Intermittent GPS-aided VIO: Online Initialization and Calibration

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ICRA 2020
31 May • 4 June 2020
Palais des Congrès de Paris
Paris • FRANCE

Motivation: Why GPS-aided VIO?

	Visual-Inertial-Odometry (VIO)
Pros	• High-quality ego-motion • Indoor/outdoor • Low-cost
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- Complementary sensor characteristics
- GPS-aided VIO: Low-cost, robust, drift-free, indoor/outdoor localization

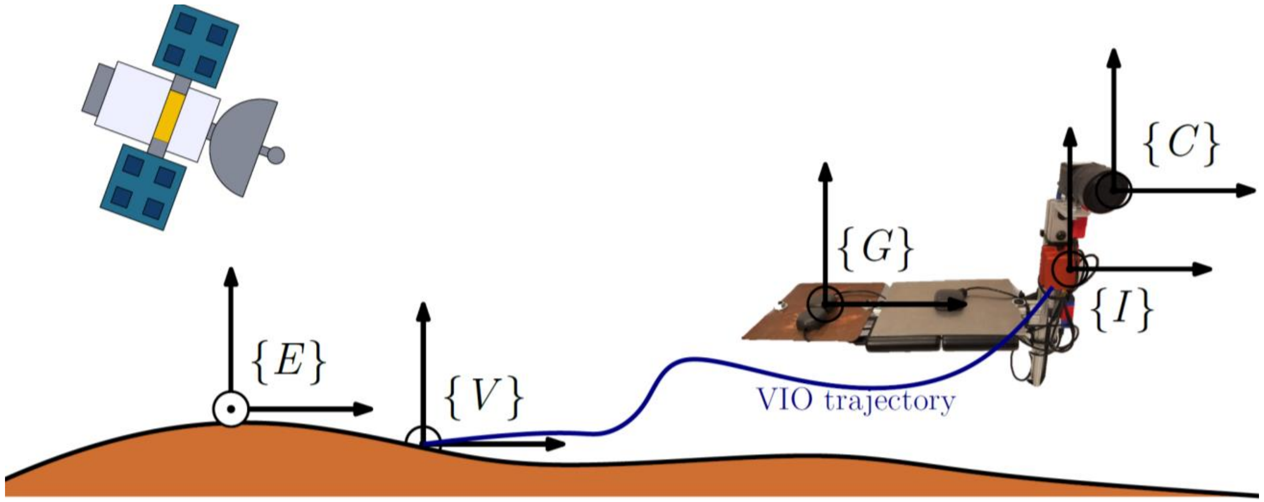
Motivation: Parameters Needed

$\{E\}$: ENU (East-North-Up) frame, GPS reference frame
$\{V\}$: VIO reference frame
$\{G\}$: GPS sensor frame
$\{I\}$: IMU sensor frame
${}^b\mathbf{p}_a$: Position of *a* in *b* frame
${}^b_a\mathbf{R}$: *a* to *b* frame rotation matrix

- GPS measurement $\mathbf{z}_{g_k}$ at time t_k

$$\mathbf{z}_{g_k} = {}^E\mathbf{p}_{G_k} = \underbrace{{}^E\mathbf{p}_V + {}^E_V\mathbf{R}}_{\text{Reference transformation between } \{V\} \text{ and } \{E\}} {}^V\mathbf{p}_{G_k} + \mathbf{n}_{g_k}$$

$${}^V\mathbf{p}_{G_k} = \underbrace{{}^V\mathbf{p}_{I_k} + {}^{I_k}_V\mathbf{R}^\top}_{\text{IMU } \{I\} \text{ pose at } t_k \text{ in } \{V\}} \underbrace{{}^I\mathbf{p}_G}_{\text{Extrinsic}}$$



Challenges

$\{E\}$: ENU (East-North-Up) frame, GPS reference frame
$\{V\}$: VIO reference frame
$\{G\}$: GPS sensor frame
$\{I\}$: IMU sensor frame
${}^{b}\mathbf{p}_{a}$: Position of *a* in *b* frame
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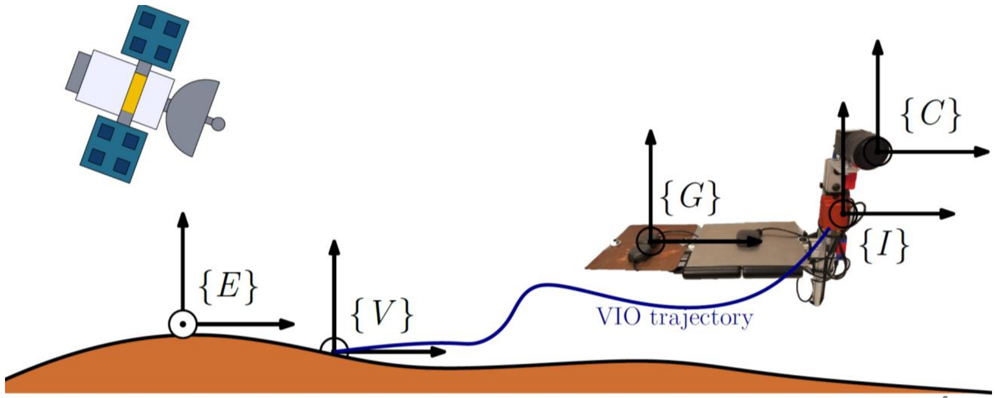
- $\{{}^{E}_{V}\mathbf{R}, {}^{E}\mathbf{p}_{V}\}$
  - No initial guess -> Need initialization
  - May not have GPS measurement at the beginning (e.g. start indoor)
  - Noisy GPS measurement -> Need robust initialization
- $\{{}^{I_k}_{V}\mathbf{R}^{\top}, {}^{V}\mathbf{p}_{I_k}\}$ $\{{}^{I}\mathbf{p}_{G}\}$
  - Asynchronicity between GPS and VIO
  - Intermittent GPS measurement
  - Time offset calibration?



Observability Analysis

- Question: Does using GPS make the state fully observable?
- State to analyze

$$ {}^{V}\mathbf{x} = \begin{bmatrix} {}^{I_k}_{V}\bar{q} & {}^{V}\mathbf{p}_{I_k} & {}^{E}_{V}\bar{q} & {}^{E}\mathbf{p}_{V} & {}^{I}\mathbf{p}_{G} \end{bmatrix} $$

${}^{b}_{a}\bar{q}$: Quaternion form of ${}^{b}_{a}\mathbf{R}$

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- Found **4 unobservable directions** corresponding to:
  - Rotation along the axis of gravity between $\{V\}$ and $\{E\}$
  - Translation between $\{V\}$ and $\{E\}$

The system still retains 4 unobservable direction inherited from VIO system, due to estimation of the frame transformation

Proposed Fully Observable System

- Transform the state and its covariance to the ENU frame $\{E\}$

$$\mathbf{x} = g({}^{V}\mathbf{x}, {}^{E}_{V}\bar{q}, {}^{E}\mathbf{p}_{V}) = [{}^{I_k}_{\mathbf{E}}\bar{q} \quad {}^{\mathbf{E}}\mathbf{p}_{I_k} \quad {}^{E}_{V}\bar{q} \quad {}^{E}\mathbf{p}_{V} \quad {}^{I}\mathbf{p}_{G}]$$

$$\tilde{\mathbf{x}} = \Psi^{V}\tilde{\mathbf{x}}, \qquad \mathbf{P}_{\oplus} = \Psi \mathbf{P}_{\ominus} \Psi^{\top}$$

- Marginalize $\{{}^{E}_{V}\bar{q}, {}^{E}\mathbf{p}_{V}\}$ term and get the following state

$$marg(\mathbf{x}) \rightarrow {}^{E}\mathbf{x} = [{}^{I_k}_{E}\bar{q} \quad {}^{E}\mathbf{p}_{I_k} \quad {}^{I}\mathbf{p}_{G}], \quad marg(\mathbf{P}_{\oplus}) \rightarrow {}^{E}\mathbf{P}$$

The system is now fully observable

GPS-VIO Initialization

1) VIO can be independently initialized without GPS measurement

   - Multi-State Constraint Kalman filter (MSCKF) state $\mathbf{x}_k$:

$$\mathbf{x}_k = \begin{bmatrix} \mathbf{x}_{I_k} & \mathbf{x}_{C_k} \end{bmatrix}$$

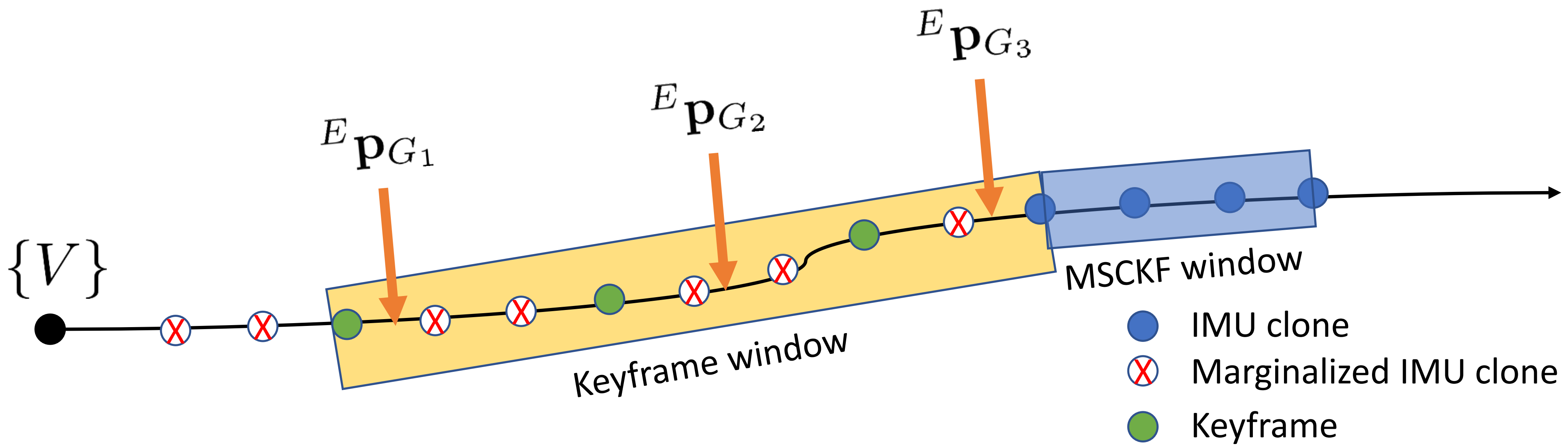
$$\mathbf{x}_{I_k} = \begin{bmatrix} {}^{I_k}_{V}\bar{q} & {}^{V}\mathbf{p}_{I_k} & {}^{V}\mathbf{v}_{I_k} & \mathbf{b}_{\omega_k} & \mathbf{b}_{a_k} \end{bmatrix}$$

$$\mathbf{x}_{C_k} = \begin{bmatrix} {}^{I_{k-1}}_{V}\bar{q} & {}^{V}\mathbf{p}_{I_{k-1}} & \cdots & {}^{I_{k-n}}_{V}\bar{q} & {}^{V}\mathbf{p}_{I_{k-n}} \end{bmatrix}$$

GPS-VIO Initialization

2) Collect GPS measurements and sparse IMU keyframes

- Collect GPS measurements $\{{}^E\mathbf{p}_{G_1}, \cdots, {}^E\mathbf{p}_{G_n}\}$
- Sparse IMU key frames bound the GPS measurement $\{{}^V\mathbf{p}_{I_1}, \cdots, {}^V\mathbf{p}_{I_n}\}$



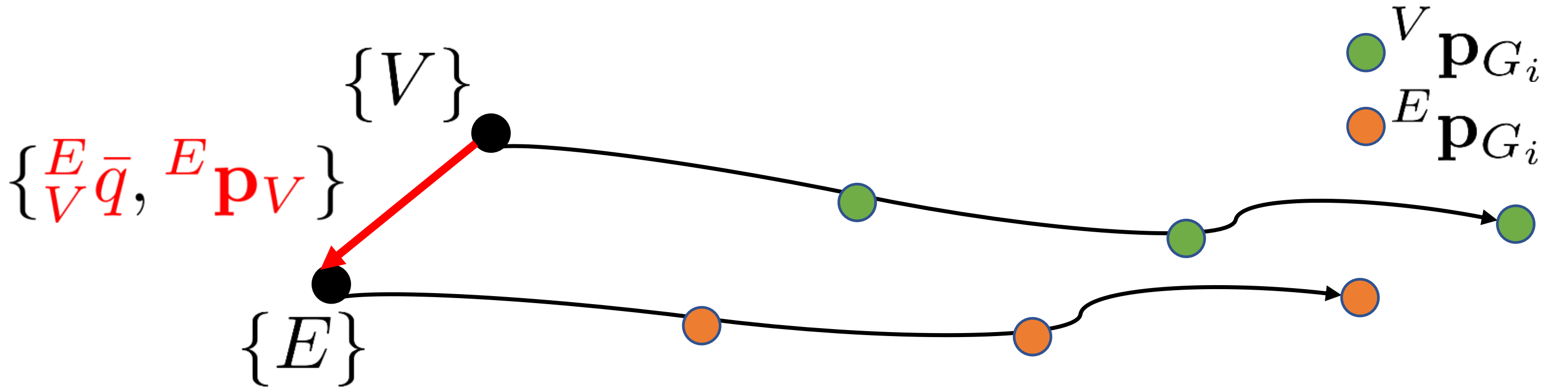
GPS-VIO Initialization

3) Compute 4 d.o.f. transformation between $\{V\}$ and $\{E\}$

- Use ${}^{I}\mathbf{p}_G$ and the IMU keyframes to compute GPS pose in $\{V\}$

$$ {}^{V}\mathbf{p}_{G_i} = {}^{V}\mathbf{p}_{I_i} + {}^{I_i}_{V}\mathbf{R}^{\top}\,{}^{I}\mathbf{p}_G \rightarrow \{{}^{V}\mathbf{p}_{G_1}, \cdots, {}^{V}\mathbf{p}_{G_n}\} $$

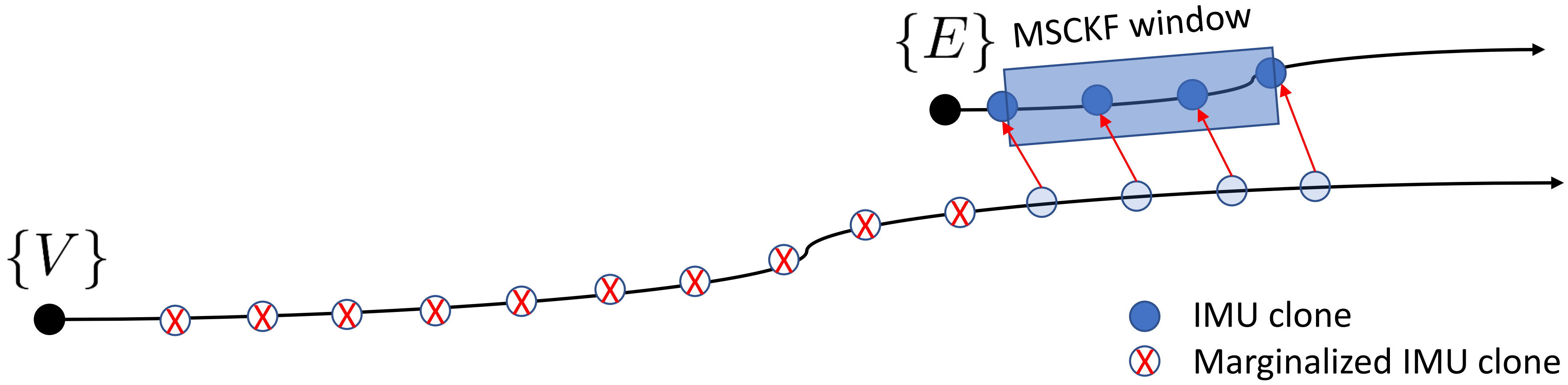
- Compute $\{{}^{E}_{V}\bar{q}, {}^{E}\mathbf{p}_V\}$ that aligns $\{{}^{E}\mathbf{p}_{G_1}, \cdots, {}^{E}\mathbf{p}_{G_n}\}$ and $\{{}^{V}\mathbf{p}_{G_1}, \cdots, {}^{V}\mathbf{p}_{G_n}\}$ by solving quadratic constraint least-squares problem



GPS-VIO Initialization

4) Post process

- Perform delayed initialization to further correct $\{{}^{E}_{V}\bar{q}, {}^{E}\mathbf{p}_V\}$
- Marginalize all the keyframes
- Transform the state to ENU $\{E\}$ reference frame
- Marginalize $\{{}^{E}_{V}\bar{q}, {}^{E}\mathbf{p}_V\}$ from the state



GPS-VIO Initialization: Simulation Results

TABLE I: Average position and orientation errors over ten runs for different initialization distances and GPS noise values in units of meters/degree.

dist\\σ	0.1m	0.5m	1m	2m	5m
5m	1.59 / 0.65	7.08 / 3.20	14.32 / 6.56	29.37 / 69.84	69.17 / 92.37
10m	1.39 / 0.52	5.23 / 2.23	10.22 / 4.39	19.80 / 47.79	45.02 / 91.85
20m	0.90 / 0.29	2.68 / 1.08	5.02 / 2.07	9.78 / 4.08	25.49 / 49.75
50m	0.55 / 0.08	0.77 / 0.16	1.09 / 0.30	1.88 / 0.61	4.58 / 1.49
100m	0.51 / 0.09	0.49 / 0.06	0.55 / 0.12	0.85 / 0.24	2.18 / 0.63

The larger GPS noise magnitude, less accurate initialization

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The larger GPS noise magnitude, less accurate initialization

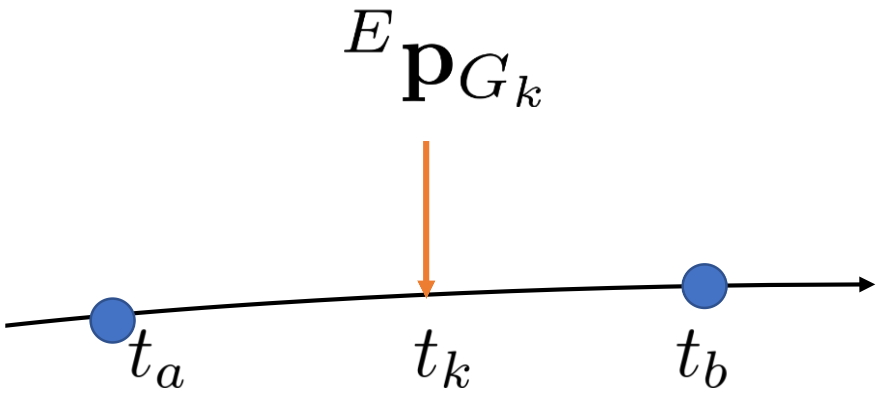
The larger GPS noise requires longer trajectory for the initialization

Initialization

GPS Measurement Update/Calibration

- GPS measurement function

$$\mathbf{z}_{g_k} := {}^{E}\mathbf{p}_{G_k} = {}^{E}\mathbf{p}_{I_k} + {}^{I_k}_{E}\mathbf{R}^{\top}\,{}^{I}\mathbf{p}_{G}$$



- The measurement is asynchronous/intermittent to the VIO system:

  No $\{{}^{I_k}_{E}\mathbf{R}, {}^{E}\mathbf{p}_{I_k}\}$ in the state

- GPS measurement can be delayed or sensor clocks mismatch:

  Need time offset model/calibration

GPS Measurement Update/Calibration

- GPS measurement function

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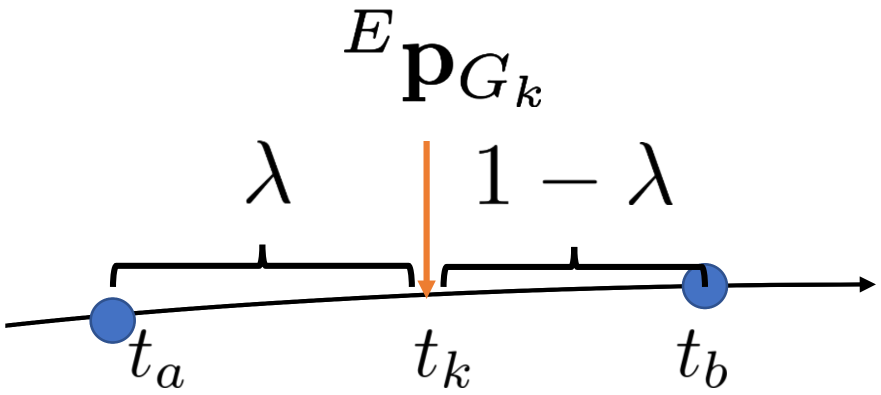


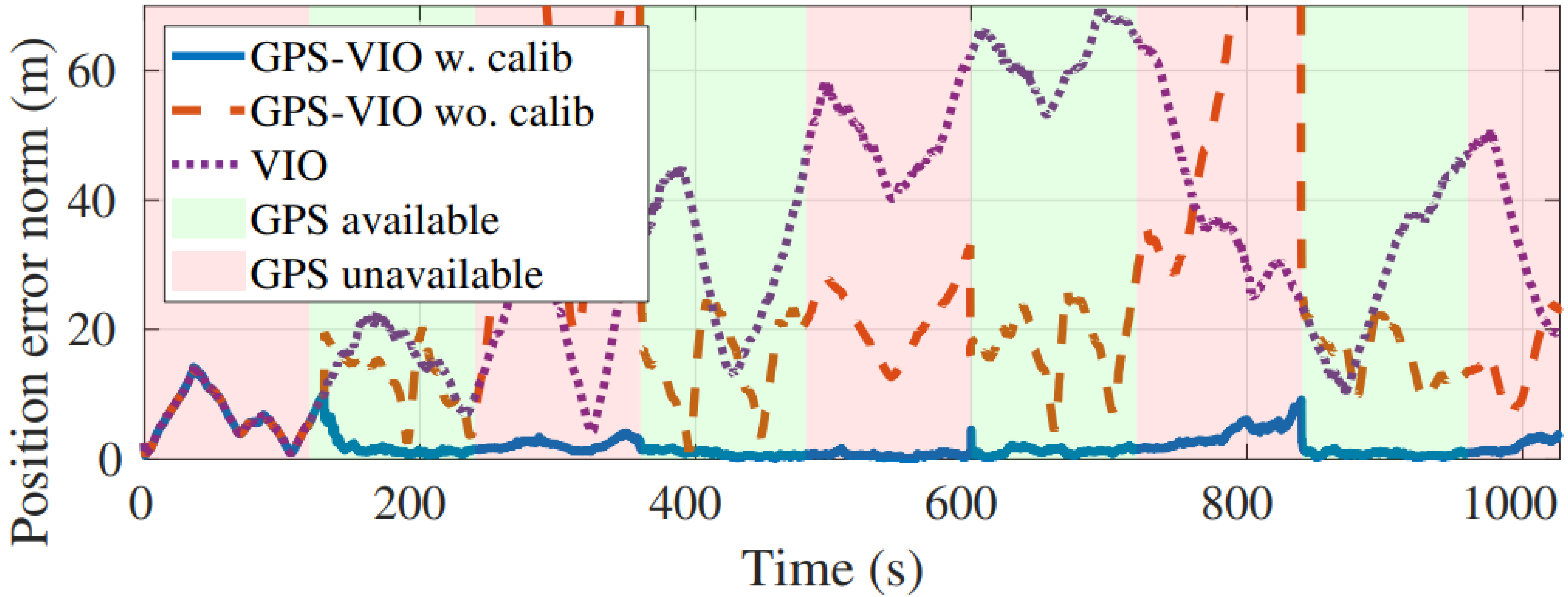
- Linear interpolation to get IMU pose at t_k & model the time offset
  - The bounding IMU poses at t_a and t_b $(t_a < t_k < t_b)$

$${}^{I_k}_{E}\mathbf{R} = \mathrm{Exp}\left(\lambda\,\mathrm{Log}\left({}^{I_b}_{E}\mathbf{R}\,{}^{I_a}_{E}\mathbf{R}^{\top}\right)\right){}^{I_a}_{E}\mathbf{R}, \quad {}^{E}\mathbf{p}_{I_k} = (1-\lambda)\,{}^{E}\mathbf{p}_{I_a} + \lambda\,{}^{E}\mathbf{p}_{I_b}$$

$$\lambda = \frac{(t_k + {}^{I}t_G - t_a)}{(t_b - t_a)}$$

Exp() and Log() are the SO(3) matrix exponential and logarithm functions

GPS-VIO Update/Cal. Simulation Results



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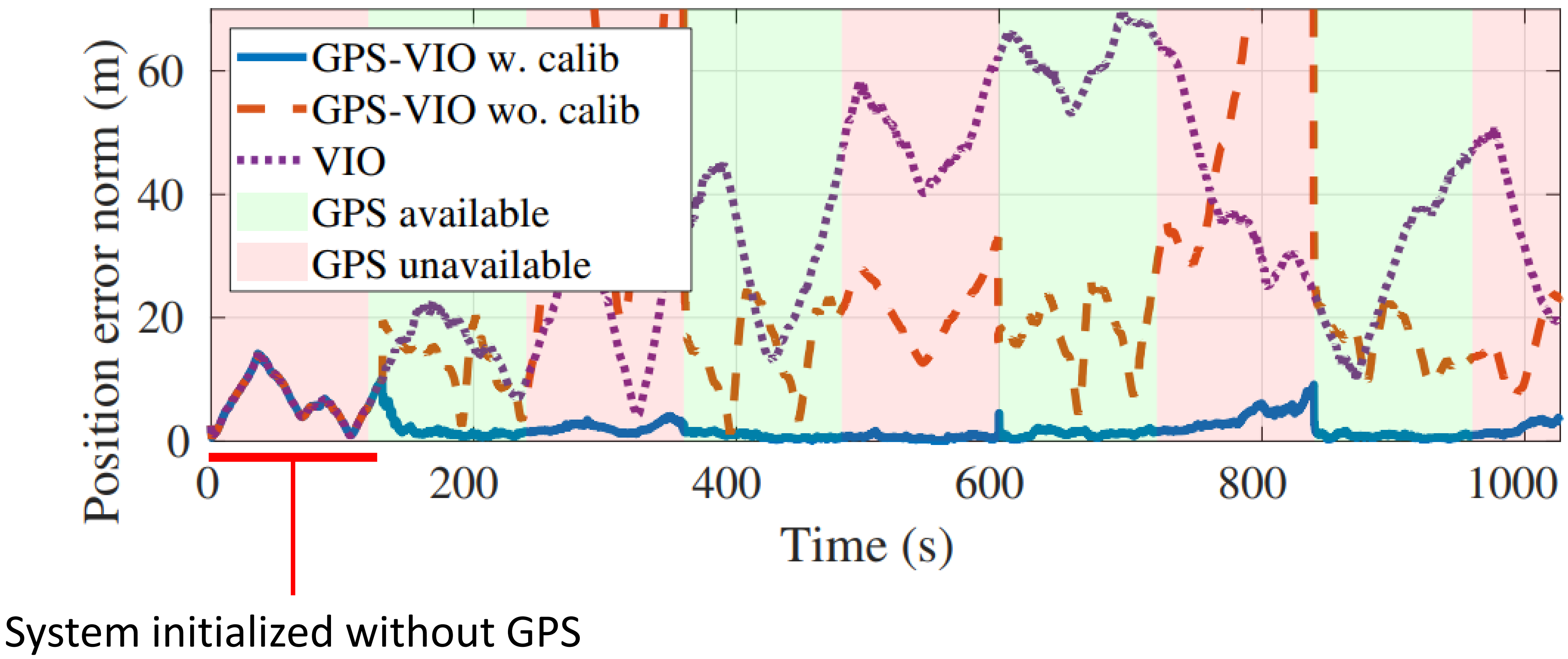

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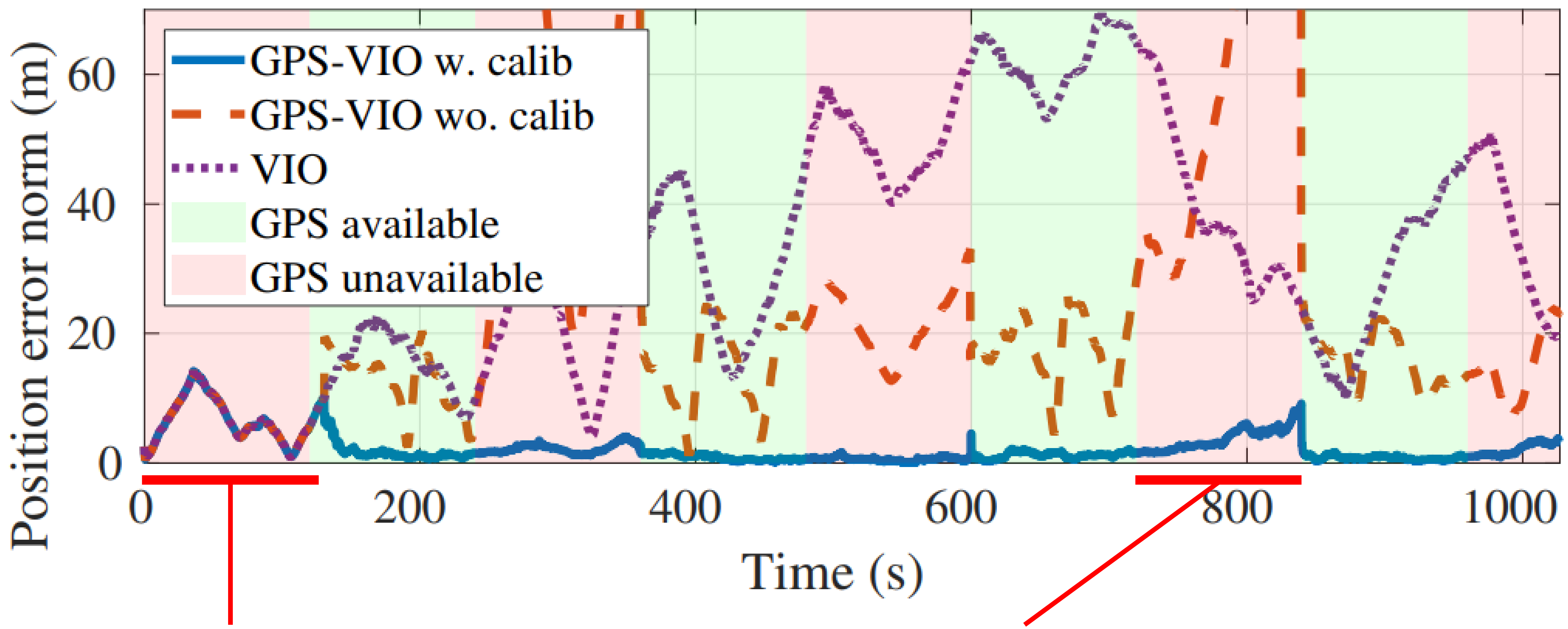
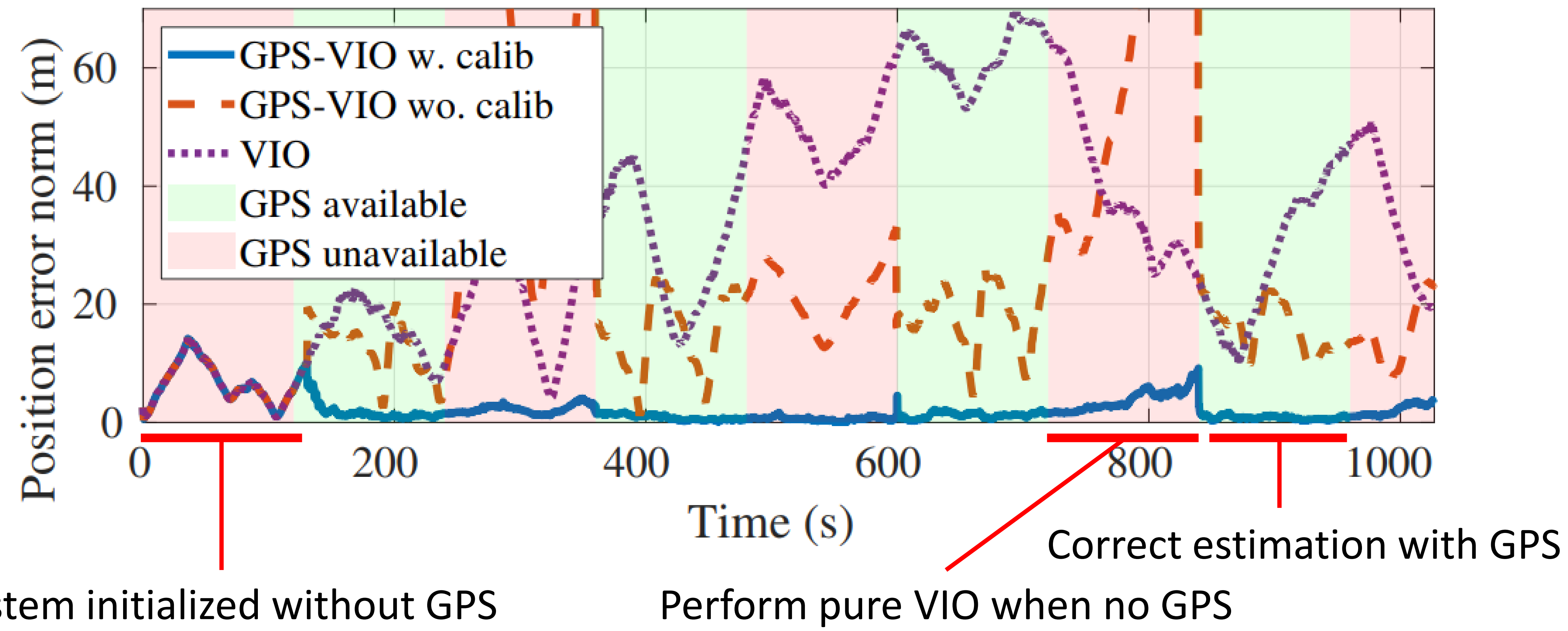


System initialized without GPS

Perform pure VIO when no GPS

GPS-VIO Update/Cal. Simulation Results



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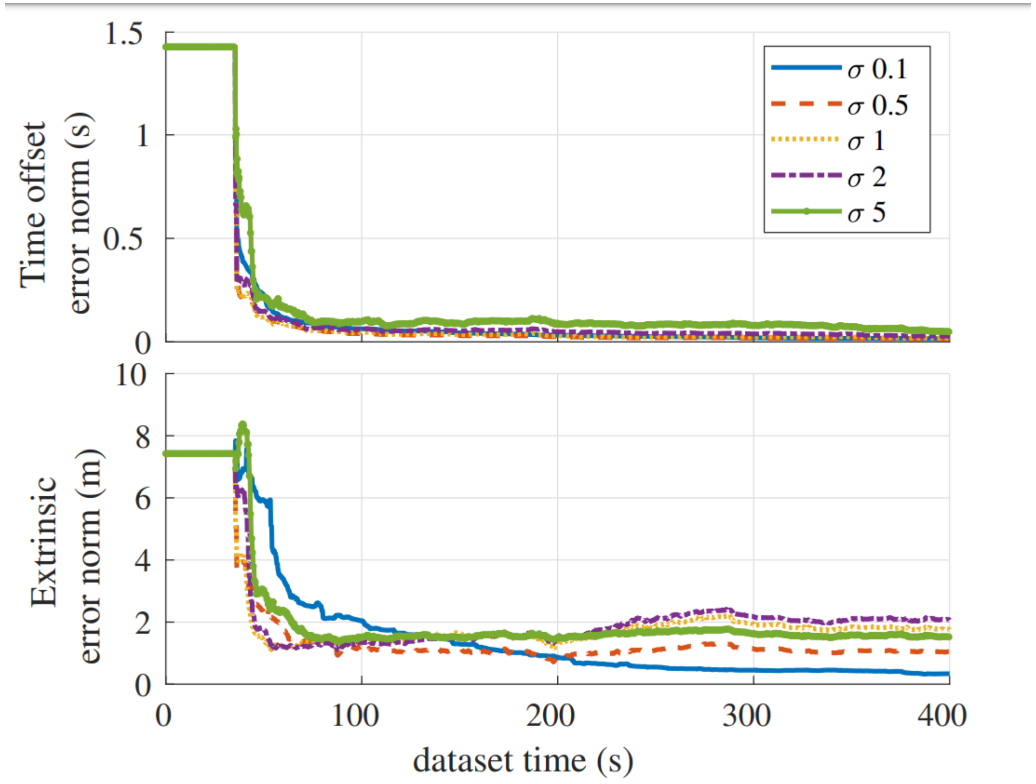
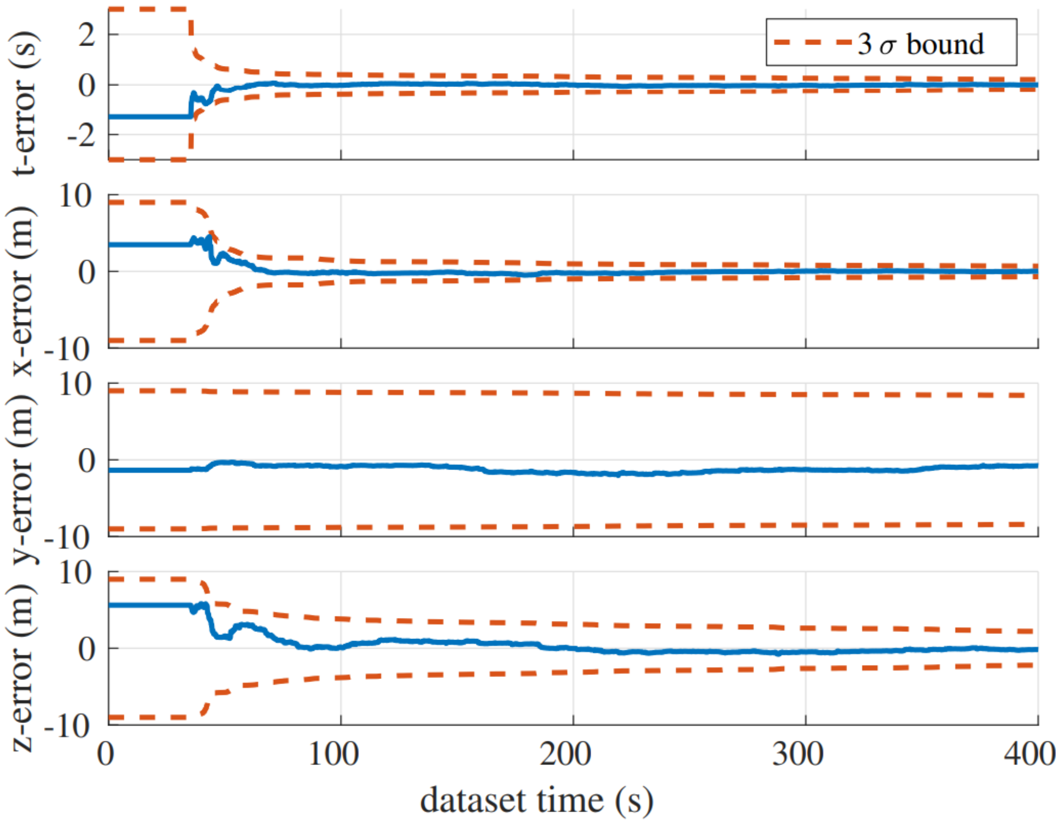


Fig. 4: The calibration errors respect to the size of GPS measurement noise.



- Can calibrate large initial errors
- Convergence affected by GPS noise magnitude

- Errors are bounded by 3 σ bound – **Consistent**!

Localization
Indoor to Outdoor

Conclusion

- Proved the state contains VIO to ENU reference frame transformation has **4 unobservable directions** by the observability analysis.
- Proposed the state transformation that removes the transformation parameters and become **fully observable**.
- Proposed the GPS-VIO initialization procedure that is **robust**, observable, and can handle intermittent GPS measurements
- Proposed asynchronous GPS measurement update method and **spatiotemporal calibration** method

Thank you

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