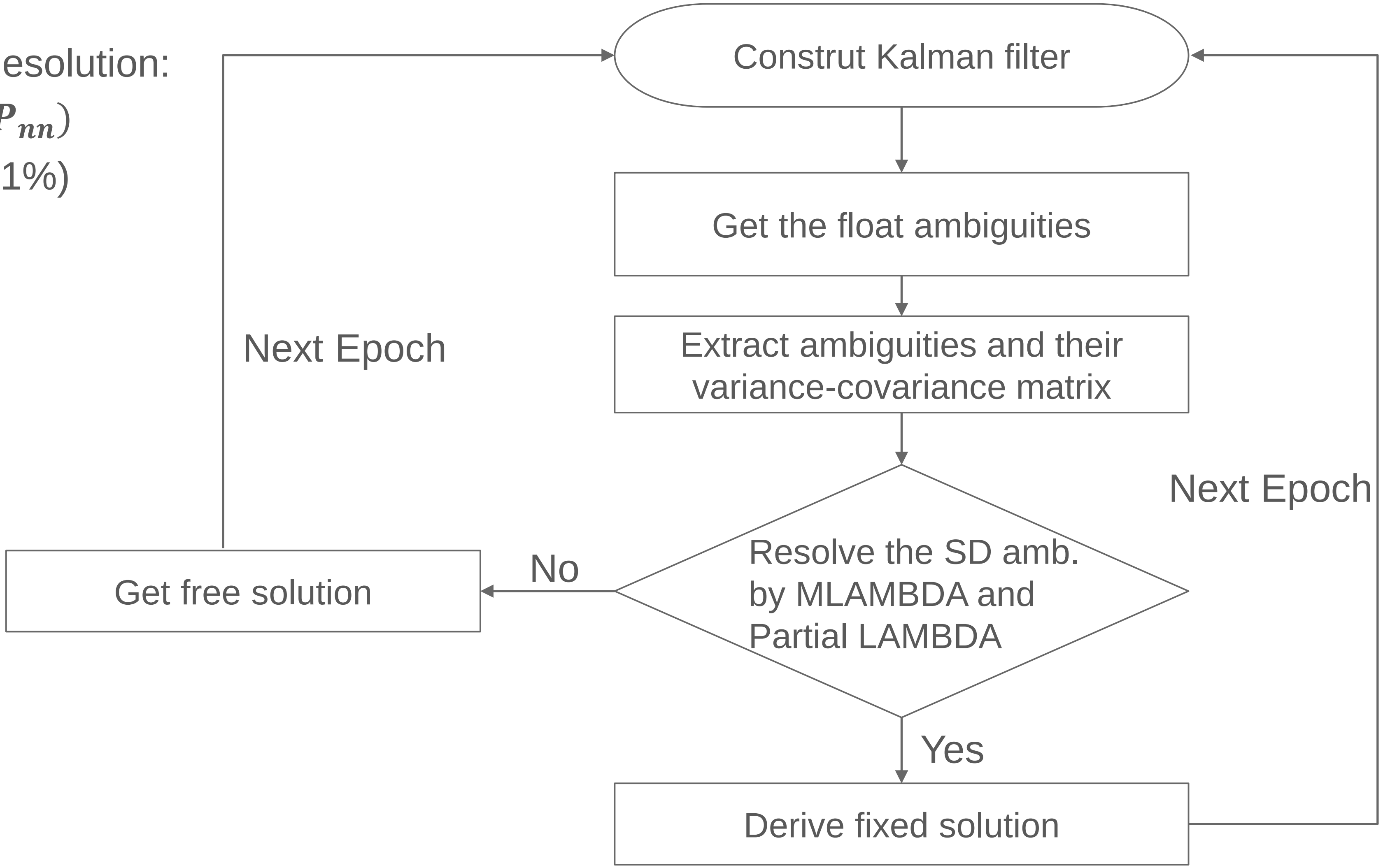
➡ **Get Free PPP Solution.**

PPP Mathematical Model

PPP with Integer Ambiguity Resolution:

Function: $\mathrm{MLAMBDA}(\boldsymbol{n}, \boldsymbol{P_{nn}})$

(Fix failure rate is set as 1%)



X. W. Chang., X. Yang, and T. Zhou. "MLAMBDA: A modified LAMBDA method for integer least-squares estimation." Journal of Geodesy, 79.9 (2005): 552-565.

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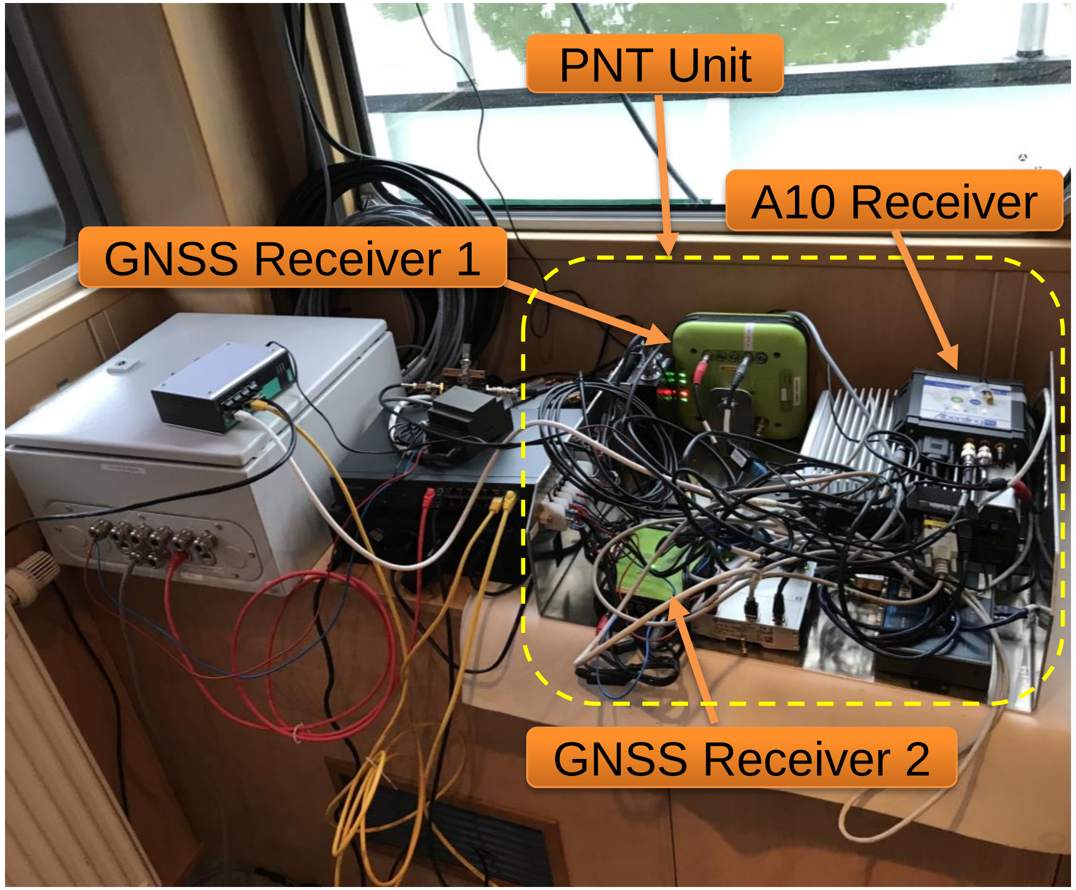
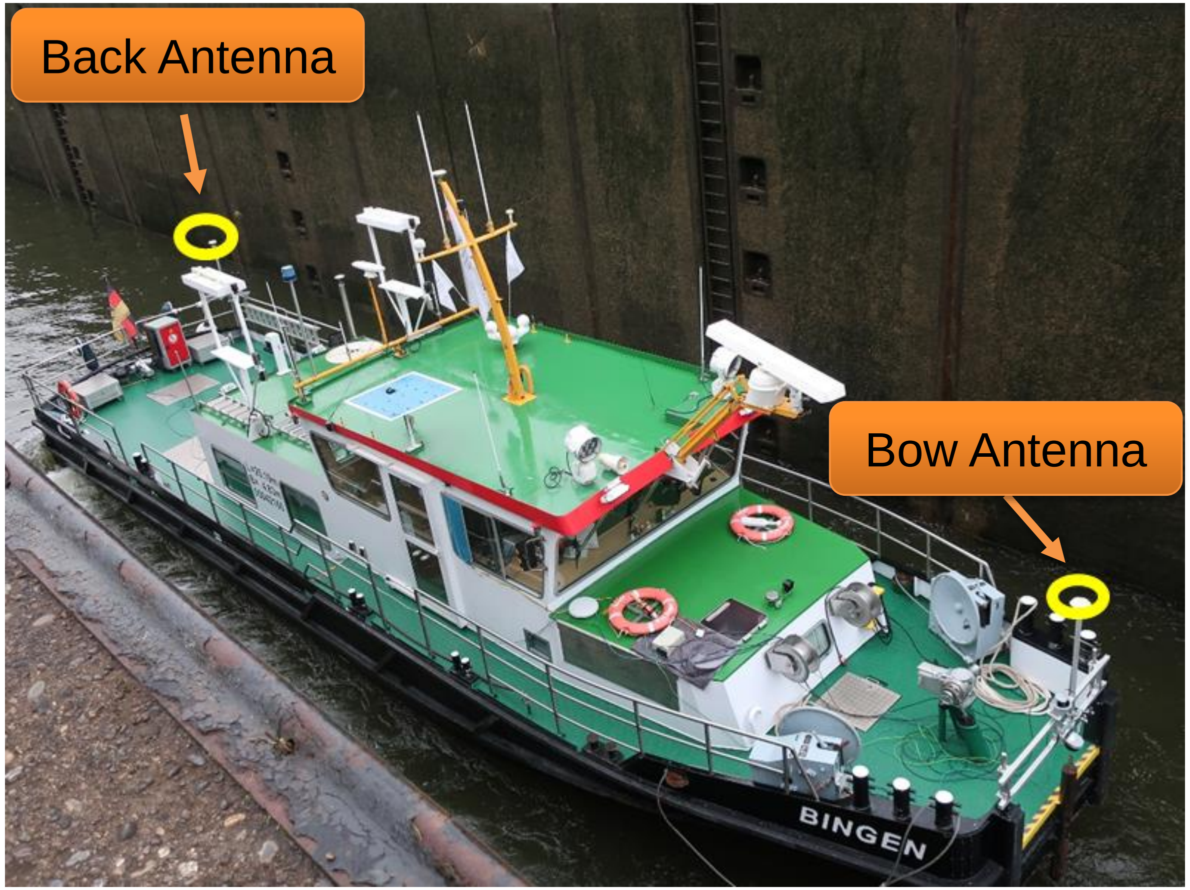
Measurement Campaign and PPP Validation

Positioning, Navigation and Timing (PNT) Unit



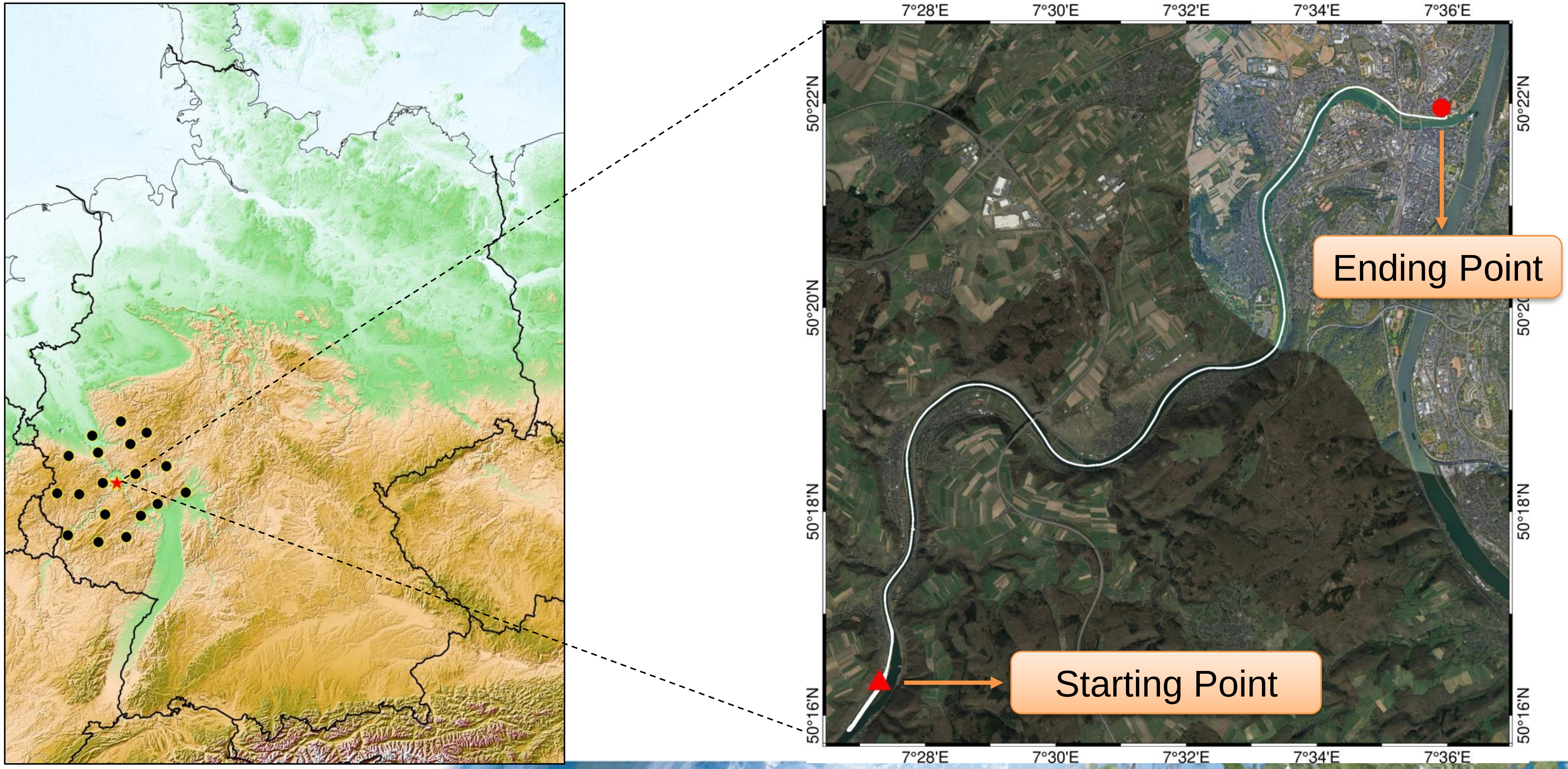
Setup of the Antennas



Measurement Campaign and PPP Validation

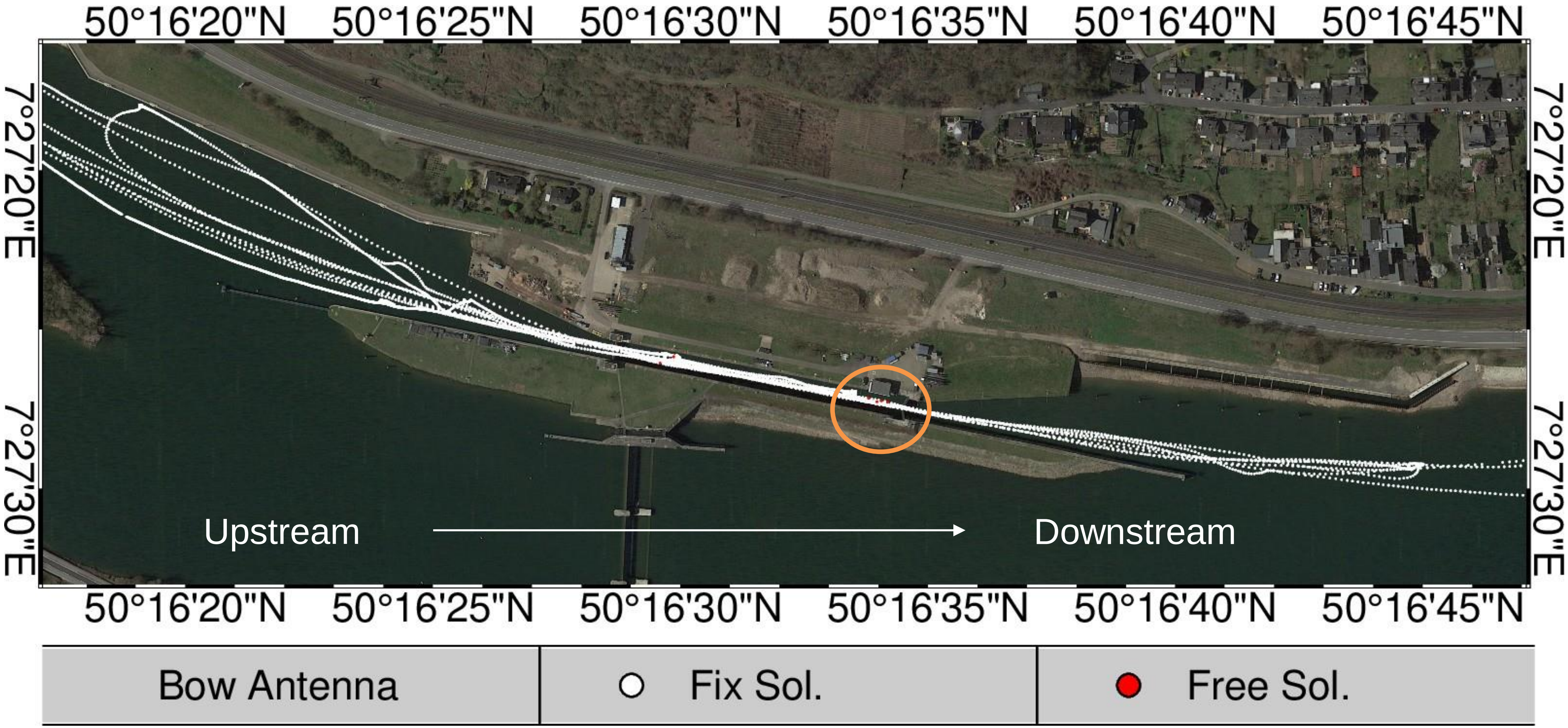
Reference Stations Used by Geo++ to Generate SSR Corrections

Area of Measurement Campaign Conducted on 2021-11-17

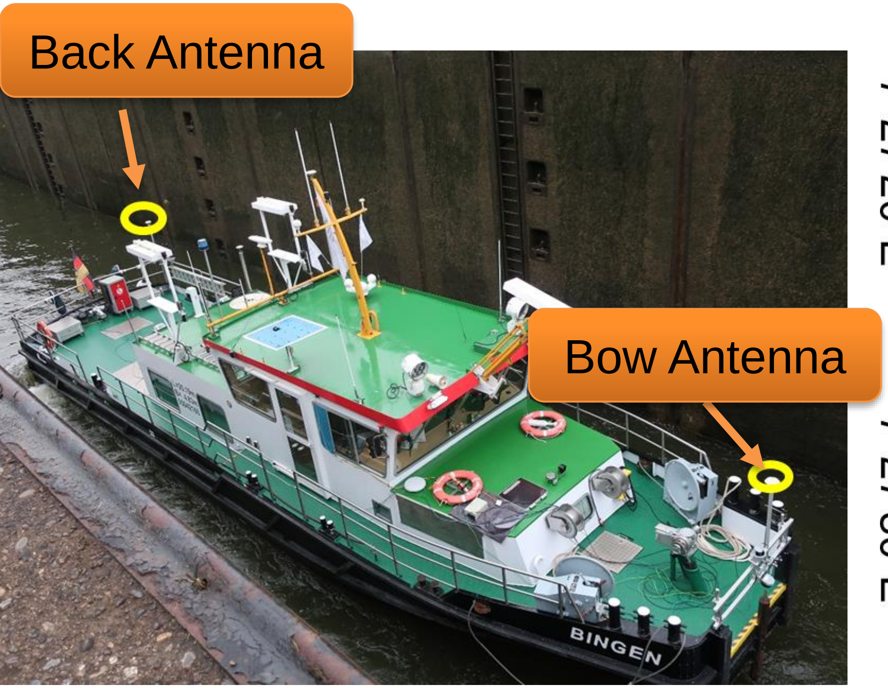


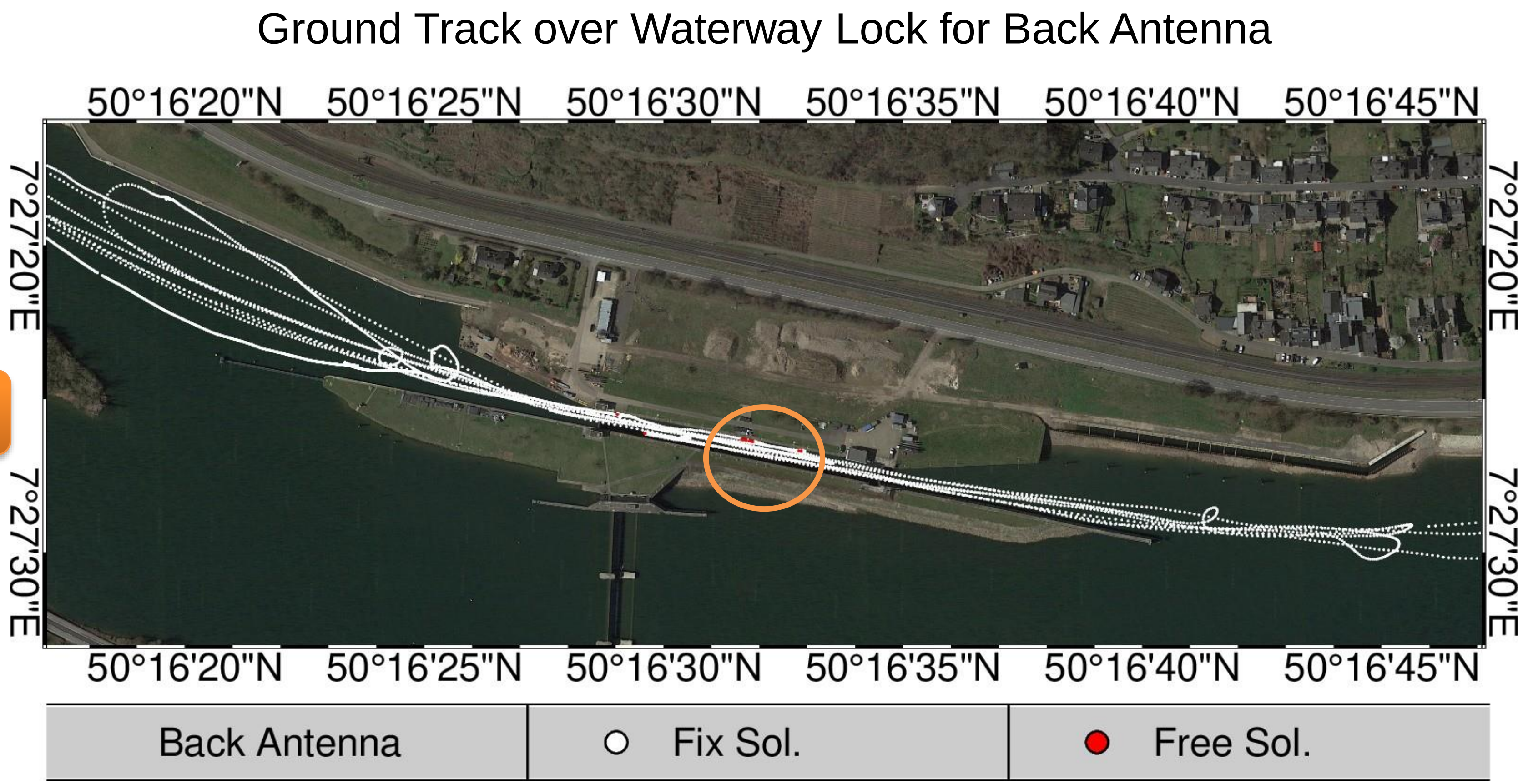
Measurement Campaign and PPP Validation

Ground Track over Waterway Lock for Bow Antenna



Measurement Campaign and PPP Validation



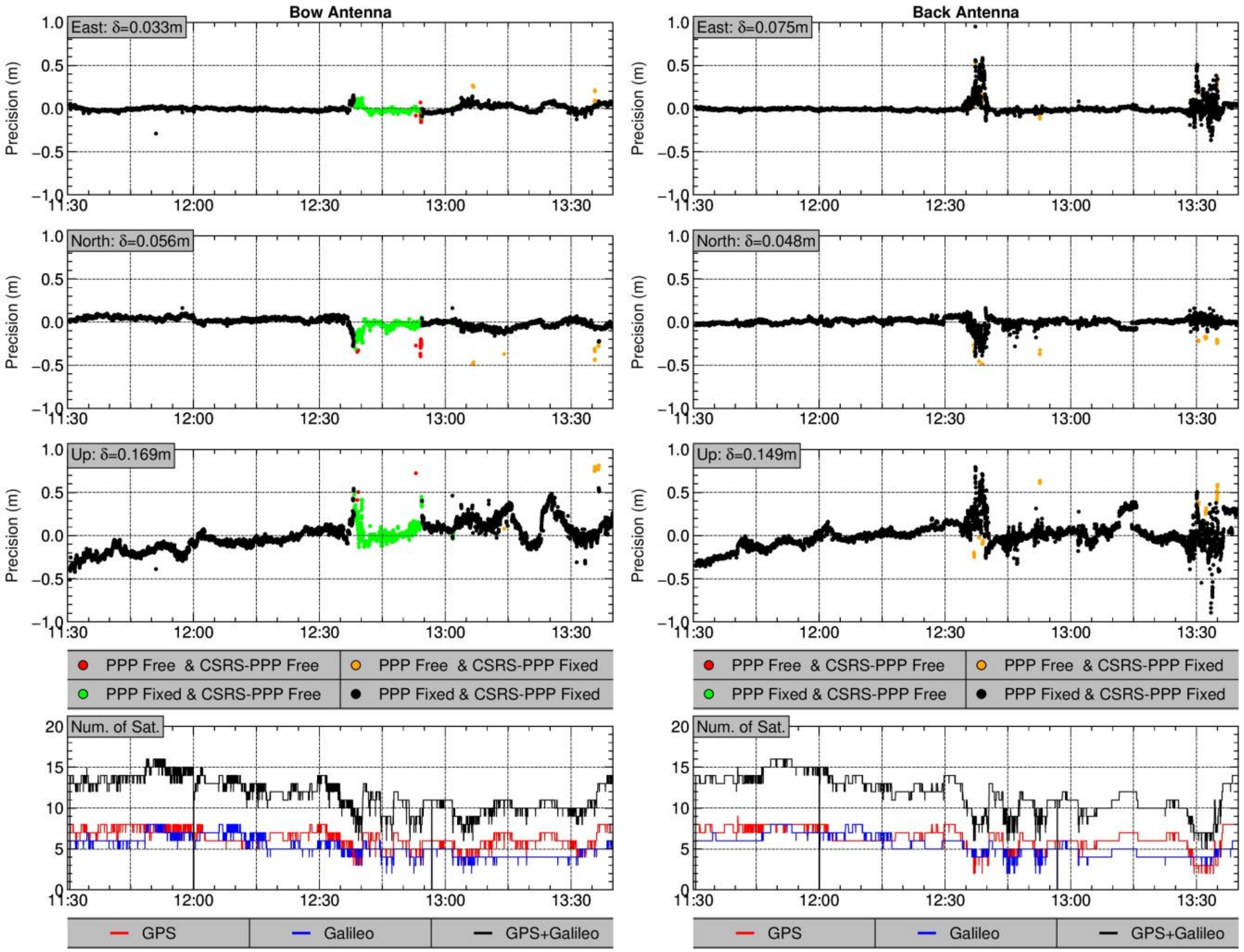


Measurement Campaign and PPP Validation

Processing Strategies Compared with Canadian Spatial Reference System (CSRS) PPP

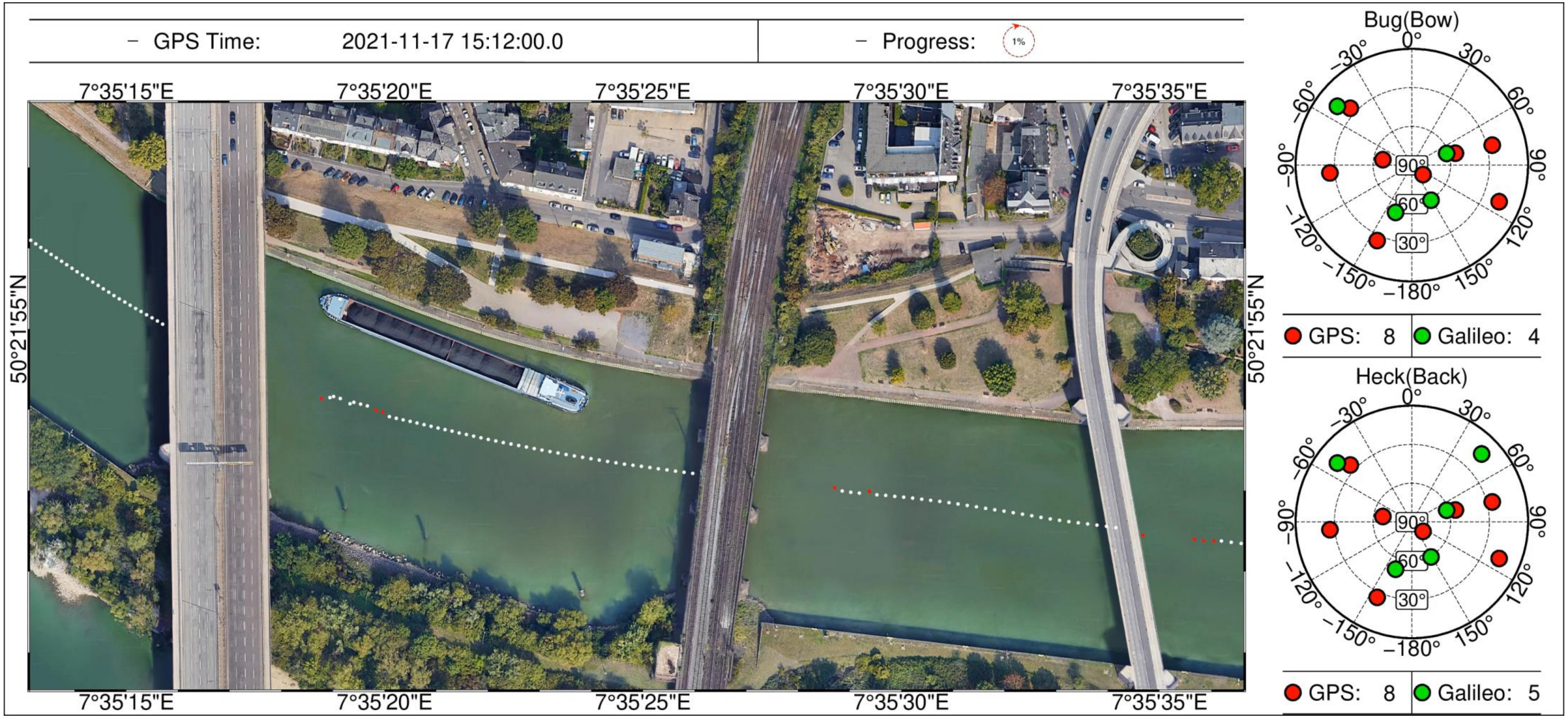
Item	Our PPP Solution	CSRS PPP Solution
Processing mode	Real-time	Post processing
GNSS	GPS+Galileo	GPS+GLONASS
Sampling interval	1s	1s
Obs Used	GPS: C1W,C2W,L1W,L2W Galileo: C1X,C5X,L1X,L5X	GPS: C1W,C2W,L1W,L2W GLONASS: C1P,C2P,L1P,L2P
Ambiguity resolution	GPS+Galileo Fixed	GPS Fixed GLONASS Float

Compared with the CSRS PPP Results



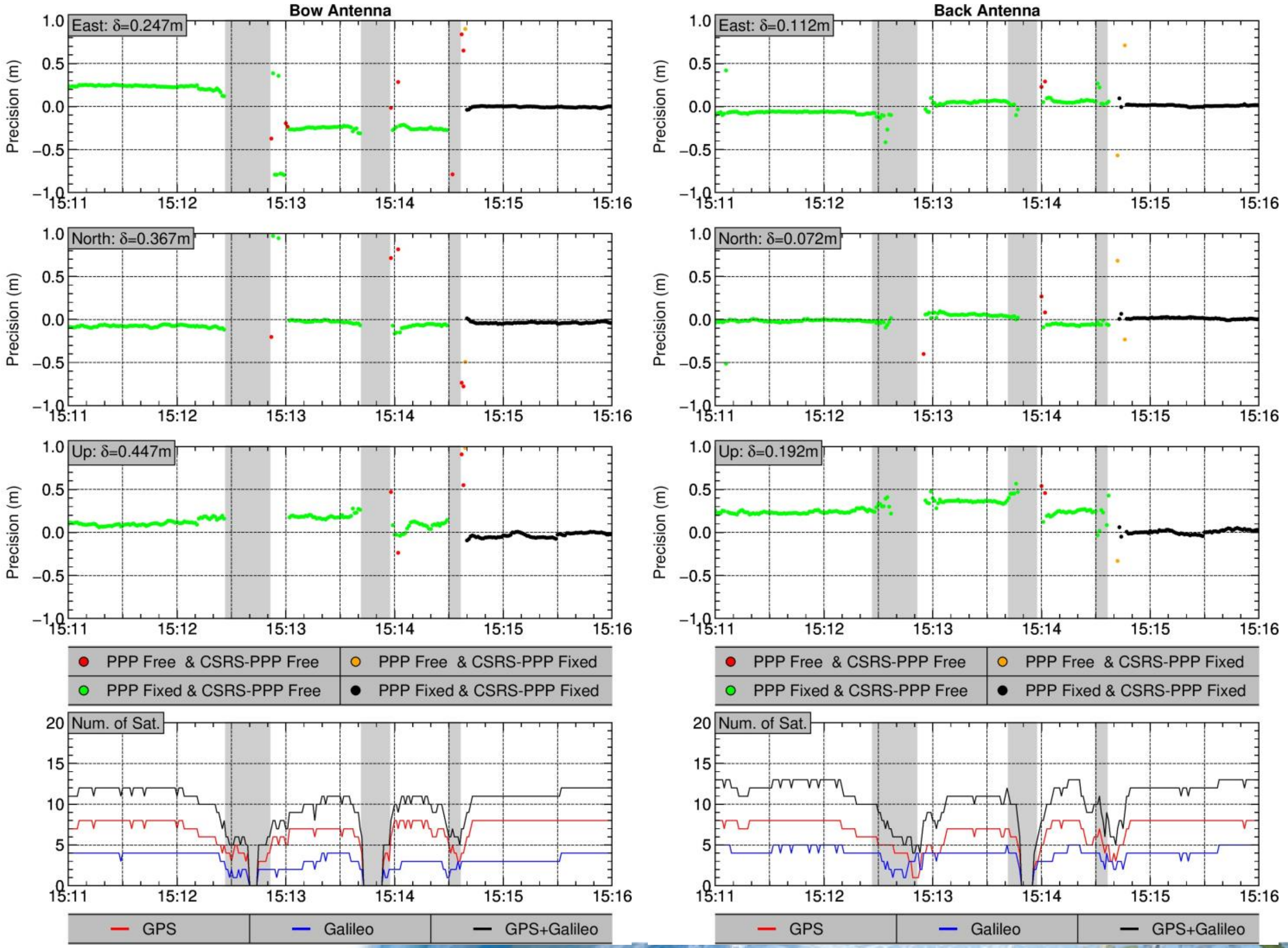
Measurement Campaign and PPP Validation

PPP Performance When Crossing Bridges



Measurement Campaign and PPP Validation

Difference between Our and CSRS PPP Results during Bridges Passing



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Conclusion and Outlook

- **Conclusion:**
  - For inland waterway navigation, when the GNSS satellites are blocked by the lock chamber or bridges, we cannot expect to derive precise positioning solutions.
  - After passing the waterway lock and bridges, the PPP can realize an instant convergence within several seconds.

- **Outlook:**
  - Combining Multi-Sensor to realize a reliable and precise navigation for waterway lock and bridge passing

Thanks for your attention!