Relative Navigation and Docking of an sUAS and an UGV

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Special thanks to Eric Suer, Richard Reinfeld, and Jakob Dommaschk

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Application Examples

Unmanned Aerial Vehicle (UAV) and Unmanned ground Vehicle (UGV) cooperate to perform a mission. Reliable knowledge of relative pose is one of the requirements for a typical mission.

- environmental monitoring,
- infrastructure inspection,
- firefighting,
- search and rescue,
- surveillance,
- law enforcement
- mapping,
- agriculture,
- aerial photography, etc.

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Relative Navigation – Knowledge of Separation, Relative Velocity, …

- **Aviation**: broadcast position & velocity repots (ADS-B)
  - Difference provides separation: $\mathbf{s}_{AG}(t_k) = \mathbf{r}_A(t_k) - \mathbf{r}_G(t_k)$
  - And relative velocity: $\mathbf{v}_{AG}(t_k) = \mathbf{v}_A(t_k) - \mathbf{v}_G(t_k)$
  - Source: standalone GNSS, SBAS and GBAS
- **Aviation**: Alternatively broadcast raw measurements rather than reports
- **Non-aviation**: use Real-Time Kinematic GNSS (required base station)

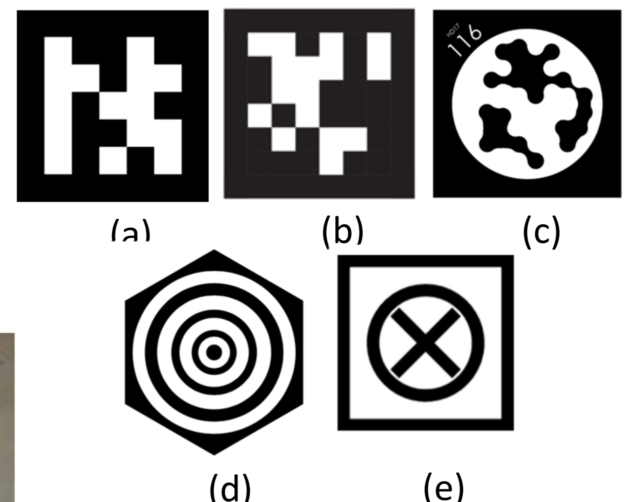
In many environments where a cooperative UAV/UGV would operate, GNSS performance is degraded or even unavailable: urban environments, under-the-canopy (forests), indoor

Solution:

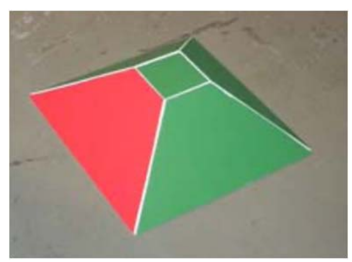
- integration of GNSS with IMU
- imaging sensors and laser scanners with or without inertial measurement units
- beacon-based navigation (i.e., pseudolites, Ultra-wide band or UWB)
- signals of opportunity

Relative Navigation – Knowledge of Separation, Relative Velocity

- **Aviation**: broadcast position & velocity repots (ADS-B)
- **Aviation**: Alternatively broadcast raw measurements rather than reports
- **Non-aviation**: use Real-Time Kinematic GNSS (required base station)
- **Aviation**: air-to-air range in TCAS via Mode-S
- **Non-aviation**: imaging sensors
  - using features/signature of the target vehicle
  - using Fiducial markers (objects used as reference points)
- **Non-aviation**: range radios
- **Non-aviation**: 3D imagers
- **Non-aviation**: LED beacons, etc.

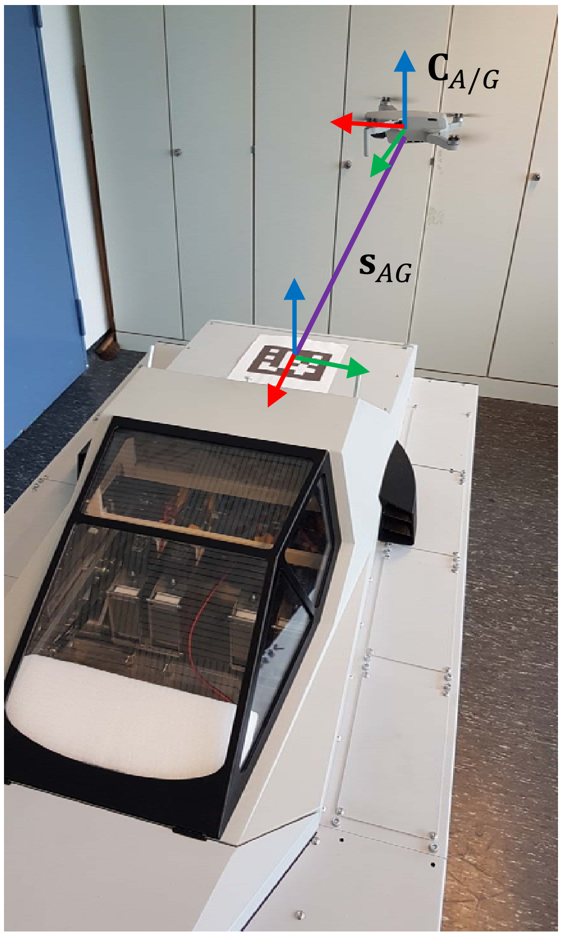


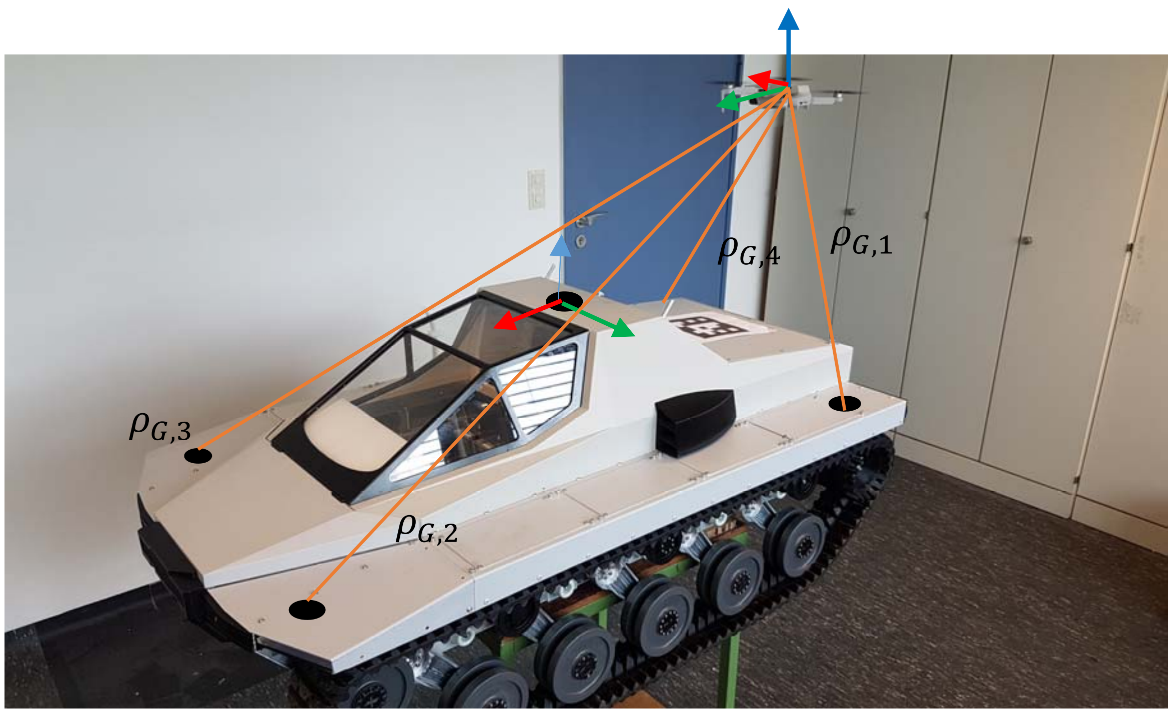
(a) ArUco maker, (b) Apriltag, (c) STags.



Using 3D docking port

Relative Pose using Fiducial Markers and Beacons





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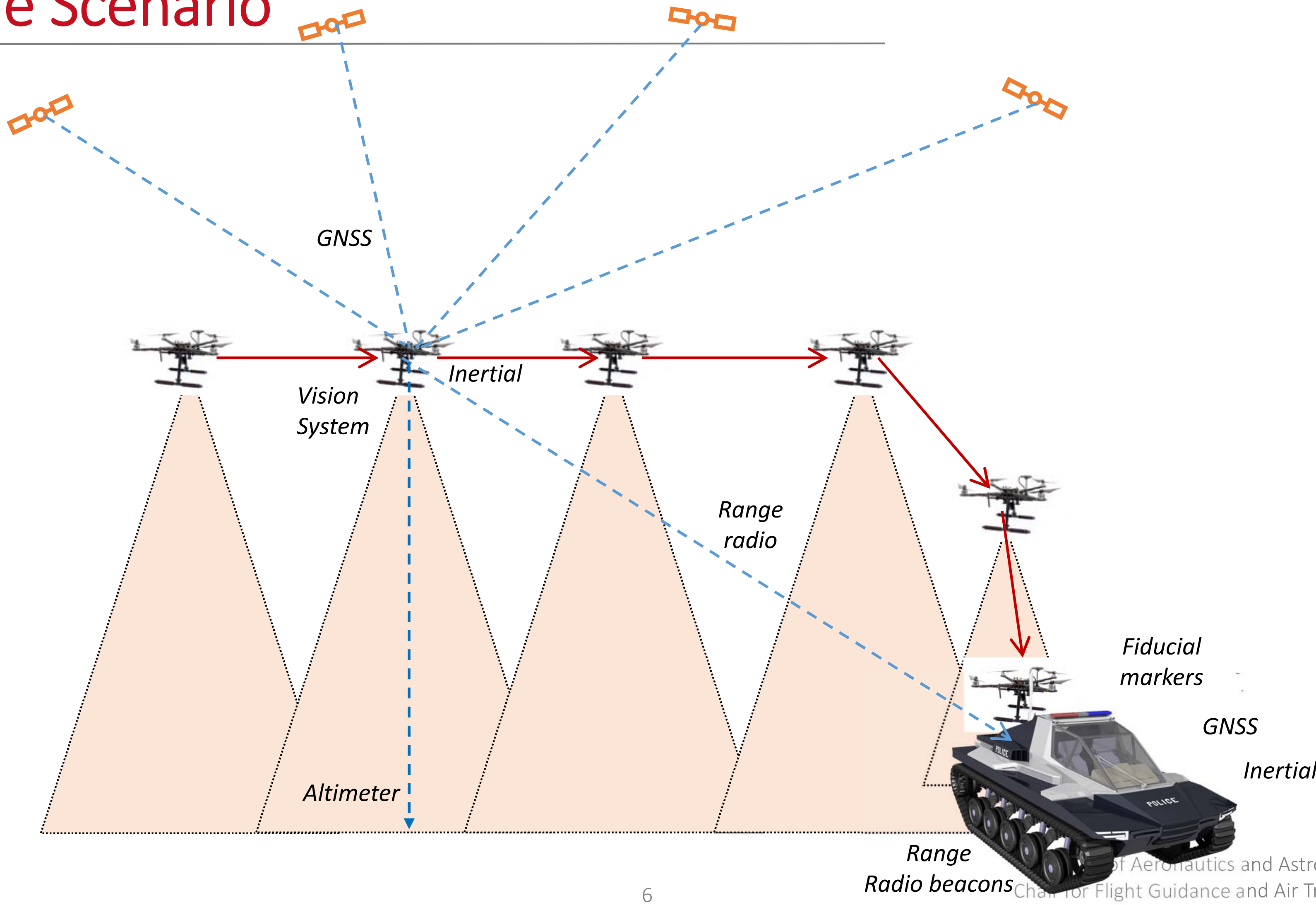
Example Scenario



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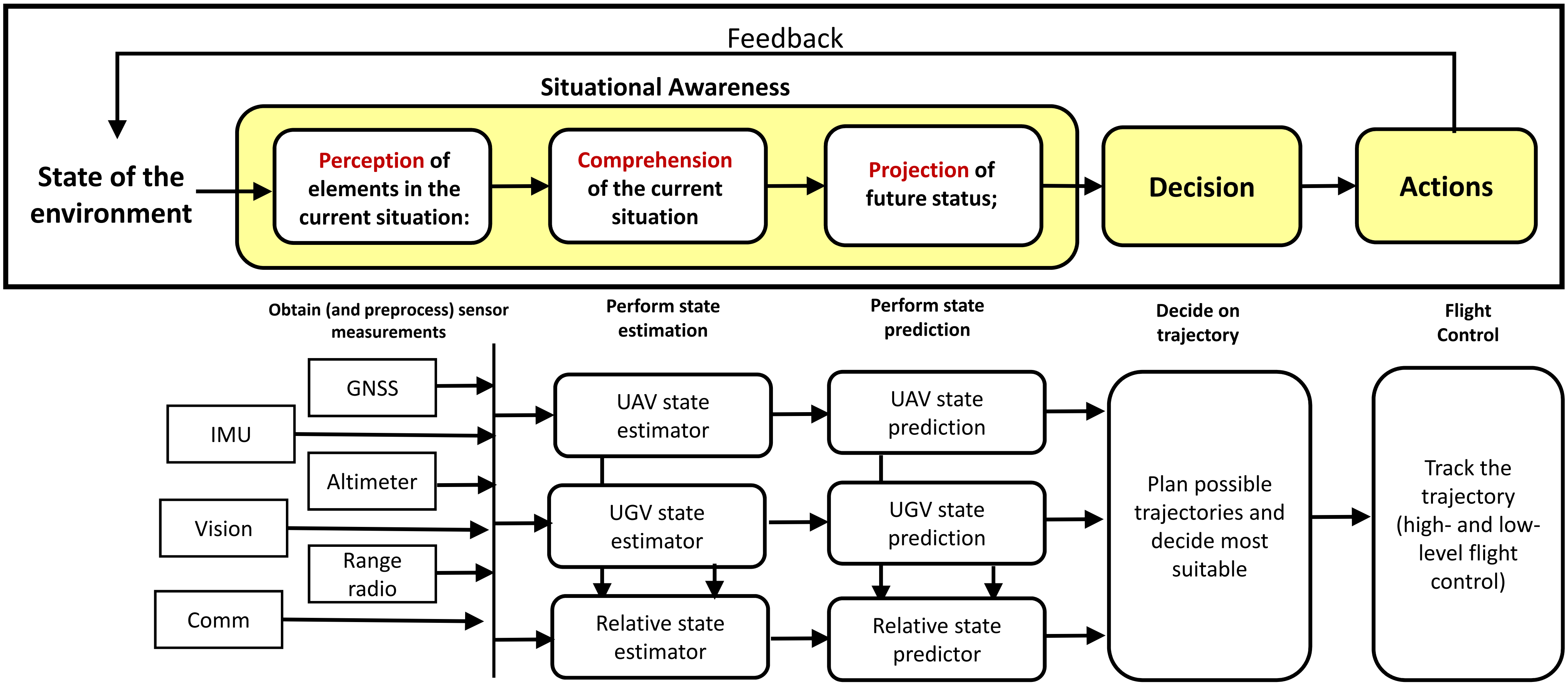
Information processing, decision making and action loop



Perception: Information Collection

	Source	With communication		Without communication
		Position/velocity reports	Measurements/corrections	
A	INS/Altimeter	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$	-	-
B	GNSS	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$	-	-
C	GNSS/INS (EKF)	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$	-	-
D	GNSS SBAS*	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$	-	-
E	GNSS SBAS CSC*	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$	-	-
F	Interferometry*	-	$\rho_{A,k}, \rho_{G,k}$	-
G	Interferometry CSC*	-	$\rho_{A,k}, \phi_{A,k}, \rho_{G,k}, \phi_{G,k}$	-
H	RTK Float	-	$\rho_{A,k}, \rho_{G,k}$	-
I	RTK Fixed	-	$\rho_{A,k}, \phi_{A,k}, \rho_{G,k}, \phi_{G,k}$	-
J	UWB	-	-	$r_{A,n}$
K	UWB/Altimeter (EKF)	-	$r_{A,n}, h_A, h_G$	$r_{A,n}, h_A$
L	UWB/Altimeter (PF)	-	$r_{A,n}, h_A, h_G$	$r_{A,n}, h_A$
M	Fiducial marker	-	$\tilde{\mathbf{r}}_{AG}, \tilde{\mathbf{C}}_{A/G}$	$\tilde{\mathbf{r}}_{AG}, \tilde{\mathbf{C}}_{A/G}$
⋮	⋮	⋮	⋮	⋮

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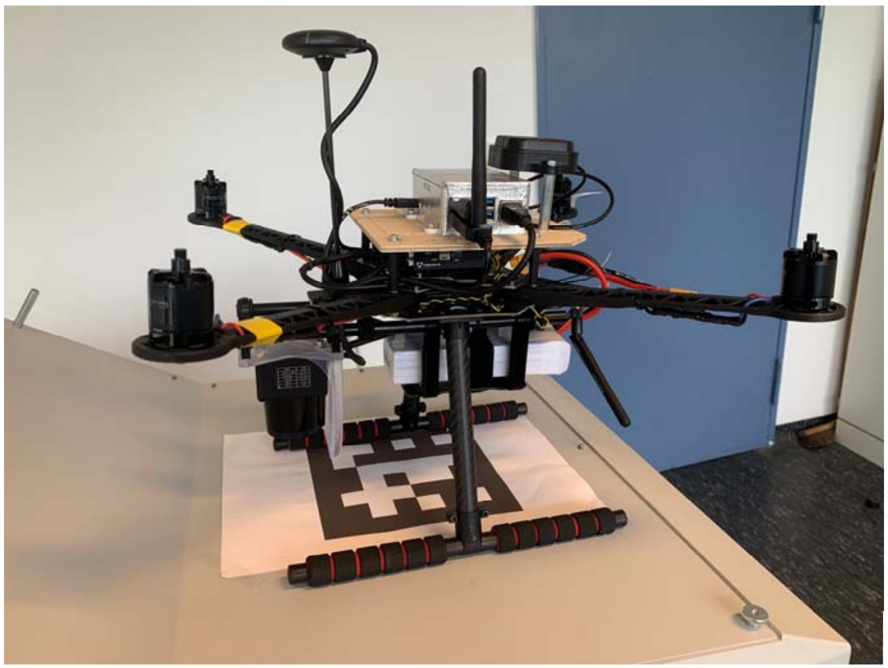
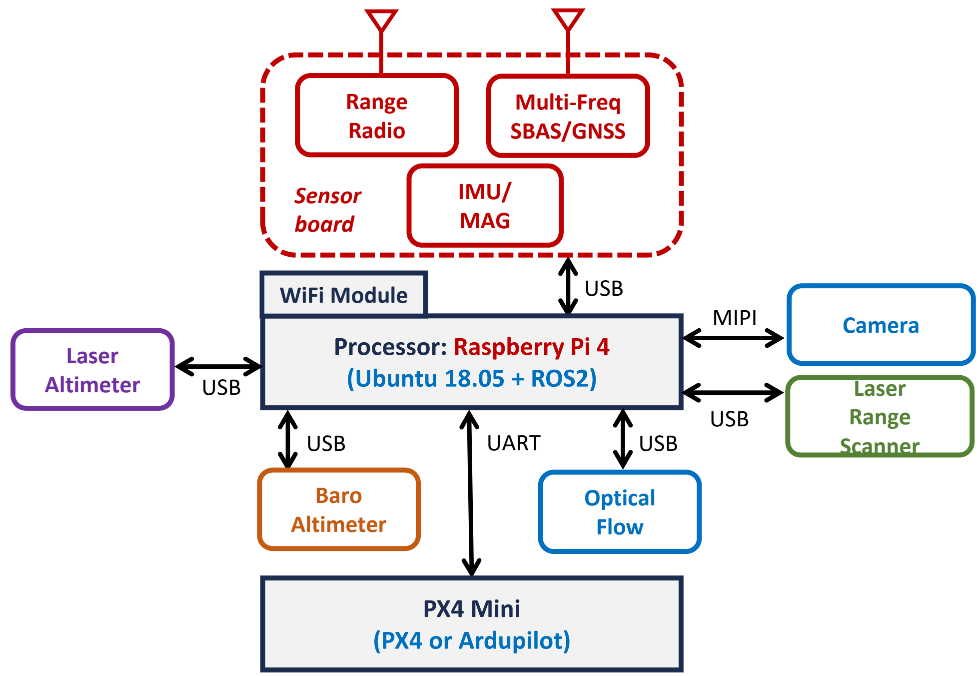
TU Berlin Test Setup: Unmanned Aerial Vehicle (UAV)





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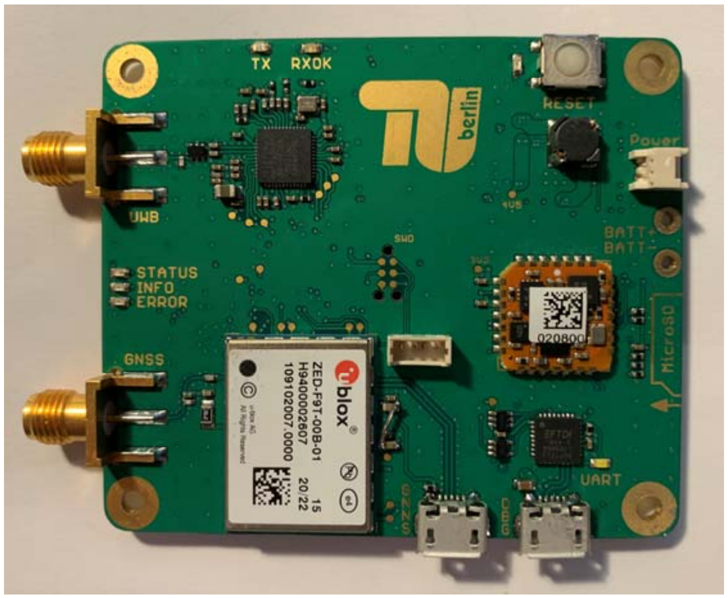
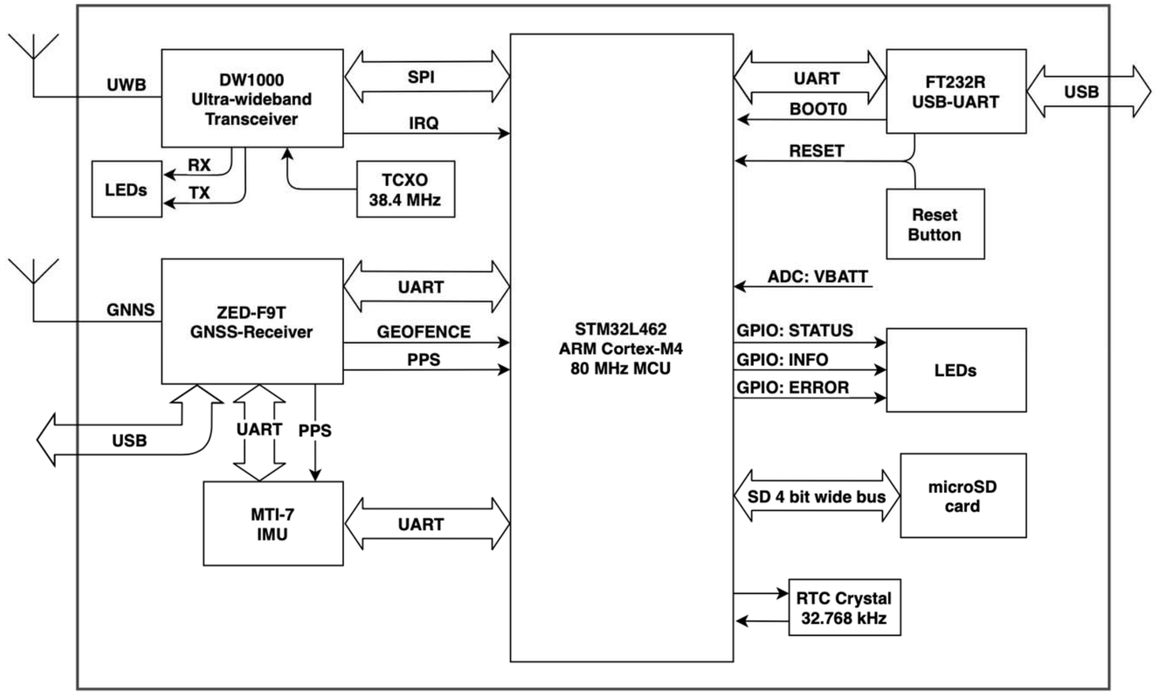
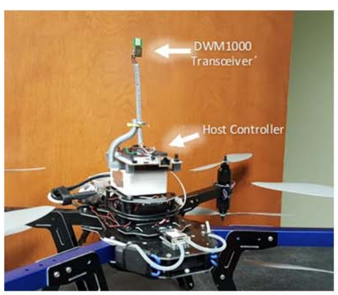
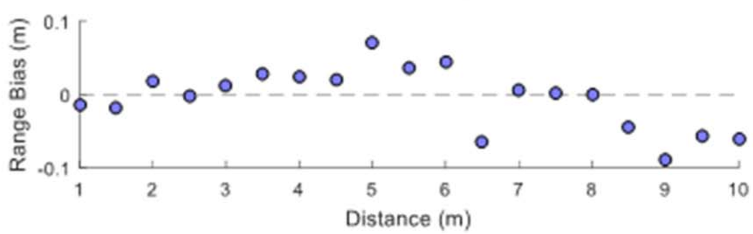
TU Berlin Test Setup: Sensor Board

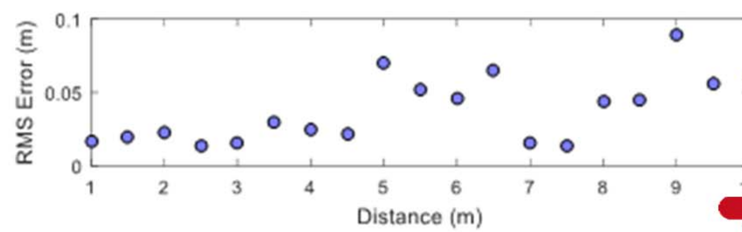




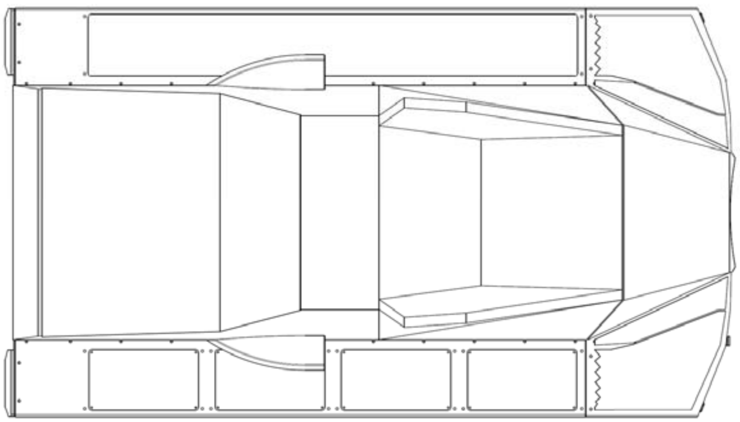
UWB Decawave design based on previous work.





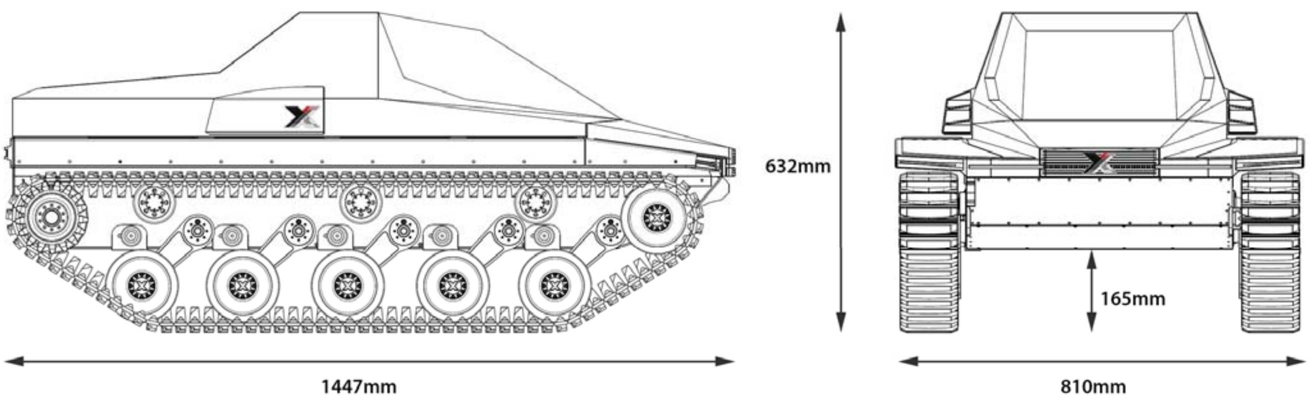


TU Berlin Test Setup: Unmanned Ground Vehicle (UGV)



SPECIFICATIONS

MOTOR	2x 4kW BLM
GEAR	2x 1:6.3
POWER	4x 21Ah 6S 22.2V LiPo (44.4V)
TORQUE	2x 200Nm
SPEED max	34 km/h
TURN RADIUS	on vertical axis (750 mm)
CTRL	RC & AC
SENSORS	RADAR,LIDAR,Stereo/Thermal-Cam
PAYLOAD	Drone-Station, Sensors, Controlers



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D	GNSS SBAS*	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$	-	-
E	GNSS SBAS CSC*	$\tilde{\mathbf{r}}_A, \tilde{\mathbf{v}}_A, \tilde{\mathbf{r}}_G, \tilde{\mathbf{v}}_G$		
F	Interferometry*	-		
G	Interferometry CSC*	-		
H	RTK Float	-		
I	RTK Fixed	-		
J	UWB	-		
K	UWB/Altimeter (EKF)	-		
L	UWB/Altimeter (PF)	-		
M	Fiducial marker	-		
⋮		⋮	.	.

System: dynamics model

$$\mathbf{x}(t_k) = \mathbf{g}[\mathbf{x}(t_{k-1})] + \mathbf{w}(t_k)$$

System: measurement model

$$\mathbf{z}(t_k) = \mathbf{h}[\mathbf{x}(t_k)] + \mathbf{v}(t_k)$$

Kalman filter: update step

$$\hat{\mathbf{x}}(t_k) = \hat{\mathbf{x}}^-(t_k) + \mathbf{K}_k[\mathbf{z}_k(t_k) - \mathbf{h}[\hat{\mathbf{x}}^-(t_k)]]$$

$$\mathbf{K}(t_k) = \frac{\mathbf{P}^-(t_k)\mathbf{H}^T}{[\mathbf{H}(t_k)\mathbf{P}^-(t_k)\mathbf{H}^T(t_k) + \mathbf{R}]}$$

$$\mathbf{P}(t_k) = [\mathbf{I} - \mathbf{K}(t_k)\mathbf{H}(t_k)]\mathbf{P}^-(t_k)$$

Kalman filter: prediction step

$$\hat{\mathbf{x}}^-(t_k) = \hat{\mathbf{x}}(t_k) + \int_{t_{k-1}}^{t_k} \mathbf{g}(\hat{\mathbf{x}}, t)dt$$

$$\mathbf{P}^-(t_k) = \mathbf{\Phi}(t_{k-1})\mathbf{P}(t_{k-1})\mathbf{\Phi}^T(t_{k-1}) + \int_{t_{k-1}}^{t_k} \mathbf{\Phi}(t_{k-1}|t)\mathbf{Q}(t_{k-1})\mathbf{\Phi}^T(t_{k-1}|t)dt$$

Included in the eventual implementation for terminal guidance (< 3m)

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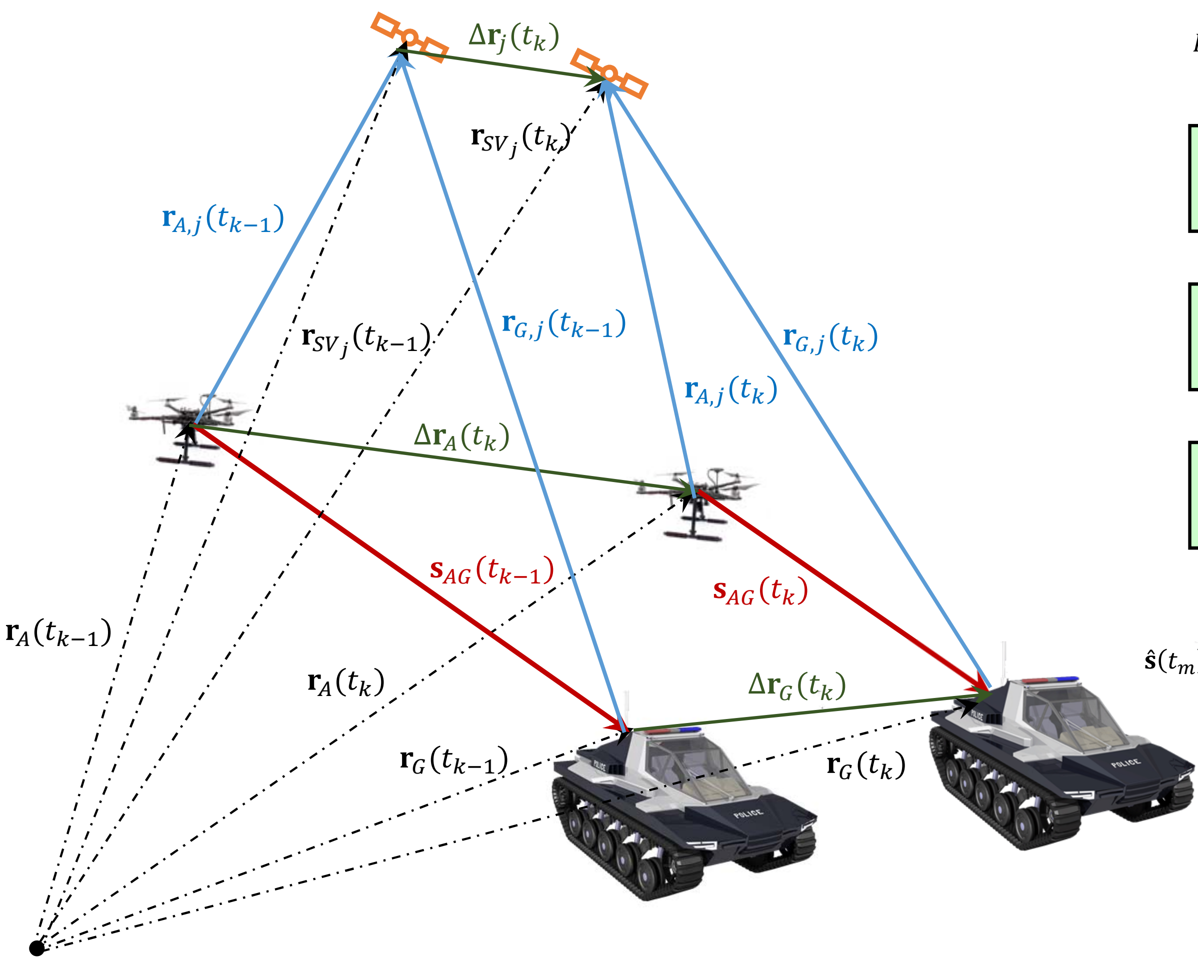
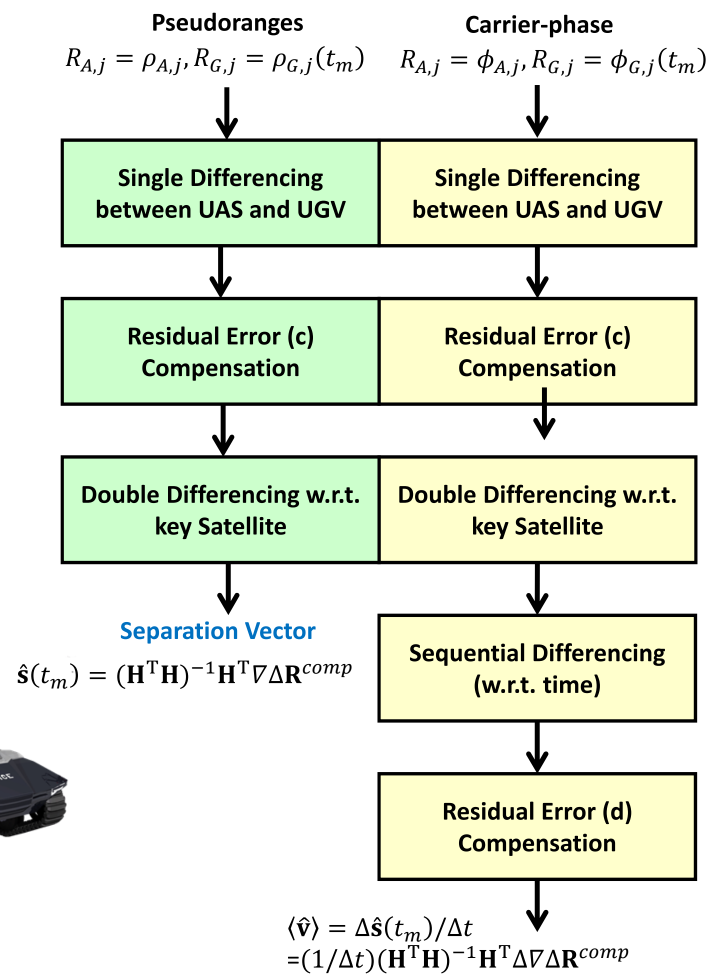
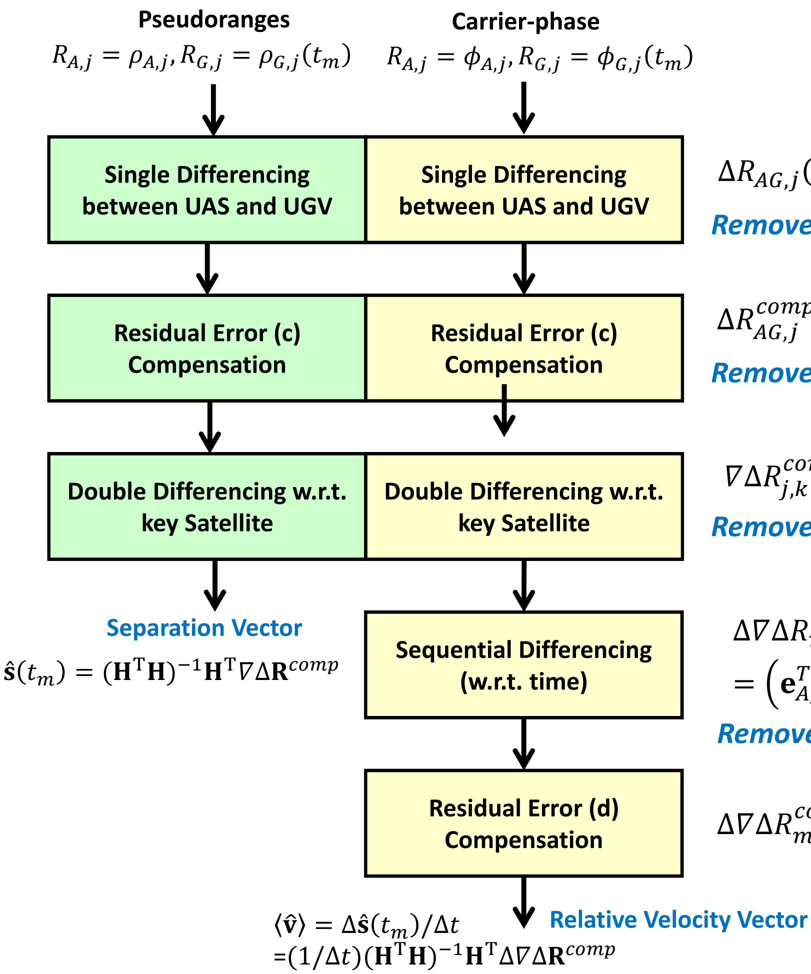
GNSS-based relative position and velocity estimation





GNSS-based relative position and velocity estimation

$$c_j = \left(\mathbf{e}_{G,j}^T(t_m) - \mathbf{e}_{A,j}^T(t_m)\right)\mathbf{r}_{\mathrm{SV}_j}(t_m) - \left(\mathbf{e}_{G,j}^T(t_m) - \mathbf{e}_{A,j}^T(t_m)\right)\mathbf{r}_G(t_m)$$
$$d_j = \left(\mathbf{e}_{A,j}^T(t_m) - \mathbf{e}_{A,j}^T(t_{m-1})\right)\mathbf{s}(t_{m-1}) - \left(\mathbf{e}_{G,j}^T(t_m) - \mathbf{e}_{G,j}^T(t_{m-1})\right)\mathbf{s}(t_{m-1})$$



$$\Delta R_{AG,j}(t_m) = R_{G,j}(t_m) - R_{A,j}(t_m) = \mathbf{e}_{A,j}^T(t_m)\mathbf{s}(t_m) + c_j$$

Remove range errors common between location A and B

$$\Delta R_{AG,j}^{comp}(t_m) = \mathbf{e}_{A,j}^T(t_m)\mathbf{s}(t_m)$$

Remove range errors that can be modeled

$$\nabla\Delta R_{j,k}^{comp} = \left(\mathbf{e}_{A,j}^T(t_m) - \mathbf{e}_{A,k}^T(t_m)\right)\mathbf{s}(t_m)$$

Remove range errors common between satellites

$$\Delta\nabla\Delta R_{m,m-1} = \nabla\Delta R_{j,k}^{comp}(t_m) - \nabla\Delta R_{j,k}^{comp}(t_{m-1})$$
$$= \left(\mathbf{e}_{A,j}^T(t_m) - \mathbf{e}_{A,k}^T(t_m)\right)\Delta\mathbf{s}(t_m) + d_j$$

Remove range errors that are temporally correlated

$$\Delta\nabla\Delta R_{m,m-1}^{comp} = \left(\mathbf{e}_{A,j}^T(t_m) - \mathbf{e}_{A,k}^T(t_m)\right)\Delta\mathbf{s}(t_m)$$

Direction	Standard Deviations (σ)		
	Head-On	Overtake	Crossing
East	4.0 mm/s	3.7 mm/s	4.5 mm/s
North	4.2 mm/s	5.2 mm/s	5.2 mm/s
Up	11.8 mm/s	11.9 mm/s	11.2 mm/s

Based on actual flight tests

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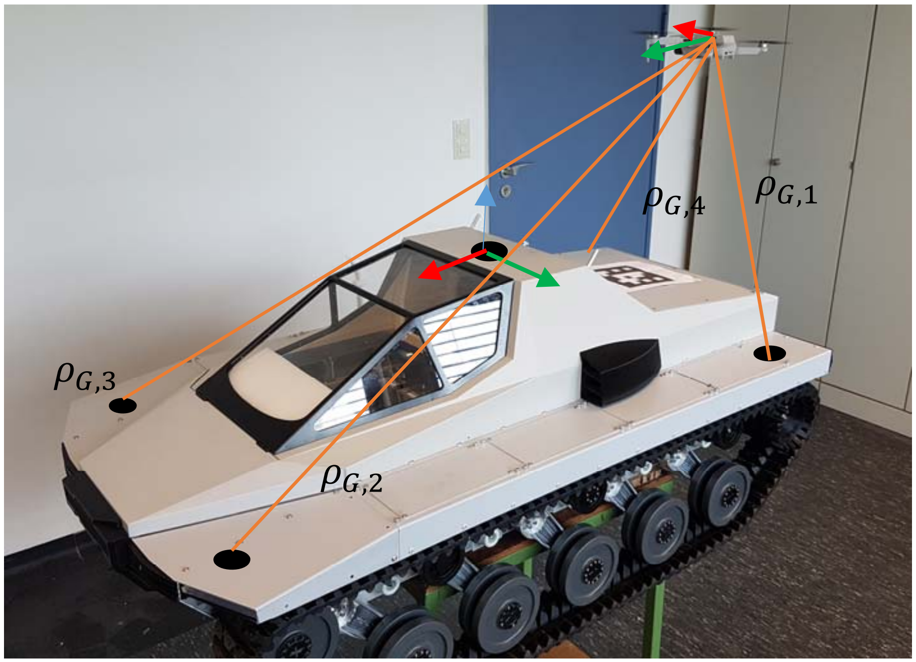
RR-based positioning



Must also evaluate the geometry of the problem because it is ill-conditioned for longer distance between both vehicles

- Measurement equation:

$$\tilde{r}_{A,n}(t_k) = \left\| \mathbf{r}_A - \mathbf{r}_{G,n} \right\| + v_{uwb} \Rightarrow \left\| \mathbf{r}_A - \mathbf{C}_b^n \mathbf{r}_{G,n}^b \right\|$$

- Linearization (way more than GNSS):

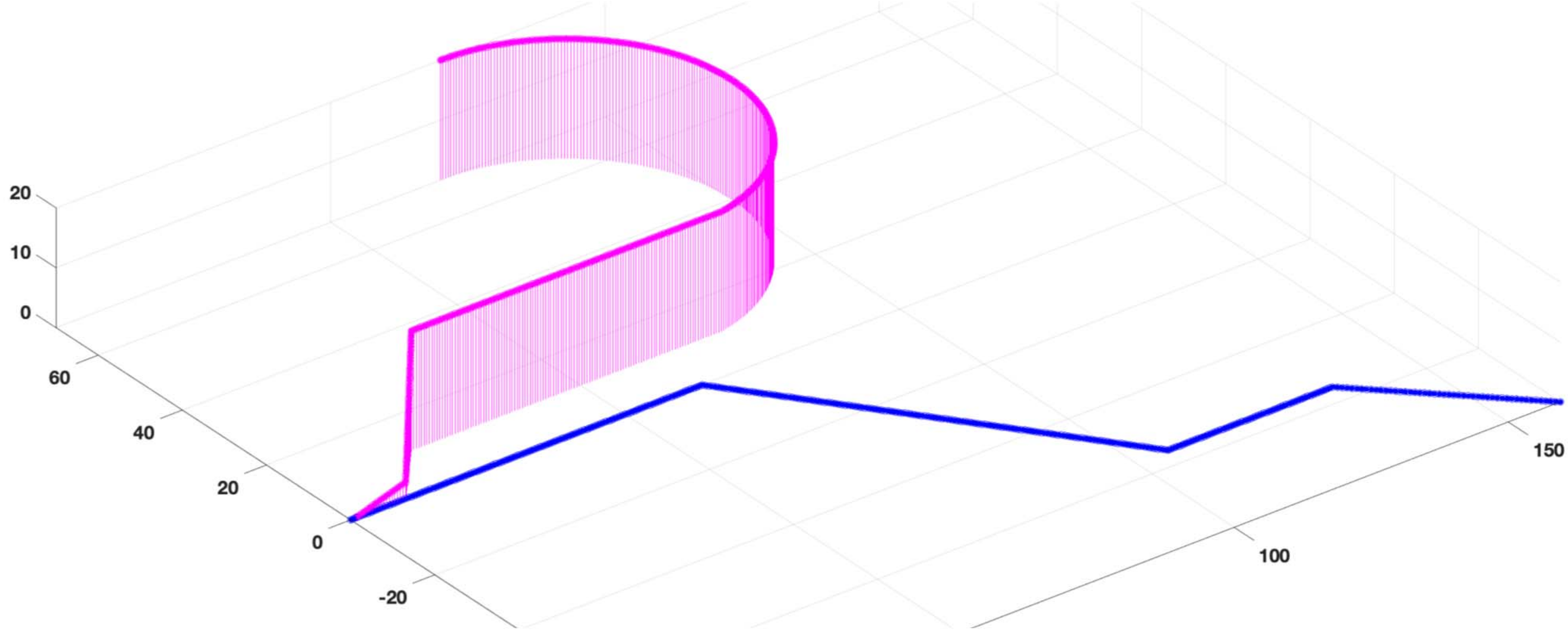
$$\mathbf{H} = \begin{bmatrix} \mathbf{e}_{G,1}^T \\ \vdots \\ \mathbf{e}_{G,N}^T \end{bmatrix} \quad \mathbf{e}_{G,n} = \left[\frac{x_A - x_{G,n}}{\left\| \mathbf{r}_A - \mathbf{r}_{G,n} \right\|} \quad \frac{y_A - y_{G,n}}{\left\| \mathbf{r}_A - \mathbf{r}_{G,n} \right\|} \quad \frac{z_A - z_{G,n}}{\left\| \mathbf{r}_A - \mathbf{r}_{G,n} \right\|} \right]^T$$

- Standard WLS: $\hat{\mathbf{x}} = \left(\mathbf{H}^{\mathbf{T}}\mathbf{W}\mathbf{H}\right)^{-1}\mathbf{H}^{\mathbf{T}}\mathbf{W}\mathbf{z}$
- With altimeter included:

$$\mathbf{H} = \begin{bmatrix} \mathbf{e}_{G,1}^T \\ \vdots \\ \mathbf{e}_{G,N}^T \\ [0 \quad 0 \quad 1] \end{bmatrix}$$

Simulation Scenario

- After detection of the UGV, the UAV flies an arc at constant altitude, then descents and lines up with the predicted UGV trajectory after which it keeps pace and slowly descents on the UGV platform.



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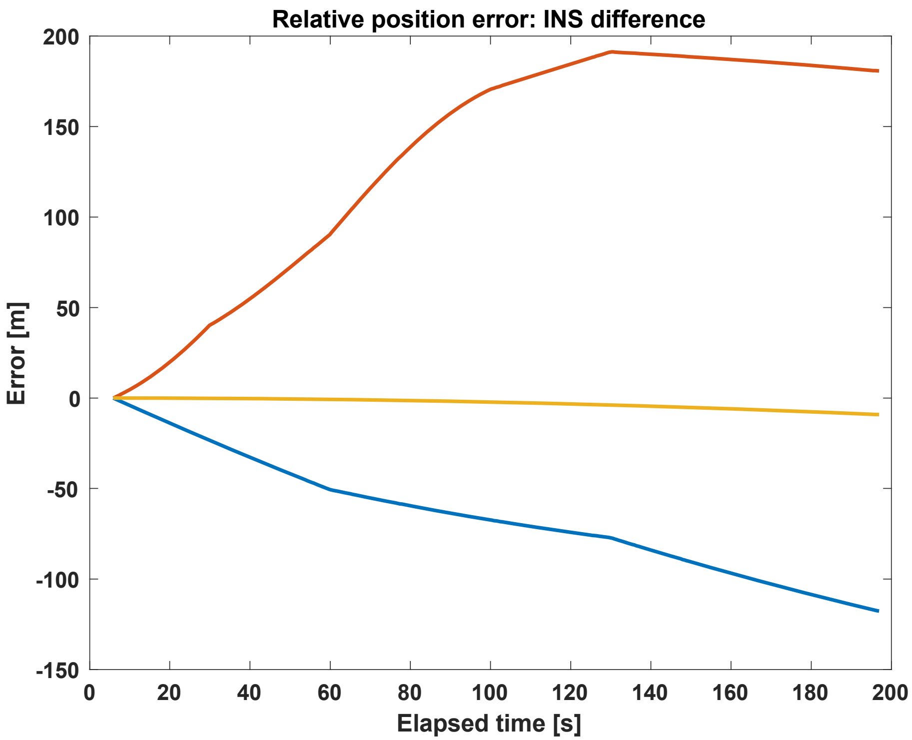
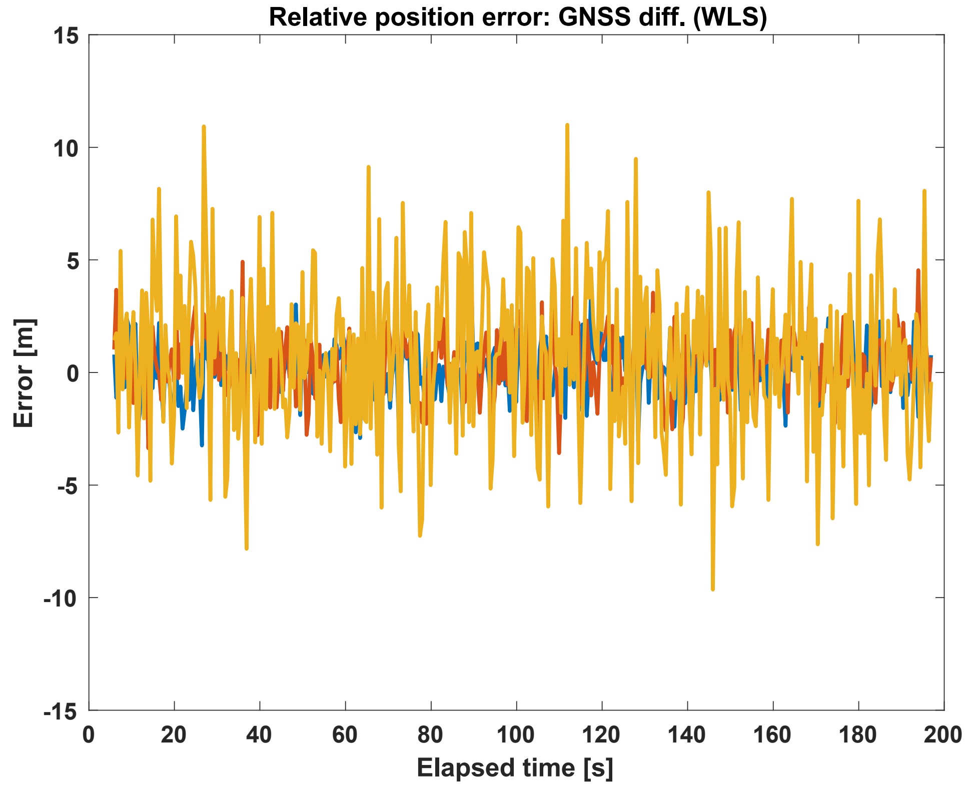
Inertial-only and GNSS-standalone

- Exchange of position reports





blue: East-direction, red: North-direction, orange: up-direction

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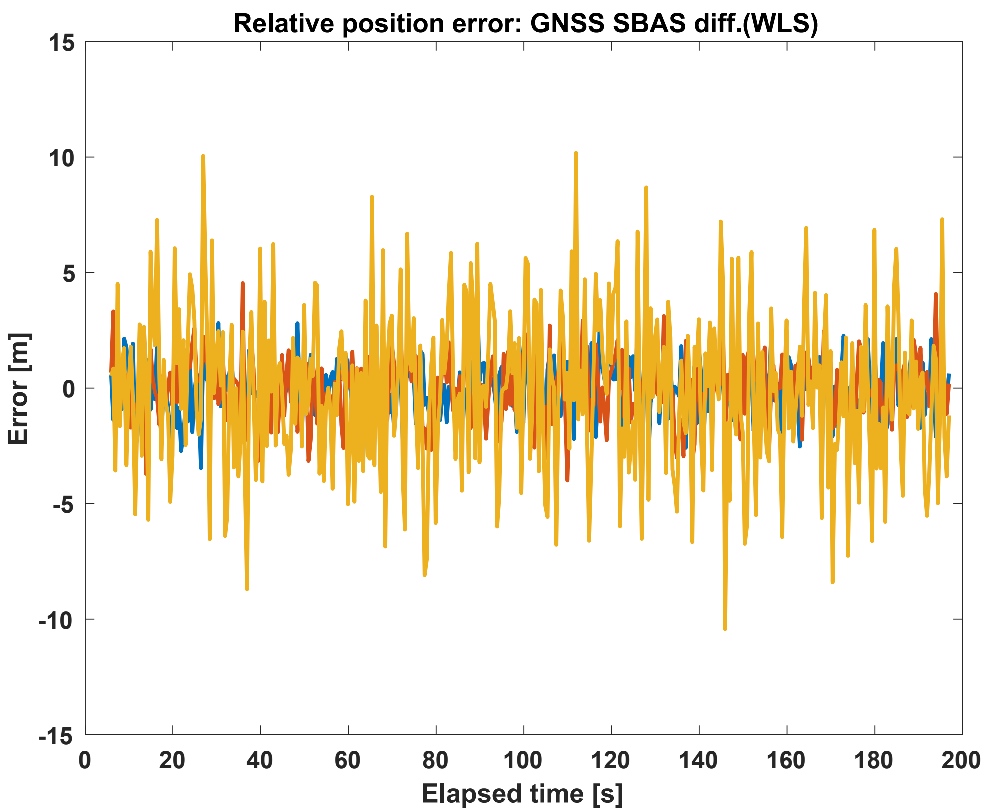
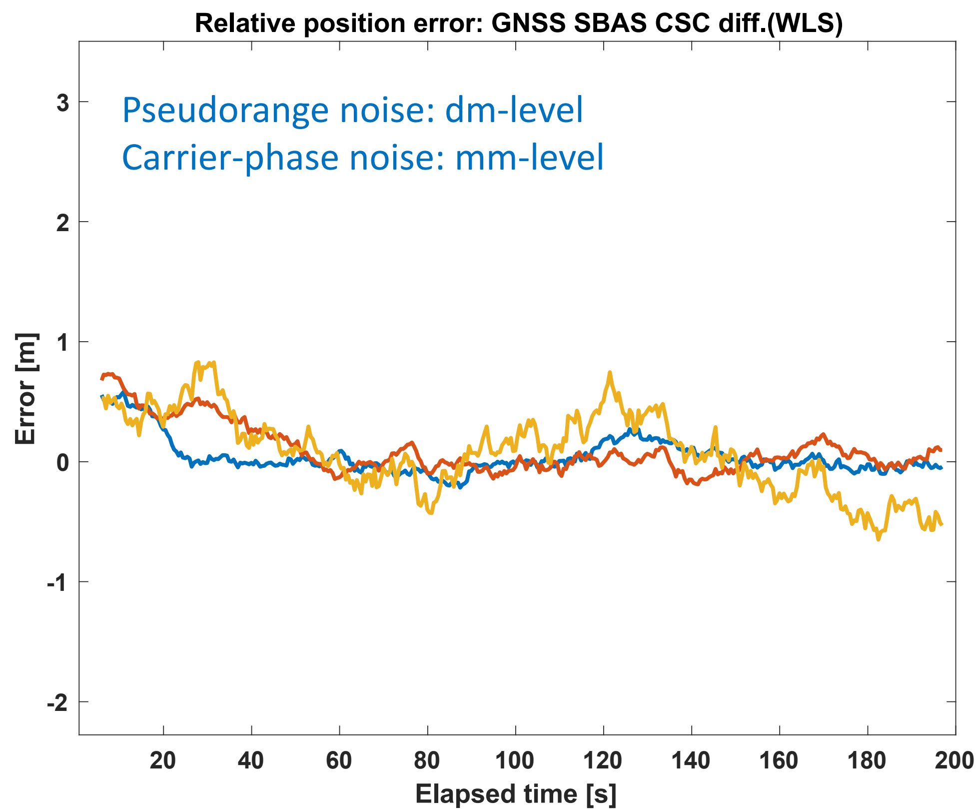
Space-based Augmentation Receivers





Right side uses Carrier-Smoothed-Code: $\rho_{i,csc}(t_k) = \frac{N-1}{N}\{\rho_{i,csc}(t_{k-1}) + \phi_i(t_k) - \phi_i(t_{k-1})\} + \frac{1}{N}\rho_i(t_k)$

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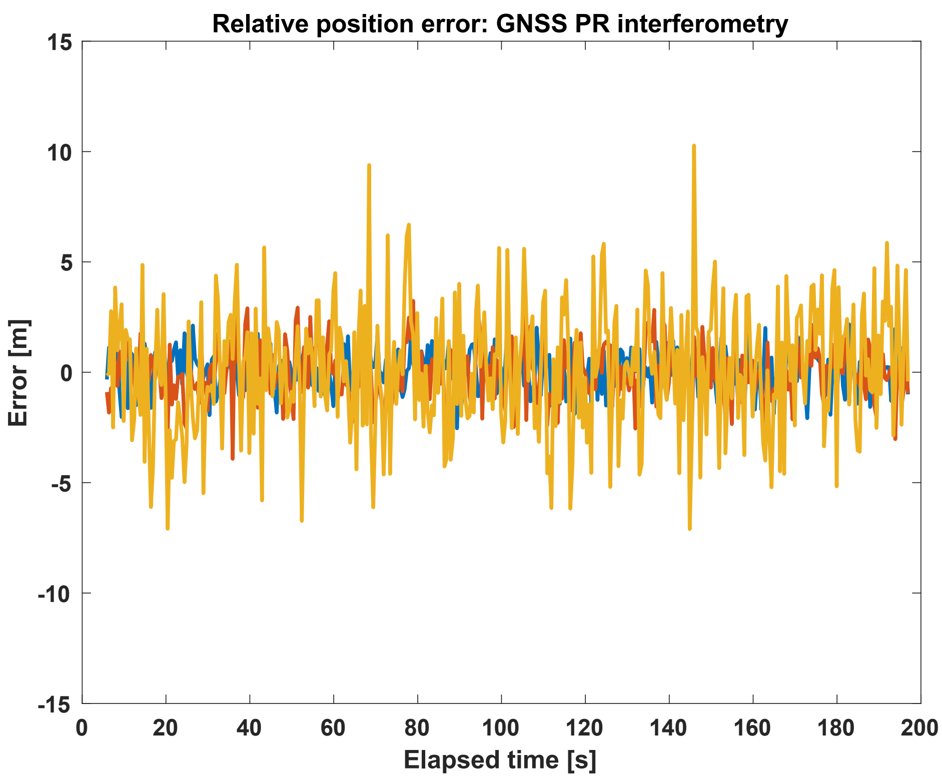
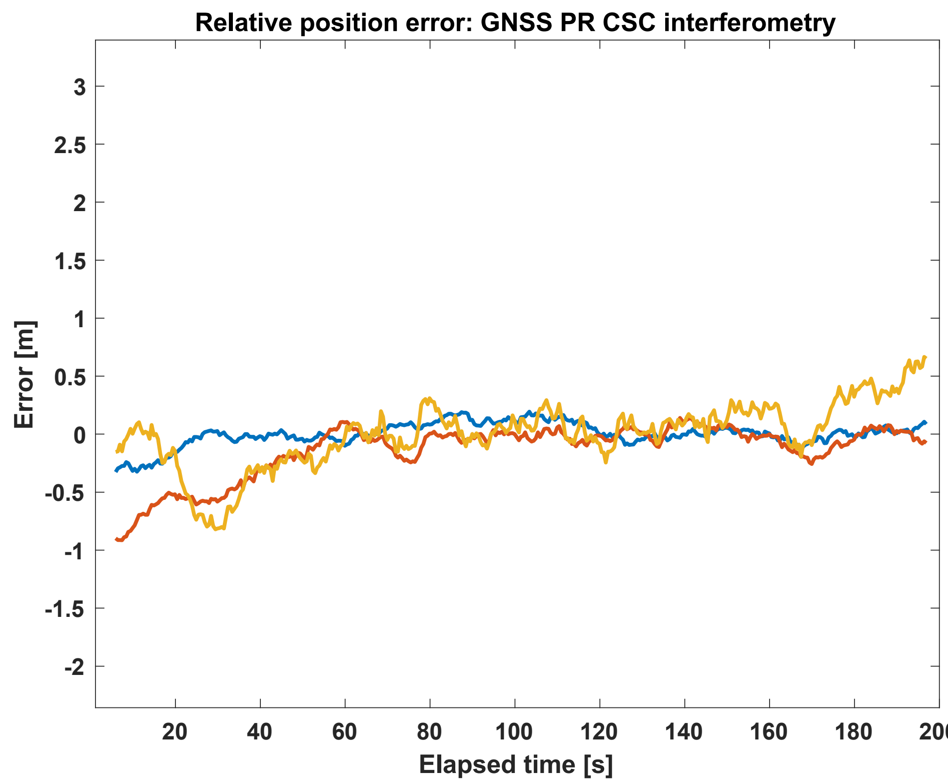
Use of Interferometry Approach (shown earlier)





Instead of using CSC, smoothing can also take place here using $\mathbf{s}_{filt}(t_m) = (1-K)\hat{\mathbf{s}}^n(t_k) + K\left[\mathbf{s}^n_{filt}(t_{k-1}) + \Delta\hat{\mathbf{s}}^n(t_k)\right]$

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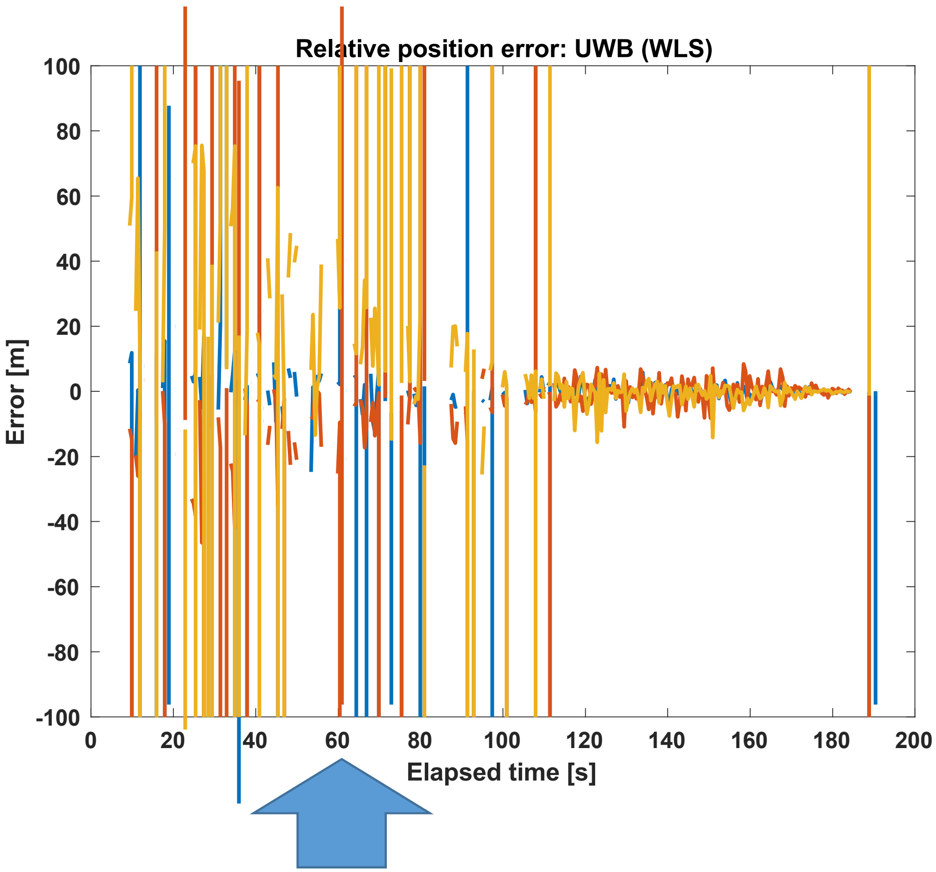
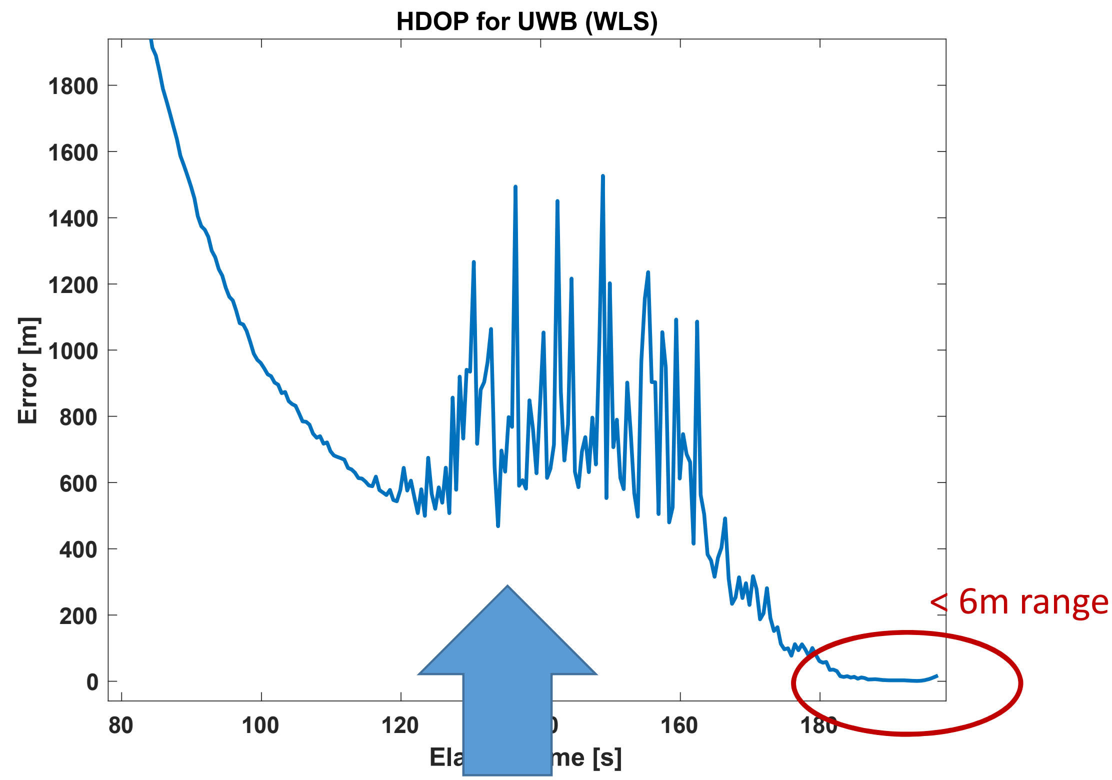
UWB RR Solution - WLS

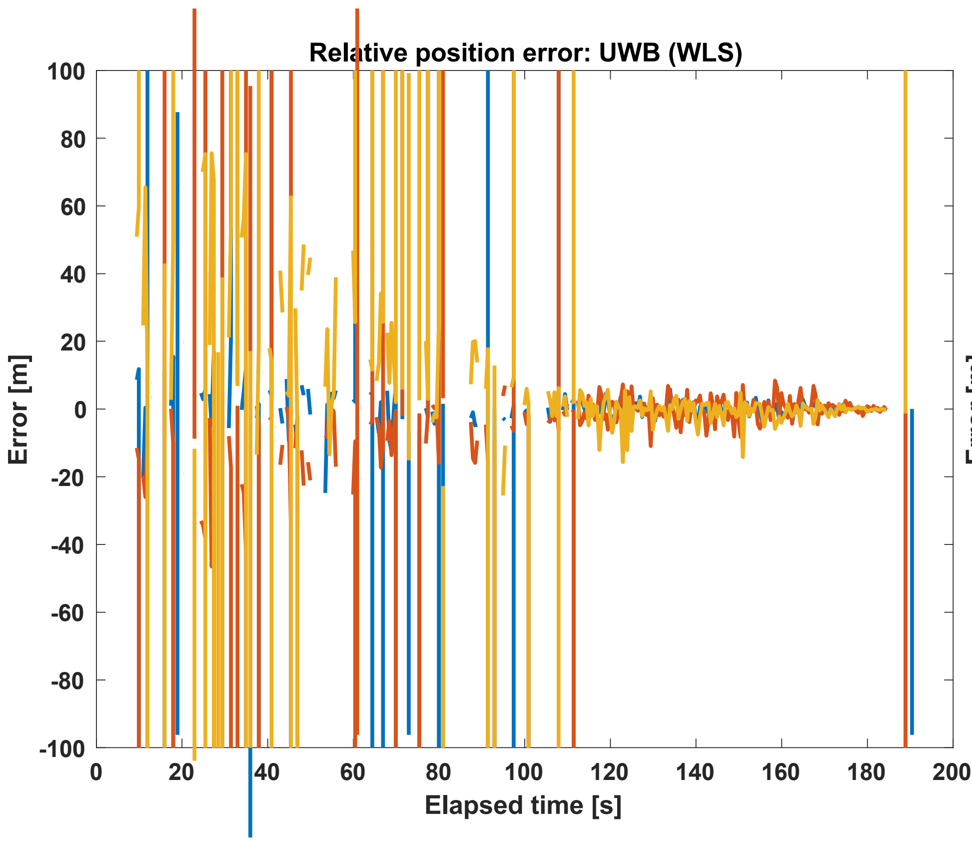


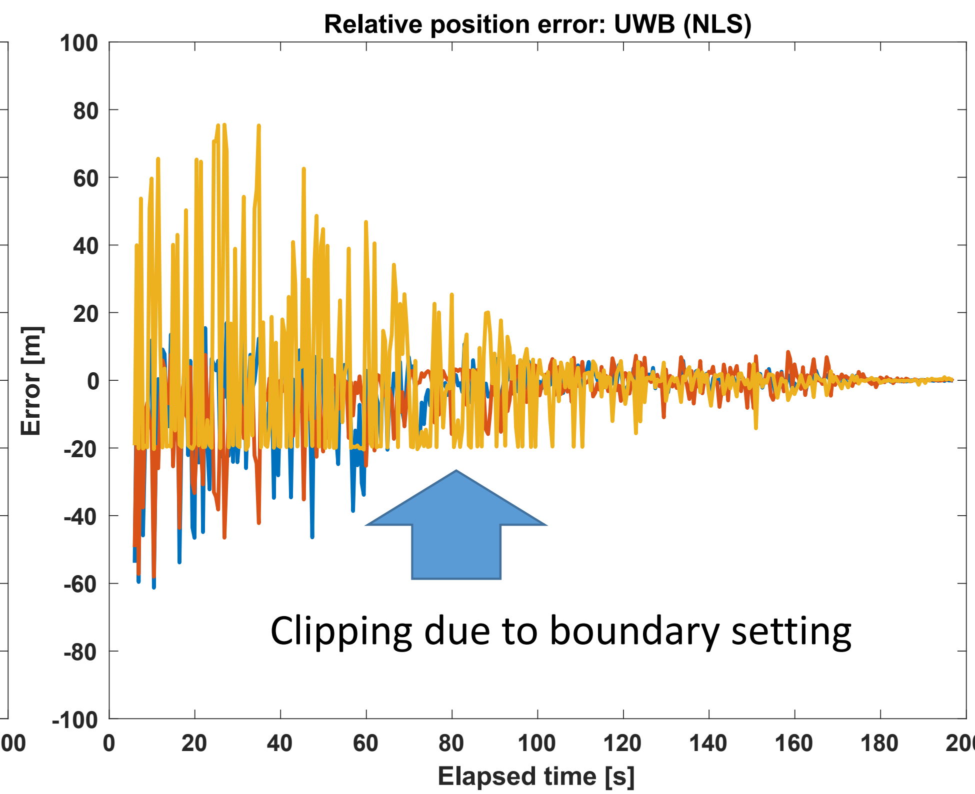
Convergence problems



When converging, geometry problems:
Remember: position error = DOP*range error

Alternatively: use of a non-linear solver





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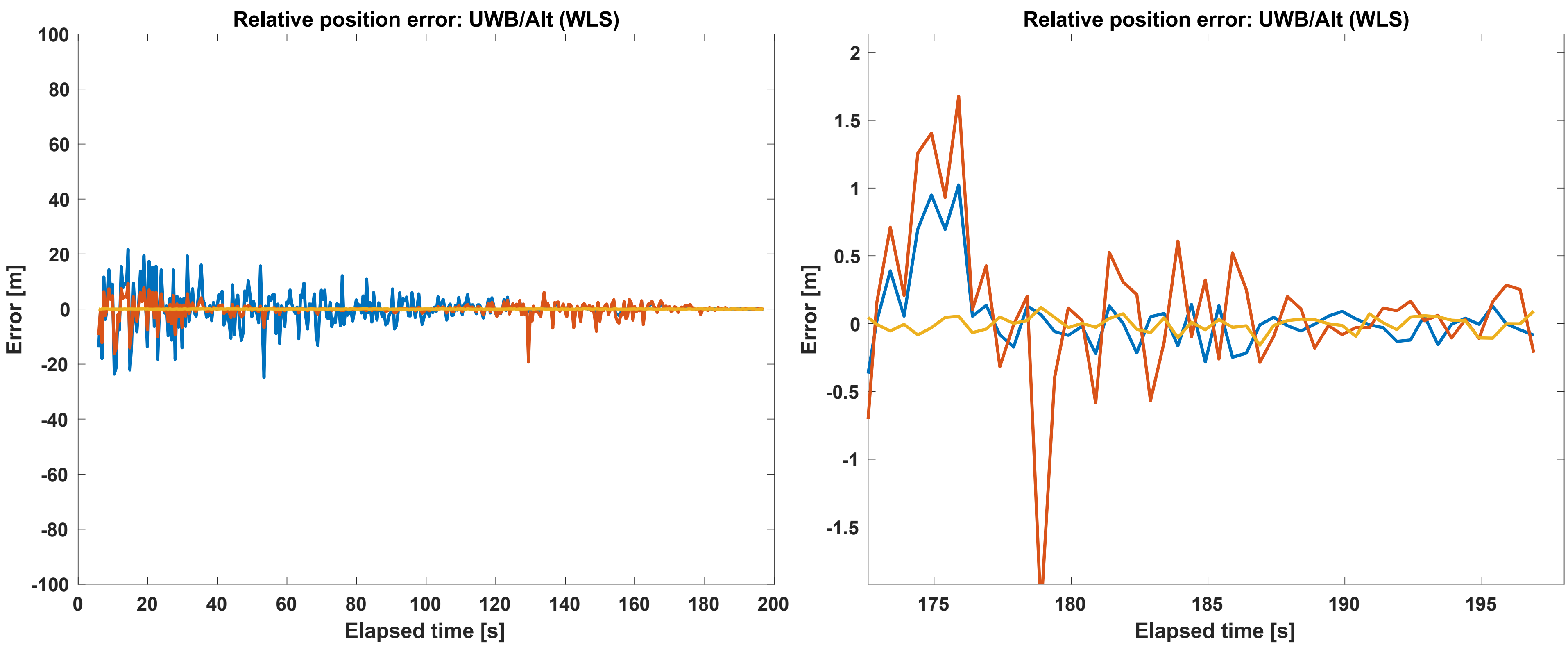
RR/Altimeter Integration



Currently work is being done on integration with inertial!

Summary and Conclusions

- Review of relative navigation approaches between a UAV and a moving UGV supporting the final approach and lading phases of the flight.
- General approach to address the problem and that allows for several methods to be incorporated.
- Introduction of a RR-based and RR/altimeter-based solution.
- Simulation results were shown to illustrate what accuracies can be achieved by some of the discussed approaches.
- RR-based methods can be used for this application but do require augmentation to obtain dm-level accuracies during the final 10m.
- Next: finalize the research setup and evaluate some of the approaches using actual data

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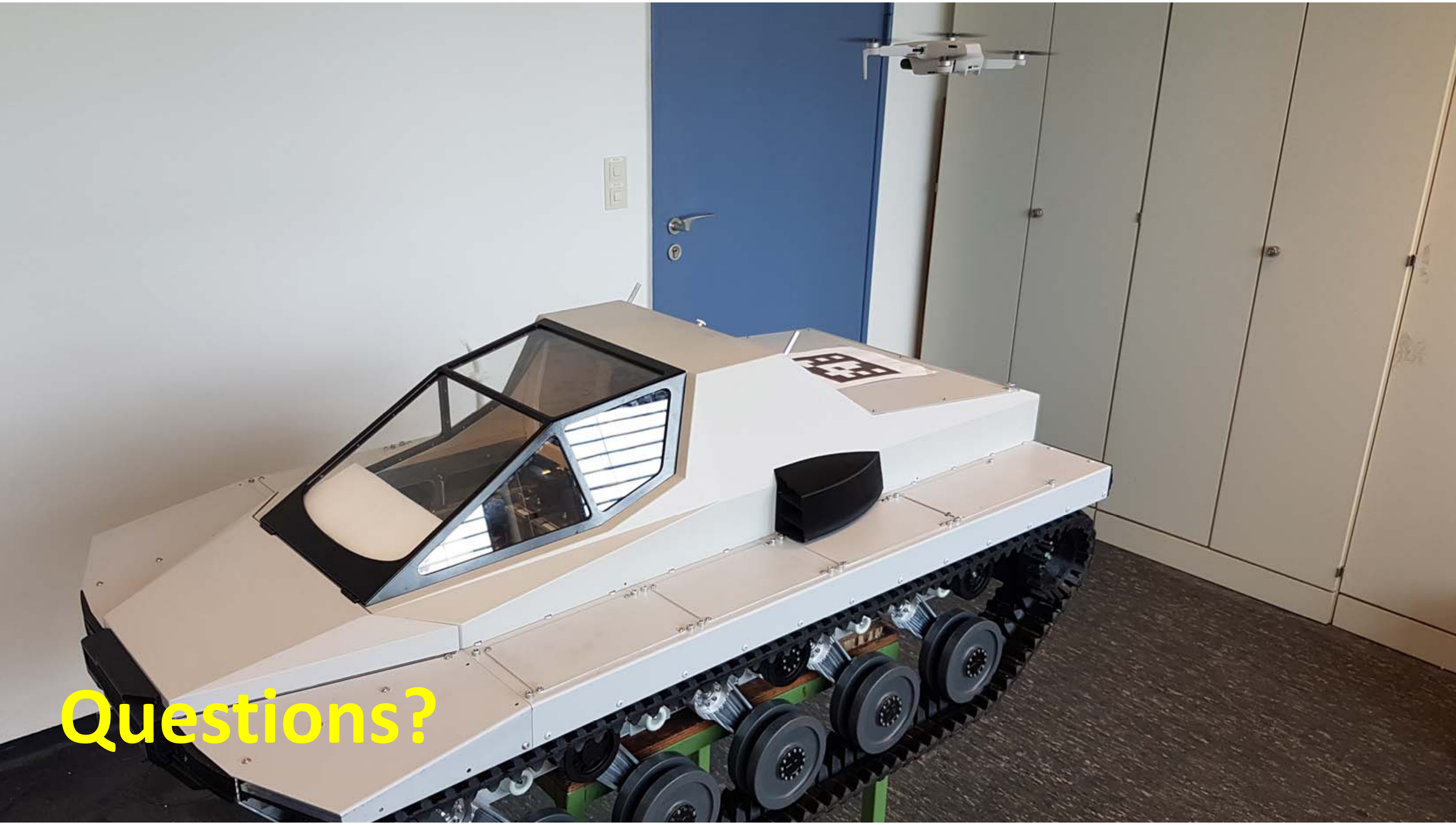
Questions?