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Joint Navigation and Synchronization using SOOP in GPS-denied environments: Algorithm and Empirical Study

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Outline

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1. Introduction
2. Measurements
   - measurement type
   - measurement model
3. Algorithm
4. Experiment
   - experiment setup
   - results
5. Conclusion

Motivation

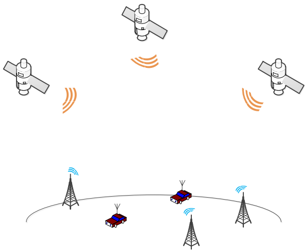


Figure: environment under investigation

- GPS-denied:
  - requires dedicated GPS receiver
  - requires open sky view
  - weak GPS signal close to noise level
  - deliberately disabled by adversaries
- singal-of-opportunity (SOOP):
  - widely available from existing infrastructure
  - relatively high SNR
  - requires *certain* prior knowledge
  - synchronization issue
    - ★ oscillators with poor quality
    - ★ passive beacon

Goal

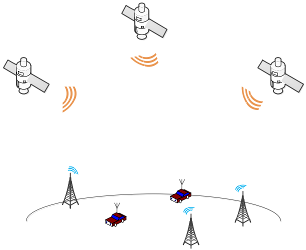


Figure: environment under investigation

- Scenarios:
  - two receivers, mobile & unsynchronised
  - two receivers cooperate with each other
  - capture SOOP in an "eavesdropping" way
  - minimum prior knowledge:
    - ★ unknown signal structure
    - ★ unknown transmit time
    - ★ unknown transmit power
    - ★ knowns: beacon states (position, velocity)

Goal: with two cooperative receivers, to jointly track a target receiver's state and its clock drifting with respect to its cooperative peer.

Navigation Scheme

- target receiver: G
- anchor receiver: A
- cooperation:
  - two receivers see a common set of beacons
  - A shares with G its received signal or beacon information derived from its received signal
  - A shares with G its own state information

Navigation Scheme

1. spectrum scanning: identify near-by available beacons
2. handshaking: agree on the beacon to receive from and the time to receive
3. information exchanging: A shared its received information and its state information with G
4. tracking: G perform self-localization and self-synchronization with information from A and its own received signal.

- SOOP are ad hoc
- bursts from beacons are received in a sequential way

Questions to answer

1. Measurements
   - what types of measurements to use?
   - how does clock drifting affect the measurement? $\longrightarrow$ proper measurement model
2. Tracking algorithm:
   - can we adapt extended Kalman filter for this problem?
   - how does the nonlinearily and uncertainty affect the performance?
3. Field experiment:
   - how well does our measurement model fit in real life?
   - how well does our algorithm perform in real life?

Outline

Measurement Type

- RSS? TOA? AOA?
- TDOA/FDOA $\leftarrow$ unknown waveform & signal characteristics
- methods to obtain measurements: cross-correlation

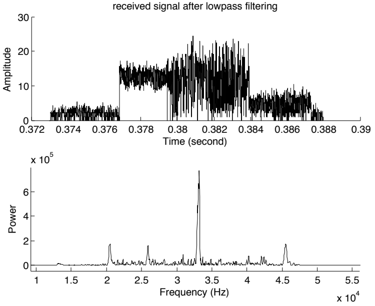


Figure: received packets from Iridium

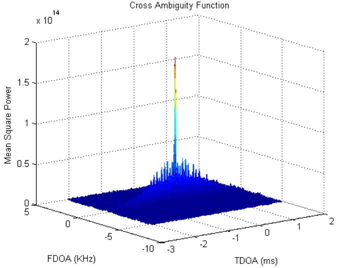


Figure: complex ambiguity function between raw signals

Measurement Model

at the l-th time slot

$$\tau_b^{(l)} \approx \left\| \mathbf{p}_1^{(l)} - \mathbf{s}_b^{(l)} \right\| - \left\| \mathbf{p}_2^{(l)} - \mathbf{s}_b^{(l)} \right\| + T_e^{(l)} \alpha^{(l)} + \theta^{(l)} + \varpi_b^{\tau}, \quad (1a)$$

$$\xi_b^{(l)} \approx (\mathbf{v}_1^{(l)} - \mathbf{v}_b^{(l)})^T \mathbf{u}_{1,b}^{(l)} - (\mathbf{v}_2^{(l)} - \mathbf{v}_b^{(l)})^T \mathbf{u}_{2,b}^{(l)} + \alpha^{(l)} + \varpi_b^{\xi}. \quad (1b)$$

- TDOA/FDOA measurement : $[\tau_b^{(l)}, \xi_b^{(l)}]$
  - $\theta^{(l)}$: clock offset up to the l-th time slot
    $\rightarrow \theta^{(l)} \approx \theta^{(l-1)} + (t_b^{(l)} - t_b^{(l-1)})\alpha^{(l-1)}$
  - $\alpha^{(l)}$: $c(\beta_2^{(l)} - \beta_1^{(l)})$ approximately
  - ϖ_b^{τ} and ϖ_b^{ξ}: measurement noise, assumed Gaussian.
- knowns: $\mathbf{s}_b^{(l)}$, $\mathbf{v}_b^{(l)}$, $\mathbf{p}_2^{(l)}$, $\mathbf{v}_2^{(l)}$
- unknowns: $[\mathbf{p}_1^{(l)}, \mathbf{v}_1^{(l)}, \theta^{(l)}, \alpha^{(l)}]$

Outline

Dynamic Model

$$\Delta_l \triangleq t_b^{(l)} - t_b^{(l-1)}$$

- clock:

$$\begin{bmatrix} \theta^{(l)} \\ \alpha^{(l)} \end{bmatrix} = \begin{bmatrix} 1 & \Delta_l \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \theta^{(l-1)} \\ \alpha^{(l-1)} \end{bmatrix} + \boldsymbol{\nu}_c^{(l)}, \quad (2)$$

- receiver movement:

$$\begin{bmatrix} \mathbf{p}^{(l)} \\ \mathbf{v}^{(l)} \end{bmatrix} = \begin{bmatrix} 1 & 1 & 1 & \Delta_l & \Delta_l & \Delta_l \\ 0 & 0 & 0 & 1 & 1 & 1 \end{bmatrix} \begin{bmatrix} \mathbf{p}^{(l-1)} \\ \mathbf{v}^{(l-1)} \end{bmatrix} + \boldsymbol{\nu}_s^{(l-1)}, \quad (3)$$

- important parameters: covariance of $\boldsymbol{\nu}_c^{(l)}$ and $\boldsymbol{\nu}_s^{(l)}$
  - $\boldsymbol{\nu}_c^{(l)}$: depends on intensity of the diffusion process of clock components.
  - $\boldsymbol{\nu}_s^{(l)}$: depends on acceleration.

Extended Kalman Filter

$$\text{dynamics:} \quad \mathbf{x}^{(l)} = \mathbf{H}_l \mathbf{x}^{(l-1)} + \boldsymbol{\nu}^{(l)}, \tag{4}$$

$$\text{measurements:} \quad \mathbf{y}^{(l)} = f(\mathbf{x}^{(l)}) + \boldsymbol{\varpi}^{(l)}. \tag{5}$$

- Gaussian assumption:
  - $\boldsymbol{\nu}^{(l)} \sim \mathcal{N}\left(0, \mathbf{Q}^{(l)}\right)$: prior knowledge
  - $\boldsymbol{\varpi}^{(l)} \sim \mathcal{N}\left(0, \mathbf{R}^{(l)}\right)$: measurement accuracy $\rightarrow$ CRLB
- linearisation: $\mathbf{F}_l = \nabla_{\mathbf{x}} f(\mathbf{x})|_{\mathbf{x}=\mathbf{x}^{(l)}}$

$$\mathbf{m}_{l|l-1} = \mathbf{H}_l \mathbf{m}_{l-1|l-1}, \tag{6a}$$

$$\mathbf{P}_{l|l-1} = \mathbf{Q}_l + \mathbf{H}_l \mathbf{P}_{l-1|l-1} \mathbf{H}_l^T, \tag{6b}$$

$$\mathbf{P}_{l|l} = \left(\mathbf{P}_{l|l-1}^{-1} + \mathbf{F}_l^T \mathbf{R}_l^{-1} \mathbf{F}_l\right)^{-1}, \tag{6c}$$

$$\mathbf{m}_{l|l} = \mathbf{m}_{l|l-1} + \mathbf{K}_l (\mathbf{y}^{(l)} - f(\mathbf{m}_{l|l-1})), \tag{6d}$$

Outline

Experiment

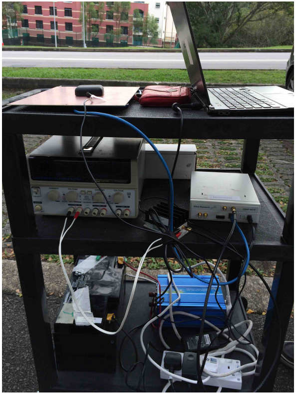
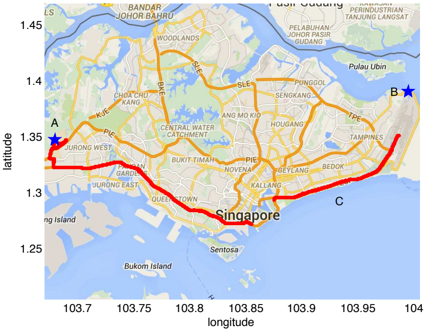


Figure: one set of receiver



- receiver: USRP N210+WBX
- beacon: Iridium satellites
- off-line processing:
  - spectrum scanning, handshaking, and information exchanging are correctly carried out.

TDOA/FDOA measurement

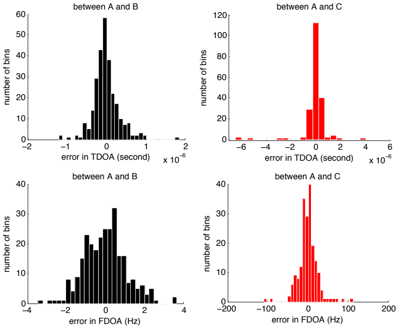


Figure: histogram for TDOA/FDOA estimation error

- mean: close to zero
- standard deviation:
  - TDOA: 2.73 μs for A-B, 1.73 μs for A-C
  - FDOA: 2.19 Hz for A-B, 36.8 Hz for A-C

Measurement Model Correctness

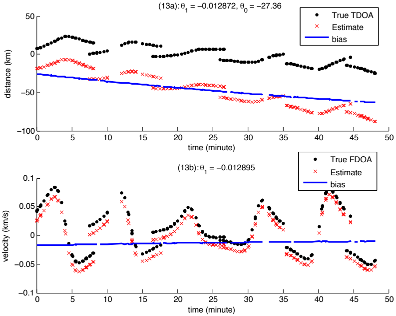
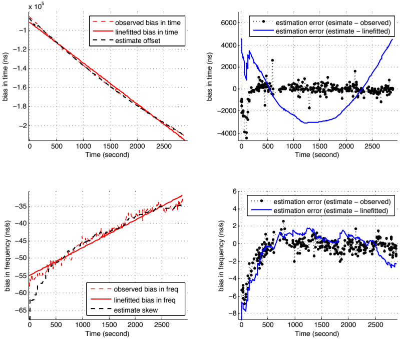


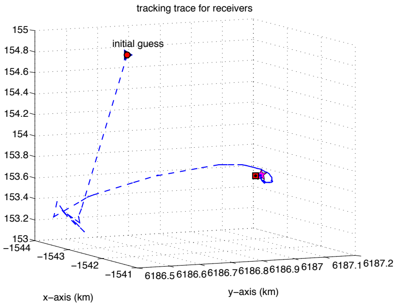
Figure: values of TDOA/FDOA v.s its true value

- from TDOA bias $\theta^{(l)} = \theta^{(0)} + T\alpha^{(l)}$: empirical value for α -0.012872
- from FDOA bias $\alpha^{(l)}$: empirical value for α -0.012895

Localizing static receiver - 1



(a) Tracking clock drifting parameters

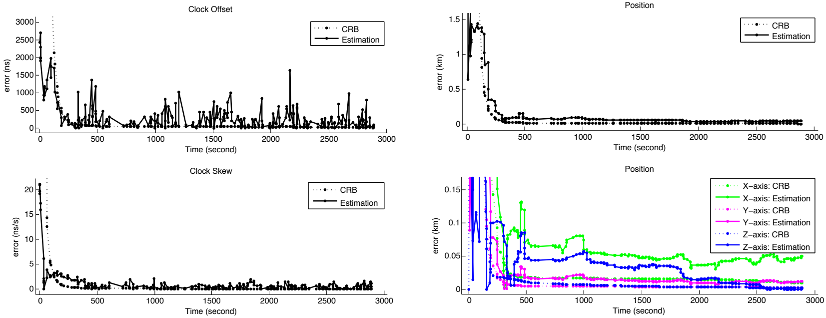


(b) Trace for estimating the receiver location

Figure: jointly estimating static receiver B's location and clock parameters.

- slightly increasing clock skew

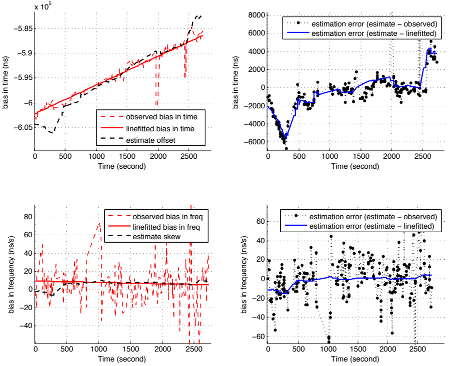
Localizing static receiver - 2



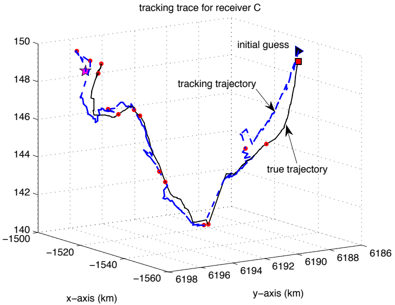
(a) clock parameters (b) position

- RMSE smaller than 50 m within 5 minutes
- clock skew model mismatch in CRLB

Tracking manoeuvring receiver



(c) Tracking clock drifting parameters



(d) Tracking the receiver state

Figure: The proposed algorithm for tracking the manoeuvring receiver C.

Summary

1. bias caused by clock drifting:
   - in TDOA: time-varying and linearly depends on clock skew
   - in FDOA: device dependent, roughly constant or slowly time-varying
2. sequential tracking algorithm:
   - dynamic model matters:
     - ★ correctly tracking the state and the clock parameters when the model fits well
     - ★ problematic when tracking manoeuvring receiver with insufficient measurements or incorrect model information
   - initial guess matters:
     - ★ the clock biases and the receiver states are correlated.

Future Work

- incorporate IMU to improve accuracy for tracking manoeuvring target.
  - to compensate for insufficient measurements due to long observation intervals
  - must deal with the accumulating error in IMU
- extend to scenarios with multiple targets.
- explore alternative beacons, including UAV, planes, and FM stations.

Thank you!