Wireless Local Positioning of Straddle Carriers, Mobile Robots, and UAVs for Tracking and Autonomous Navigation

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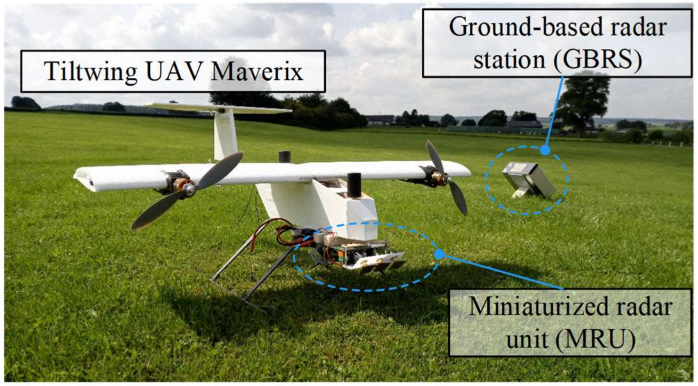
Outline

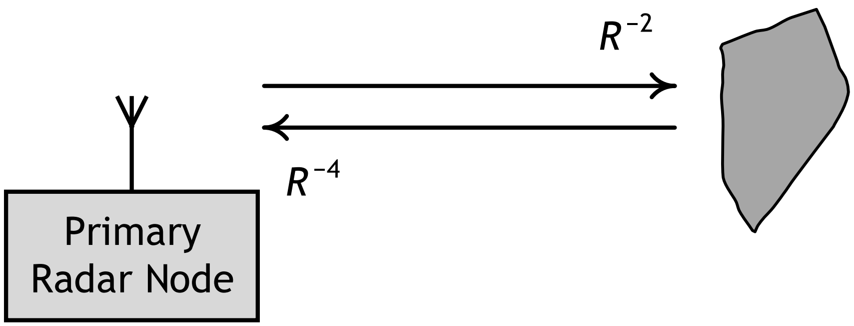
1. **Motivation & Secondary Radar**
2. Established Application: Wireless Local Positioning System (WLPS) for Container Terminal Logistics
3. New Approach: RTOF + DOA
   1. 6 DoF WLPS for Space Exploration and Terrestrial Applications
   2. 2D WLPS for Healthcare Service Robotics
   3. 3D WLPS with Minimum Infrastructure for UAVs
4. Conclusion & Outlook

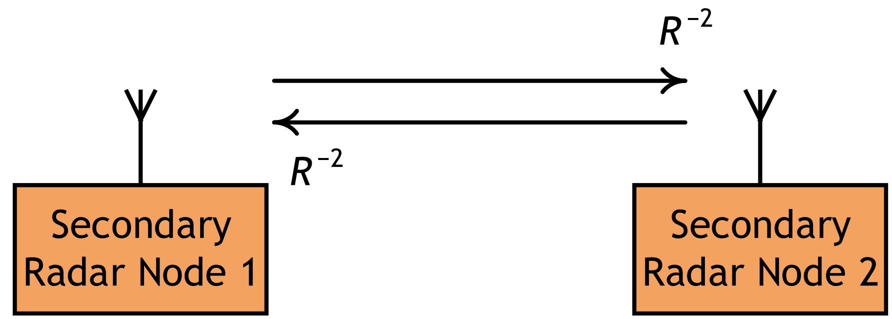
Motivation

- Autonomous vehicles to grow in importance
  - Offer lower cost and higher reliability than human labor
  - Self-driving cars in complex and dynamic environments such as urban areas still a challenge
  - Autonomous vehicles on the rise in simpler scenarios in logistics, manufacturing, and service sectors
  - **Localization crucial for navigation**
- Localization technology
  - State of the art: GNSS (GPS / RTK) → global, but not available near buildings, under cranes, indoors, …
  - **Wireless local positioning to complement GNSS and enable coverage in difficult situations**



Primary and Secondary Radar





Primary radar

- Detects passive targets
- Rx power dependent on RCS and range with R^{-4}
- Target ID difficult
- No synchronization necessary

→ **Imaging applications**

Secondary radar

- Active target
- Rx power dependent on relative orientation and range with R^{-2}
- Target ID known
- Sync challenging

→ **Positioning applications**

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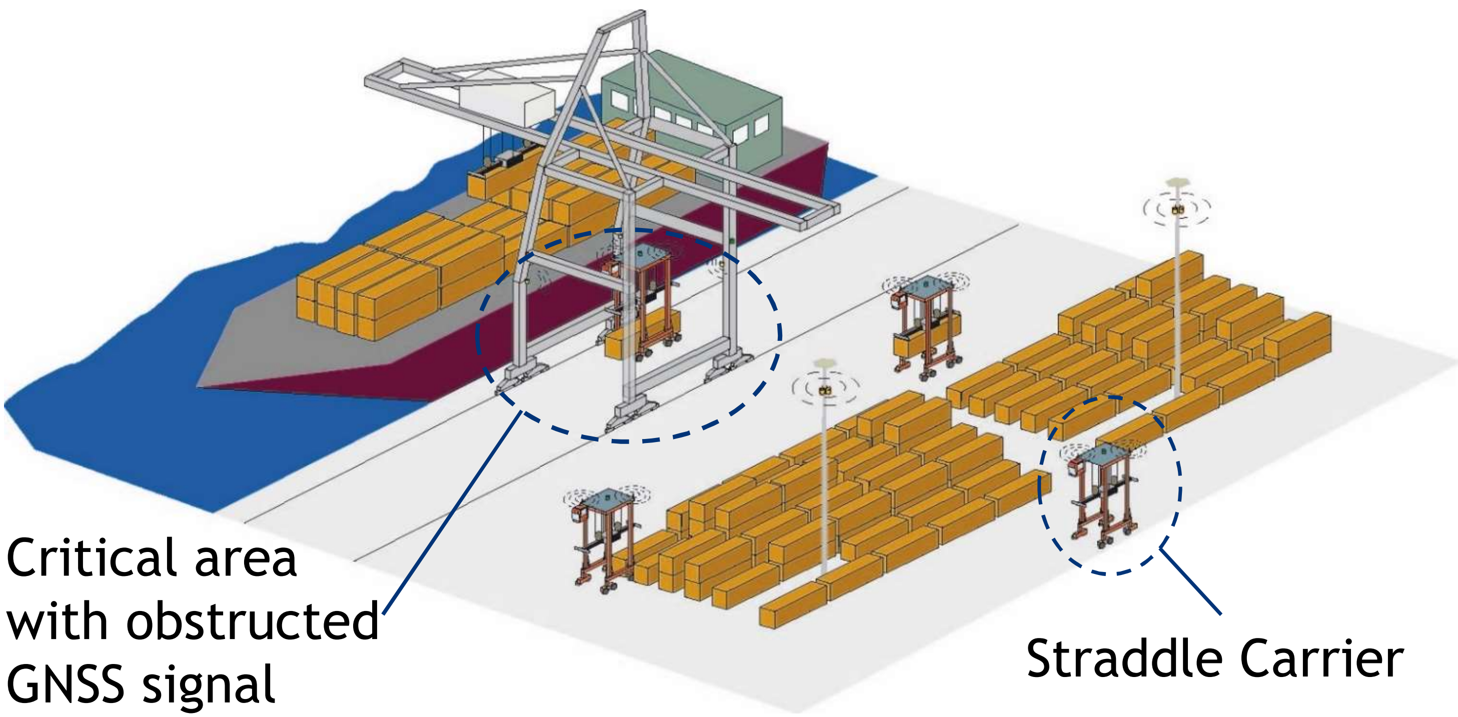
Container Terminal Logistics Hamburger Hafen und Logistik AG (HHLA) terminal in Hamburg, Germany

- Maritime logistics depends on efficient container handling
- Localization important for container tracking, route optimization, collision avoidance, **automation**

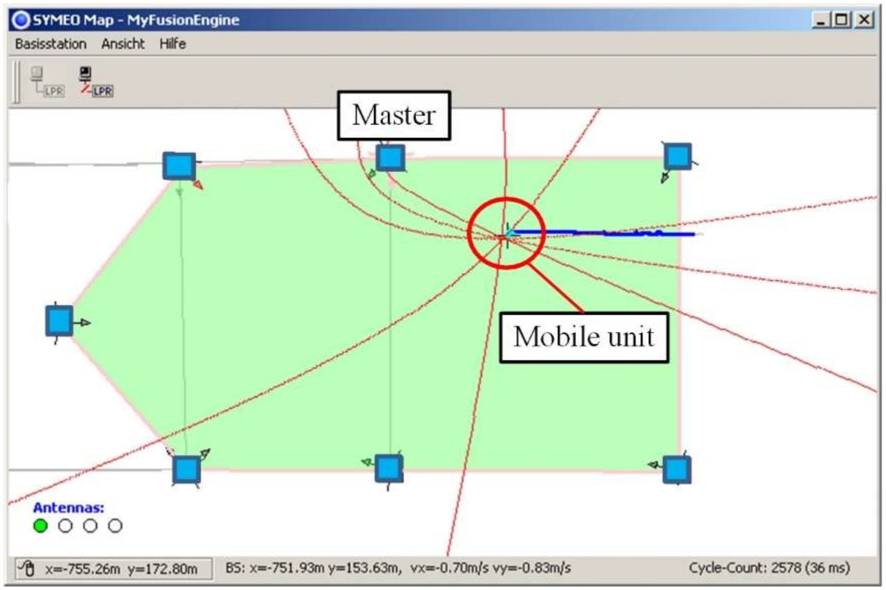
- Cranes block and disturb GNSS signals

→ Wireless local positioning system (WLPS) used additionally

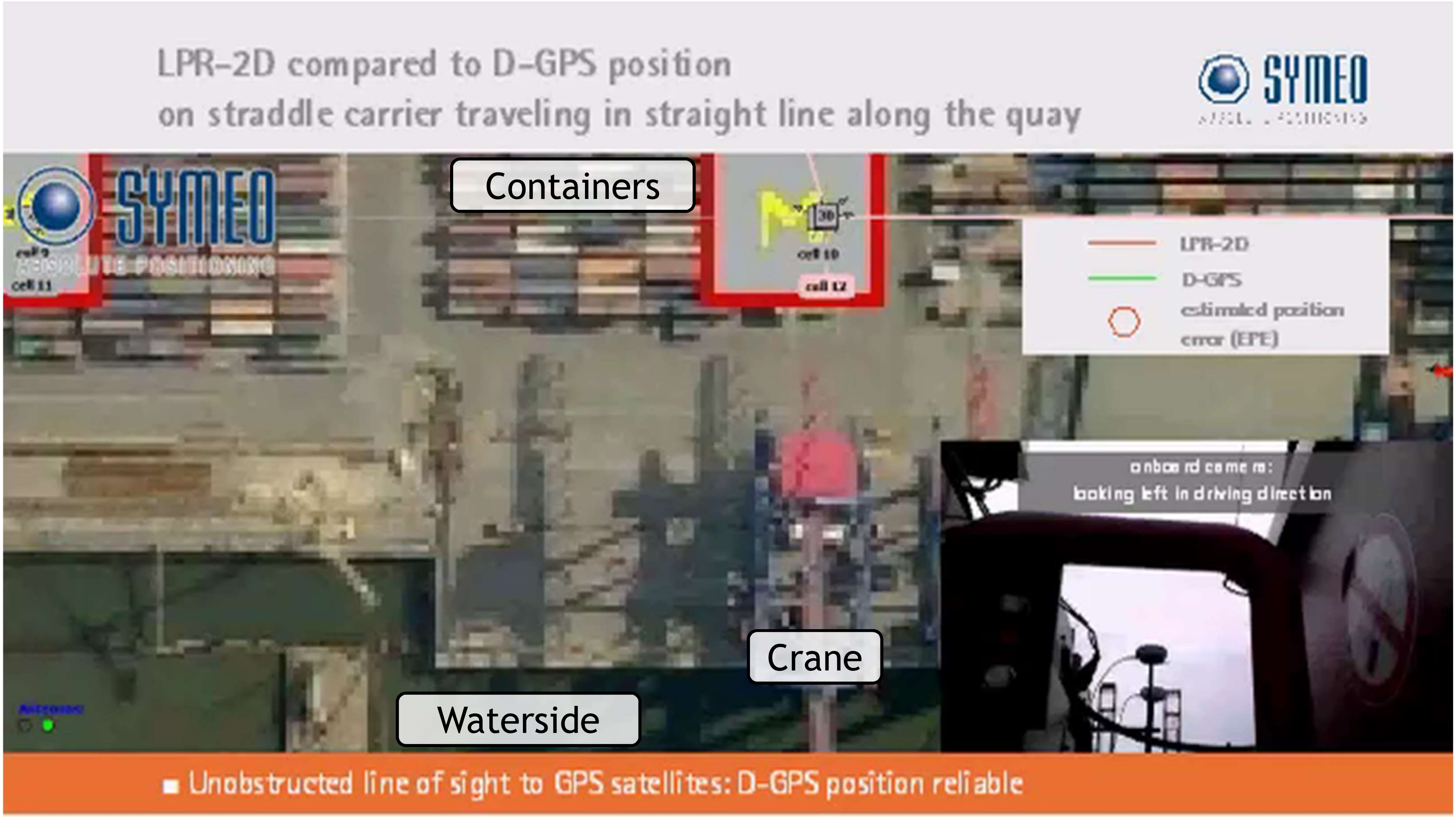


Terminal Logistics WLPS

- Based on 5.8 GHz FMCW secondary radar with 100 MHz bandwidth
- 5-6 anchor nodes precisely synchronize wirelessly
- Anchor nodes periodically transmit
- Mobile nodes receive signals and compute position using inverse TDOA (ITDOA), similar to GPS using TOA
  → **Arbitrary number of mobile nodes**

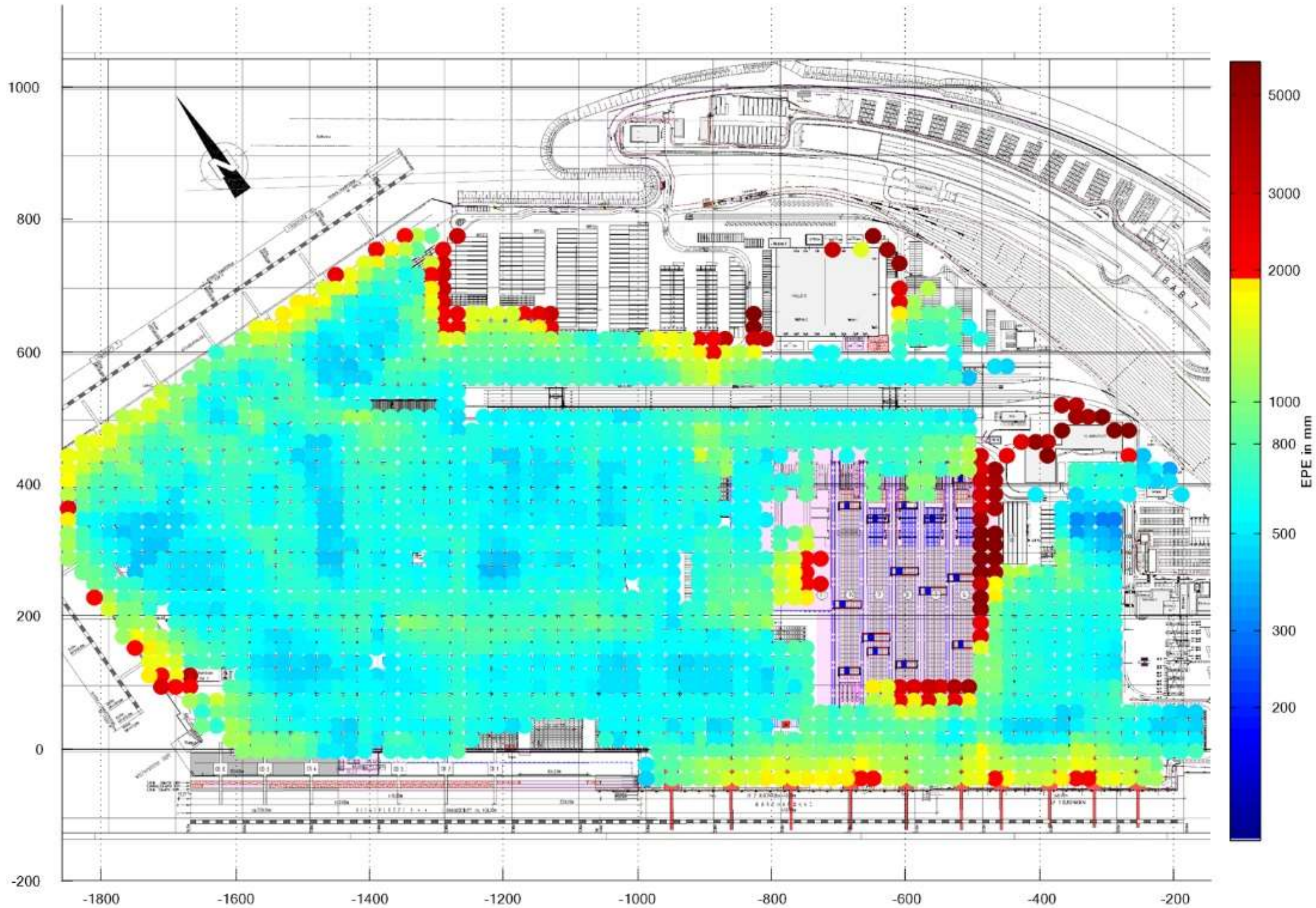


WLPS at Hamburg Terminal



Results at Hamburg Terminal

- Coverage: 73.6 % with GNSS vs. 99.4 % with WLPS
- Estimated Positioning Error (EPE) mostly < 60 cm (95 %)



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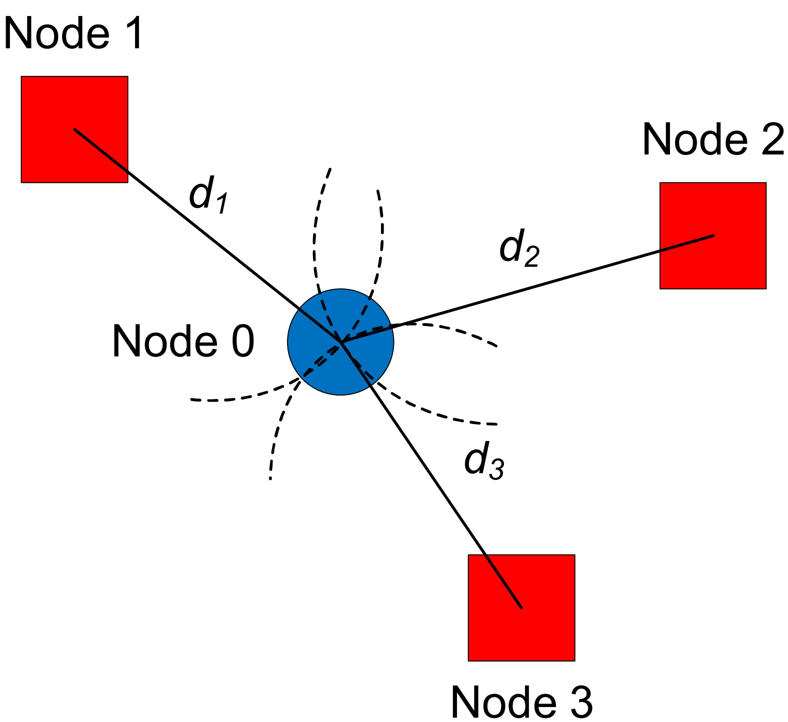
Multilateration vs. RTOF+DOA

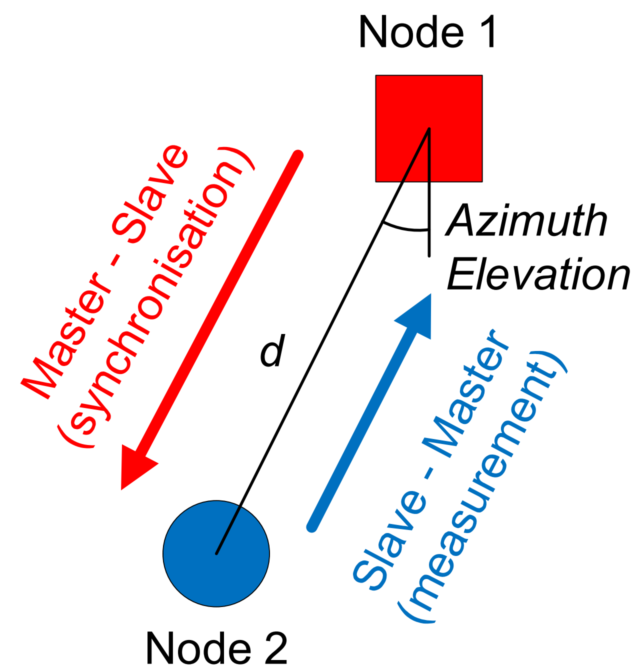
Multilateration / multiangulation
(TDOA, TOA, RTOF / DOA)

- Complex infrastructure
- Low reliability

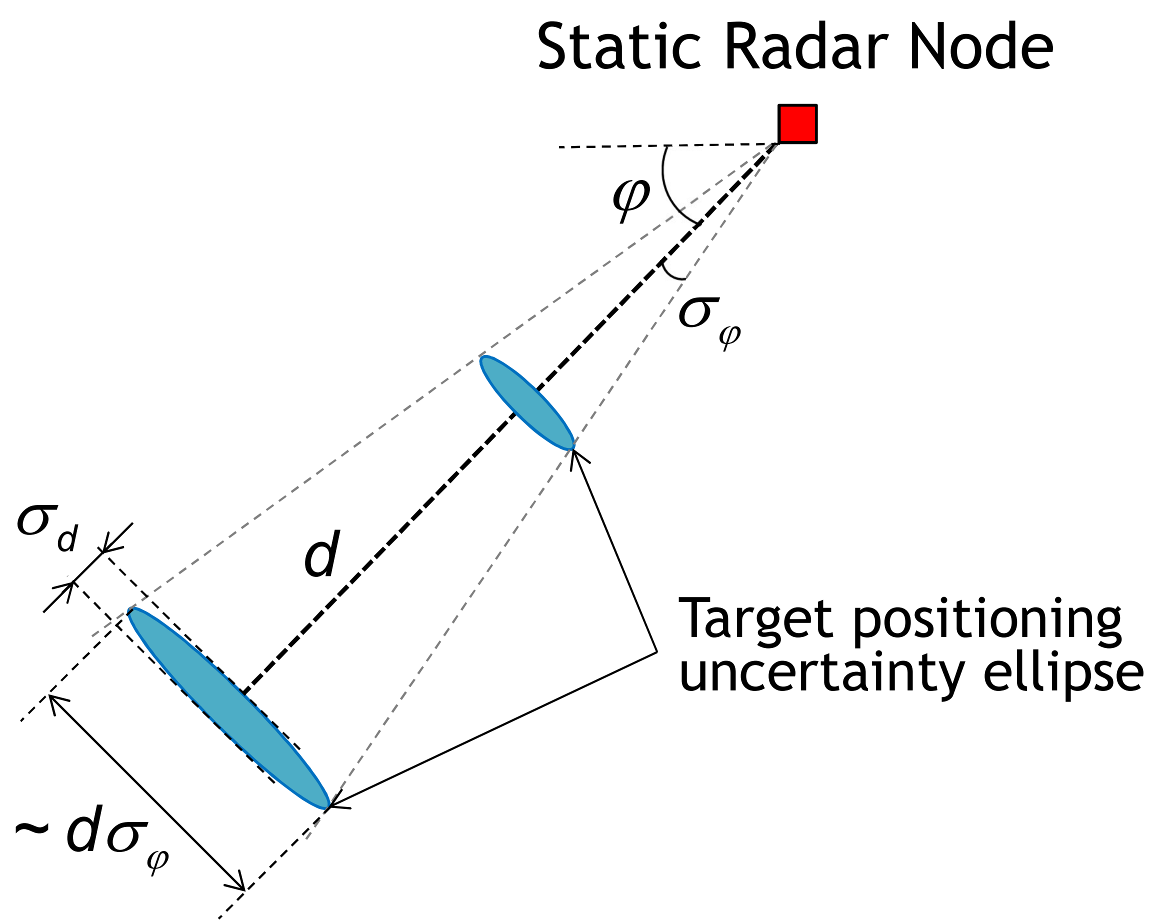


Proposed solution
(bilateral RTOF + 2D DOA)

- Minimum infrastructure
- High reliability
- Orientation estimation



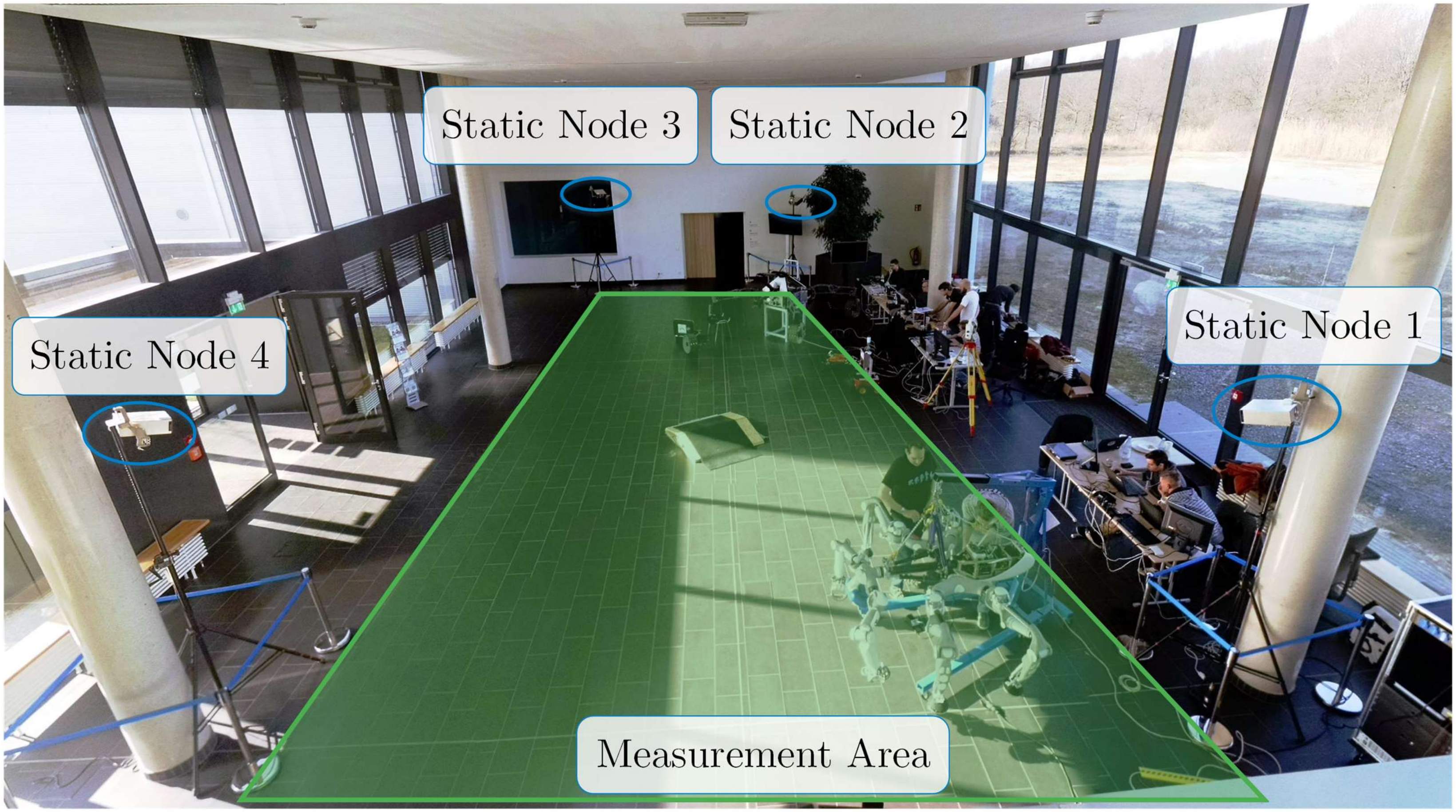
RTOF + DOA Position Estimation Accuracy



→ Cross-range error increases with range

Test Scenario

4 static nodes measuring RTOF + DOA to a mobile node



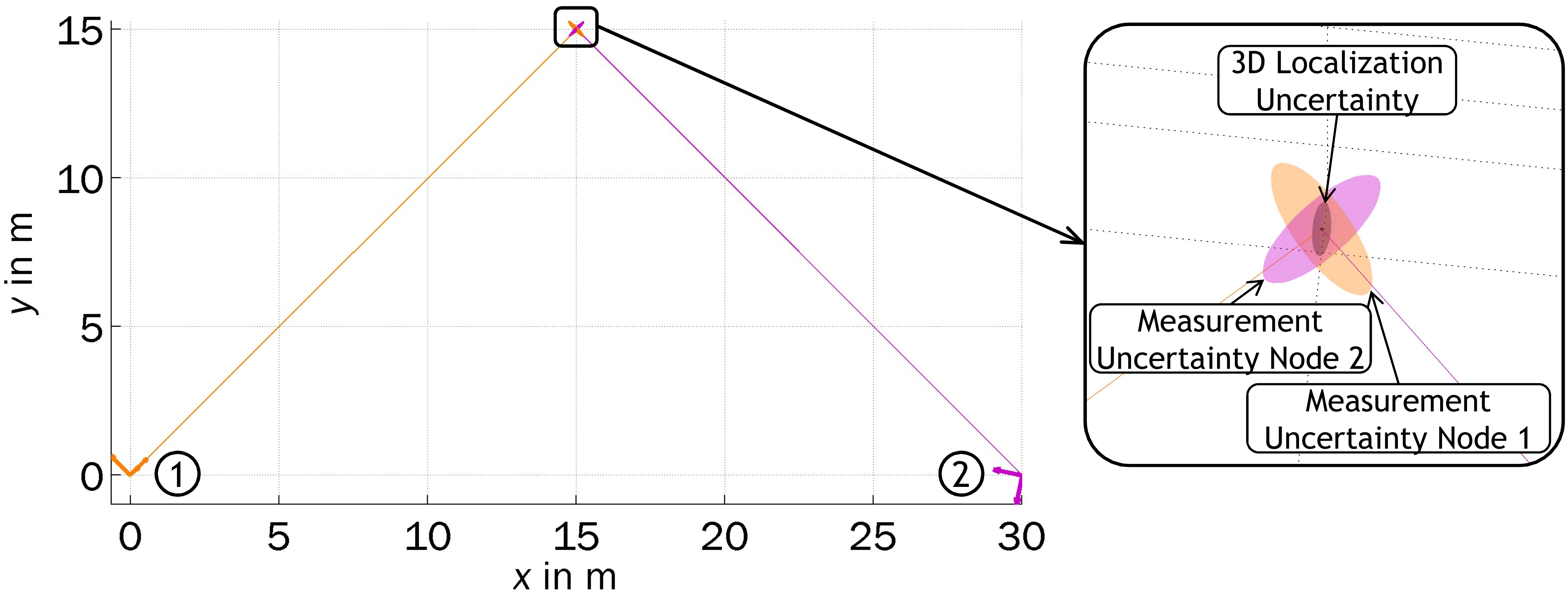
Measurements in Entrance Hall in DFKI Building, Bremen

RTOF+DOA: Optimizing Node Placement

- Achievable accuracy depends on target and node positions

→ **Optimal: Intersections geometrically orthogonal**

→ **Kalman filter attains CRLB**



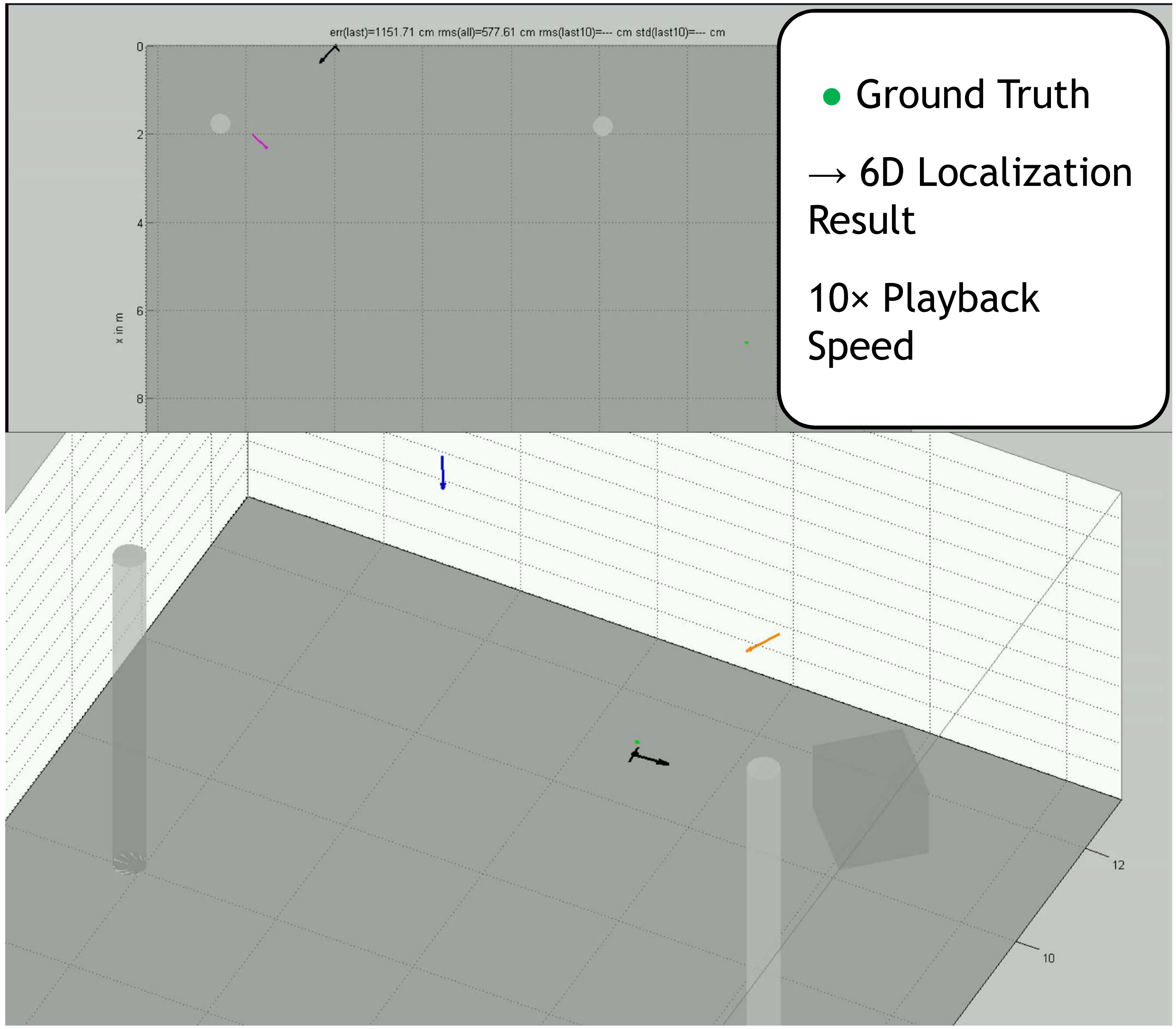
EKF-Based Mobile Robot Localization with Secondary Radar

- 24 GHz FMCW radar, 8 Rx channels
- Achieved accuracy: 12 cm (95 %)
- Applications
  - Space exploration (Rover)
  - Warehouse (Forklift)
  - Logistics (Straddle carrier)

→ Simultaneous 3D position and 3D orientation

Developed as part of the project TransTerrA funded by the German Aerospace Center (DLR)

Measurement campaign in collaboration with Robotics Innovation Center DFKI Bremen



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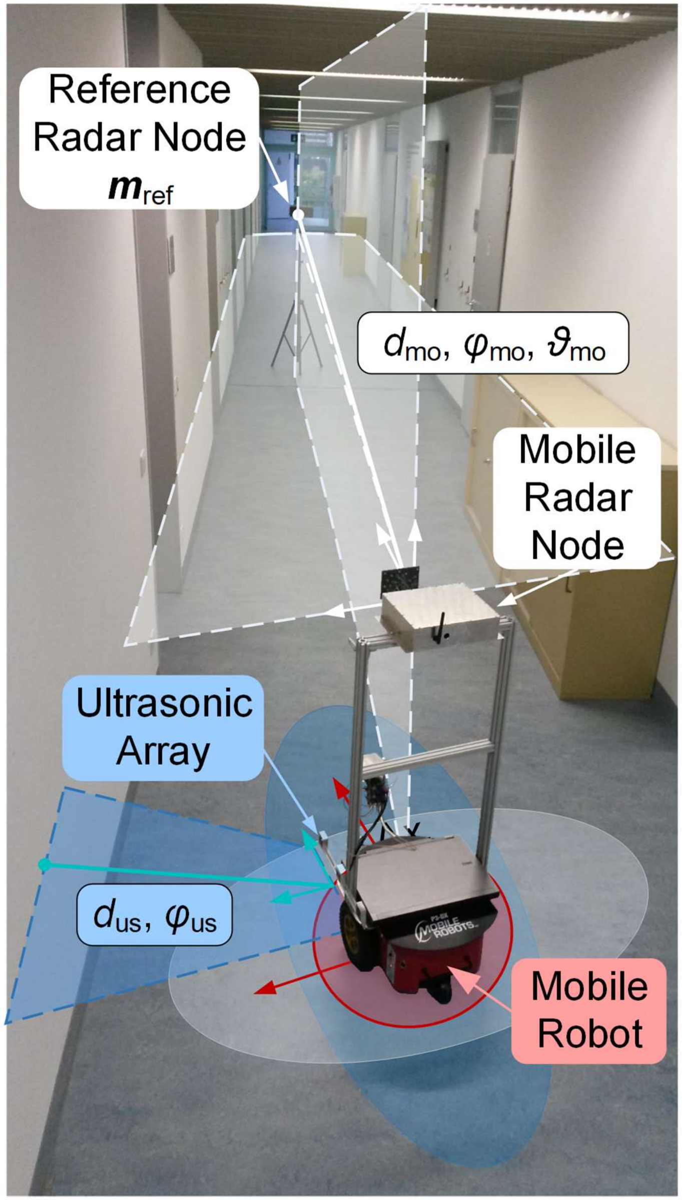
WLPS for Healthcare Service Robotics

- Population aging → Strong demand for hospital workers
- Nursing staff spend much time for transportation tasks

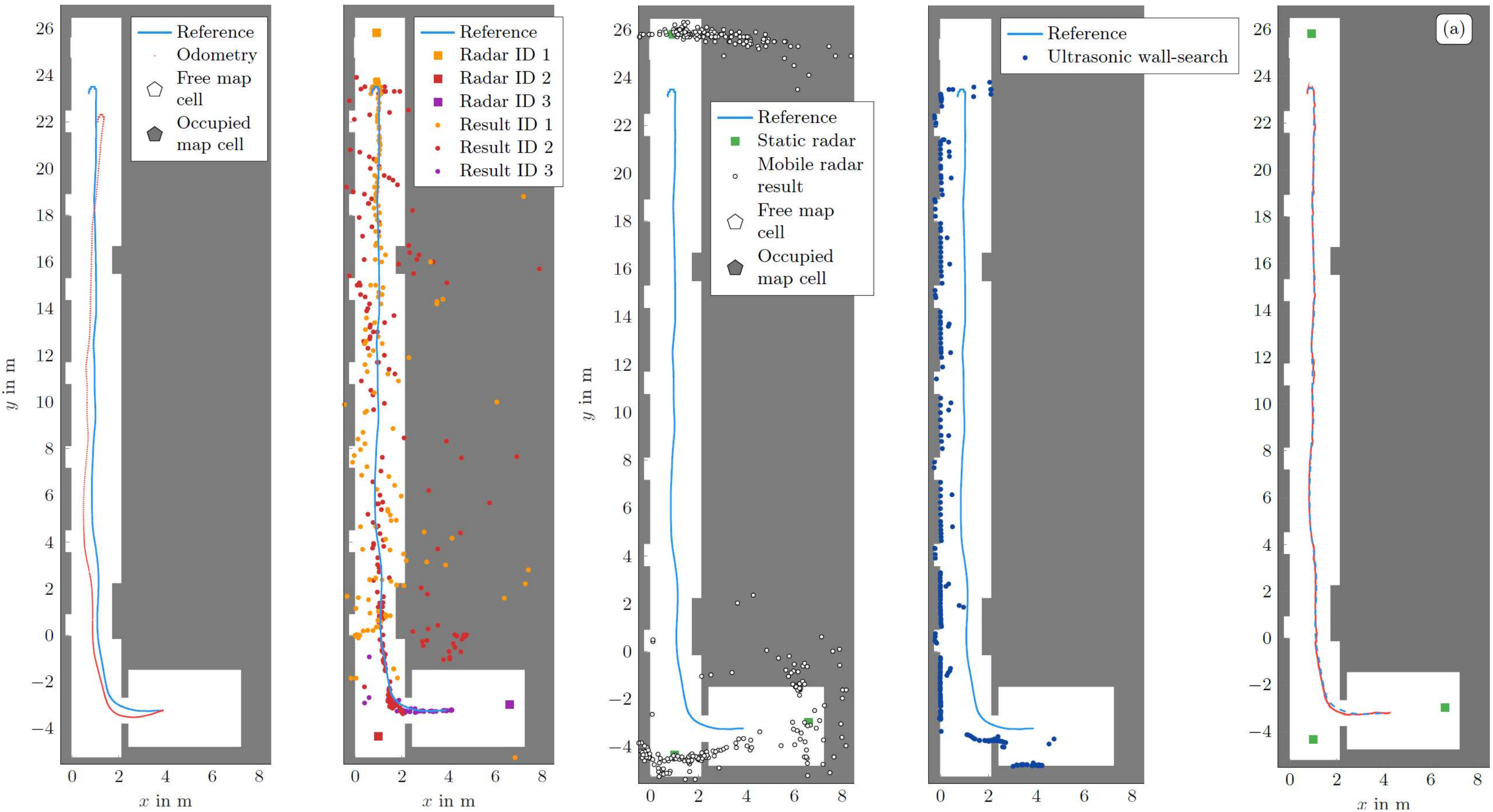
→ **Develop an autonomous service robot system to relieve nursing staff**

Indoor WLPS for Hospitals

- Indoor environment challenges
  - no GPS
  - Cluttered rooms and long narrow corridors → numerous multipath reflections
  - Small spaces → high accuracy requirements
- Approach: Multi-modal sensor fusion (EKF)
  - Secondary radar
  - Ultrasonic wall-detection system
  - Odometry



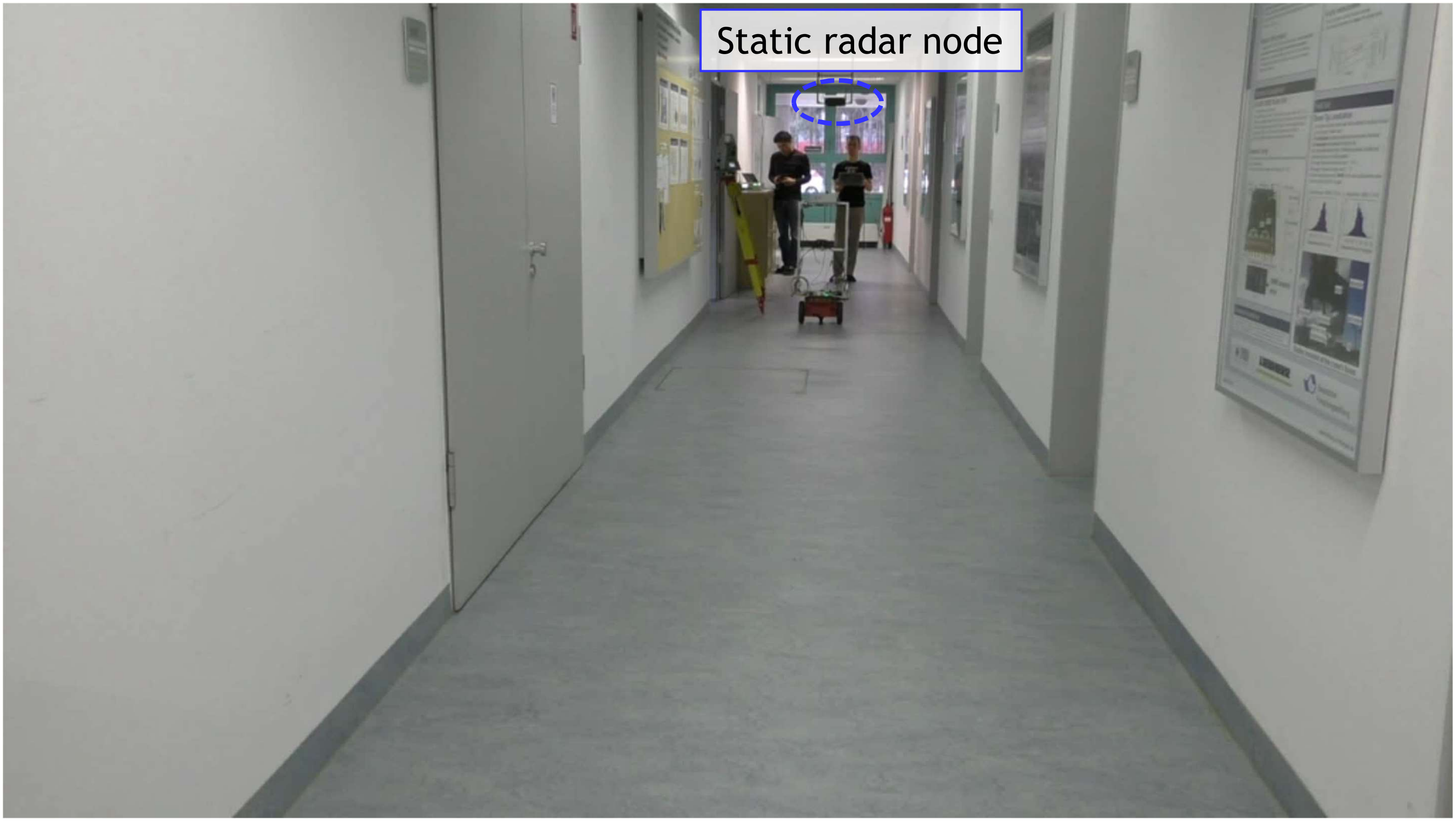
Sensor Measurement Results in Indoor Environment



Odometry | Static Radar | Mobile Radar | Ultrasound | Sensor Fusion

Localization Results

- Localization result (robot)
- Reference (total station)
- Person
- Static radar node
- Corridor walls / doors / cabinets



Developed as part of the project iserveU funded by the Federal Ministry of Education and Research of Germany (BMBF)

Tests in Katharinenhospital, Stuttgart, Germany

- Test in realistic scenarios
- Achieved 2D position accuracy of 10 cm
- Demonstrated stability
- Performance comparable to laser scanner

→ **Indoor radar localization feasible**

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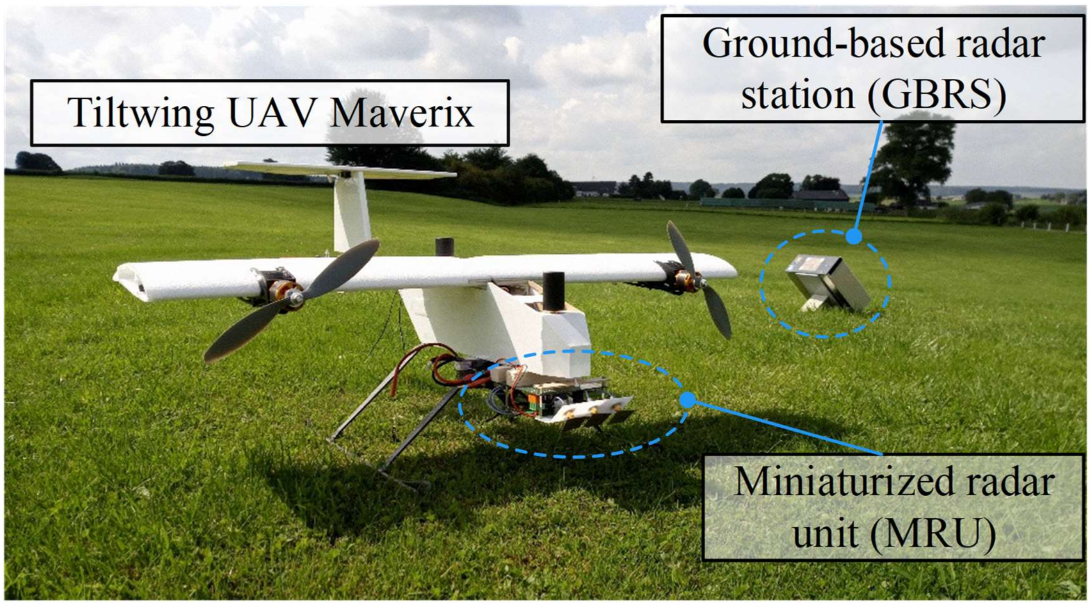
UAV 3D Localization

- Applications: Parcel delivery, surveillance, automated warehouse inventory, etc.
- Main Challenges: Reliability, safety, GNSS jamming
- Takeoff / landing most critical flight phase

  → **Robust localization crucial**



UAV 3D Localization

Measurement campaign in cooperation with Yavor Dobrev, Institute of Flight System Dynamics (FSD), RWTH Aachen

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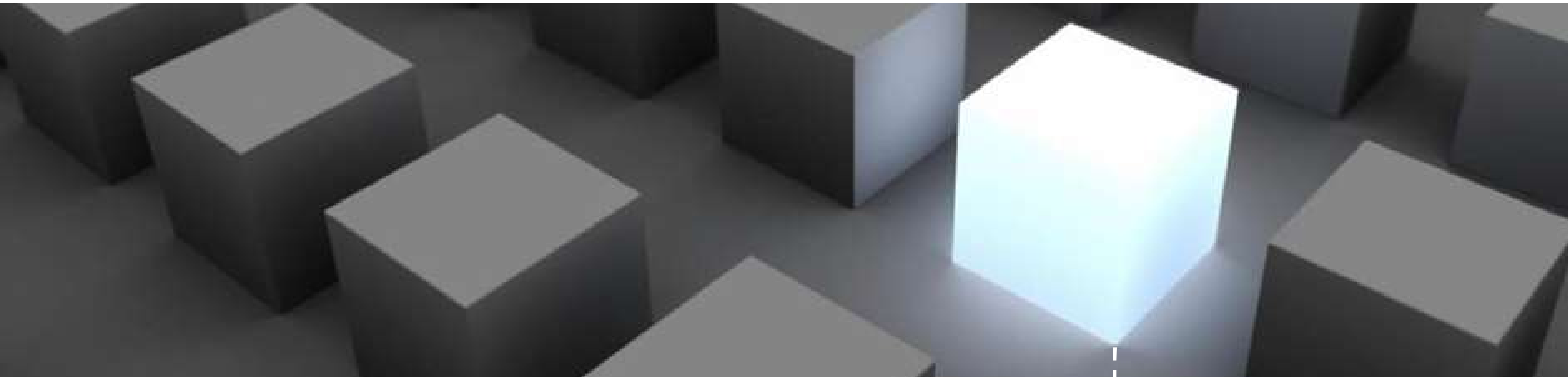
Conclusion and Outlook

- Conclusion
  - **Autonomously operating devices** such as mobile service robots, straddle carriers, forklifts, UAVs with huge growth potential
  - **Wireless local positioning** enables robust and accurate localization in indoor and challenging outdoor scenarios
  - **Range and angle measurements** with secondary radar enable positioning with **minimum infrastructure**
- Outlook: 77 GHz highly integrated automotive radar chips provide higher bandwidth, more channels, miniaturization, hybrid primary / secondary operation

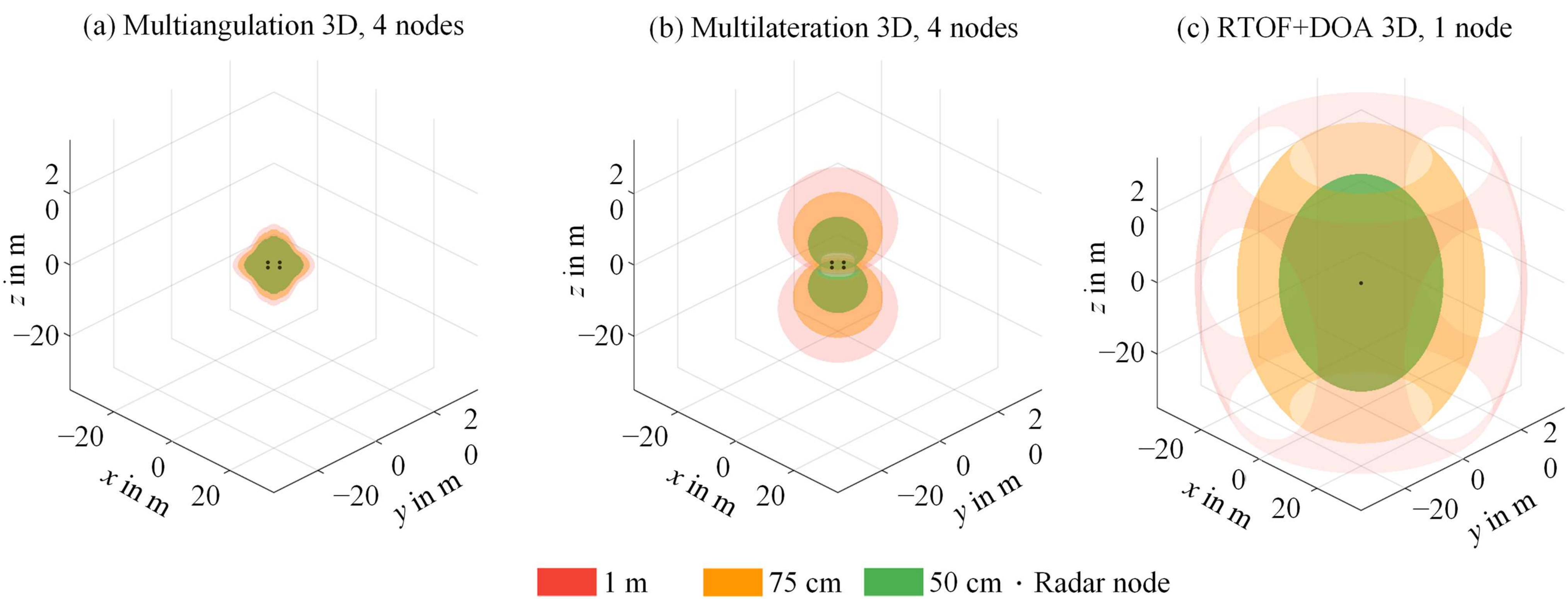
Thank you for your attention! 🙏

SYMEO
ABSOLUTE POSITIONING



Backup Slides

CRLB Multiangulation vs. Multilateration vs. RTOF+DOA

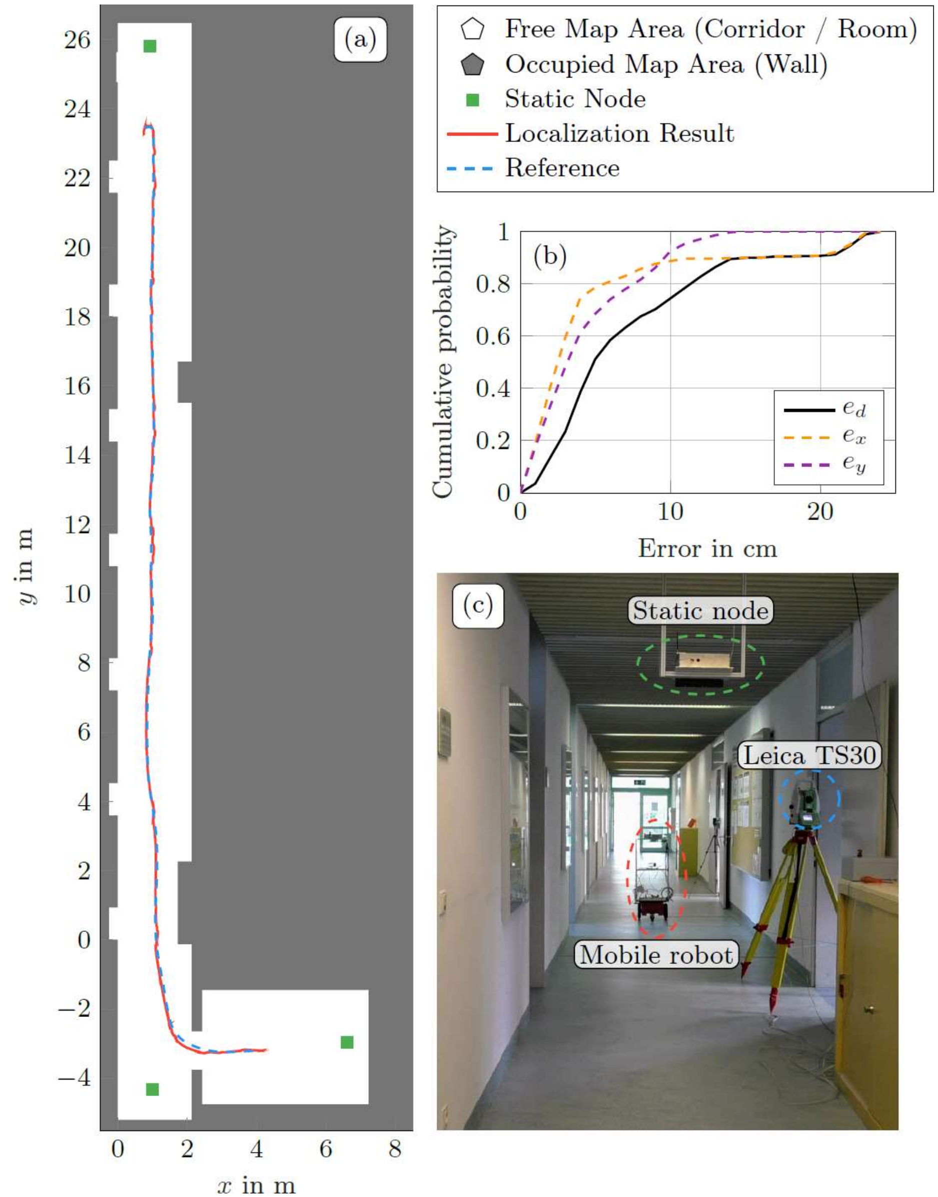


- RTOF+DOA: Only a single radar node sufficient
- Provides reliable coverage of a larger volume
- Orientation estimation possible

Sensor Fusion – Results

- Angle estimation severely disturbed in corridor
- Ultrasonic wall-detection system helps in cross-range
- Odometry useful when other sensors disturbed
- Achieved 2D position accuracy of 10 cm

→ Localization sufficiently robust and accurate for navigation



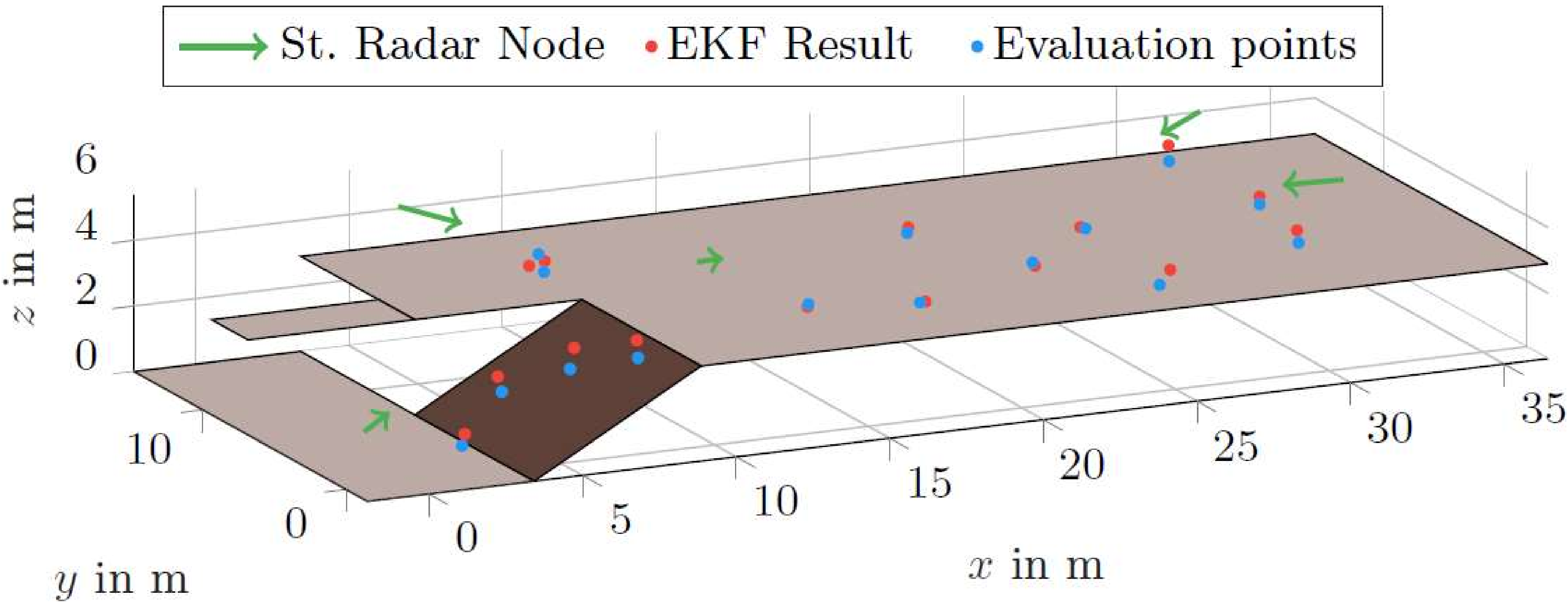
Microsoft Indoor Localization Competition 2016

- Annual event
- 31 contestants in 2016 (18 in 3D and 13 in 2D category)

Evaluation area in the Dachfoyer hall of the Hofburg building (former imperial palace) in Vienna, Austria

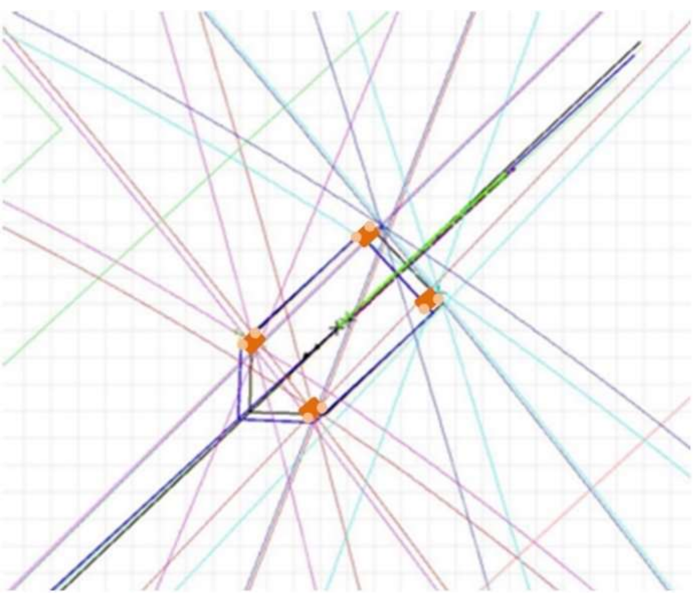
Microsoft Indoor Localization Competition 2016 – Results

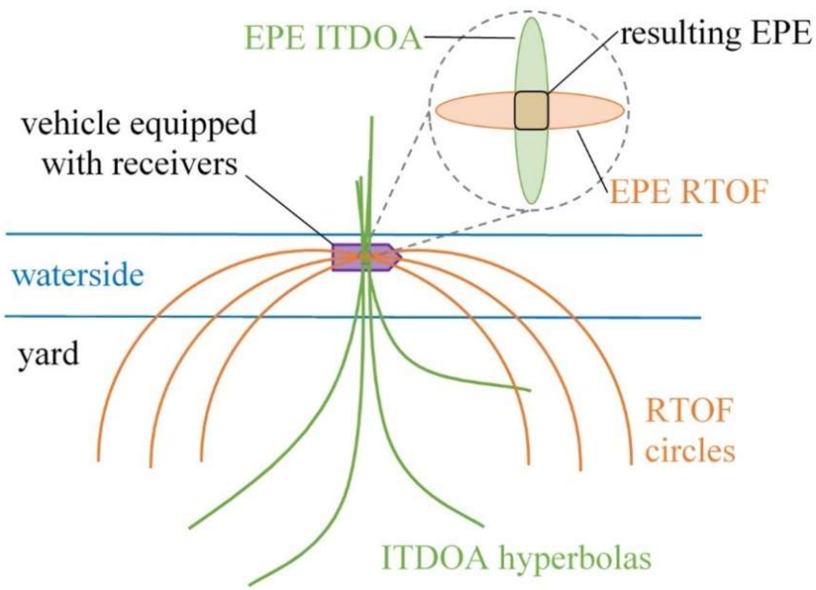
- Mean absolute error 37 cm → 4th place
- **Almost all other systems used UWB and multilateration with much larger bandwidth!**



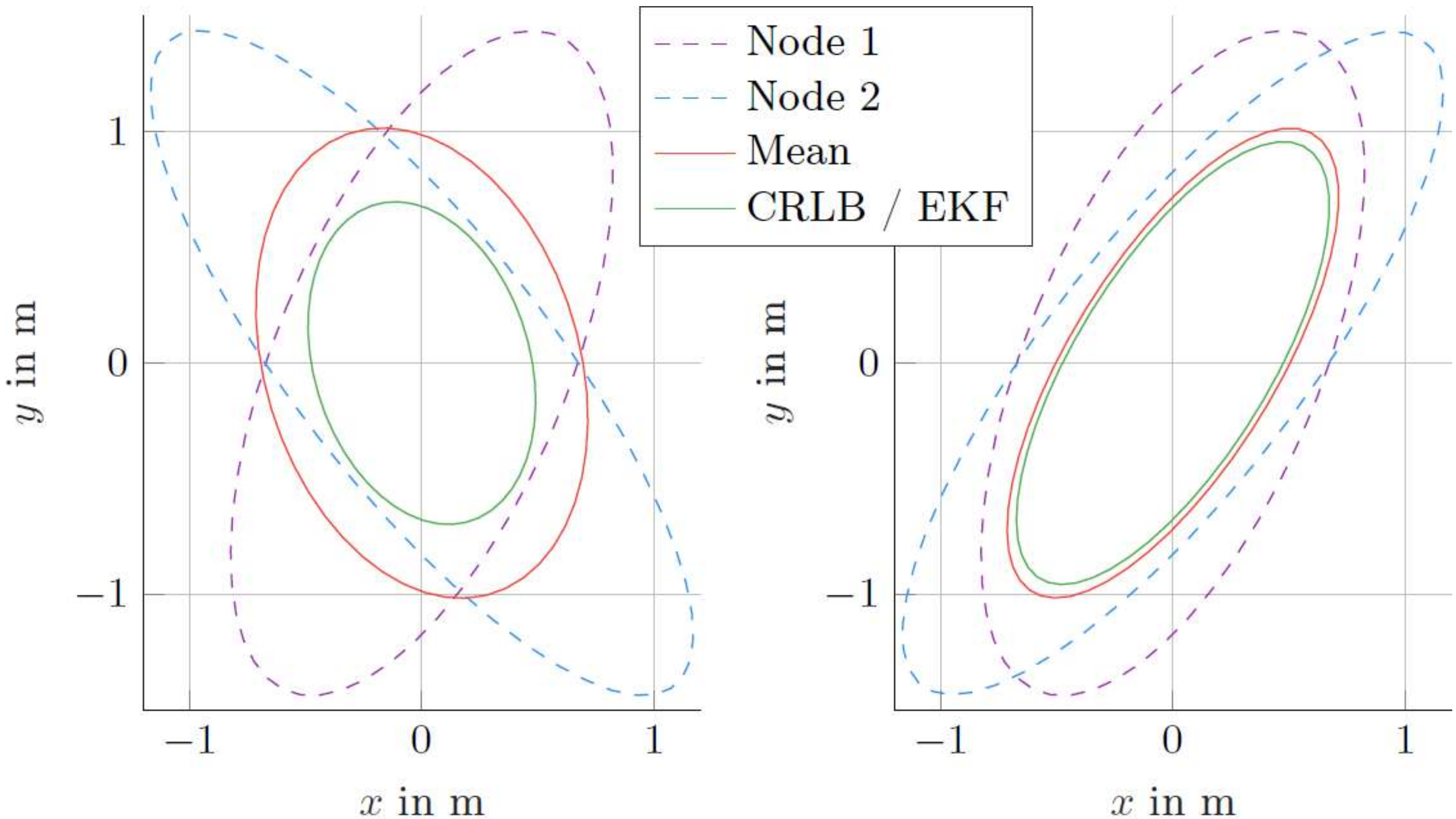
Terminal Logistics WLPS

- Each vehicle equipped with 4 radar nodes with 2 antennas for diversity
- Sensor fusion with IMU and odometry
- Combination of ITDOA and RTOF to improve DOP in areas under cranes → 95 % of errors < 9 cm
- **Outlook: Automation requires 95 % of errors < 5 cm**





RTOF+DOA
Best / Worst Node Placement



(a) Good PDOP (b) Bad PDOP

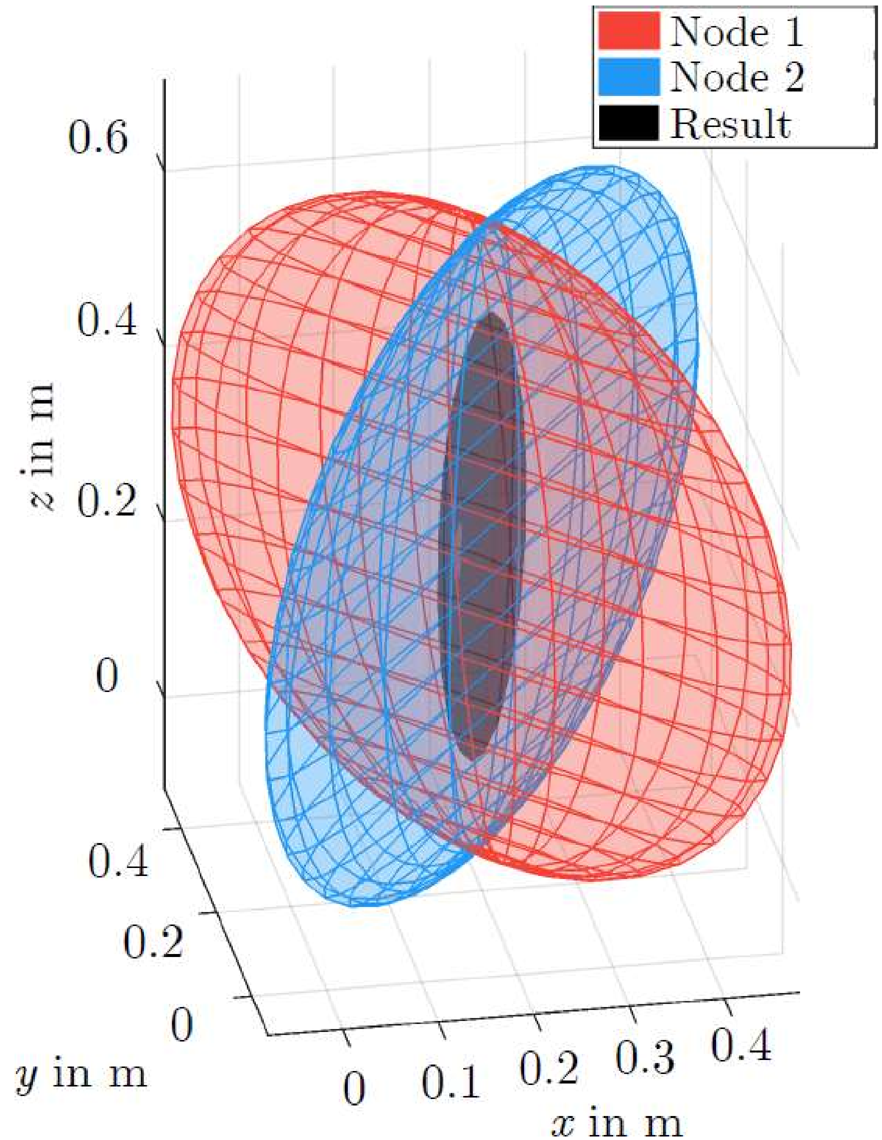
Geometrically orthogonal

Geometrically parallel

RTOF+DOA
Resulting Covariance in 3D

- CRLB for 3D can be derived analogously
- When nodes arranged in plane, worse PDOP in z
- Arithmetic mean does not attain CRLB
- Kalman Filter attains CRLB

→ **Use EKF to fuse radar measurements for 3D position estimation**



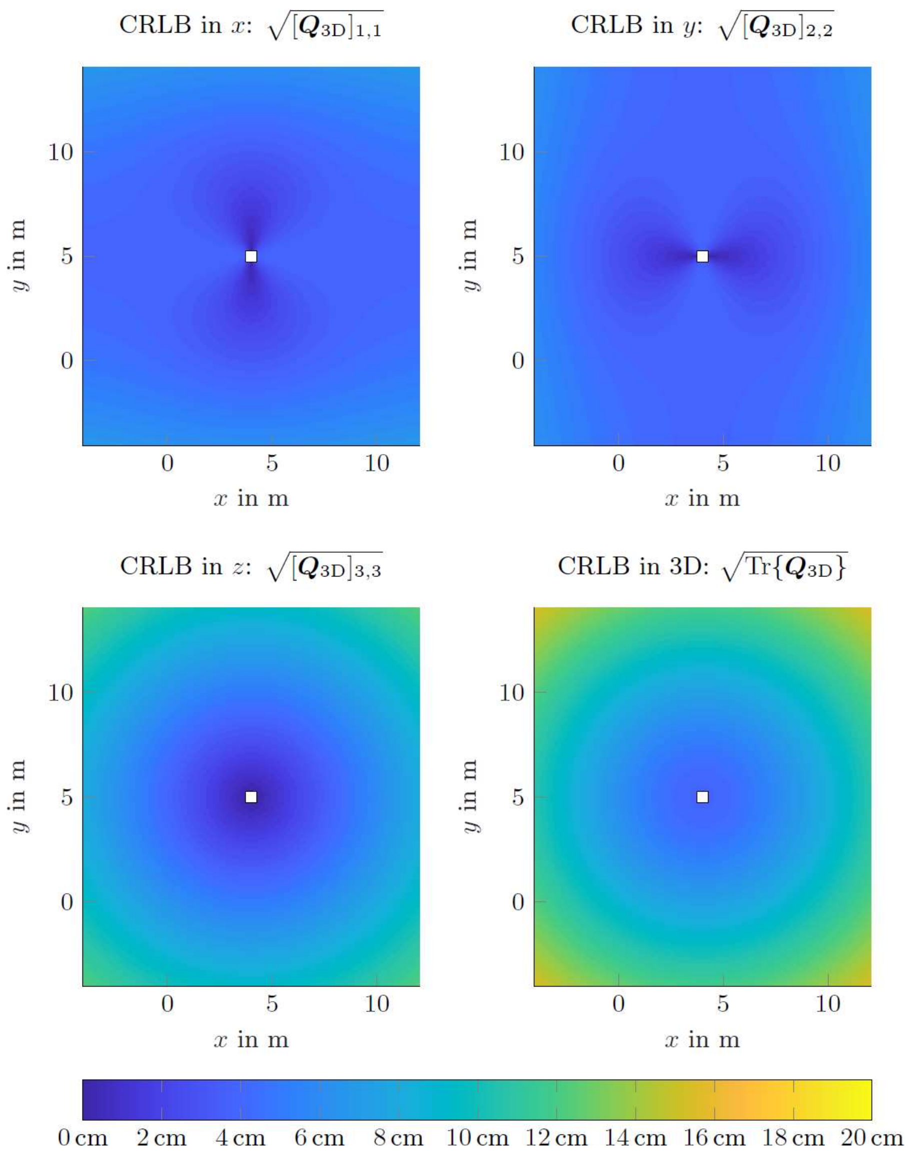
Single Node RTOF+DOA CRLB

- Measure distance d and angles φ, ϑ
- Determine 3D position covariance $\Sigma_{ad,3D}$ from measurement covariance $\boldsymbol{Q}$

$$\sigma_d = 8\text{ cm}$$

$$\sigma_\varphi = 0.8°, \sigma_\vartheta = 1.2°$$

→ **3D localization with one node possible**



Multilateration CRLB

- Measure distance d_n between node position $\boldsymbol{p}_{s,n}$ and target position $\boldsymbol{p}_t$

$$\boldsymbol{p}_{s,n} = \begin{bmatrix} x_n & y_n & z_n \end{bmatrix}^T, \boldsymbol{p}_t = \begin{bmatrix} x & y & z \end{bmatrix}^T$$

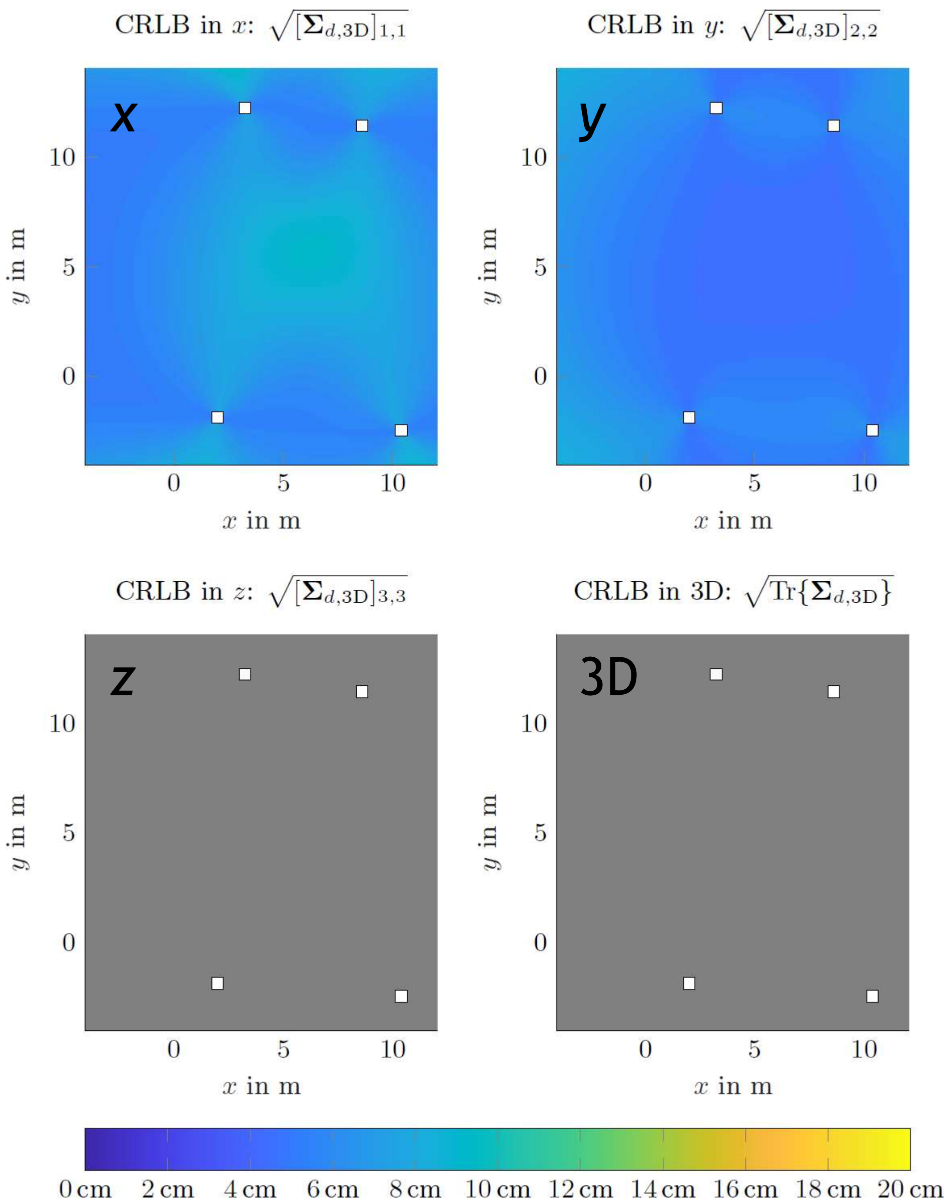
$$d_n = \sqrt{(x-x_n)^2 + (y-y_n)^2 + (z-z_n)^2}$$

- Determine 3D position covariance $\boldsymbol{\Sigma}_{d,3D}$ from measurement covariance $\boldsymbol{Q}$

$$\boldsymbol{G}(\boldsymbol{p}_{s,n}, \boldsymbol{p}_t) = \frac{\partial \boldsymbol{d}}{\partial \boldsymbol{p}_t}, \boldsymbol{Q} = \sigma_d{}^2 \boldsymbol{I}$$

$$\boldsymbol{\Sigma}_{d,3D} = (\boldsymbol{G}^T \boldsymbol{Q}^{-1} \boldsymbol{G})^{-1}, \sigma_d = 8 \text{ cm}$$

→ No 3D



Multiangulation CRLB

- Measure angles φ_n, ϑ_n between node and target

$$\varphi_n = \mathrm{atan2}(y - y_n, x - x_n)$$

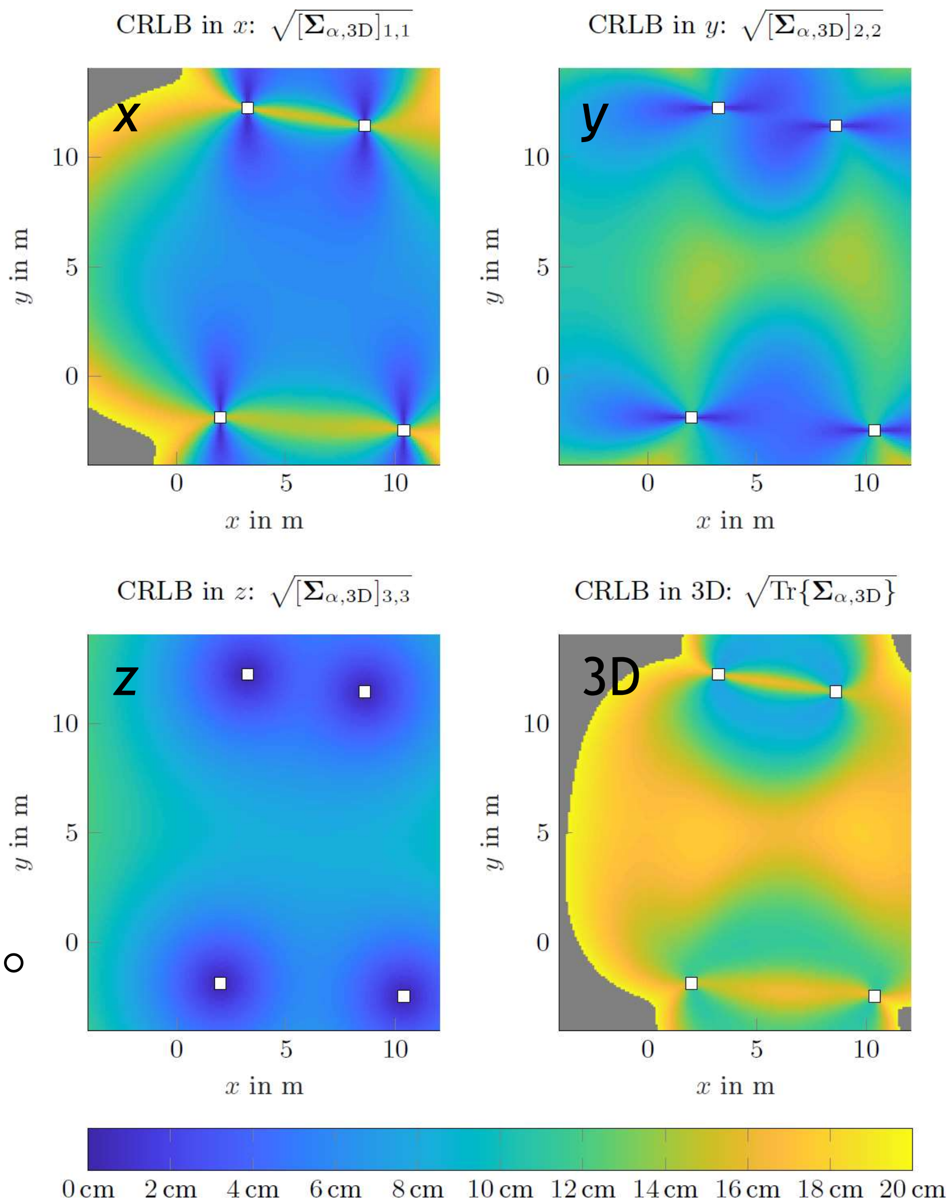
$$\vartheta_n = \mathrm{asin}\left((z - z_n)/d_n\right)$$

- Determine 3D position covariance $\mathbf{\Sigma}_{\alpha,\mathrm{3D}}$ from measurement covariance $\boldsymbol{Q}$

$$\boldsymbol{G}(\boldsymbol{p}_{\mathrm{s},n}, \boldsymbol{p}_{\mathrm{t}}) = \frac{\partial \boldsymbol{\alpha}}{\partial \boldsymbol{p}_{\mathrm{t}}}, \boldsymbol{Q}_n = \begin{bmatrix} \sigma_\varphi^2 \boldsymbol{I} & \mathbf{0} \\ \mathbf{0} & \sigma_\vartheta^2 \boldsymbol{I} \end{bmatrix}$$

$$\mathbf{\Sigma}_{\alpha,\mathrm{3D}} = (\boldsymbol{G}^{\mathrm{T}} \boldsymbol{Q}^{-1} \boldsymbol{G})^{-1}, \sigma_\varphi = 0.8°, \sigma_\vartheta = 1.2°$$

→ **Areas with large PDOP**



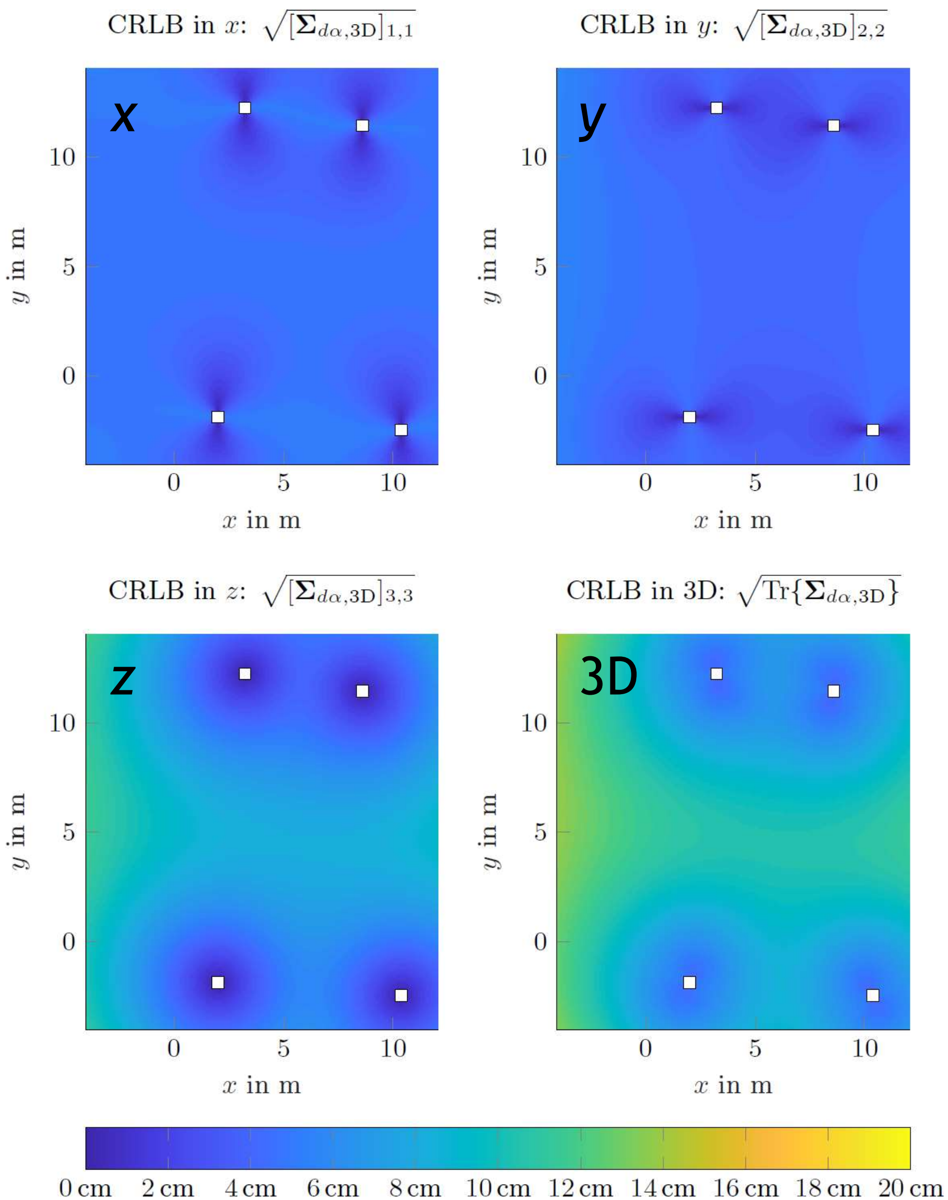
RTOF+DOA CRLB

- Measure distance d_n and angles φ_n, ϑ_n
- Determine 3D position covariance $\boldsymbol{\Sigma}_{\alpha d,\mathrm{3D}}$ from measurement covariance $\boldsymbol{Q}$

$$\boldsymbol{G}(\boldsymbol{p}_{\mathrm{s},n},\boldsymbol{p}_{\mathrm{t}}) = \frac{\partial[d,\varphi,\vartheta]^{\mathrm{T}}}{\partial \boldsymbol{p}_{\mathrm{t}}}, \boldsymbol{Q} = \boldsymbol{I}\begin{bmatrix}\sigma_d^2\\ \sigma_\varphi^2\\ \sigma_\vartheta^2\end{bmatrix}$$

$$\boldsymbol{\Sigma}_{d\alpha,\mathrm{3D}} = \left(\sum_{n=1}^{N}\boldsymbol{G}_n^{\mathrm{T}}\boldsymbol{Q}_n^{-1}\boldsymbol{G}_n\right)^{-1}$$

→ **Throughout low 3D PDOP**

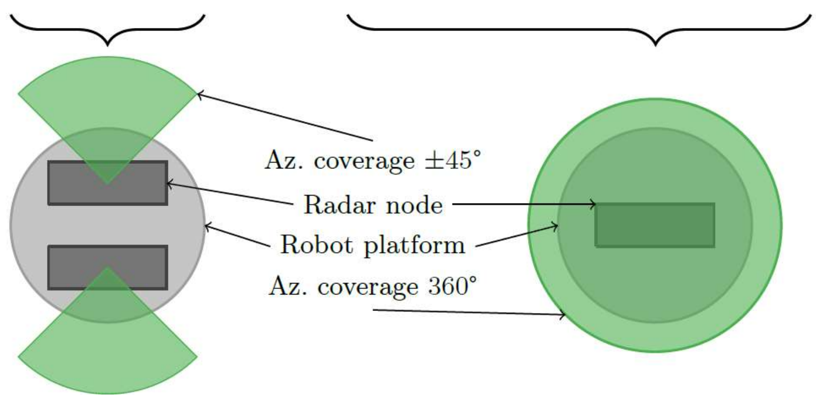


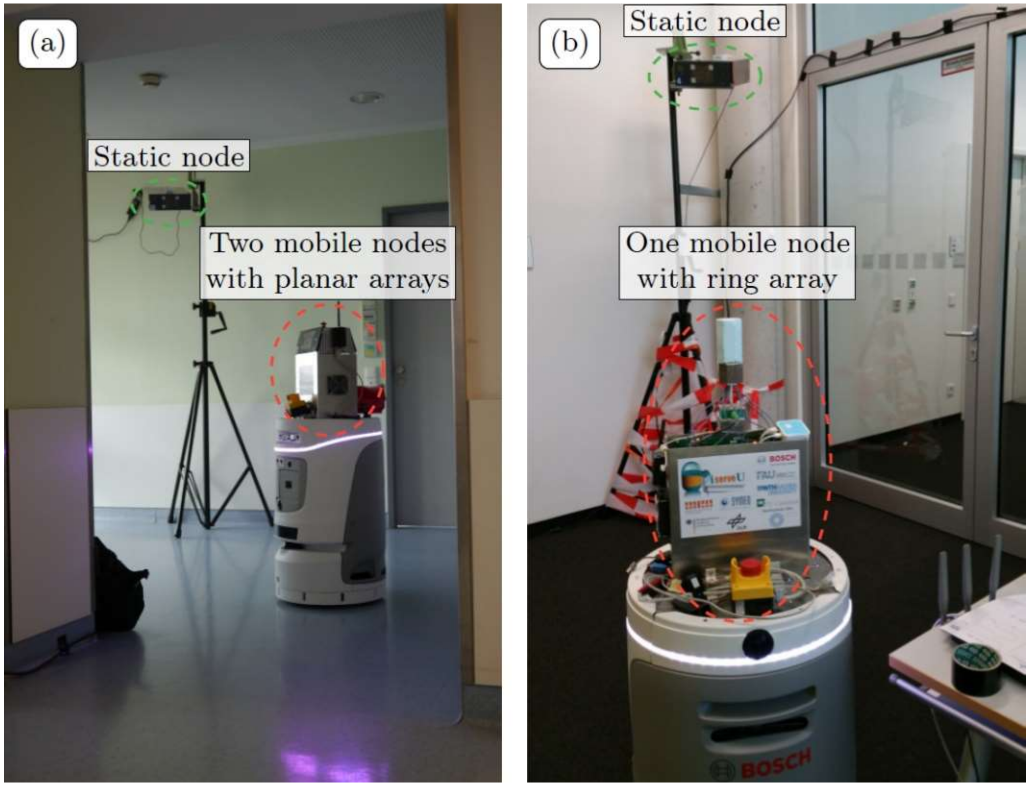
Robot Configurations

(a) Demonstrator robot platform with two radar nodes with planar arrays

(b) Demonstrator robot platform with one radar node with ring array

(c) Test robot platform with one radar node with ring array

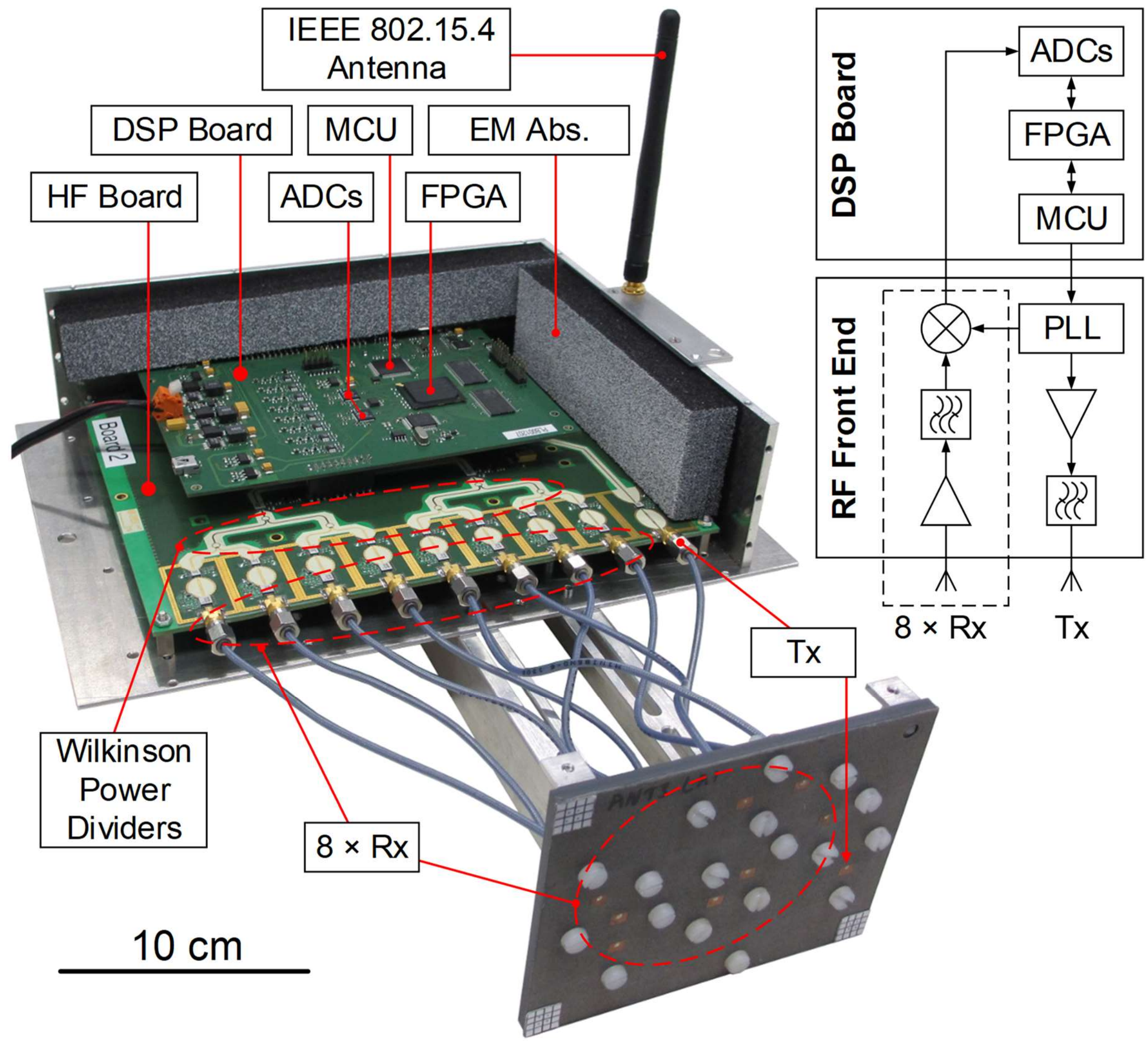




Mobile robot with secondary radar in 2 indoor scenarios

24 GHz FMCW SIMO Secondary Radar

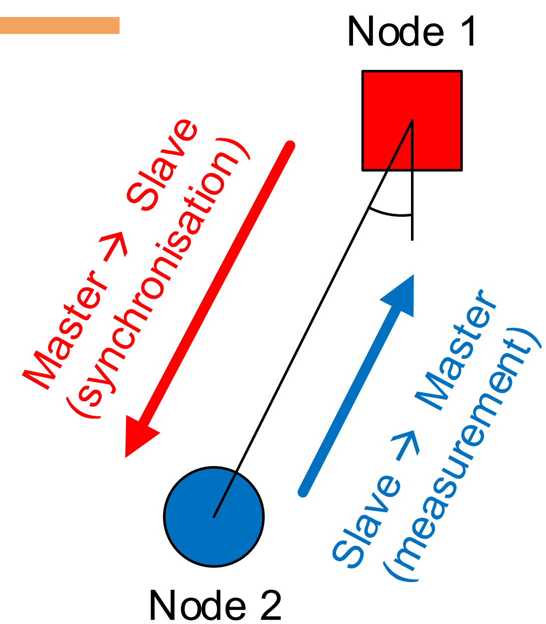
- 8 channel FMCW SIMO
- 2D sparse antenna array
  - Azimuth and elevation DOA estimation
- RF front end
  - Center frequency: 24.125 GHz
  - Sweep Bandwidth: 250 MHz
- DSP board
  - 14-bit ADCs
  - Signal processing on FPGA / ARM CPU

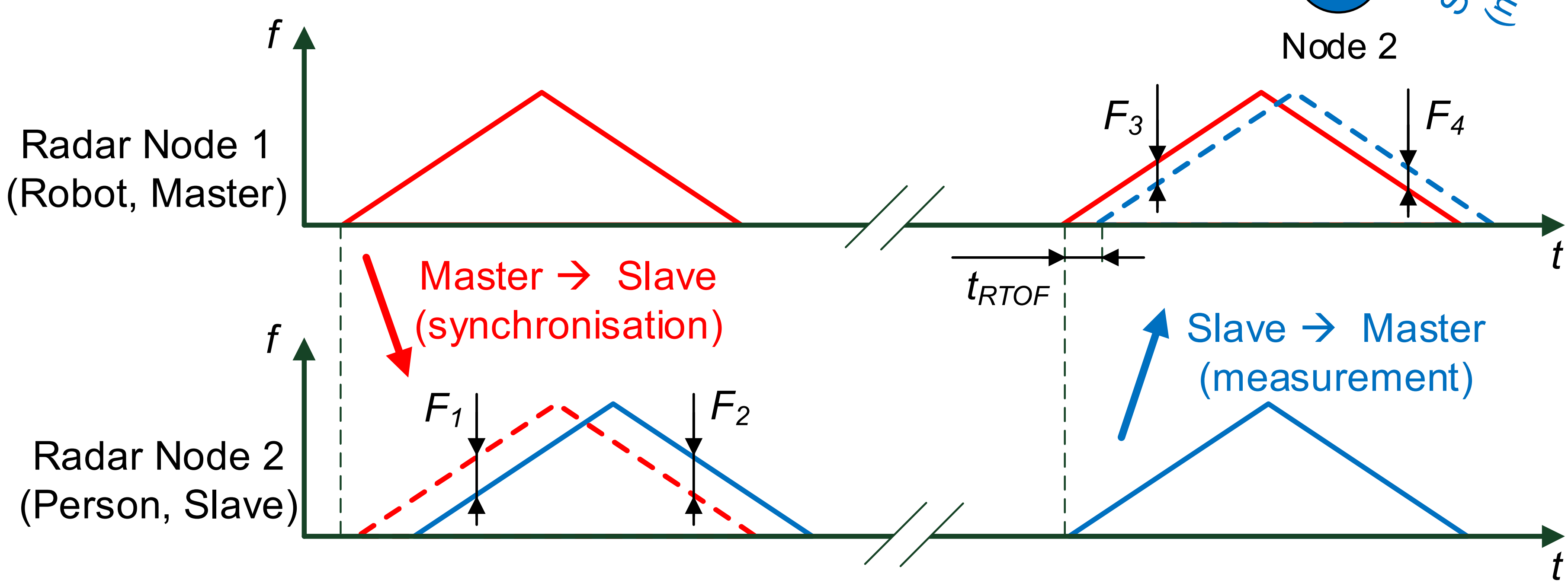


24 GHz Secondary Radar

Operation principle

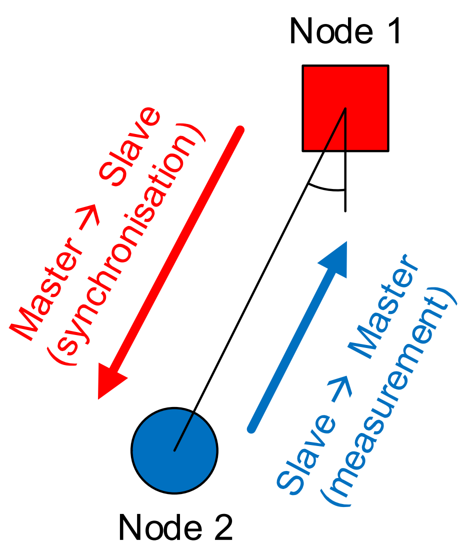
- Coarse pre-synchronization over IEEE 802.15.4
- Master sends synchronization FMCW ramps
- Slave synchronizes precisely in time and frequency
- Slave sends measurement FMCW ramps
- Master calculates distance from RTOF



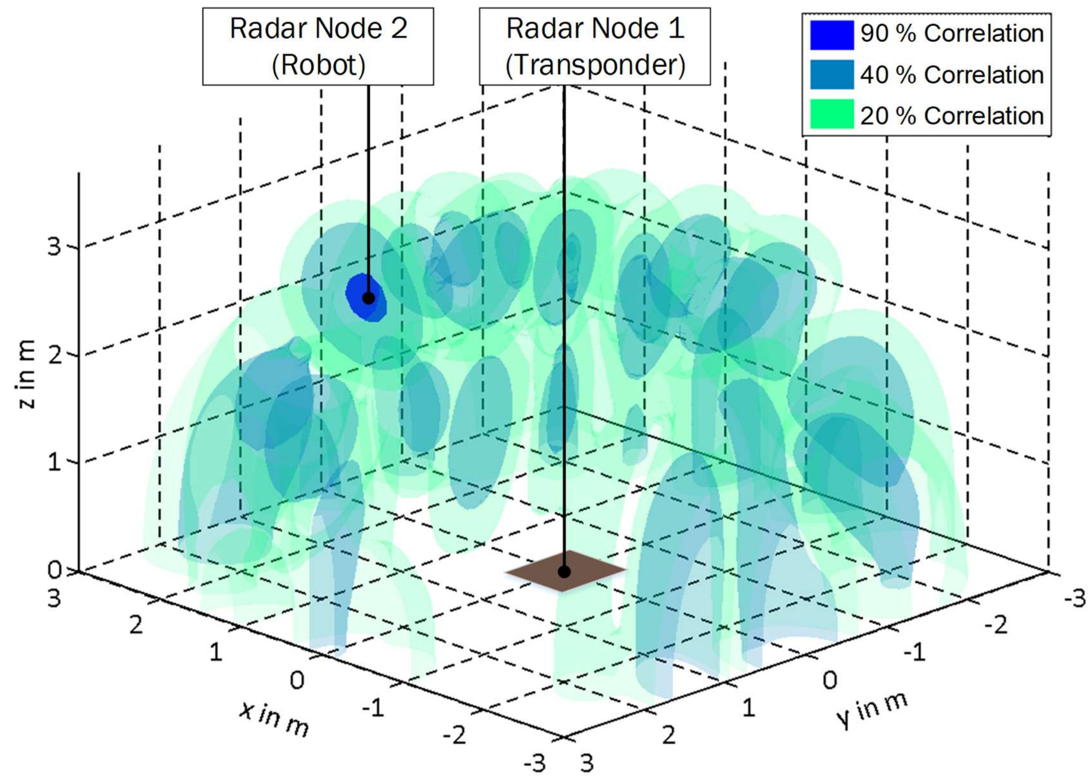


3D Localization – Operation Principle

- Precise synchronization using FMCW ramps enables accurate RTOF measurement (and thus distance measurement)
- Azimuth and elevation measurement using digital beamforming
- Angle estimation accurate and reliable in rooms and foyers
- Disturbance by multipath signals in long narrow corridors

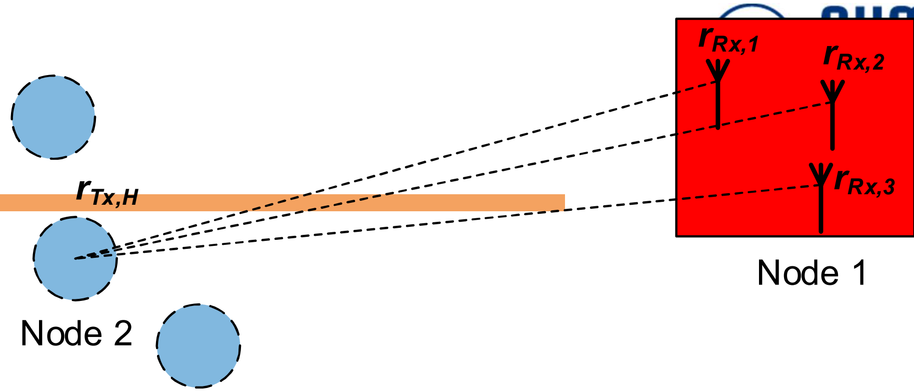


Operation Principle



3D Spatial Matched Filter Pseudo-Spectrum

3D Localization



- Signal model for IF signal

$$s_n(t) = A_n \cos(2\pi f_n t + \varphi_{g,n} + \varphi_{c,n})$$

  - f_n: frequency in channel n
  - $\varphi_{g,n}$: Phase due to TOF
  - $\varphi_{c,n}$: Phase mismatch

- 3D spatial matched filter H_n

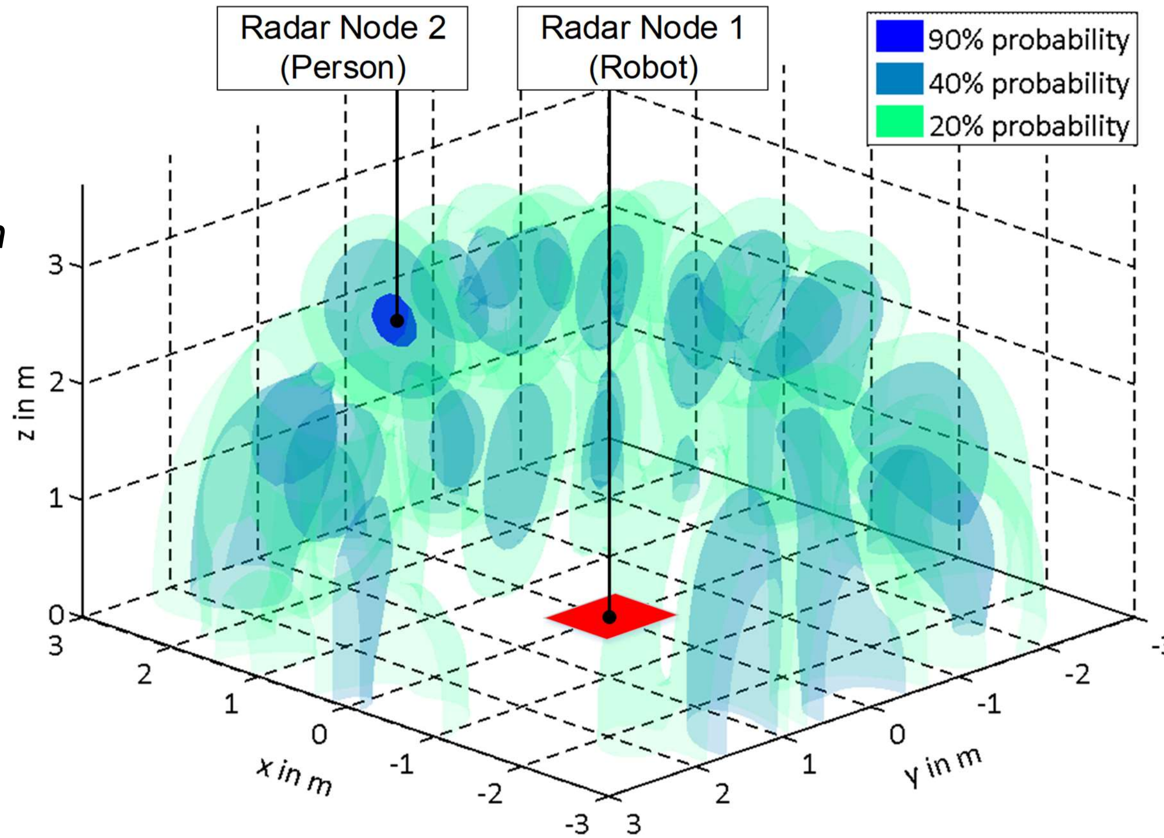
$$H_n = \exp\left(-j2\pi \frac{\left\| \boldsymbol{r}_{Rx,n} - \boldsymbol{r}_{Tx,H} \right\|_2}{\lambda}\right)$$

  - $\boldsymbol{r}_{Rx,n}$: 3D location of antenna n
  - $\boldsymbol{r}_{Tx,H}$: Hypothesis in 3D

- 3D probability distribution

$$I(\boldsymbol{r}_{Tx,H}) = \left| \sum_{n=1}^{8} S_n H_n \right|, S_n = \mathcal{F}(s_n(t))$$

Normalized probability density distribution



→ **3D localization of a person possible**

2D Array Calibration

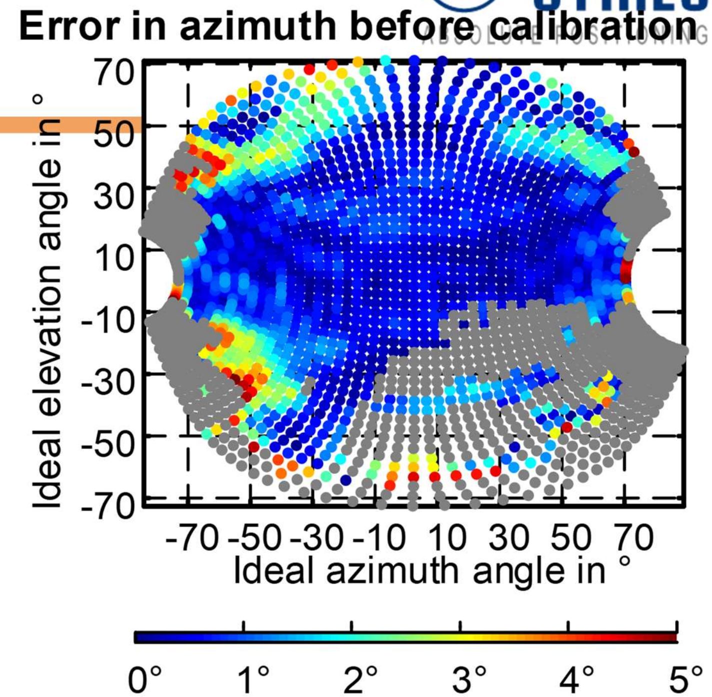
- Problem: Side lobes rising due to channel-to-channel phase mismatch $\varphi_{c,n}$
- Calibration approach: Model channel mismatch and mutual coupling by 8 × 8 complex matrix $\boldsymbol{C}$
  - Measurements to a target at multiple known positions in anechoic chamber
  - Formulate and solve least-squares problem to obtain $\boldsymbol{C}$
  - Apply calibration to measurement $\boldsymbol{S}$

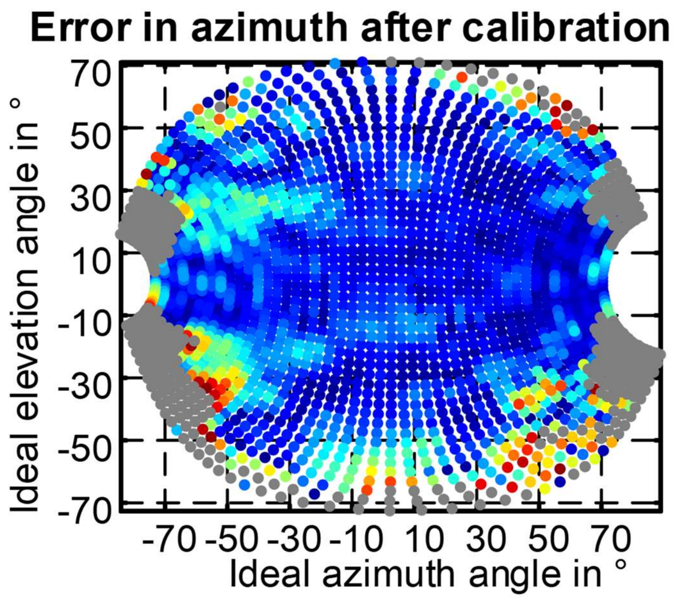
$$\boldsymbol{S}_{cal} = \boldsymbol{C}^{-1}\boldsymbol{S}$$

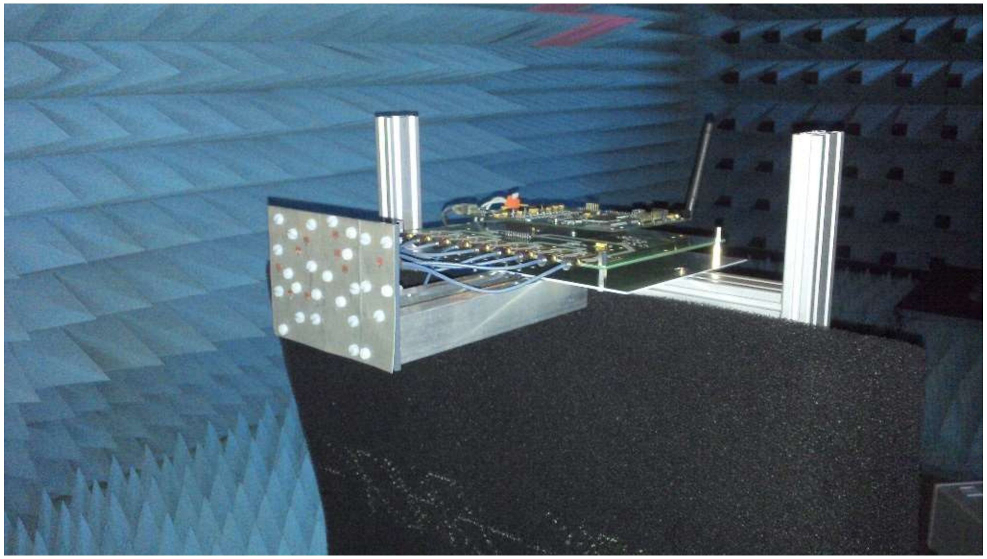
→ **Unambiguous measurement range extended to >±45° in both azimuth and elevation**

→ **Mean absolute error <1°**

→ **SLL reduced to close-to-ideal levels**

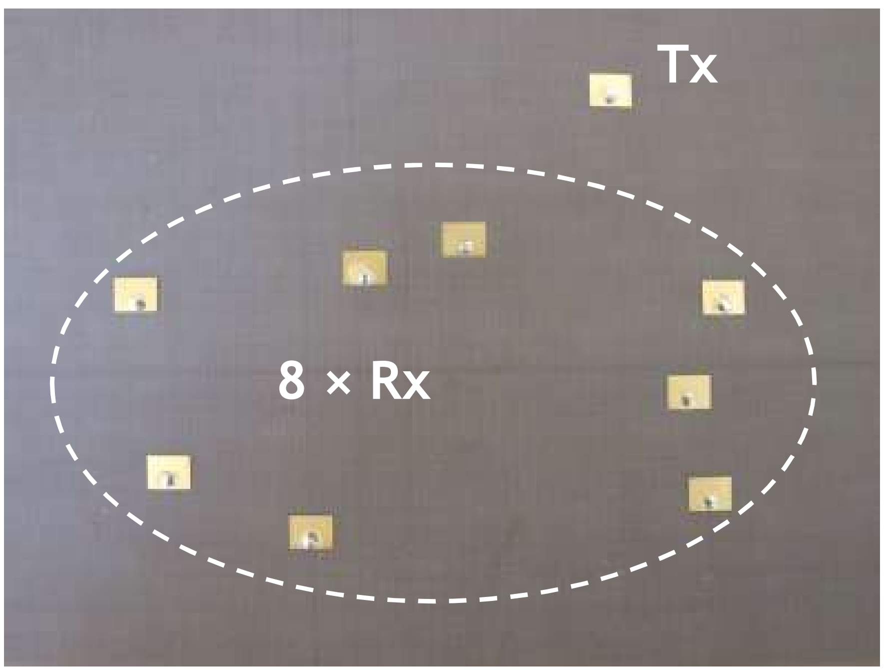




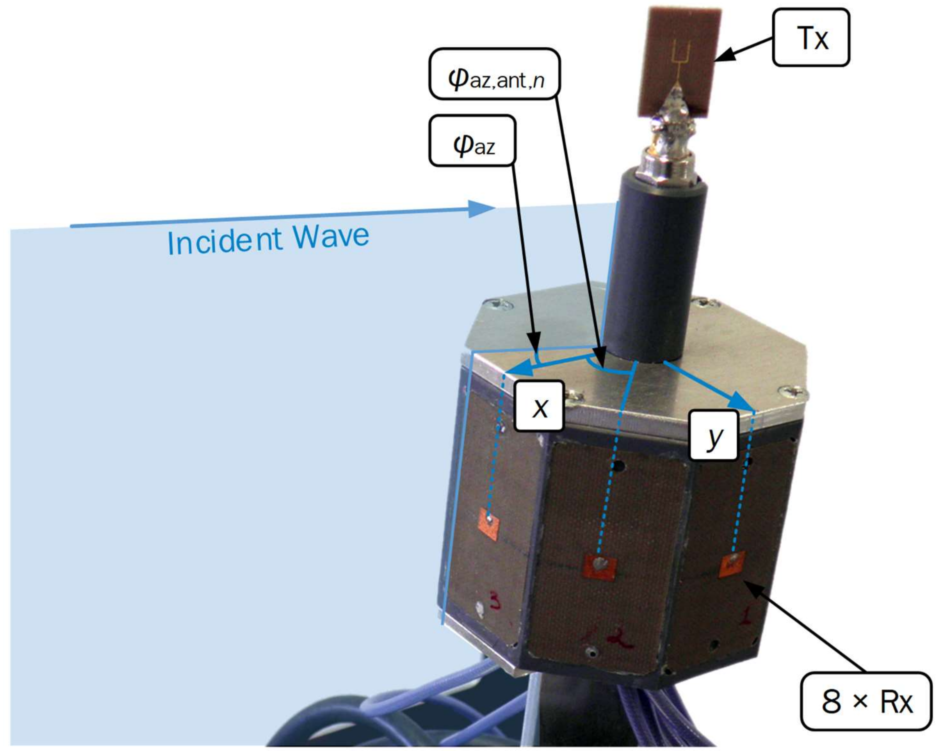


Sparse Antenna Arrays

- Planar Antenna Array
  - Unambiguous measurement range >±45° in azimuth and elevation
  - Accuracy RMSE ≈ 1°
  - → Stationary reference nodes



- Ring Antenna Array
  - Measurement range 360° in azimuth
  - Accuracy RMSE ≈ 2°
  - → Mobile node



Ring Array – Angle Estimation

- Signal model for channel *n*:

$$S_n = A_n \cdot \exp(\phi_{\mathrm{g},n} + \phi_{\mathrm{c},n})$$

- Amplitude monopulse

$$A_{n,\mathrm{h}}(\varphi_{\mathrm{az,h}}) = \mathrm{RP}(\mathrm{wrap}(\varphi_{\mathrm{az,ant},n} - \varphi_{\mathrm{az,h}}))$$

$$R(\varphi_{\mathrm{az,h}}) = \sum_{n=1}^{8} |\,\overline{A_n} - A_{n,\mathrm{h}}(\varphi_{\mathrm{az,h}})\,|$$

$$\varphi_{\mathrm{az,AM}} = \underset{\varphi_{\mathrm{az,h}}}{\mathrm{argmin}}\{R(\varphi_{\mathrm{az,h}})\}$$

- $\varphi_{\mathrm{az,AM}}$ is a coarse but stable and unambiguous estimate
- Use signal phases and Bartlett beamformer for better accuracy