PLAN Group's Software-Based Receiver: Current Status, Ongoing Work and Ultra-Tight GNSS/INS Integration

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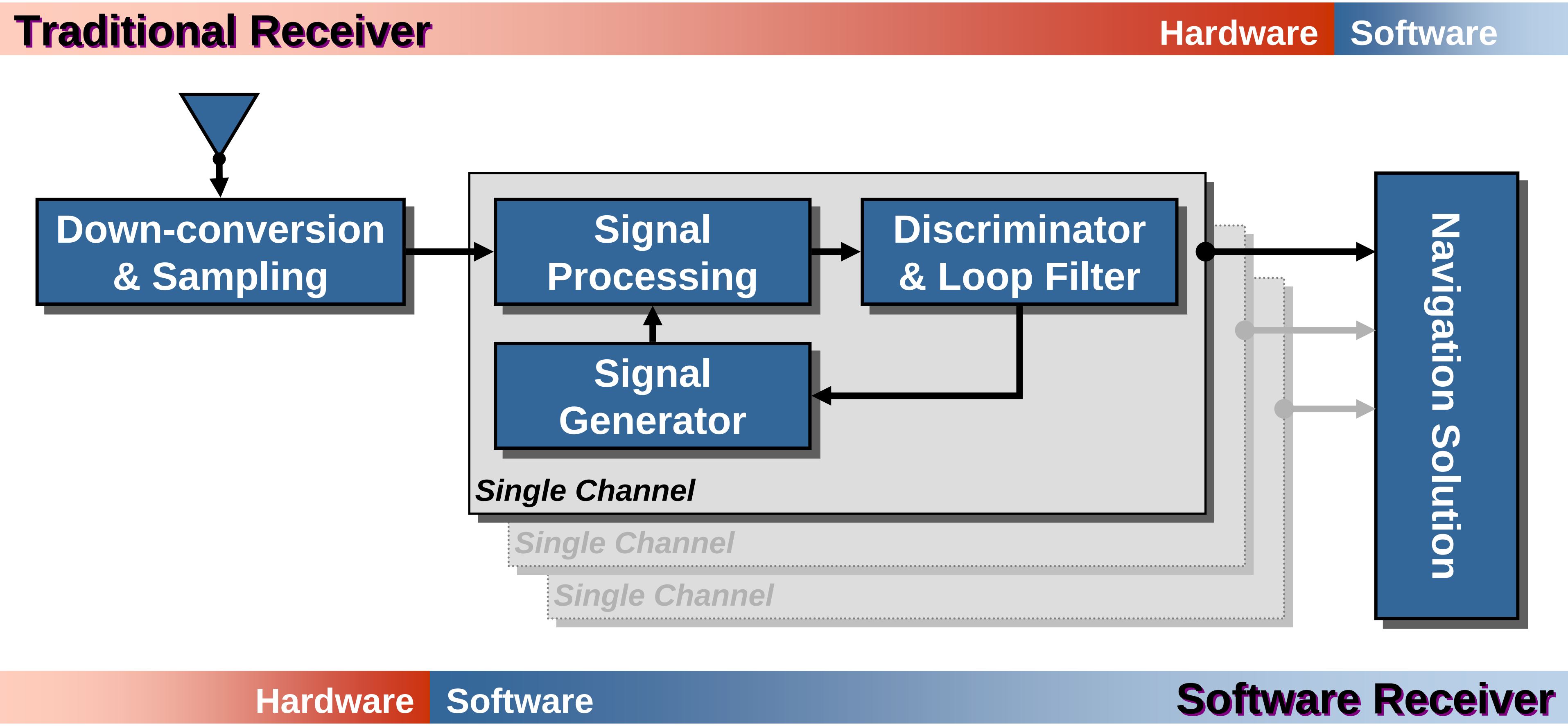
Outline

- Motivation and Challenges
- Current Receiver Status
  - Receiver characteristics and capabilities
- Current Versions
- Sample Results
  - Advanced receiver architectures
- Ongoing Work
- Related Work

Concept of Software Receivers

- Basic idea is to move as many of the receiver processes into software as possible



Why Software Receivers?

- Full control over receiver operations
  - Receiver is no longer a "black box"
- Customize implementation for specific applications
  - Don't need to have a "blanket solution"
- Implementation and testing of new acquisition and tracking algorithms
  - Current (legacy) signals
  - Future signals and systems
  - New receiver architectures
- More information is available for data analysis
  - Critical for leading edge research

Calculation Summary per Second

Operations per Satellite per Second for Doppler Removal and Correlation Only

Operation	Number of Operations
Transcendental Functions	2 x Sample rate
Multiplications	10 x Sample rate
Additions	8 x Sample rate

- For a 4 MHz sample rate and 4 satellites…
  - 32M transcendental functions per second
  - 160M multiplications per second
  - 128M additions per second
  - Plus all additional receiver computations!
- Real-time processing is a major challenge

Current Status

GSNRx™ Overview

- Modular design written entirely in C++
- All receiver processing implemented in software
- Flexible design facilitates evaluation of different algorithms
  - Standard tracking
  - Estimator-based tracking (Kalman Filtering)
  - Vector-based tracking (code phase and carrier Doppler)
  - Ultra-tight GPS/INS integration
- Currently operates in post-mission mode
- Generates pseudorange, Doppler and carrier phase observations for further processing
  - Demonstrated post-mission centimetre-level positioning
- Generates standalone PVT solution
  - Select least-squares adjustment or Kalman filter

Software Capabilities (1/2)

- Input
  - Real or complex samples
  - User-selectable sampling rate
  - User-selectable intermediate frequency
- Acquisition
  - Time-domain or frequency-domain processing
  - Configurable acquisition strategies
  - Can reduce initial acquisition by specifying code phase and Doppler (and corresponding uncertainties)

Software Capabilities (2/2)

- Tracking
  - Specify selected tracking loop parameters
  - Various tracking states to ensure robust tracking
  - User-selectable maximum coherent integration time (limited by data modulation)
  - Corrects for half-cycle lock errors
    - Necessary for centimetre-level positioning
- Measurement generation and navigation solution
  - Output at user-selectable rate
  - Navigation solution can be computed using least-squares or a Kalman filter

Summary of Initial Testing

- Single point positions are accurate to metre-level
- Good relative carrier phase tracking
  - Relative (over time) positions are accurate to millimetre-level over one second
  - Zero-baseline testing shows millimetre-level phase noise
- Good absolute carrier phase tracking
  - RTK positioning accuracy at centimetre-level

Current Versions

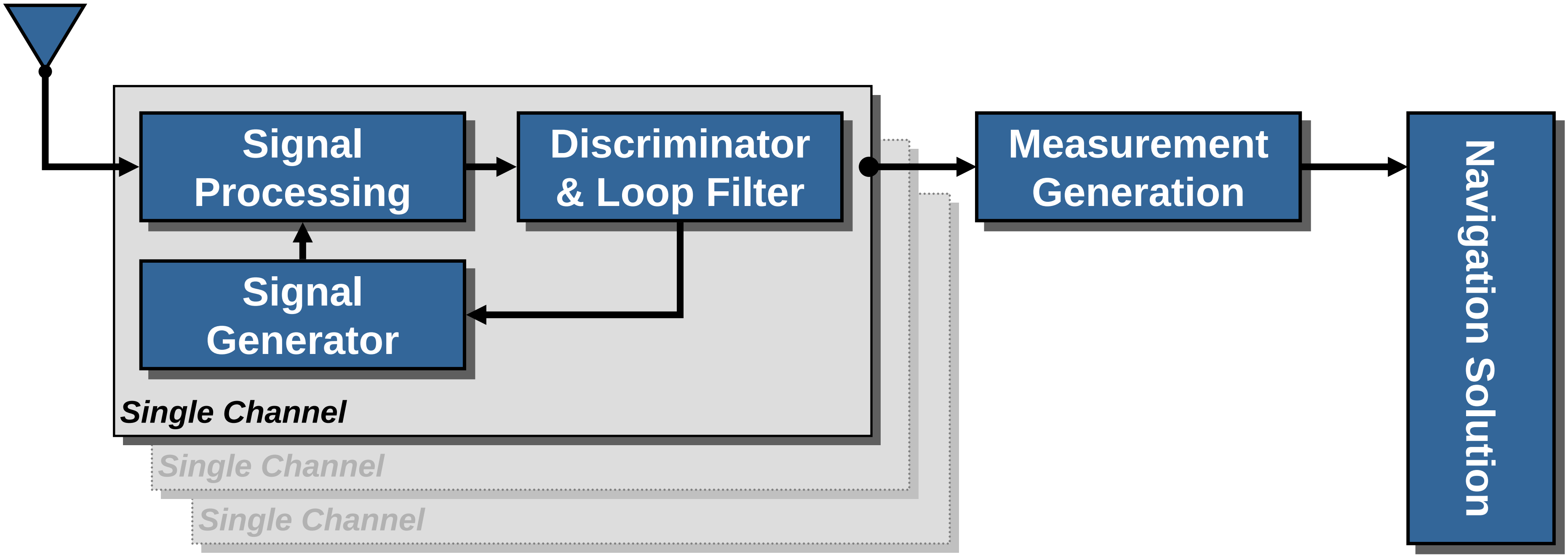
Version Summary

- There are currently four different versions of the GNSRx™ software
  - Standard: GSNRx™
  - Estimator-based: GSNRx-eb™
  - Vector-based: GSNRx-vb™
  - Ultra-tight GPS/INS: GSNRx-ut™

Each version is based on previous version(s) for ease of support and maintenance

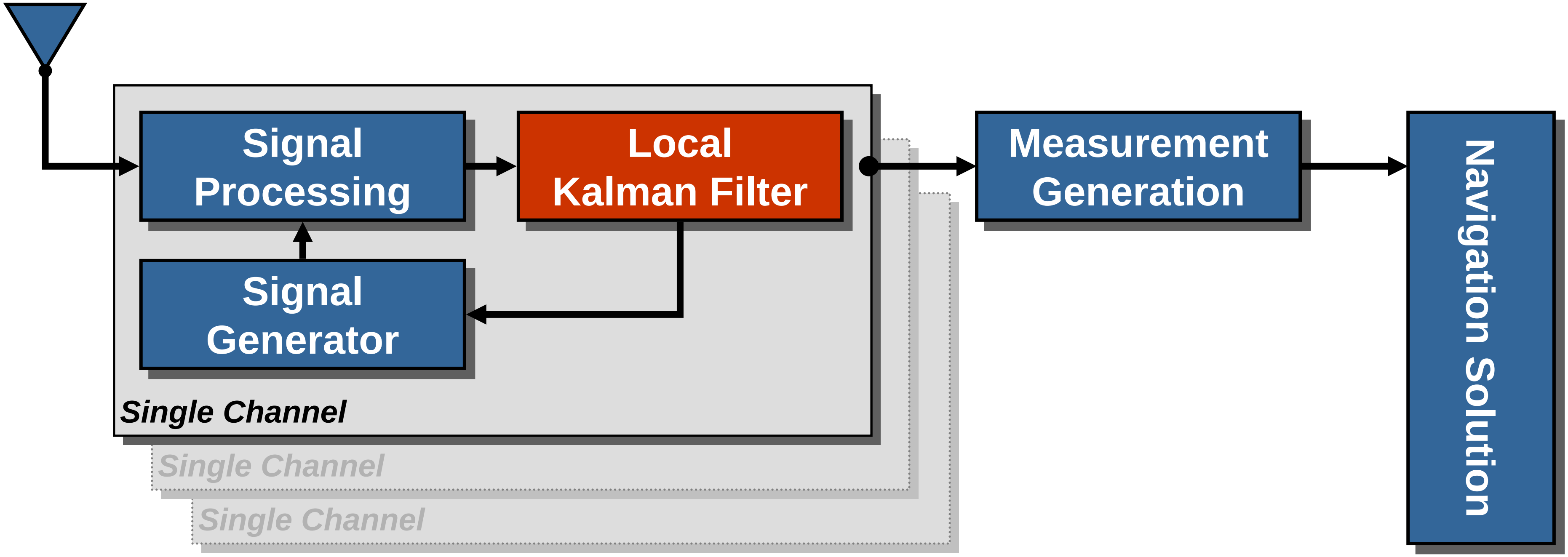
- Each receiver architecture is briefly discussed on the following slides

Standard Receiver Architecture



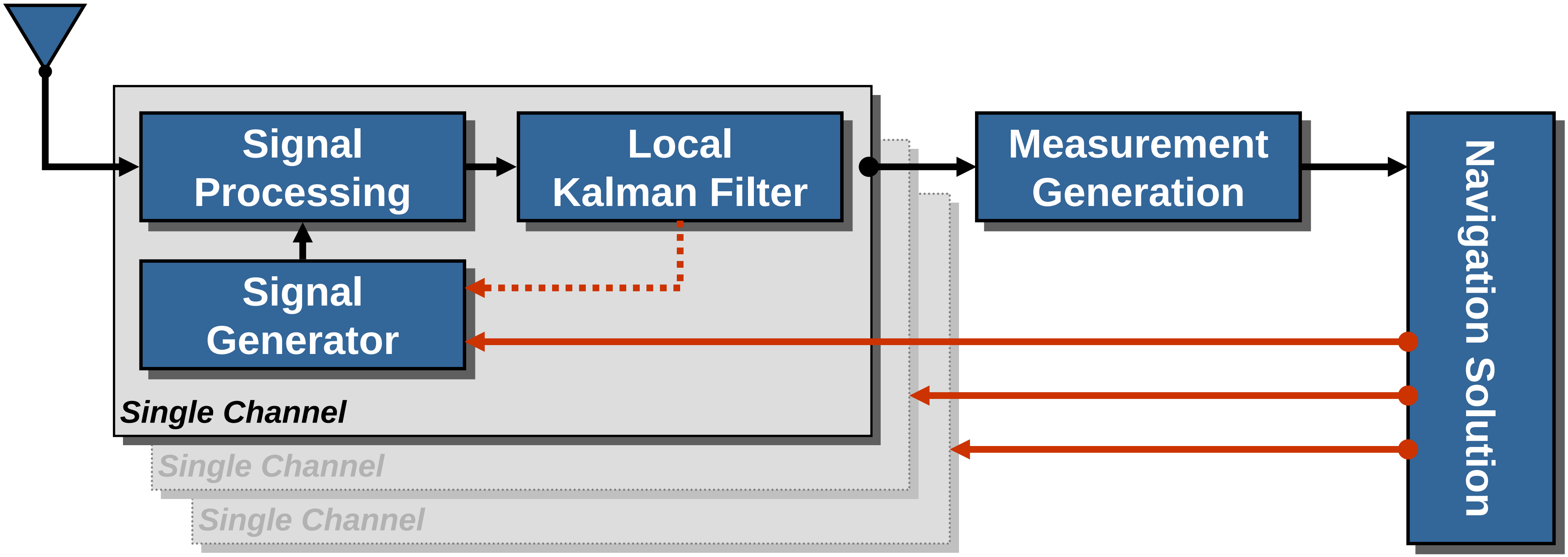
- Channels operate independently
  - Relatively simple to implement
- Robust to errors in any given channel
- Information is not shared between channels

Estimator-Based Receiver Architecture



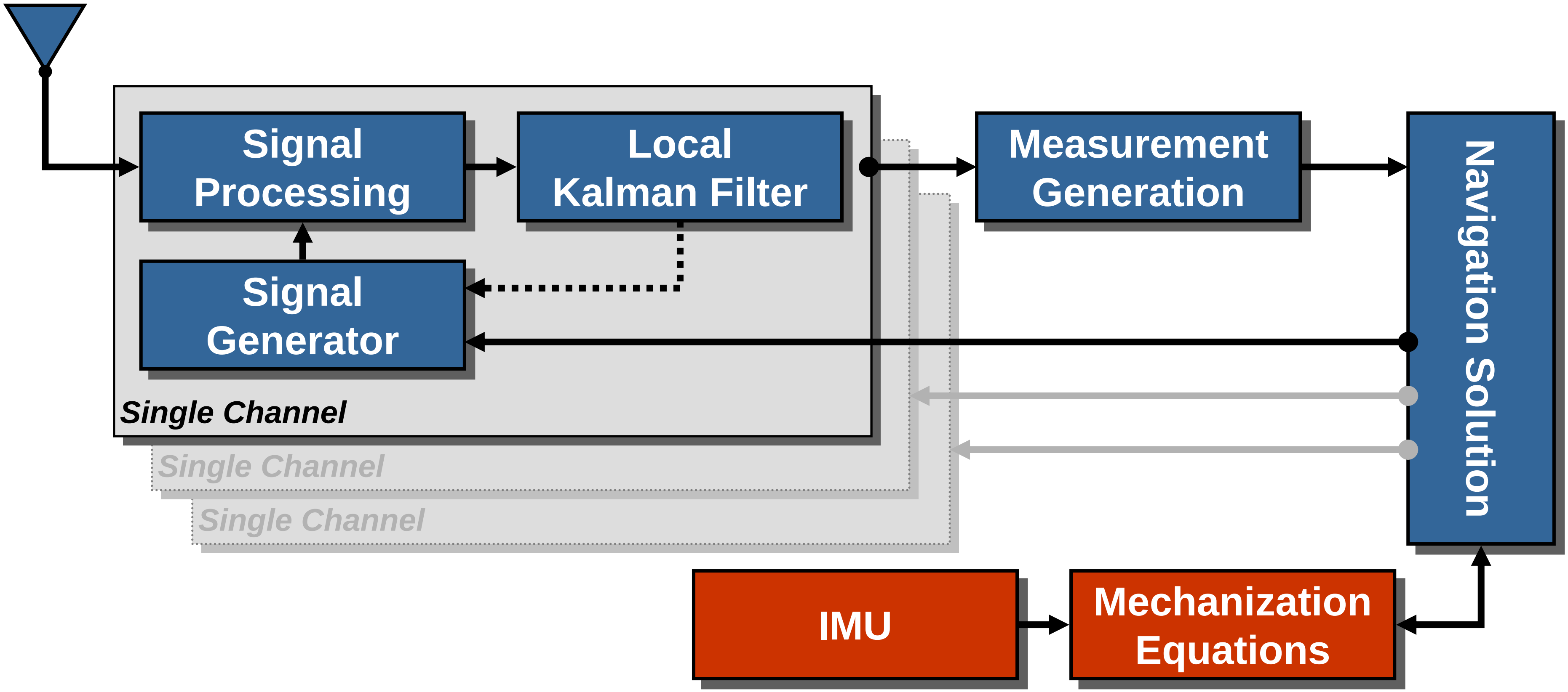
- Channels still operate independently
- Use a Kalman filter to estimate tracking errors
  - Optimal estimation
  - Better in the presence of dynamics

Vector-Based Receiver Architecture



- Code and frequency tracking is based on the position and velocity of the antenna
- Carrier phase tracking is still independent of navigation solution
  - Solution is not accurate enough

Ultra-Tight GNSS/IMU Architecture

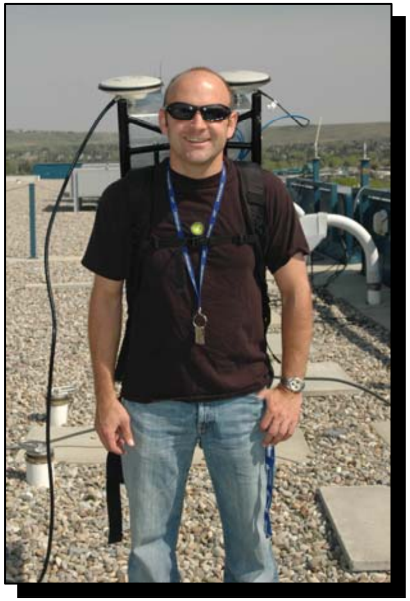


- Same as vector case but with inertial information
  - Measure and account for vehicle motion (at a higher rate)
  - Phase wind-up effects

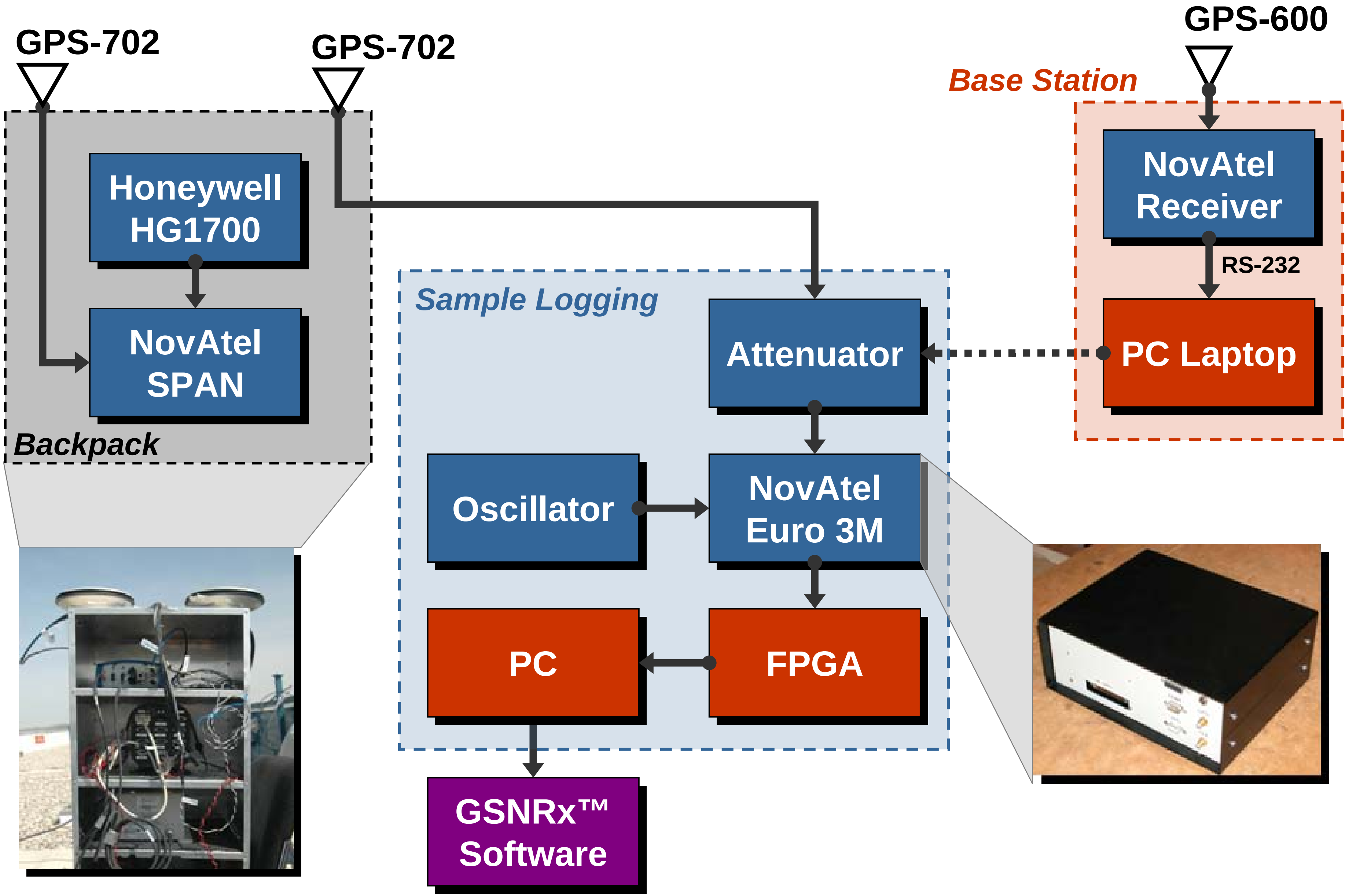
Sample Results

Data Collection

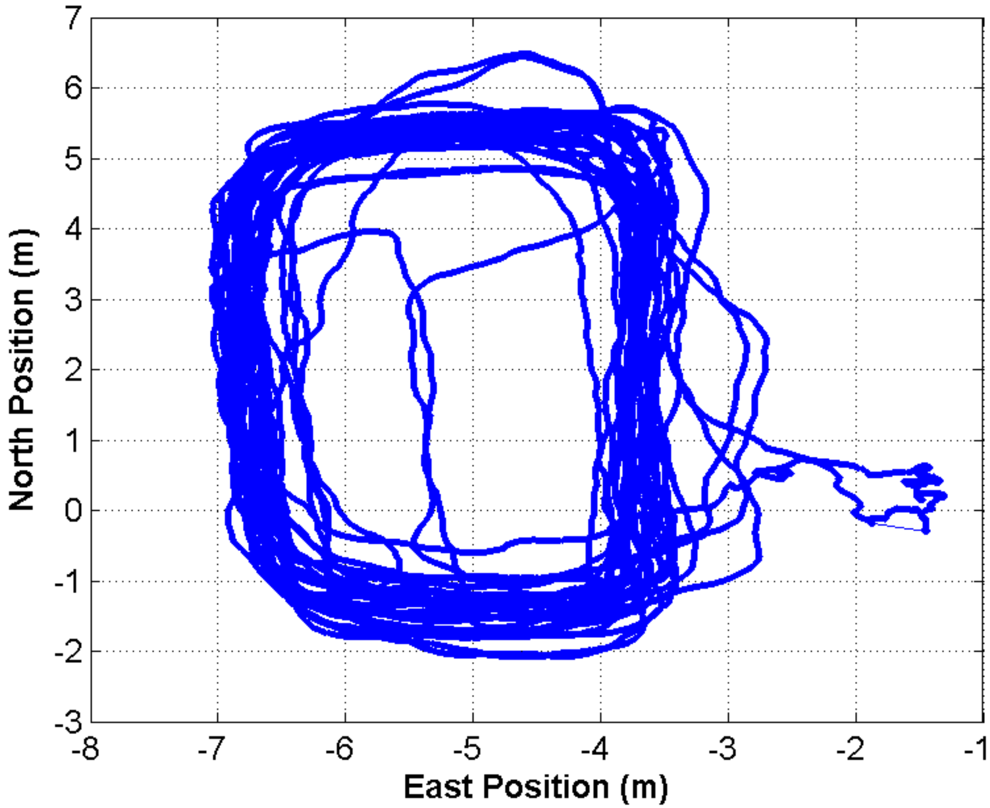
- **Pedestrian navigation**
  - Open sky environment
- **Equipment**
  - 10 MHz IF samples
  - HG1700 IMU (1 deg/h)
  - Symmetricom oscillator
    - Coherent integration > 15 s
  - Signal attenuator
    - 1 dB every 4 seconds
- **Reference Solution**
  - SAINT™ (100 Hz)
  - Fixed ambiguities throughout kinematic portion



Pedestrian-Based Test Setup



Trajectory

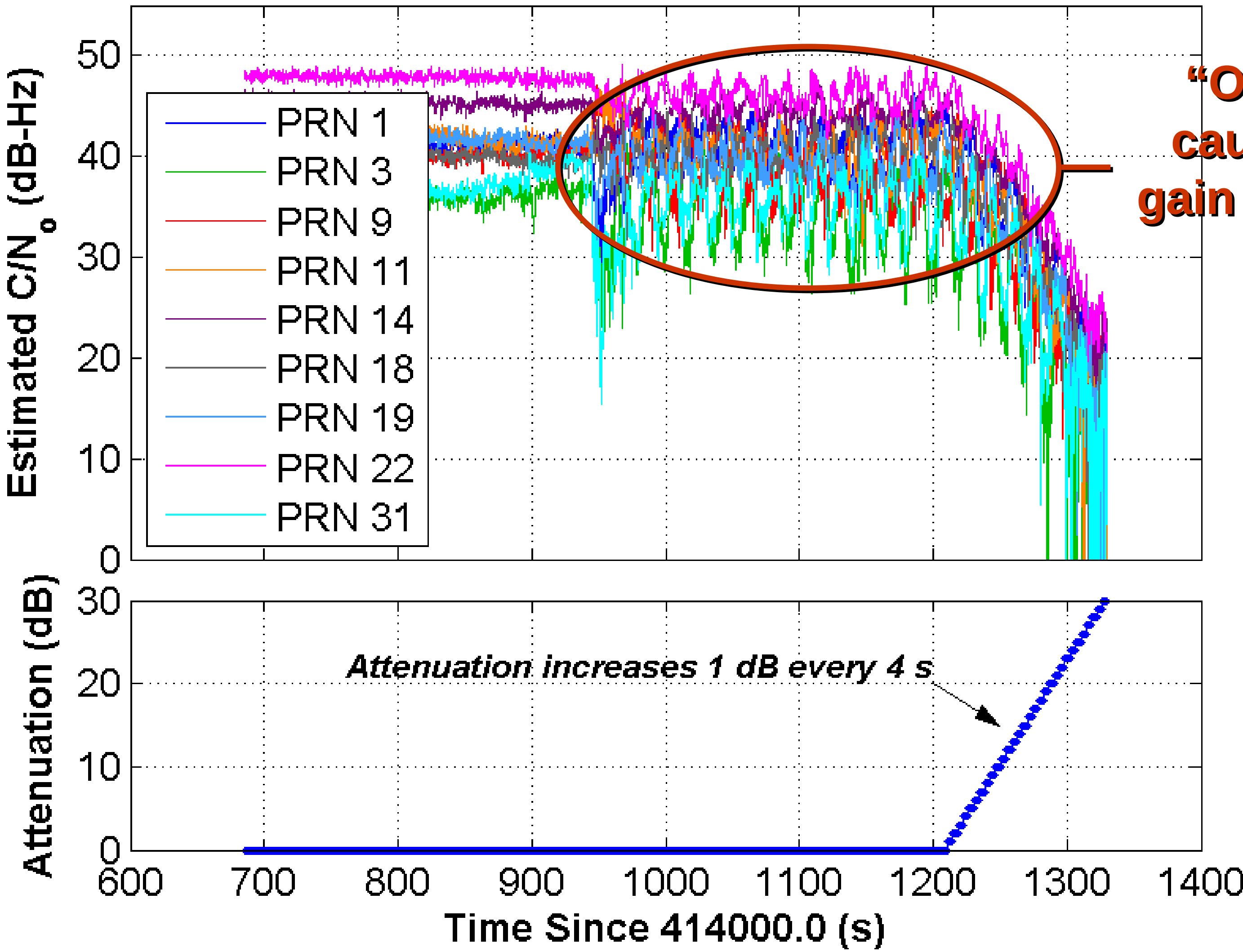


- **Low velocity**
  - **About 1-2 m/s**
- **Peak-to-peak accelerations of about 1 G**

Processing Strategy

- Process IF data samples with software receivers
- Receiver settings are "equivalent" in both cases
  - Maximum 20 ms integration
    - Only assess relative performance of each receiver, not the absolute performance
  - Output pseudorange, Doppler and carrier phase data
  - No minimum required PLL lock indicator
- Process data with FLYKIN+™
  - L1-only processing
  - Try to fix the ambiguities as integers

Measured C/N$_o$ and Attenuator Level



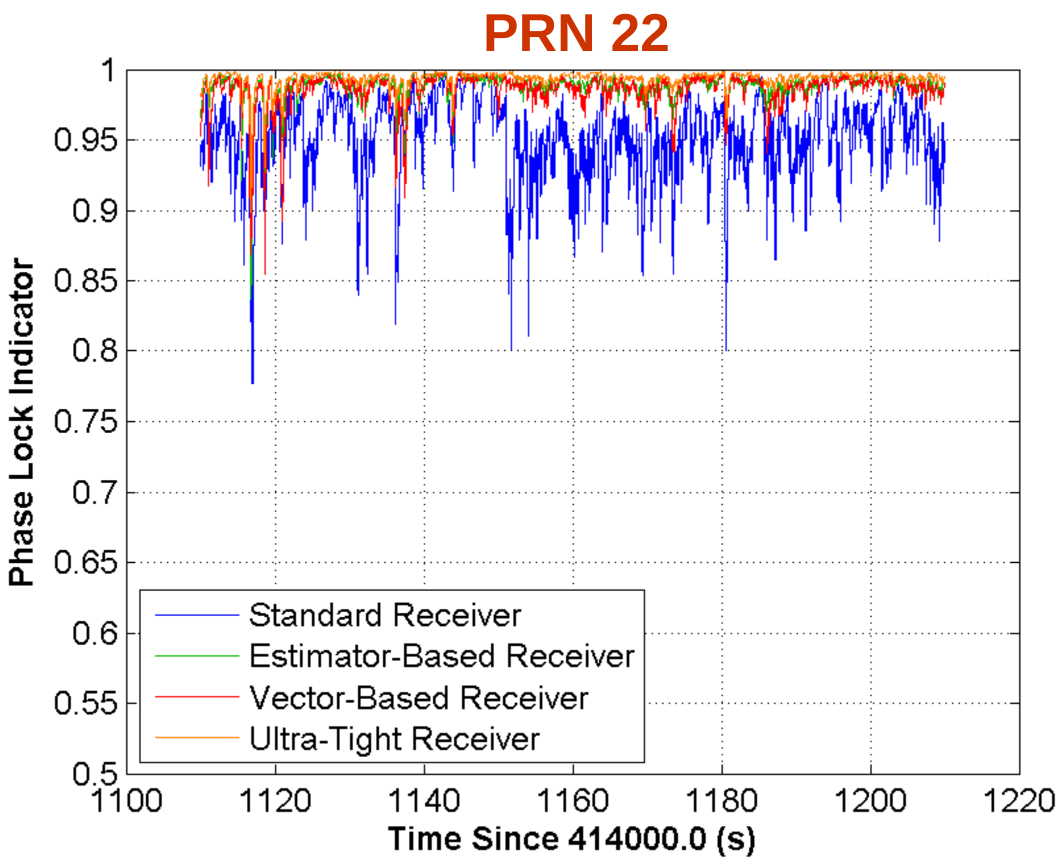
"Oscillations" are caused by antenna gain pattern and pitch of antenna

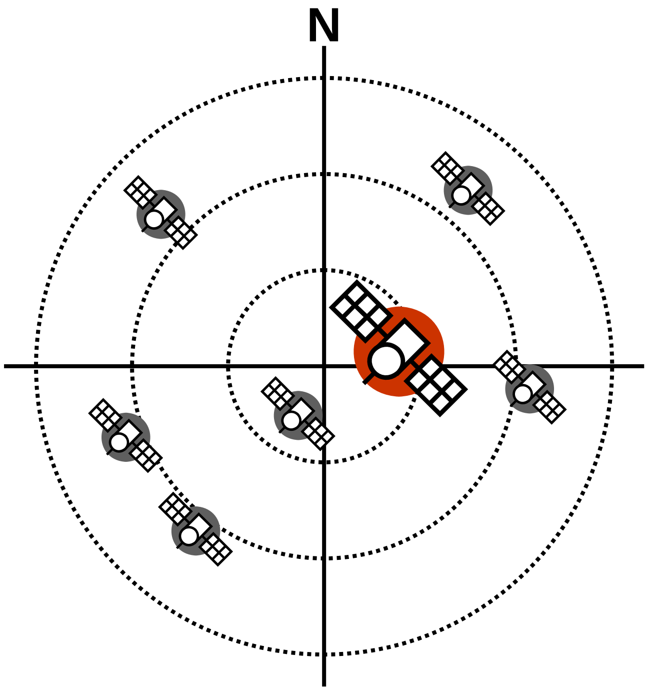
Phase Lock Indicator (PLI)

- The phase lock indicator (PLI) is computed internal to the receiver
  - Full range is [-1 , 1]
  - A value of unity implies perfect phase lock

- Using a smoothed version to mitigate the effect of noise
  - Same smoothing constant is used for all receiver architectures

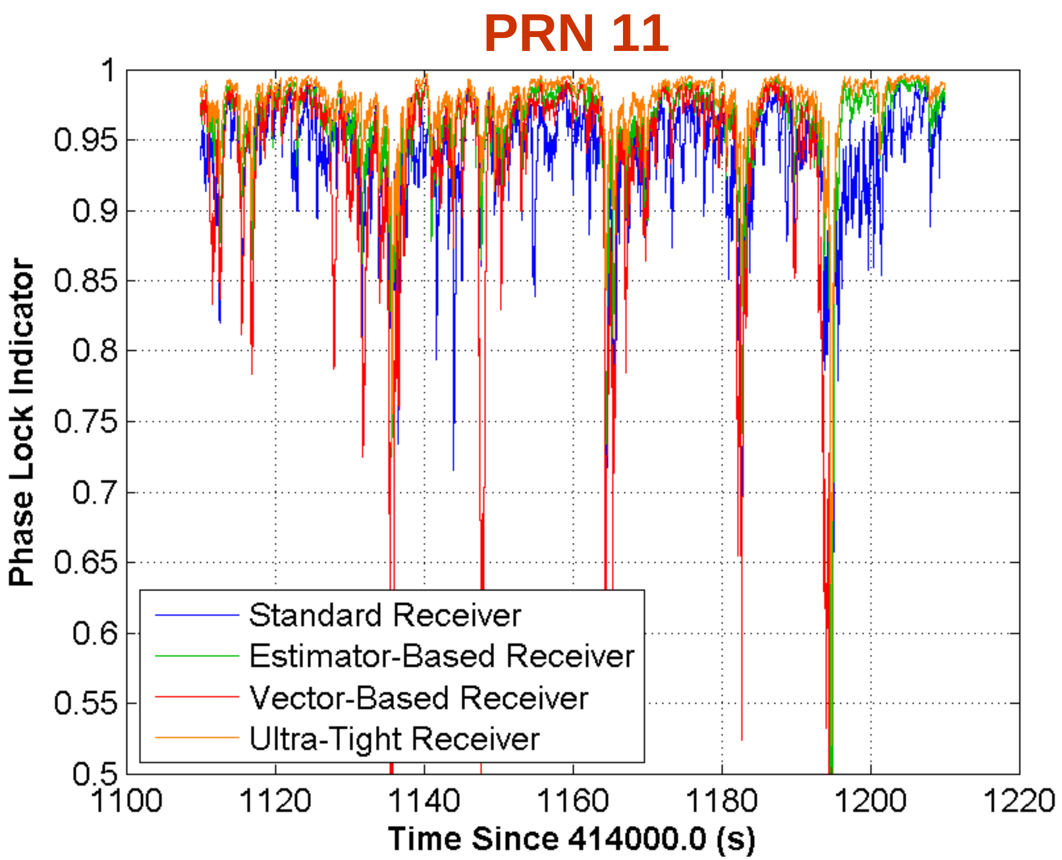
PLI with Strong Signals (1/2)

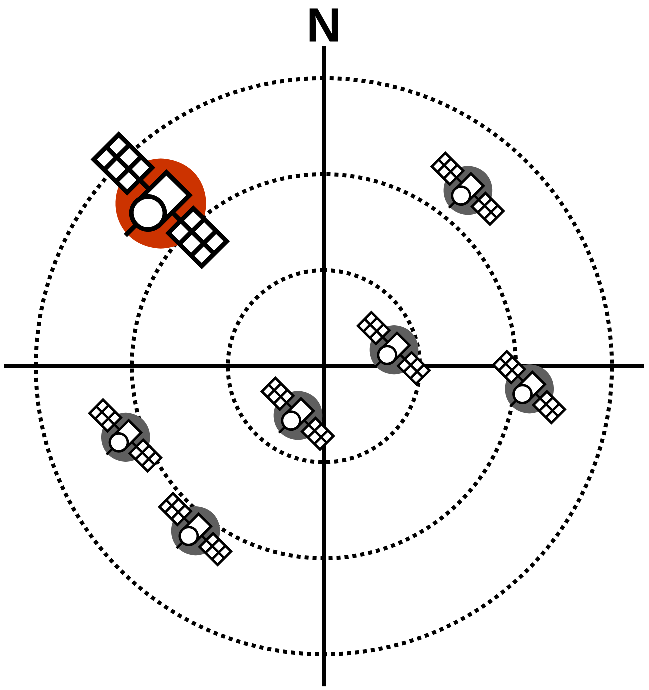




- **Little signal dynamics (horizontal motion)**
- **Standard receiver performs the worst**
- **Ultra-tight shows marginal improvement over other receiver architectures**

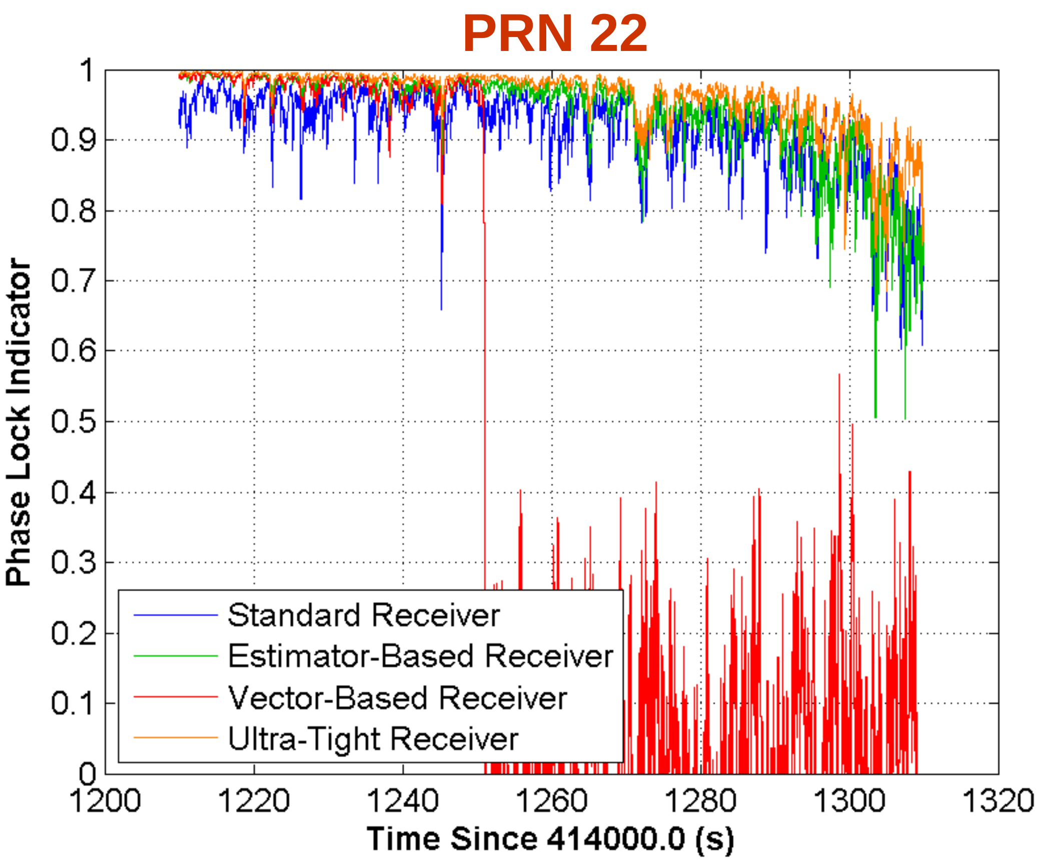
PLI with Strong Signals (2/2)

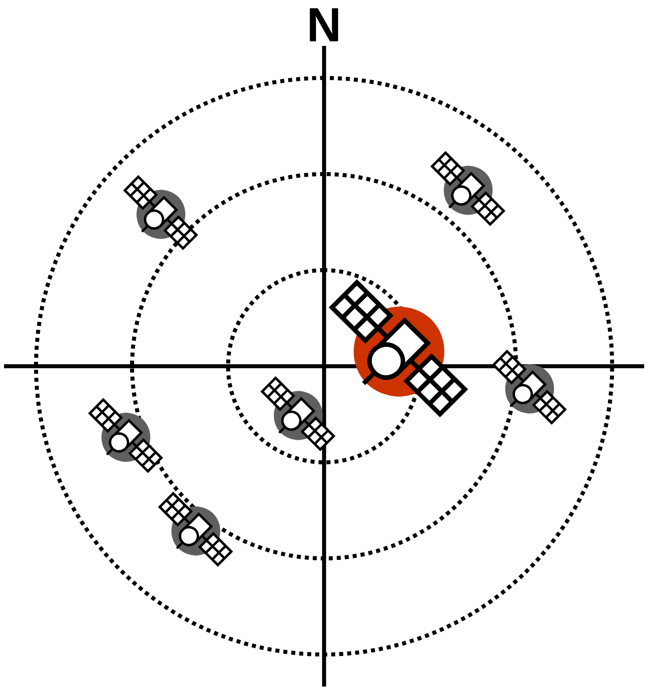




- **Lower elevation satellite has more dynamics**
  - **Ultra-tight receiver still performs best**
  - **Vector-based receiver appears more sensitive to dynamics**

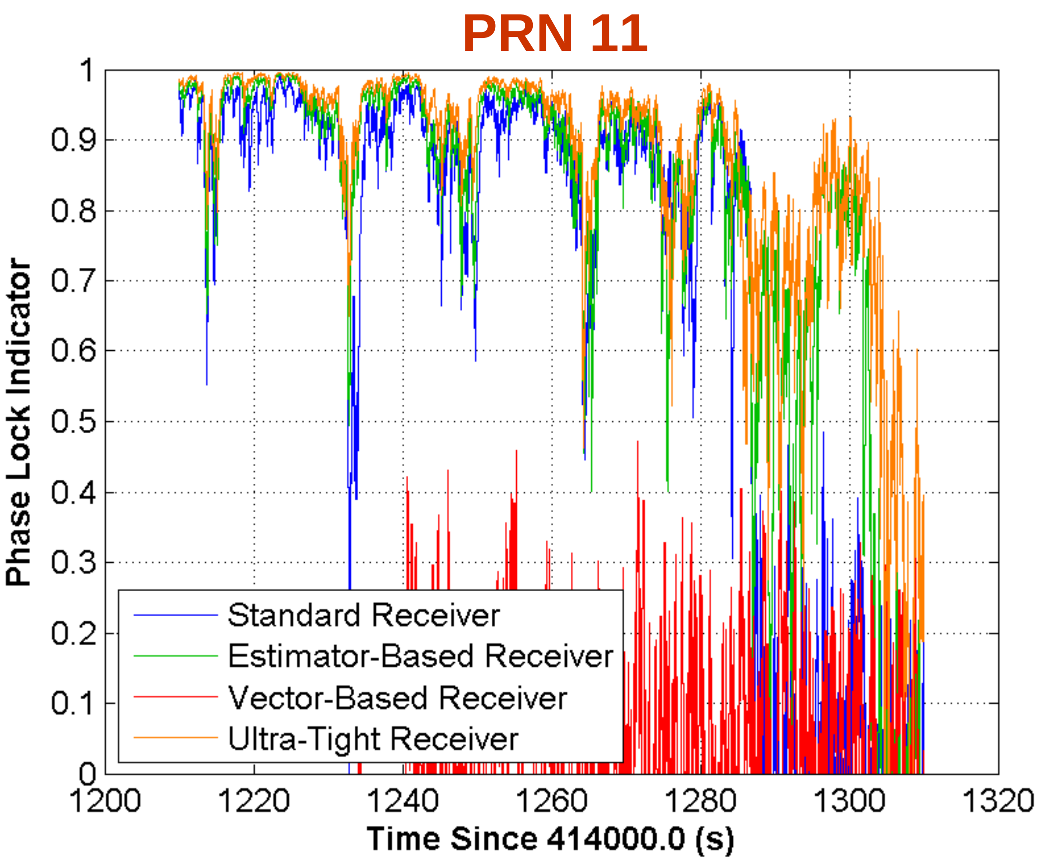
PLI with Weaker Signals (1/2)

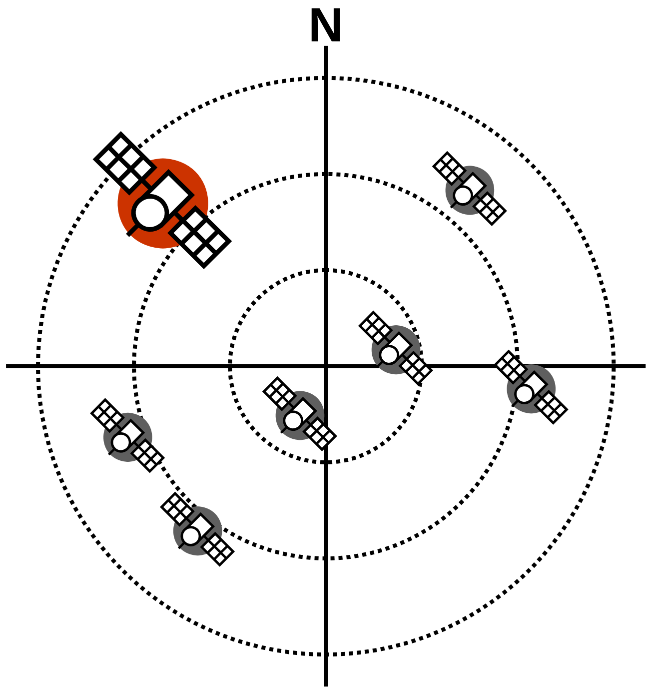




- **Noticeable improvement with ultra-tight receiver**
  - **Better able to compensate for receiver dynamics**
- **Vector-based receiver loses lock quite early**

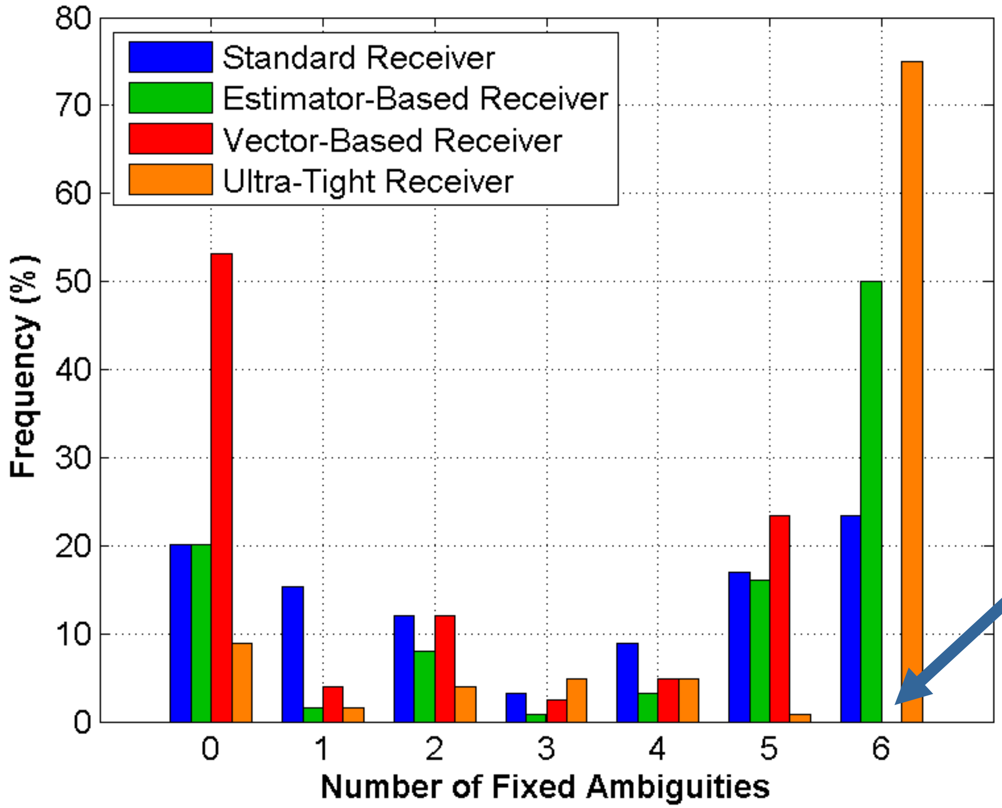
PLI with Weaker Signals (2/2)





- **Ultra-tight receiver still performs best even in the presence of higher signal dynamics**
  - **Similar results observed for other low-elevation satellites as well**

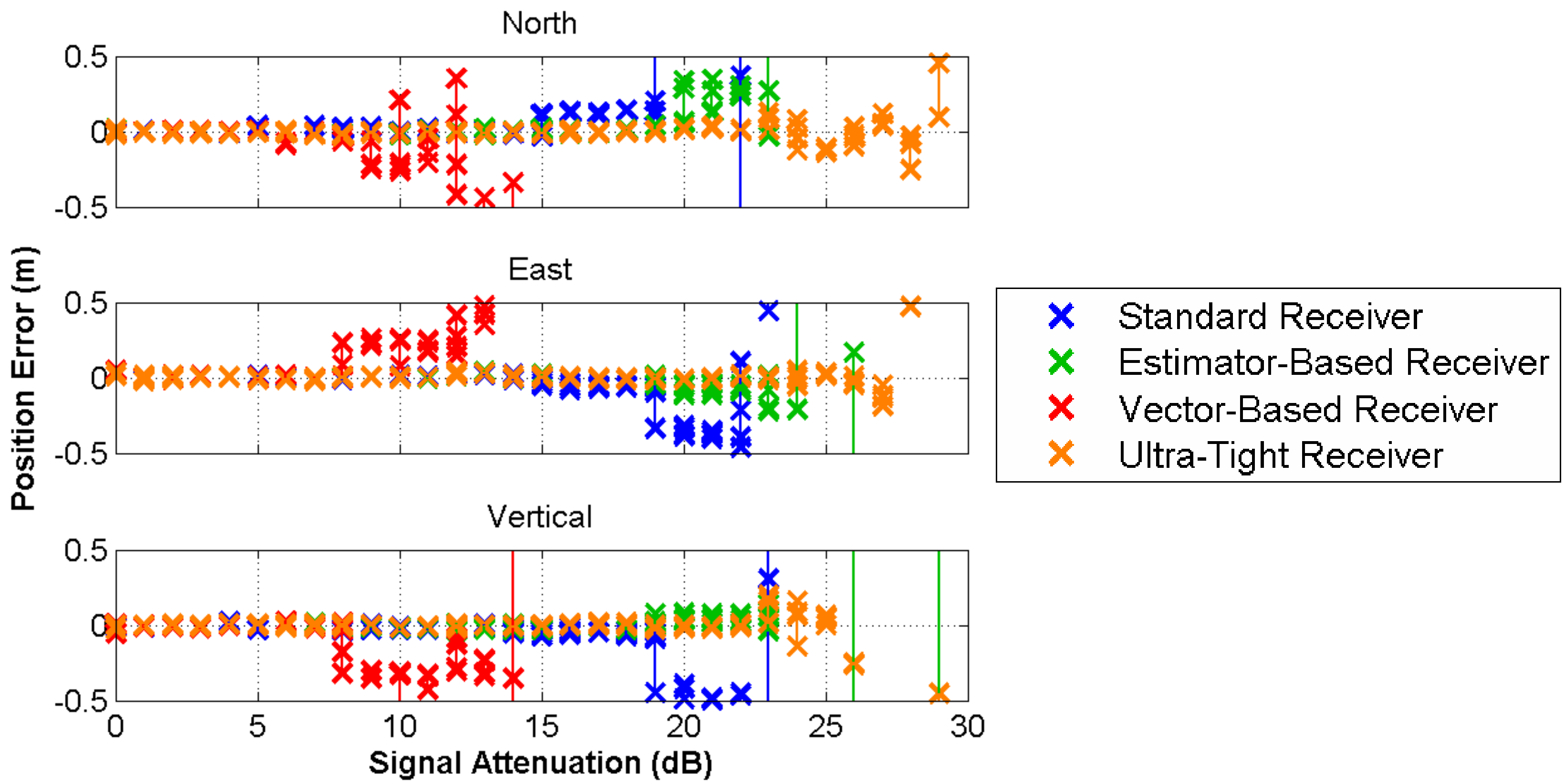
Histogram of Fixed Ambiguities



One satellite was intentionally removed from vector-based processing due to a wrong ambiguity fix

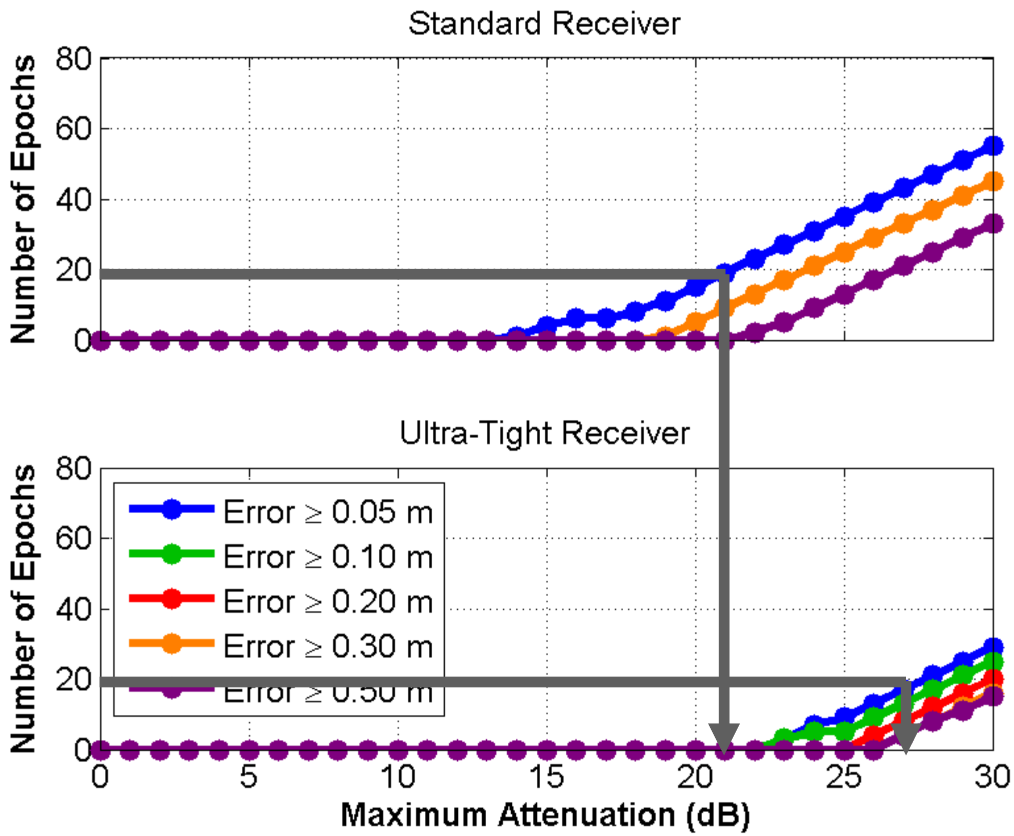
- **More ambiguities are fixed with ultra-tight tracking**
  - **Ambiguities remain fixed longer (not shown)**
- **What about position-domain results?**
  - **Are the ambiguities fixed correctly?**

Position Error vs. Attenuation



- **Ultra-tight receiver shows considerable improvement**
- **Vector-based receiver performs worst**
- **Estimator-based receiver provides significant benefit over standard receiver**

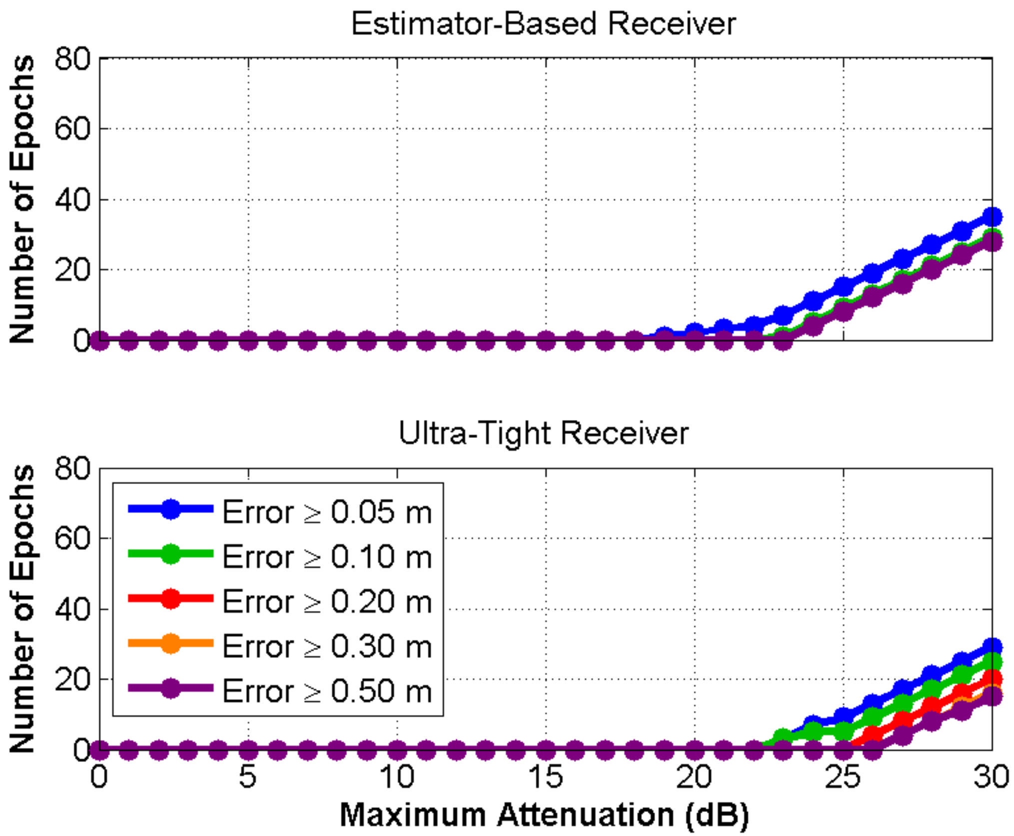
Vertical Error Histogram (1/2)



Each point on the graph is the number of epochs, at or below a given attenuation level, that have a position error greater than a certain level

For a given epoch count and position accuracy, the ultra-tight receiver provides, on average, about 7 dB of sensitivity improvement over the standard receiver

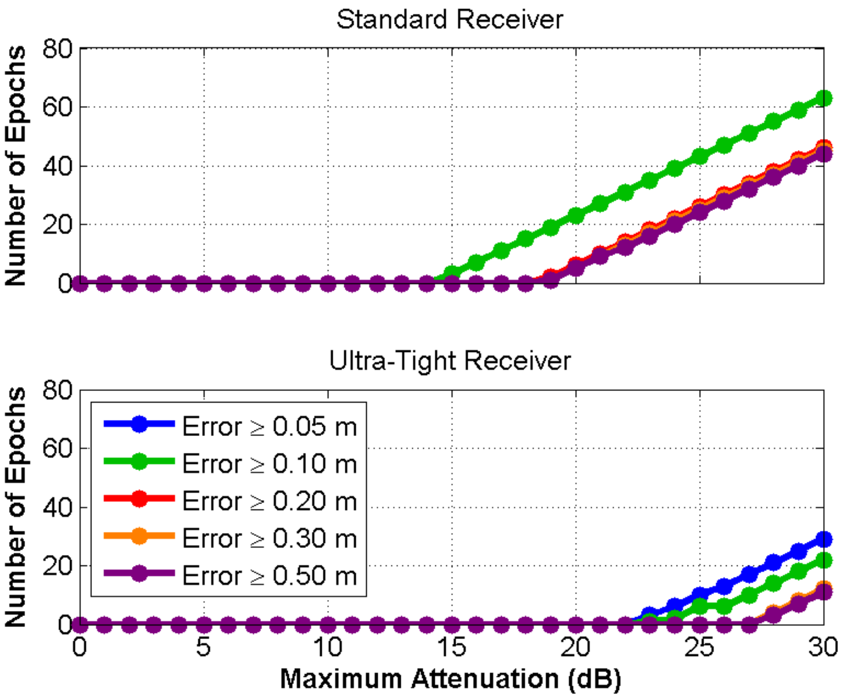
Vertical Error Histogram (2/2)



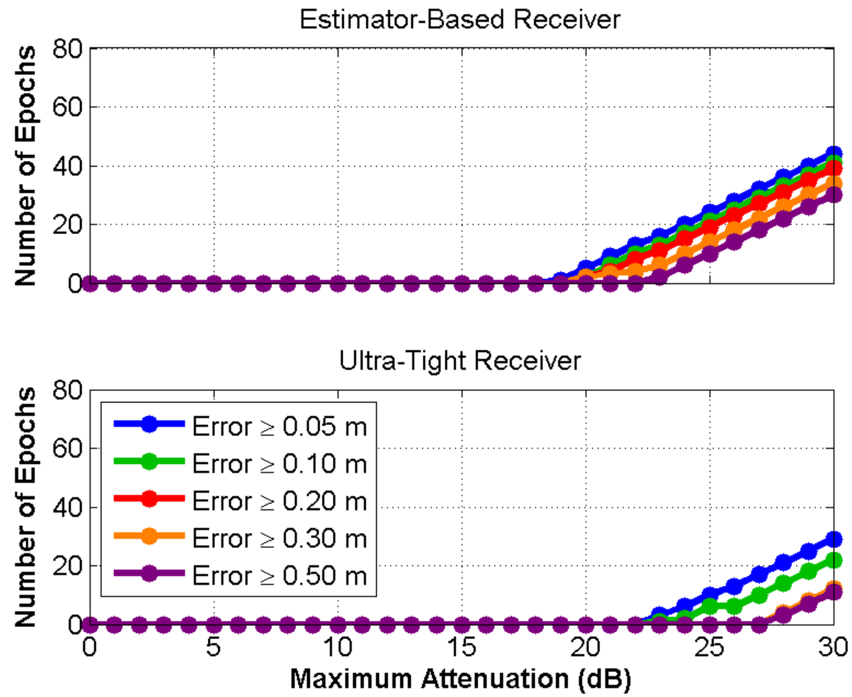
- **Ultra-tight receiver provides about 1-3 dB sensitivity improvement over the estimator-based receiver**
  - **Estimator-based receiver is a viable option for weaker signal tracking**

Horizontal Error Histograms

Standard vs Ultra-Tight Receiver



Estimator-Based vs Ultra-Tight Receiver



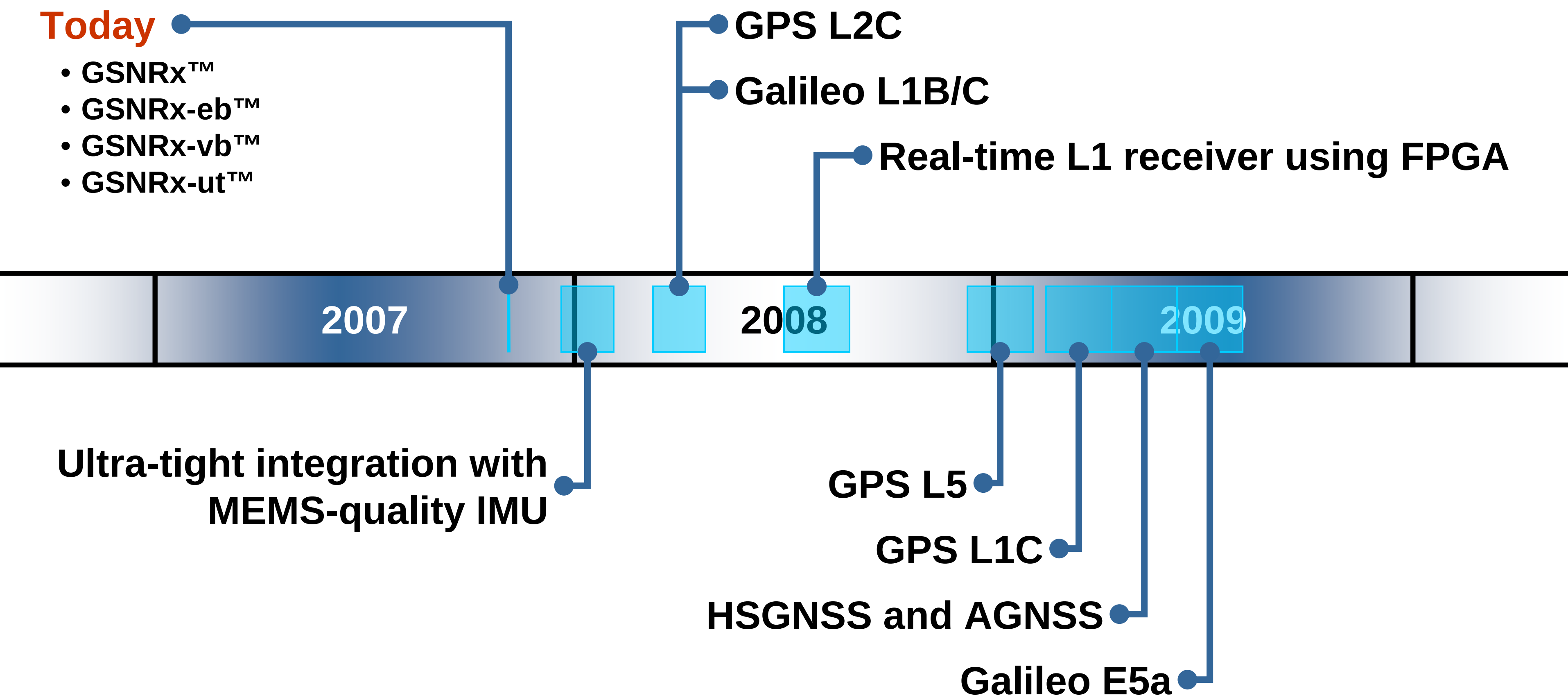
- **Ultra-tight still yields best sensitivity**
  - **About 7 dB sensitivity improvement over standard receiver**
  - **About 3 dB sensitivity improvement over estimator-based receiver**

Ongoing Work

Summary of Ongoing Work

- Currently working on acquisition and tracking capability for
  - GPS L1C, L2C and L5
  - Galileo L1 and E5a
  - GLONASS L1 and L2
- Moving towards real-time implementation
  - Use of FPGA for high rate processing (Doppler removal and correlation)
  - Multi-threading techniques for operation on PC
- Investigation of weak signal acquisition/tracking techniques is also ongoing
- Investigating oscillator performance
- Assessing when an ultra-tight GNSS/INS system is oscillator-limited vs. IMU-limited

Schedule – Receiver Capability



Some Related Work

New Acquisition Strategies

- Generalized differential combination of signals
  - Pre-correlation
  - Post-correlation

- Idea is to improve acquisition sensitivity without increasing coherent integration
  - Reduced Doppler search space
  - But, more computationally intensive than traditional, non-coherent techniques

- Initial results are promising

Collaborative Tracking

- Multiple signals from a single satellite are used to collaboratively acquire and track the satellite
  - Currently focusing on combining L1 and L2C signals
  - Idea can be extended to any combination of signals on a single satellite

- Improve acquisition over L1 alone by 2-3 dB
  - Allows for reduced coherent integration times, which improve acquisition times

Weak Signal Tracking

- **Extend coherent integration time to beyond 100 ms**
- **Investigate methods of handling the data bits**
- **Develop more optimized tracking loop parameters**
  - **Investigating Kalman filter tracking loops for this purpose**

IMU vs Oscillator Limited Systems

- Any receiver must track both the user dynamics and the local oscillator errors
- In an ultra-tight receiver the IMU tracks the user dynamics only
  - Inertial errors still remain
- Very long coherent integration times will be limited by a combination of IMU quality and oscillator stability
  - When is a system IMU-limited or oscillator-limited?

Ultra-Tight with Reduced IMUs

- **Reduce the IMU to consist of fewer than three accelerometers and three gyros**
  - **For cost-sensitive applications**

- **Can such a system still be useful in an ultra-tight configuration?**
  - **If so, what are the limitations?**

Patents Pending

- Novel method of tracking BOC(n,n) signals to avoid side-peak tracking
  - Thesis by O. Julien
- Use of multiple correlators to improve weak-signal tracking
  - Papers by S. Shanmugam et al.
  - Most recent paper at ION GNSS 2006 conference
- Efficient method of performing Doppler removal and correlation
  - Paper by M. Petovello and G. Lachapelle at ION GNSS 2006 conference

Selected References

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