

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

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*Autonomous Systems – Perception & Distributed Sensing*

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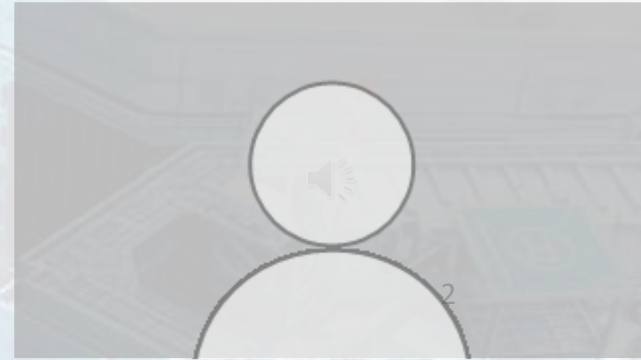
*January 2023*

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# Outline

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



# Problem

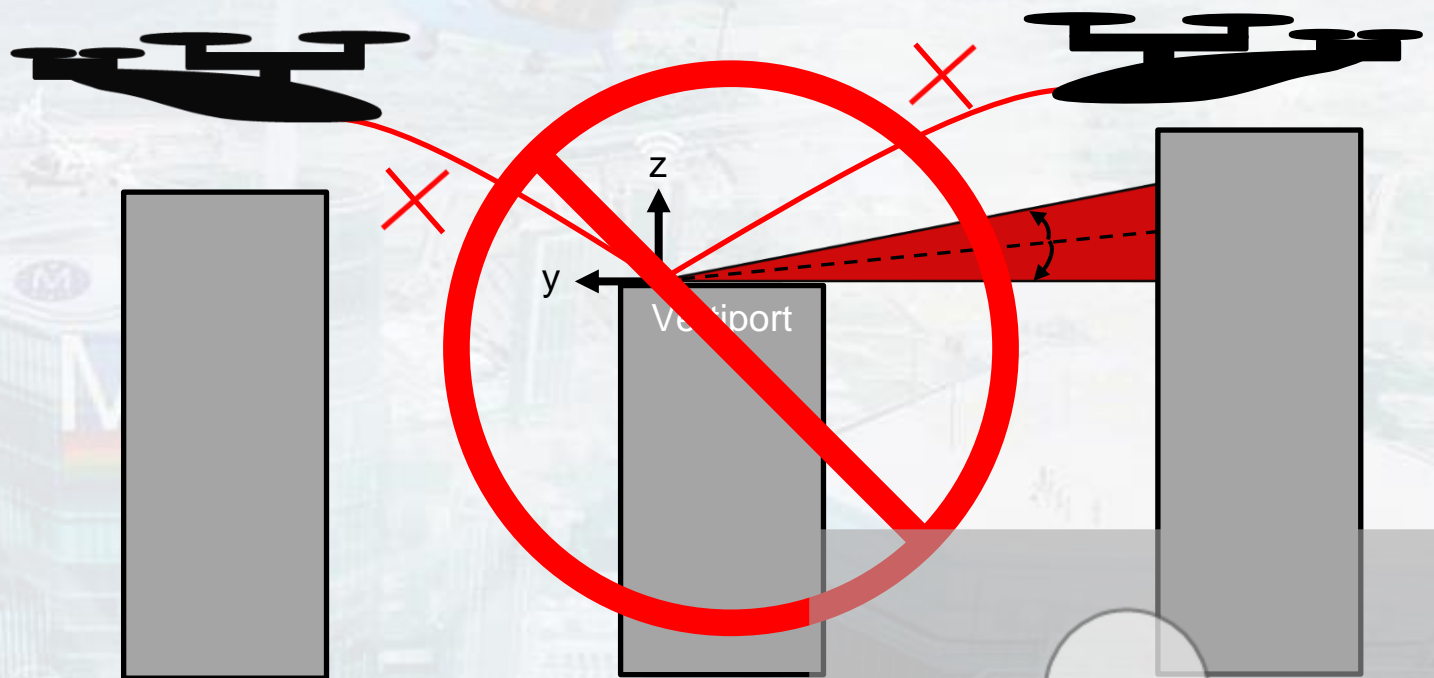
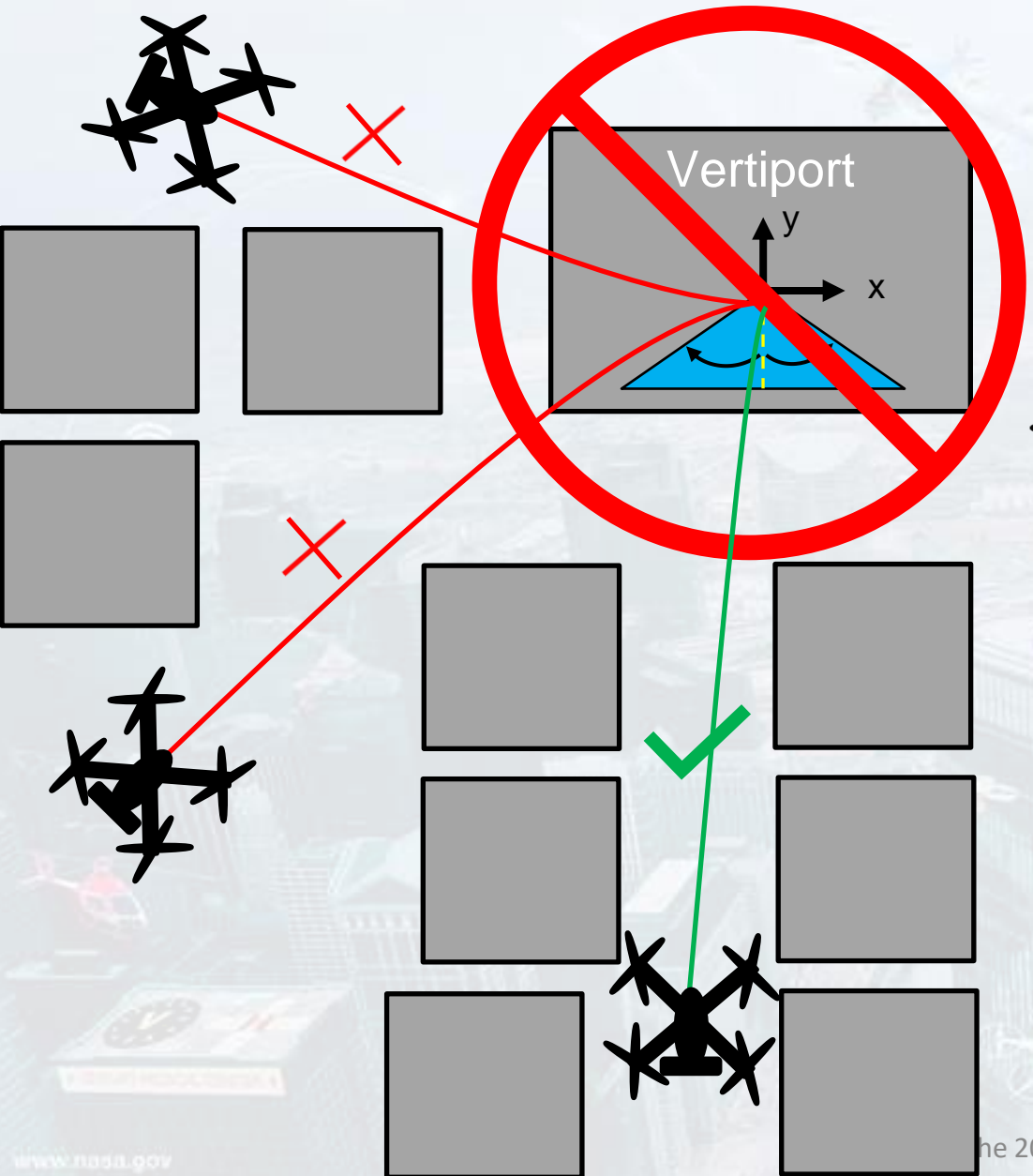
- AAM needs accurate and autonomous approach and landing systems
- Baseline perception and requirements come from existing technology: vision, IR, radar, glideslope indicators, and GPS
- Challenges for approach and landing in urban environments
  - GPS degradation
  - Narrow glideslope and localizer 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](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](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>

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

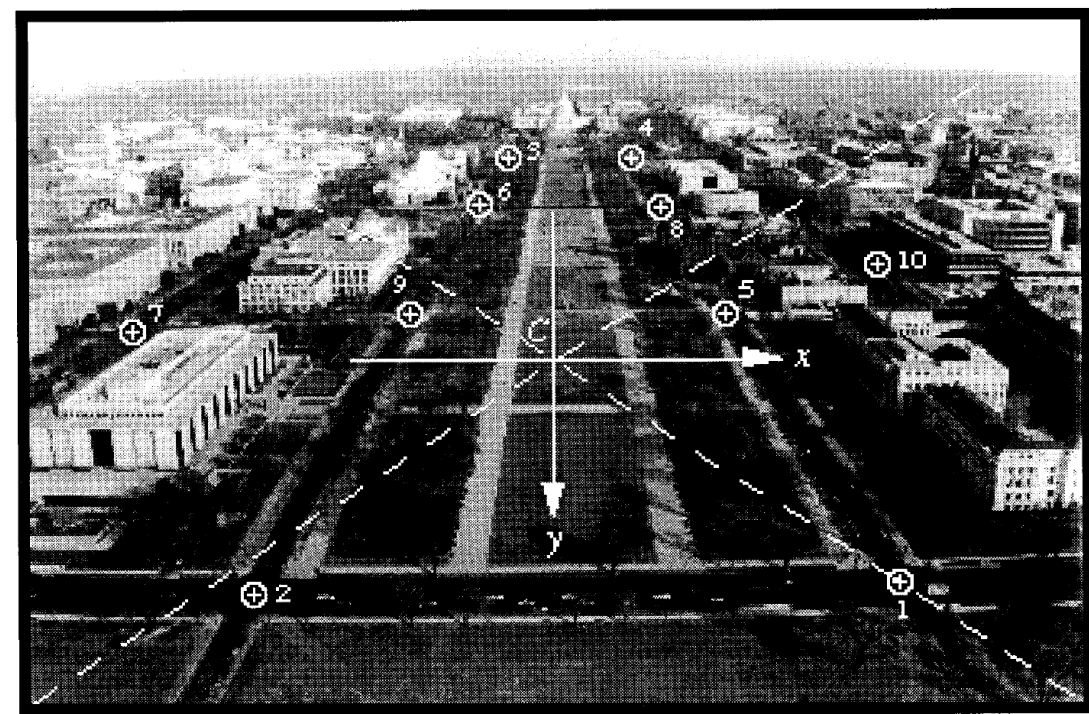
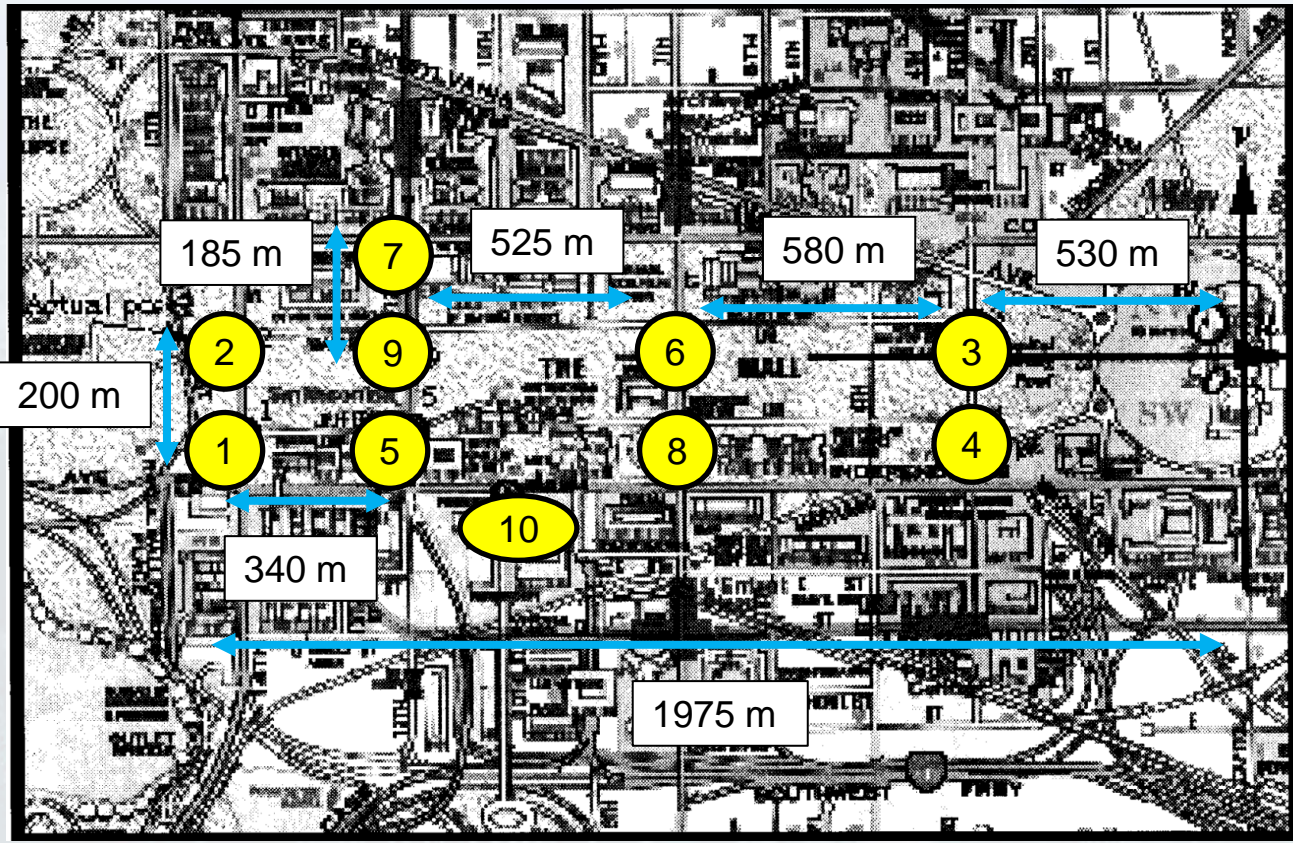


FIG. 13. The Mall in Washington, D.C., from the top of the Washington Monument, with feature points and image coordinate system.

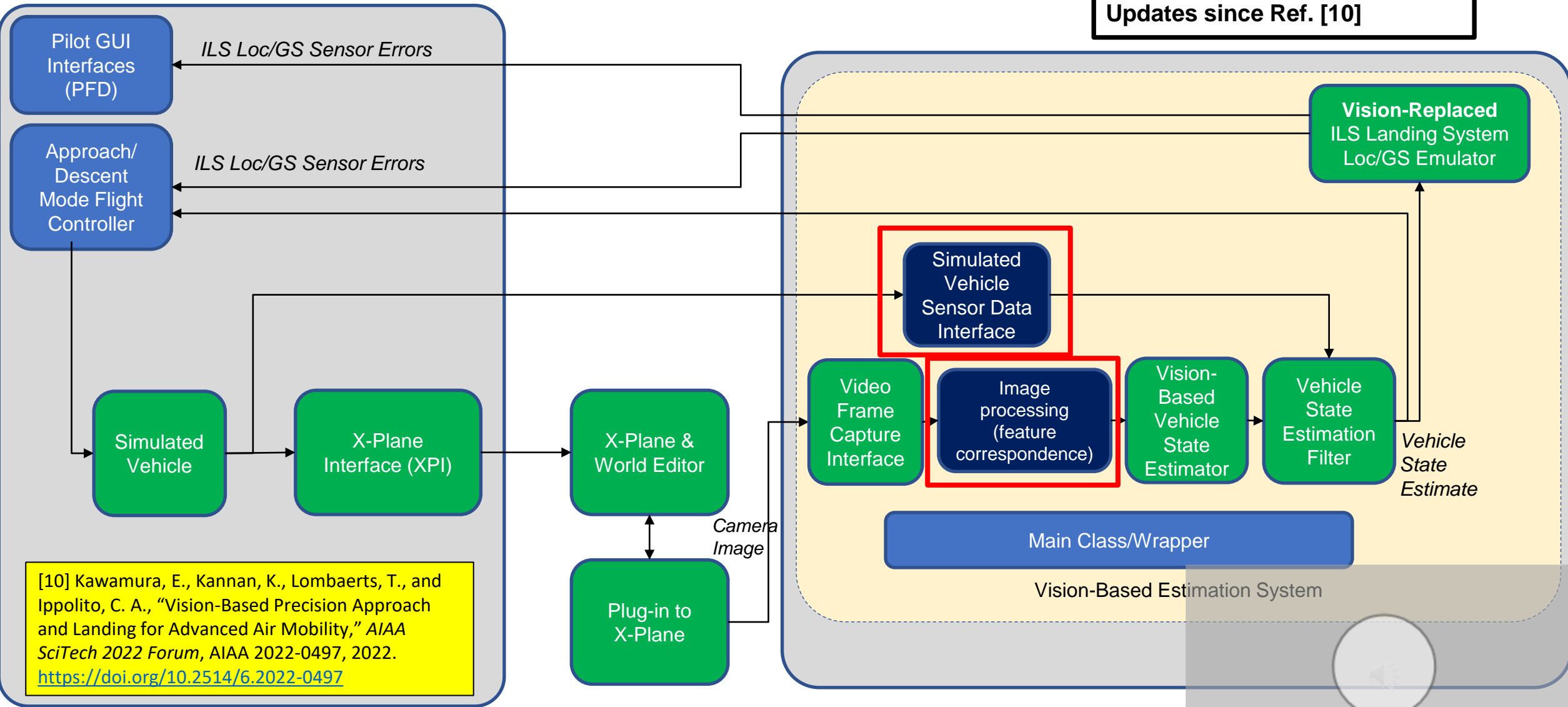
**Constraint: requires at least four coplanar points**

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

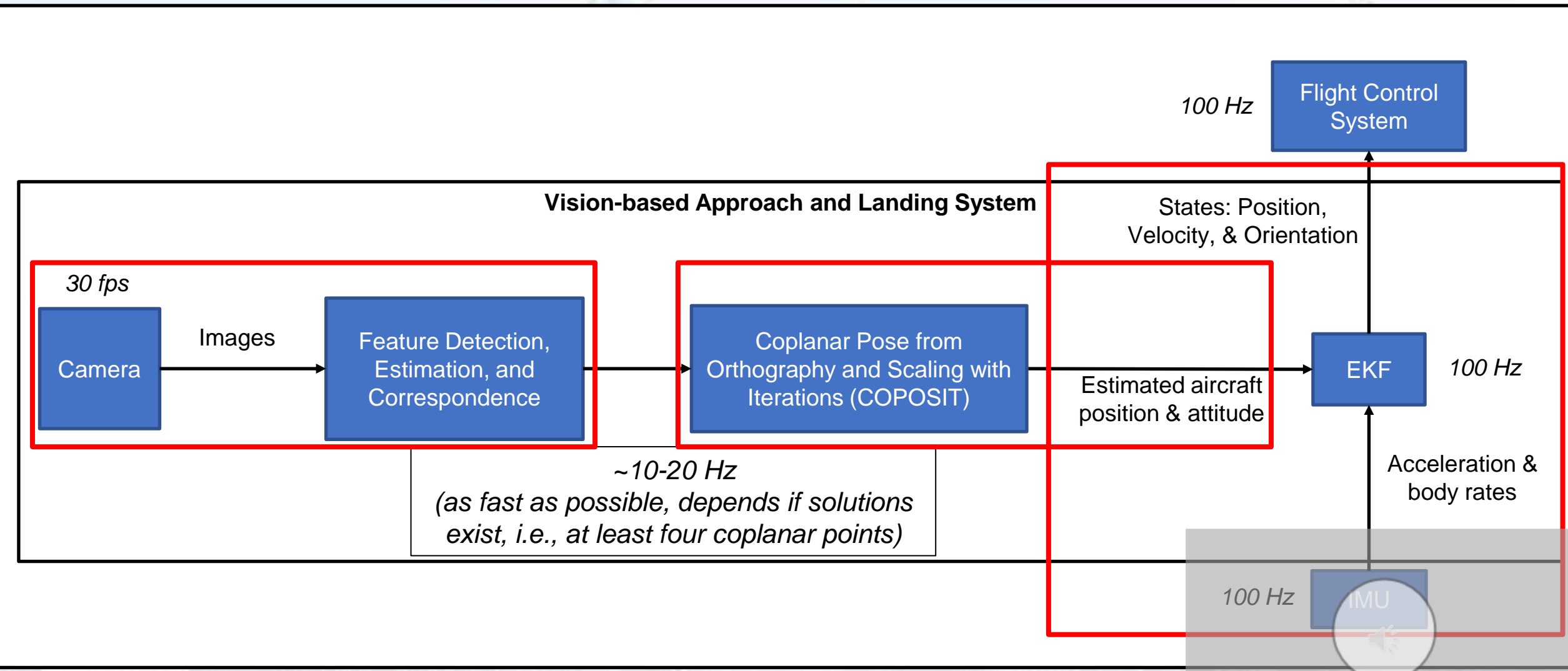
[9] Oberkamp, D., DeMenthon, D. F., and Davis, L. S., "Iterative Pose Estimation Using Coplanar Feature Points," *Computer Vision and Image Understanding*, Vol. 63, No. 3, 1996, pp. 495–511. <https://doi.org/10.1006/cvui.1996.0037>

# 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

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>



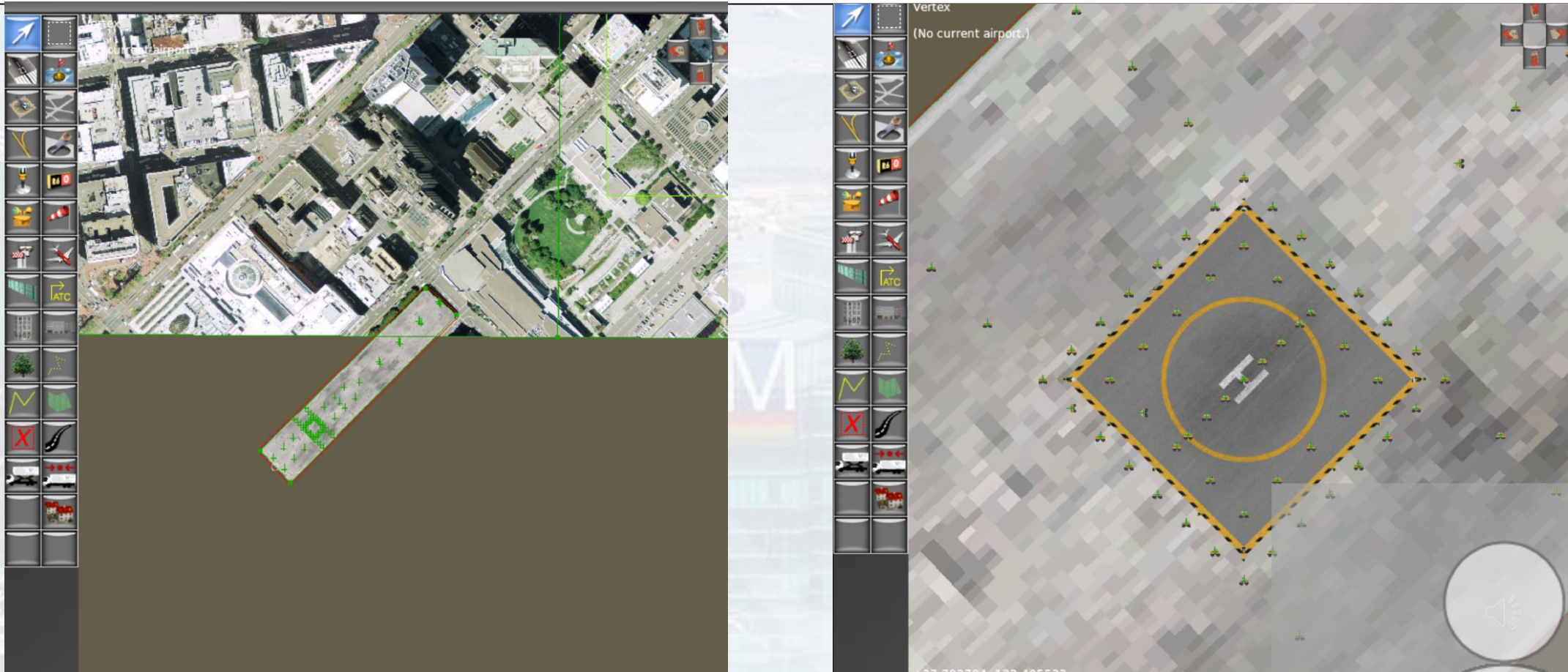
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- NASA Ames Reflection software simulates AAM aircraft models and trajectories such as vertiport approach and landing at Fifth & Mission Garage (FMG) in San Francisco.
- X-Plane (visualization tool) is a flight simulator that renders the Reflection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



- 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

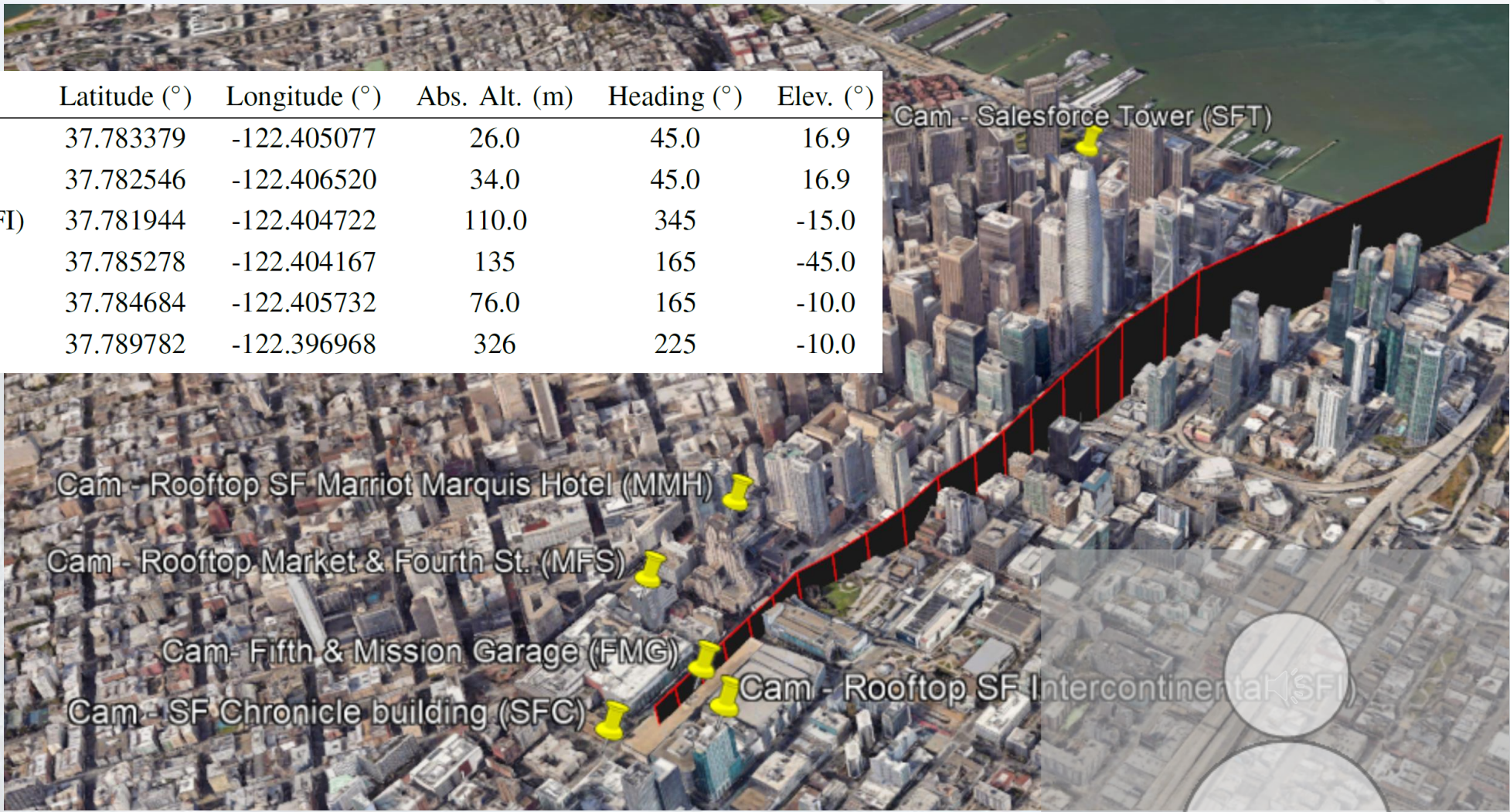


[2] Federal Aviation Administration, "AC 150/5390-2C - Heliport Design," 2012. URL [https://www.faa.gov/documentLibrary/media/Advisory\\_Circular/150\\_5390\\_2c.pdf](https://www.faa.gov/documentLibrary/media/Advisory_Circular/150_5390_2c.pdf)

[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>

- 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

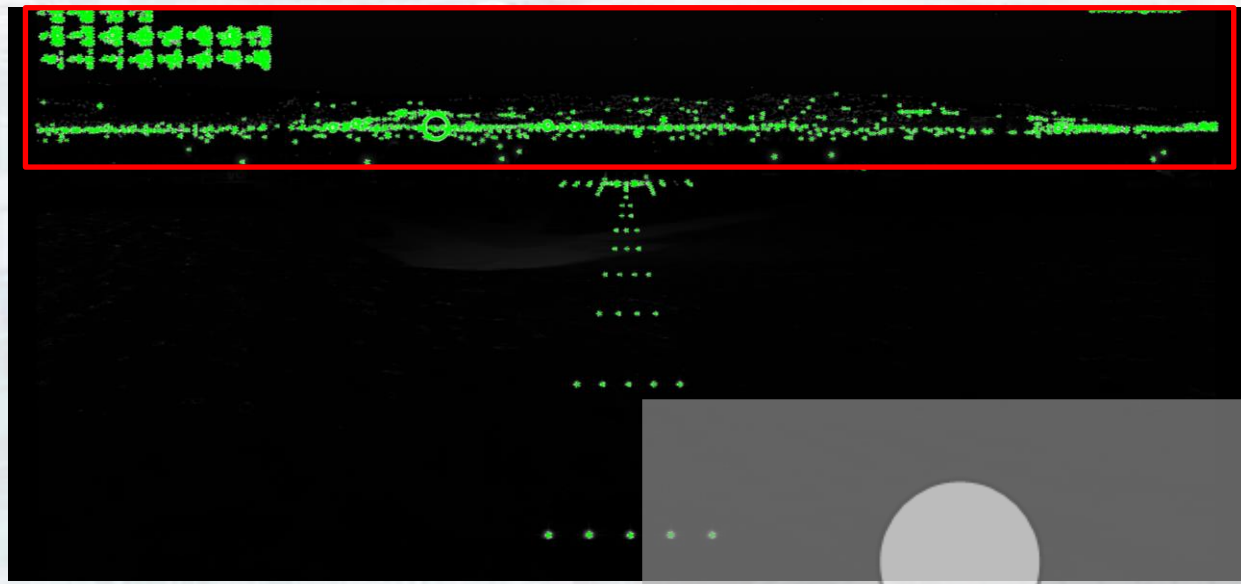
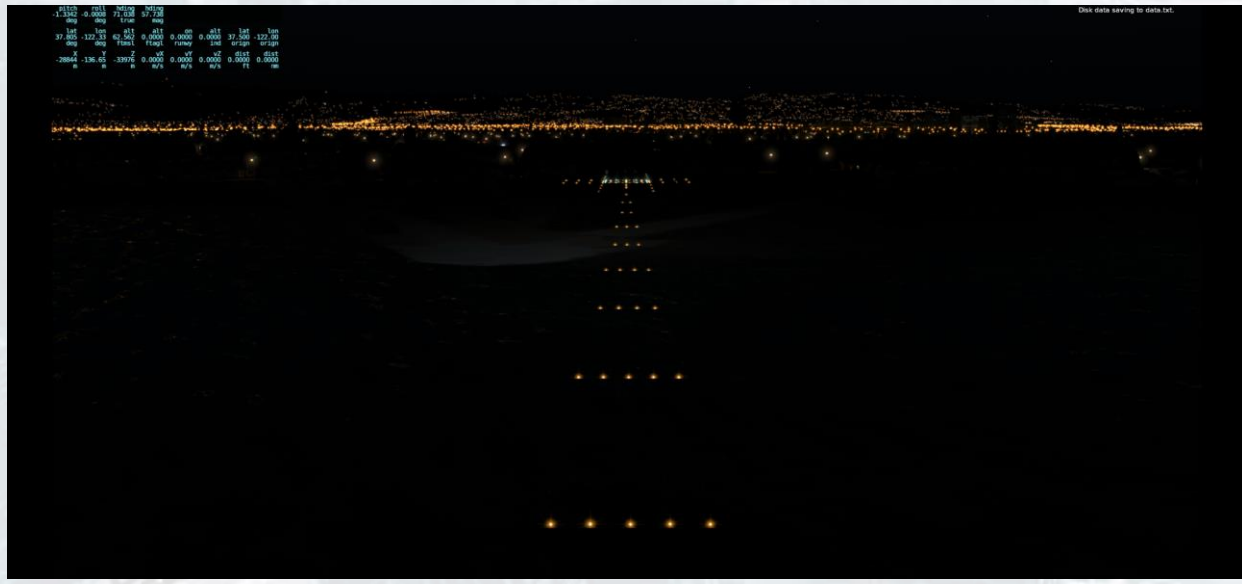
Camera Name	Latitude (°)	Longitude (°)	Abs. Alt. (m)	Heading (°)	Elev. (°)
Fifth & Mission Garage (FMG)	37.783379	-122.405077	26.0	45.0	16.9
San Francisco Chronicle (SFC)	37.782546	-122.406520	34.0	45.0	16.9
San Francisco Intercontinental (SFI)	37.781944	-122.404722	110.0	345	-15.0
Marriot Marquis Hotel (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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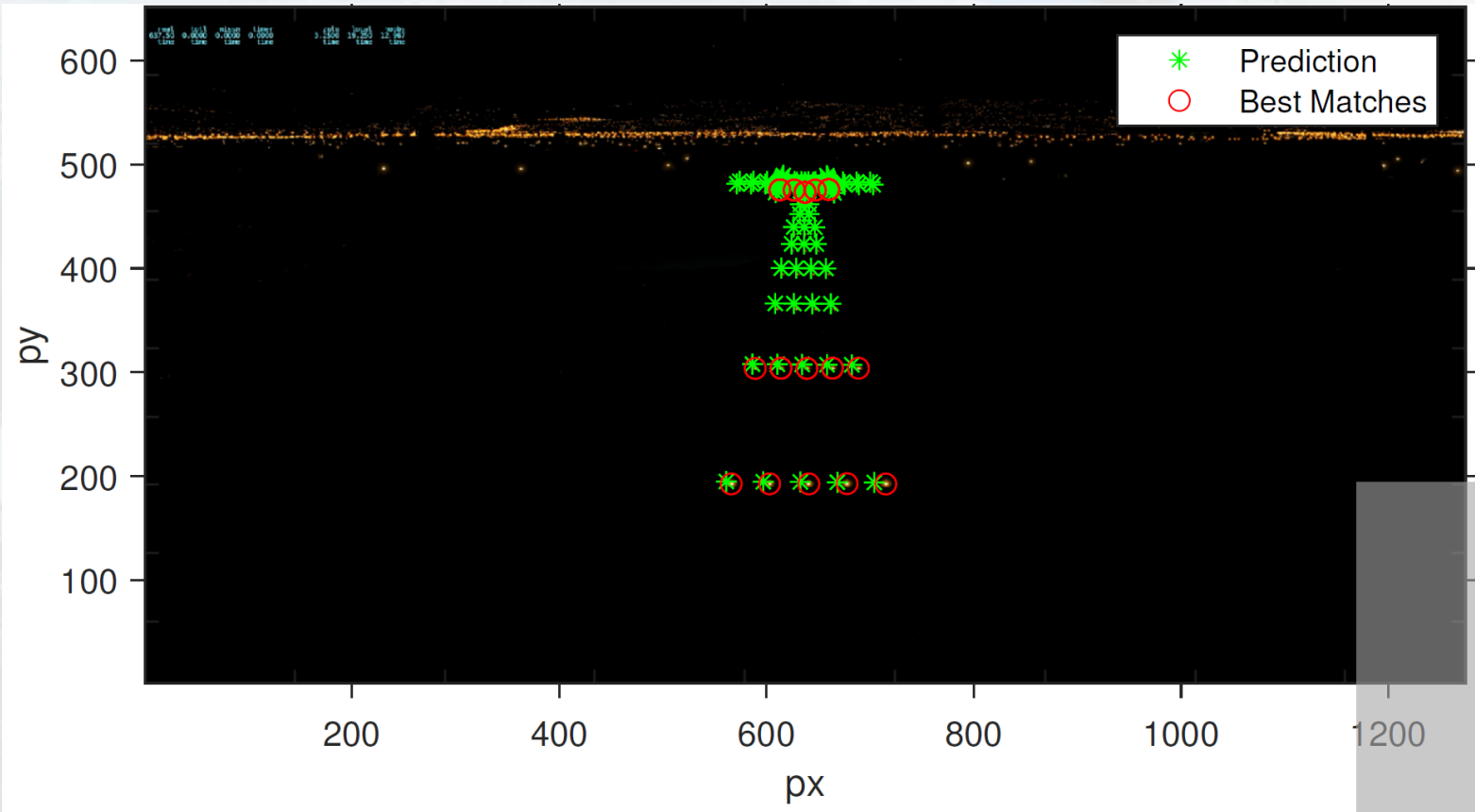
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- Conducted preliminary tests for feature detection methods at Middle Harbor Shoreline Park (Oakland): Hough circle detector, SURF, Harris corner detection, FAST, template matching, and image registration
- **Hough circle detector** finds the circular 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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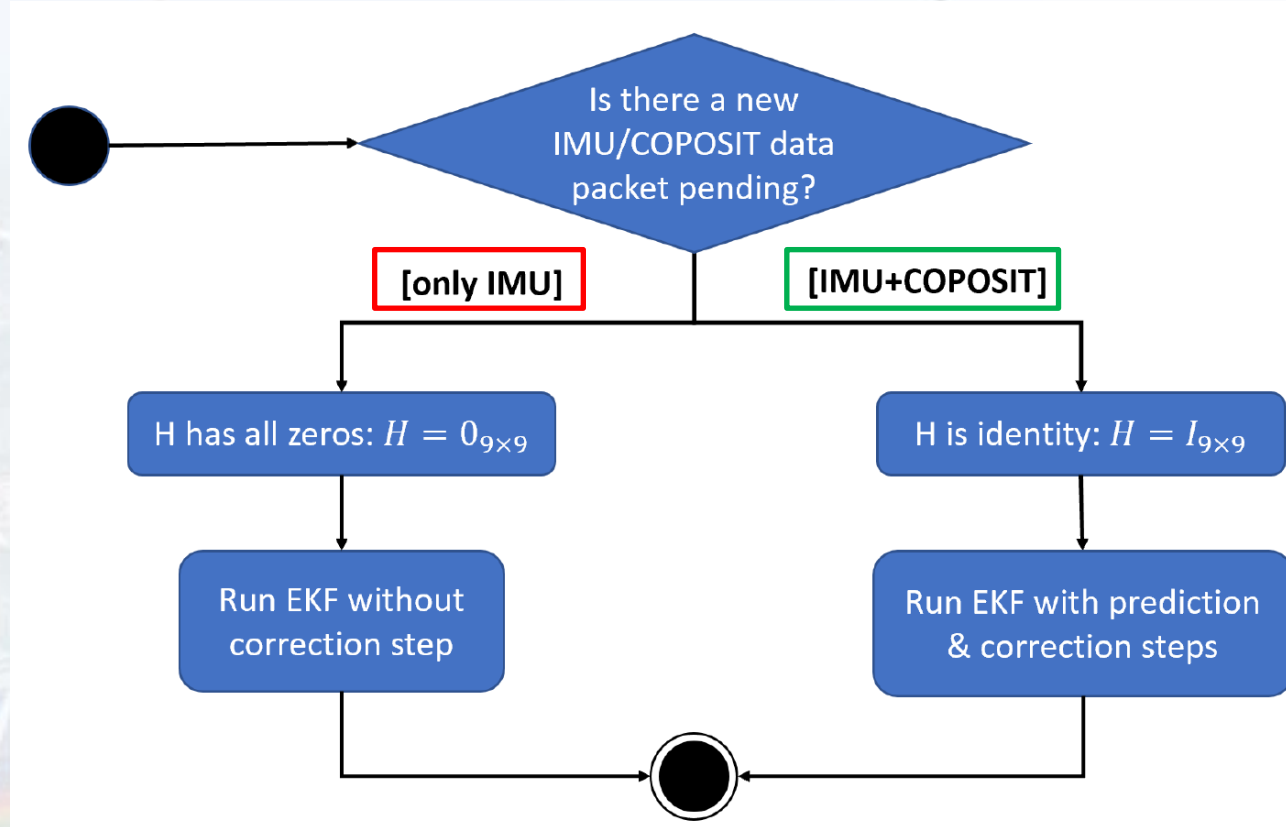


- Follows the EKF design in [10]:
  - IMU in input vector,  $u$ ,
  - COPOSIT in measurement vector,  $z$

- 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



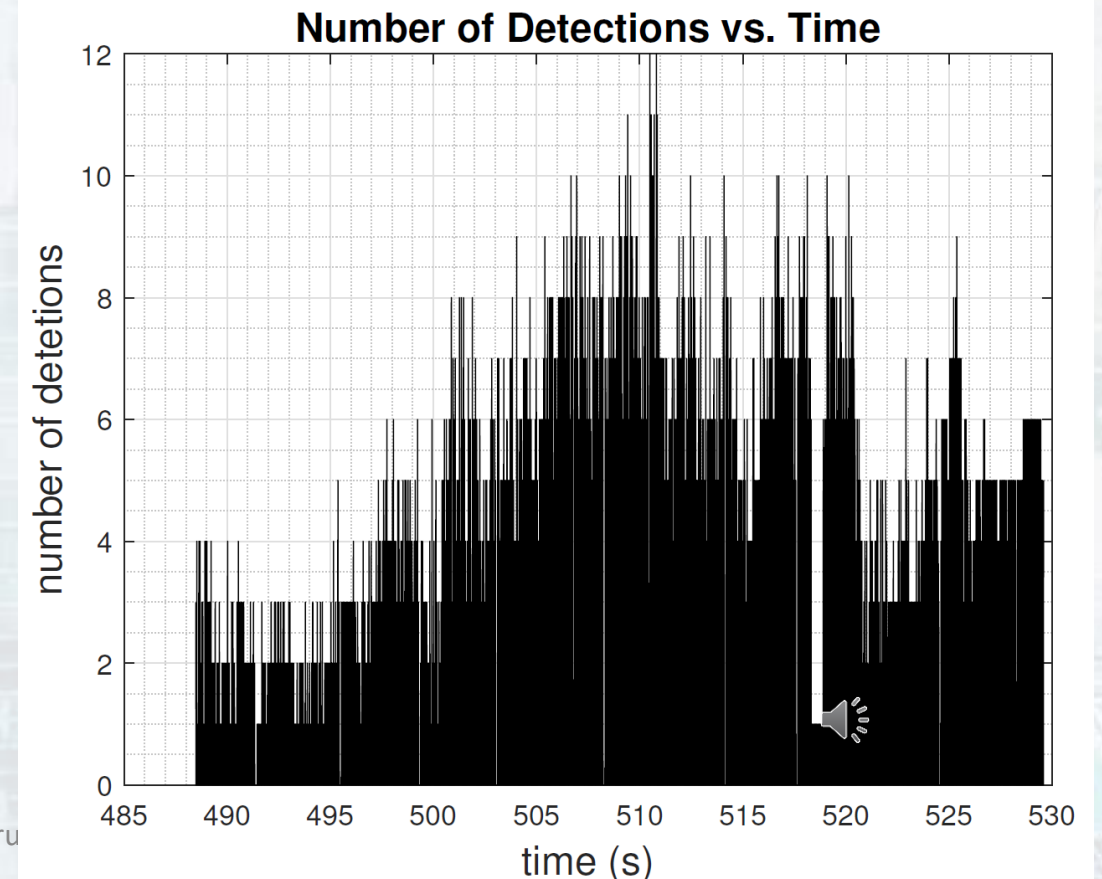
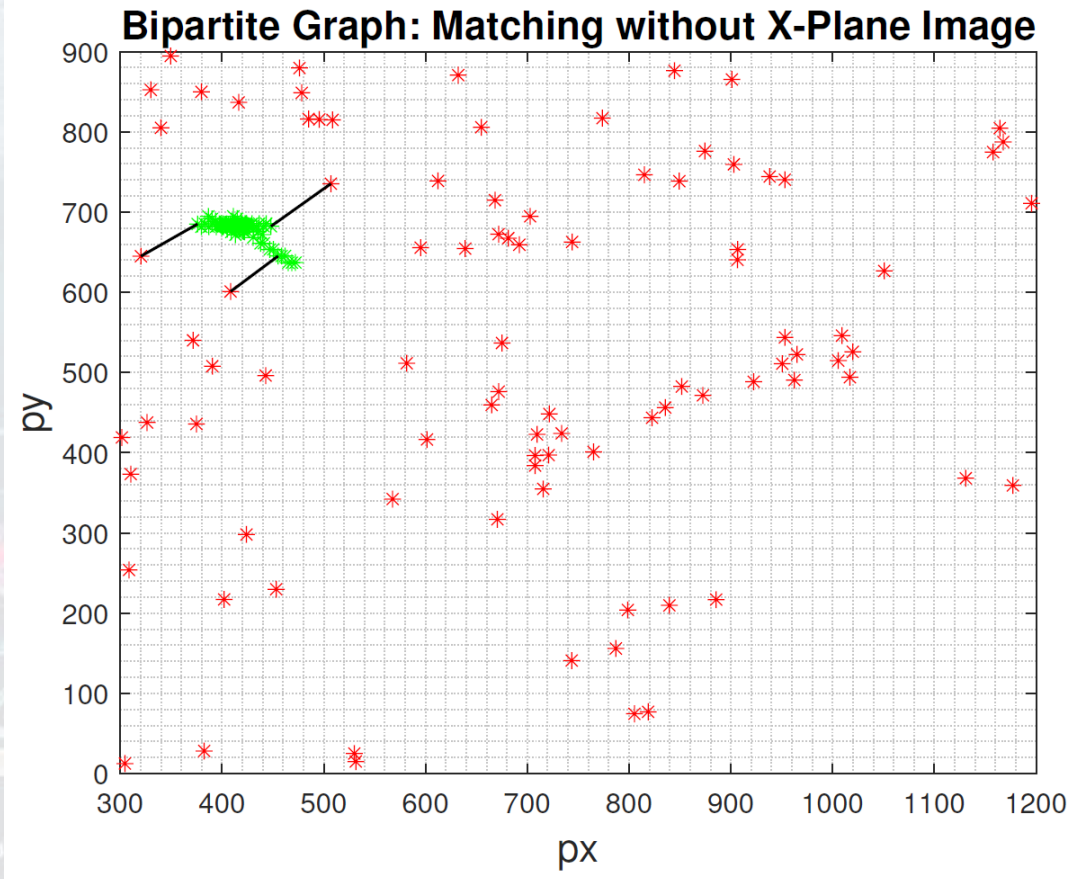
[10] Kawamura, E., Kannan, K., Lombaerts, T., and Ippolito, C. A., "Vision-Based Precision Approach and Landing for Advanced Air Mobility," *AIAA SciTech 2022 Forum*, AIAA 2022-0497, 2022. <https://doi.org/10.2514/6.2022-0497>

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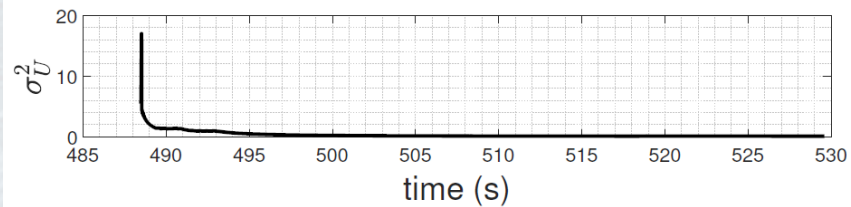
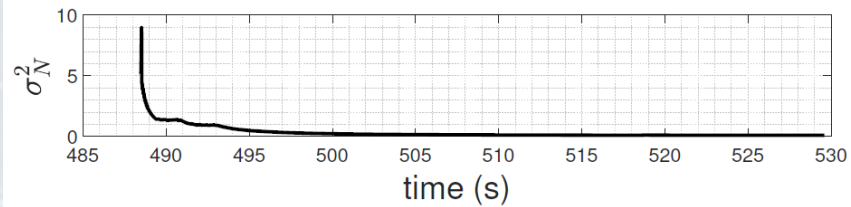
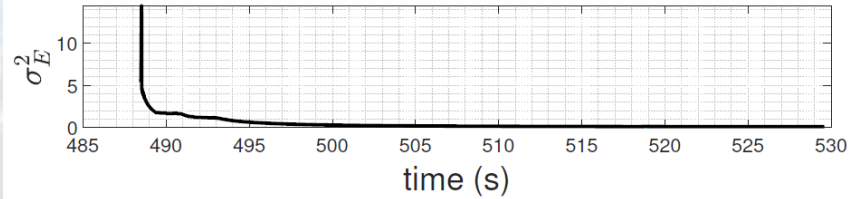


- Adequate feature detection and correspondence with some offset
- There are usually at least four detections (coplanar points), which leads to several COPOSIT measurements for more correction steps in the EKF (accurate state estimation)

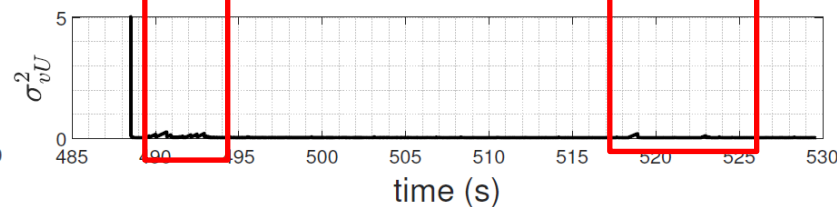
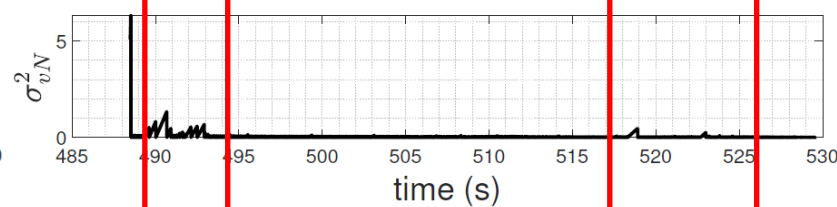
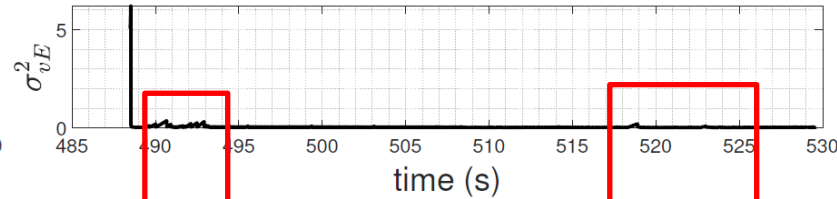


- Error covariances converge quickly
- Small spikes and fluctuations without COPOSIT measurements
- Small values for covariances: high confidence and low uncertainty in estimate

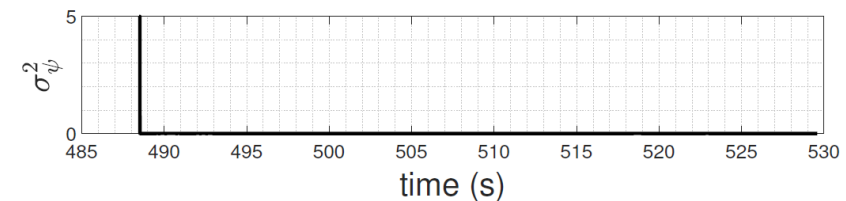
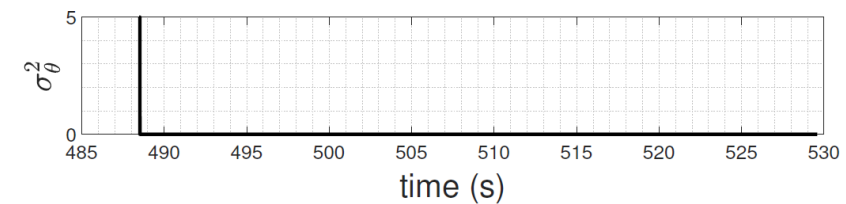
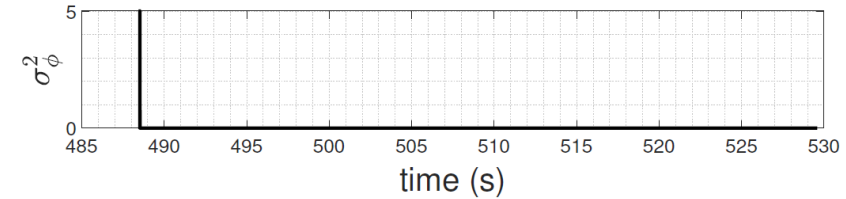
Error Covariance for Position



Error Covariance for Velocity



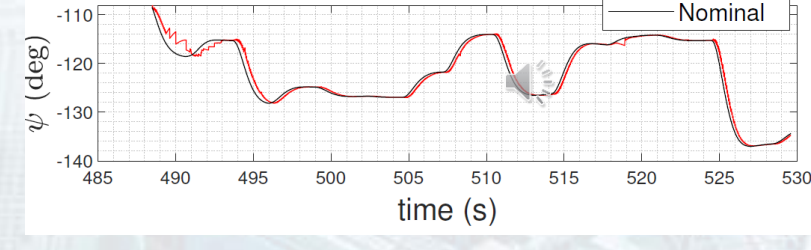
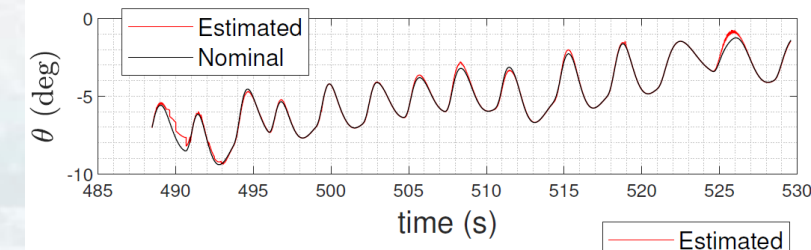
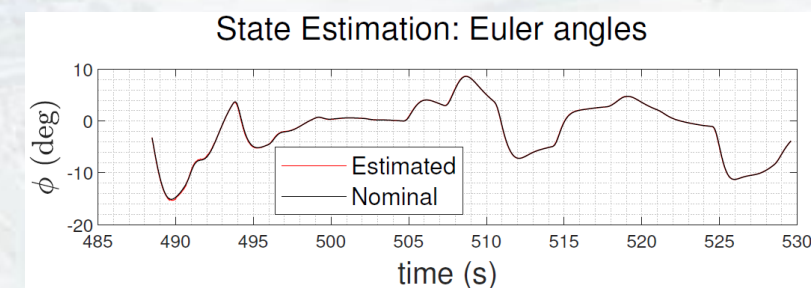
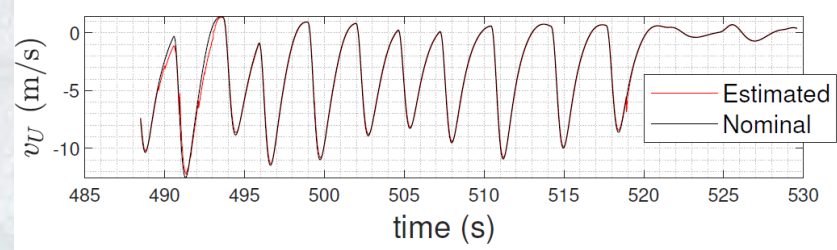
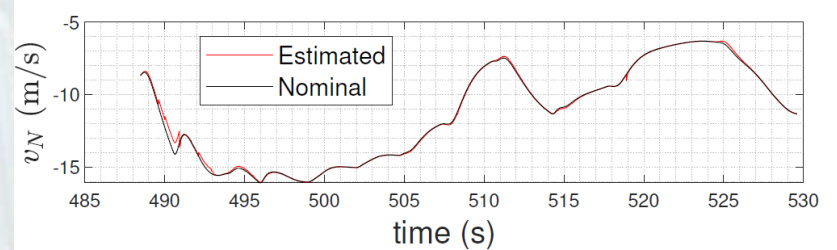
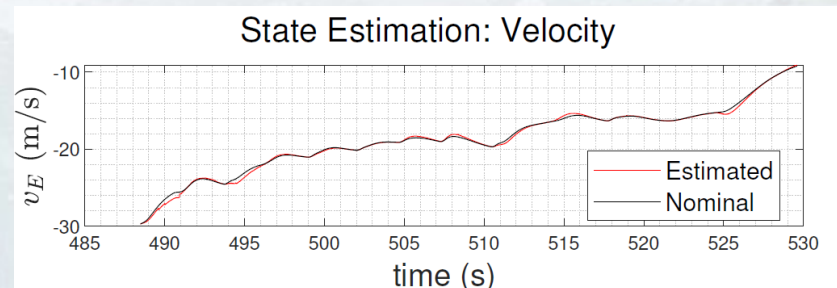
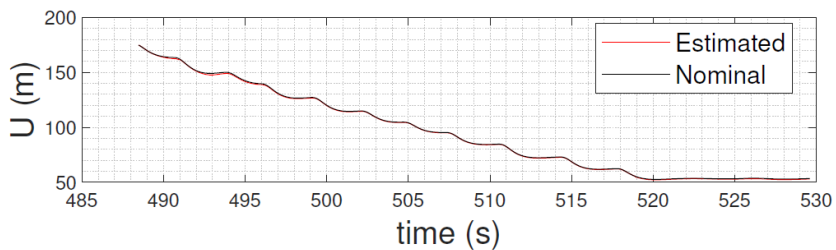
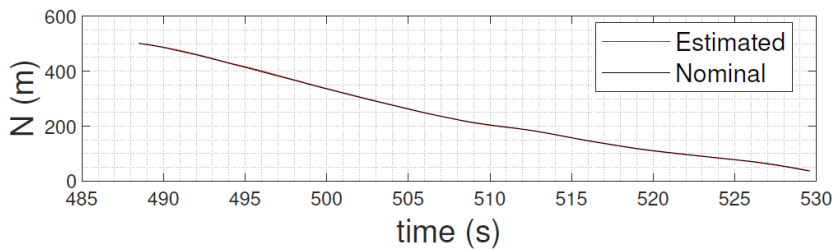
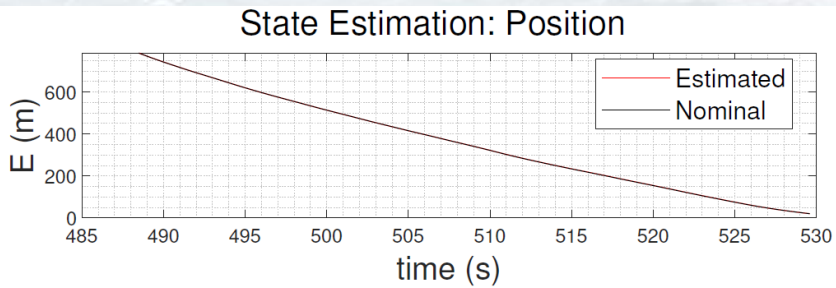
Error Covariance for Euler angles



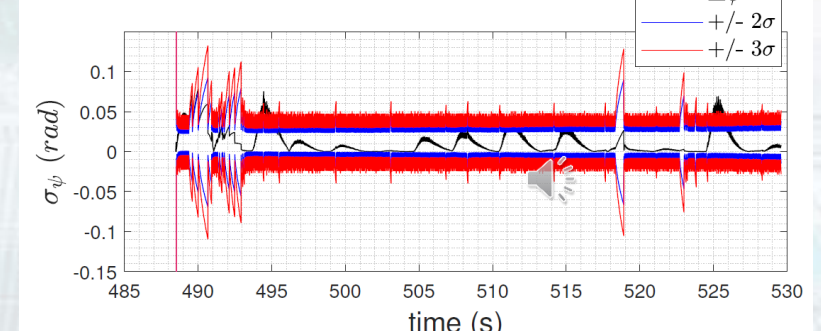
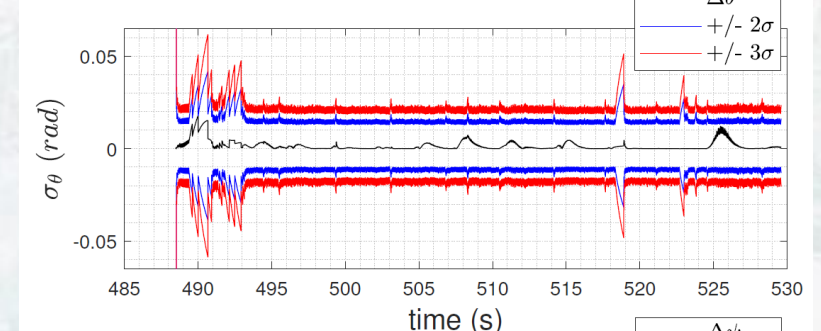
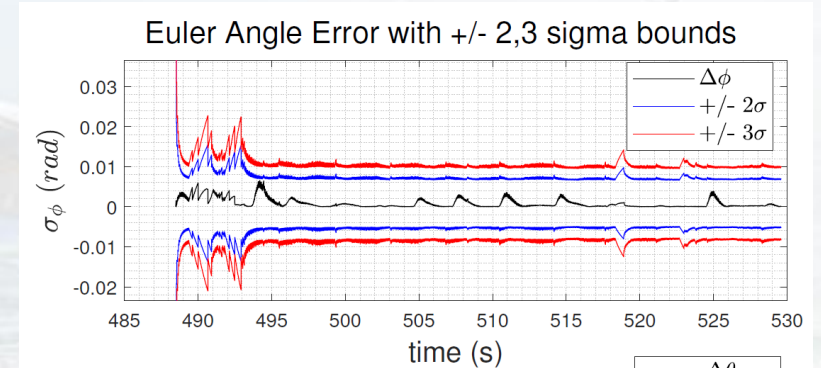
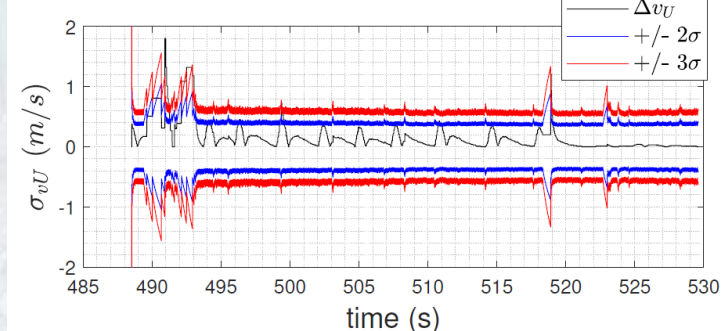
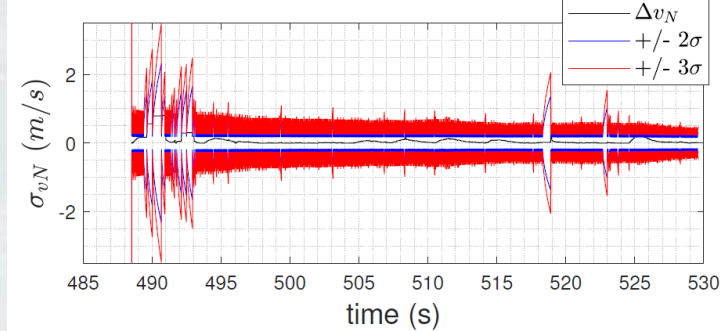
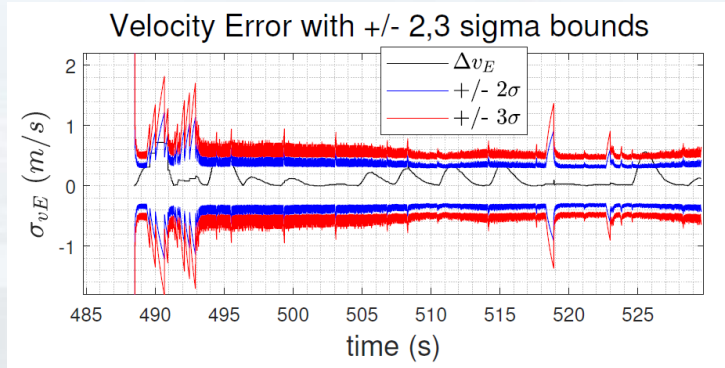
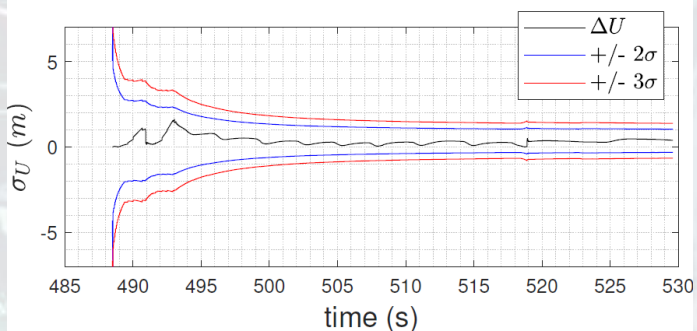
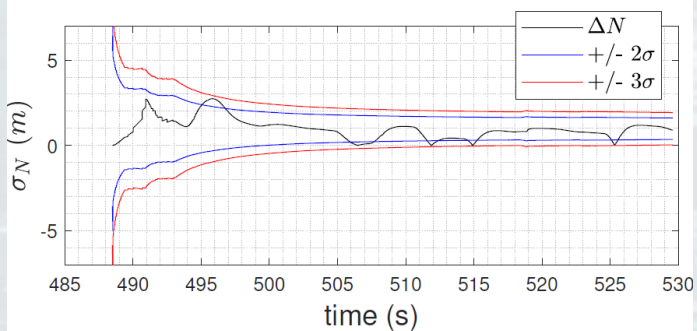
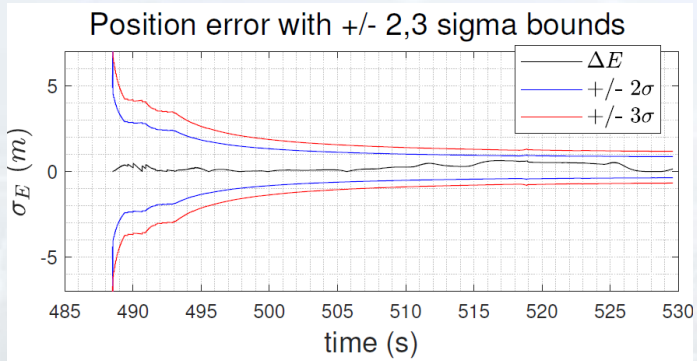
# Simulation Results: VAL EKF

- 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)	$\phi$ (rad)	$\theta$ (rad)	$\psi$ (rad)
$\mu$	0.256	0.980	0.365	0.135	0.067	0.162	0.000856	0.00156	0.0116
$\sigma$	0.203	0.576	0.253	0.169	0.135	0.241	0.00115	0.00265	0.0151

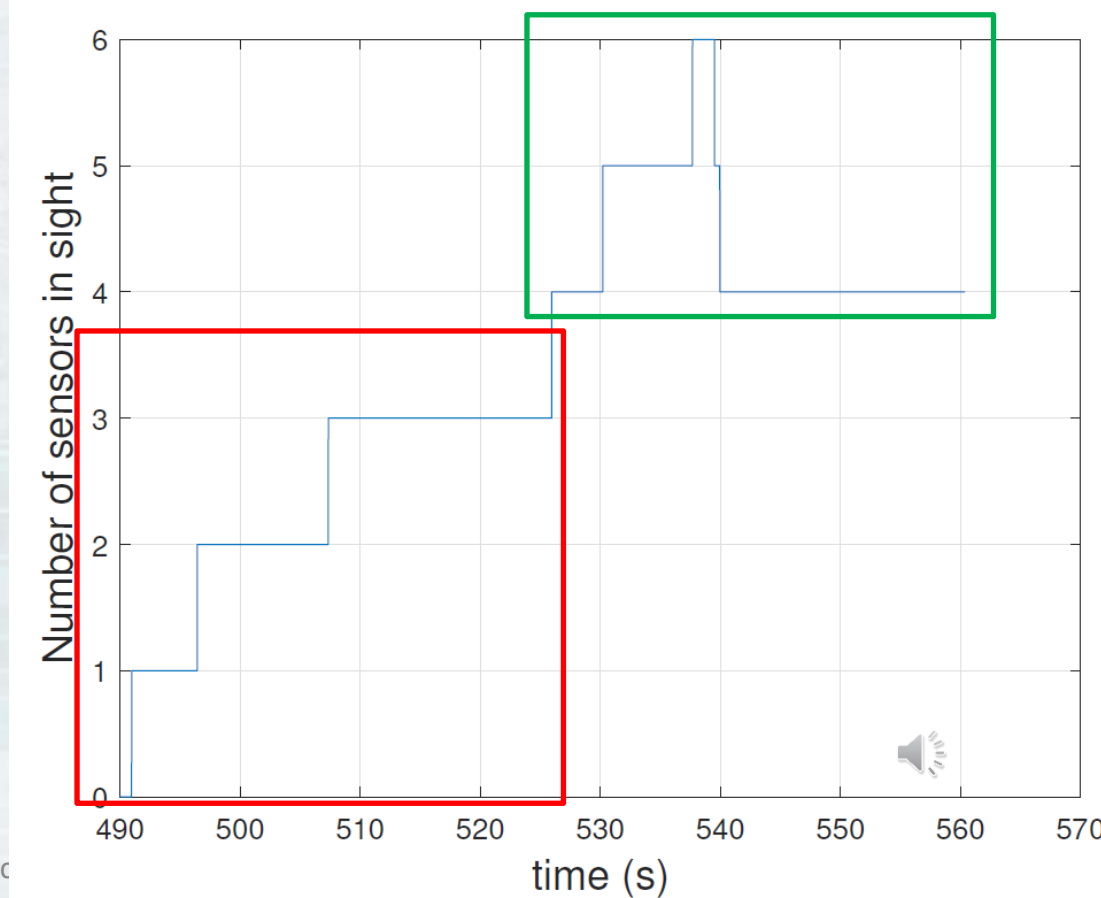
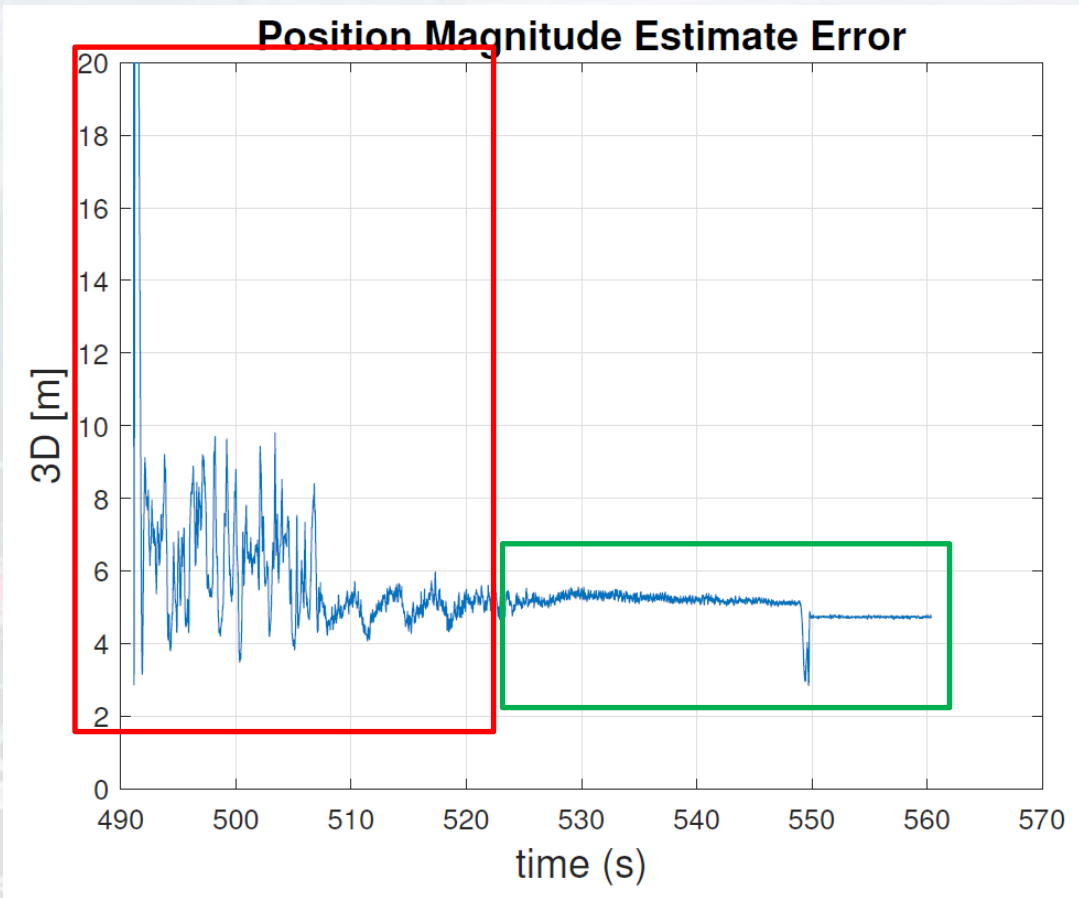


- Mean error (black line) generally stays between the  $\pm 2,3\sigma$  bounds (blue & red lines)
- Bounded error -> confident in state estimation

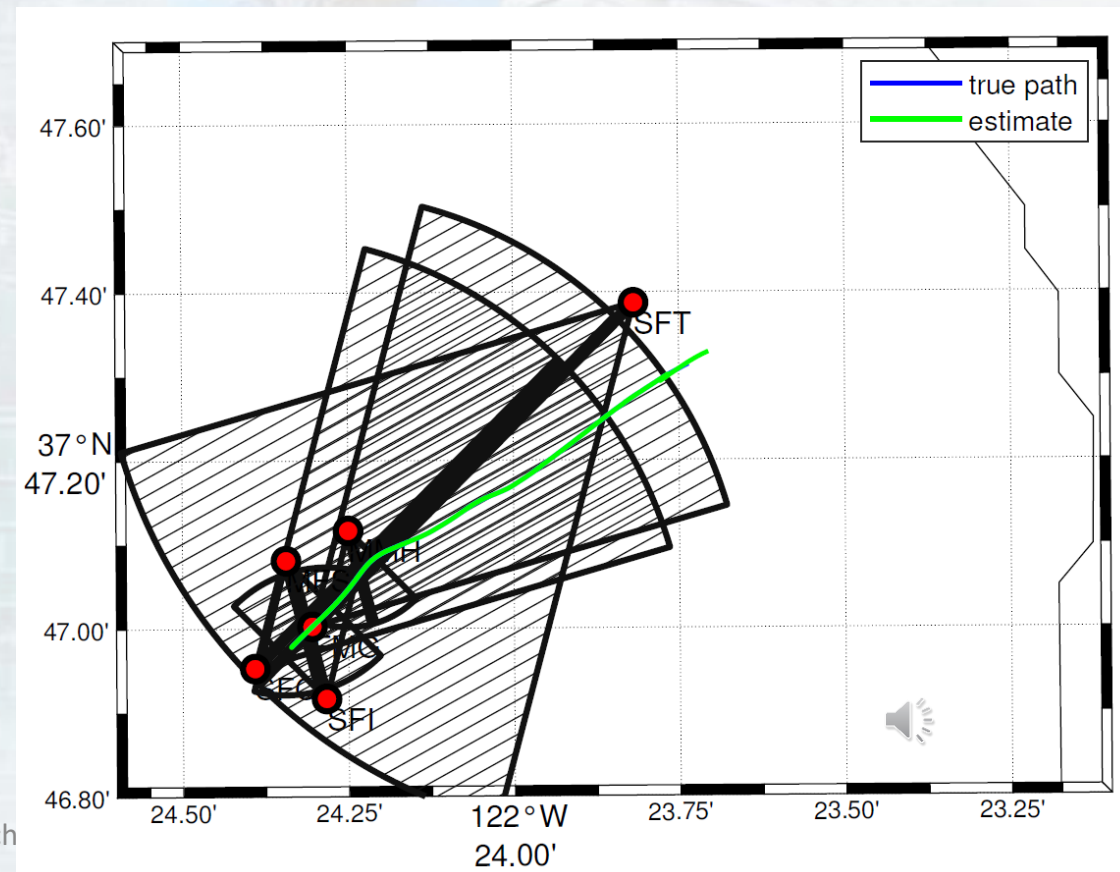
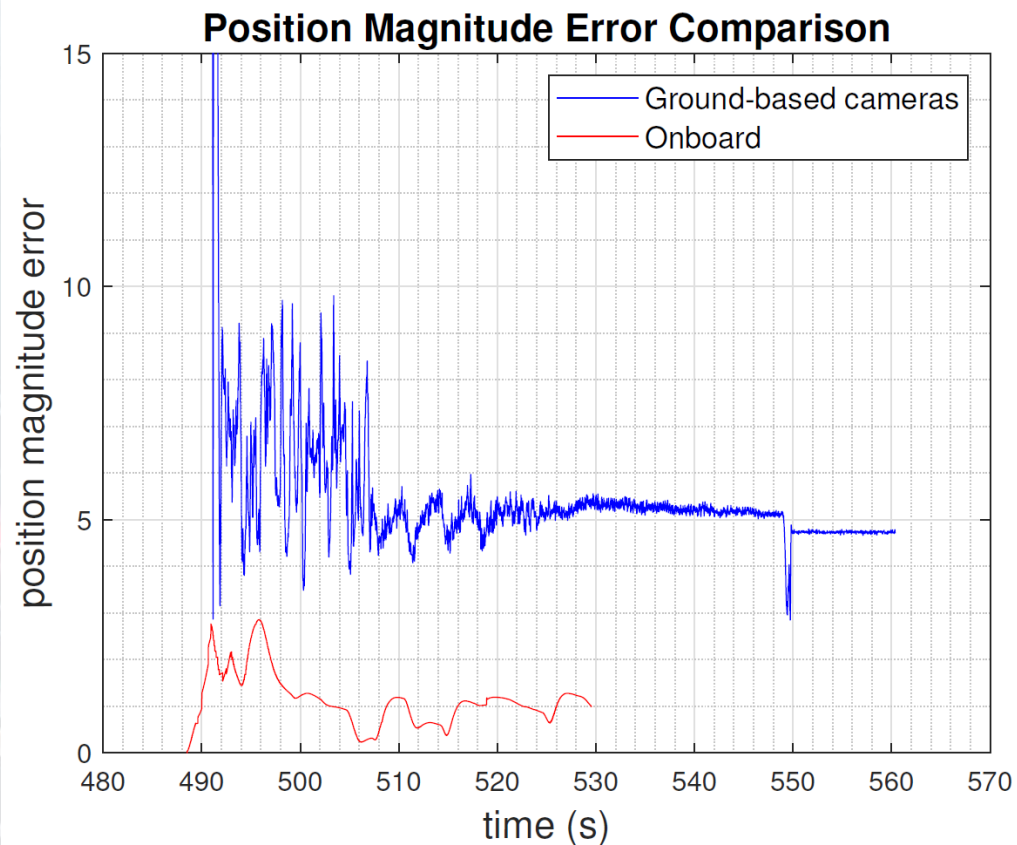


- Position magnitude error of tracked aircraft decreases with more cameras
- Accurate with at least four cameras seeing the aircraft
- Lots of noise when there are less than three cameras

[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.



- 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

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](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](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>
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***Thank you for listening! Questions?***

