Collaborative High Precision GNSS

ITSNT 2024

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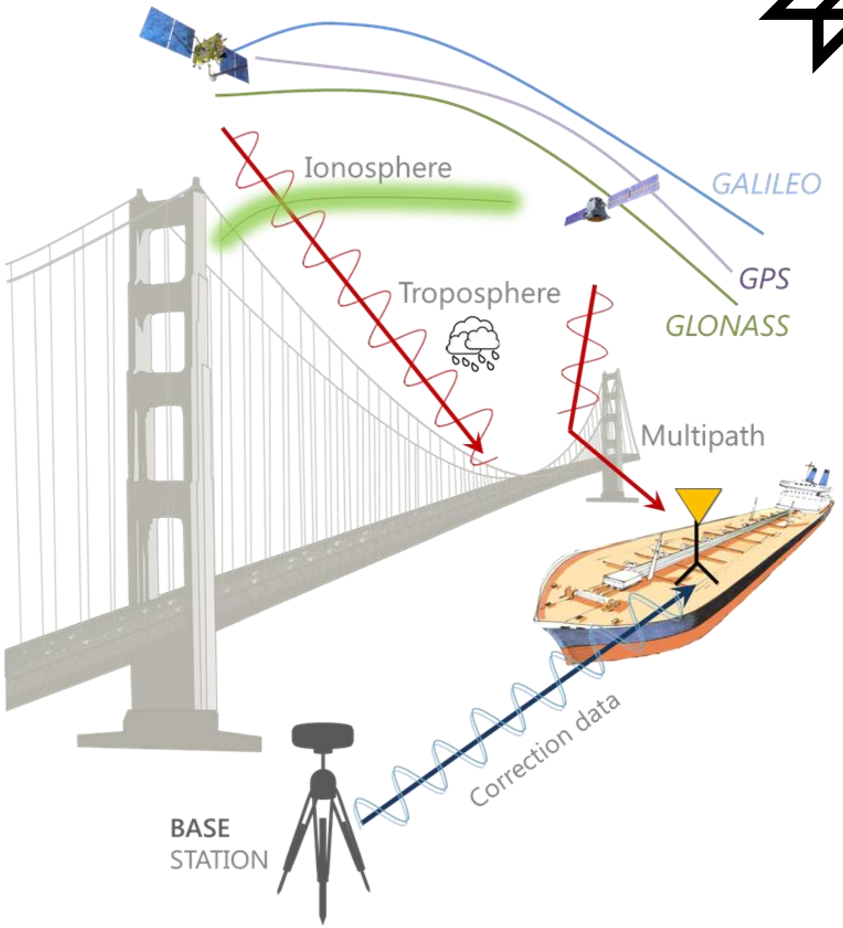
Overview on GNSS

GNSS is the main information source for Positioning, Navigation and Timing (PNT)

Challenge #1: Precision
The accuracy of standard *code*-based navigation is limited → <10 meters positioning & poor attitude

Challenge #2: Robustness
Multipath and other local effects strongly degrade the performance → large errors, low availability

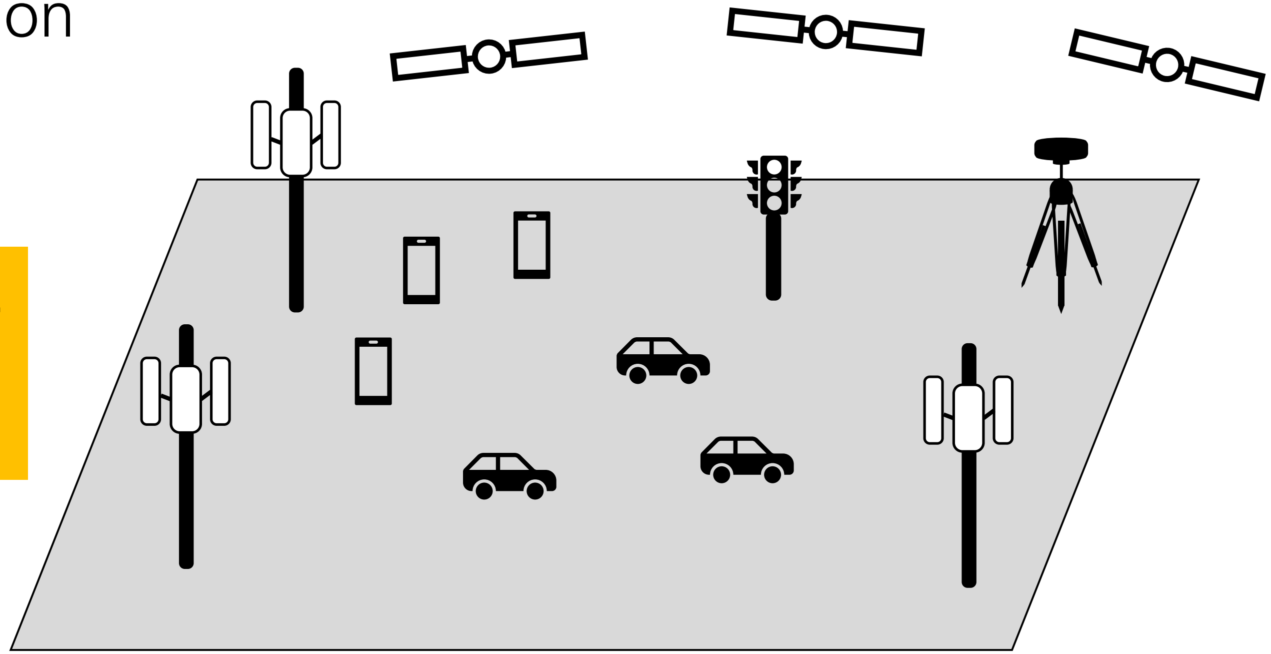


- The use of carrier phase observations is the key for high precision navigation
- Collaborative positioning may overcome the limitations on carrier phase obs.

Why Collaborative?

- GNSS is **least performing when most needed**: poor visibility, multipath, etc.
- GNSS chipsets are now integrated with communication ones
- With the **advances on V2X technology**:
  (1) Broad and heterogeneous network of users
  (2) Fast and low-latency communication
  (3) Ranging capabilities

Collaborative approaches may be the right solution for precise & reliable navigation (the quest for autonomy)

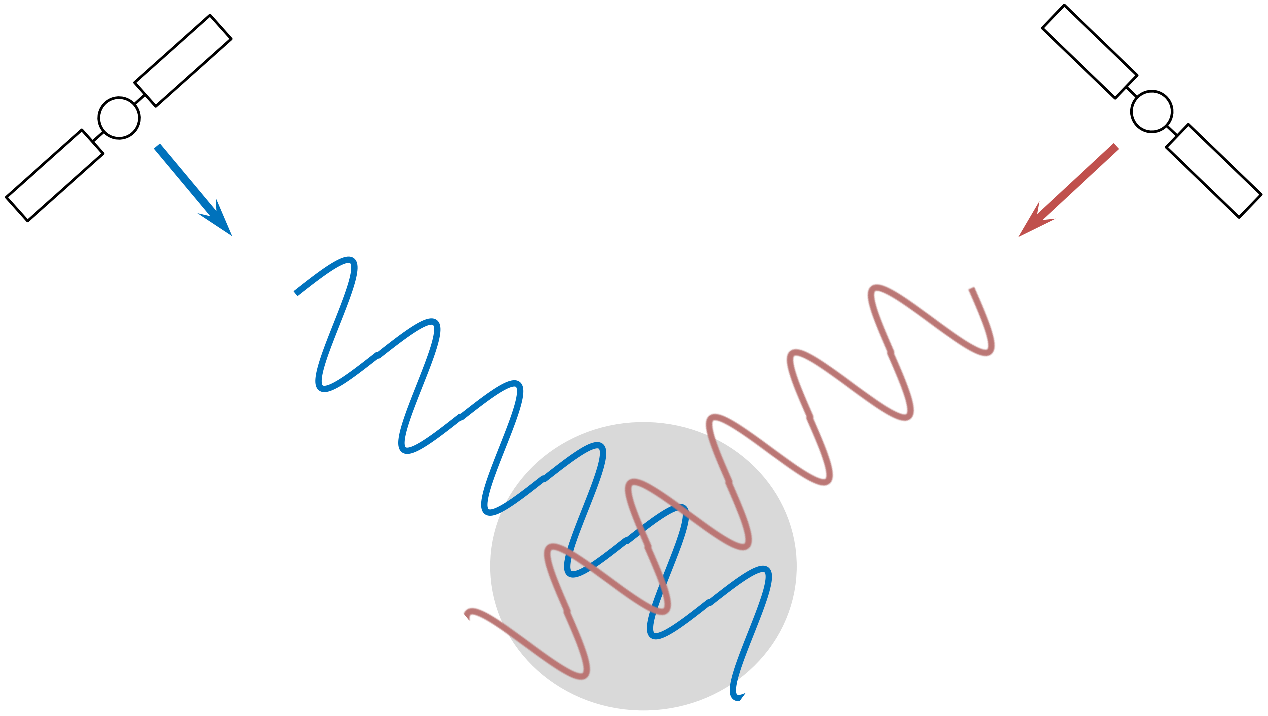


In today's conversation…

- **Basics of precise GNSS**: estimation problems for RTK, PPP-RTK & limitations
- **Understanding cooperation**: architectures, advantages, limitations
- **Cooperative RTK (C-RTK)**: the idea behind, performance evaluation
- **Research & industry perspectives**

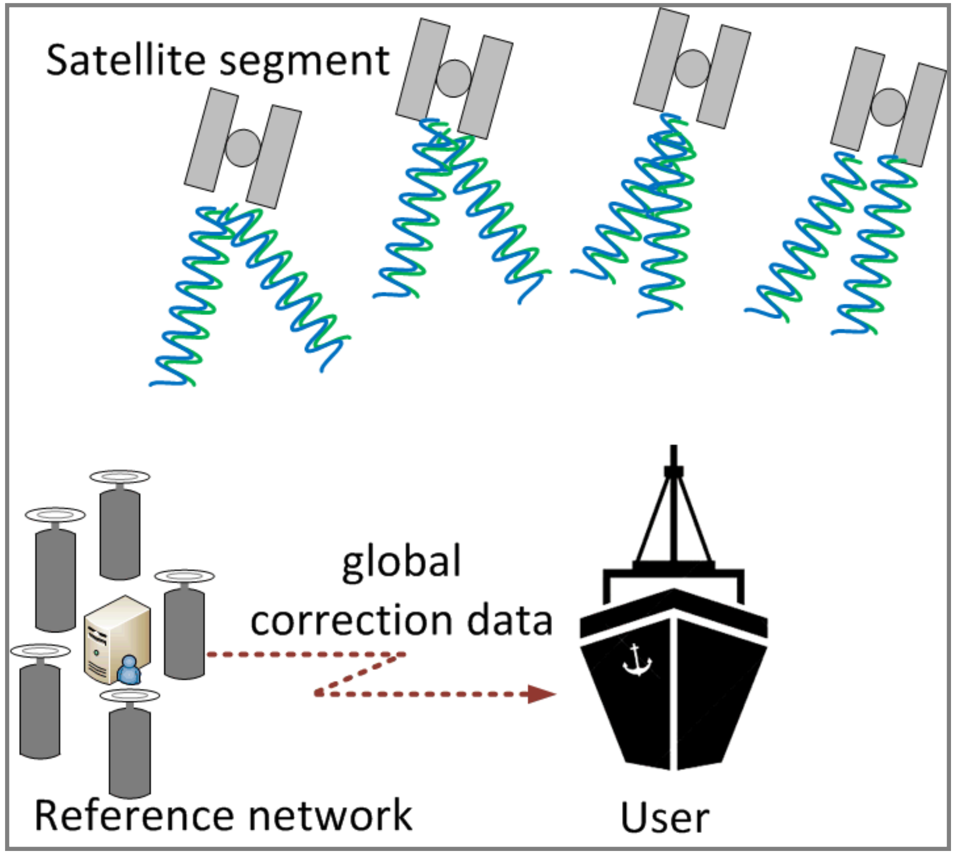
Precise Positioning

Reaching cm-level positioning accuracy

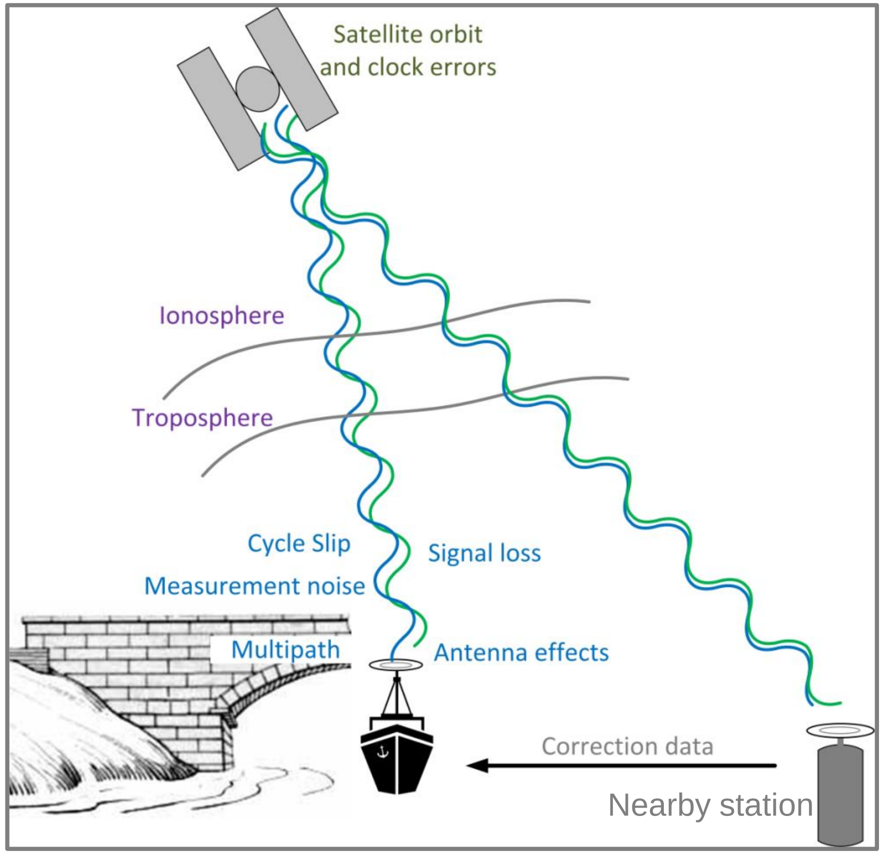


High Precision GNSS Techniques

Precise Point Positioning (PPP)



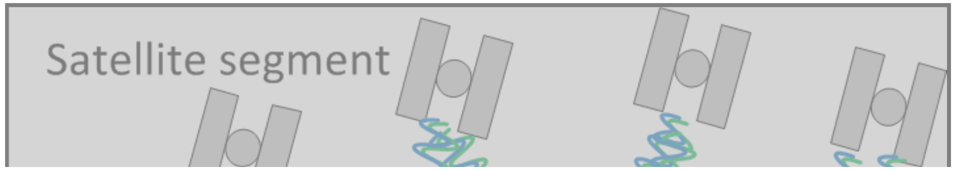
Real Time Kinematic (RTK)



High precision GNSS is all about correction data streams & Integer Ambiguity Resolution
Nearby users are exposed to the same atmospheric (and sometimes local) effects

High Precision GNSS Techniques

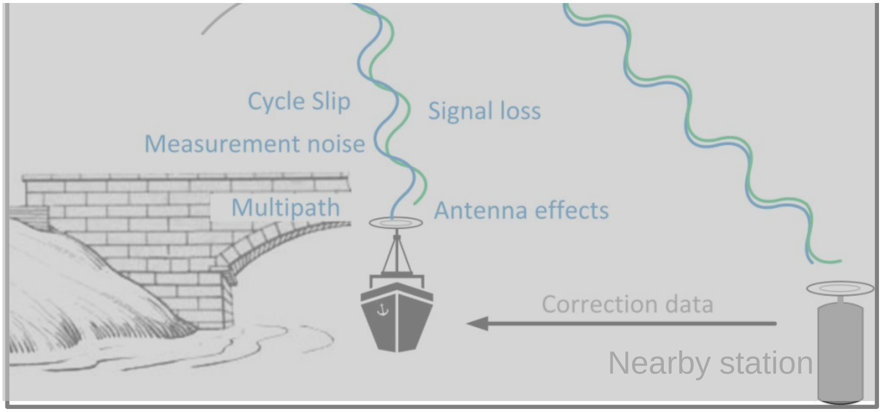
Precise Point Positioning (PPP)



- Limited by convergence time
- “low observability” of nuisance parameters: iono, tropo, etc.
- Limited real-time usability due to delay on the corrections (*HAS)

Real Time Kinematic (RTK)

- Unfeasible to deploy a sufficiently dense network of base stations



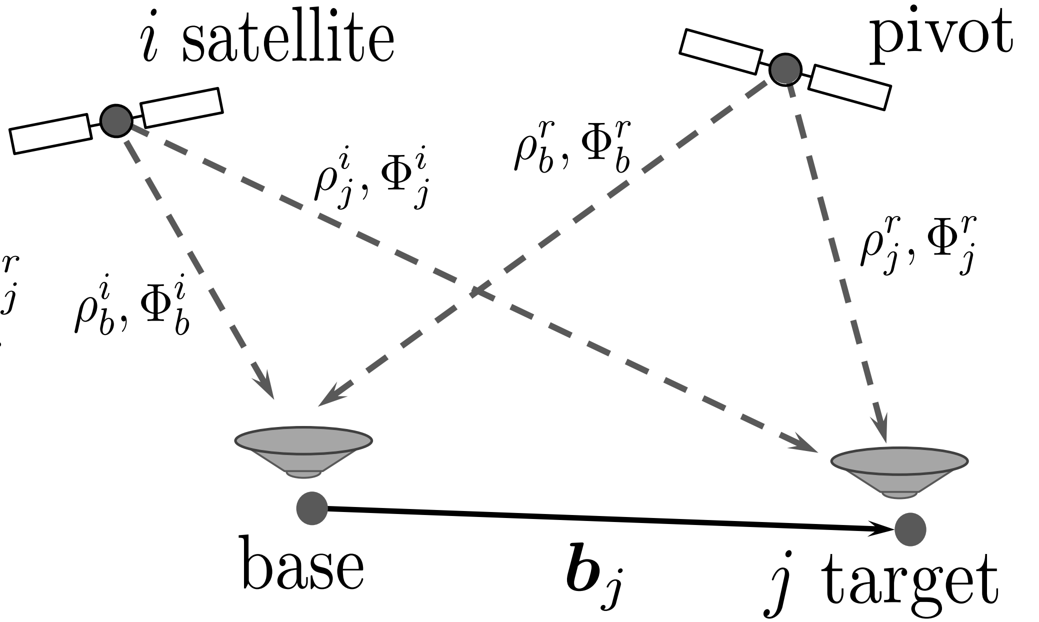
High precision GNSS is all about correction data streams & Integer Ambiguity Resolution
Nearby users are exposed to the same atmospheric (and sometimes local) effects

RTK Positioning Model

RTK is a differential positioning method → code & carrier phase observations from the *j*th vehicle and the base station are used

$$\Phi_j^i = \|\boldsymbol{p}^i - \boldsymbol{p}_j\| - I^i + T^i + c\left(-dt^i + dt_j\right) + \lambda N_j^i + \varepsilon_j^r$$
$$(-)\quad \Phi_b^i = \|\boldsymbol{p}^i - \boldsymbol{p}_b\| - I^i + T^i + c\left(-dt^i + dt_m\right) + \lambda N_b^i + \varepsilon_b^r$$

$$\Phi_j^r = \|\boldsymbol{p}^r - \boldsymbol{p}_j\| - I^r + T^r + c\left(-dt^r + dt_j\right) + \lambda N_j^r + \varepsilon_j^r$$
$$(-)\quad \Phi_b^r = \|\boldsymbol{p}^r - \boldsymbol{p}_b\| - I^r + T^r + c\left(-dt^r + dt_m\right) + \lambda N_b^r + \varepsilon_b^r$$



Set of observations

$$\boldsymbol{y}_j = \left[\boldsymbol{DD\Phi}_j{}^\top, \boldsymbol{DD\rho}_j{}^\top\right]^\top$$

The *Mixed Real-Integer Model*

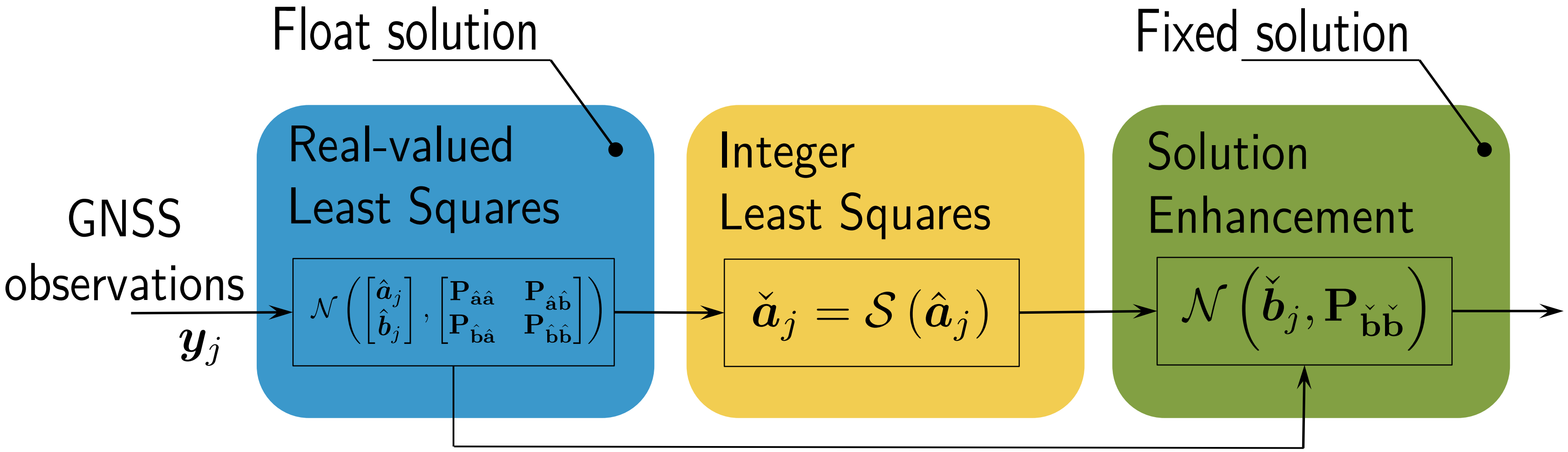
$$\boldsymbol{y}_j \sim \mathcal{N}\left(\boldsymbol{A}\boldsymbol{a}_j + \boldsymbol{B}\boldsymbol{b}_j, \boldsymbol{\Sigma}_j\right),\ \boldsymbol{a}_j \in \mathbb{Z}^n, \boldsymbol{b}_j \in \mathbb{R}^3$$

And… how to solve the mixed model?

RTK Positioning Model
Estimation Process and Bounds

$$\|\hat{\mathbf{e}}\|^2_{\boldsymbol{\Sigma}_j} + \min_{\mathbf{a}_j \in \mathbb{Z}^n} \left(\|\hat{\mathbf{a}}_j - \mathbf{a}_j\|^2_{\mathbf{P}_{\hat{\mathbf{a}}\hat{\mathbf{a}}}} + \min_{\mathbf{b}_j \in \mathbb{R}^3} \left\|\hat{\mathbf{b}}_j(\mathbf{a}) - \mathbf{b}_j\right\|^2_{\mathbf{P}_{\hat{\mathbf{b}}(\mathbf{a})}} \right)$$

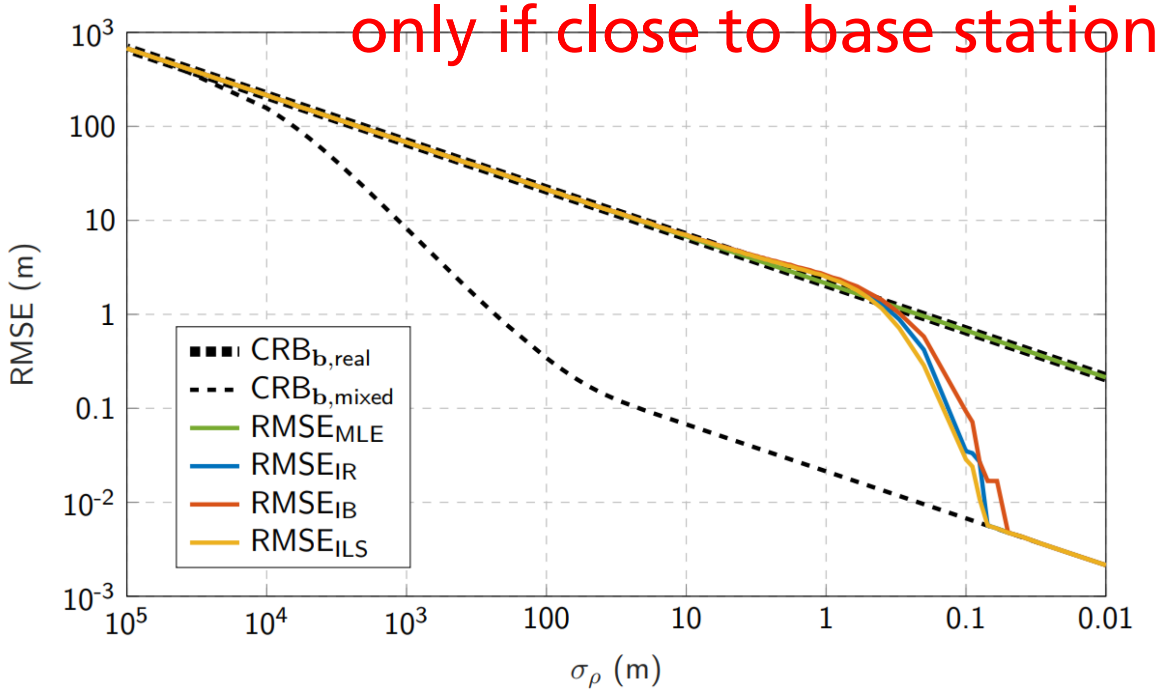
Float solution | Integer Ambiguity Resolution (IAR) | Fixed solution

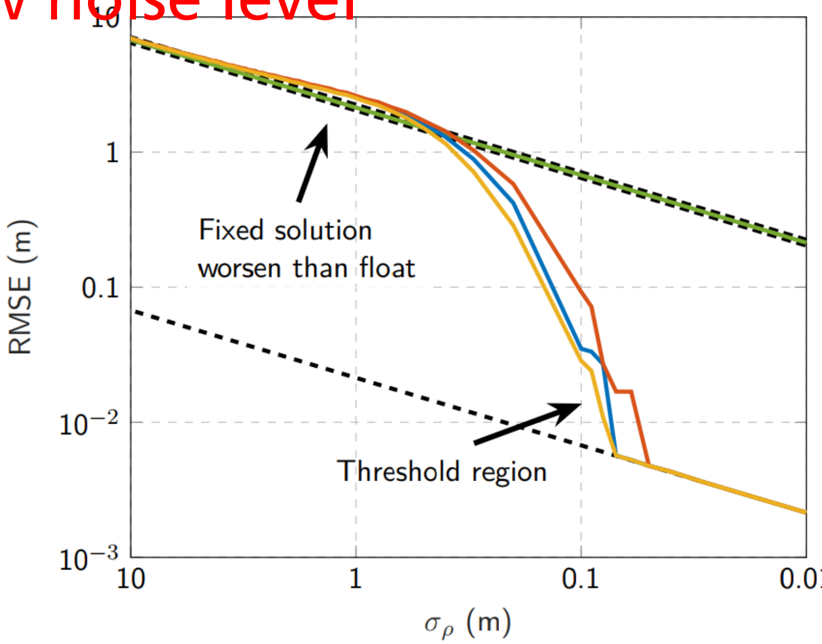


RTK Positioning Model
Estimation Process and Bounds

$$\left\|\hat{\mathbf{e}}\right\|^2_{\boldsymbol{\Sigma}_j} + \min_{\mathbf{a}_j \in \mathbb{Z}^n} \left(\left\|\hat{\mathbf{a}}_j - \mathbf{a}_j\right\|^2_{\mathbf{P}_{\hat{\mathbf{a}}\hat{\mathbf{a}}}} + \min_{\mathbf{b}_j \in \mathbb{R}^3} \left\|\hat{\mathbf{b}}_j(\mathbf{a}) - \mathbf{b}_j\right\|^2_{\mathbf{P}_{\hat{\mathbf{b}}(\mathbf{a})}} \right)$$

! We have efficient estimators, but…
only if close to base station, low noise level

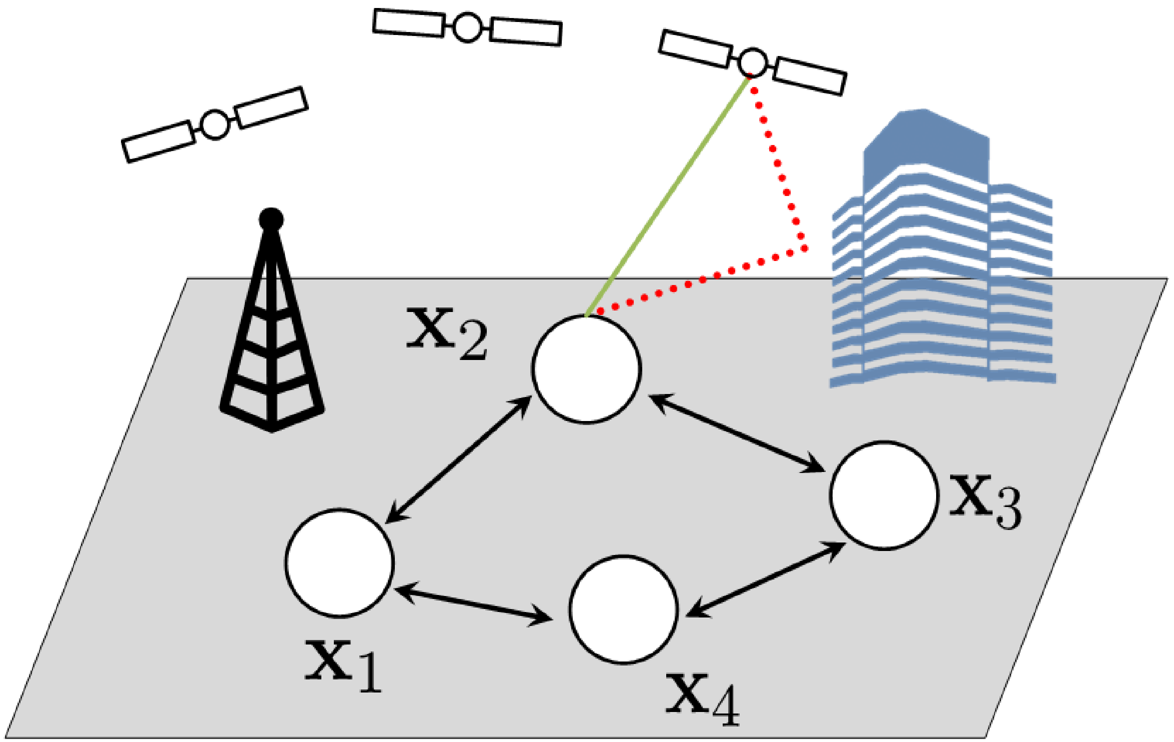




Medina, D., Vilà-Valls, J., Chaumette, E., Vincent, F., & Closas, P. (2021). Cramér-Rao bound for a mixture of real-and integer-valued parameter vectors and its application to the linear regression model. Signal Processing

Cooperative Positioning

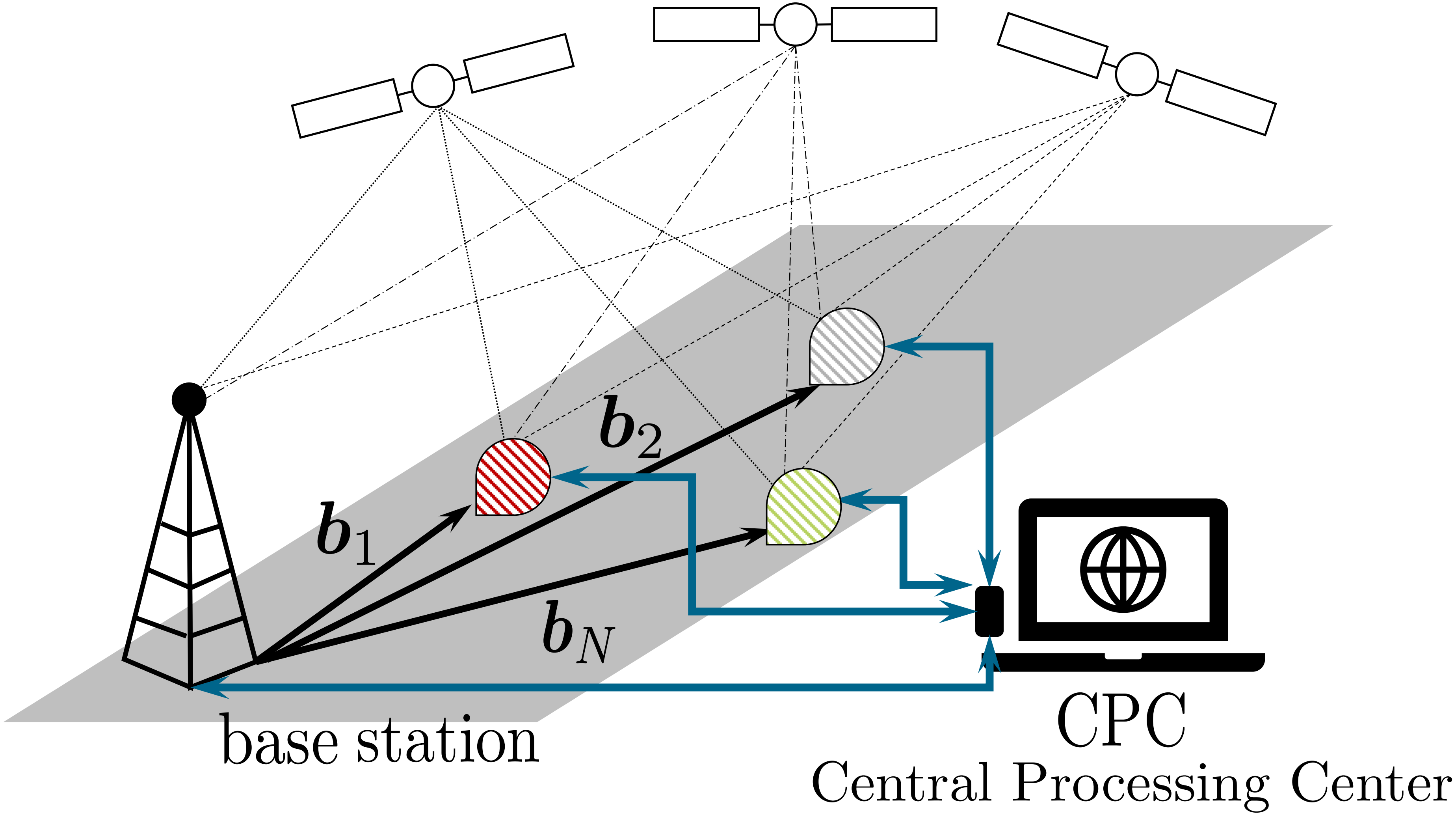
Network of users helping each other



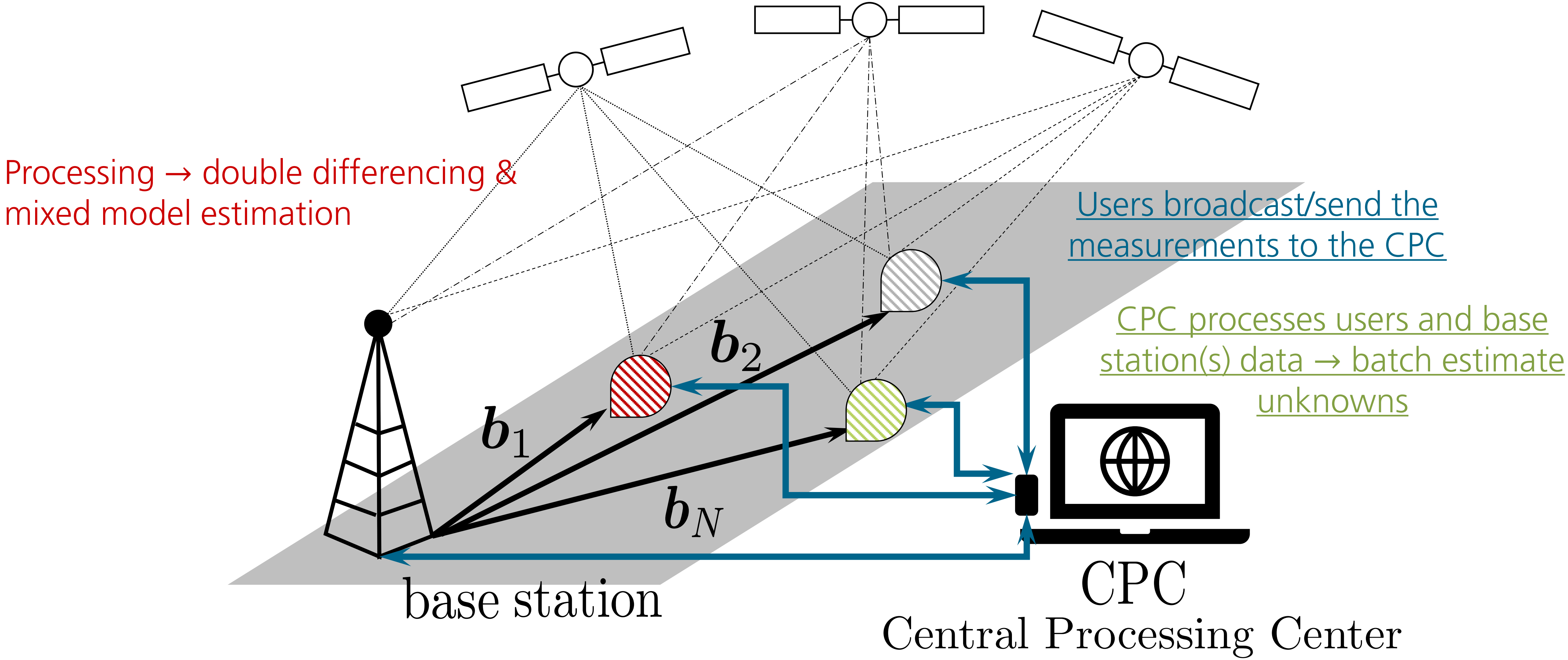
Collaborative Localization (with or without GNSS)

- **Type of collaboration**
  - Active – inter-user ranging, exchange location information
  - Passive – broadcast of observations, non-location info
- **Architectures**
  - Centralized – the solutions for all users are jointly estimated
  - Distributed – each user estimates their solution
- **Points of concern**
  - Intentional / unintentional interference: MP
  - Respect of privacy
- **Existing literature**
  - Estimation for cooperative localization: works of Wymeersch, Win, Buehrer
  - For GNSS: works of Caceres (GNSS+ranging), Minetto (measurement correlation), Calatrava (Massive Differentiation)

Collaborative-RTK (C-RTK) – Conceptual & Technical Idea



Collaborative-RTK (C-RTK) – Conceptual & Technical Idea



C-RTK – Positioning Problem

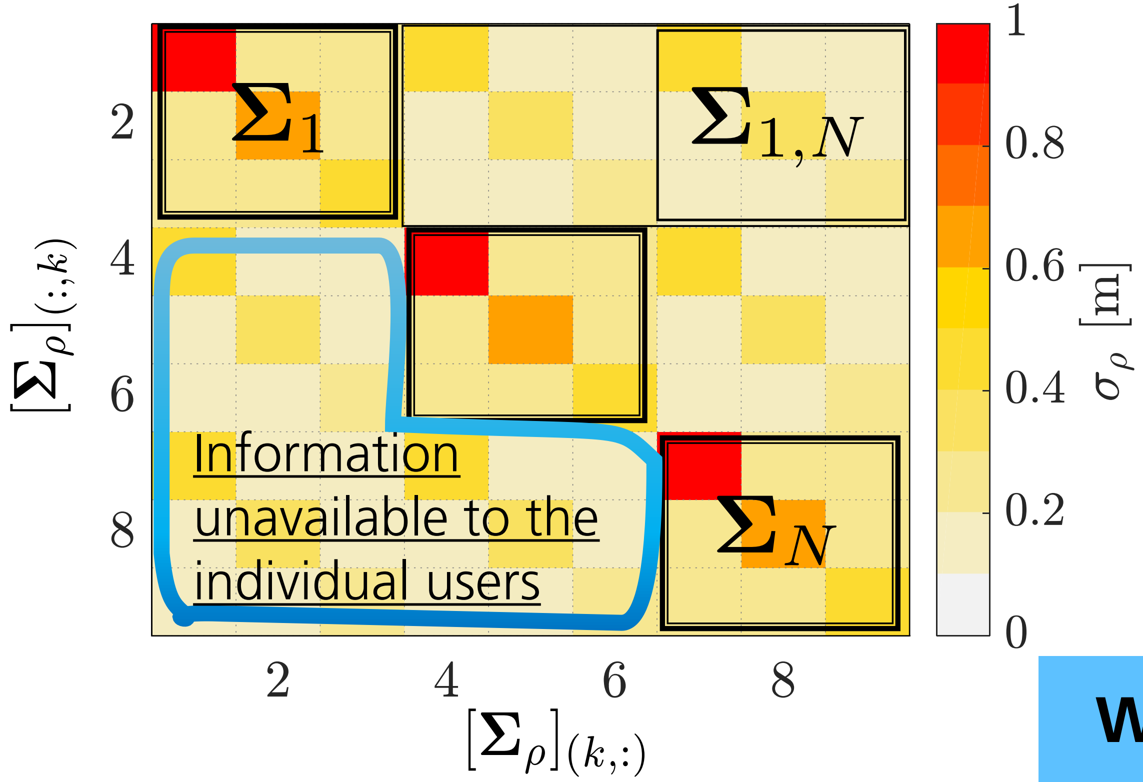
Conventional RTK

$$\boldsymbol{y}_j \sim \mathcal{N}\left(\boldsymbol{A}\boldsymbol{a}_j + \boldsymbol{B}\boldsymbol{b}_j, \boldsymbol{\Sigma}_j\right)$$

for N users →

Collaborative RTK

$$\tilde{\boldsymbol{y}} \sim \mathcal{N}\left(\tilde{\boldsymbol{A}}\tilde{\boldsymbol{a}} + \tilde{\boldsymbol{B}}\tilde{\boldsymbol{b}}, \tilde{\boldsymbol{\Sigma}}\right), \quad \tilde{\boldsymbol{a}} \in \mathbb{Z}^{n \cdot N}, \tilde{\boldsymbol{b}} \in \mathbb{R}^{3 \cdot N}$$



"Extended" version of obs., unknowns, matrices

$$\tilde{\boldsymbol{y}} = \left[\boldsymbol{DD\Phi}_1^\top, \ldots, \boldsymbol{DD\Phi}_N^\top, \boldsymbol{DD\rho}_1^\top, \ldots, \boldsymbol{DD\rho}_N^\top\right]^\top$$

$$\tilde{\boldsymbol{a}} = \left[\boldsymbol{a}_1^\top, \ldots, \boldsymbol{a}_N^\top\right]^\top, \quad \tilde{\boldsymbol{b}} = \left[\boldsymbol{b}_1^\top, \ldots, \boldsymbol{b}_N^\top\right]^\top$$

The importance of stochastic modeling

- The cross-correlations due to combining observations wrt. base station → **fundamental information!**

We can leverage on the existing CRBs and estimators for the mixed model problem

Monte Carlo Performance Analysis

Study Cases:

1) Open Sky

- *N*=6 vehicles, "fully connected network"

2) Urban Scenario

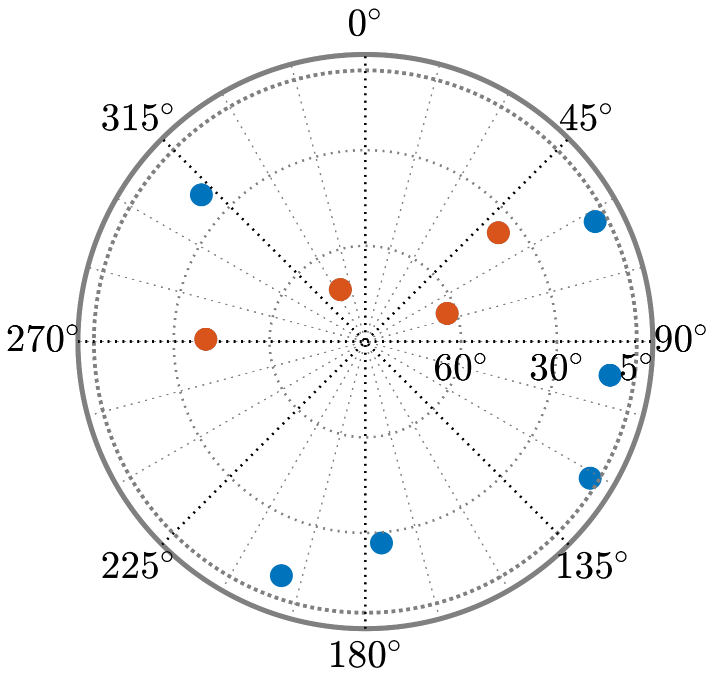
- 2 vehicles limited view + 4 open sky

Stochastic modelling

- Unweighted model, equal noise across users
- 1 to 100 ratio for phase/code std
- A range of precision levels is evaluated

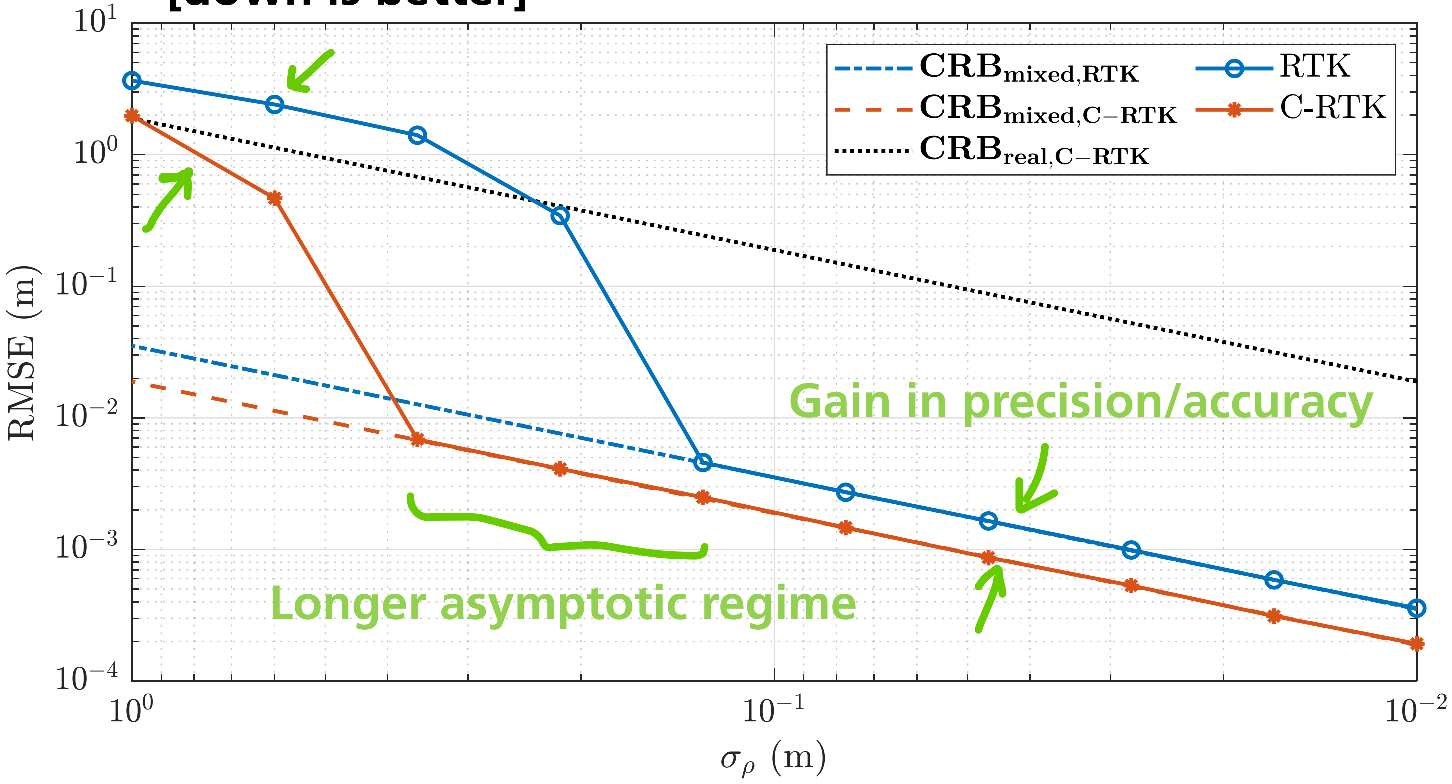
Metrics:

- Comparison of the positioning RMSE & IAR performance

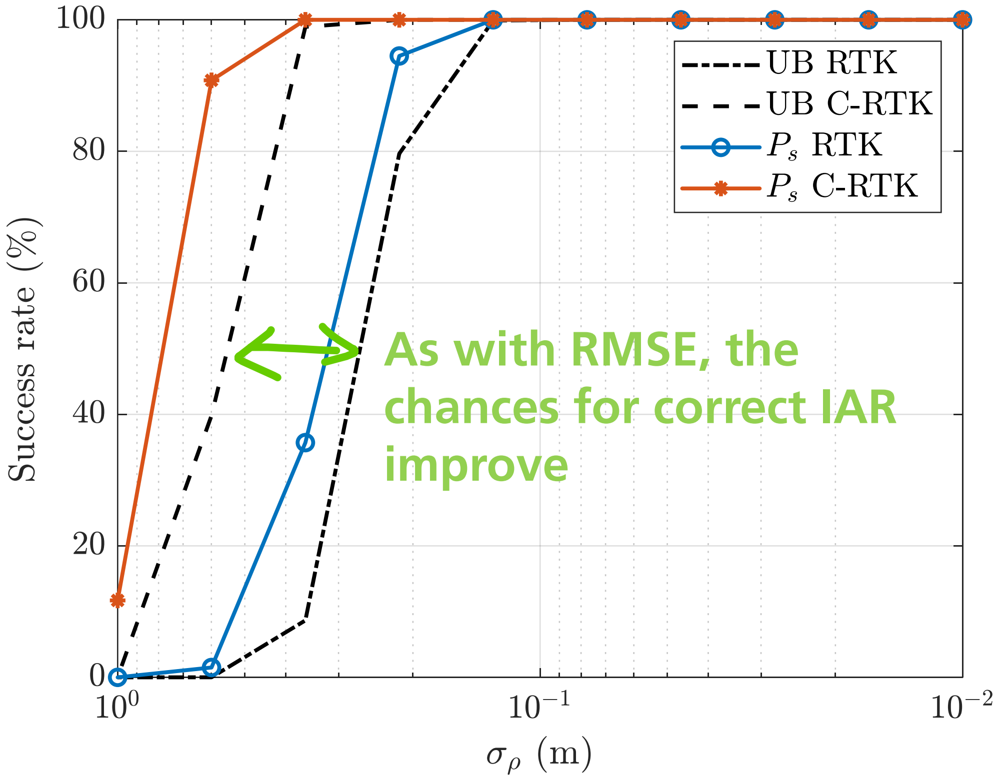


Monte Carlo based Performance Analysis

[down is better]



[up and left is better]



Medina, D., Calatrava, H., Castro-Arvizu, J. M., Closas, P., & Vila-Valls, J. (2023, April). A Collaborative RTK Approach to Precise Positioning for Vehicle Swarms in Urban Scenarios. In 2023 IEEE/ION PLANS

C-RTK – Overview, Benefits, Limitations

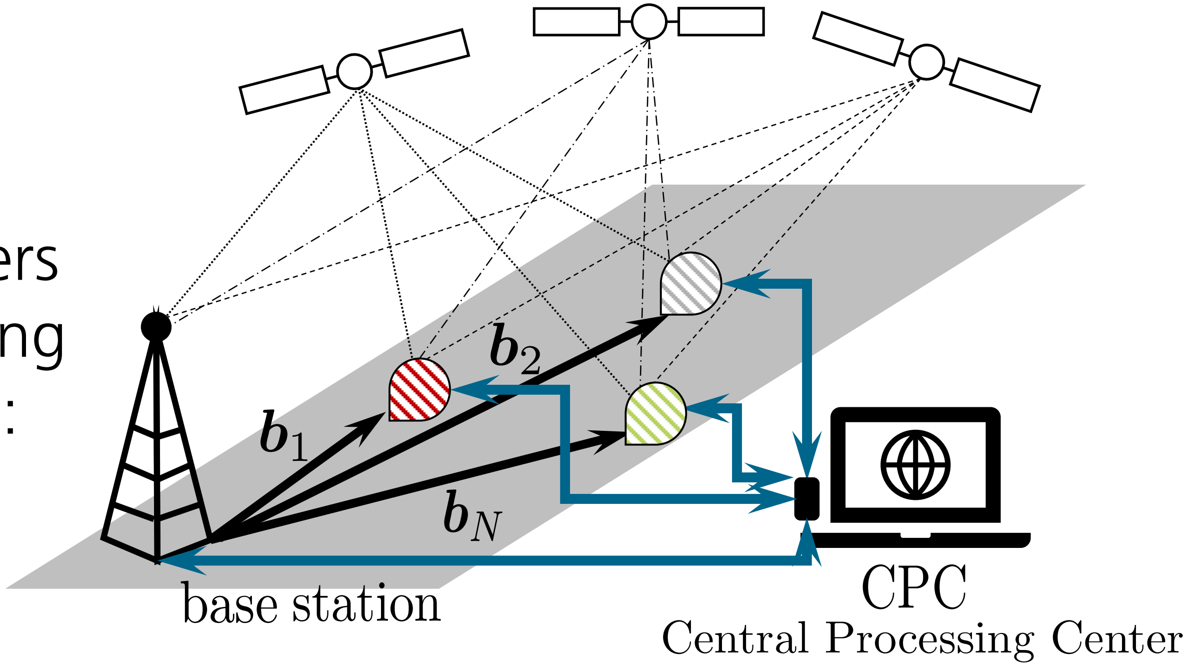
- Regular RTK: involves base station to users communication
- C-RTK is a centralized, passive collaboration architecture

✓ **Privacy preserving:** users do not compromise their localization information

✓ **Performance gain**: greater availability and precision

? **Can we live without base stations?**

✗ A low-latency, 2-way communication
✗ Growing complexity with number of users
✗ Careful with: *i)* undetected faults affecting the overall estimation; *ii)* "*byzantine*" users: those purposely attacking the network



Industry and Research Perspectives

From industry & standards:

- Advancement on communication & ranging technologies
- Protocols for the exchange of GNSS-related messages
- **Attractive solution for the largest GNSS market share**

From research:

- Feasibility of **base station-less RTK** and **regional PPP-RTK**
- The role of Machine Learning: network-wide stochastic modeling, better IAR
- ***Robust* estimation**: detecting/dealing with non-Gaussian effects
- Relationship to robotics community: active SLAM, distributed perception, …

- Cooperative localization is an attractive paradigm with lots to do (regarding GNSS) + solution to main issues for urban

Say hi at:
daniel.ariasmedina@dlr.de

Thanks for your attention!

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Impressum

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Institut:	Communications and Navigation
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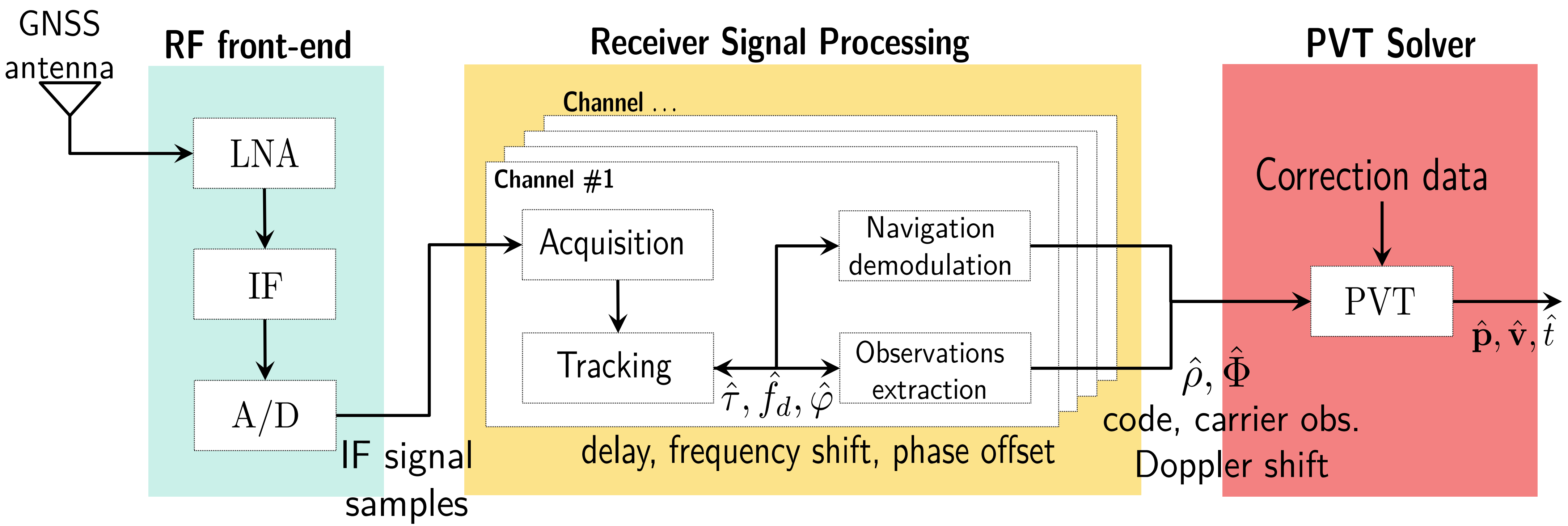
BACK UP SLIDES

General GNSS Receiver Architecture



RTK Processing

State estimate

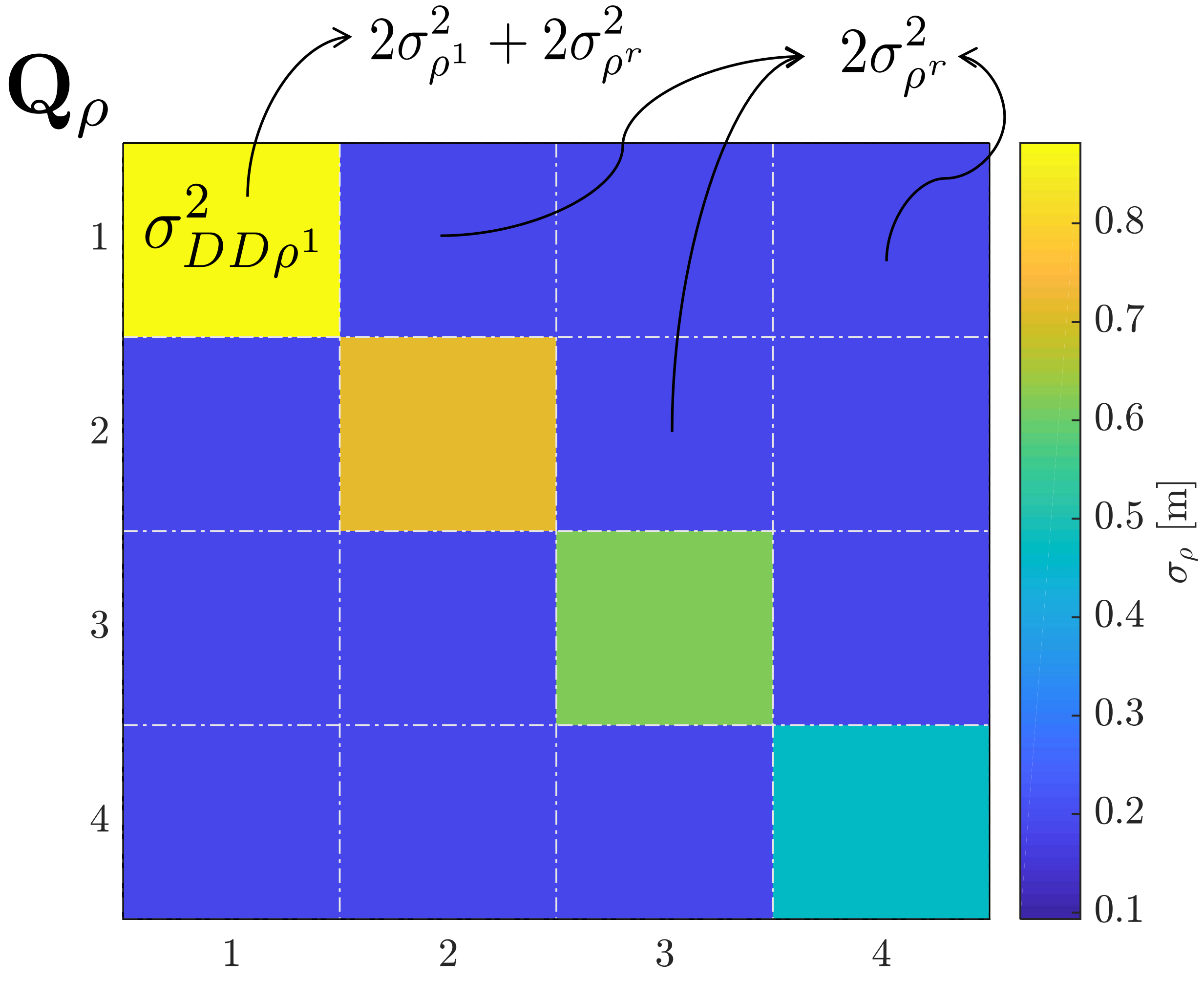
$$\mathbf{x} = \begin{bmatrix} \mathbf{a} \\ \mathbf{b} \end{bmatrix}, \ \mathbf{a} \in \mathbb{Z}^n, \ \mathbf{b} \in \mathbb{R}^3$$

Set of observations

$$\mathbf{y} = \begin{bmatrix} \boldsymbol{DD\Phi} \\ \boldsymbol{DD\rho} \end{bmatrix}, \ \mathbf{y} \in \mathbb{R}^{2n}$$

Careful with noise statistics

$$\boldsymbol{\eta} \sim \mathcal{N}\left(\mathbf{0}_{2n,1}, \underbrace{\begin{bmatrix} \mathbf{Q}_\Phi & \\ & \mathbf{Q}_\rho \end{bmatrix}}_{\mathbf{Q}_y}\right)$$

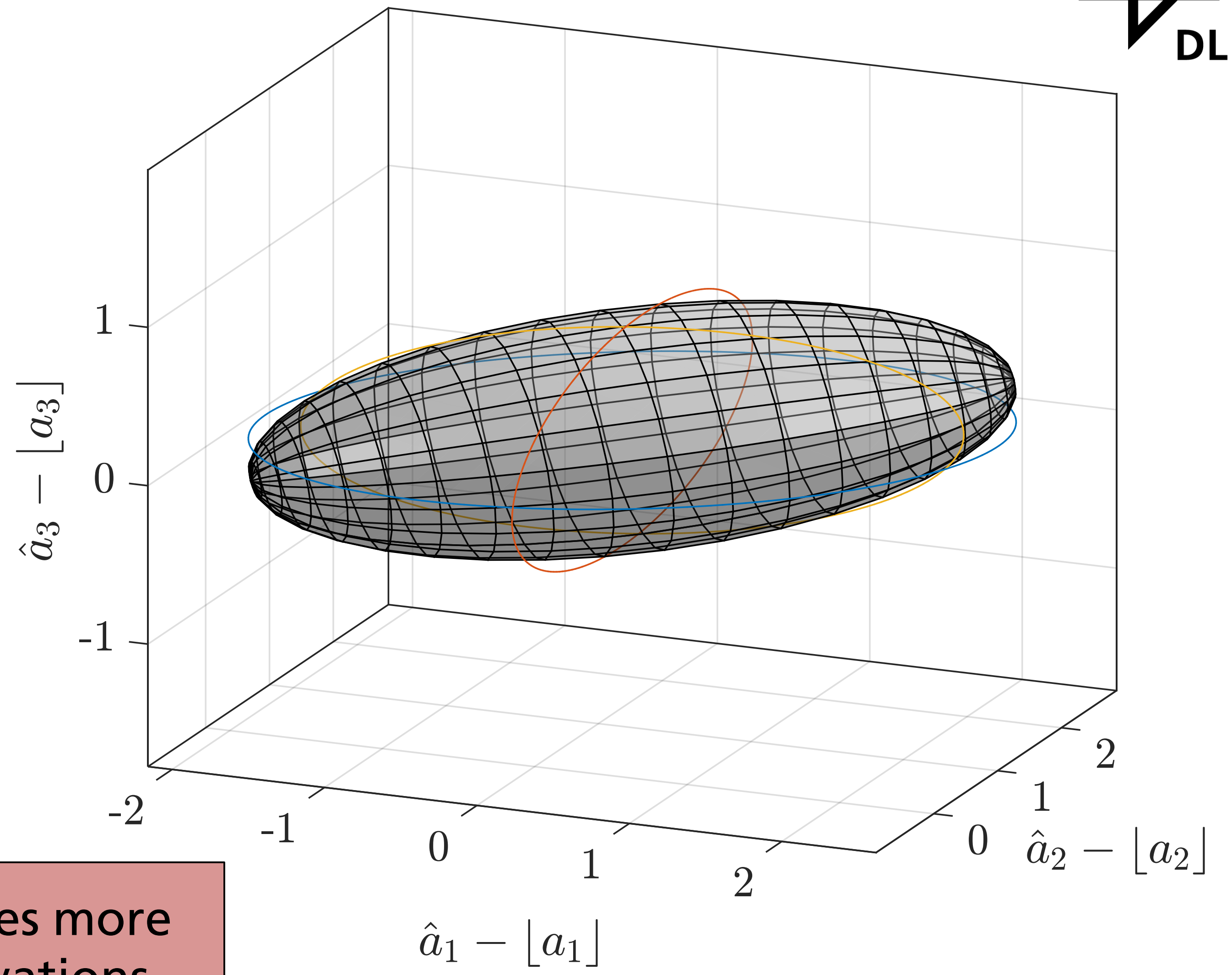


Integer Ambiguity Resolution

Some basic integer solving

$$\hat{a} = \begin{bmatrix} 15.23 \\ -36.55 \\ 44.11 \end{bmatrix}$$

$$\mathbf{Q}_{\hat{a}} = \begin{bmatrix} 2 & 0.5 & 0.2 \\ 0.5 & 1.5 & 0.05 \\ 0.2 & 0.05 & 0.2 \end{bmatrix}$$



Integer ambiguity resolution becomes more complex with the number of observations

Basics on Integrity Monitoring for GNSS

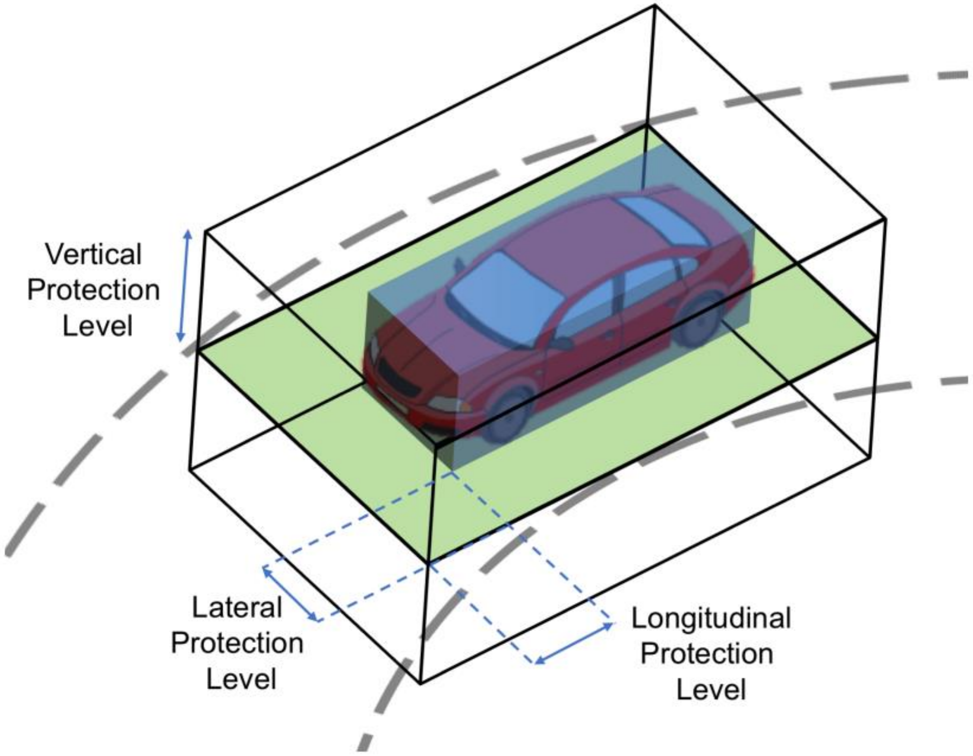
Integrity monitoring measures the trust on the navigation estimates & provides timely warnings when an unacceptable fault occurs / system is unreliable

Navigational requirements

- Accuracy
- Continuity
- Availability

Integrity components

- Alert Limit
- Integrity Risk
- Time to Alert
- Protection Level



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State of the Art on Integrity Monitoring: the limitations

- Standard solutions are derived specifically for aviation purposes:
  - open sky assumption
  - **very low number of faults** (only due to satellite faults)
  - not applicable to landing / take-off maneuvers
- Typically, **only code observations** are used (or code-carrier smoothing)
- **Only snapshot solutions** are considered (no recursive estimation)
- Multi sensor integration and related challenges are not contemplated
- Availability of Integrity Support Message (ISM), meaning “perfect” stochastic modeling

There is a need for new methods on Integrity Monitoring!