Abstract—Accurate, reliable and robust GPS localization is desirable for many navigation applications. Unfortunately, it is challenging for a single GPS receiver to always provide accurate positioning solutions. In urban environments, intermittent signal availability leads to degraded GPS signal tracking and position estimation of the single GPS receiver. In addition, equipment malfunction of the single GPS receiver results in inaccurate navigation solutions.

This paper presents a deeply-coupled Multi-Receiver Vector Tracking (MRVT) architecture that improves the reliability and robustness of GPS signal tracking and position estimation. MRVT jointly tracks GPS signals received by multiple GPS receivers, mitigating GPS signal tracking disruptions, improving the reliability of GPS localization in periods of intermittent signal availability. In addition, the MRVT receiver is more robust to equipment malfunctions than the single GPS receiver.

We implemented a MRVT receiver using commercial radio frequency front ends and our PyGNSS software. We experimentally validated the reliability of our MRVT receiver in periods of intermittent GPS availability experienced in downtown San Francisco. Our MRVT receiver exhibited consistent GPS signal tracking and position estimation as compared to vector tracking. In addition, we experimentally validated the robustness of our MRVT receiver to the failure of a single GPS receiver.

Index Terms—Global positioning system (GPS), global navigation satellite systems (GNSS), multiple GPS receivers, vector tracking

I. INTRODUCTION

GPS receivers, providing absolute position coordinates under all weather, platforms and visual conditions, are increasingly relied upon for urban navigation [1]. Unfortunately, a single GPS receiver suffers from intermittent GPS signal availability in urban environments, leading to signal tracking disruptions and position estimation challenges [2]. In addition, equipment malfunction of the single GPS receiver results in inaccurate position solutions. To improve the reliability and robustness of GPS localization, existing approaches include sensor fusion [3] with vision [4] and inertial measurements [5]. Instead of augmenting the single GPS receiver with additional sensors, there is inherent potential in leveraging multiple GPS receivers [6].

A. Related Work

Existing approaches using multiple GPS receivers include “loosely-coupled” and “tightly-coupled” architectures. A well-known example with both loosely-coupled and tightly-coupled implementations is Differential GPS (DGPS) [7]. The loosely-coupled implementation uses position differences while the tightly-coupled implementation uses pseudorange differences. Adding to the vast work on tightly-coupled architectures, our prior work included integration of pseudorange measurements from multiple GPS receivers using an Extended Kalman Filter (EKF) [8], an Unscented Kalman Filter (UKF) [9] and Probabilistic Graphical Models (PGM) [10], [11]. Tightly-coupled architectures, while improving the robustness of the final GPS navigation solution, do not improve the performance of GPS signal tracking within the individual GPS receivers, as shown in Fig. 1 (a). Disruptions in GPS signal tracking lead to degraded GPS measurements, adversely affecting the final GPS navigation solution.

To improve the reliability and robustness of GPS signal tracking, other existing approaches used antenna array processing of controlled radiation pattern antennas (CRPA) [12]. Antenna array processing exploits the accurately known antenna array geometry to beamform [13]–[15], increasing the signal-to-noise ratio (SNR) of visible satellites, creating a combined signal equivalent to the output of a single high quality antenna. Antenna arrays, however, require precise calibration [16] or additional processing with significantly higher computational loads [17], as shown in Fig. 1 (b). Bias errors would otherwise be introduced into the combined signal [16].

B. Our Approach and Contributions

We propose Multi-Receiver Vector Tracking (MRVT) to improve the reliability and robustness of GPS signal tracking and position estimation. MRVT is a deeply-coupled receiver architecture that jointly tracks the signals received by multiple GPS receivers. Our MRVT receiver architecture is different from existing approaches in two ways. Unlike loosely-coupled and tightly-coupled architectures, our MRVT receiver architecture jointly tracks multiple GPS receivers using feedback to vector tracking loops within individual GPS receivers. MRVT is thus a deeply-coupled architecture that augments GPS signal tracking. Unlike antenna arrays, our MRVT receiver does not...
require precise calibration nor significant additional processing. An illustration comparing MRVT to existing approaches is shown in Fig. 2.

Prior to this paper, our first iteration of MRVT [18] used an average navigation solution from multiple GPS receivers as feedback. In addition, vector tracking within each GPS receiver was implemented using an EKF with a constant acceleration motion model and a constant, heuristically specified process noise covariance. The coherent processing interval was 1 millisecond. Experiments were conducted in an open-sky environment, using 4 Universal Software Radio Peripherals (USRPs), with timing signals split from 1 Chip Scale Atomic Clock (CSAC).

Our second iteration of MRVT [19], [20] used a Minimum Mean Square Error (MMSE) combination of navigation solutions as feedback. In addition, the EKF implementation within each GPS receiver was improved with a time-varying process noise covariance that addressed vehicle accelerations as process noise. The coherent processing interval was extended to 20 milliseconds. Additional sub-sample time synchronization was implemented in our PyGNSS software receiver. Using the previous experimental data, navigation solutions with reduced noise, increased reliability, and robustness was demonstrated.

In this paper, we improve upon previous iterations and combine navigation solutions from multiple GPS receivers using an EKF [21], [22]. Following navigation estimation in the individual GPS receivers, we concatenate the states and state error covariances from multiple GPS receivers into an overall measurement input vector and an overall measurement noise covariance input matrix for the overall EKF. We then use the state of the overall EKF as feedback to augment vector tracking within the individual GPS receivers, closing the overall MRVT loop.

We conducted further experiments using different equipment configurations and different experiment scenarios to evaluate our MRVT receiver architecture. We defined reliability and robustness as key performance criteria:

- consistent and accurate GPS signal tracking and position estimation in periods of intermittent signal availability,
- tolerant to equipment malfunctions resulting in degradation of the received signal, such as attenuation.

The rest of this paper is organized as follows. We begin by detailing the MRVT receiver architecture in Section II. In Section III, we discuss our implementation and experiment results. Section IV summarizes the paper.

II. MULTI-RECEIVER VECTOR TRACKING

The MRVT receiver architecture consists of multiple GPS receivers and an overall navigation filter, as shown in Fig. 2. Implemented within each GPS receiver in the MRVT architecture is vector tracking. In vector tracking, multiple channels are jointly tracked through shared receiver states, typically via an EKF [23]. In MRVT, the receiver states of multiple GPS receivers, estimated in the EKF measurement update, are fused to estimate shared multi-receiver states. The shared multi-receiver states are also estimated using an EKF. Using an EKF improves the reliability of MRVT in periods of intermittent signal availability, while mitigating the effects of degraded receiver states on the joint signal tracking and navigation effort in the event of equipment malfunction. The shared multi-receiver states are then used as feedback to the EKF time update of multiple GPS receivers, closing the MRVT loop. MRVT is thus a deeply-coupled joint signal tracking and position estimation architecture. Information integration and redundancy from multiple GPS receivers lend MRVT its reliability and robustness [24]. A block diagram is given in Fig. 3.

Section II-A describes vector tracking within individual receivers while Section II-B describes the deeply-coupled MRVT receiver architecture. In addition, Section II-C describes modifications to the MRVT receiver architecture when using unsynchronized receiver front ends.

A. Vector Tracking Within Individual Receivers

Implemented within each GPS receiver in the MRVT architecture is vector tracking, as shown in Fig. 4. We used the non-coherent Vector Delay and Frequency Lock Loop (VDLLL) [25], [26] with the following state vector:

$$X : \text{state vector of an individual receiver}$$

$$= \begin{bmatrix} x, y, z, c\delta t, \dot{x}, \dot{y}, \dot{z}, c\delta \dot{t} \end{bmatrix}^T$$
where \( x, y, z \) and \( c \delta t \) are the three-dimensional (3D) position coordinates and clock bias in \( (m) \); \( \dot{x}, \dot{y}, \dot{z} \) and \( c \delta t \) are the 3D velocity coordinates and clock drift in \( (m \text{s}^{-1}) \). The speed of light \( c \) is given as \( 299792458 \) \( (\text{m} \text{s}^{-1}) \).

Other state notations used within this paper:

- \( X^i \): state vector of \( i \)th satellite, with \( N \) satellites in view
- \( X_{ECEF} \): state vector expressed in ECEF
- \( X_{ECI} \): state vector expressed in ECI
- \( X_{ECEF} \): state vector of satellite
- \( X_{ECI} \): state vector of satellite
- \( ECEF \): Earth-Centered-Earth-Fixed reference frame
- \( ECI \): Earth-Centered-Inertial reference frame

The navigation filter is an EKF [27], [28], with a 2-step update process: measurement update producing receiver state corrections at epoch boundaries and time update predicting new receiver states, used to update the channel parameters, for the next epoch boundary.

For the measurement update at epoch \( k \), the input to the EKF is derived from code phase and carrier frequency residuals \( (\Delta \Phi_{\text{code}} \text{ (chips)}, \Delta f_{\text{carr}} \text{ (Hz)}) \) measured by the code and carrier discriminators. These measurements, coming from multiple channels, are first scaled into pseudorange and pseudorange rate residuals \( \Delta \rho \text{ (m)}, \Delta \rho \text{ (ms}^{-1}) \), then concatenated to form the error input vector \( \epsilon \) to the EKF.

The EKF measurement update equations at epoch \( k \):

\[
\begin{align*}
\epsilon &= \text{error input vector} \\
&= [\Delta \rho^1, \ldots, \Delta \rho^N, \Delta \rho^1 \ldots \Delta \rho^N]^T \\
W &= \text{error noise covariance input matrix} \\
&= \text{diag}\{\sigma_{\Delta \rho}^1, \ldots, \sigma_{\Delta \rho}^N, \sigma_{\dot{\rho}}^1, \ldots, \sigma_{\dot{\rho}}^N\} \\
\Delta \rho &= \text{pseudorange error (m)} \\
&= \frac{c}{f_{C/A}} \Delta \Phi_{\text{code}} \\
\Delta \dot{\rho} &= \text{pseudorange rate error (m} \text{s}^{-1}) \\
&= \frac{c}{f_{L1}} \Delta f_{\text{carr}} \\
\Delta \Phi_{\text{code}} &= \text{code phase residual (chips)} \\
\Delta f_{\text{carr}} &= \text{carrier frequency residual (Hz)}
\end{align*}
\]

\( f_{C/A} \): C/A code frequency, \( 1.023 \times 10^6 \text{ (chips} \cdot \text{s}^{-1}) \)

\( f_{L1} \): L1 carrier frequency, \( 1575.42 \times 10^6 \text{ (Hz)} \)

The code and carrier discriminator functions are the normalized early-minus-late amplitude and the four quadrant arc-tangent [29], [30]. The measurement noise variances are estimated using 20 past discriminator outputs. The coherent processing interval and EKF update interval \( \Delta T \) is the same and set to 20 milliseconds [31]–[33]. We perform navigation bit wipe-off in our PyGNSS software to allow coherent processing across navigation bit boundaries.

The EKF measurement update equations at epoch \( k \) to estimate the current state \( X_k \) continues as follows:

\[
\begin{align*}
K &= \text{Kalman gain matrix} \\
&= \hat{\Sigma}_k H^T (H\hat{\Sigma}_k H^T + W)^{-1} \\
\Delta X_{ECI} &= \text{state error vector in ECI coordinates} \\
&= K \epsilon \\
\hat{\Sigma}_k &= \text{predicted state error covariance matrix} \\
H &= \text{geometry matrix in ECI coordinates} \\
&= \begin{bmatrix}
H_{los}^1 & H_{los}^2 & \ldots & H_{los}^N
\end{bmatrix} \\
H_{los} &= \begin{bmatrix}
-l_{1,los} & -l_{2,los} & -l_{3,los} & 1 \\
\ldots & \ldots & \ldots & \ldots \\
-l_{N,los} & -l_{N,y,los} & -l_{N,z,los} & 1
\end{bmatrix} \\
\hat{X}_k &= \text{corrected state vector} \\
&= \hat{X}_{k} + \Delta X \\
\hat{\Sigma}_k &= \text{corrected state error covariance matrix} \\
&= (I_{8 \times 8} - K H) \hat{\Sigma}_k \\
I_{8 \times 8} &= 8 \times 8 \text{ identity matrix}
\end{align*}
\]

For the EKF time update to predict the next state \( \hat{X}_{k+1} \), we use a constant acceleration motion model and a dynamic process noise model [34], [35] that addresses vehicle accelerations as process noise. The equations for the EKF time update at epoch \( k + 1 \) are thus given as:

\[
\begin{align*}
\hat{X}_{k+1} &= \text{predicted state vector} \\
&= F \hat{X}_k \\
\hat{\Sigma}_{k+1} &= \text{predicted state error covariance matrix} \\
&= F \hat{\Sigma}_k F^T + Q_k \\
F &= \text{state propagation matrix} \\
&= \begin{bmatrix}
1 & 0 & 0 & 0 & \Delta T & 0 & 0 & 0 \\
0 & 1 & 0 & 0 & 0 & \Delta T & 0 & 0 \\
0 & 0 & 1 & 0 & 0 & 0 & \Delta T & 0 \\
0 & 0 & 0 & 1 & 0 & 0 & 0 & \Delta T \\
0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 & 1
\end{bmatrix}
\end{align*}
\]
\( Q_k \): state process noise covariance matrix

\[
\begin{bmatrix}
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0 \\
0 & 0 & 0 & 0 & 0 & 0 & 0
\end{bmatrix}
\]

(14)

\( \Phi \): process noise due to vehicle accelerations

\[
\sigma_{\Delta t}^2 = (c \cdot \sigma_\tau)^2
\]

(15)

\( \sigma_\tau \): Allan deviation of front end oscillator

The process noise of the front end oscillator is calculated from the Allan deviation as:

\( \sigma_{\Delta t}^2 \): process noise due to vehicle accelerations

(16)

of the \( i^{th} \) satellite

\[
\Phi_{carr,k} = \Phi_{carr,k}^i + f_{carr,k}^i \Delta T
\]

(21)

\( \Phi_{code,k+1}^i \): predicted code phase of the \( i^{th} \) satellite

\[
\Phi_{code,k+1}^i = \Phi_{code,k}^i + f_{code,k}^i \Delta T
\]

(20)

\( \Phi_{code,k}^i \): corrected code phase of the \( i^{th} \) satellite

\[
\Phi_{code,k}^i = \frac{-f_{code,k}^i}{c} (\|X_{x,y,z,ECI} - X_{c\delta t}^i\| + (X_{c\delta t}^i - X_{c\delta t}^i))
\]

(19)

where the process noise due to vehicle accelerations in the

\( \sigma_{\Delta t}^2 \): process noise due to vehicle accelerations

\[
\sigma_{\Delta t}^2 = 1 + 250/(\min(\max(|X_{x,y,z}|^2, 5^2, 25^2))
\]

in a constant acceleration motion model

(17)

B. Deeply-Coupled MRVT Architecture

In MRVT, the state vector \( X \) of multiple receivers is jointly

\( \Phi_{code,k} \):

\( \Phi_{carr,k} \):

\( \Phi_{code,k+1} \):

\( \Phi_{code,k} \):

\( \Phi_{carr,k} \):

\( \Phi_{code,k} \):

\( \Phi_{carr,k} \):

\( X_{j,k} \): state vector of \( j^{th} \) receiver

\( X_{j,k}^+ \): MRVT augmented state vector of \( j^{th} \) receiver

\( e_m \): multi-receiver error input vector

\( W_m \): multi-receiver error covariance input matrix

\( H_m \): multi-receiver geometry matrix
\[ H_j : \text{geometry matrix element} \]  
\[ = I_8 \times 8 \]

\[ \Delta X_{m,k} : \text{multi-receiver state error vector} \]  
\[ = K_m e_m \]

\[ X_{m,k} : \text{corrected multi-receiver state vector} \]  
\[ = \hat{X}_{m,k} + \Delta X_{m,k} \]

\[ \Sigma_{m,k} : \text{corrected multi-receiver state error covariance matrix} \]  
\[ = (I_8 - K_m H_m) \hat{\Sigma}_{m,k} \]

The predicted multi-receiver state error covariance matrix \( \hat{\Sigma}_{m} \) is initialized using past multi-receiver state vectors \( X_{m-1,...} \), calculated using weighted least squares. The MRVT EKF time update is performed together with the EKF time update of the individual receivers. The equations are the same and given in Eq. (11) to Eq. (15).

Through MRVT, shared multi-receiver states jointly track the states of multiple receivers which jointly track the states of multiple channels, achieving deeply coupled multi-receiver signal tracking. Joint tracking increases signal availability while leveraging information redundancy for robustness. This is possible for multiple receivers installed in close proximity, on a rigid body and sharing the same front end oscillator [6], [24]. Section II-C describes modifications to the MRVT architecture for unsynchronized front ends.

C. Modifications for Unsynchronized Front Ends
For the case of unsynchronized front ends, additional clock bias and clock drift states are appended to \( X_m \).

\[ X_m = [x, y, z, c\delta t_1, \dot{x}, \dot{y}, \dot{z}, c\delta t_1, \dot{c}\delta t_2]^{T} \]

The rest of the MRVT equations are updated accordingly:

\[ e_m = \begin{bmatrix} X_{1,m,k} - \hat{X}_{m,x,y,z,c\delta t_1,\dot{x},\dot{y},\dot{z},c\delta t_1,\dot{c}\delta t_2} \\ X_{2,m,k} - \hat{X}_{m,x,y,z,c\delta t_2,\dot{x},\dot{y},\dot{z},c\delta t_2} \end{bmatrix} \]

\[ W_m = \begin{bmatrix} \Sigma_{1,k} & \Sigma_{2,k} \end{bmatrix} \]

\[ H_m = \begin{bmatrix} H_1 \\ H_2 \end{bmatrix} \]

\[ H_1 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \]

\[ H_2 = \begin{bmatrix} 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \]

The MRVT EKF time update equations are also modified:

\[ \hat{X}_{m,k+1} : \text{predicted multi-receiver state vector} \]
\[ = F_m X_{m,k} \]

\[ \hat{\Sigma}_{m,k+1} : \text{predicted multi-receiver state error covariance matrix} \]
\[ = F_m \Sigma_{m,k} F_m^T + Q_{m,k} \]

\[ F_m : \text{multi-receiver state propagation matrix} \]
\[ = \begin{bmatrix} 1 & 0 & 0 & 0 & \Delta T & 0 & 0 & 0 & 0 \\ 0 & 1 & 0 & 0 & 0 & \Delta T & 0 & 0 & 0 \\ 0 & 0 & 1 & 0 & 0 & 0 & \Delta T & 0 & 0 \\ 0 & 0 & 0 & 1 & 0 & 0 & 0 & \Delta T & 0 \\ 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 0 & 1 & 0 \end{bmatrix} \]

\[ Q_{m,k} : \text{multi-receiver state process noise covariance matrix} \]
\[ = \begin{bmatrix} F_m \Sigma_{m,k} F_m^T + Q_{m,k} \end{bmatrix} \]

\[ \sigma^2_{c\delta t_j} : \text{process noise of } j^{th} \text{ front end oscillator} \]

III. Implementation and Experiment Results
We implemented 3 different MRVT receiver configurations and conducted 3 different experiments to evaluate the performance of our MRVT receiver architecture.

Section III-A describes an experiment in downtown San Francisco using 2 unsynchronized radio frequency (RF) front ends with lower RF sensitivity and lower oscillator stability. This experiment validates the reliability of our MRVT receiver architecture in periods of intermittent signal availability while using only 2 GPS receivers. The total cost of this setup purchased in the year 2015 is approximately $630.

Section III-B describes an experiment in our University of Illinois at Urbana-Champaign campus using 4 synchronized RF front ends with higher RF sensitivity and higher oscillator stability. This experiment validates the reliability of our MRVT receiver architecture in periods of limited signal availability while using more GPS receivers, and of higher quality. The total cost of this setup purchased in the year 2014 is approximately $12000.
TABLE I
EXPERIMENT SETUPS

<table>
<thead>
<tr>
<th>Experiment</th>
<th>A. Urban Environment with 2 Receivers</th>
<th>B. Suburban Environment with 4 Receivers</th>
<th>C. Equipment Malfunction (1 of 2 Receivers Malfunctioning)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Location</td>
<td>Downtown San Francisco</td>
<td>University of Illinois at Urbana-Champaign</td>
<td>University of Illinois at Urbana-Champaign</td>
</tr>
<tr>
<td>Number of receivers</td>
<td>2</td>
<td>4</td>
<td>2</td>
</tr>
<tr>
<td>RF front end</td>
<td>SiGe GN3S Sampler v3</td>
<td>USRP N210</td>
<td>USRP N210</td>
</tr>
<tr>
<td>Sampling frequency</td>
<td>2.046 MHz</td>
<td>2 MHz</td>
<td>5 MHz</td>
</tr>
<tr>
<td>Sampling precision</td>
<td>2-bit</td>
<td>14-bit</td>
<td>14-bit</td>
</tr>
<tr>
<td>Bandwidth</td>
<td>2.2 MHz</td>
<td>8 MHz</td>
<td>8 MHz</td>
</tr>
<tr>
<td>Oscillator</td>
<td>TCXO</td>
<td>CSAC</td>
<td>CSAC</td>
</tr>
<tr>
<td>Oscillator frequency</td>
<td>16.368 MHz</td>
<td>10 MHz</td>
<td>10 MHz</td>
</tr>
<tr>
<td>Phase noise</td>
<td>−80 dBc/Hz</td>
<td>−50 dBc/Hz</td>
<td>−50 dBc/Hz</td>
</tr>
<tr>
<td>Frequency bias</td>
<td>±100 Hz</td>
<td>±0.005 Hz</td>
<td>±0.005 Hz</td>
</tr>
<tr>
<td>Allan deviation</td>
<td>$1.0 \times 10^{-8} \cdot s^{-1}$</td>
<td>$2.5 \times 10^{-11} \cdot s^{-1}$</td>
<td>$2.5 \times 10^{-11} \cdot s^{-1}$</td>
</tr>
<tr>
<td>Synchronized</td>
<td>No</td>
<td>Splitter</td>
<td>MIMO cable</td>
</tr>
</tbody>
</table>
| Remarks     | • validate reliability in periods of intermittent signal availability  
              • lower RF sensitivity       
              • lower oscillator stability  
              • unsynchronized oscillators | • validate reliability  
              • more receivers in architecture  
              • higher RF sensitivity  
              • higher oscillator stability  
              • synchronized oscillators | • validate robustness to equipment malfunction  
              • higher RF sensitivity  
              • higher oscillator stability  
              • synchronized oscillators |

Section III-C describes an experiment using 2 synchronized GPS receivers where we physically loosened the antenna connection of 1 GPS receiver, resulting in an SNR degradation of 15 dB per channel for that GPS receiver. This experiment validates the robustness of our MRVT receiver to equipment malfunctions of a single GPS receiver.

Table I provides an overview of the 3 experiment setups.

A. Experiment in Urban Environment With 2 GPS Receivers

We implemented a 2-receiver MRVT architecture using 2 sets of RF components: 2 ANT-555 magnetic mount active patch antennas [40] and 2 SiGe GN3S version 3 samplers [41], as shown in Fig. 5. The 2 patch antennas and SiGe samplers have lower RF sensitivities as compared to configurations described in subsequent sections. This configuration is thus more susceptible to reduced signal availability. In addition, the SiGe samplers have independent, unsynchronized oscillators, introducing additional clock bias and clock drift parameters into the shared multi-receiver state vector. Referenced against the GPS time solution, the SiGe samplers had inherent clock drifts that were 200 Hz apart. Using this MRVT receiver configuration, with 2-bit complex sampling and a sampling frequency of 2.046 MHz, we collected a 10-minute data set in downtown San Francisco. The signals were first processed using vector tracking in our PyGNSS software.

The densely located buildings in downtown San Francisco provided rich signal obstruction, resulting in frequent signal disruptions. The navigation results from vector tracking, as plotted on Google Maps [42], are shown in Fig. 6 (a). The blue and red curves correspond to vector tracking results using signals received by patch antennas installed on the left and right edges of the vehicle’s roof. The blue receiver lost track at a location with a particularly tall building on the left, as shown in Fig. 6 (b). The red receiver lost track at a location with a particularly tall building on the right, as shown Fig. 6 (c). Both vector tracking receivers did not manage to lock back onto the received signals after the initial loss of lock.

Fig. 5. Experiment setup in downtown San Francisco using 2 GPS receivers. Implementation using 2 patch antennas and 2 SiGe GN3S version 3 samplers.

Fig. 6. Navigation results from vector tracking (VT) of the 2 GPS receivers, plotted using Google Maps [43]. (a) The blue and red receivers lost track at the locations indicated by blue and red triangles. (b) Google street view [44] of the location where the blue receiver lost track, a particularly tall building is on the left. (c) Google street view of the location where the red receiver lost track, a particularly tall building is on the right.
Fig. 7. Signal acquisition results using a 25 dB SNR threshold, discontinuities represent signal outages. Since the 2 receivers are closely located on the roof of the same road vehicle, most signal disruptions are concurrent. On the other hand, periods where the 2 receivers did not concurrently experience signal disruptions exist. These are opportunities for joint signal tracking via MRVT. (a) Acquired carrier doppler frequency of PRN 3; (b) acquired code phase of PRN 3; (c) acquired carrier doppler frequency of PRN 32; (d) acquired code phase of PRN 32. The above plots have been processed to reject outliers.

On the other hand, a plot of GPS signal visibility in Fig. 7 showed that GPS signals received by the blue and red receivers were not always disrupted and the disruptions were not always simultaneous. Opportunities for MRVT to improve the reliability of GPS signal tracking and position estimation exist.

Using MRVT, we jointly processed the GPS signals received by both the blue and red receivers. The signal tracking errors, referenced to signal acquisition, is shown in Fig. 8. MRVT accurately and consistently tracked the received GPS signals. In comparison, vector tracking using the blue receiver lost track at the times indicated by the blue arrows. The navigation results using MRVT are plotted in Fig. 9. MRVT effectively mitigated GPS signal tracking disruptions of the individual GPS receivers through joint signal tracking across multiple GPS receivers. MRVT leveraged multiple GPS receivers to increase the reliability of GPS localization, consistently providing accurate positioning solutions even when the performance of vector tracking was degraded.

Fig. 8. Signal tracking errors referenced to signal acquisition. MRVT accurately and consistently tracked the received GPS signals. In comparison, vector tracking using the blue receiver resulted in large signal tracking residuals at the times indicated by the blue arrows. (a) Carrier doppler frequency residual of PRN 3; (b) code phase residual of PRN 3; (c) carrier doppler frequency residual of PRN 32; (d) code phase residual of PRN 32. Acquisition performed using coarse 0.5 chip intervals and fine frequency estimation.

Fig. 9. MRVT accurately and consistently positioned the vehicle in downtown San Francisco, demonstrating reliable GPS signal tracking and position estimation in periods of intermittent signal availability. In comparison, vector tracking of the blue and red receivers lost track at the locations indicated by the blue and red triangles within the orange box, as shown in Fig. 6 (a). Results were plotted using Google Maps [42].
B. Experiment With 4 GPS Receivers

We implemented a 4-receiver MRVT architecture using 4 sets of RF components: 4 AntCom 3GNSSA4-XT-1 GNSS antennas [45] and 4 Ettus Research N210 Universal Software Radio Peripherals (USRPs) [46], each equipped with a DB-SRX2 daughterboard [47], as shown in Fig. 10. Compared to the patch antennas and SiGe samplers in the previous configuration, the AntCom antennas and USRPs have increased sensitivity to weak signals. In addition, the USRPs were synchronized using timing signals from a common external oscillator, a Microsemi Quantum SA.45s Chip Scale Atomic Clock (CSAC) [39]. Compared to the previous configuration, this configuration is synchronized, with a stable front end oscillator.

We conducted 2 experiments on our University of Illinois at Urbana-Champaign campus to validate the reliability of MRVT in periods of intermittent and limited signal availability.

The first experiment was conducted on Green St, a suburban environment with tall buildings. Vector tracking results are shown in Fig. 11 (a); where the 4 GPS receivers are distinguished using 4 different colors. MRVT results, in black, are shown in Fig. 11 (b). In addition, we plotted an EKF combination of the vector tracking results, considered a loosely-coupled architecture, in orange. In comparison to vector tracking and combined vector tracking, MRVT demonstrated improved reliability with consistently smoother tracks on the correct side of the road.

The second experiment was conducted in the parking lot of an apartment complex. Due to partial obstruction by the apartment building, the number of satellites in view from the stationary vehicle was less than 4. Vector tracking results are shown in Fig. 12 (a); MRVT results are shown in Fig. 12 (b). While vector tracking lost track of the stationary vehicle, MRVT reliably estimated the position of the stationary vehicle.

C. Experiment With Equipment Malfunction

In many critical systems, redundancy, the multiplication of crucial components, aids in increasing robustness to equipment malfunction. Using MRVT of multiple GPS receivers, we are able to mitigate the effects of a single malfunctioning receiver, increasing the robustness of GPS localization. We thus demonstrate in this experiment, the robustness of MRVT to equipment malfunction of a single GPS receiver.

We implemented a 2-receiver MRVT configuration using 2 patch antennas and 2 USRPs. In addition to the CSAC, we synchronized the USRPs using a MIMO cable provided by the manufacturer, Ettus Research. We then physically loosened
MRVT is a deeply-coupled multi-receiver architecture that leveraged multiple GPS receivers for joint signal tracking and position estimation. Using 3 different MRVT implementations in 3 different experiment scenarios, we experimentally validated the reliability of our MRVT receiver in periods of intermittent GPS availability, and the robustness of our MRVT receiver to the failure of a single GPS receiver.

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Yuting Ng received her B.S. degree in electrical engineering and her M.S. degree in aerospace engineering from the University of Illinois at Urbana-Champaign, Illinois, USA in 2014 and 2016. Her research interests are in machine learning, radar signal processing, GNSS signal tracking, navigation and time synchronization.

Grace Xingxin Gao received her B.S. degree in mechanical engineering and her M.S. degree in electrical engineering from Tsinghua University, Beijing, China in 2001 and 2003. She received her PhD degree in electrical engineering from Stanford University in 2008. From 2008 to 2012, she was a research associate at Stanford University. Since 2012, she has been an assistant professor in the Aerospace Engineering Department at University of Illinois at Urbana-Champaign. Her research interests are systems, signals, control, and robotics. She is a senior member of IEEE and a member of ION.