Simulated Vision-based Approach and Landing System for Advanced Air Mobility

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Autonomous Systems – Perception & Distributed Sensing

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Outline

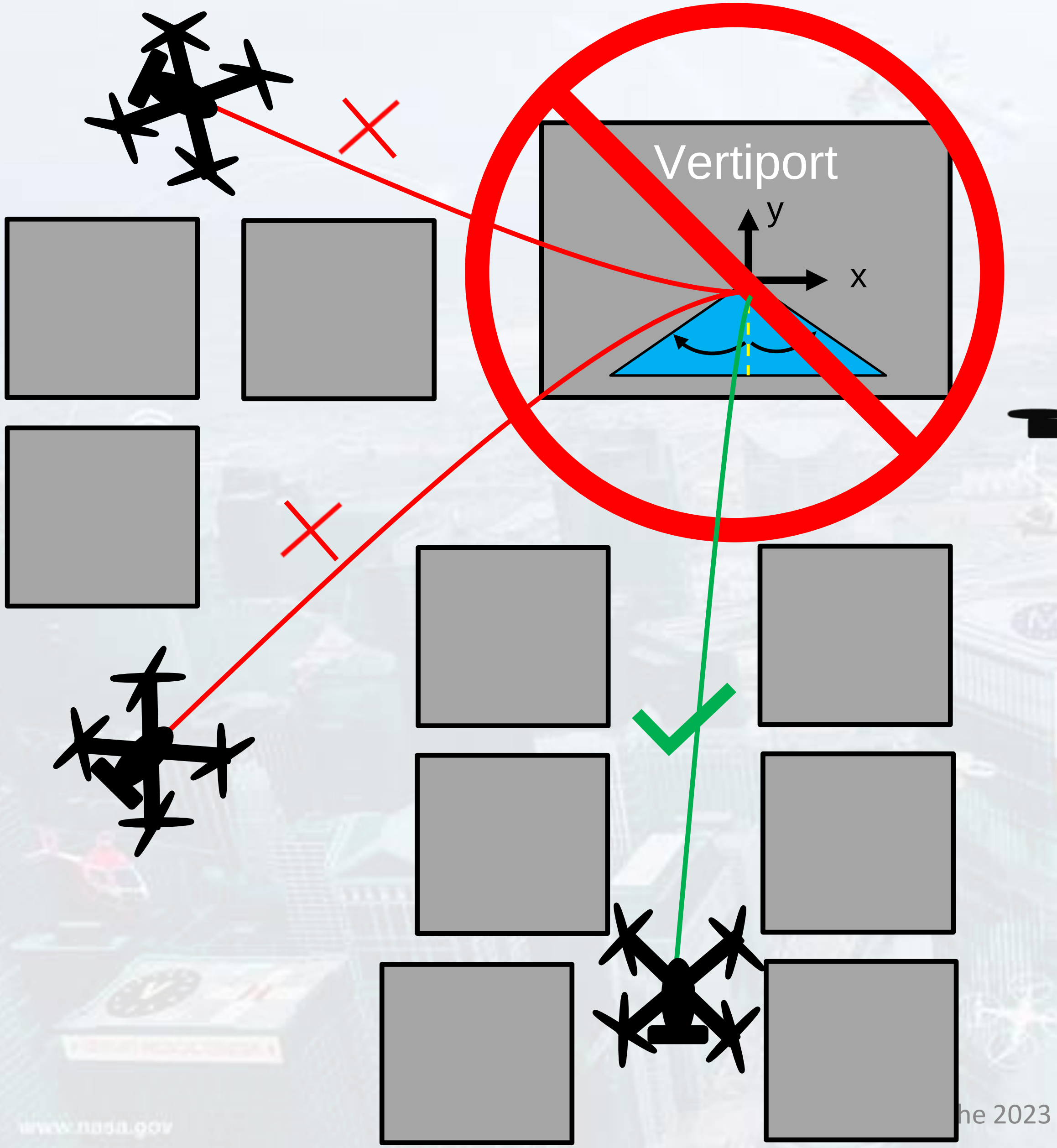
Problem

- AAM needs accurate and autonomous approach and landing systems
- Baseline perception and requirements come from existing technology: vision, IR, radar, glideslope indicators, and GPS
- Challenges for approach and landing in urban environments
  - GPS degradation
  - Narrow glideslope and localizer beams
  - Reduction in landing angles & paths at vertiports due to buildings or vision navigation aids
- No active FAA vertiport documents for requirements (canceled in 2010 [1])
- Similar FAA documents provide adequate requirements and standards:
  - FAA Advisory Circular 150/5390-2C: Heliport Design [2]
  - Engineering Brief No. 105, Vertiport Design [3] – interim guidance

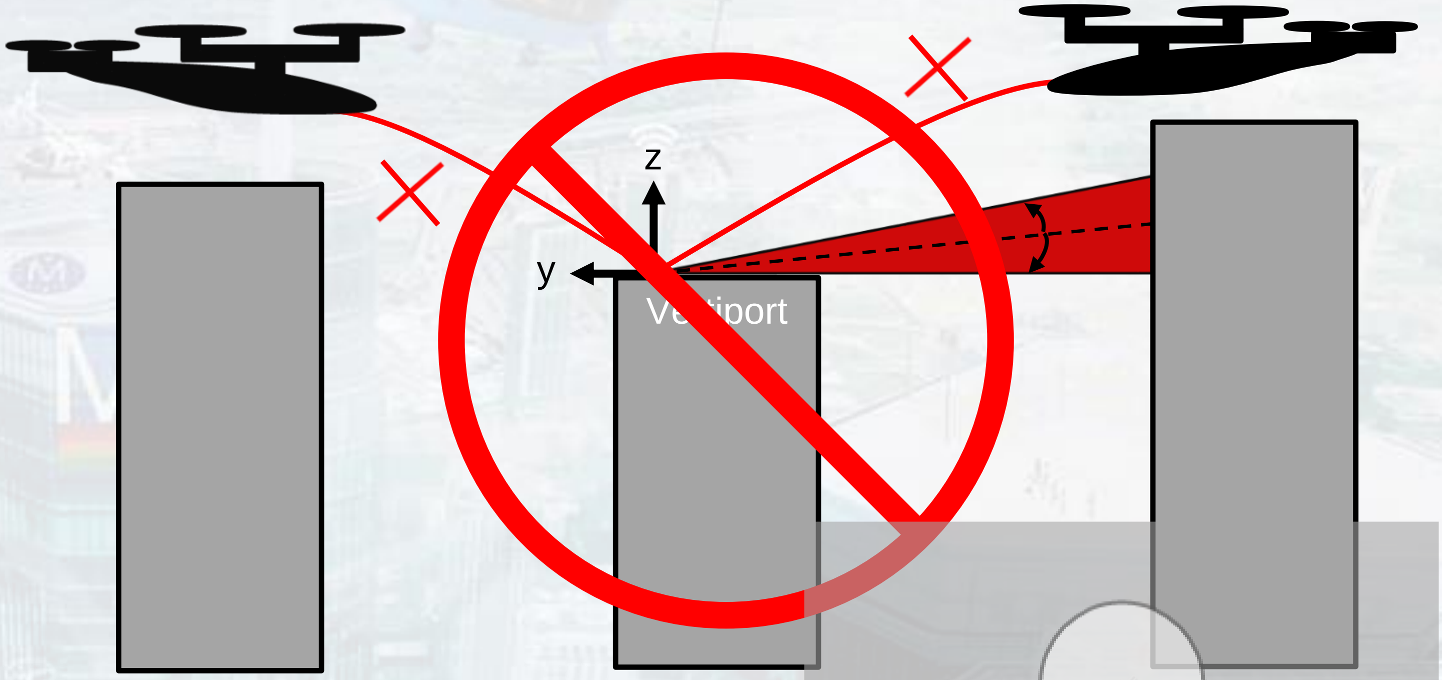
[1] Federal Aviation Administration, “AC 150/5390-3 (Cancelled) - Vertiport Design,” 2010. URL https://www.faa.gov/documentLibrary/media/advisory_circular/150-5390-3/150_5390_3.PDF
[2] Federal Aviation Administration, “AC 150/5390-2C - Heliport Design,” 2012. URL https://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf
[3] Bassey, R., “Engineering Brief No. 105, Vertiport Design,” U.S. Department of Transportation, 2022. URL https://www.faa.gov/sites/faa.gov/files/2022-09/eb-105-vertiports.pdf

Traditional and Current Landing Systems

Glideslope: altitude deviation (**red**)
Localizer: lateral deviation (**blue**)



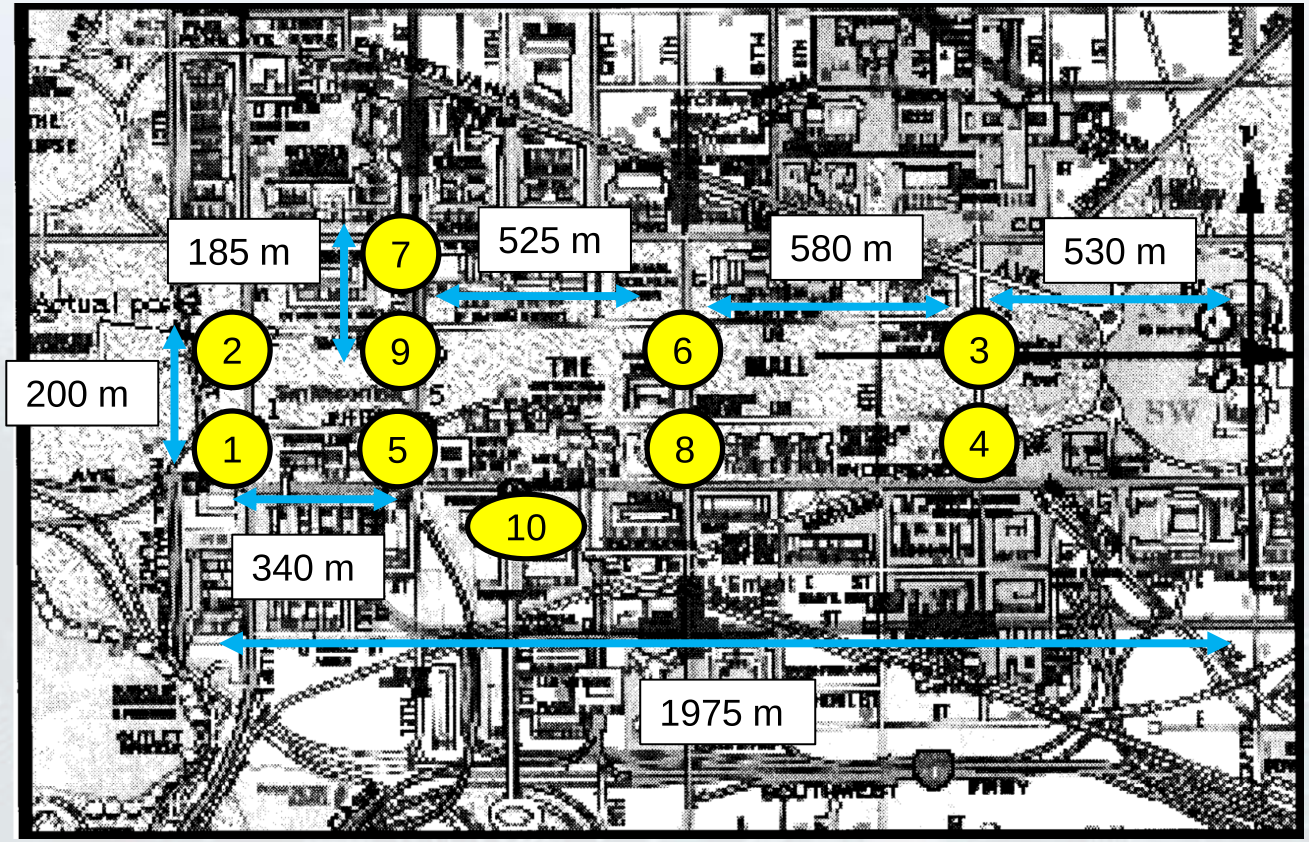
- Narrow beams -> not many alternative incoming angles for approach and landing [8]
- Difficult to maintain a consistent glidepath around buildings



[8] Peisen, D., and Sawyer, B., "Heliport/Vertiport MLS Precision Approaches," U.S. Department of Transportation, 1994. URL http://www.tc.faa.gov/its/worldpac/techrpt/rd94-23.pdf

Coplanar POSIT (COPOSIT) Algorithm

- POSIT = **P**ose from **O**rthography and **S**caling with **It**erations
- Goal: compute **position** and **orientation** of a camera with respect to a known object



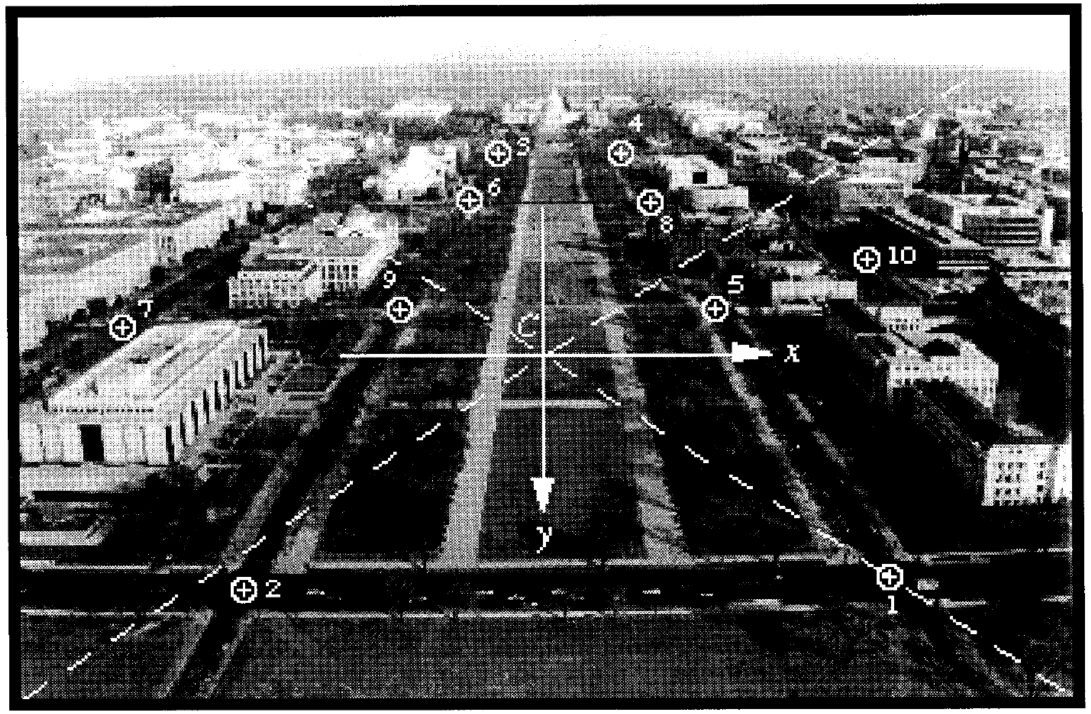


FIG. 13. The Mall in Washington, D.C., from the top of the Washington Monument, with feature points and image coordinate system.

Experiment at Mall in Washington, DC (camera at the top of Washington Monument):
$$\Delta U = 3\ m, \Delta V = 4\ m, \Delta W = 2\ m$$

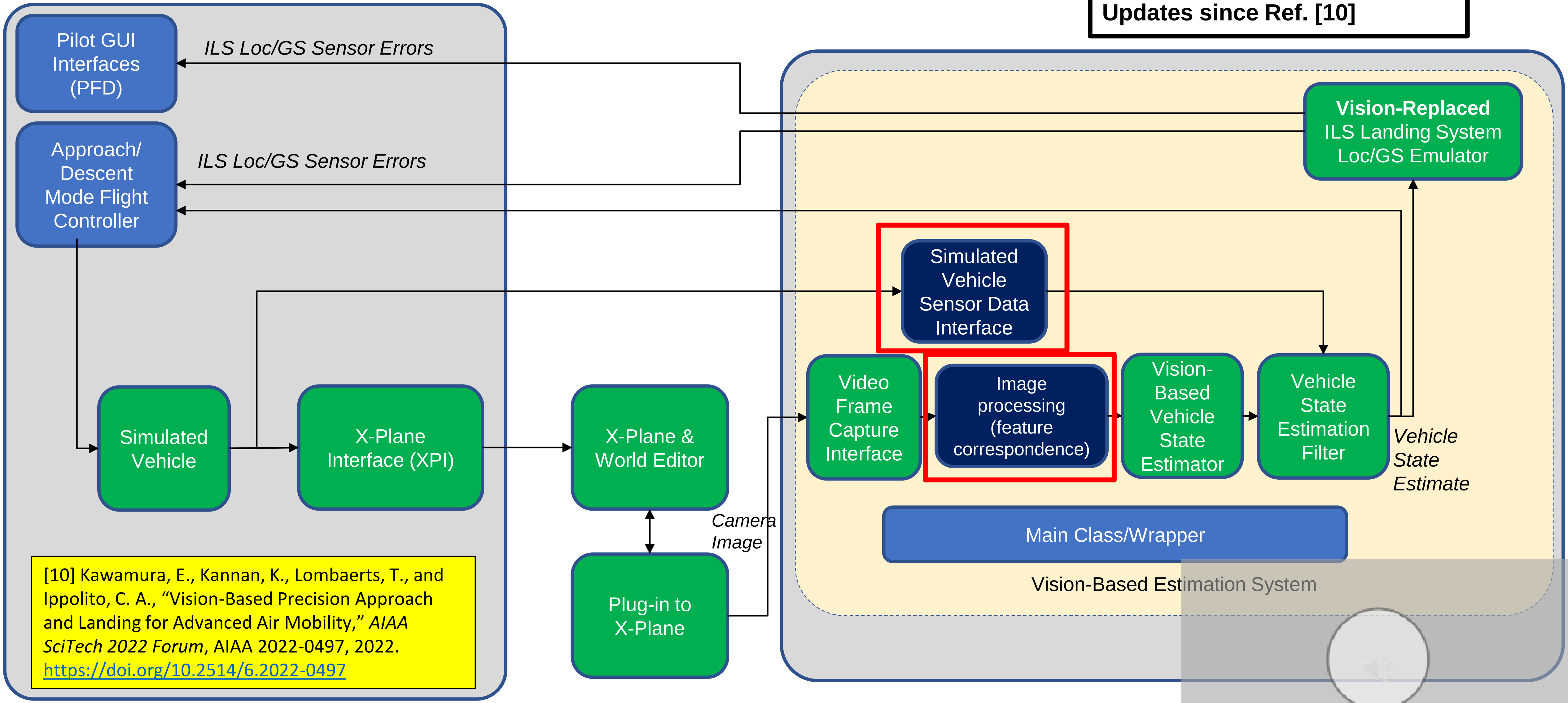
Constraint: requires at least four coplanar points

[9] Oberkampf, D., DeMenthon, D. F., and Davis, L. S., “Iterative Pose Estimation Using Coplanar Feature Points,” *Computer Vision and Image Understanding*, Vol. 63, No. 3, 1996, pp. 495–511. https://doi.org/10.1006/cviu.1996.0037

http://www.daniel.umiacs.io/Site_2/Code.html

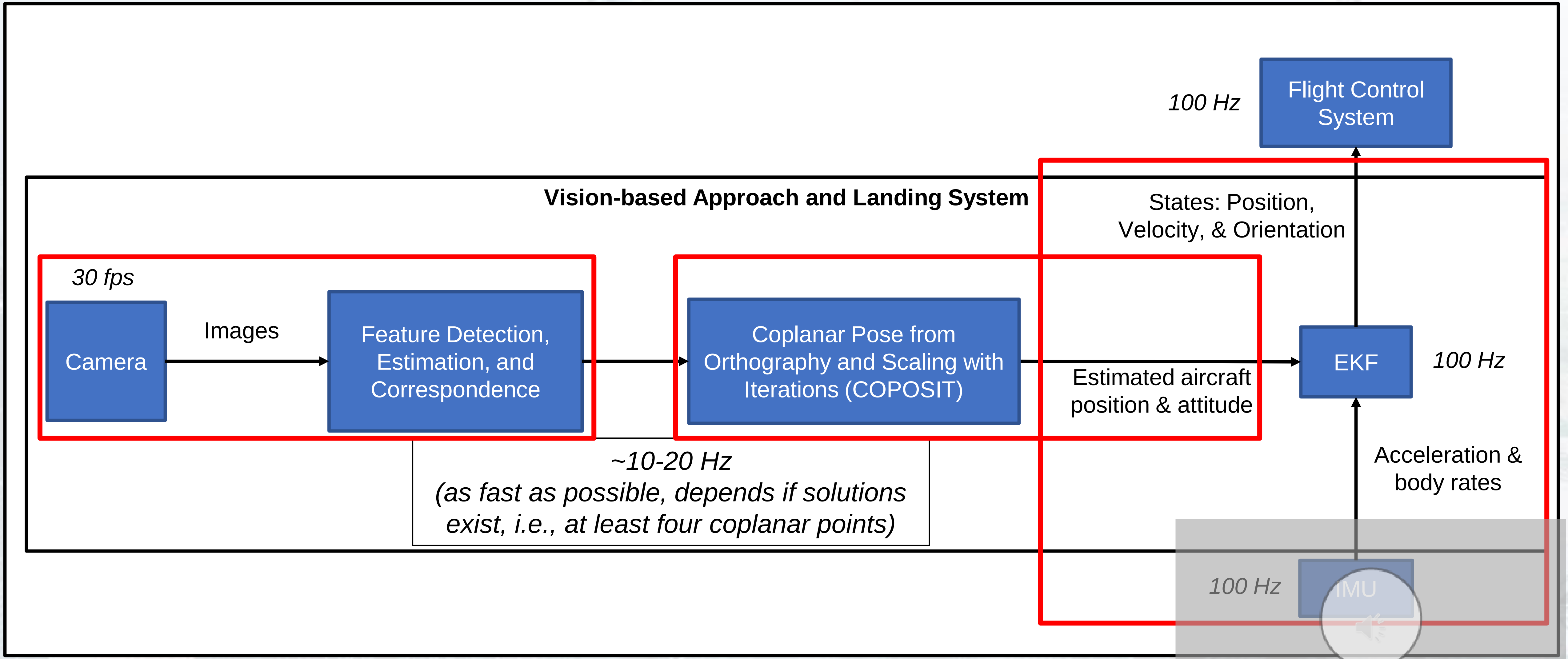
Overview of Work

Legend
Work-in-progress
Operational via post-processing
Updates since Ref. [10]



[10] Kawamura, E., Kannan, K., Lombaerts, T., and Ippolito, C. A., "Vision-Based Precision Approach and Landing for Advanced Air Mobility," *AIAA SciTech 2022 Forum*, AIAA 2022-0497, 2022. https://doi.org/10.2514/6.2022-0497

Overview of Work: System Block Diagram



Overview of Work

Builds on previous work [10]

1. moderately high-fidelity simulation for AAM precision approach and landing (PAL) with NASA Reflection software and X-Plane &World Editor
2. computer vision feature correspondence methods
3. ground-based distributed sensor network that tracks an AAM aircraft during PAL
4. comparison between the onboard AAM aircraft's navigation solution with the distributed sensor network's tracking solution
5. simulate a vertiport at Fifth & Mission Garage (FMG) in San Francisco, CA & render landing lights on its rooftop
6. design a curved approach and landing trajectory from the bay, starting near Oakland Bay Bridge and ending at the rooftop of FMG

[10] Kawamura, E., Kannan, K., Lombaerts, T., and Ippolito, C. A., "Vision-Based Precision Approach and Landing for Advanced Air Mobility," *AIAA SciTech 2022 Forum*, AIAA 2022-0497, 2022. https://doi.org/10.2514/6.2022-0497

Outline

1. Introduction
2. Kinematics & Dynamics
3. Distributed Cameras
4. Simulation Setup
5. Feature Detection & Correspondence
6. EKF Design
7. Simulation Results
8. Conclusion

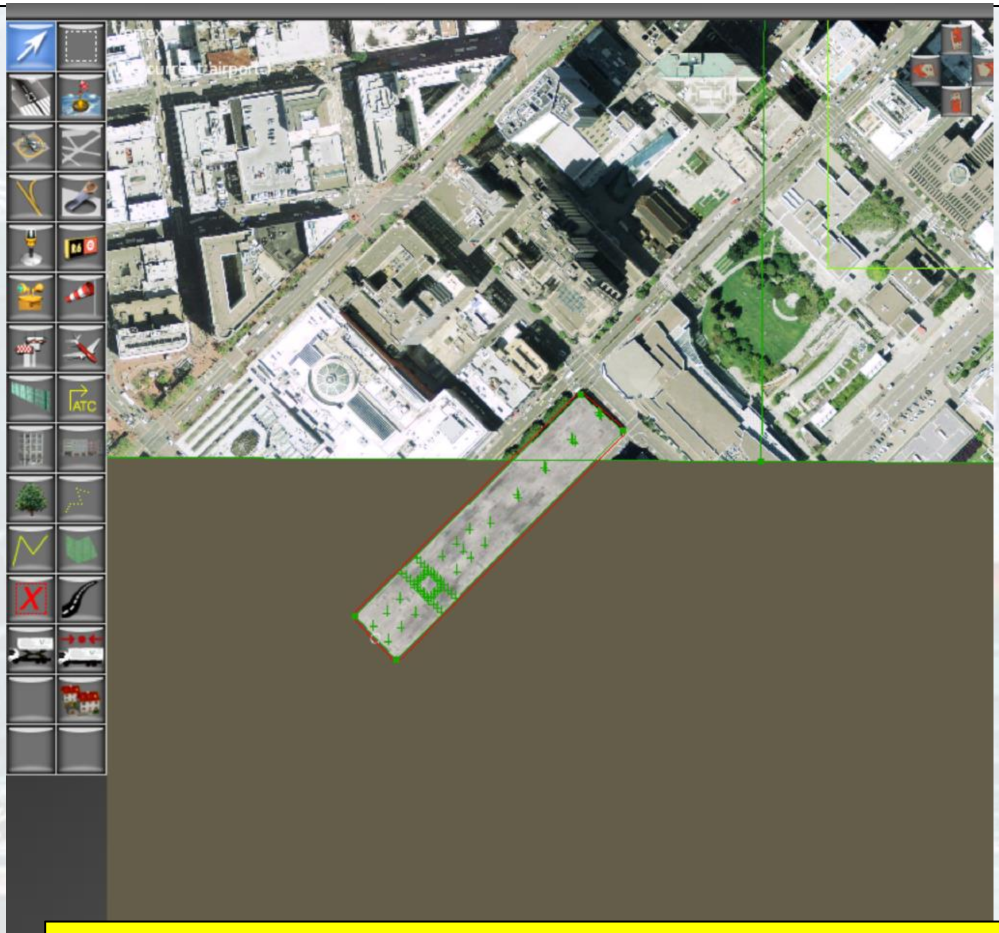
Simulation Setup: Reflection and X-Plane Interface [14]

- NASA Ames Reflection software simulates AAM aircraft models and trajectories such as vertiport approach and landing at Fifth & Mission Garage (FMG) in San Francisco.
- X-Plane (visualization tool) is a flight simulator that renders the Reflection simulation

[14] Kannan, K., Baculi, J., Lombaerts, T., Kawamura, E., Gorospe, G., Holforty, W., Ippolito, C., Stepanyan, V., Dolph, C., and Brown, N., "A Simulation Architecture for Air Traffic Over Urban Environments Supporting Autonomy Research in Advanced Air Mobility," AIAA SciTech 2023 Forum, 2023.

Simulation Setup: X-Plane and World Editor

- World Editor allows users to create and modify airports and scenery.
- Create a simulated Fifth & Mission Garage vertiport in World Editor with heliport landing lights [2]
- Future simulations can use the vertiport landing light configuration proposed in [3] or when the vertiport design advisory circular gets approved

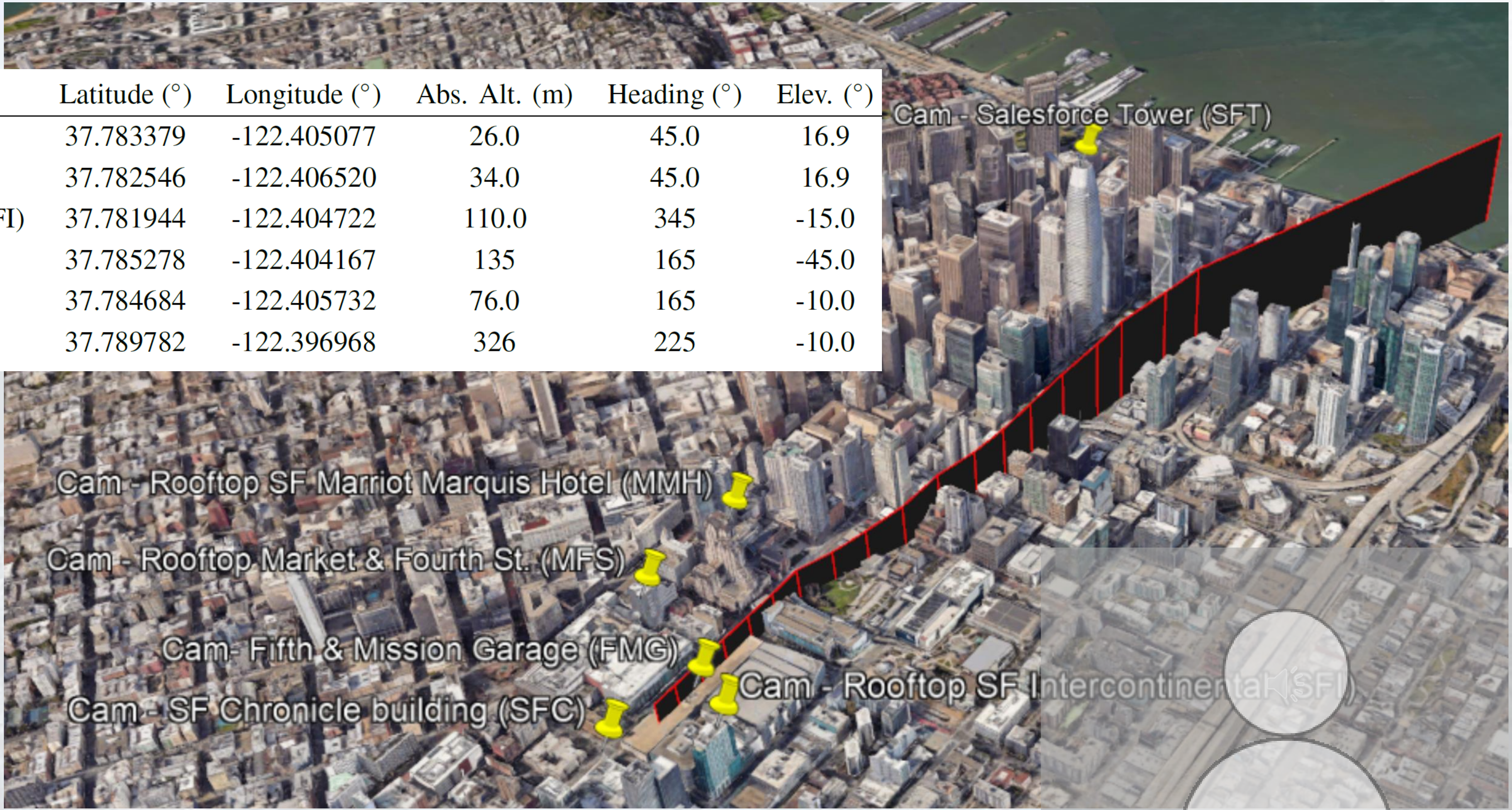


[2] Federal Aviation Administration, "AC 150/5390-2C - Heliport Design," 2012. URL https://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf
[3] Bassey, R., "Engineering Brief No. 105, Vertiport Design," U.S. Department of Transportation, 2022. URL https://www.faa.gov/sites/faa.gov/files/2022-09/eb-105-vertiports.pdf

Simulation Setup: Trajectory and Distributed Cameras

- Carefully place waypoints around the buildings in San Francisco
- Geometrically difficult to maintain a constant glidepath (curved trajectory)
- Placed cameras on rooftops to maintain visual coverage of the aircraft throughout the trajectory

Camera Name	Latitude (°)	Longitude (°)	Abs. Alt. (m)	Heading (°)	Elev. (°)
Fifth & Mission Garage (FMG)	37.783379	-122.405077	26.0	45.0	16.9
San Francisco Chronicle (SFC)	37.782546	-122.406520	34.0	45.0	16.9
San Francisco Intercontinental (SFI)	37.781944	-122.404722	110.0	345	-15.0
Marriot Marquis Hotel (MMH)	37.785278	-122.404167	135	165	-45.0
Market & Fourth Street (MFS)	37.784684	-122.405732	76.0	165	-10.0
Salesforce Tower (SFT)	37.789782	-122.396968	326	225	-10.0



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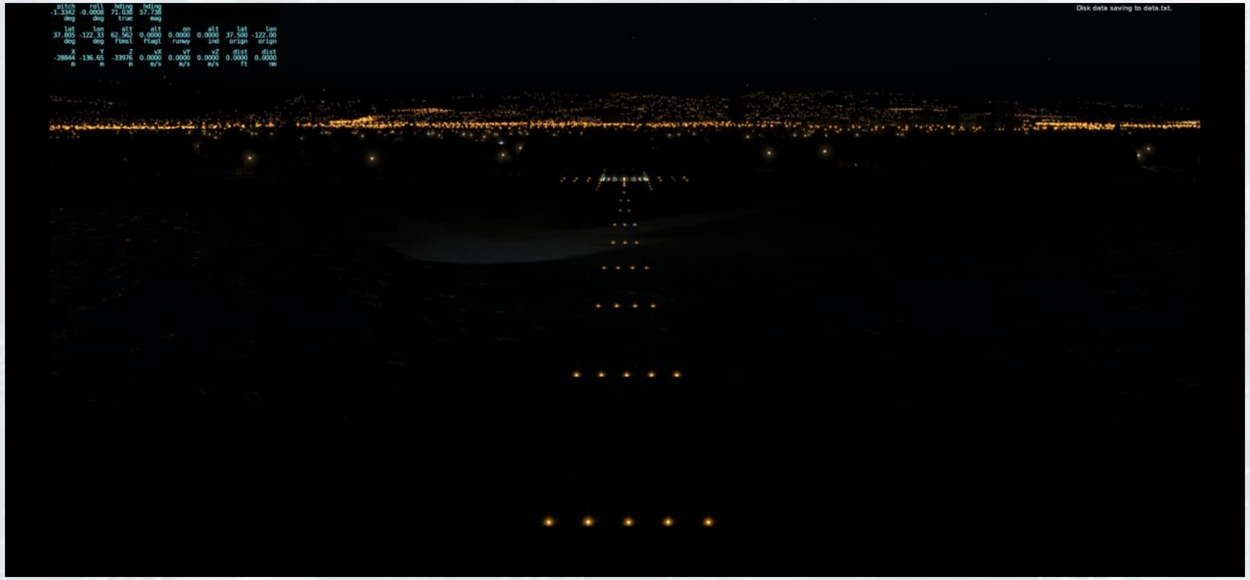
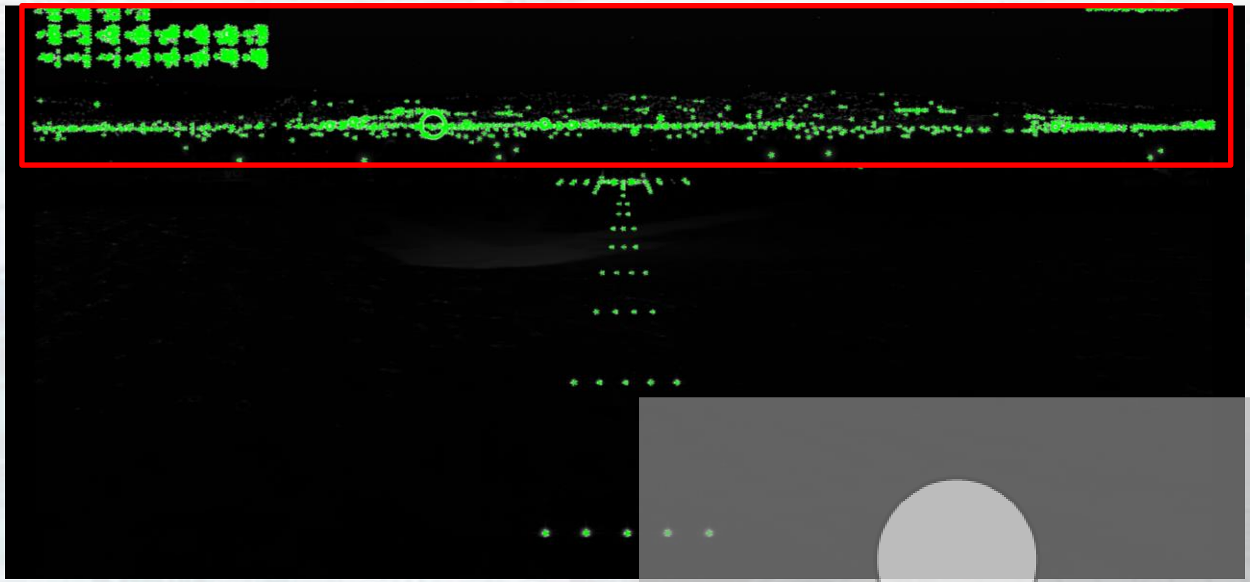
Feature Detection

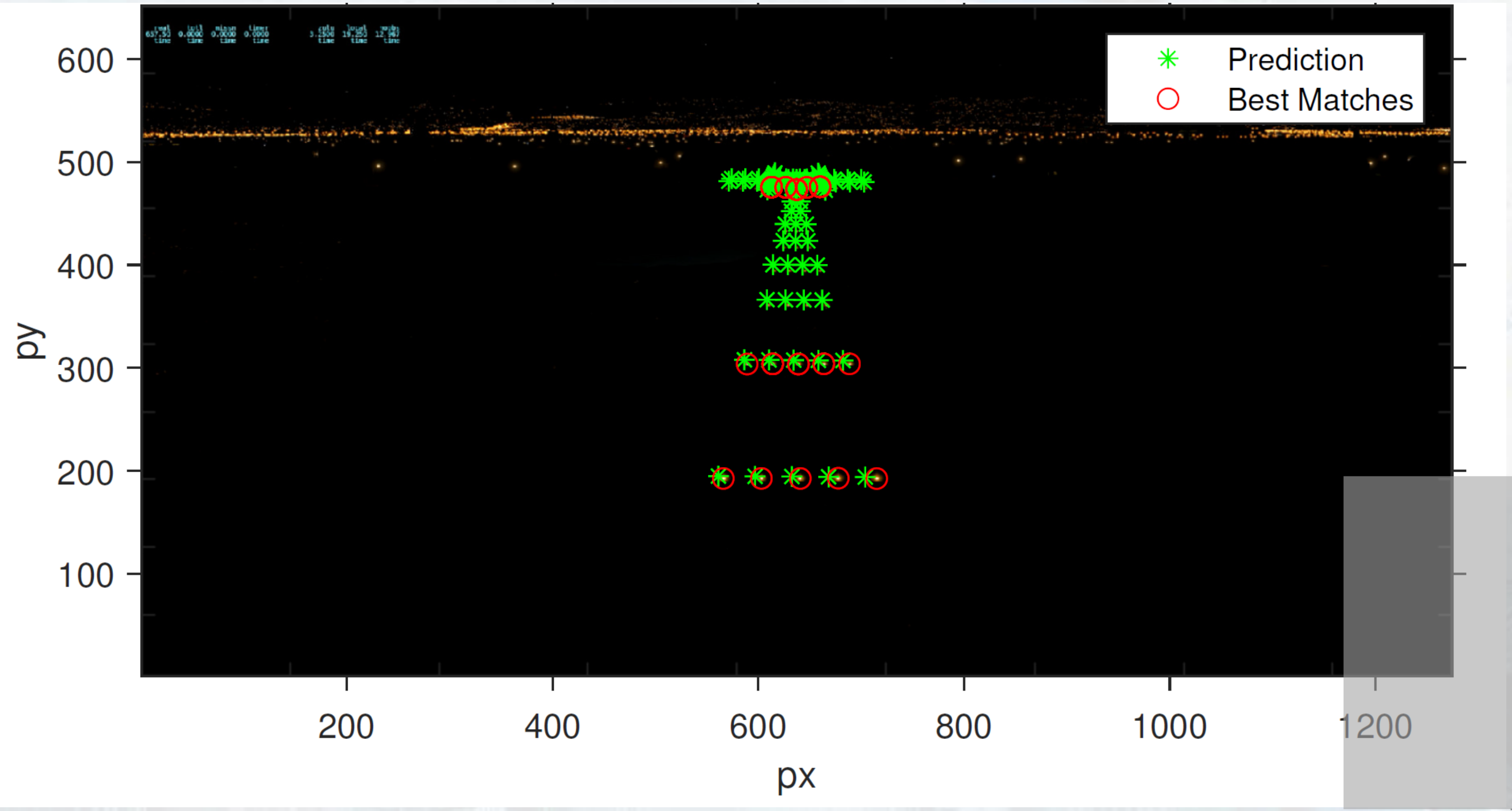
- Conducted preliminary tests for feature detection methods at Middle Harbor Shoreline Park (Oakland): Hough circle detector, SURF, Harris corner detection, FAST, template matching, and image registration
- **Hough circle detector** finds the circular landing lights very well
- Detect undesired background lights and X-Plane overlay information





Feature Correspondence

- Find the closest Hough circle detections to the predictions
- Ignore detections far away from the predictions
- Determine the WCS for the detections by matching the indices between the predicted and detected landmarks



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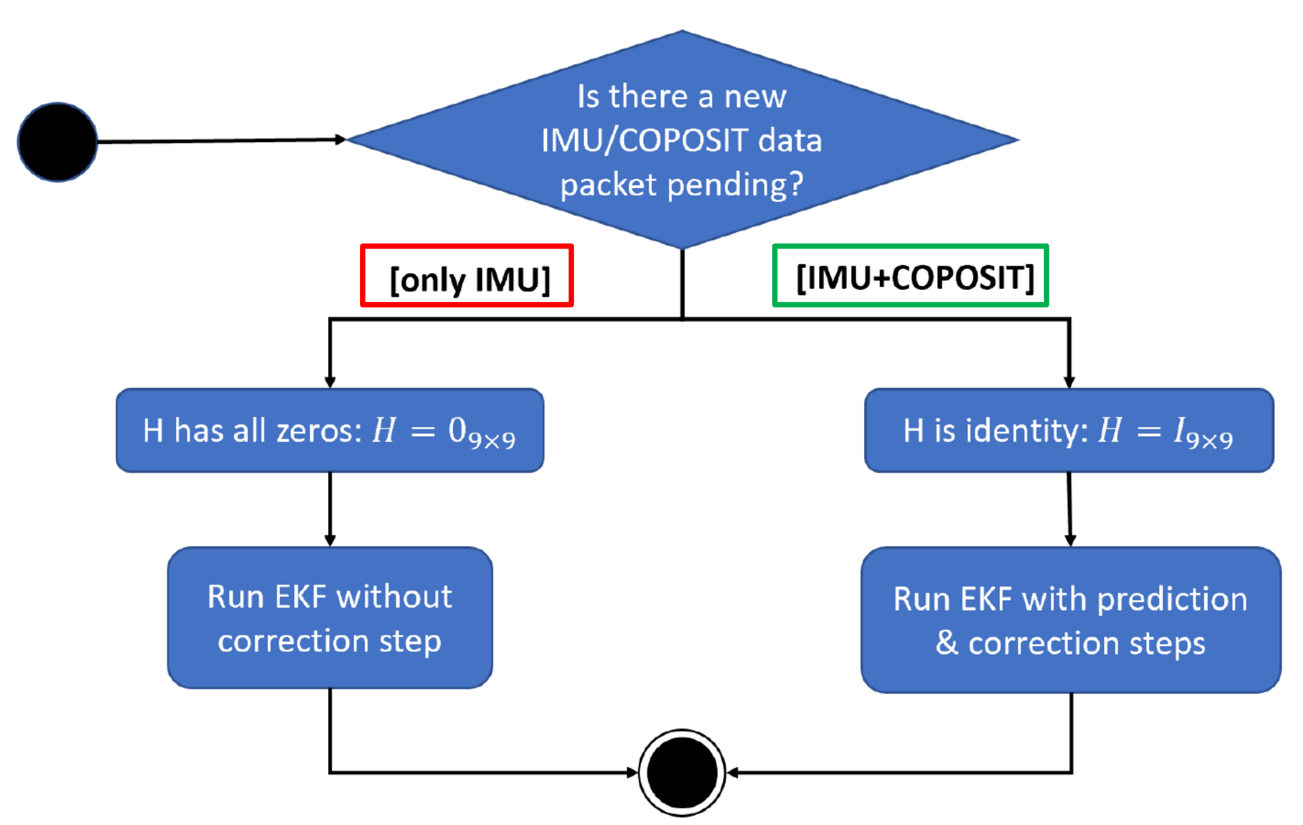
EKF Design

- Follows the EKF design in [10]:
  - IMU in input vector, u,
  - COPOSIT in measurement vector, z
- Different from [10] with velocity measurements based on the COPOSIT position measurements through finite difference:

$$v_{coposit,i} = \frac{p_{coposit,i} - p_{coposit,i-1}}{t_i - t_{i-1}}$$

- Divergence and inaccurate estimation occur without COPOSIT velocity measurements
- Two options based on available measurements



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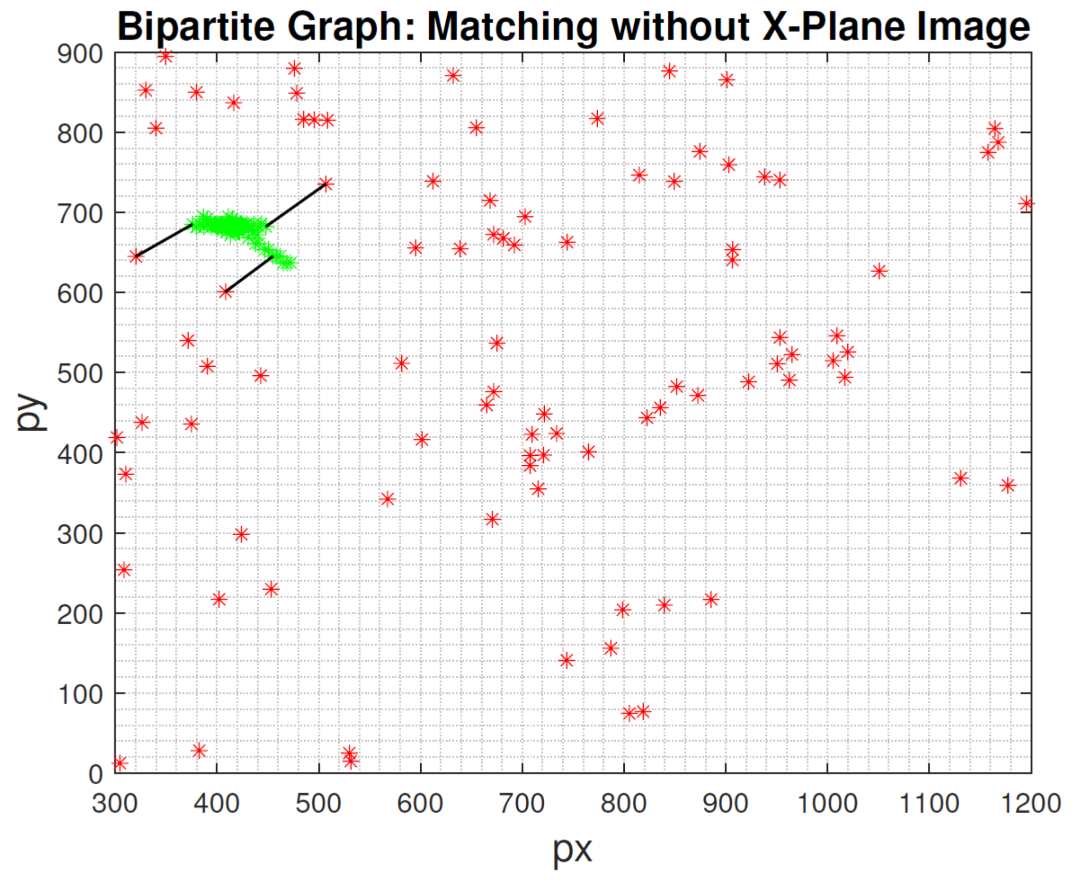
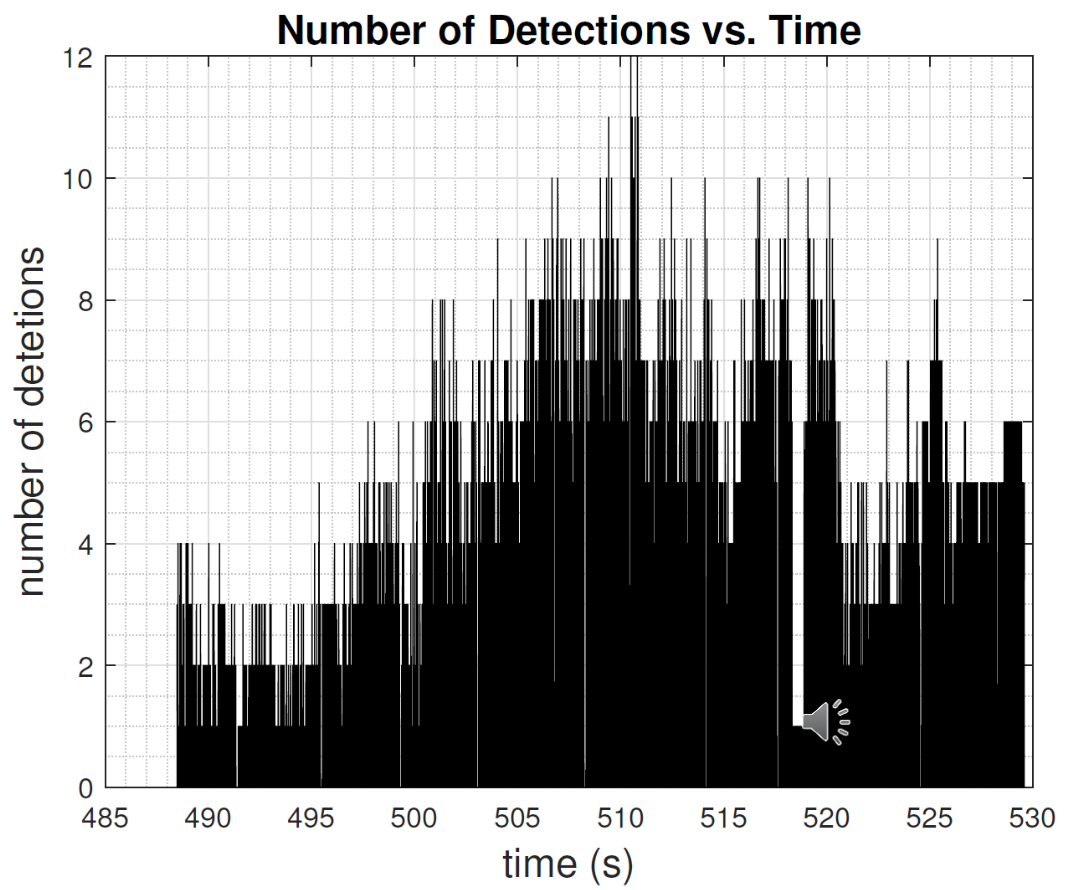
Simulation Results

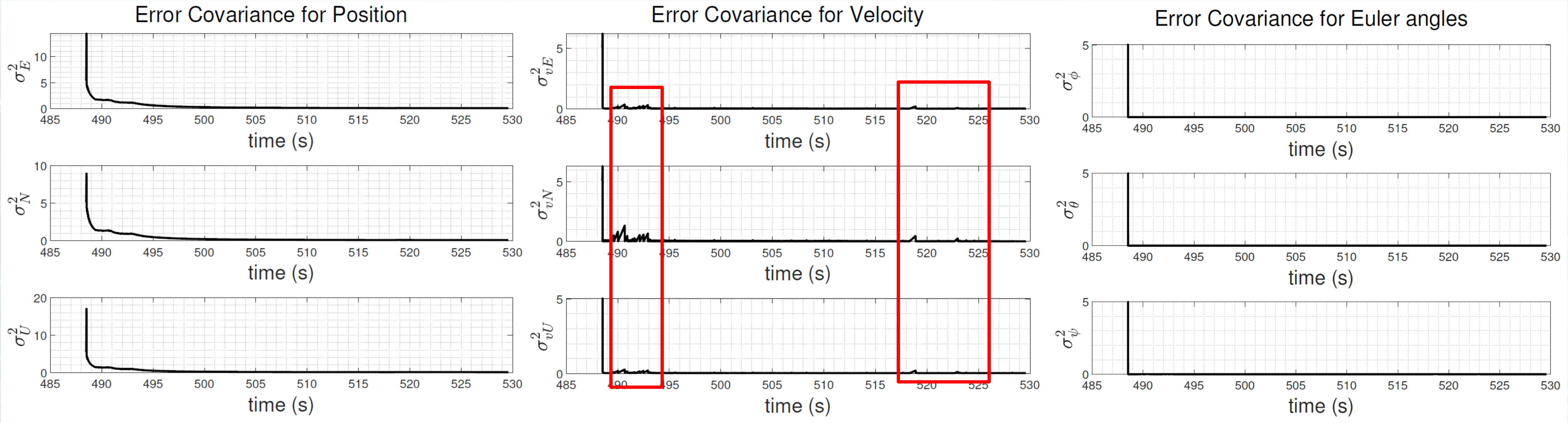
- Adequate feature detection and correspondence with some offset
- There are usually at least four detections (coplanar points), which leads to several COPOSIT measurements for more correction steps in the EKF (accurate state estimation)





Simulation Results: VAL EKF

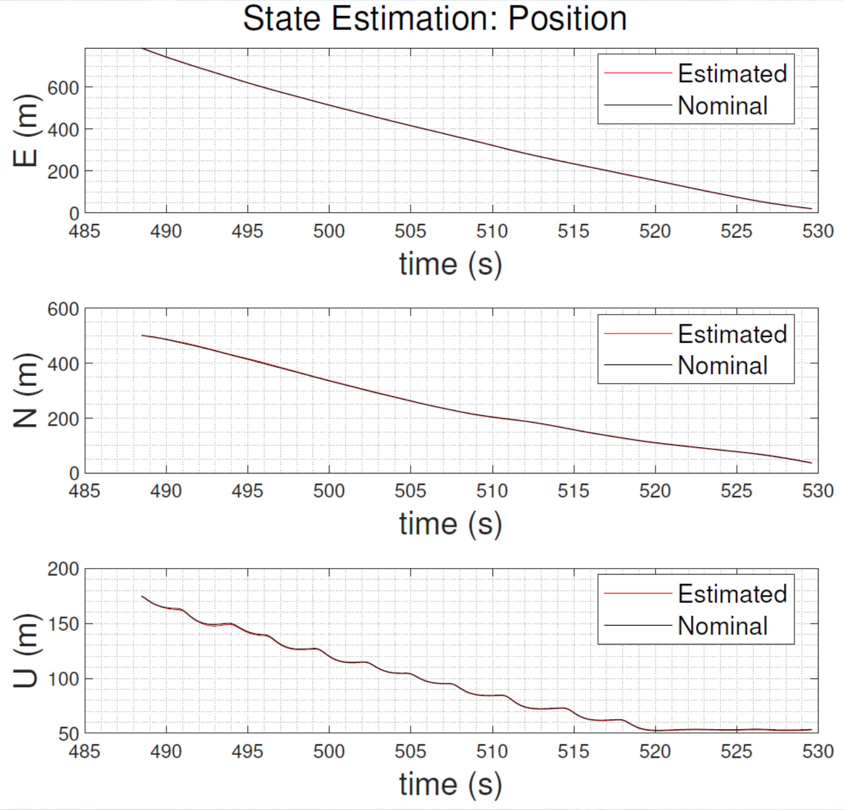
- Error covariances converge quickly
- Small spikes and fluctuations without COPOSIT measurements
- Small values for covariances: high confidence and low uncertainty in estimate

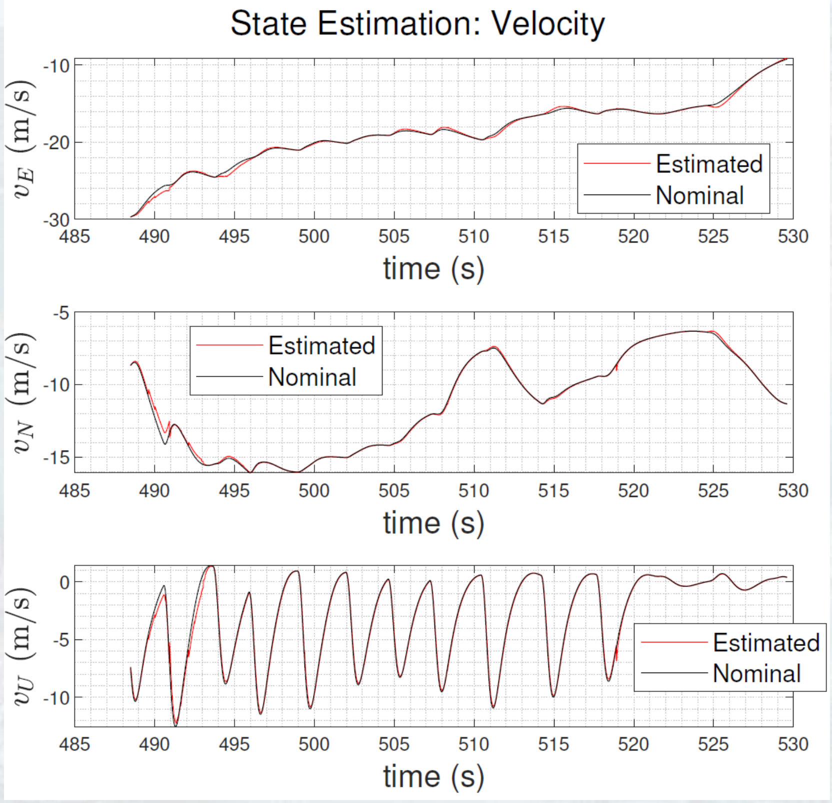


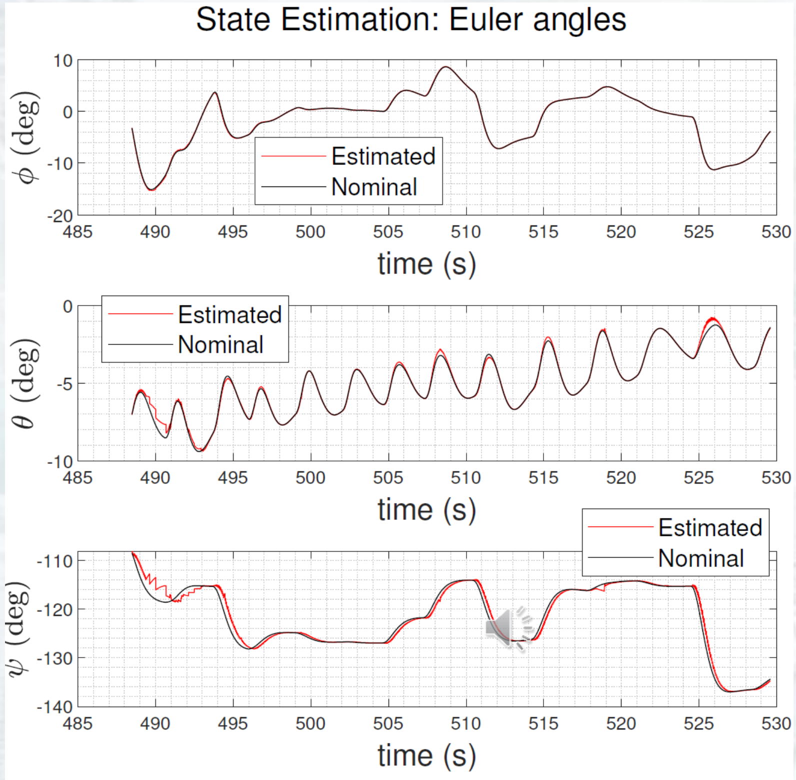
Simulation Results: VAL EKF

- Minor fluctuations and deviations occur without COPOSIT measurements
- Accurate state estimation (Ex: submeter position accuracy)

	E (m)	N (m)	U (m)	v_E (m/s)	v_N (m/s)	v_U (m/s)	ϕ (rad)	θ (rad)	ψ (rad)
μ	0.256	0.980	0.365	0.135	0.067	0.162	0.000856	0.00156	0.0116
σ	0.203	0.576	0.253	0.169	0.135	0.241	0.00115	0.00265	0.0151

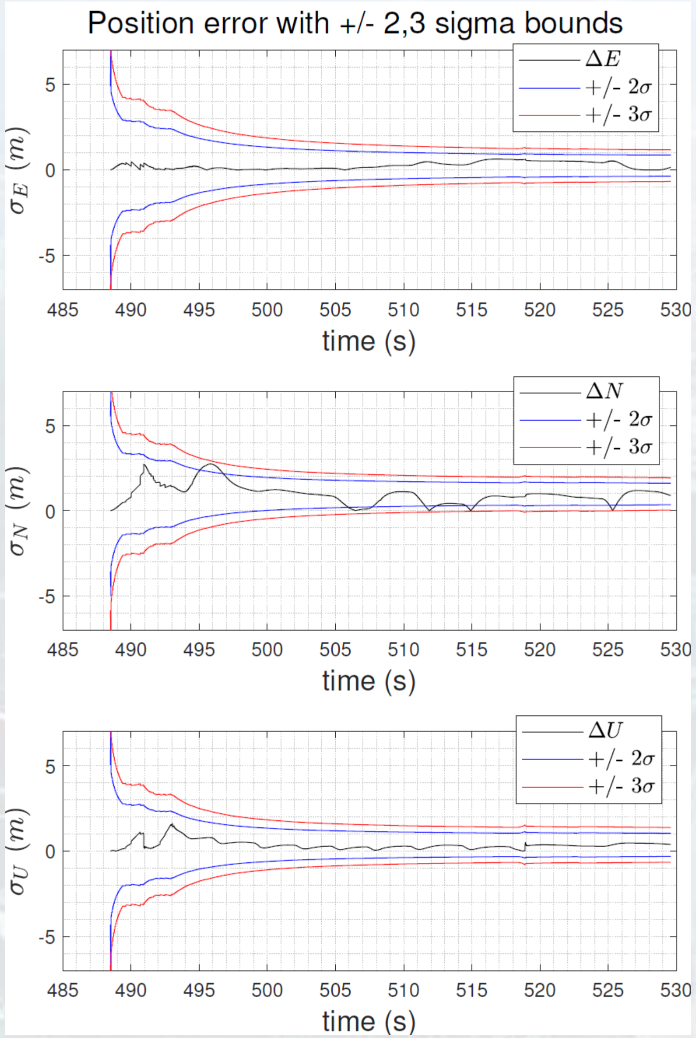


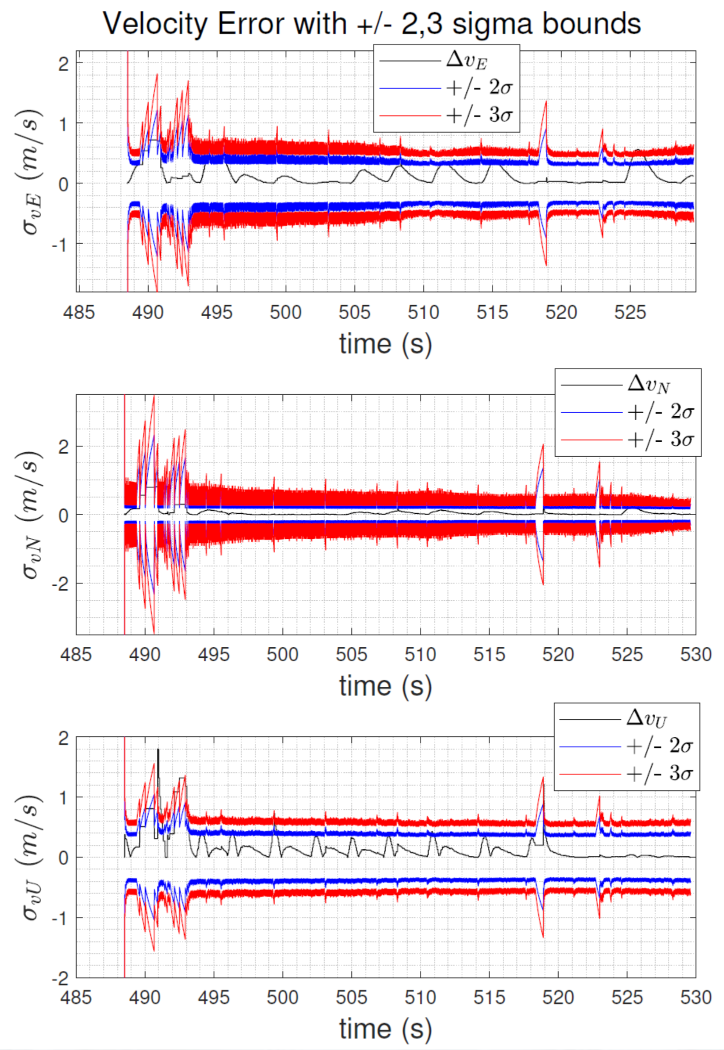


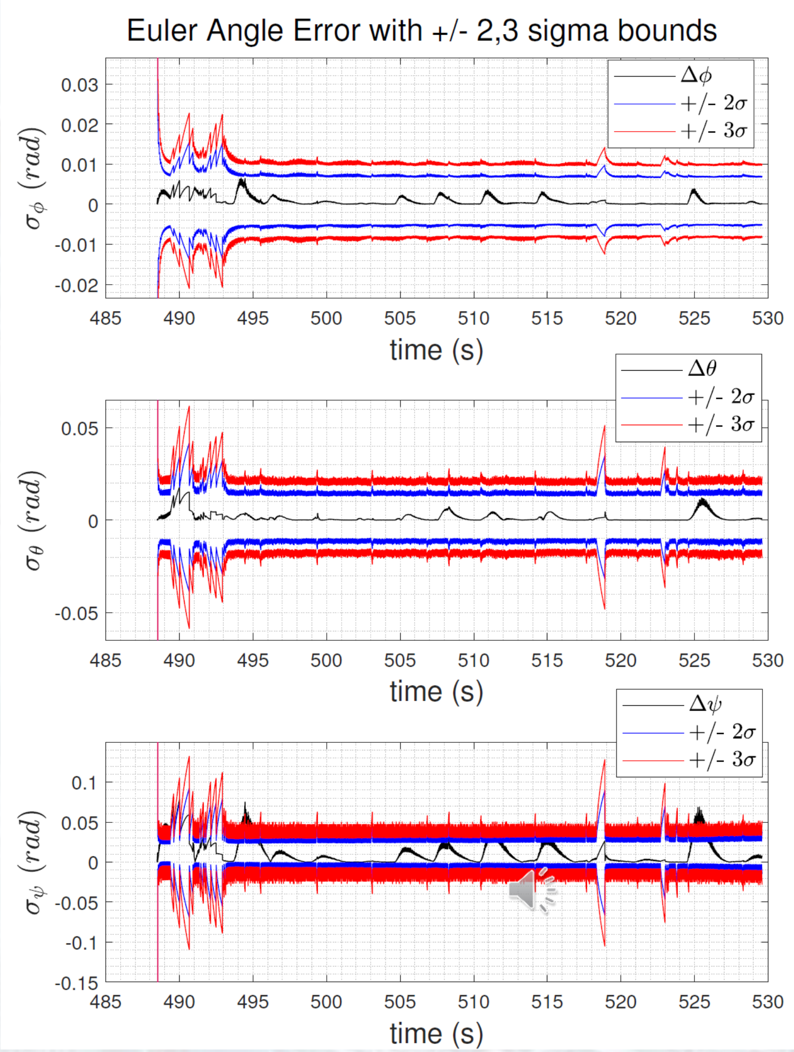


Simulation Results: VAL EKF

- Mean error (black line) generally stays between the $\pm 2{,}3\sigma$ bounds (blue & red lines)
- Bounded error -> confident in state estimation



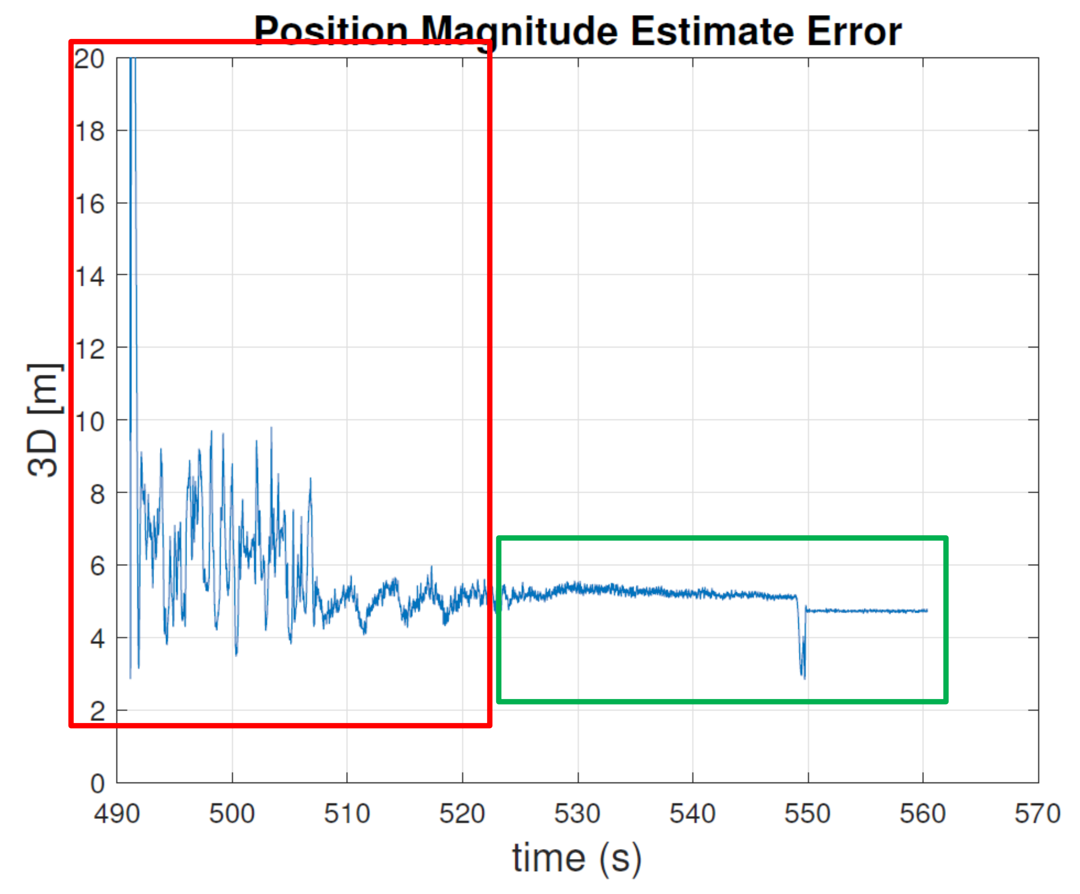


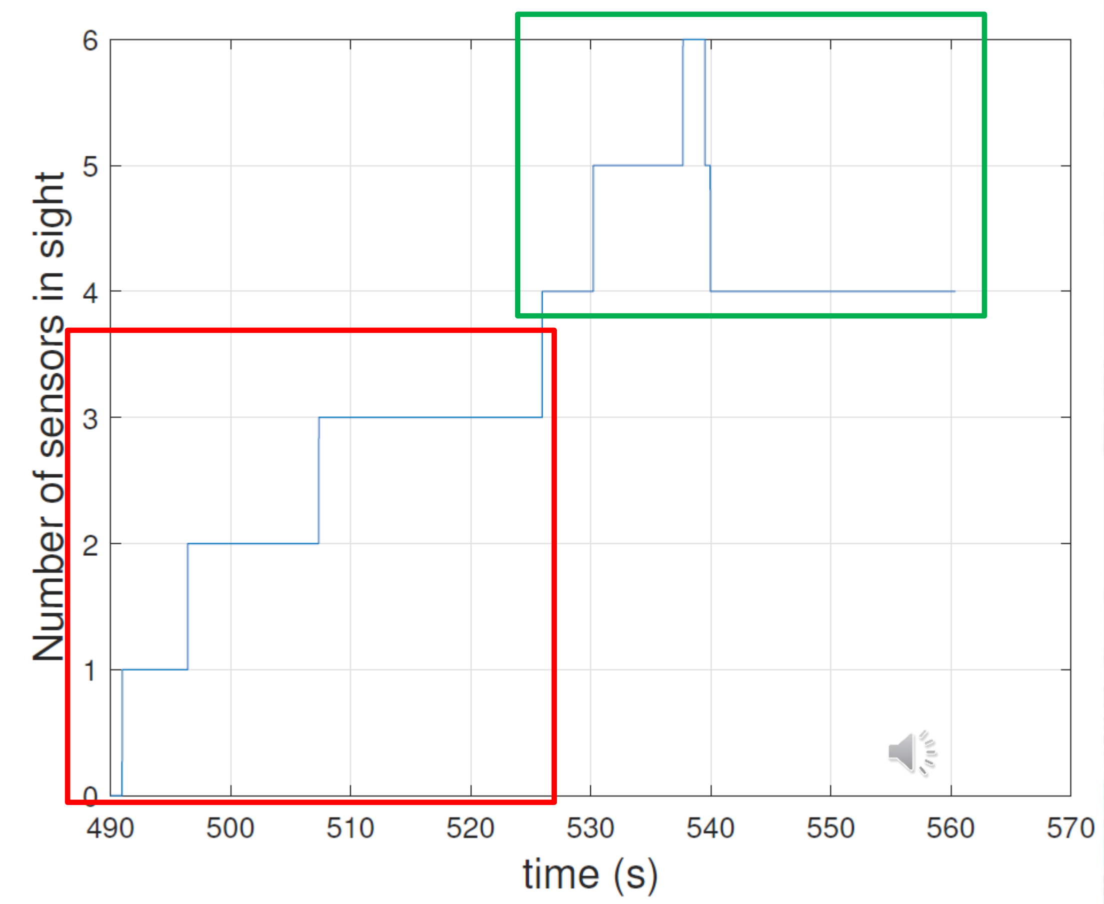


Simulation Results: Distributed Cameras

- Position magnitude error of tracked aircraft decreases with more cameras
- Accurate with at least four cameras seeing the aircraft
- Lots of noise when there are less than three cameras

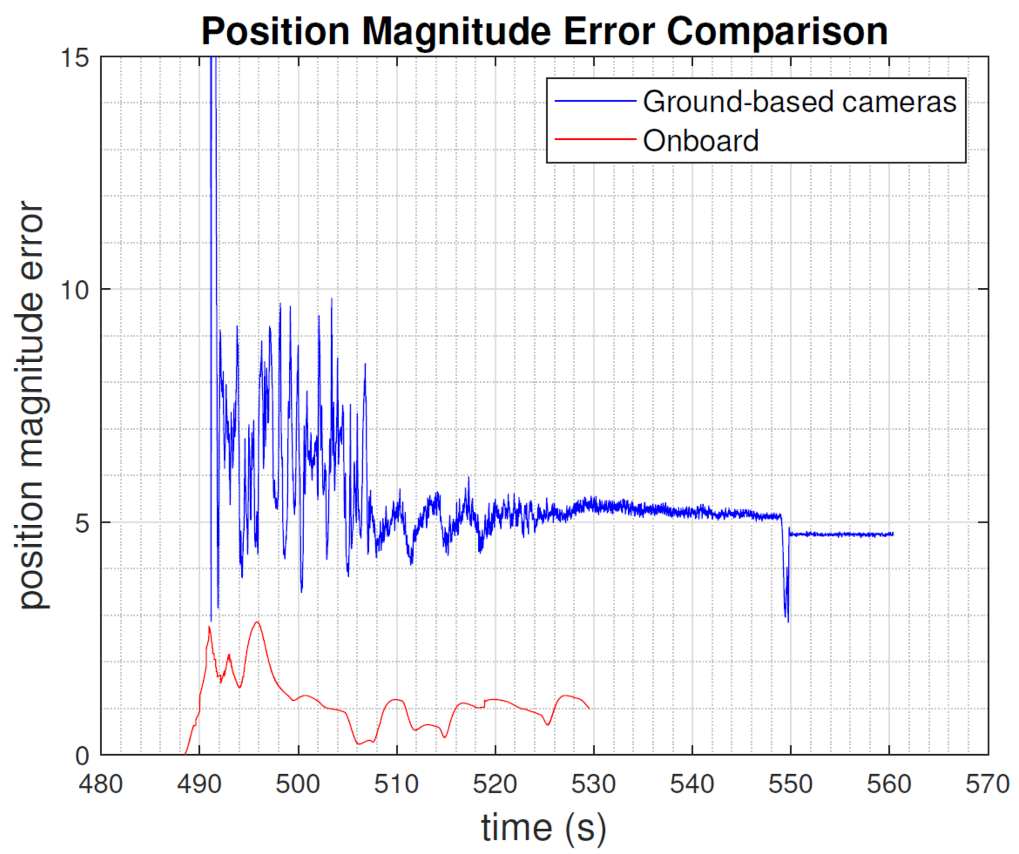
[15] Lombaerts, T., Kannan, K., Dolph, C., Stepanyan, V., George, G., and Ippolito, C., "Distributed Ground Sensor Fusion Based Object Tracking for Autonomous Advanced Air Mobility Operations," AIAA SciTech 2023 Forum, 2023.

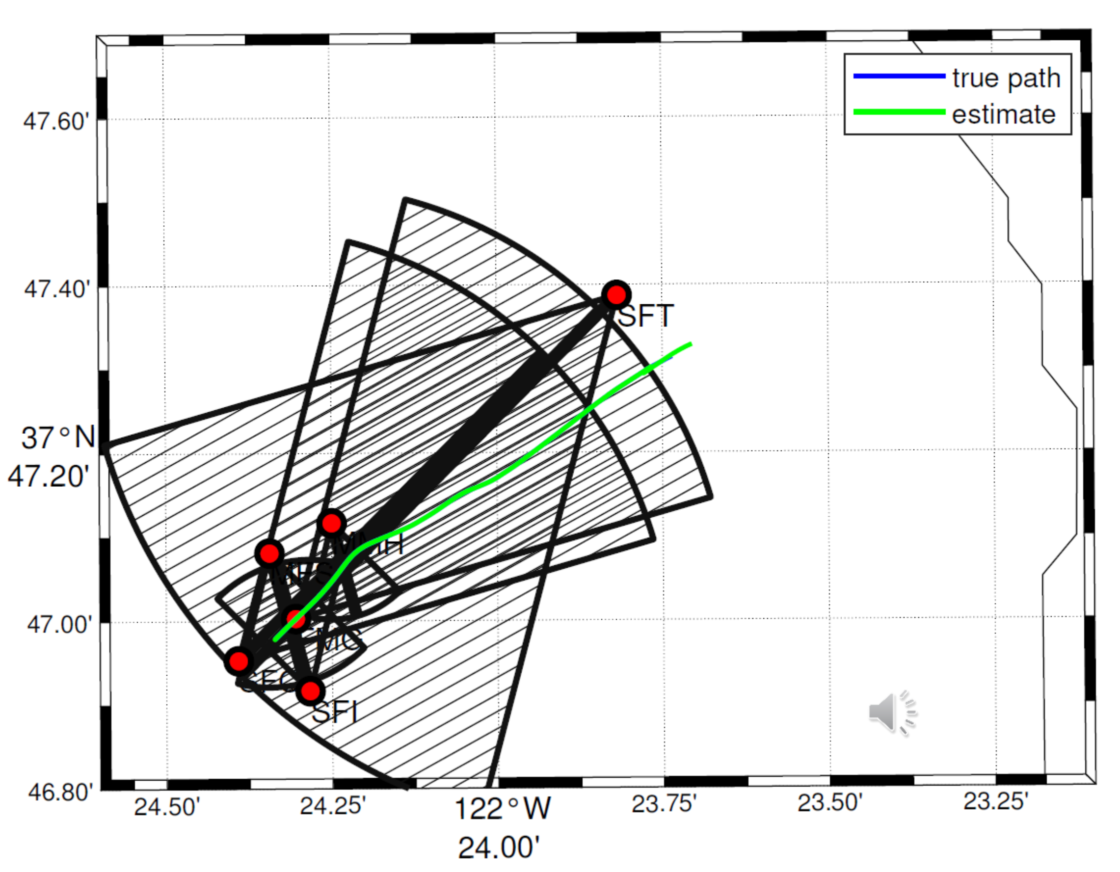




Simulation Results: VAL EKF vs. DS Cameras

- The onboard VAL EKF is more accurate due to in situ measurements but lacks the landing phase (finishes about 30 seconds earlier)
- Overlapping distributed camera coverage of the trajectory provides a backup navigation solution
- Maintaining communication between the ground-based and airborne-based navigation solutions increases the confidence in the state estimation, which helps ensure safe landings.





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Conclusion

- Hough circle detection and feature correspondence -> robust to false positives (detections are radially "close enough")
- Feature detection and correspondence steps are slow (~5 seconds), so real-time implementation is possible if these steps run faster
- Accurate airborne state estimation (submeter position accuracy) with frequent COPOSIT measurements
- COPOSIT velocity measurements yields accurate estimation and covariance convergence
- Onboard AAM estimation is more accurate than the ground-based camera estimation due to in situ measurements
- Maintain communication between airborne and ground-based solutions for increased confidence in state estimation with periodic checks, corrections, or assistance to maintain safety and accuracy for vertiport approach and landing
- This initial vision-based approach and landing simulation paves the way for new research activities in vertiport approach and landing to enhance future AAM operations and research

References

1. Federal Aviation Administration, "AC 150/5390-3 (Cancelled) - Vertiport Design," 2010. URL https://www.faa.gov/documentLibrary/media/advisory_circular/150-5390-3/150_5390_3.PDF

2. Federal Aviation Administration, "AC 150/5390-2C - Heliport Design," 2012. URL https://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf

3. Bassey, R., "Engineering Brief No. 105, Vertiport Design," U.S. Department of Transportation, 2022. URL https://www.faa.gov/sites/faa.gov/files/2022-09/eb-105-vertiports.pdf

4. Clearman, B., *Transportation-Markings Database: Aeronautical Navigation Aids*, Mount Angel Abbey, 2001.

5. Oliveira, P., Silva, J., and Soares, P., "A Comparative Study Between ILS and GBAS Approaches: The Case of Viseu Airfield," *Journal of Airline and Airport Management*, Vol. 10, No. 2, 2020, pp. 65–75. http://dx.doi.org/10.3926/jairm.168

6. Ciezkowski, M., "Triangulation Positioning System Based on a Static IR Beacon-Receiver System," *2017 22nd International Conference on Methods and Models in Automation and Robotics (MMAR)*, IEEE, 2017, pp. 84–88. https://doi.org/10.1109/MMAR.2017.8046803

7. Mondal, M., Shidlovskiy, S., Shashev, D., and Okunsky, M., "Autonomous Infrared Guided Landing System for Unmanned Aerial Vehicles," International Conference on Distributed Computer and Communication Networks, Springer, 2021, pp. 387–395. https://doi.org/10.1007/978-3-030-97110-6_30

8. Peisen, D., and Sawyer, B., "Heliport/Vertiport MLS Precision Approaches," U.S. Department of Transportation, 1994. URL http://www.tc.faa.gov/its/worldpac/techrpt/rd94-23.pdf

9. Oberkampf, D., DeMenthon, D. F., and Davis, L. S., "Iterative Pose Estimation Using Coplanar Feature Points," *Computer Vision and Image Understanding*, Vol. 63, No. 3, 1996, pp. 495–511. https://doi.org/10.1006/cviu.1996.0037

10. Kawamura, E., Kannan, K., Lombaerts, T., and Ippolito, C. A., "Vision-Based Precision Approach and Landing for Advanced Air Mobility," *AIAA SciTech 2022 Forum*, AIAA 2022-0497, 2022. https://doi.org/10.2514/6.2022-0497

11. Schaub, H., and Junkins, J. L., Analytical Mechanics of Space Systems, 4th ed., AIAA, 2018.

12. Lombaerts, T., Shish, K. H., Keller, G., Stepanyan, V., Cramer, N. B., and Ippolito, C. A., "Adaptive Multi-Sensor Fusion Based Object Tracking for Autonomous Urban Air Mobility Operations," AIAA SciTech 2022 Forum, 2022, p. 0362. https://doi.org/10.2514/6.2022-0362

13. Chu, P., Mulder, J. A. B., and Breeman, J., "Real-time Identification of Aircraft Physical Models for Fault Tolerant Flight Control," *Fault Tolerant Flight Control*, Springer, 2010, pp. 129–155. https://doi.org/10.1007/978-3-642-11690-2_4

14. Kannan, K., Baculi, J., Lombaerts, T., Kawamura, E., Gorospe, G., Holforty, W., Ippolito, C., Stepanyan, V., Dolph, C., and Brown, N., "A Simulation Architecture for Air Traffic Over Urban Environments Supporting Autonomy Research in Advanced Air Mobility," AIAA SciTech 2023 Forum, 2023.

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Thank you for listening! Questions?