Improved GPS Carrier Phase Tracking in Difficult Environments Using Vector Tracking Approach

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Presentation Overview

- Introduction
  - Motivation
  - Prior Art
- Software Receiver Architecture
  - Scalar and Vector Tracking
  - Vector Aided Phase Lock Loops
- Experimental Setup
  - GPS Front End
  - Data Collection Environments
- Results
  - Tracking Performance
  - Carrier Phase Accuracy
  - Comparison to COTS Receiver
- Conclusion and Future Work

Motivation

- Provide accurate and reliable carrier phase measurements in difficult environments
- Environmental Factors
  - Low power jamming
  - Heavy foliage
  - Urban canyons
- Applications
  - Any scenario requiring high accuracy positioning in environments were GPS carrier phase tracking is difficult
  - Precision mapping un-exploded ordinance
  - Autonomous vehicle operation
  - Precision agriculture

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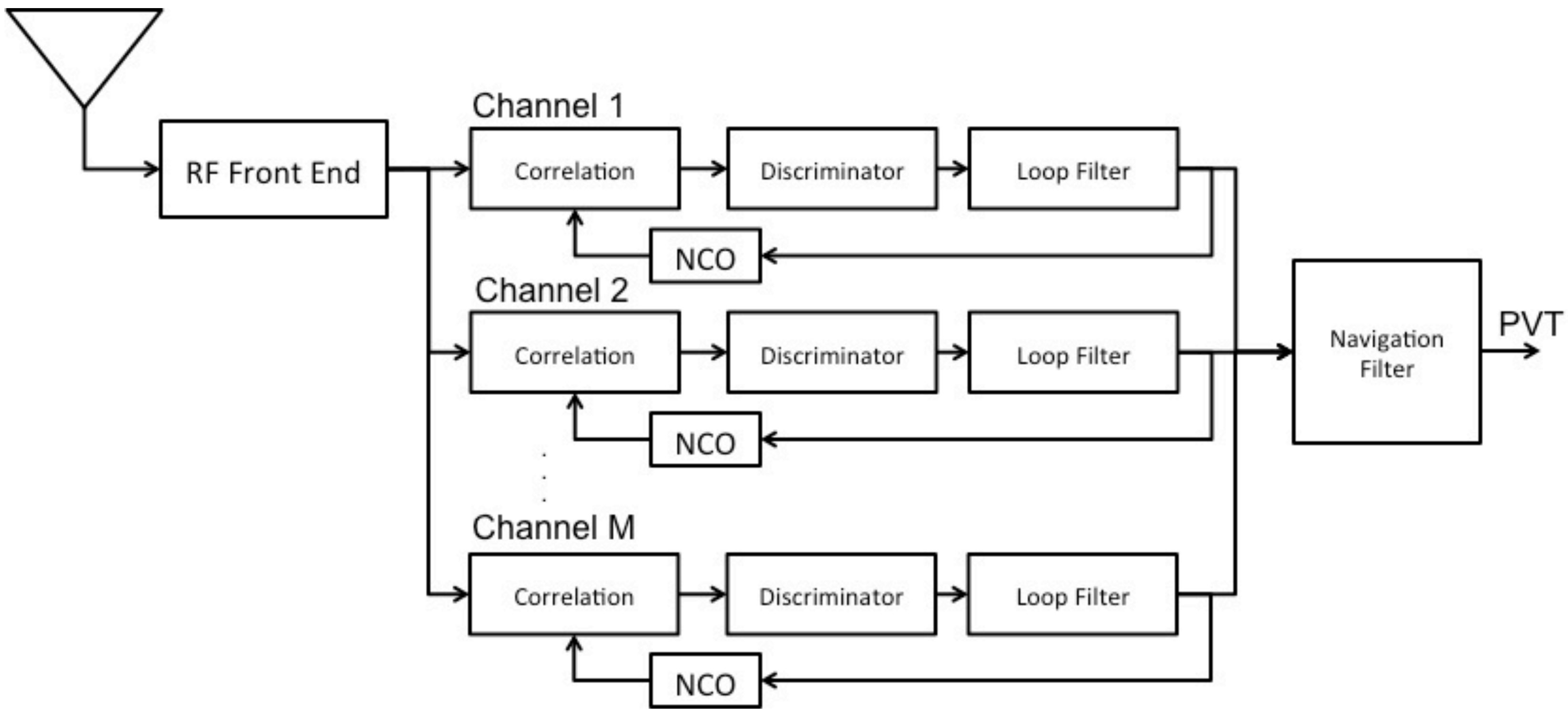
Prior Art

Previous Improved Tracking Approaches

- Vector delay lock loop – Spilker 1996
- Vector delay and frequency lock loop – Pany 2006, Lashley 2010
- Carrier phase tracking in weak signals – Petovello, Driscoll, Lachapelle 2008
- Deep Integration – Crane 2007, Soloviev 2007, Groves 2007
- Vector FLL Aided Carrier Tracking – Kiesel 2008

Traditional Scalar Receiver

- Each channel code and carrier NCO controlled by individual loop filter
- No feedback from the navigation processor



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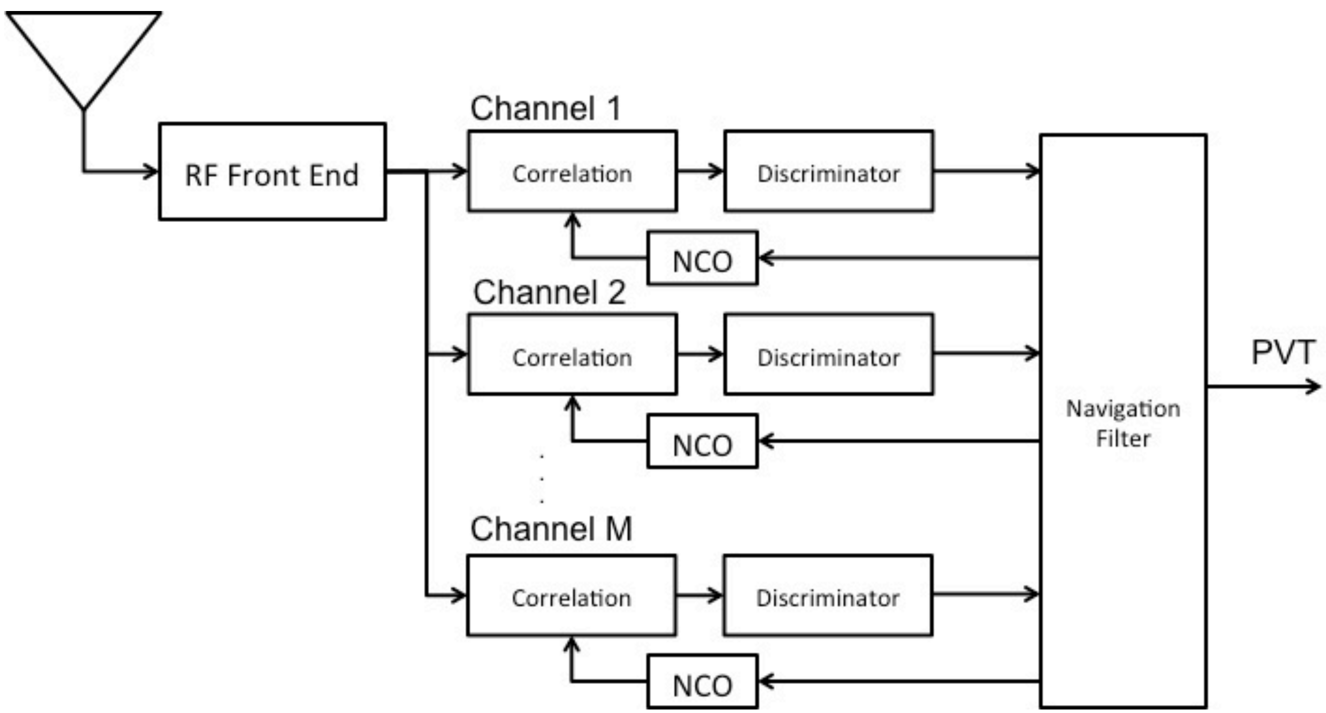
Vector Tracking Receiver

- Individual loop filters replaced by feedback from navigation processor
- Position, Velocity, and Clock estimates used to predict code phase and carrier frequency
- Estimates updated with discriminator outputs



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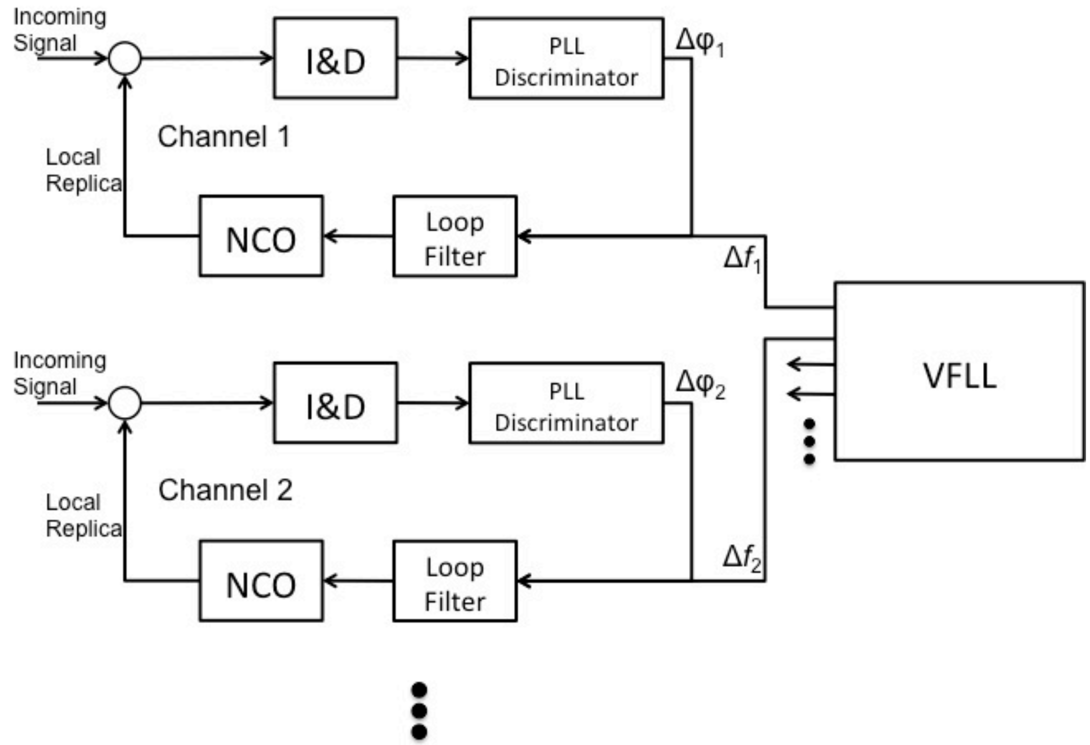
Vector FLL Aiding

- Combine robustness of VFLL with accuracy of PLL
- Velocities estimates from navigation Kalman filter estimate carrier frequency
- Feedback estimated carrier frequency discriminator
- Fused in loop filter with scalar PLL discriminator to update carrier NCO
- VDLL used to drive code NCO for robust code tracking



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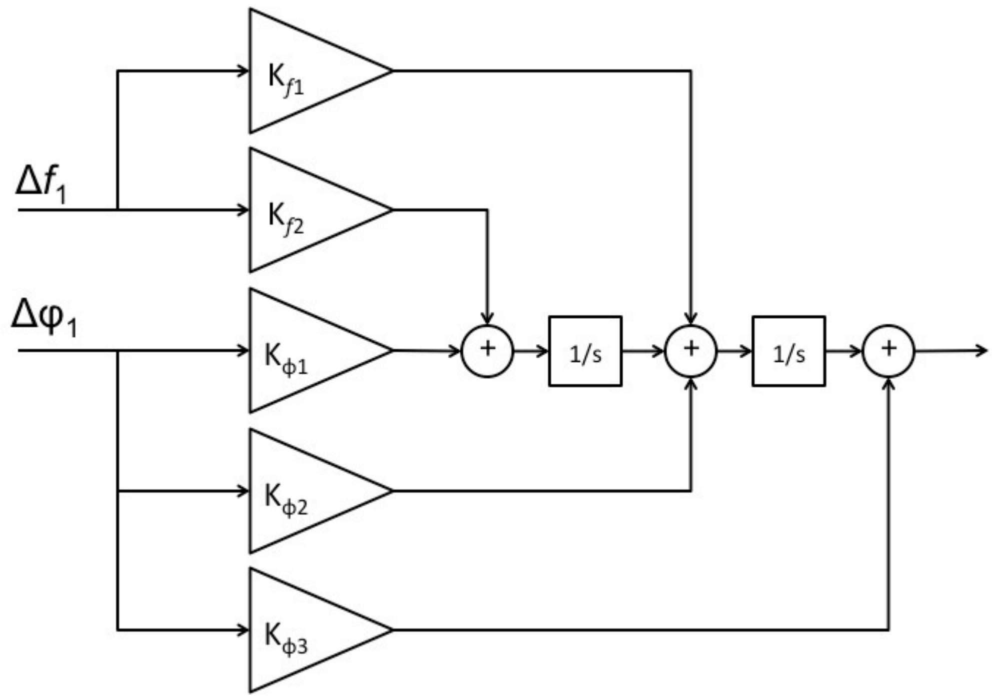
FLL-Assisted PLL

- Second Order FLL-Assisted PLL Loop Filter [Ward]
- FLL robust to line of sight dynamics, PLL improved accuracy
- PLL discriminator two quadrant arc tangent
- VFLL discriminator estimates using state estimates
- Gains are a function of loop bandwidth
  - $Bn_f = 4$ Hz
  - $Bn_p = 18$ Hz
- Longer integration periods cause discrepancy between desired bandwidth and actual bandwidth in digital implementation



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Kalman Filter Propagation

- Error state Kalman filter estimating position, velocity, clock bias and drift
- Unmodeled receiver dynamics assumed zero mean tuning parameters (σ^2=2m^2/s^4)
- Clock disturbance model based on [Brown] (σ_b^2=c^{2}x10^{-19}, σ_r^2=4πc^{2}x10^{-20})

$$\boldsymbol{X} = [\delta x \quad \delta \dot{x} \quad \delta y \quad \delta \dot{y} \quad \delta z \quad \delta \dot{z} \quad \delta c_b \quad \delta \dot{c}_b]^{\mathrm{T}}$$

$$\boldsymbol{X}(k+1) = A_d \boldsymbol{X}(k) \qquad P(k+1) = A_d P(k) A_d^T + Q_d$$

$$A_d = \begin{bmatrix} \alpha_d & 0_{2x2} & 0_{2x2} & 0_{2x2} \\ 0_{2x2} & \alpha_d & 0_{2x2} & 0_{2x2} \\ 0_{2x2} & 0_{2x2} & \alpha_d & 0_{2x2} \\ 0_{2x2} & 0_{2x2} & 0_{2x2} & \alpha_d \end{bmatrix} \qquad Q_d = \begin{bmatrix} Q_x & 0_{2x2} & 0_{2x2} & 0_{2x2} \\ 0_{2x2} & Q_y & 0_{2x2} & 0_{2x2} \\ 0_{2x2} & 0_{2x2} & Q_z & 0_{2x2} \\ 0_{2x2} & 0_{2x2} & 0_{2x2} & Q_c \end{bmatrix}$$

$$\alpha_d = \begin{bmatrix} 1 & T \\ 0 & 1 \end{bmatrix} \qquad Q_x = Q_y = Q_z = \begin{bmatrix} \sigma^2 \frac{T^3}{3} & \sigma^2 \frac{T^2}{2} \\ \sigma^2 \frac{T^2}{2} & \sigma^2 T \end{bmatrix} \qquad Q_c = \begin{bmatrix} \sigma_b^2 T + \sigma_r^2 \frac{T^3}{3} & \sigma_r^2 \frac{T^2}{2} \\ \sigma_r^2 \frac{T^2}{2} & \sigma_r^2 T \end{bmatrix}$$

Kalman Filter Measurements

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

- Range residuals (ϵ_r) calculated using early minus late power discriminator [Crane]

$$Y_R = IE^2 + QE^2 - IL^2 - QL^2$$

$$Y_R = \frac{A^2 2\epsilon_r}{\beta} + \eta$$

$$\epsilon_r = \frac{Y_R \beta}{A^2 2}$$

- Range rate residuals (ϵ_{rr}) calculated using carrier frequency and carrier frequency discriminator

$$\Delta f = \tan^{-1}\left(\frac{IP_1QP_2 - IP_2QP_1}{IP_1IP_2 + QP_1QP_2}\right)$$

$$\tilde{\dot{\rho}} = (f_{IF} - f_{carr} - \Delta f)\lambda_{L1}$$

$$\epsilon_{rr} = \tilde{\dot{\rho}} - \hat{\dot{\rho}}$$

Kalman Measurement Covariance

- Range and range rate residual covariance is calculated as a function of C/N_0
- C/N_0 estimated by compared amplitude estimates from early and late correlators to noise variance estimates from noise correlators

$$E\{v_r^2\} = \frac{\beta^2 \left(1 + 2T \frac{C}{N_0}\right)}{2T \frac{C}{N_0}} \left(\frac{\rho_e^2}{\beta^2} + \frac{1}{4}\right) \qquad E\{v_{rr}^2\} = \frac{2 + 2R^2(\rho_e) T \frac{C}{N_0}}{T \frac{C}{N_0}} \left(\frac{1}{\pi T}\right)^2$$

$$\frac{C}{N_0} = 10 \log_{10}\left(\frac{A^2}{\eta^2}\right) \qquad \tilde{A}^2 = (IE + IL)^2 + (QE + QL)^2$$

$$A^2 = \tilde{A}^2 - 4\eta^2$$

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Kalman Filter Correction

- Measurement vector of range and range rate residuals
- Measurement matrix unit vectors defining satellite geometry
- Diagonal covariance matrix from variance of measurement noise
- Best estimates at the end of a correction step are used to calculated code phase for the code NCO and carrier frequency discriminator for VFLL/PLL loop filter

$$H = \begin{bmatrix} a_{x,1} & 0 & a_{y,1} & 0 & a_{z,1} & 0 & 1 & 0 \\ 0 & a_{x,1} & 0 & a_{y,1} & 0 & a_{z,1} & 0 & 1 \\ \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots & \vdots \\ a_{x,m} & 0 & a_{x,m} & 0 & a_{x,m} & 0 & 1 & 0 \\ 0 & a_{x,m} & 0 & a_{x,m} & 0 & a_{x,m} & 0 & 1 \end{bmatrix} \qquad z = \begin{bmatrix} \epsilon_{r_1} \\ \epsilon_{rr_1} \\ \vdots \\ \epsilon_{r_m} \\ \epsilon_{rr_m} \end{bmatrix}$$

$$\boldsymbol{X}(k)^+ = \boldsymbol{X}(k)^- + K(z - H\boldsymbol{X}(k)^-)$$

$$P(k)^+ = (I - KH)P(k)^-$$

$$R = \begin{bmatrix} E\{v_r^2\} & 0 & 0 \\ 0 & E\{v_{rr}^2\} & 0 \\ 0 & 0 & \ddots \end{bmatrix}$$

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Software Receiver Operation

Vector Aided Receiver Architecture implemented in a software receiver for post process testing

- Acquisition
- Scalar Tracking
- Data Decoding and First Position
- Vector Tracking
- Pseudorange, Carrier Phase, C/N_0, Doppler measurements output at 1 Hz

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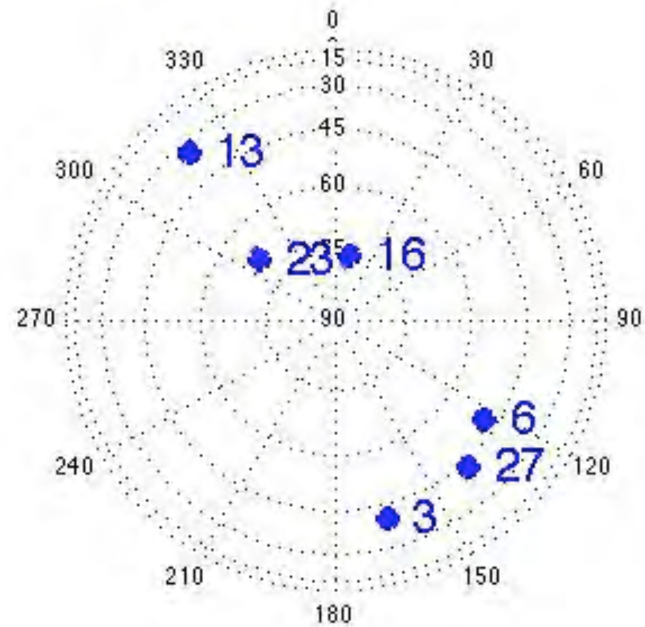
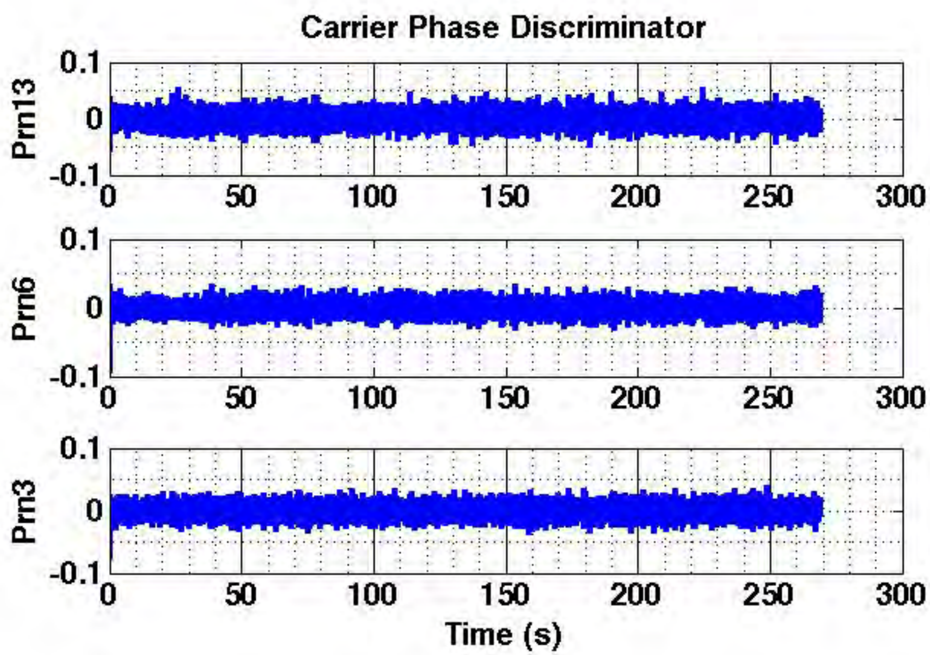
Experimental Data Collection

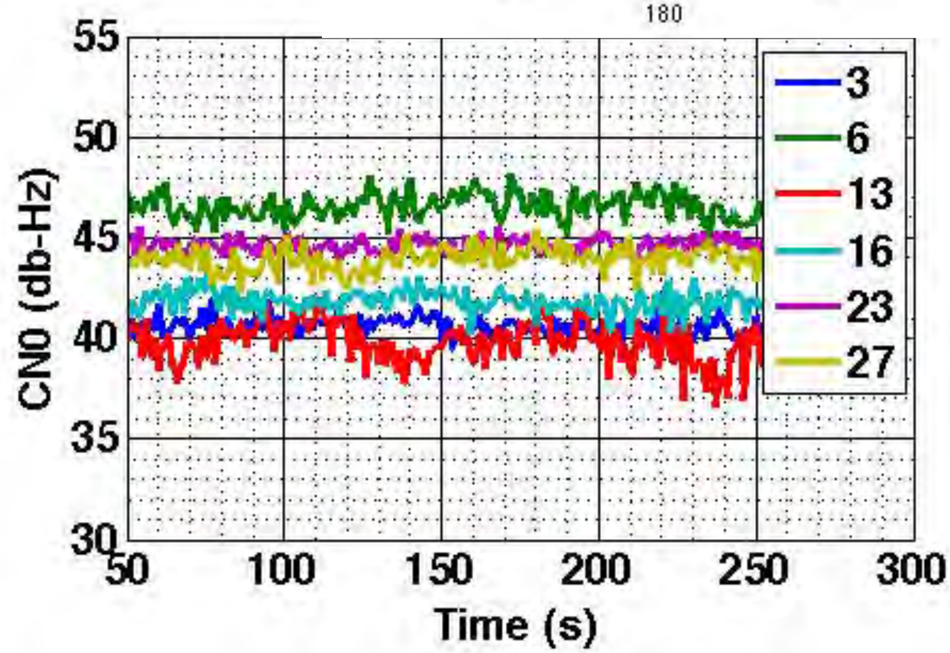
- Nordnav Rxx-2 IF Data Recorder
  - 2 Bit Samples 16.3676 MHz
  - IF Frequency 4.1304 MHz
  - Processed with Software Receiver
- Clear Sky Static and Dynamic Testing
- Dynamic Testing in Moderate and Heavy Foliage
- Reference Receivers
  - Septentrio Pola Rx
  - Novatel Propak V3 receivers

Tracking Static Scenario

- Static clear sky tracking of carrier phase
- Carrier discriminator shows errors less than 0.1 cycle





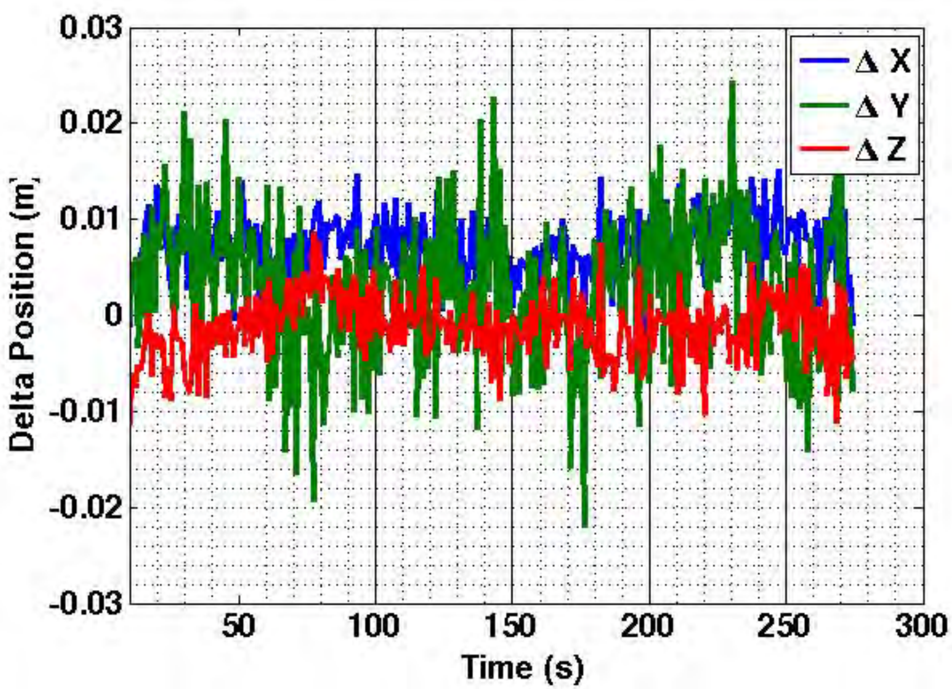


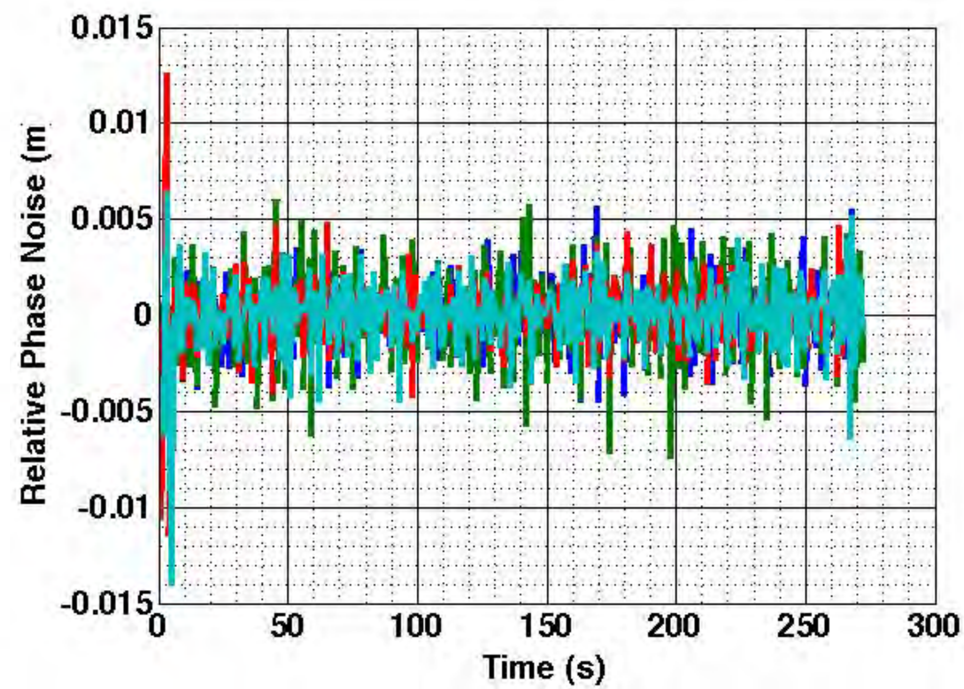
Accuracy Static Scenario

- Delta position estimates using carrier phase measurements millimeter level errors (left)
- Triple Difference [Misra, Enge] with Novatel receiver millimeter level errors (right)

$$\delta\phi_{ur}^{kl} = \phi_{ur}^{kl}(t_{i+1}) - \phi_{ur}^{kl}(t_i)$$

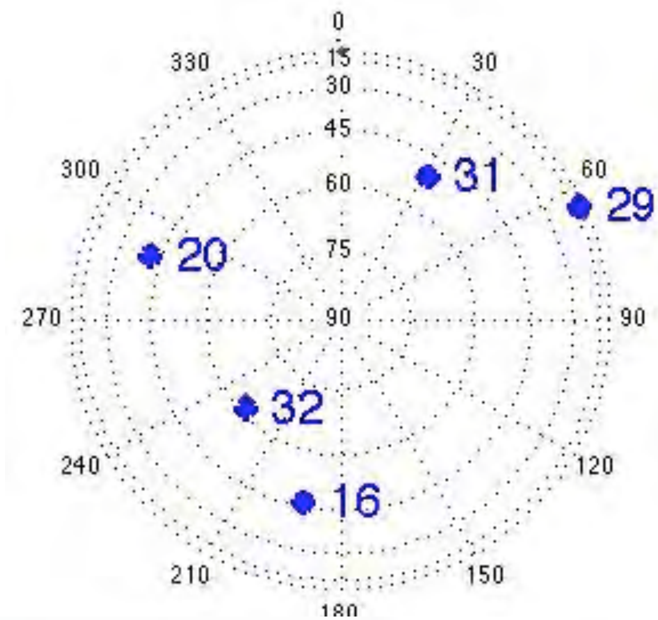
$$\delta\phi_{ur}^{kl} = \lambda^{-1}\delta r_{ur}^{kl} + \delta\varepsilon_{phi,ur}^{kl}$$

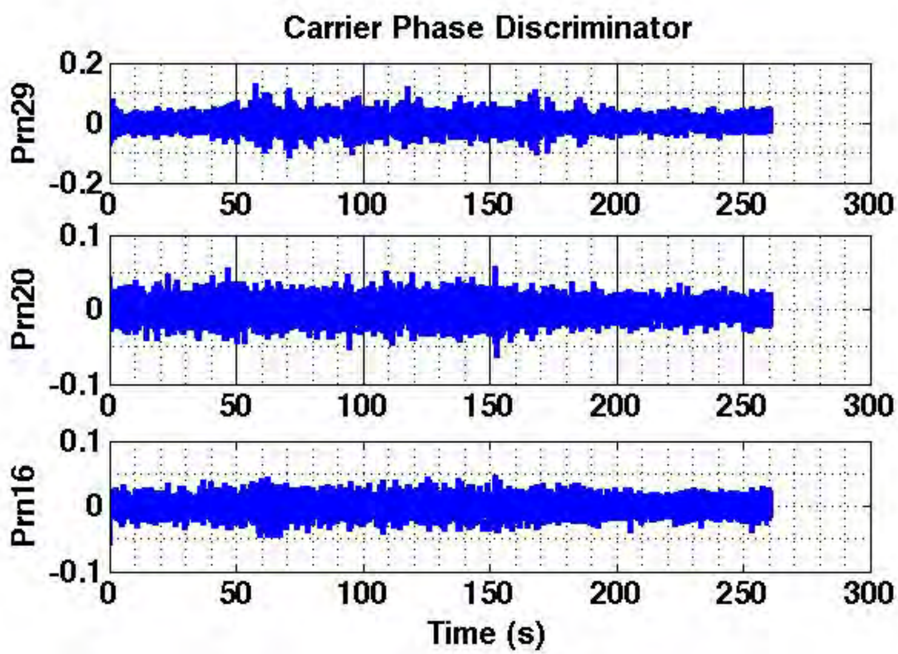


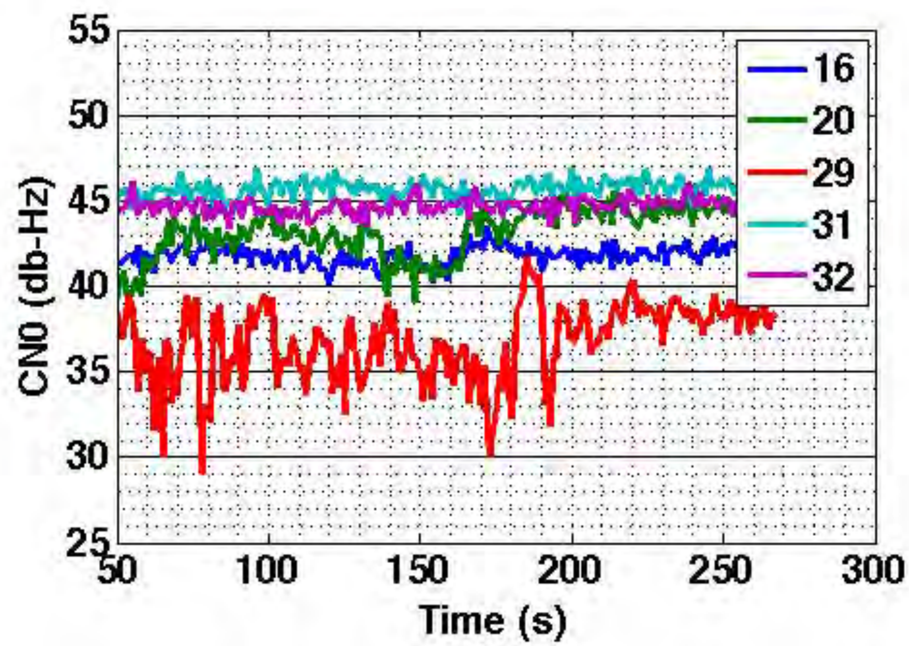


Tracking Dynamic Clear Sky

- Dynamic clear sky tracking of carrier phase
- Only 5 SV with one SV near horizon
- Carrier discriminators shows errors less than 0.1 cycle except SV29 which remains less than 0.2 cycle

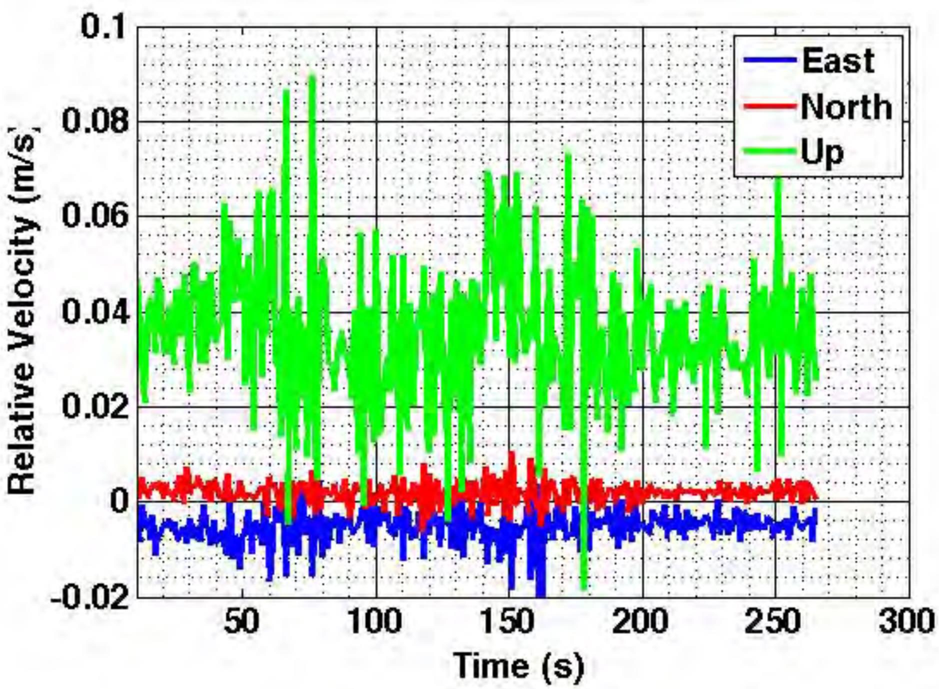


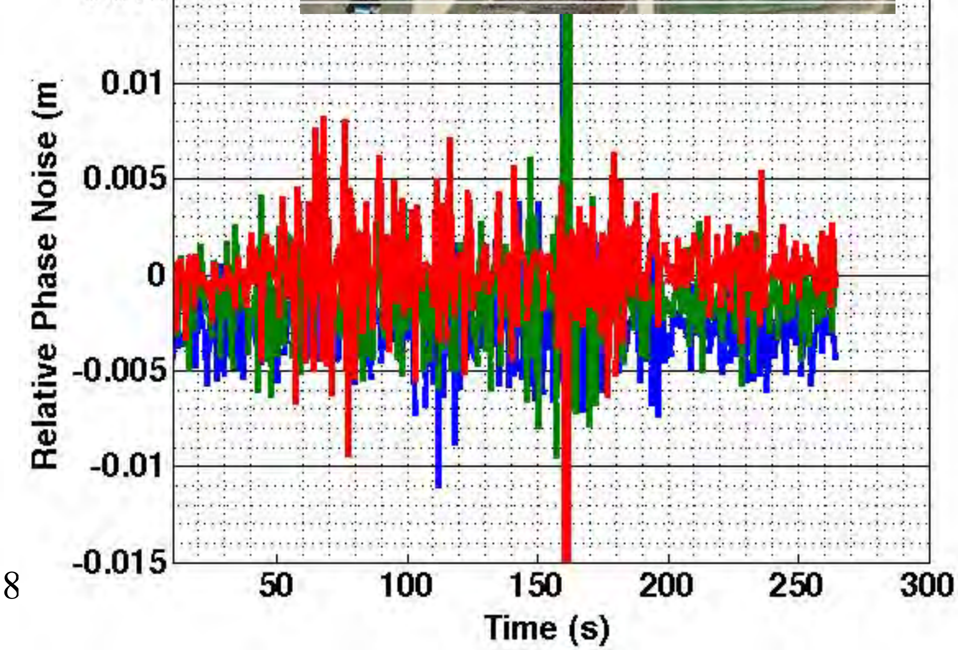




Accuracy Dynamic Clear Sky

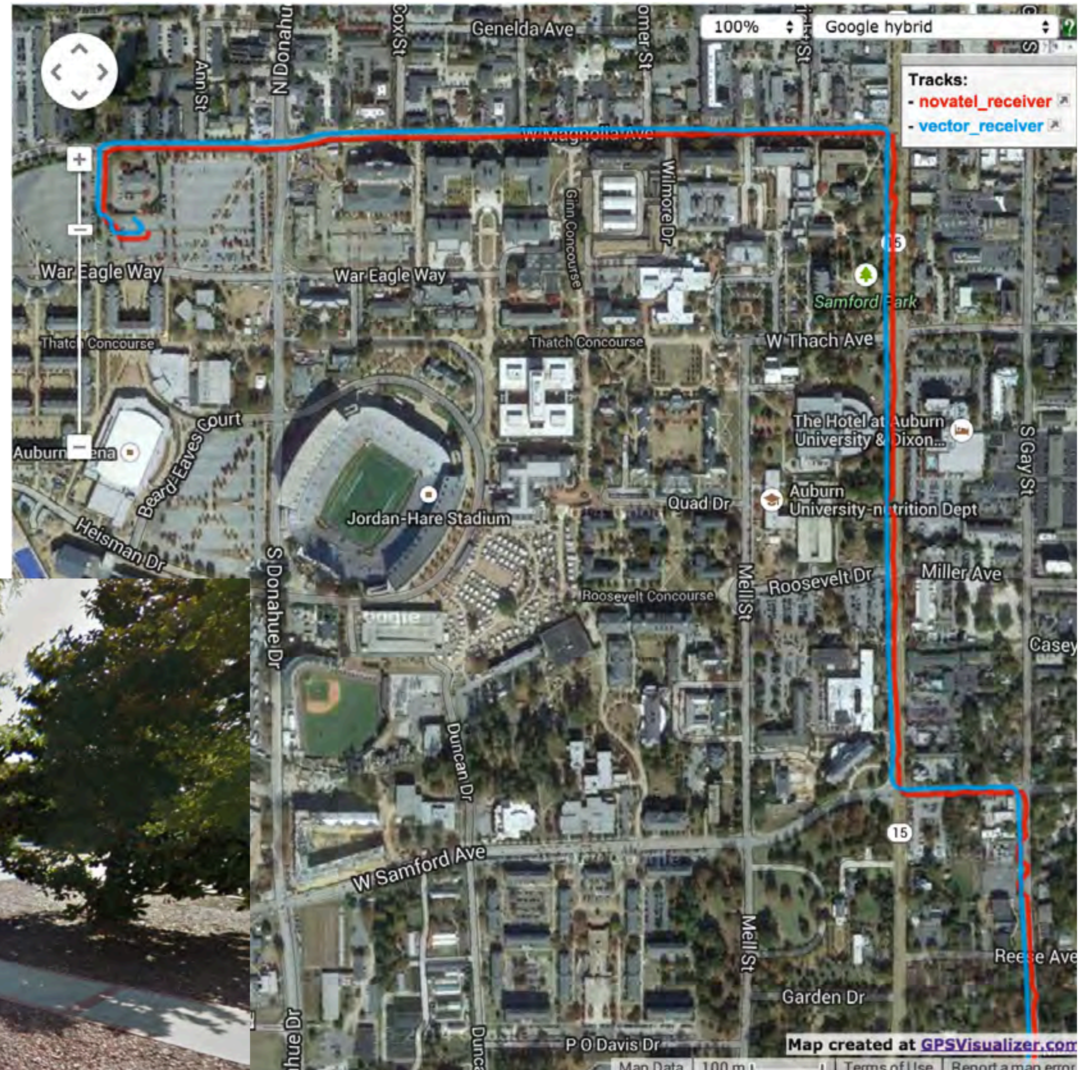
- Delta position estimates using carrier phase measurements millimeter level errors (left)
- Time differenced double difference with Septentrio receiver millimeter level errors (right)





Results Moderate Foliage

- Moderate foliage data collection
- Nordnav and Novatel Data



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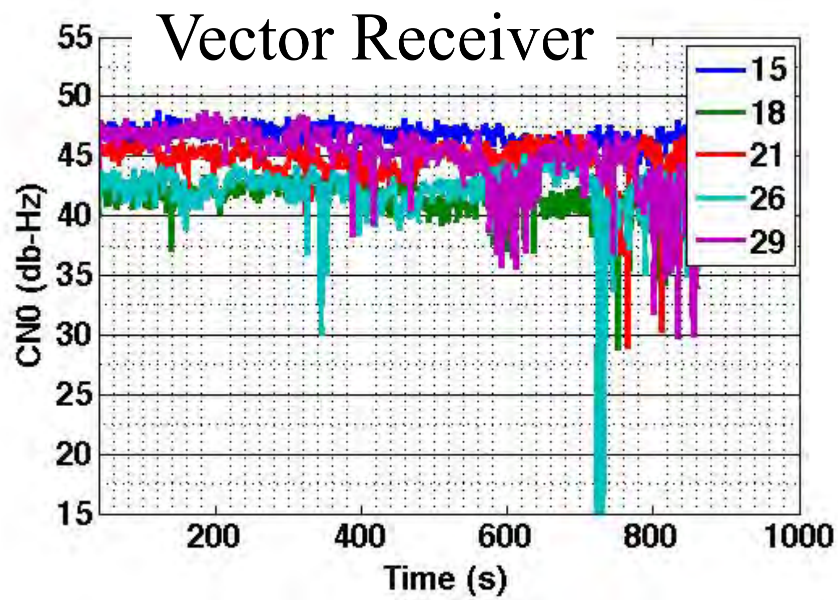
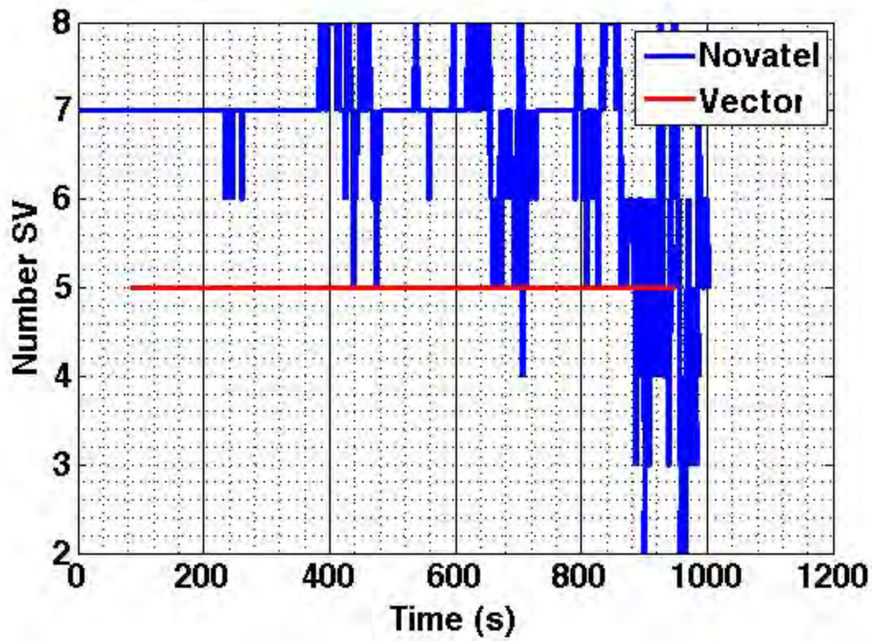
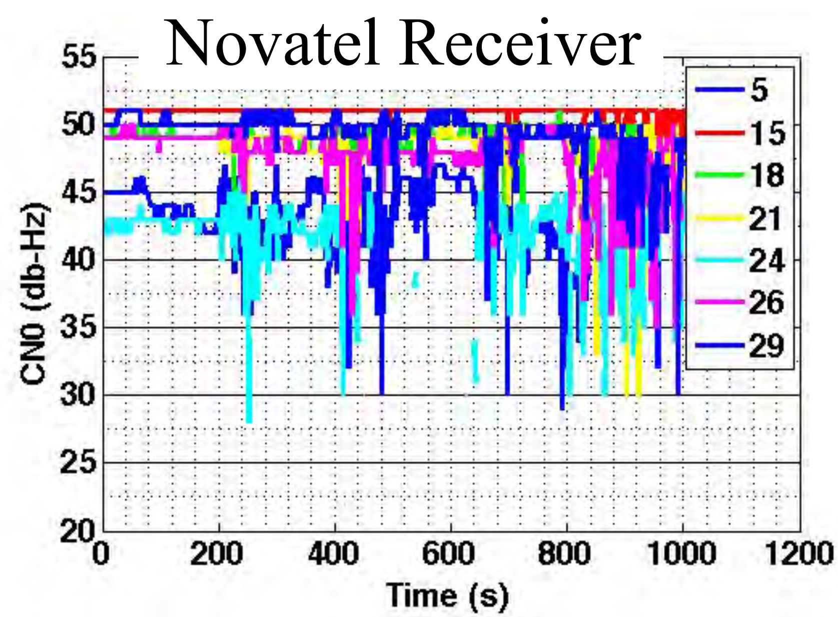
Conditions Moderate Foliage

- Novatel – 9 epochs with less than 4 SV
- Novatel – longest period with less than 4 SV 3 seconds





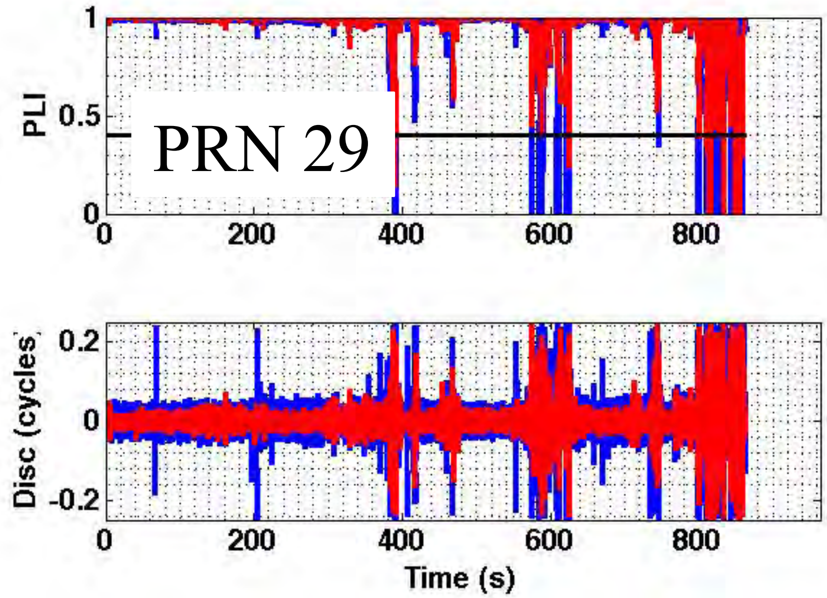


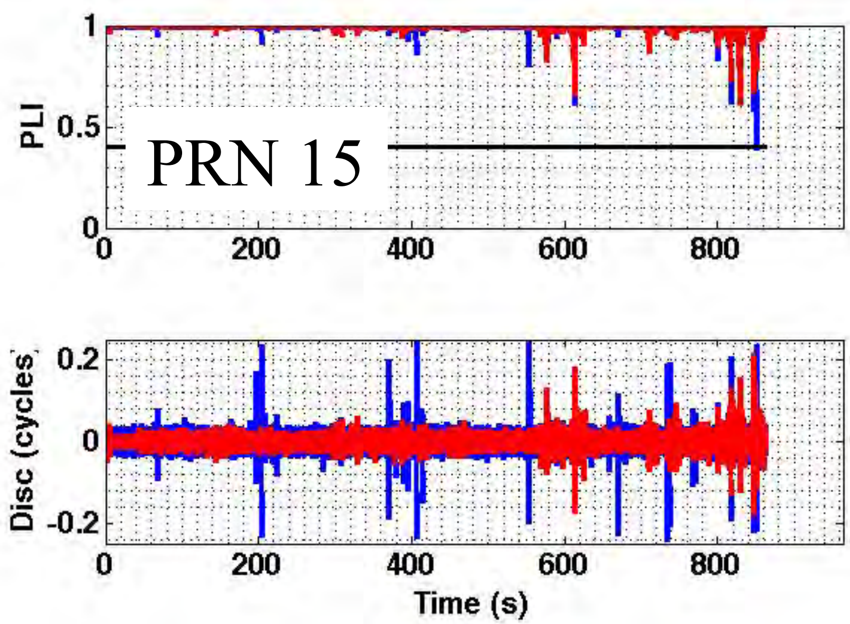
Tracking Moderate Foliage

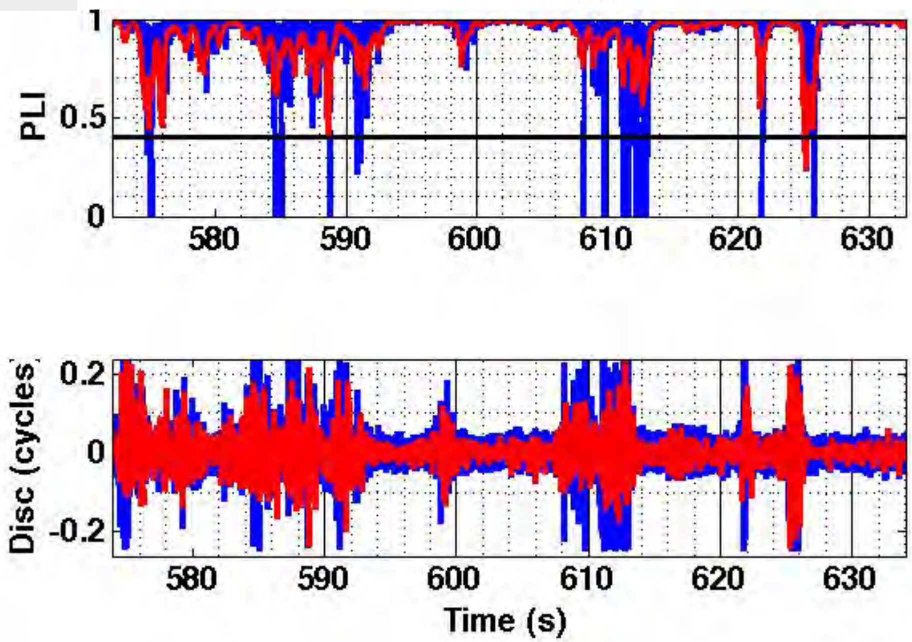
- Vector tracking software receiver (red) compared to traditional scalar software receiver (blue)

Mean Time To Fault

	15	18	21	26	29
Scalar	850 s	6.6 s	4.2 s	5.1 s	8.5 s
Vector	NA	19.4 s	56.8 s	19.4 s	37.5 s







Results Heavy Foliage

- Heavy foliage data collection
- Nordnav and Novatel Data

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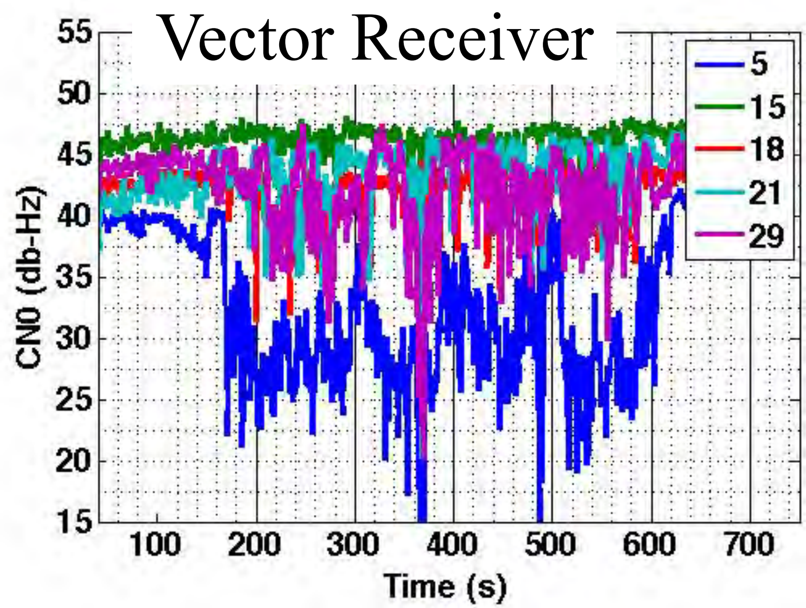
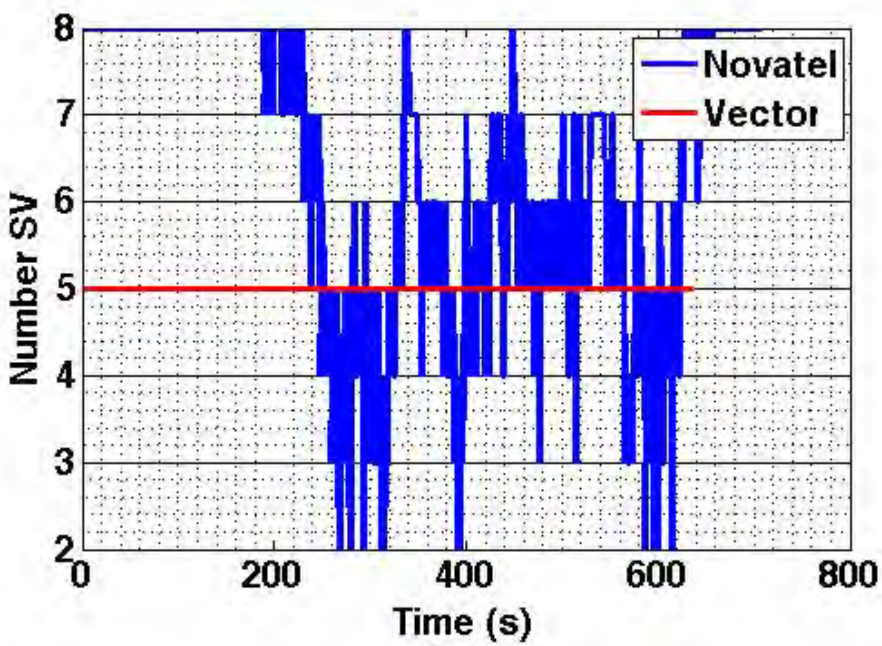
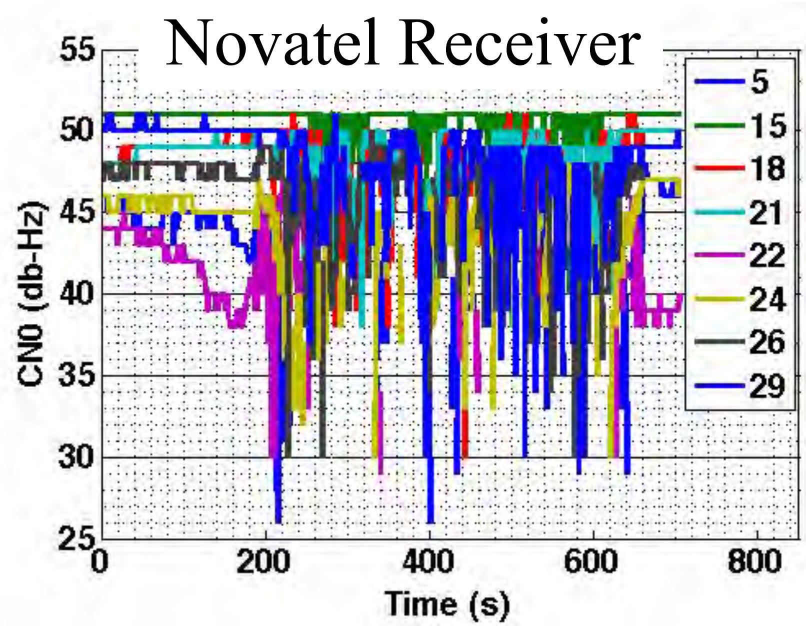
Conditions Heavy Foliage

- Novatel – 55 epochs with less than 4 SV
- Novatel – longest period with less than 4 SV 7 seconds

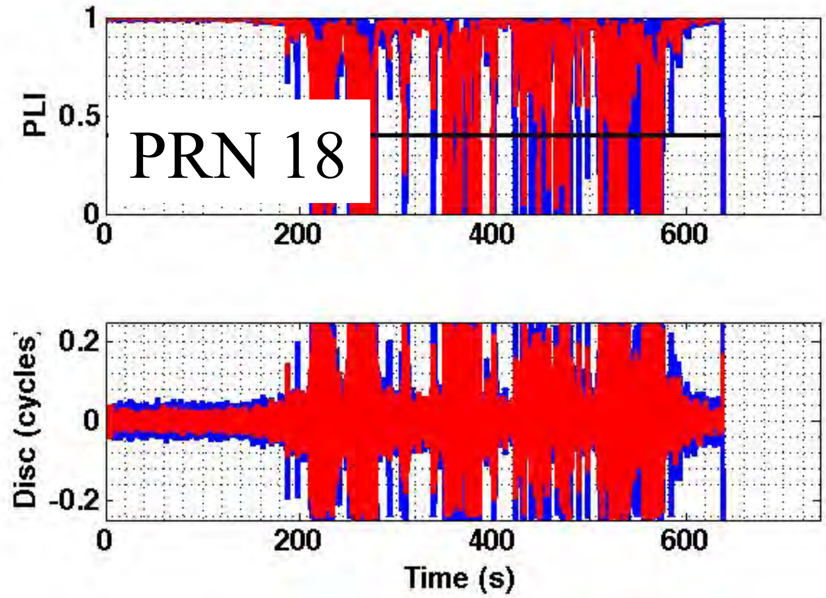






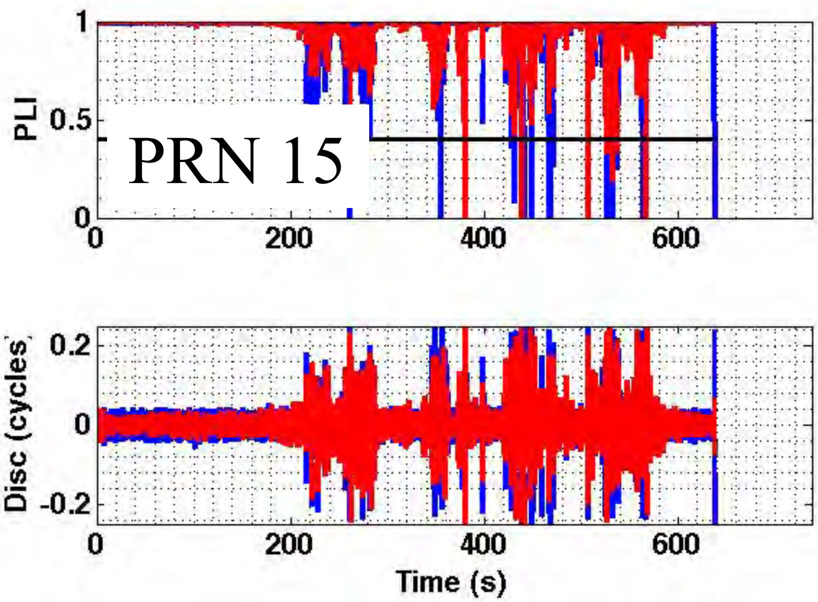
Tracking Heavy Foliage

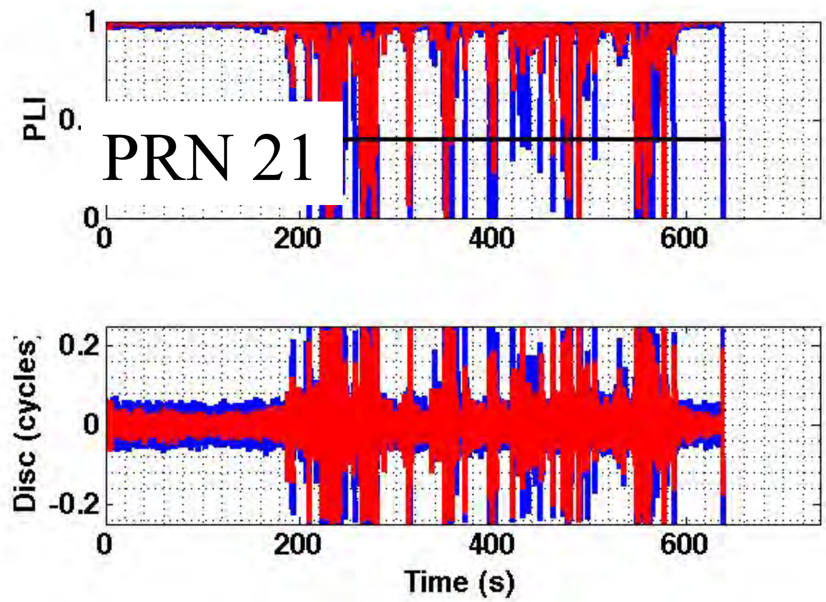
- Vector tracking software receiver (red) compared to traditional scalar software receiver (blue)



Mean Time To Fault

	5	15	18	21	29
Scalar	0.3 s	3.3 s	0.9 s	1.5 s	0.6 s
Vector	1.5 s	26.9 s	5.7 s	10.9 s	4.9 s





Conclusions

- Described a Vector Frequency Lock Loop aided PLL implementation
- Investigated accuracy of carrier phase measurements by comparing software receiver to COTS receiver in clear sky environments
- Comparison of carrier phase tracking between vector aided PLL and traditional scalar receiver

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Future Work

- Performance comparison with scalar FLL aided PLL to isolate improvement due to vector tracking
- Investigate carrier cycle slips in heavy foliage
- Demonstrate ambiguity resolution and RTK positioning with software receiver
- Improve satellite acquisition capability

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Questions?

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