Tightly-coupled GNSS-aided Visual-Inertial Localization

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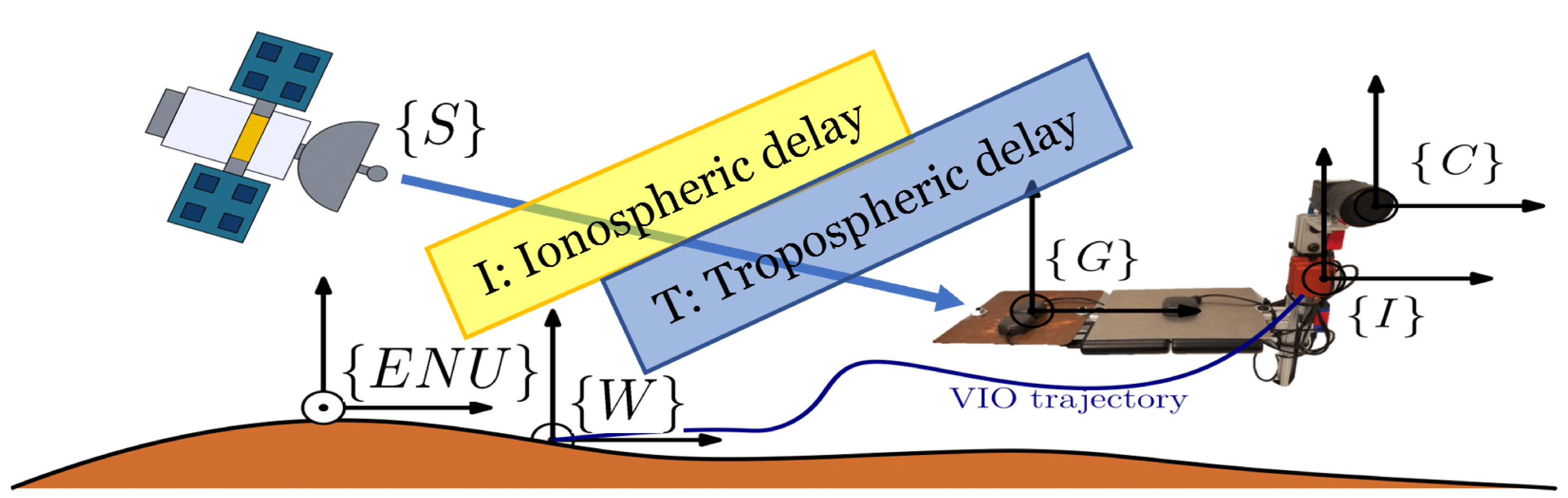
Motivation & Contribution

- **GNSS fusion with VIO**: Globally accurate and locally precise localization system.
- Utilize **raw GNSS measurements** simplifying models without losing information.
- Propose a novel way of tightly couple GNSS with VIO by adapting differential GNSS technique to **remove atmospheric effects** (ionospheric and tropospheric delays).
- Propose **2-step GNSS initialization** method that recovers all necessary parameters for raw GNSS fusion.
- Thoroughly evaluated in both simulation and real world data and showed robustness and accuracy of the proposed system.

IMU, Camera, and raw GNSS Measurements



- IMU: Measures angular velocity and linear acceleration. Used to propagate the state.

$$\mathbf{a}_m = \mathbf{a} + {}^{I}_{W}\mathbf{R}\mathbf{g} + \mathbf{b}_a + \mathbf{n}_a, \quad \boldsymbol{\omega}_m = \boldsymbol{\omega} + \mathbf{b}_g + \mathbf{n}_g$$

- Camera: Measures feature bearing information. Used to update the state.

$$\mathbf{z}_k = \boldsymbol{\Pi}({}^{C}_{I}\mathbf{R}\,{}^{I_k}_{W}\mathbf{R}({}^{W}\mathbf{p}_f - {}^{W}\mathbf{p}_{I_k}) + {}^{C}\mathbf{p}_I) + \mathbf{n}_k$$

- Raw GNSS: Measures dynamics of both GNSS sensor $\{G\}$ and satellite $\{S\}$. Used to update the state.
  - Pseudorange

$$z_p = ||{}^{E}\mathbf{p}_G - {}^{E}\mathbf{p}_S||_2 + c(b_G - b_S) + I + T + M + n_p$$

  - Carrier Phase

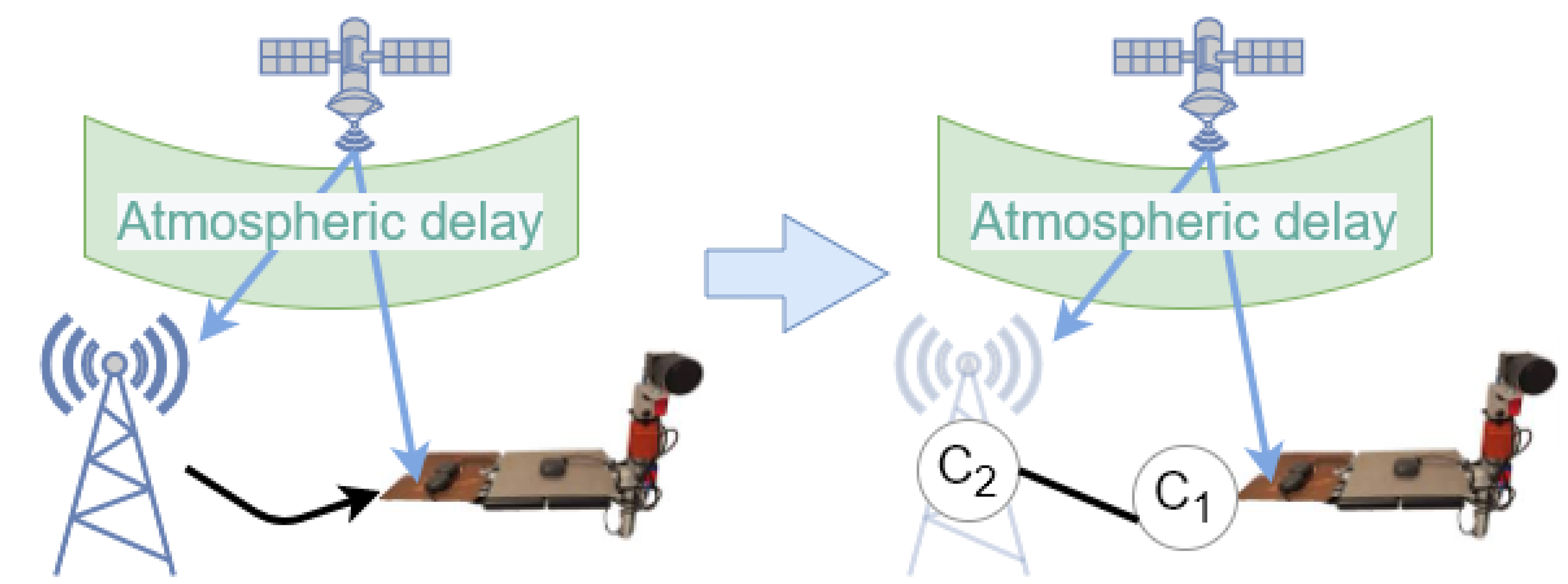
$$z_c = ||{}^{E}\mathbf{p}_G - {}^{E}\mathbf{p}_S||_2 + c(b_G - b_S) - I + T + M + \lambda N + n_c$$

  - Doppler Shift

$$z_d = -\left((\mathbf{k}^\top({}^{E}\mathbf{v}_S - {}^{E}\mathbf{v}_G) + c(\dot{b}_G - \dot{b}_S)\right)/\lambda + n_d$$

Atmospheric delays (I, T) are hard to model.

Sequential-Differential GNSS



- Two sequential GNSS measurements from the same satellite have approximately the same atmospheric delays.
- Subtract two **sequential** raw GNSS measurements to **cancel out atmospheric delays (I, T)**.
- This is equivalent to performing **differential GNSS** with base station right next to rover.
- Differential Pseudorange

$$\begin{aligned} z_{Dp} &:= z_{p,k+1} - z_{p,k} \\ &= \Delta d + c(b_{G,k+1} - b_{S,k+1}) - c(b_{G,k} - b_{S,k}) + n_{Dp} \end{aligned}$$

- Differential Carrier Phase

$$\begin{aligned} z_{Dc} &:= z_{c,k+1} - z_{c,k} \\ &= \Delta d + c(b_{G,k+1} - b_{S,k+1}) - c(b_{G,k} - b_{S,k}) + n_{Dc} \end{aligned}$$

- Doppler Shift (the same)

$$z_d = -\left((\mathbf{k}^\top({}^{E}\mathbf{v}_S - {}^{E}\mathbf{v}_G) + c(\dot{b}_G - \dot{b}_S)\right)/\lambda + n_d$$

- The measurements are now only functions of **robot & satellite dynamics and their clock biases**.

2-Step Initialization

- 0th-step: Information collection (GNSS SPP measurements, VIO poses)
- 1st-step: ECEF-to-World frame $\{W\}$ initialization. Find transformation that aligns GNSS and VIO trajectories by solving linear least-squares with quadratic constraint problem
- 2nd-step: GNSS sensor parameter $(b, \dot{b})$ initialization by solving linear least-squares problem

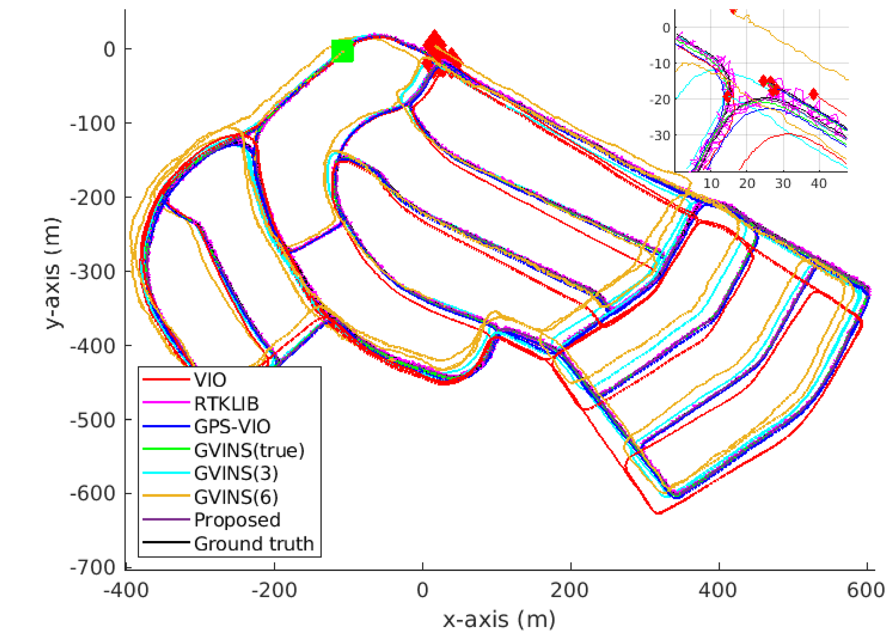
Simulation Results

- Hyper-parameter sensitivity of initialization (deg/m)

dist\σ	0.1m	0.5m	1m	2m	5m
5m	1.57 / 0.58	6.25 / 2.91	14.52 / 6.79	30.66 / 71.75	69.26 / 88.42
10m	1.31 / 0.52	5.54 / 2.19	9.45 / 4.17	20.41 / 44.94	47.45 / 94.93
20m	0.79 / 0.27	2.47 / 0.99	4.84 / 2.01	10.24 / 4.10	26.96 / 51.54
50m	0.53 / 0.07	0.80 / 0.16	0.97 / 0.27	1.79 / 0.62	4.86 / 1.48
100m	0.45 / 0.09	0.49 / 0.06	0.50 / 0.12	0.78 / 0.24	2.11 / 0.65

  - Evaluated initialization performance with different initialization distances and GNSS SPP noise values.
  - Initialization accuracy tend to improve with **the longer distance** collected and **the smaller GNSS SPP noise**.

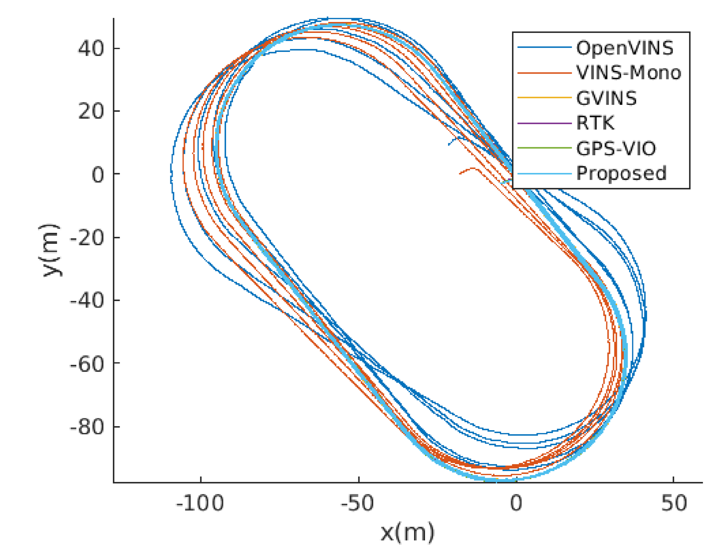
- Localization with different atmospheric delays



Algorithms	40m RPE
OpenVINS [1]	0.08 / 0.26
GPS-VIO [2]	0.07 / 0.21
RTKLIB [3]	0.53 / 2.59
GVINS(true) [4]	0.07 / 0.18
GVINS(3)	0.46 / 1.21
GVINS(6)	1.18 / 3.09
Proposed	**0.076 / 0.185**

  - Proposed method showed **robustness** to different levels of atmospheric delays.
  - Proposed method showed **the smallest RPE error** among all tested

Real World Results



Algorithms	RMSE(m)
VINS-Mono [5]	9.189
OpenVINS	11.265
GPS-VIO	0.374
GVINS	0.327
Proposed	**0.319**

- Proposed method showed **the smallest RMSE error** among all tested

[1] Geneva, Patrick, et al. "Openvins: A research platform for visual-inertial estimation." 2020 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2020.
[2] Lee, Woosik, et al. "Intermittent gps-aided vio: Online initialization and calibration." 2020 IEEE International Conference on Robotics and Automation (ICRA). IEEE, 2020.
[3] T. Takasu and A. Yasuda, "Development of the low-cost rtk-gps receiver with an open source program package rtklib," in International symposium on GPS/GNSS, vol. 1. International Convention Center Jeju Korea, 2009
[4] Cao, Shaozu, Xiuyuan Lu, and Shaojie Shen. "GVINS: Tightly Coupled GNSS–Visual–Inertial Fusion for Smooth and Consistent State Estimation." IEEE Transactions on Robotics (2022).
[5] Qin, Tong, Peiliang Li, and Shaojie Shen. "Vins-mono: A robust and versatile monocular visual-inertial state estimator." IEEE Transactions on Robotics 34.4 (2018): 1004-1020.