Reliable RF Navigation in Degraded Environments using Advanced Signal Processing

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GPS & Vehicle Dynamics Laboratory

Automated Truck Convoys

Precise Longitudinal Positioning

Precise Lateral Positioning

Precise Relative Positioning and Control

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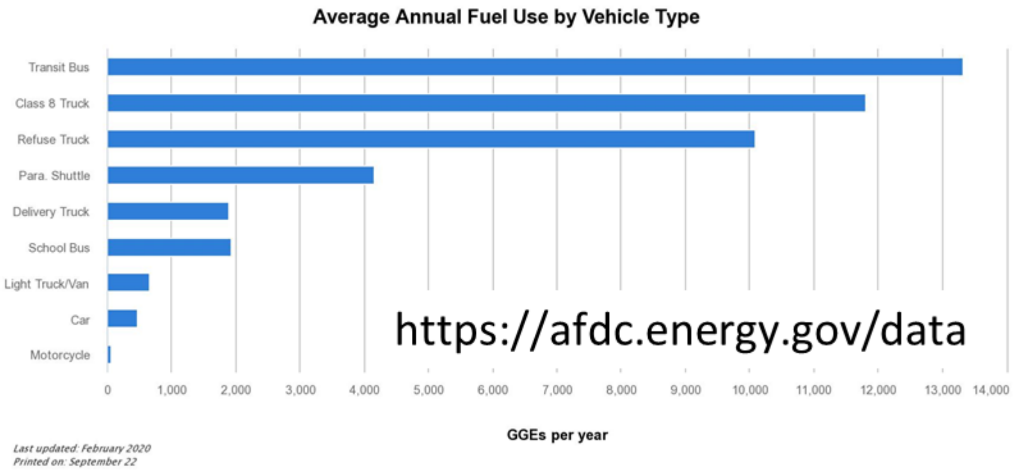
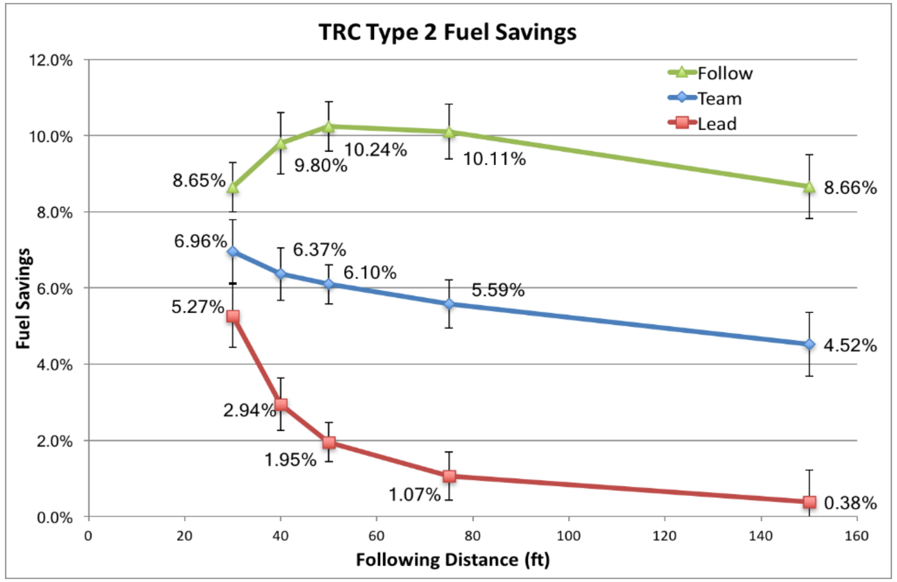
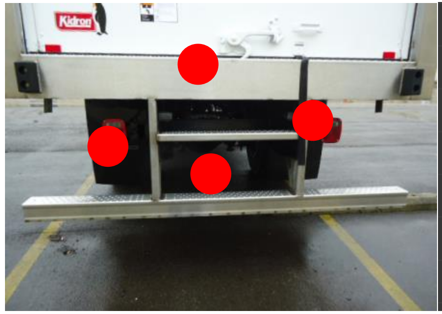
Motivation

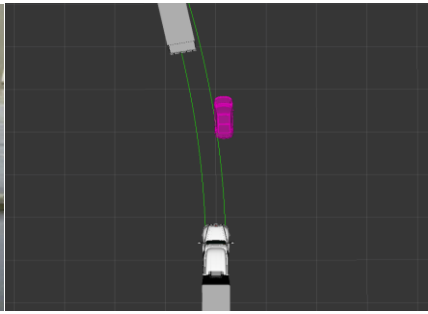


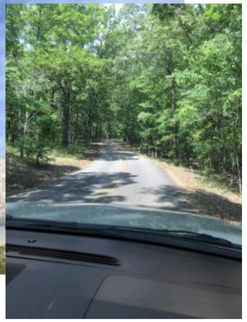


Resources

Limitations





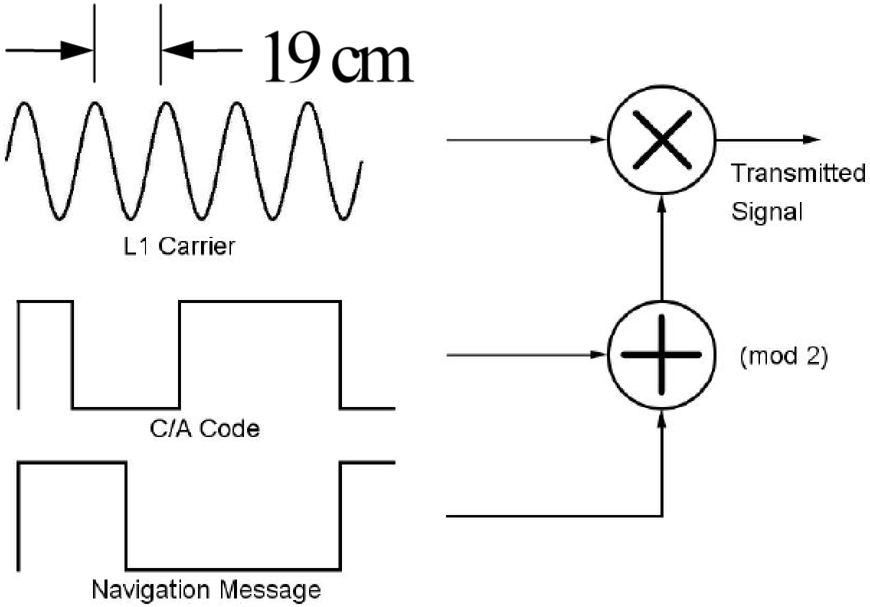


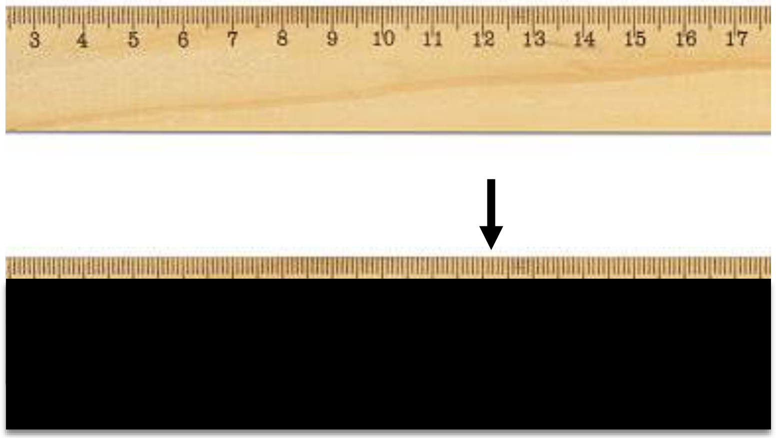
Outline

- Radar/GPS Fusion
  - Carrier Phase Differential Positioning
  - Probabilistic Data Association Filter
- Coherent Differential Vector Tracking
  - Position Domain Signal Tracking
  - Precise Positioning in Degraded Conditions
- Signals of Opportunity
  - Ultra-tightly Coupled LTE/GPS
- Fault Detection and Mitigation
  - Signal Level Error Rejection

Carrier Phase Differential GPS

- Carrier phase is measured 1-10% of a wavelength
- Cycle ambiguity must be estimated
- Local base station needed to remove atmospheric errors
  - Fixed - Global
  - Dynamic – Relative (RPV)
- Position solution centimeter accuracy

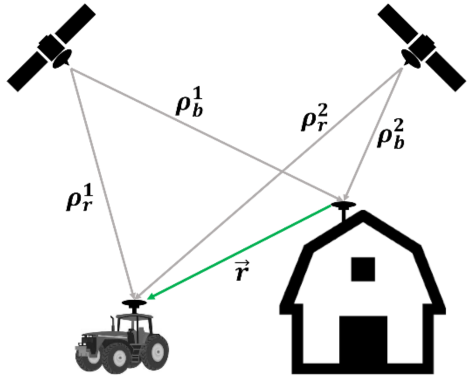




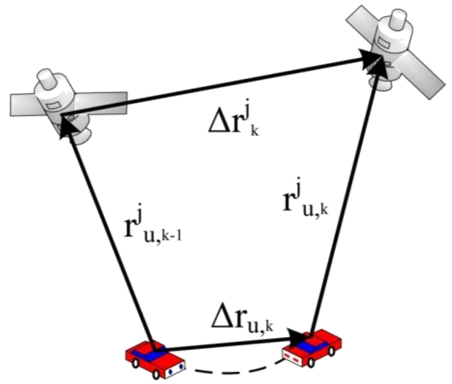
Differential GPS Approach

- Dynamic Real Time Kinematic (DRTK)
  - Position can be estimated to centimeter accuracy
- Time Differenced Carrier Phase (TDCP)
  - An accurate (cm) odometry solution of leader or follower
- Path Generation
  - Following vehicle steers toward a virtual lead vehicle position derive from DRTK and TDCP

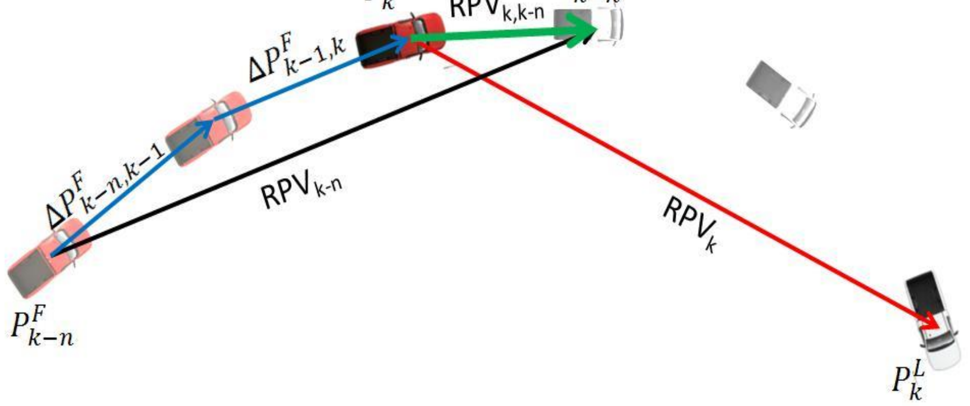
Differential Positioning



Odometry



Path Following



Dynamic Base Real Time Kinematic Positioning

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- Majority of errors can be mitigated by differencing these measurements from two receivers
- Carrier phase ambiguity must be estimated

Carrier Phase Measurement Model

$$\phi_r^j(t) = r_r(t) + \lambda N_r^j + b^j(t-\tau) + b_r(t) - I(t) + T(t) + v_r^j(t)$$
$$\phi_b^j(t) = r_b(t) + \lambda N_b^j + b^j(t-\tau) + b_b(t) - I(t) + T(t) + v_b^j(t)$$

Single Different Observable

$$\Delta\phi_{rb}^j(t) = r_{rb}^j(t) + \lambda N_{rb}^j + b_{rb}(t) + v_{rb}^j(t)$$

Estimator State Vector

$$\hat{X} = \left[r_{rb_x}\ \dot{r}_{rb_x}\ r_{rb_y}\ \dot{r}_{rb_y}\ r_{rb_z}\ \dot{r}_{rb_z}\ b_{rb}\ \dot{b}_{rb}\ N_{rb}^1 \dots N_{rb}^m\right]^{\mathrm{T}}$$

- Least squares AMBiguity Decorrelation Adjustment (LAMBDA) used to “fix” ambiguities
- Ratio test statistic determines fix

$$\chi = \frac{\left(\hat{N} - \tilde{N}_1\right)P_N^{-1}\left(\hat{N} - \tilde{N}_1\right)^{\mathrm{T}}}{\left(\hat{N} - \tilde{N}_2\right)P_N^{-1}\left(\hat{N} - \tilde{N}_2\right)^{T}}$$

Carrier Phase Range Observable Model

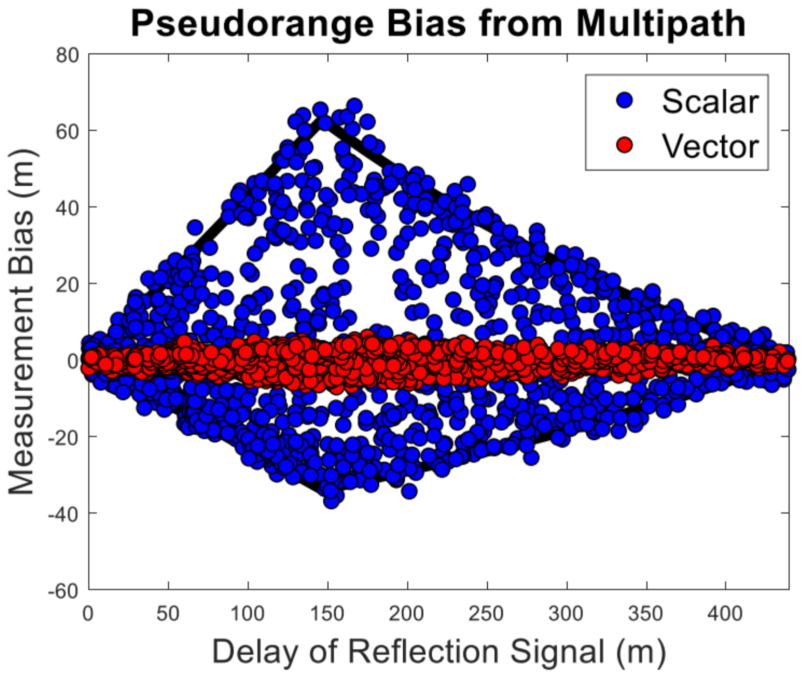
$$\Delta\nabla\phi_{rb} - \lambda\Delta\nabla N_{rb} = \Delta\vec{u}_r\vec{r}_{rb} + v_{rb}$$

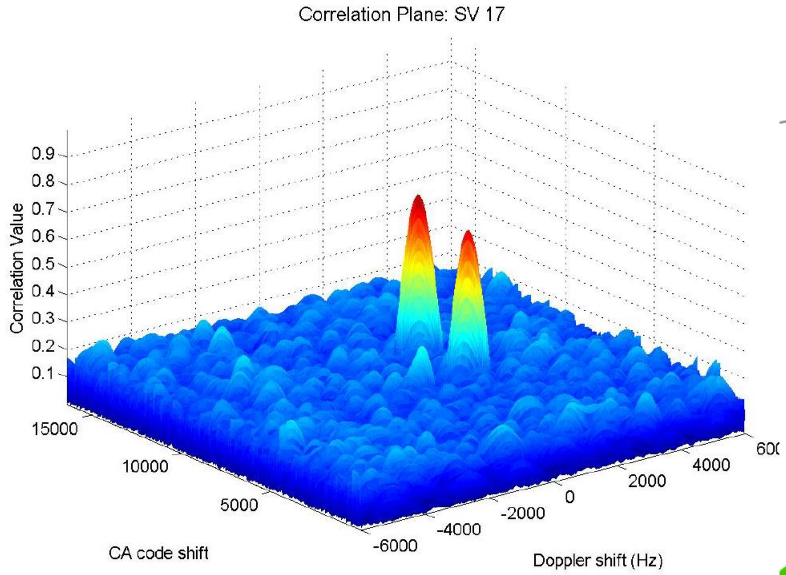
Least Squares High Precision RPV

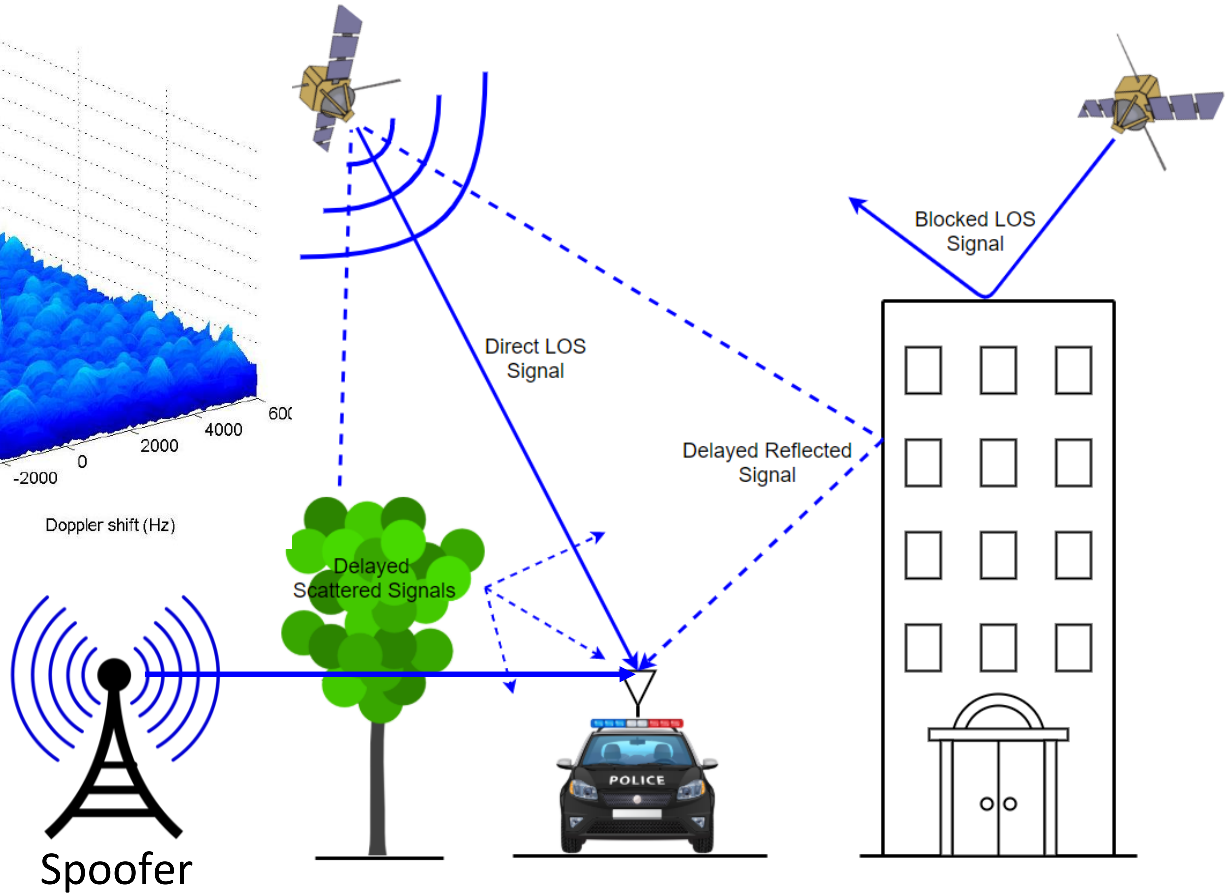
$$\vec{r}_{rb} = \left(\Delta\vec{u}_r^T\Delta\vec{u}_r\right)^{-1}\Delta\vec{u}_r^T\left(\Delta\nabla\phi_{rb} - \lambda\Delta\nabla N_{rb}\right)$$

GPS Limitations

- Multipath/Spoofing generate multiple replicas of GPS signal
- Correlated interference results in range error or inauthentic position solution



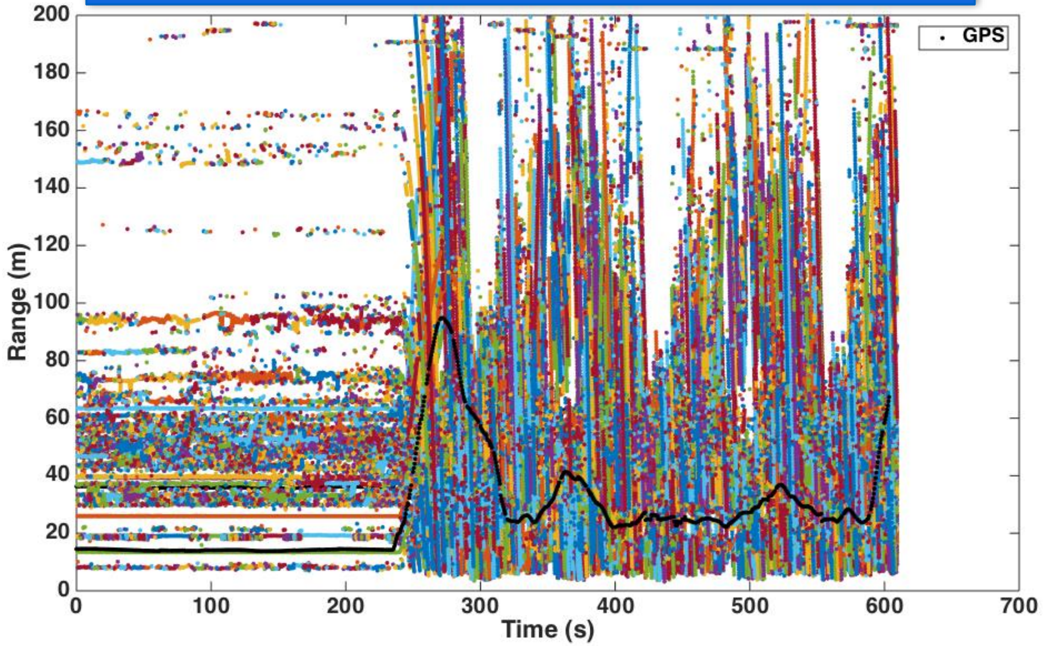




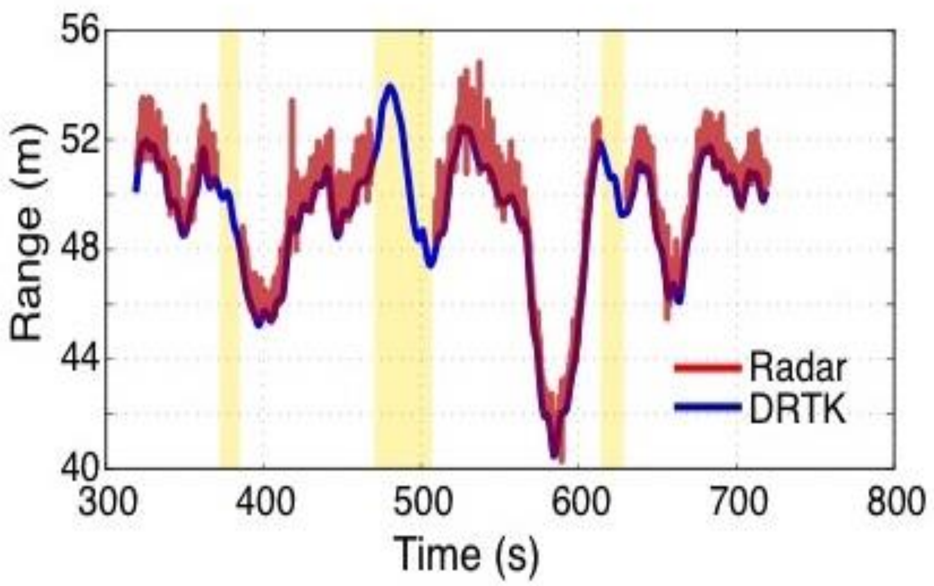
GPS/Radar Fusion for Reliable Following

- GPS interference causes increased error and short-term outages
- Radar tracks are difficult to distinguish in isolation
- Cut-ins and curves break line-of-sight
- GPS/Radar fusion minimizes deficiencies of individual solutions

Delphi ESR Raw Range Measurements

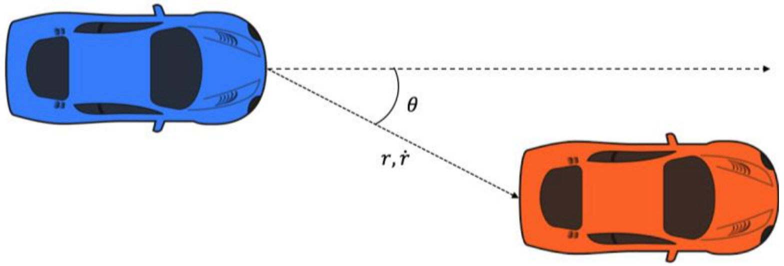


Filtered Range Estimate with GPS DRTK

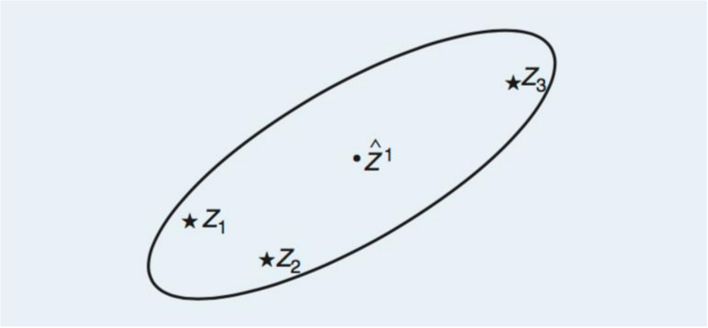


Probabilistic Data Association Filter

- PDAF
  - Uses innovation probability density to associate tracks
  - Kalman Filter
- Validation Region
  - Centered about current estimate
  - Elliptical shape based Gaussian error model for predicted measurement
- Association Probability Calculation
  - Probability, β, that the measurement Z_j originated from desired target
- Aggregate Innovation
  - Acts as a weighted mean
    - » m_k is # of validated measurements
    - » $\tilde{z}_k^j = z_k^j - \hat{z}_k$



Validation Region



Yaakov Bar-Shalom, Fred Daum, and Jim Huang. *The probabilistic data association filter*. IEEE Control Systems, vol. 29(6), December 2009.

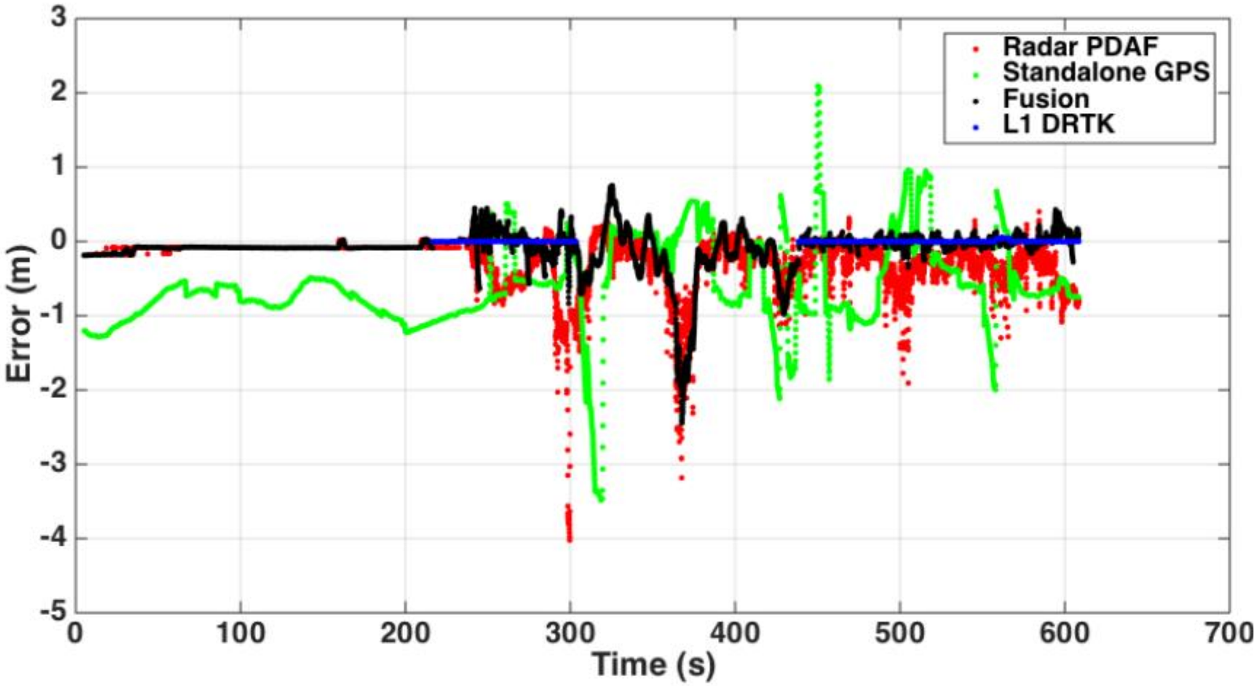
Aggregate Innovation $\tilde{\boldsymbol{z}}_{\boldsymbol{k}} = \sum_{j=1}^{m_k} \boldsymbol{\beta}_{\boldsymbol{k}}^{\boldsymbol{j}} \tilde{\boldsymbol{z}}_{\boldsymbol{k}}^{\boldsymbol{j}}$

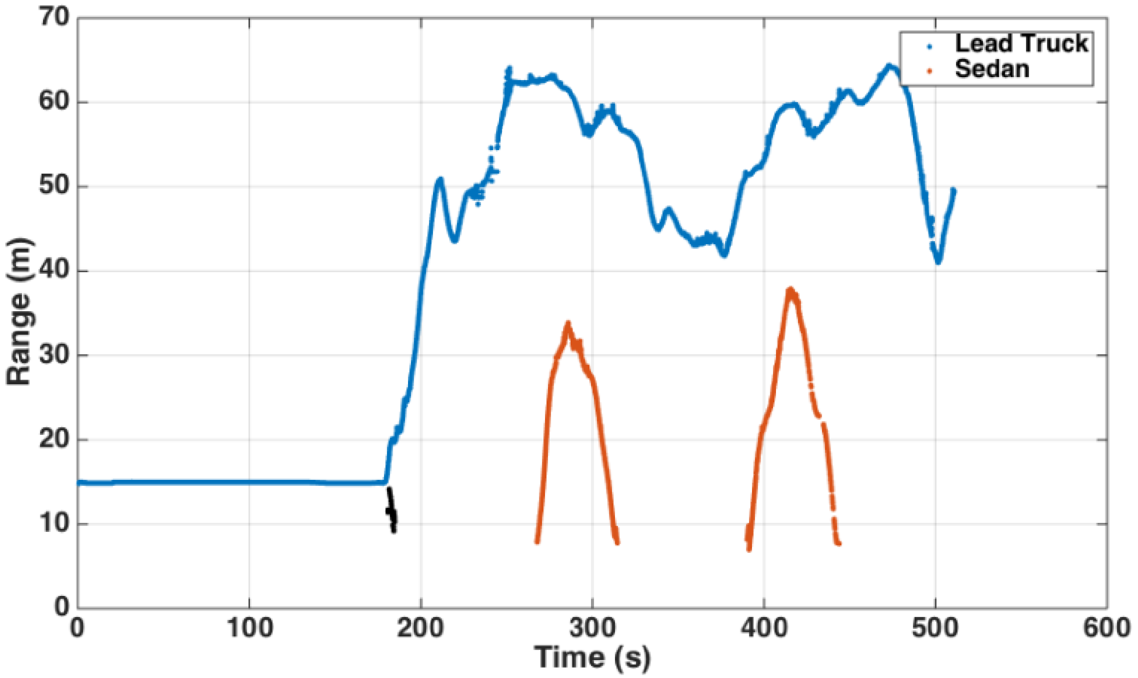
Kalman Update $\hat{\boldsymbol{x}}_{\boldsymbol{k}} = \hat{\boldsymbol{x}}_{\boldsymbol{k-1}} + \boldsymbol{L}_{\boldsymbol{k}} \tilde{\boldsymbol{z}}_{\boldsymbol{k}}$

DRTK/Radar PDAF Results

- Improved solution availability
- Reduced error variance
- Cut-in detection

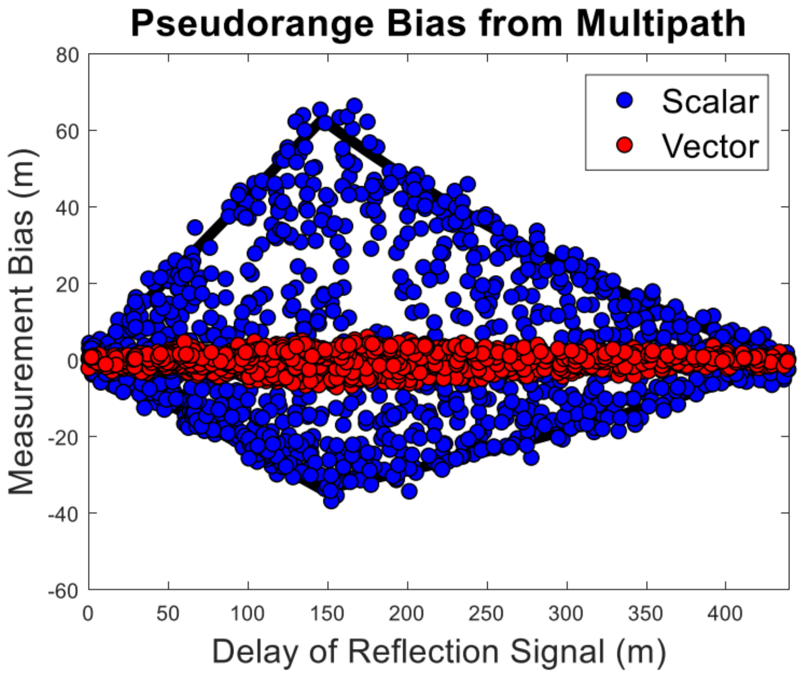
Solution	Standard Deviation (m)	Mean Error (m)
Radar PDAF	0.3479	0.2666
Standalone GPS	0.6057	0.7390
L1 DRTK	0.0075	0.0028
DRTK/PDAF	0.2830	0.1531

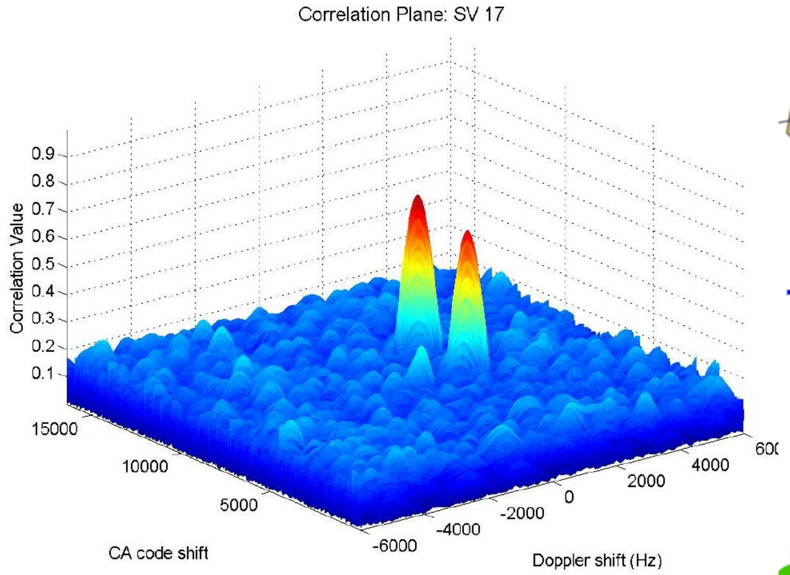


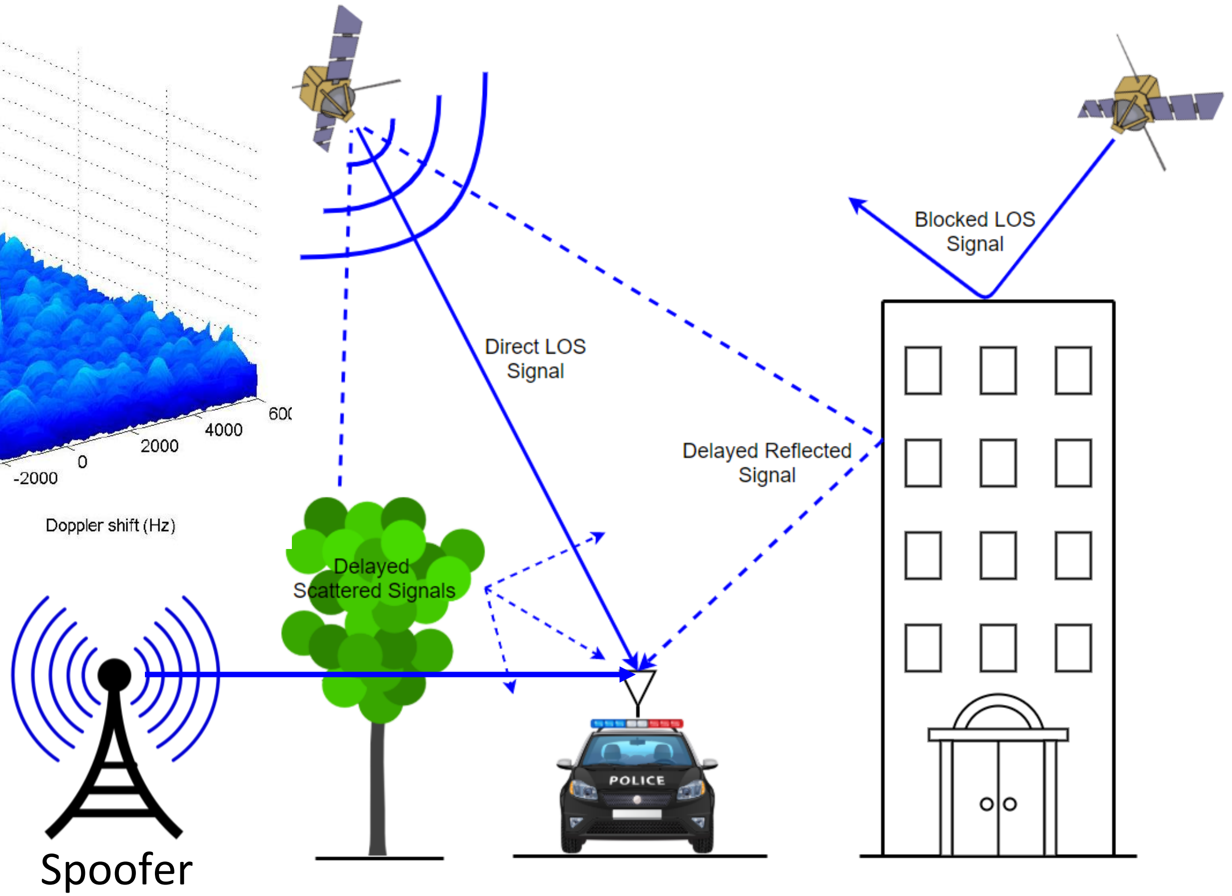


GPS Fault Detection and Mitigation

- Multipath/Spoofing generate multiple replicas of GPS signal
- Correlated interference results in range error or inauthentic position solution







Spoofing Detection

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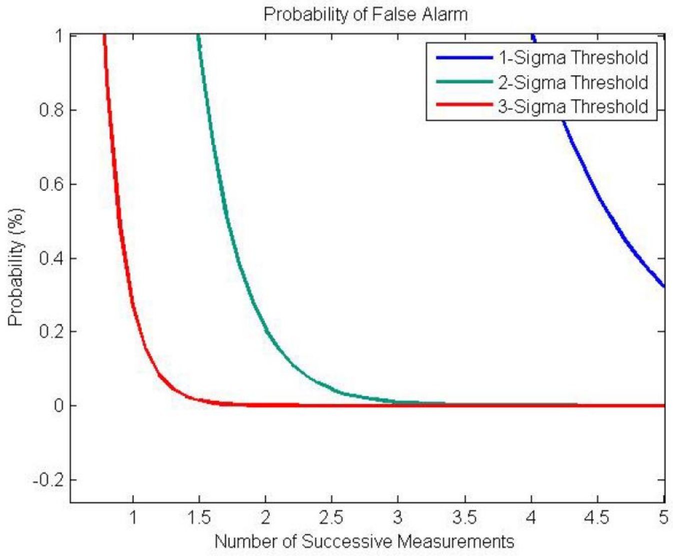
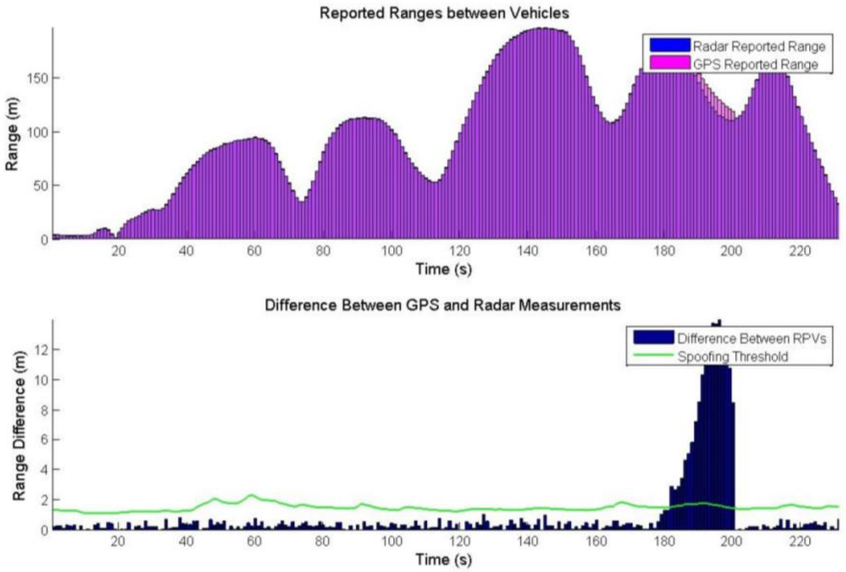
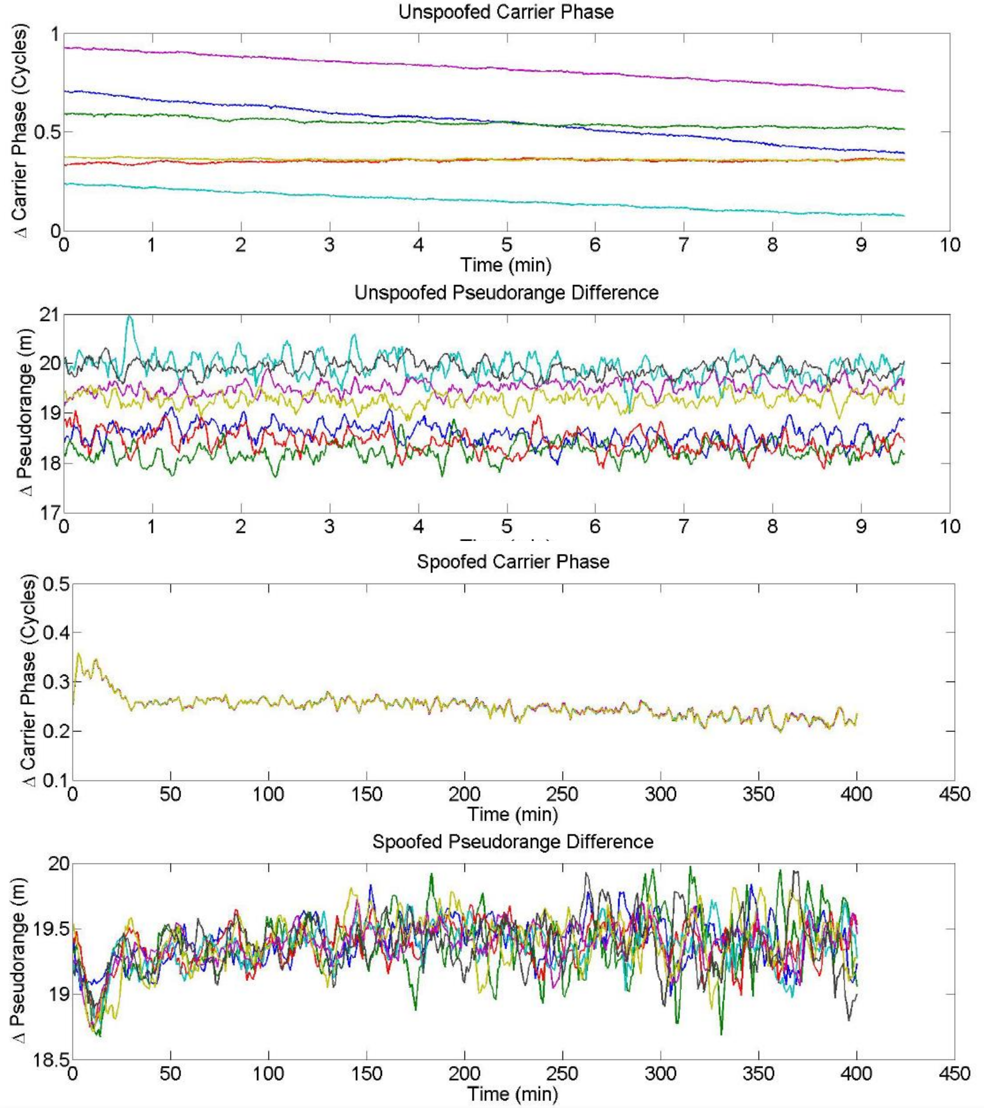
- Phase Difference Convergence
- Radar/GPS RPV Divergence
  - Multiple statistically significant deviations trigger spoof identification

Radar/GPS RPV Divergence





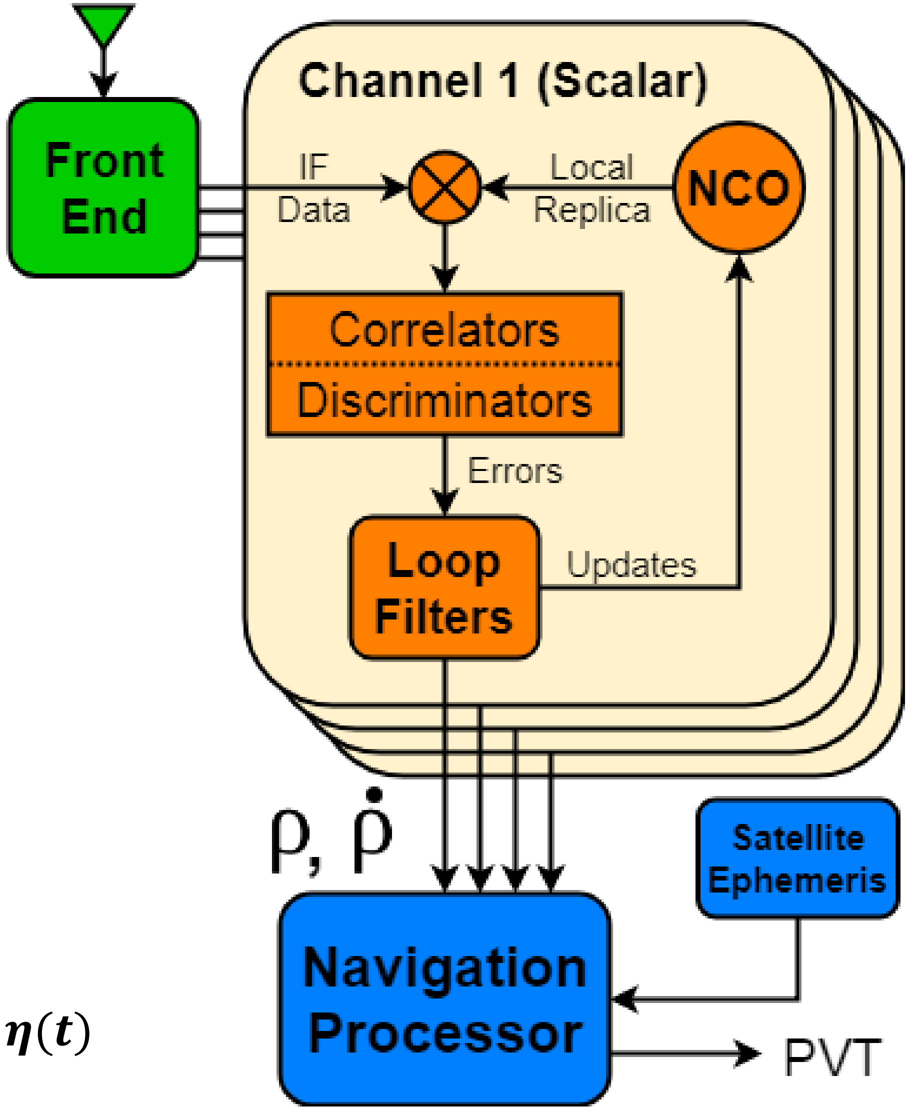


Phase Difference Convergence

GPS Receiver Signal Tracking

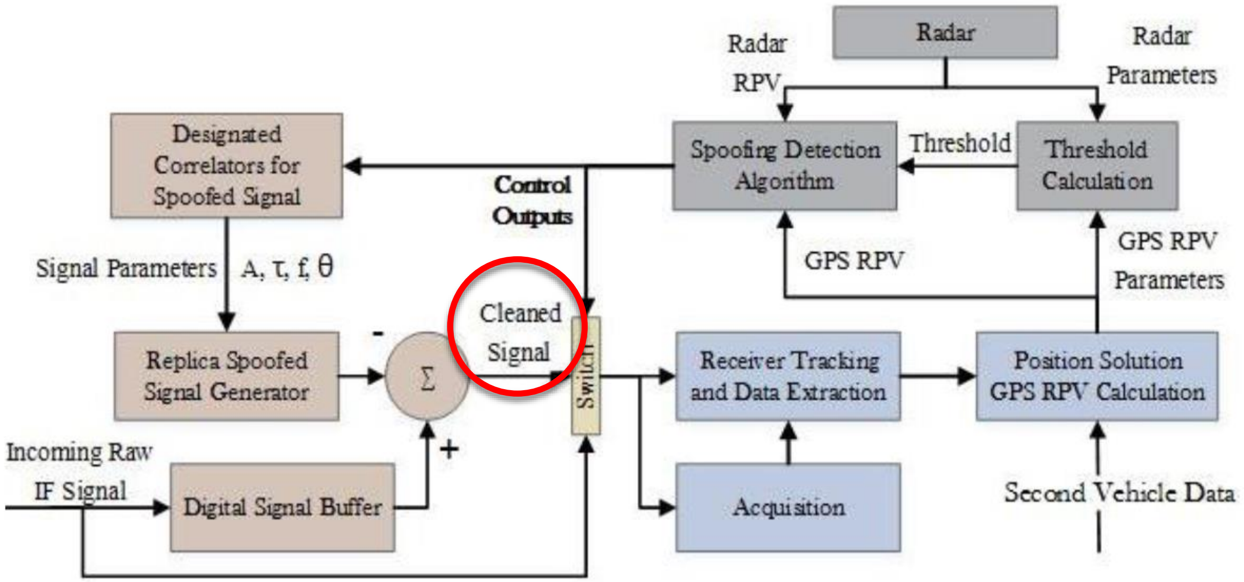
- Three main processors
  - Front-end
  - Signal Tracking (per channel)
  - Navigation
- Phase Lock Loop (PLL) tracks each channel's carrier
  - Extracts Doppler measurements ($\dot{\rho}$)
  - Can also use Frequency Lock Loop (FLL)
- Delay Lock Loop (DLL) tracks each channel's PRN code
  - Extracts pseudorange measurements (ρ)

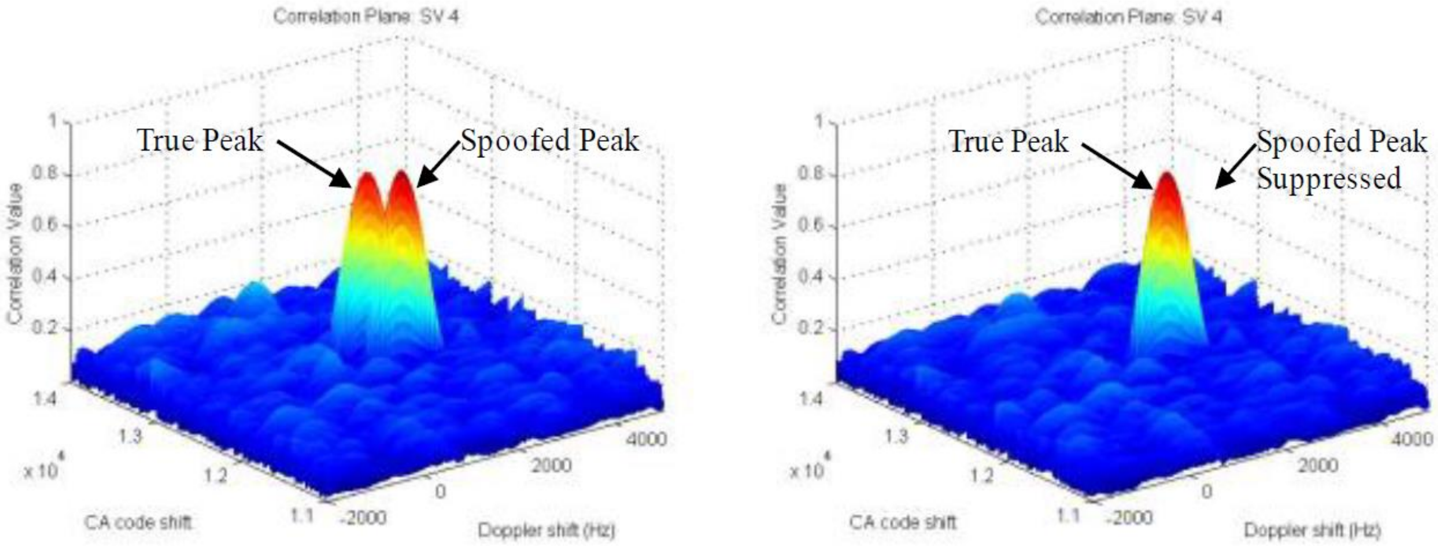
$$s_i(t) = A\,C(t+\tau)\,D(t+\tau)\cos\left(2\pi\left(f_{L1}+f_{Dop}\right)(t+\tau)+\theta\right)+\eta(t)$$



Successive Interference Cancellation

- Tracking parameters used to wipe-off spoof signal
- Clean signal processed traditionally to produce carrier phase measurements



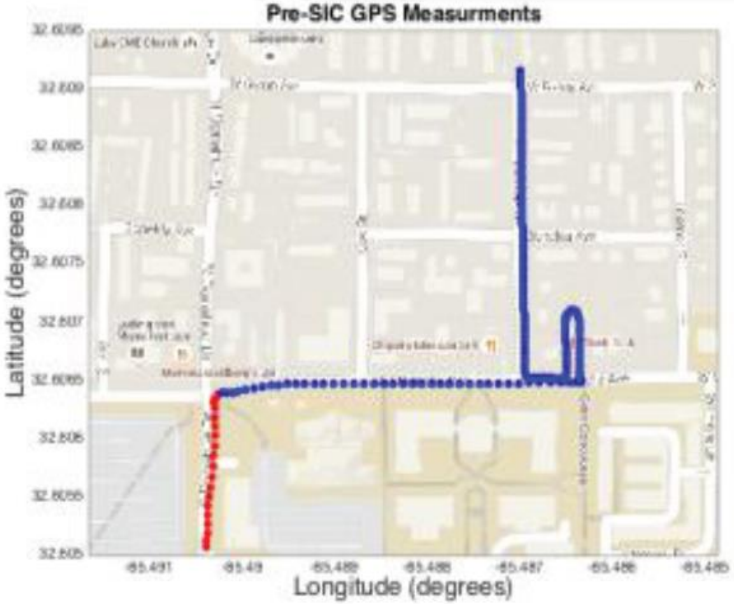


SIC – Positioning Performance

- Stationary spoofed position and drag-off spoofed position rejected
- COTS receiver recovered true trajectory after SIC applied

Stationary Spoofed Position

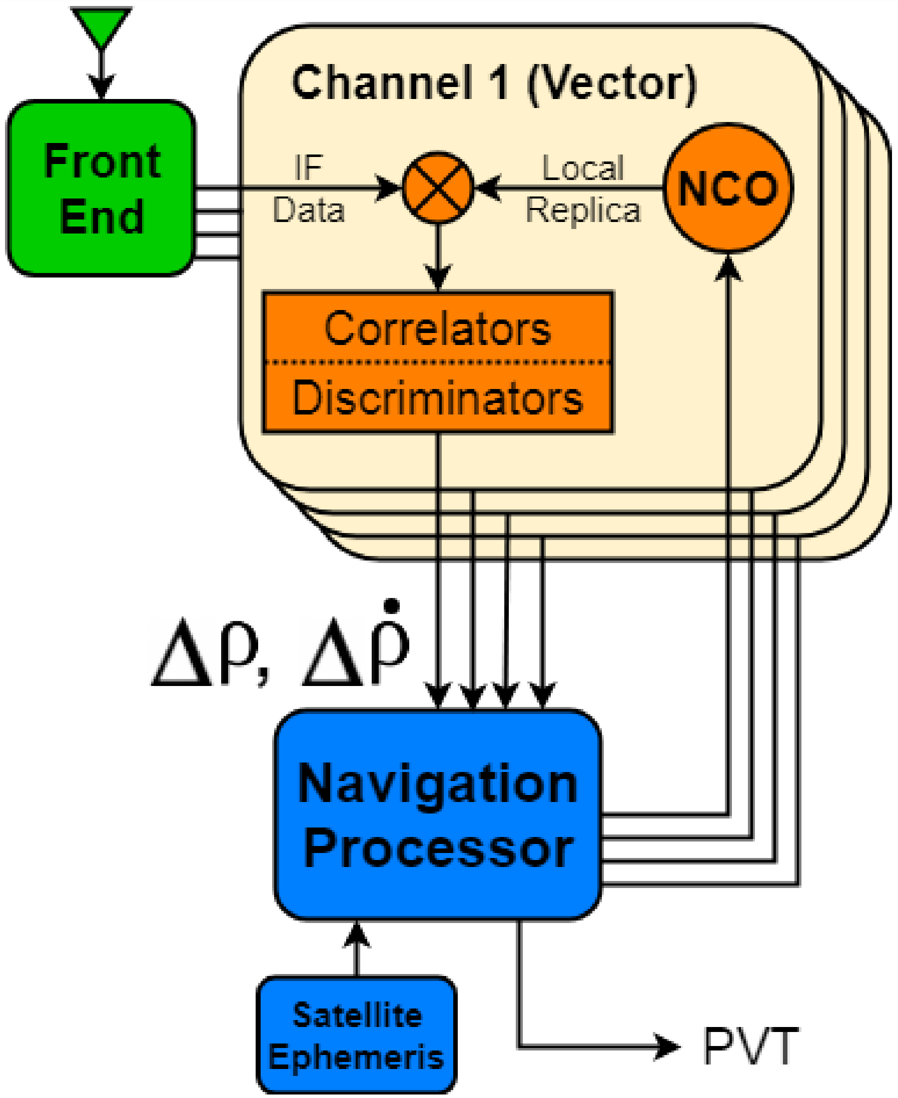
Drag-off Spoofed Position



GPS Vector Tracking

- Software defined receiver implementation
- Signal tracking and navigation processors are coupled together
- Vector Frequency Lock Loop (VFLL)
  - Carrier tracking is coupled to velocity estimator
- Vector Delay Lock Loop (VDLL)
  - Code tracking is coupled to position estimator
- Individual loop filters replaced with centralized extended Kalman filter
  - Satellite channels track all signals together

Vector Tracking



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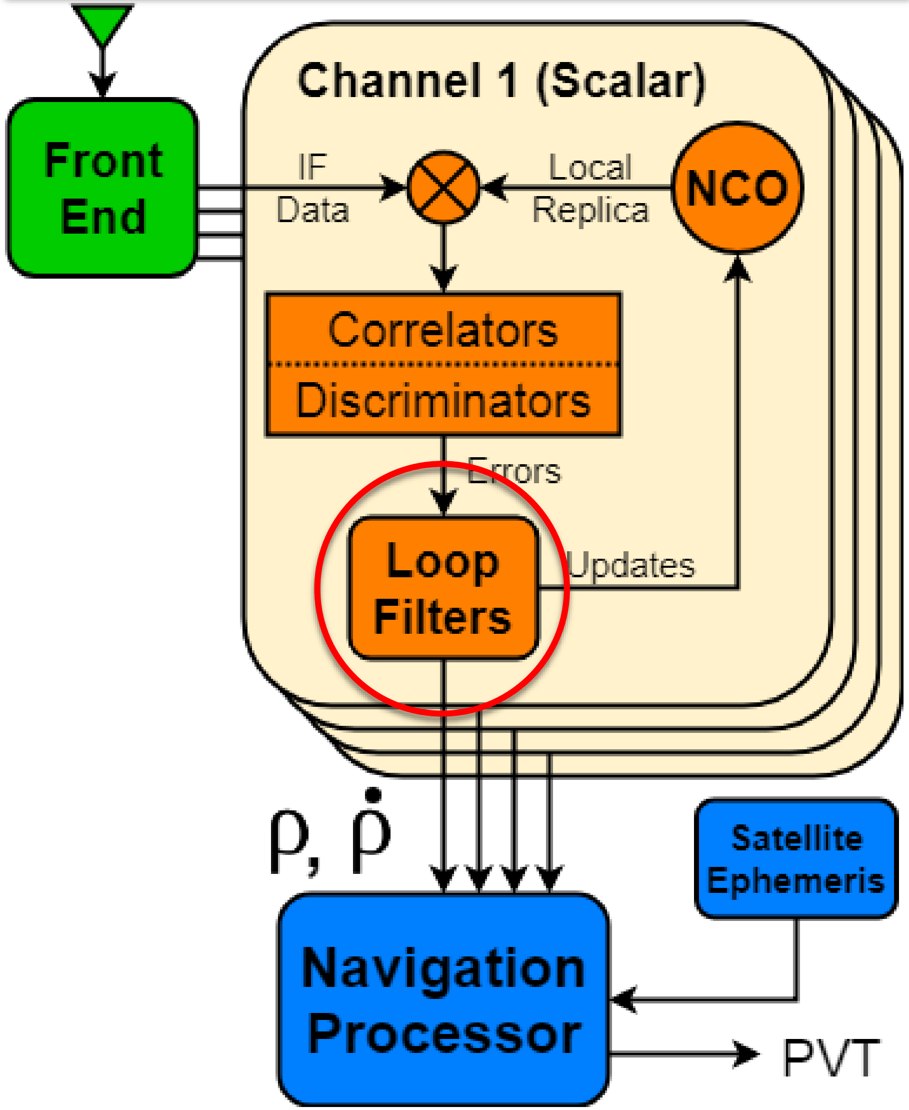
Traditional Scalar Tracking



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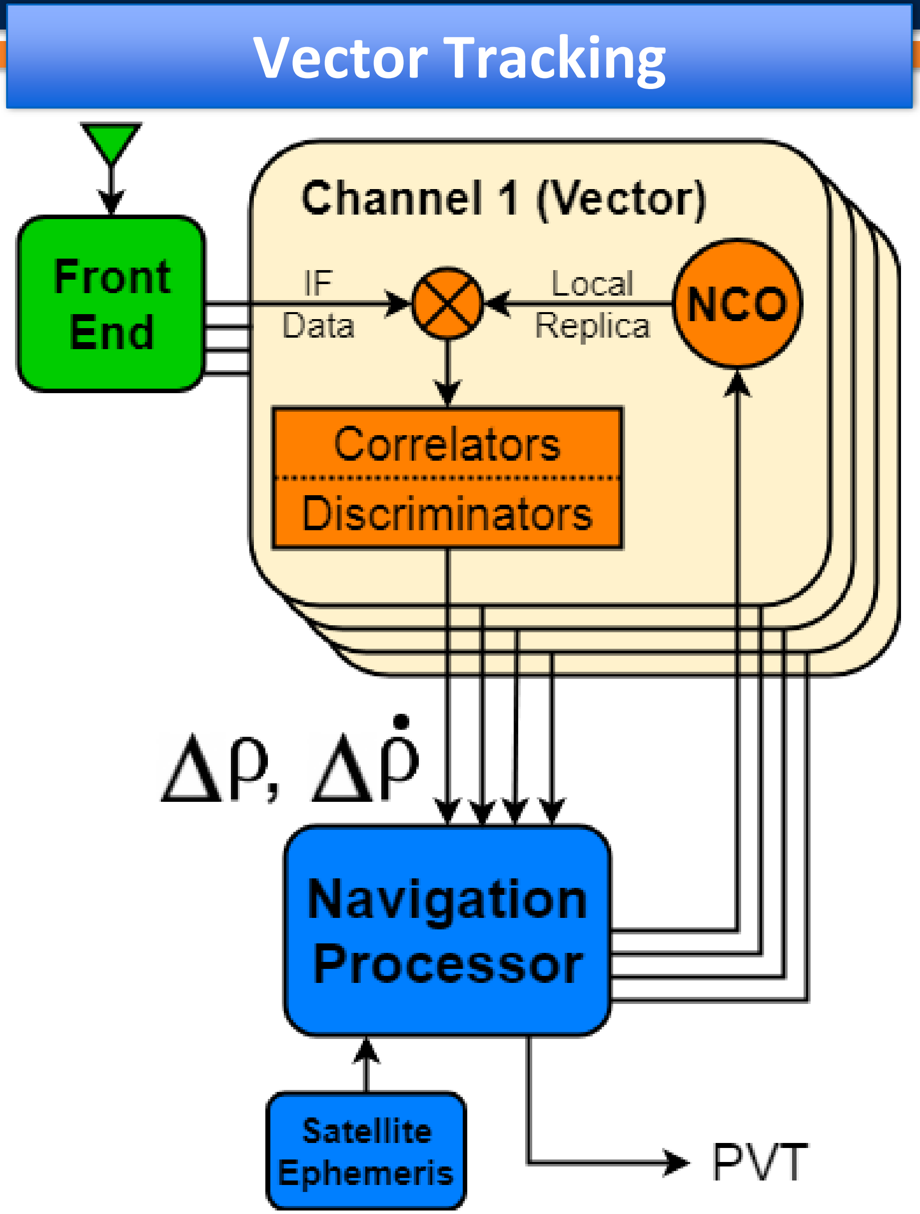
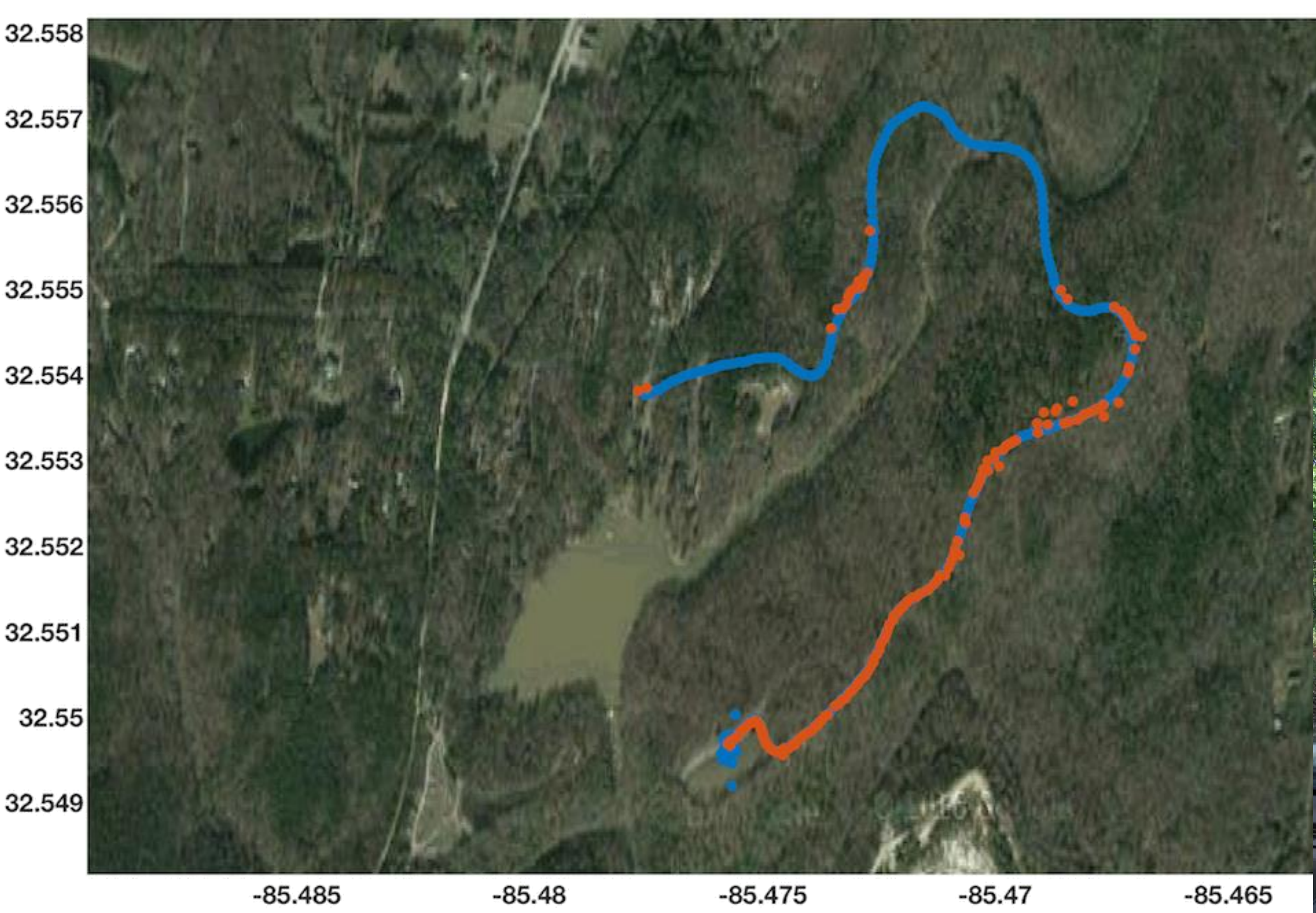
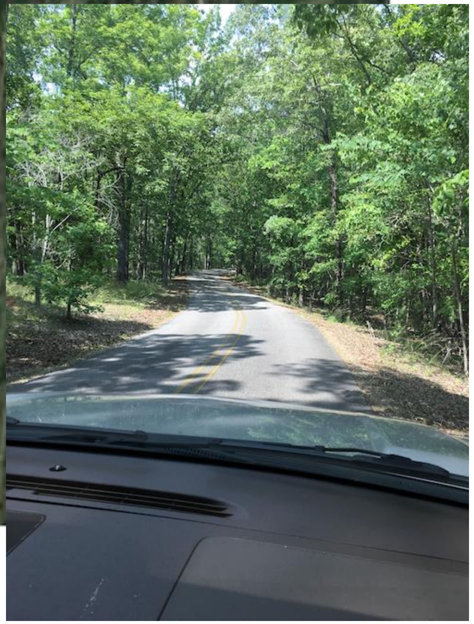


Vector Tracking – Heavy Foliage

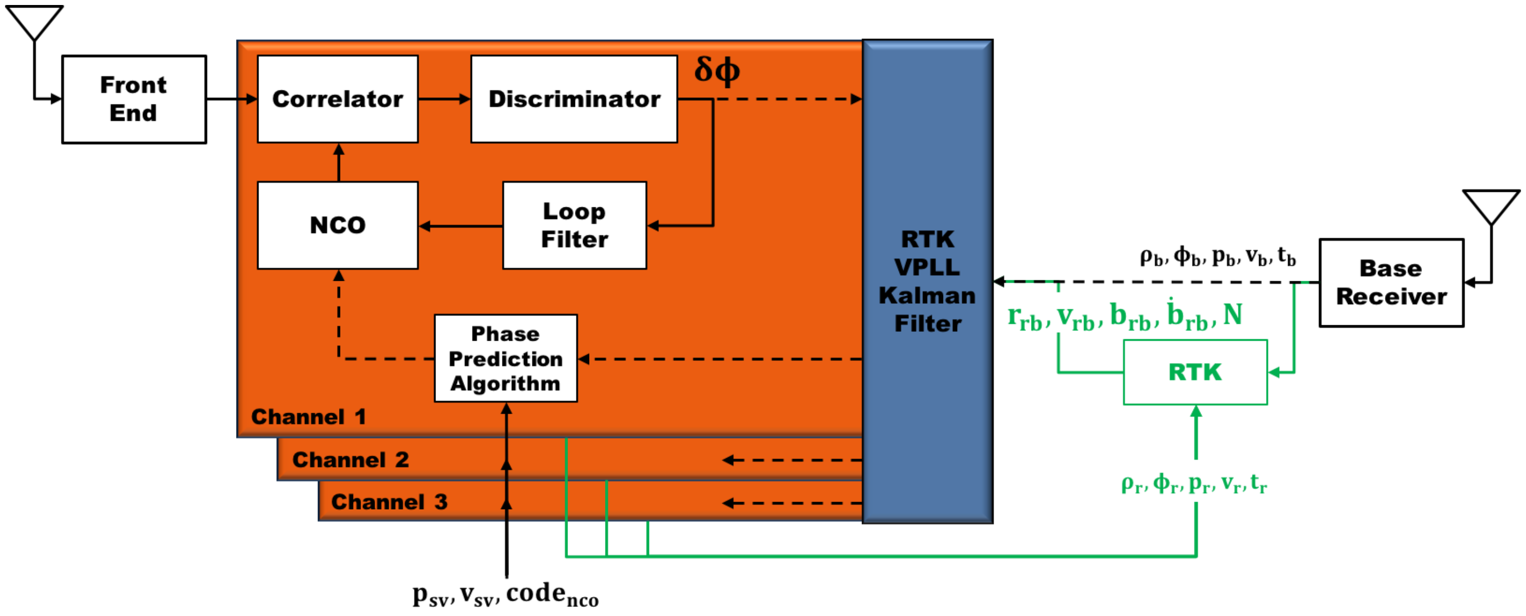




COTS Fix = 57%, VT Fix = 100%

Robust Carrier Phase Differential Positioning

- Carrier loop closed with measurements from base receiver, relative position vector, satellite information, discriminators
- Ambiguities estimates from the Kalman filter are floating point
- LAMBDA used to initialize integer values



RTK-VPLL Measurement Model

- Initialized with high precision relative position vector, relative velocities, clock states and Fixed Ambiguities from RTK
- Ambiguities are assumed to remain constant during operation
- Filter allowed to settle before phase prediction step begins

State Vector

$$\hat{X} = \left[r_{rb_x} \; \dot{r}_{rb_x} \; r_{rb_y} \; \dot{r}_{rb_y} \; r_{rb_z} \; \dot{r}_{rb_z} \; b_{rb} \; \dot{b}_{rb} \right]^{T}$$

Measurement Vector

Initialization - $Z = \left[\Delta\phi_{rb}^{1 \dots m} - \lambda N_{rb}^{1 \dots m} \right]$

Vector Mode - $Z = \left[-\delta\phi_{r}^{1 \dots m} \right]$

Costas Discriminator

$$\delta\phi_r^1 = \tan^{-1}(Q_p / I_p)$$

Measurement Variance

$$\sigma_z^2 = \frac{\lambda}{4\pi T \frac{C}{N_0}}$$

Correlator Outputs

$$I_p(k,\tau) = AR(\epsilon + \tau) D(k) \cos(\pi f_{err} T + \theta_{err}) + \eta_{IE(k)}$$

$$Q_p(k,\tau) = AR(\epsilon + \tau) D(k) \sin(\pi f_{err} T + \theta_{err}) + \eta_{QE(k)}$$

RTK-VPLL Phase Prediction Model

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- State estimates propagated to end of integration period
- Base receiver phase predicted at end of integration period
- Base receiver phase and filter states used to predict rover phase
- Predicted change in phase used to set carrier NCO

State Vector

$$\hat{X} = \left[r_{rb_x}\ \dot{r}_{rb_x}\ r_{rb_y}\ \dot{r}_{rb_y}\ r_{rb_z}\ \dot{r}_{rb_z}\ b_{rb}\ \dot{b}_{rb} \right]^{T}$$

Dynamic Model

$$A = \begin{bmatrix} \alpha & 0_{2x2} & 0_{2x2} & 0_{2x2} \\ 0_{2x2} & \alpha & 0_{2x2} & 0_{2x2} \\ 0_{2x2} & 0_{2x2} & \alpha & 0_{2x2} \\ 0_{2x2} & 0_{2x2} & 0_{2x2} & \alpha \end{bmatrix} \quad \alpha = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix}$$

Kalman Prediction Model

$$\hat{X}(k+1) = A\hat{X}(k)$$

$$P(k+1) = AP(k)A^{T} + Q$$

← Process uncertainty tuned based on expected motion

Predicted Phase at Base

$$\phi_b^j(k+1) = \phi_b^j(k) + f_{dopp}T$$

Predicted Phase at Rover

$$\phi_r^j(k+1) = \phi_b^j(k+1) + H^j\hat{X}(k+1) + N^j$$

RTK-VPLL Performance

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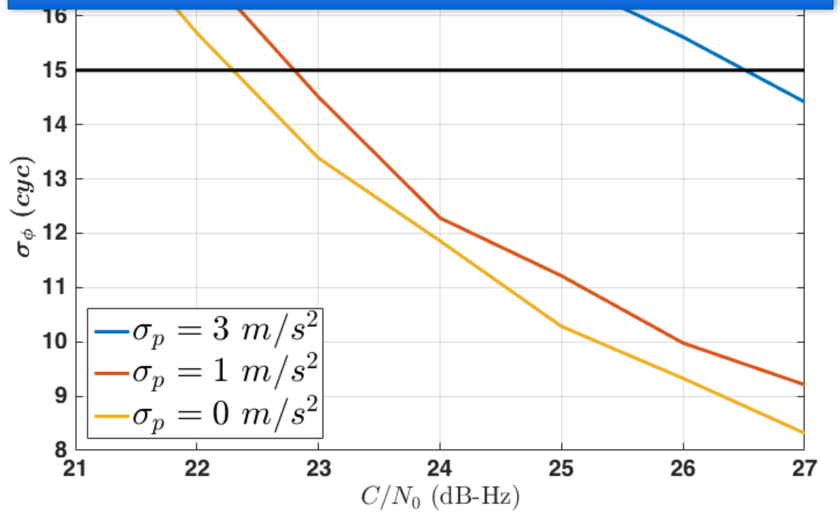
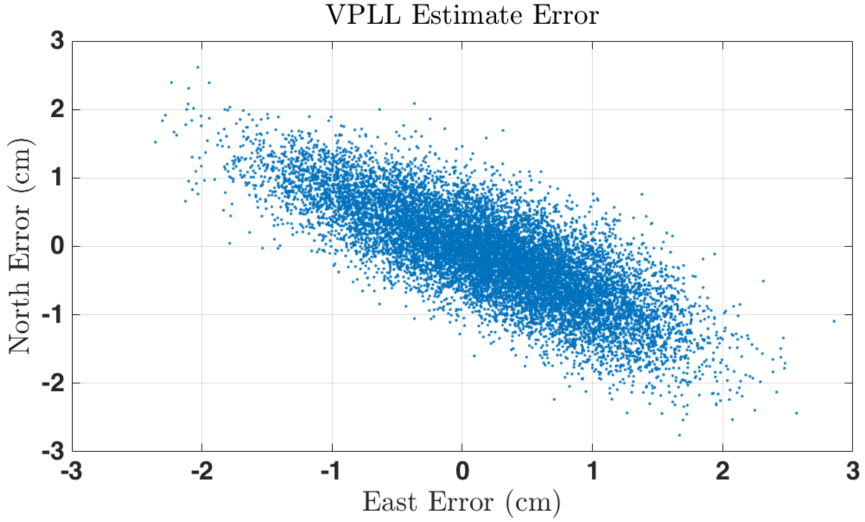
- RTK-VPLL shows 5 – 6 dB more sensitivity than traditional scalar PLL
- Experimental Accuracy Consistent with traditional RTK GPS in clear sky

Simulated Tracking Performance



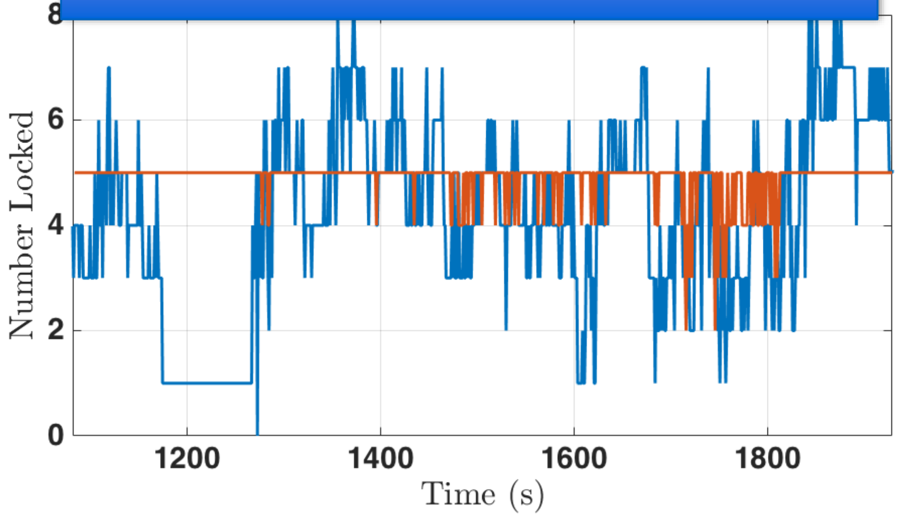
Experimental Positioning Performance



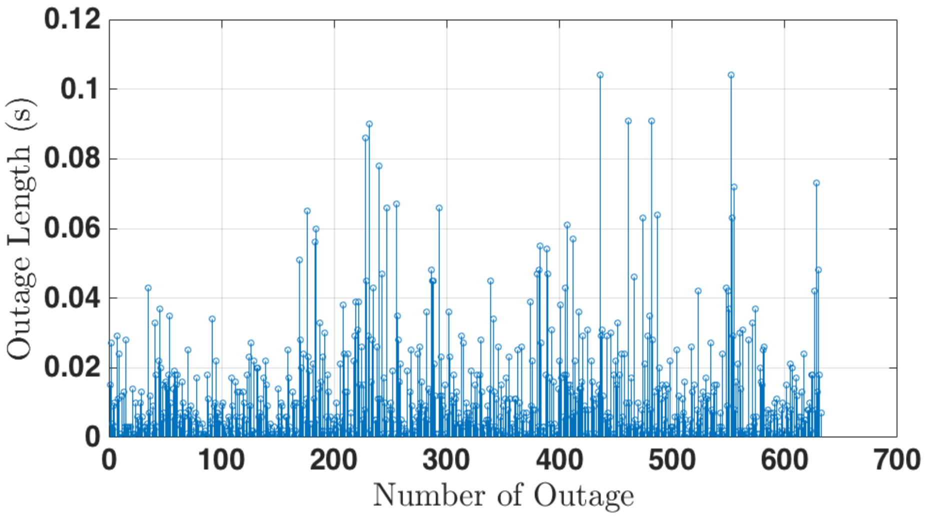
RTK-VPLL Degraded Performance

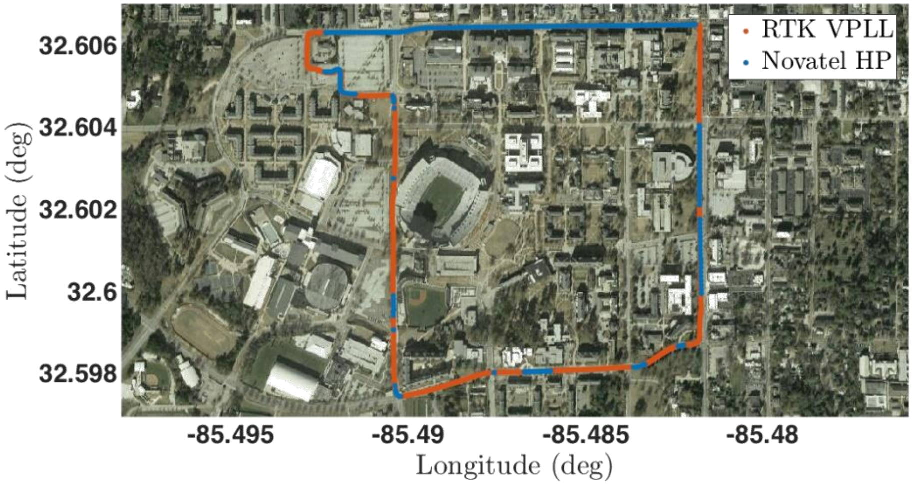
- RTK-VPLL outperforms COTS survey grade receiver in degraded environment
- Outages (less than 4 locked) are brief with RTK-VPLL
  - External aiding from IMU or camera may be used as bridge

Comparison to COTS RTK



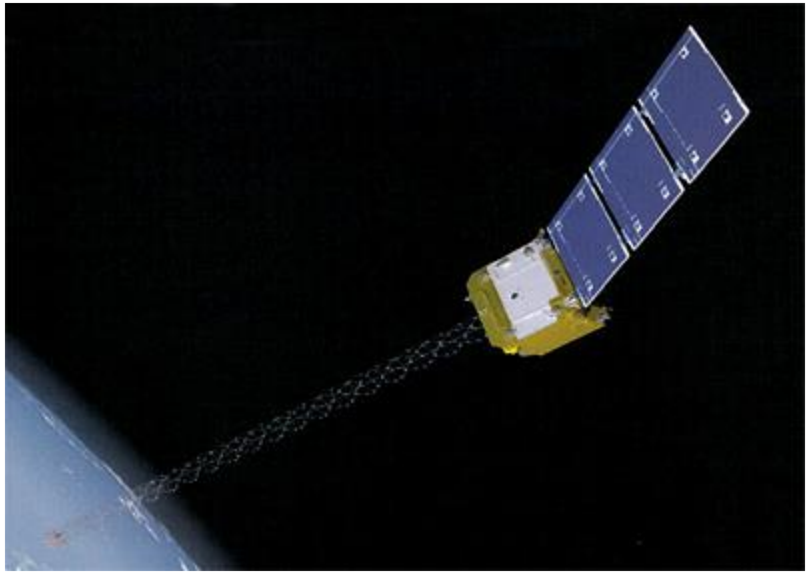
External Sensor (IMU, Camera) Span Outage

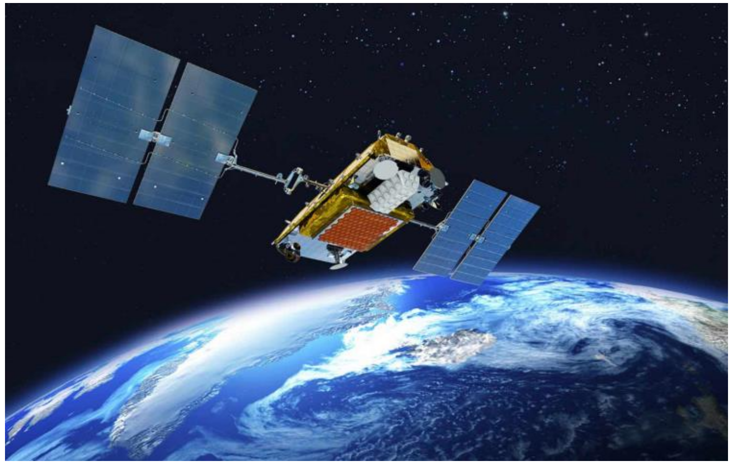




Signals Of Opportunity

- GNSSs are not adequate for emerging technologies
  - Urban canyon etc.
  - Heavy Foliage
- See signals of opportunity
  - Ambient signals that have navigation potential





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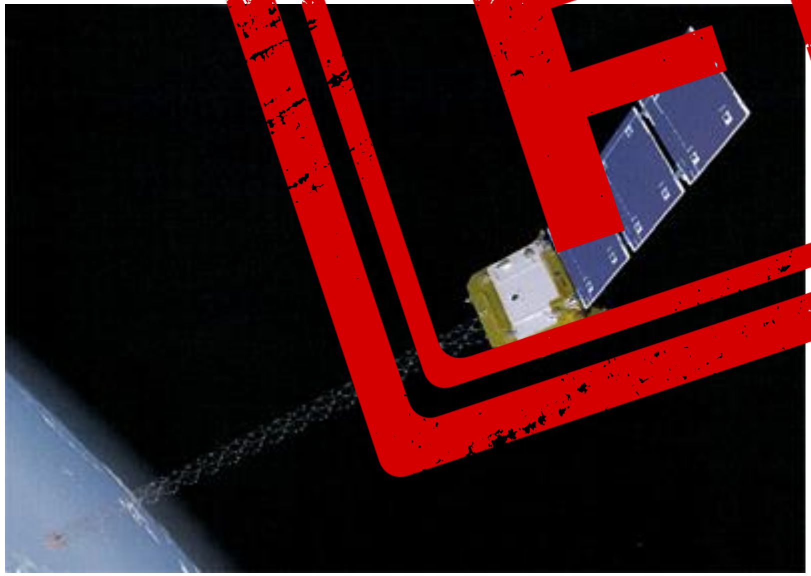


LTE Signal

- Orthogonal Frequency Division Multiplex Signal
- Adopted by 3GPP as a standard for 4G and 5G
  - Terrestrial SOP
- Many transmit frequencies
  - 400-6000MHz
- Many bandwidths
  - 1.4, 3, 5, 10, 15, 20MHz
- Challenges
  - Not intended for navigation
  - Specialized receiver must be designed

$$x_c(t) = \sqrt{\frac{C}{N}} \sum_{n=0}^{N-1} b(n) \exp\left(\frac{j2\pi nt}{T}\right),$$
$$0 < t < T$$

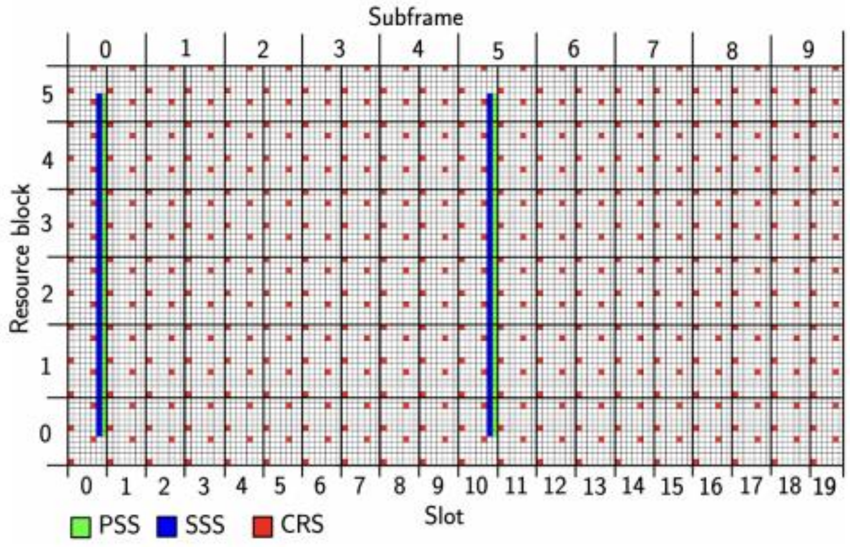
C := power of band-pass signal
N := total # of subcarriers
b(n) := complex symbol at n-th subcarrier
T := OFDM symbol period = 66.7us

$$f_{sc} = \frac{1}{T} = 15kHz$$

Cellular Tracking Methods

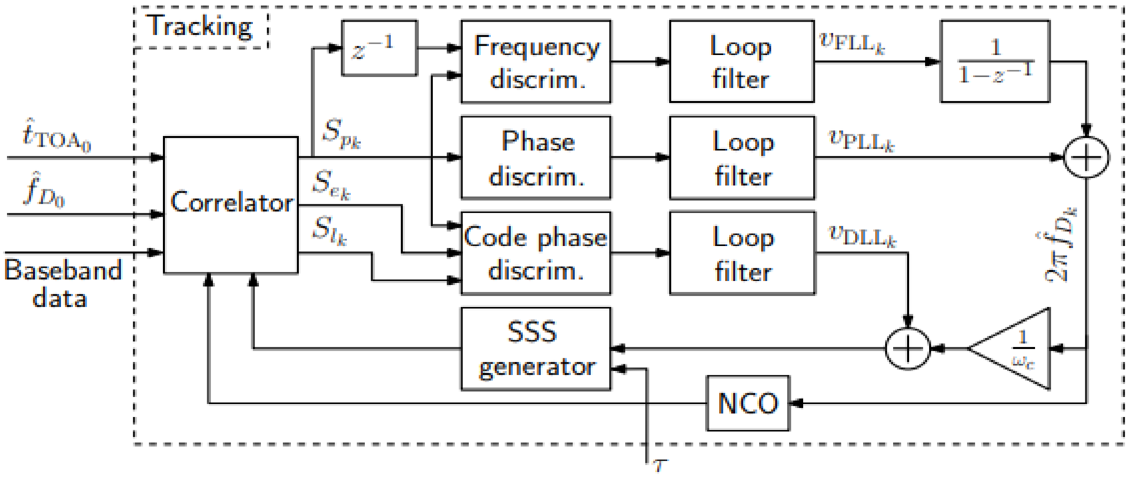
SSS

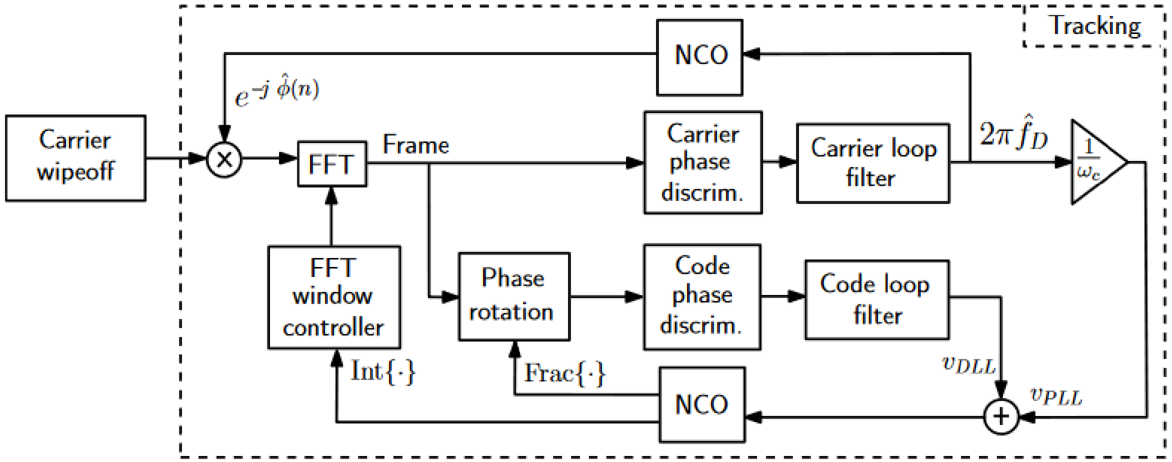
- GPS-like tracking scheme
- Correlators, Discriminators, loop filter
- Less accurate



CRS

- More complicated to receive
- Decode for number of antennas and resource blocks
- Similar tracking approach after initialization
- More accurate





Vector Tracking LTE/GPS

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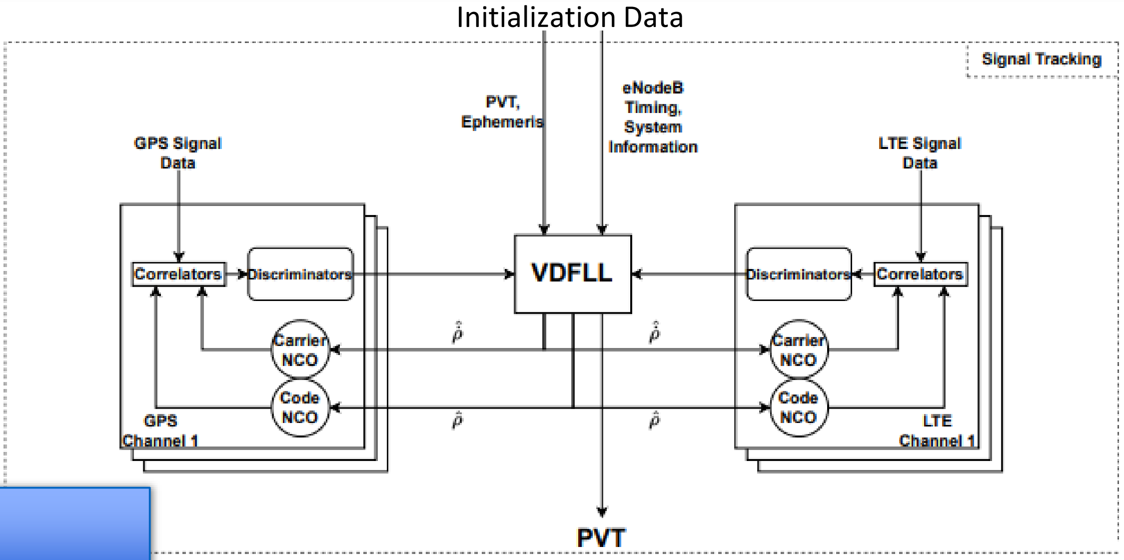
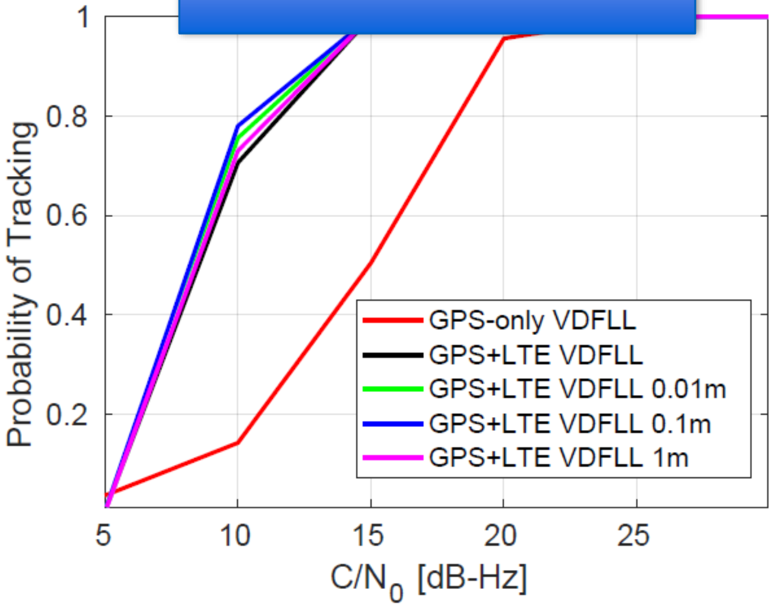
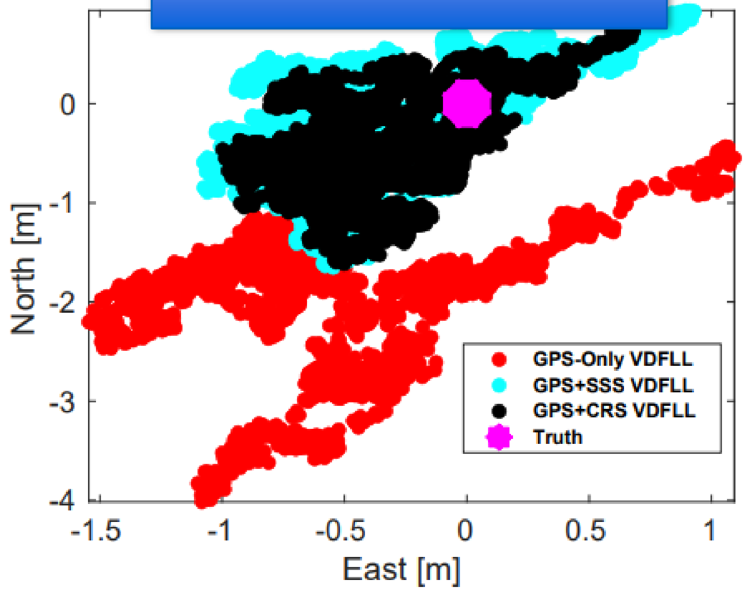
- LTE and GNSS coupled at signal tracking level
- GNSS instantly reacquired after outage
- Probability of tracking at low signal strength improved



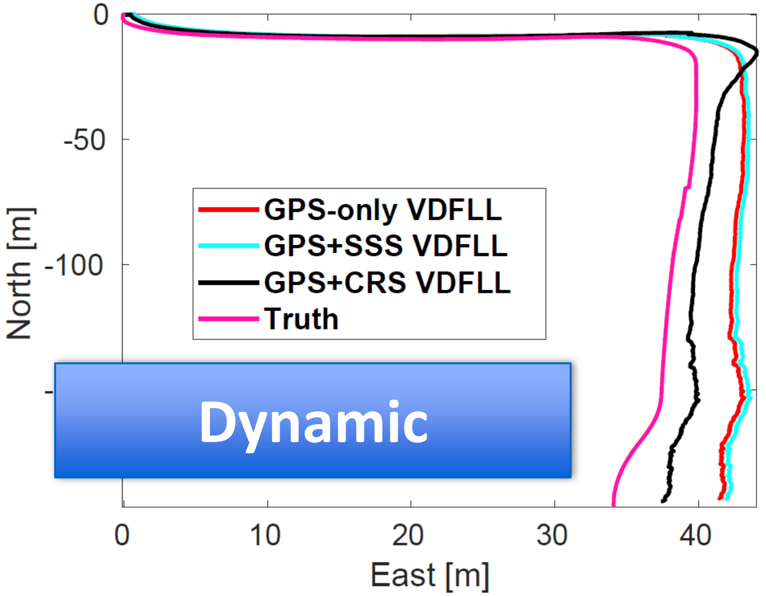
Simulation



Static



Dynamic



Conclusions

- Automated truck convoys
  - reduce driver fatigue
  - improve fuel economy
  - require robust/accurate relative positioning
- Radar / GPS fusion
  - Complimentary
  - GPS fault rejection
- Signal procession improvement
  - Vector tracking
  - LTE / GPS fusion

Thank You

Questions?

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