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PRECISE POINT POSITIONING

PART 2: A DEEPER DIVE

Tuesday, April 14, 2015

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2 pm–3:30 pm Mount
3 pm–3:30 pm Central
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WELCOME TO
Precise Point Positioning - Part 2: A Deeper Dive

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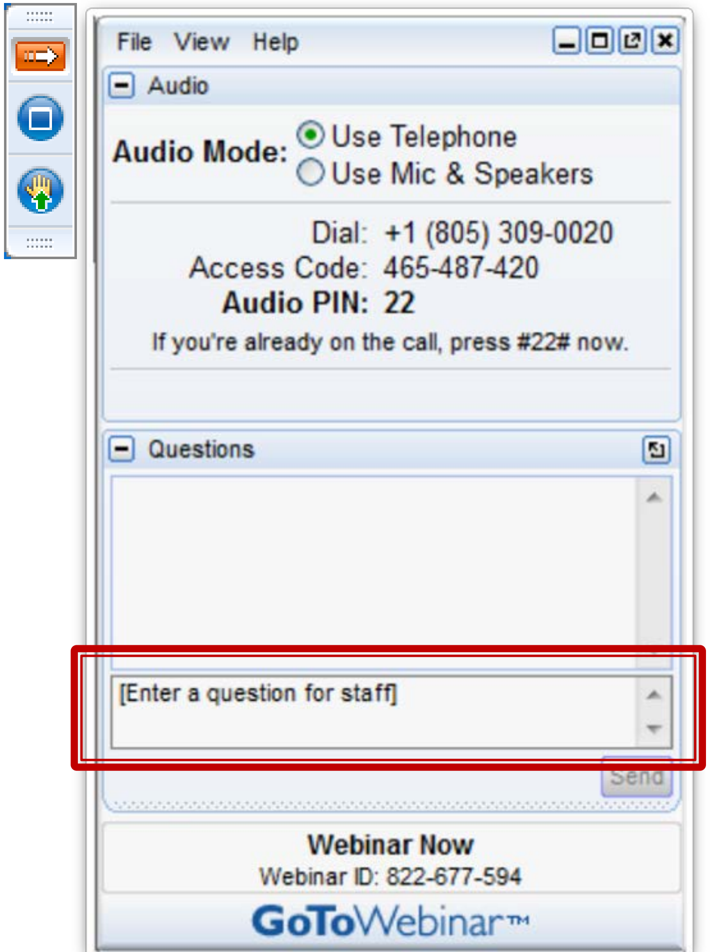
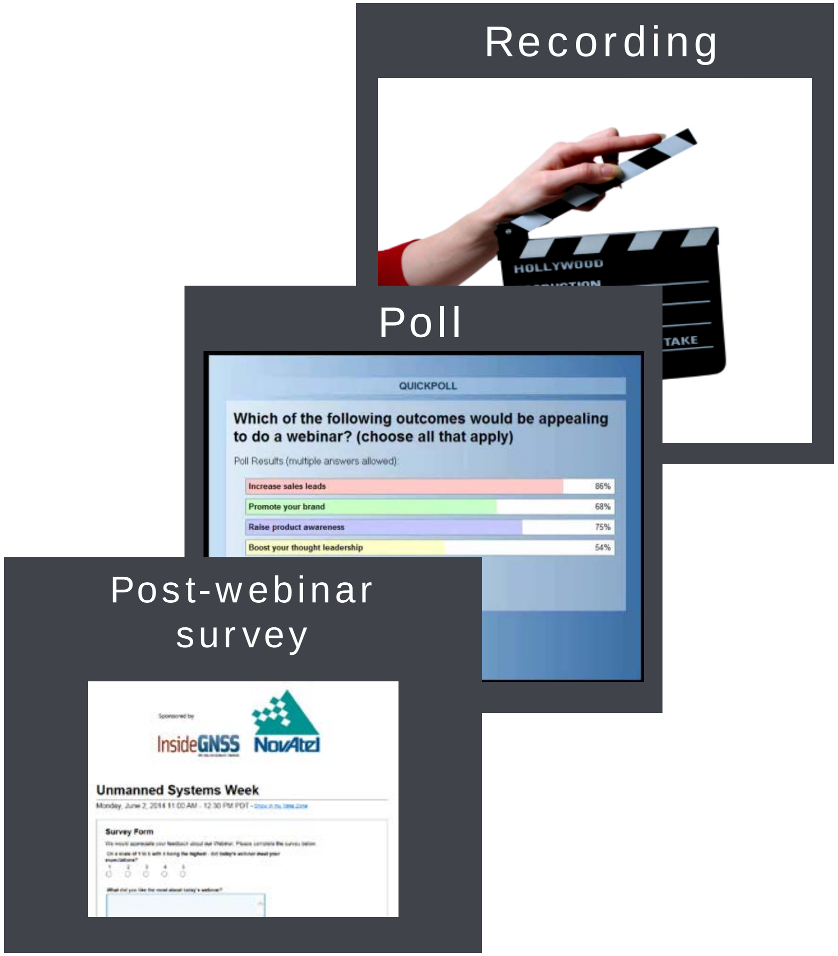




Who's In the Audience?

A diverse audience of over 600 professionals registered from 50 countries, 29 states and provinces representing the following industries:

23% GNSS Equipment Manufacturer

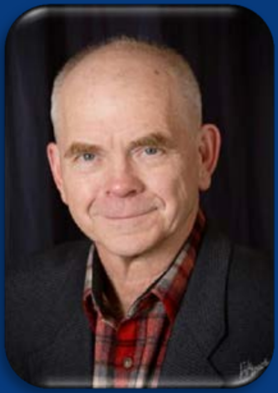
23% Professional User

12% System Integrator

15% Product/Application Designer

27% Other

Welcome from *Inside GNSS*



Glen Gibbons

Editor and Publisher
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A word from the sponsor

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Precise Point Positioning - Part 2: A Deeper Dive

Demoz Gebre-Egziabher
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Poll #1

In next year or two PPP services will be available to all(choose one)

- On all GPS/GNSS receivers (e.g mobile, surveying, etc)
- Retrofitted to all receivers
- On newer high-end receivers only
- What is PPP?

Today's Speakers

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York University, Toronto

Receiver Considerations for High-Accuracy Applications

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Sanjeev Gunawardena
Research Assistant Professor
Air Force Institute of Technology

Review: Antenna and Front-End Comparisons

Receiver Type → Design Parameters ↓	Mass Market / Consumer	Aviation Grade / Machine Control	Geodetic / Reference Station
Antenna Type Coverage Bands Approximate Size	Passive chip or helical element Covers L1 bands (GPS, GLONASS) Surface Mount Package <2cm 	Patch on controlled dielectric single element (L1 band) or Stacked (L1 and L1/L5 bands) Integrated diplexer and LNA 10 cm 	Multipath Limiting Elements Stable Phase Center External Choke Ring Design In-system calibration of inter-channel biases 30 cm 
GNSS Bands	GPS L1 C/A, and GLONASS L1 and/or BeiDou B1 SBAS on L1	GPS L1 C/A GPS L5 SBAS on L1 and L5	GPS L1 C/A, P(Y)* GPS L2 C, P(Y)* GPS L5
Pre-correlation Bandwidths	<2MHz (GPS C/A) <2 MHz (GLONASS)	4-16 MHz (L1) 16 MHz (L5)	16-24 MHz (L1, L2, L5)
Sample quantization and effective sample data rate (Mbytes/sec)	1 or 2 bits/sample 0.5-1.0	2-4 bits/sample 8-32	2-8 bits/sample 24-150
Pre-Correlation Interference Detection/Suppression	none	CW, Swept CW, FM Non-uniform quantization J/N meter	Pulse-suppression, notch filter, frequency-domain excision
Reference Oscillator Type and stability	TCXO ($<=10^{-6}$)	High-performance TCXO or OCXO (10^{-6} – 10^{-7})	OCXO or atomic standard (10^{-9})

* Using codeless or semi-codeless tracking techniques

Review: Baseband Processing Comparisons

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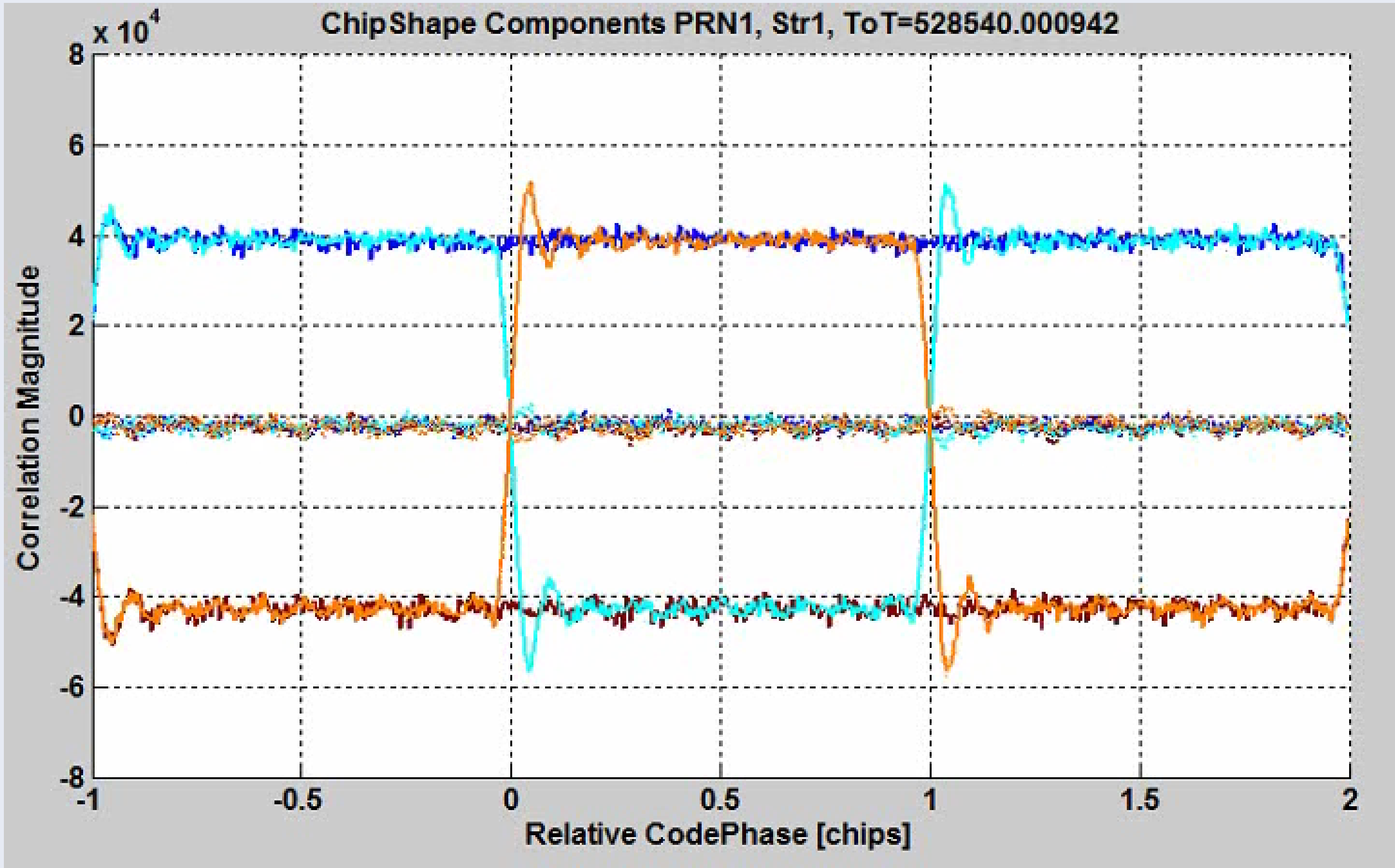
Receiver Type → Design Parameters ↓	Mass Market / Consumer	Aviation Grade / Machine Control	Geodetic / Reference Station
Carrier Tracking Architecture	None (A-GNSS) FLL (standalone GNSS)	FLL-assisted PLL or PLL (inertial aiding)	PLL (ephemeris aiding)
Code Tracking Architecture	None (A-GNSS) carrier-aided DLL (standalone)	carrier-aided DLL	carrier-aided DLL
Multipath Mitigating Technology	none	Narrow-correlator Double-delta correlator	Narrow-correlator Double-delta correlator Multi-correlator estimation
Typical Early-Late Correlator Spacing (GPS L1 C/A Chips)	1.0	0.3-0.1	0.1-0.01
Inter-Channel Pseudorange Bias Correction (Primarily for GLONASS)	None OR Model-wide calibration table	Device-specific calibration table (part of device testing and qualification process)	Dynamic calibration
Other features	Massive banks of parallel correlators for ‘flash acquisition and long coherent integration	Dynamic multipath estimation and mitigation	Interference and signal deformation monitoring
Typical Implementation (2015)	System on chip (SOC) ASIC with integrated RF and baseband (standalone)	2-ASICs (RF + Baseband) Single SMD module or card	Front-end: RFIC-based Baseband: ASIC or FPGA + embedded processor
Power consumption and Cost	<2 W < $3	<20W $300-$3,000	>30W $6000-30,000

OVERVIEW

- Receiver Considerations for High-Accuracy Applications
  - Nominal Signal Deformation
  - Front-End Component Effects
  - Multipath
  - In-Band Interference: detection and mitigation
- Extension to GNSS
  - GLONASS inter-channel biases
  - High-Accuracy GNSS Receivers: what to expect in coming years

Nominal Chip Shapes of Live Sky GPS-SPS Signals



GPS-SPS Nominal Signal Deformation

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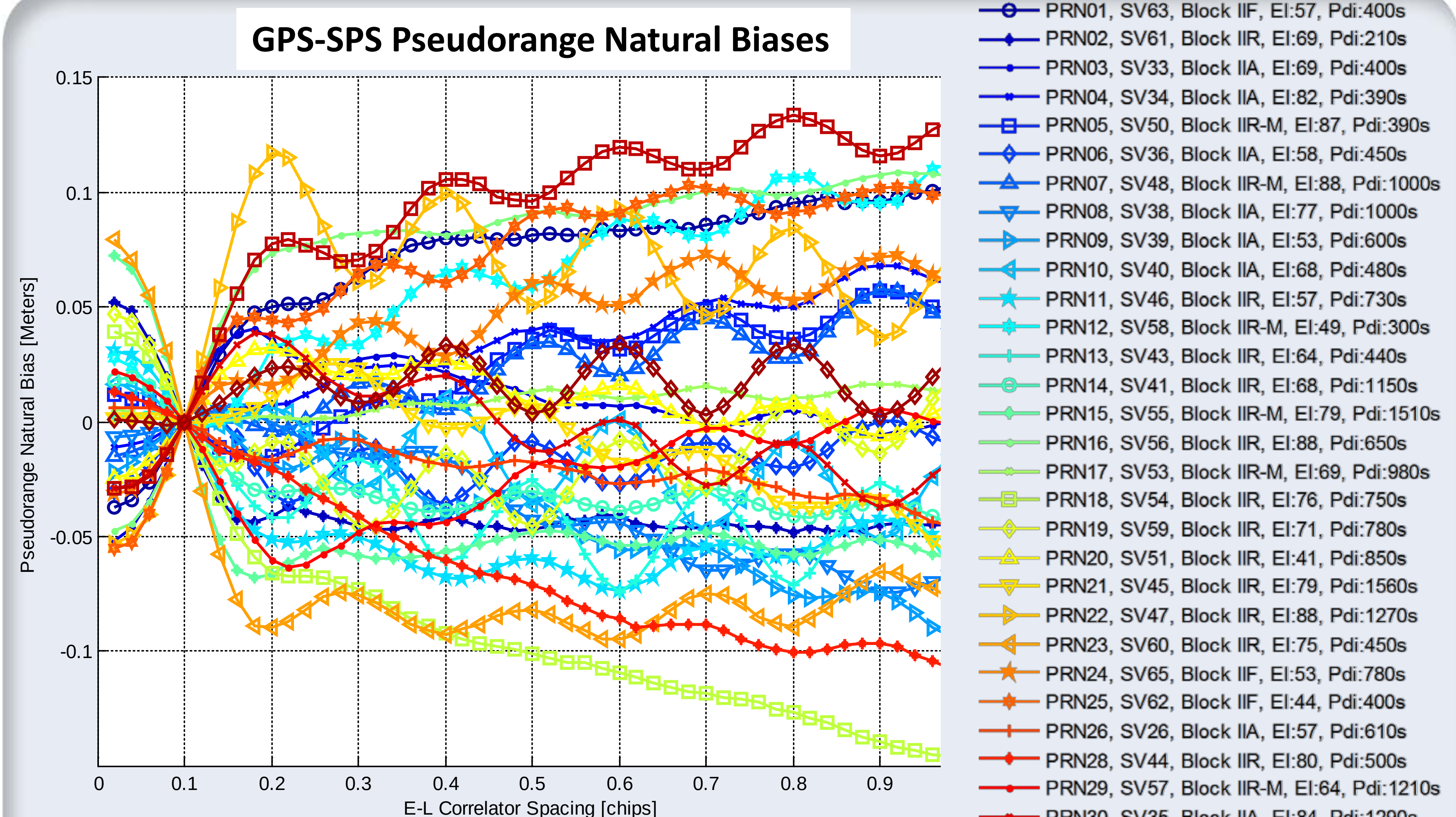
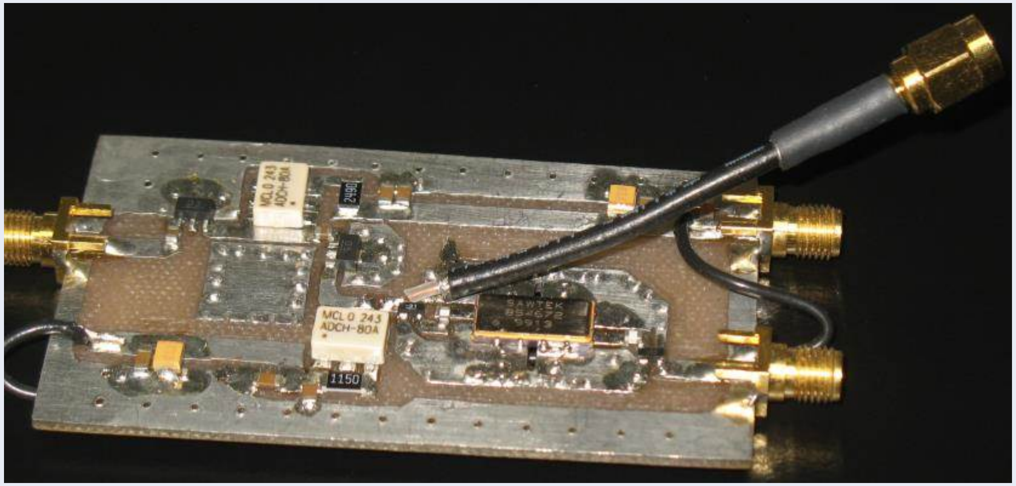


cm-level errors for differential GPS users using dissimilar receivers

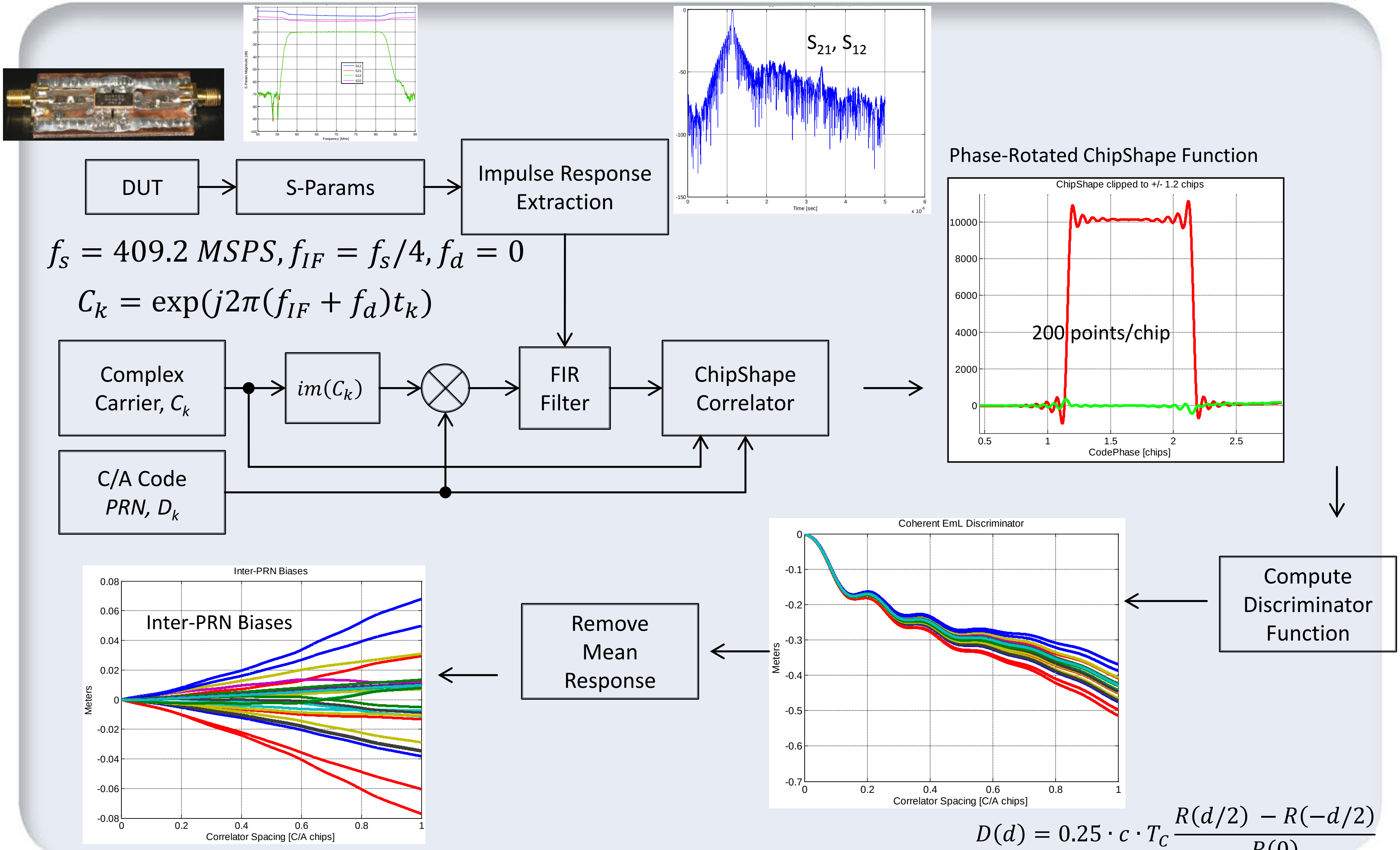
IF Filter Analysis: Transversal SAW vs LC Filters

TriQuint SAWTEK 854672, f_c: 70 MHz, BW_{3dB}: 24 MHz



6x Mini-Circuits SBP 70+, f_c: 70 MHz, BW_{3dB}: 18 MHz

Component Effects: Processing Overview



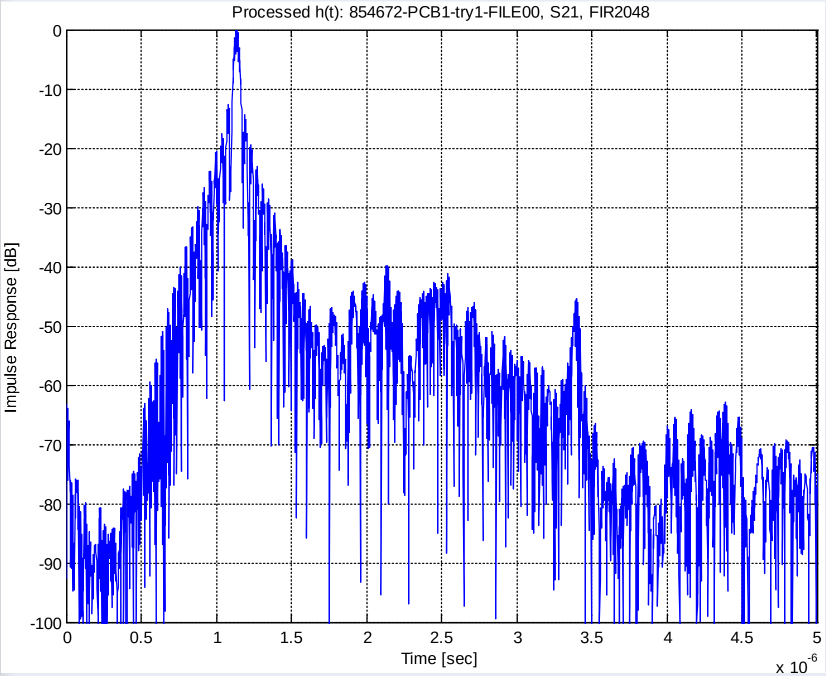
$$f_s = 409.2\ MSPS, f_{IF} = f_s/4, f_d = 0$$

$$C_k = \exp(j2\pi(f_{IF} + f_d)t_k)$$

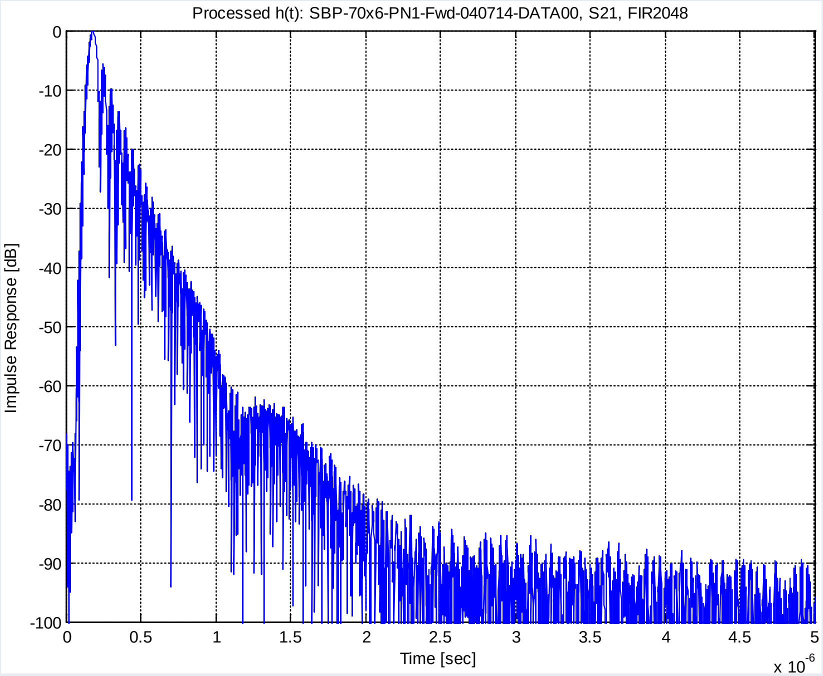
$$D(d) = 0.25 \cdot c \cdot T_C \frac{R(d/2) - R(-d/2)}{R(0)}$$

Impulse Response: Transversal SAW vs LC Filters

Transversal SAW

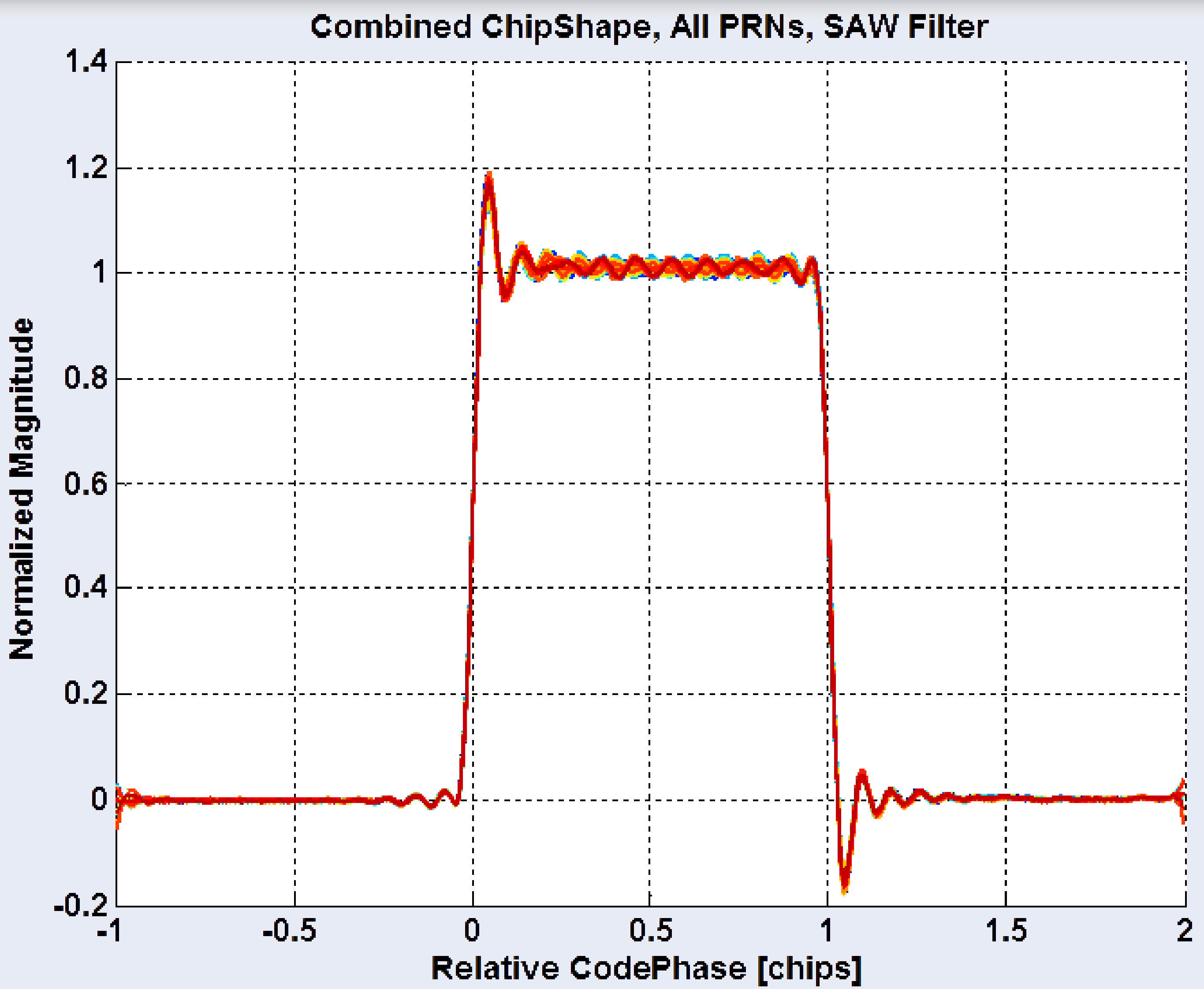


LC Elliptic Response



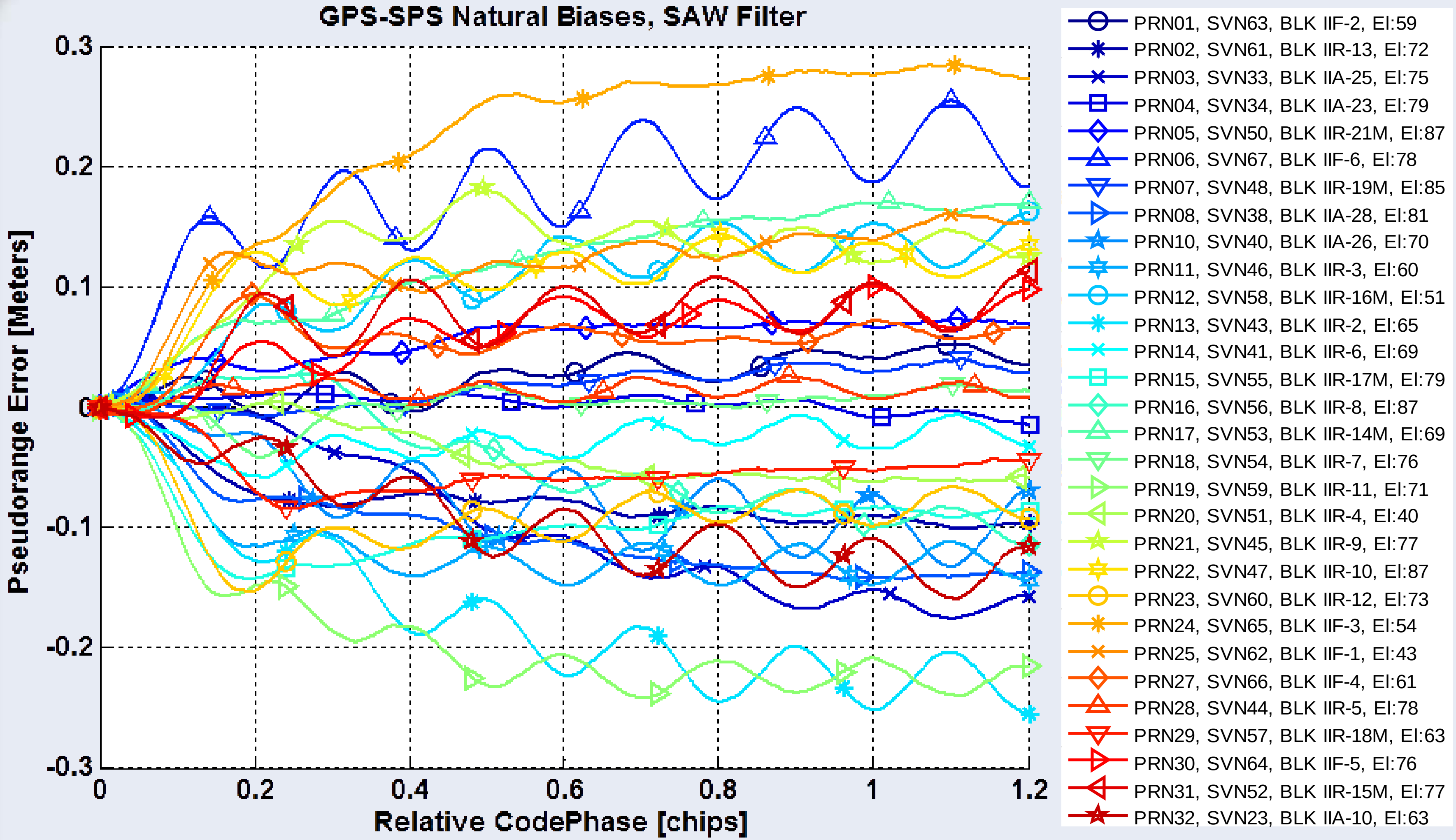
$R'(\tau)$ for SAW and LC Filters

for all PRNs, $T_{pdi} = 600\ sec$



GPS-SPS Natural Biases

w.r.t. d=0.002, $T_{pdi} = 600\ sec$

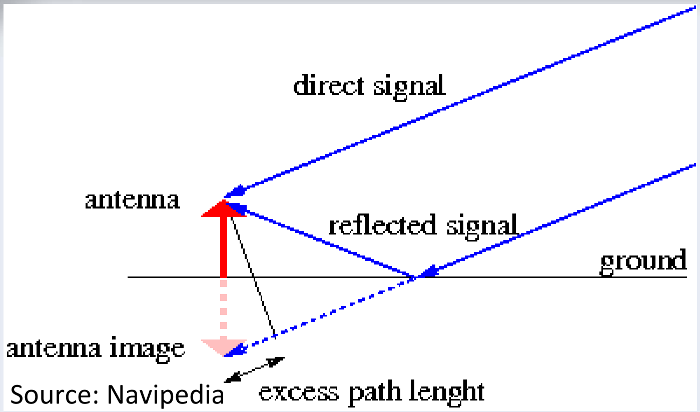


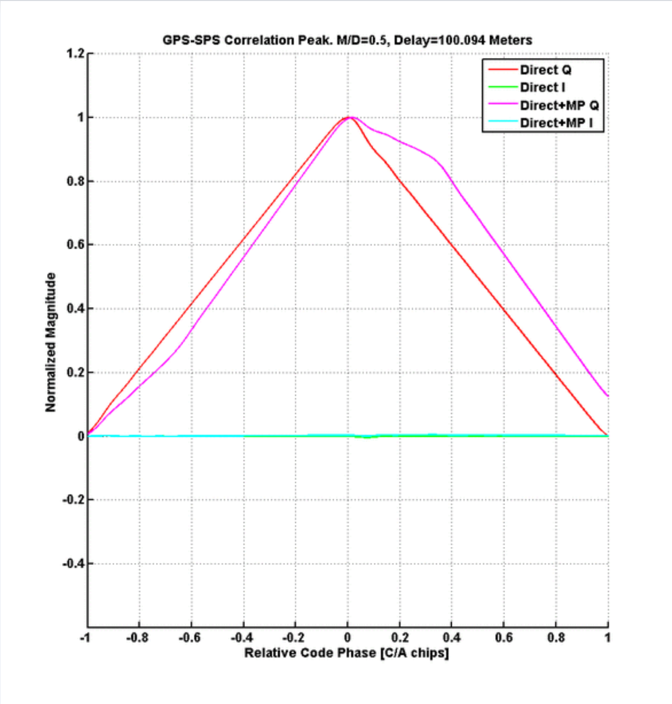
Gunawardena & Van Graas, "GPS-SPS Inter-PRN Pseudorange Biases Compared for Transversal SAW and LC Filters Using Live Sky Data and ChipShape Software Receiver Processing," *ION ITM 2015* measured device-to-device GPS-SPS pseudorange variation and inter-PRN biases for various filter types used in GNSS receivers

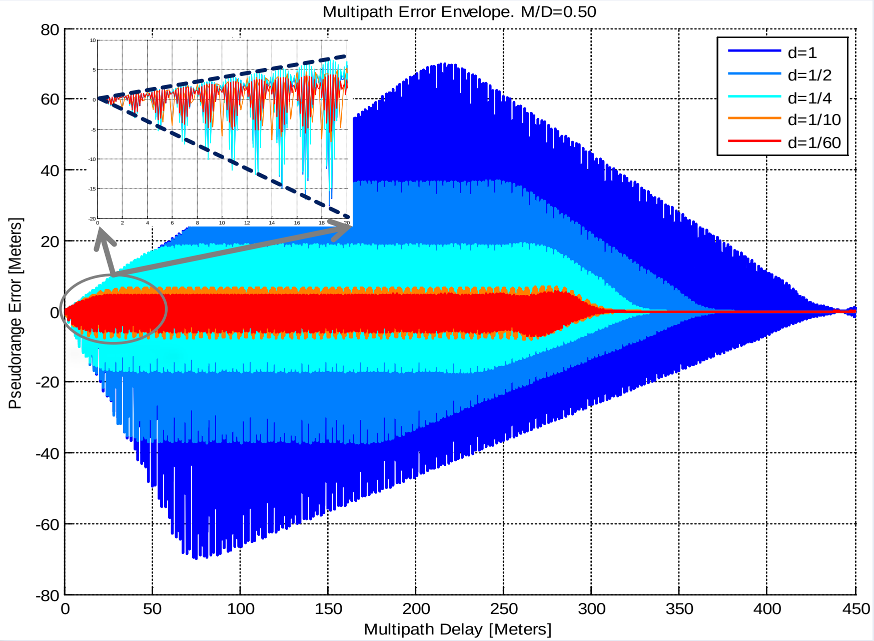
Filter: 3 dB BW & Type	#Devices Tested	Device-device variation [cm]		Inter-PRN bias [cm]	
	corr. spacing->	0.1	0.3	0.1	0.3
24 MHz L1 6-pole Cavity	1			<0.12	<0.12
20 MHz L1 3-pole Ceramic	2	<1.0	<5.0	<0.12	<0.12
40 MHz L1 BAW	2	< 20	< 70	<0.06	<0.12
24 MHz IF SAW	3	< 20	< 30	< 4.0	< 8.0
20 MHz IF SAW	5	< 12	< 30	< 1.5	< 3.0
16 MHz IF LC	2	<10	<20	<0.20	<0.30

Gunawardena & Van Graas, "Analysis of GPS-SPS Inter-PRN Pseudorange Biases due to Receiver Front-End Components," *ION GNSS+ 2014*

Multipath







- Narrowing correlator spacing reduces the effect of correlation peak distortion due to multipath
- Also reduces code measurement error since thermal noise on E and L become correlated (but reduces code tracking threshold)
- To reduce E-L spacing, need sufficient bandwidth to prevent top-rounding of correlation function
- More advanced techniques in use: MEDLL MET, PAC™, Strobe™ Enhanced Strobe™, double-delta
- Mitigating short-delay multipath (<15m) is still challenging

Multipath Error Envelopes (M/D = 0.5)

- 'Wide' 1 chip Early-minus-Late
- 1992: 'Narrow' 0.1 chip Early-minus-Late
- 1994: Multipath Eliminating Technology (MET™)
- 1999: Pulsed Aperture Correlator (PAC™) (double-delta)

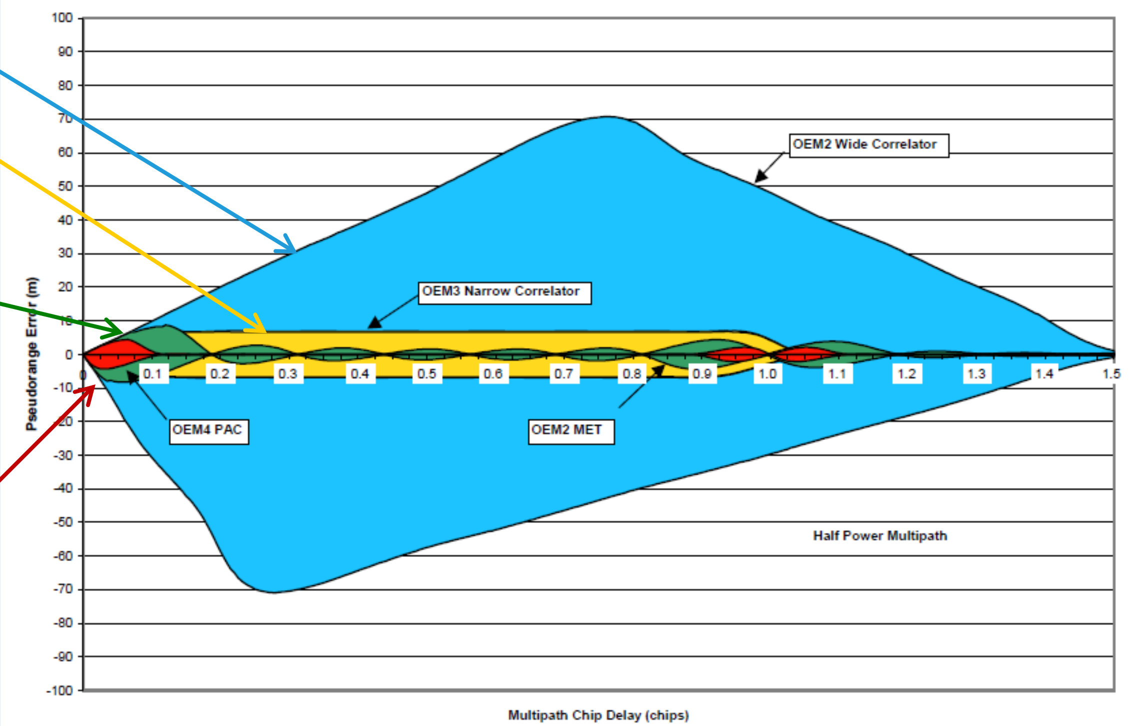
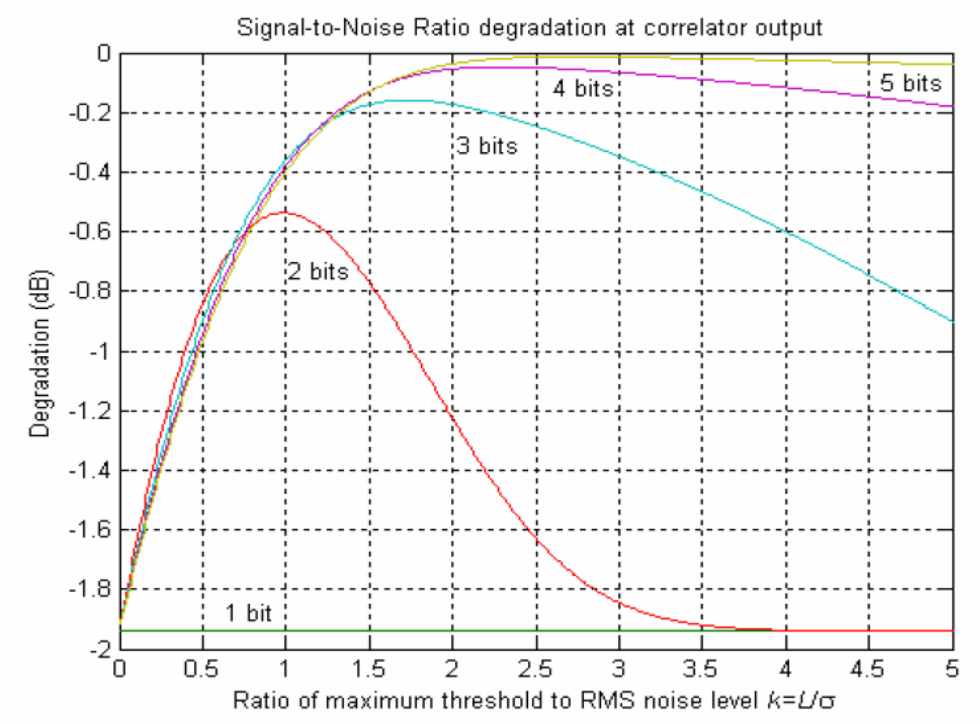


Figure 12: Comparison of multipath error envelopes

Jones, Fenton & Smith, "Theory and Performance of the Pulse Aperture Correlator"
http://www.novatel.com/assets/Documents/Papers/PAC.pdf

ADC Quantization Losses: S/N_0 degradation at correlator output in the presence of thermal noise only



Quantizer	1-bit	2-bit	3-bit	4-bit	5-bit
Optimal L/σ	N/A	0.9860	1.7310	2.2910	2.7225
Min Loss (dB)	1.96	0.5369	0.1589	0.0472	0.0138

Ref: Federick. Bastide, Analysis of the Feasibility and Interests of Galileo E5a/E5b and GPS L5 Signals for Use with Civil Aviation, Ph.D. Dissertation, Oct 2004

Non-Uniform ADC Levels and CW Interference Suppression

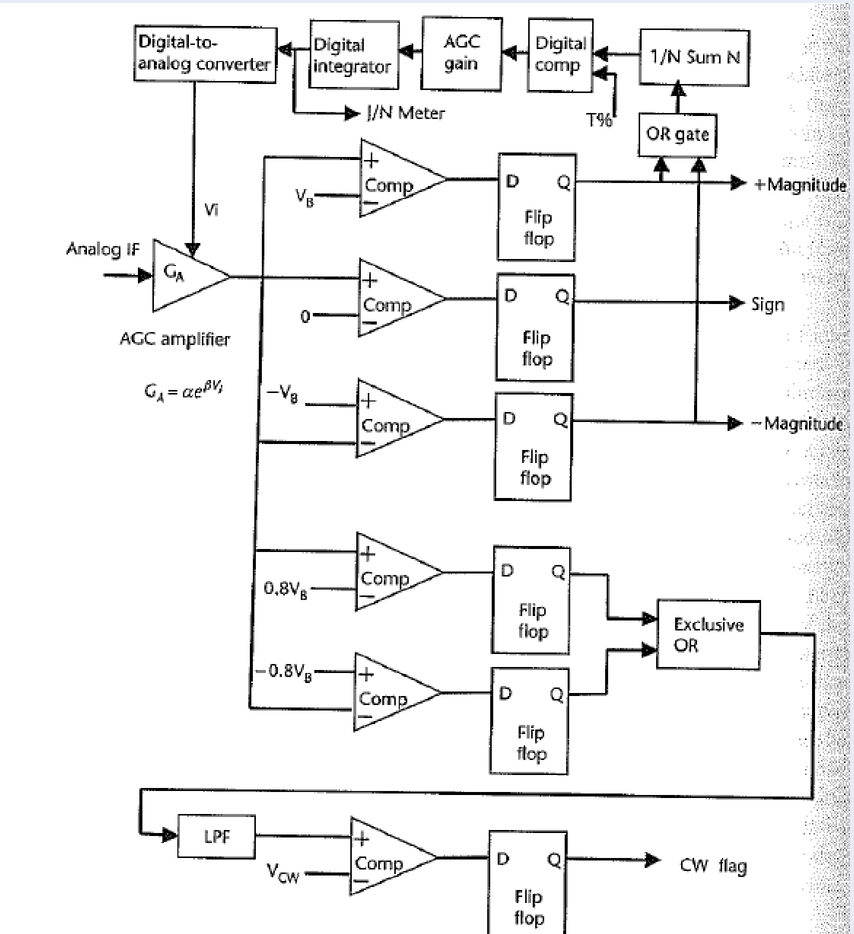


Figure 6.1 AGC amplifier followed by a nonuniform ADC, CW detector, and digital J/N meter.

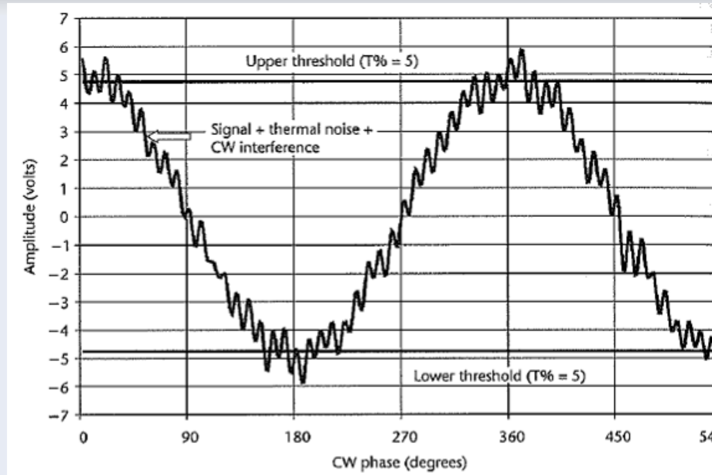
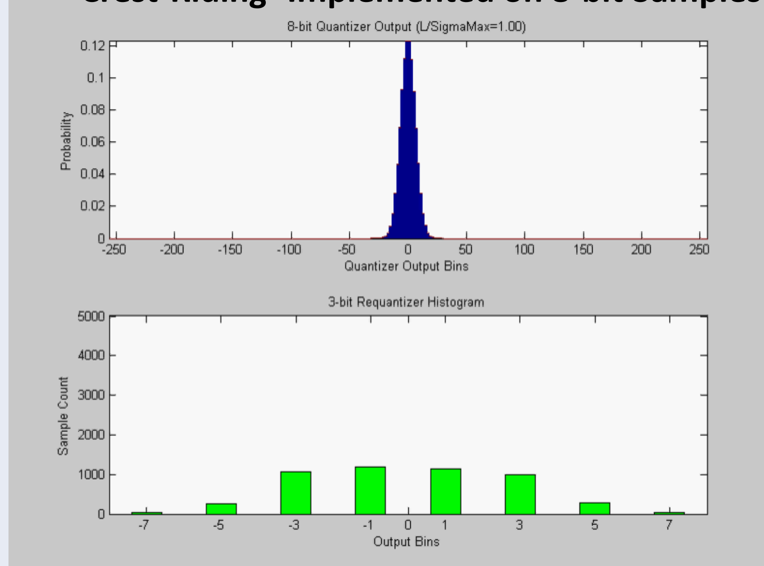


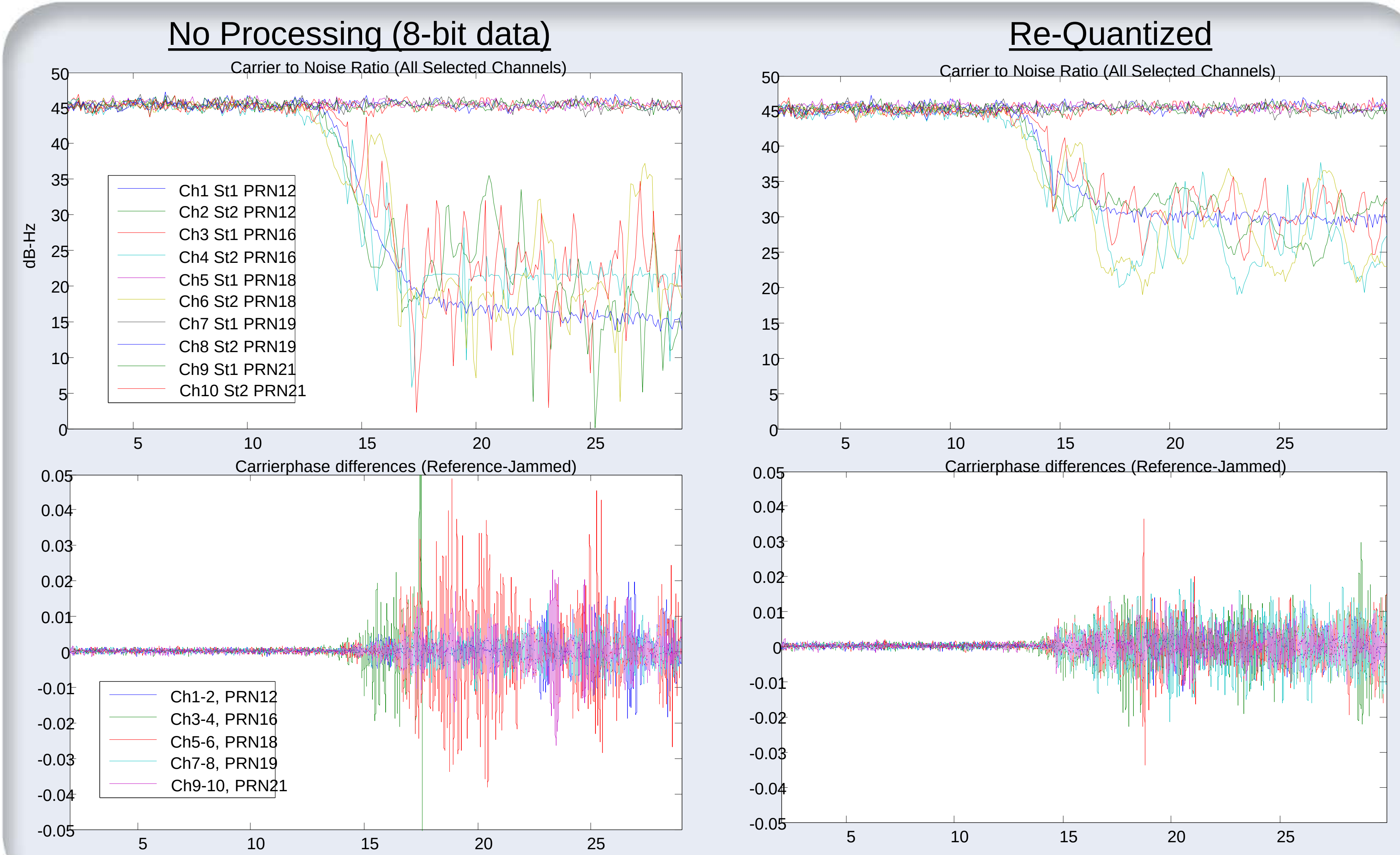
Figure 6.3 Setting nonuniform ADC threshold to exploit constant envelope interference statistics.

'Crest-Riding' Implemented on 8-bit Samples



scanned images from Kaplan & Hegarty, "Understanding GPS: Principles and Applications, Second Edition," Nov. 2005

Digital 'Crest Riding' Re-Quantizer Performance
50 dB ISR Swept FM, 1MHz Span

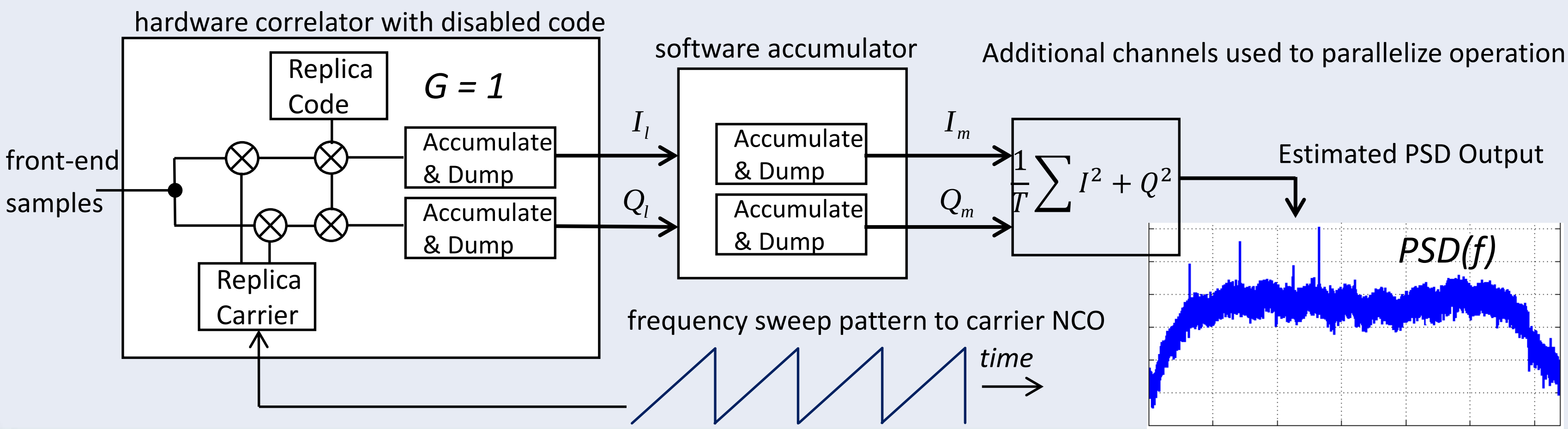


Ref: Gunawardena, et al, Multi-Channel Wideband GPS Anomalous Event Monitor,' ION GNSS 2011

In-Band Signal Situational Awareness Monitoring

Technique	Pros	Cons
AGC voltage monitoring as an indicator of in-band interference	• Free indicator (already exists in most receiver front-ends) • Can be used to activate other situational awareness indicators	AGC voltage changes due to temperature variations and antenna orientation → false alarms
Dedicated sample variance and FFT processing blocks	Dedicated/direct estimators of in-band power and spectrum for reporting GNSS band quality	Requires integration into new receiver designs. Needs dedicated resources. Increased power consumption
Swept-Frequency PSD estimator using one or more existing receiver channels	Can be implemented on existing receivers (one or more spare channels). Frequency resolution adjustable via pre-detection integration time	Cannot observe 'instantaneous' spectrum; may misrepresent pulsed interference; consumes receiver channels

Low-Cost Swept-Frequency Spectral Situational Awareness Monitor using Spare Channel(s)



More on GPS PPP

Sunil Bisnath
Associate Professor
York University

PPP CONCEPT IN RELATION TO POINT POSITIONING

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Standard Positioning Service

m-level real-time **broadcast** GPS orbit and clock information

+

User GPS satellite C/A-code tracking information

+

Epoch measurement filtering

=

m-level user position estimate

Precise Point Positioning

cm-level real-time or post-processed **precise** GPS orbit and clock information

+

User GPS satellite L1/L2 code and phase tracking information

+

Sequential measurement filtering

+

Additional error modeling

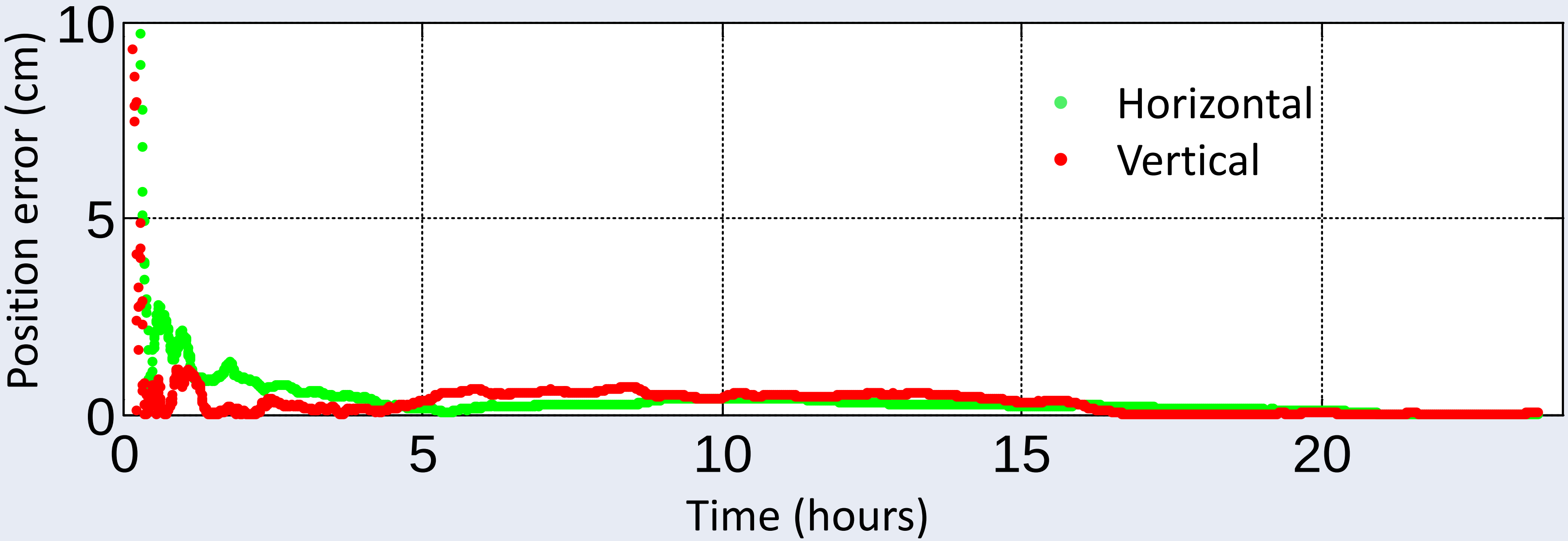
=

dm- to mm-level user position estimate

DIFFERENCES BETWEEN PPP AND (NETWORK) RTK

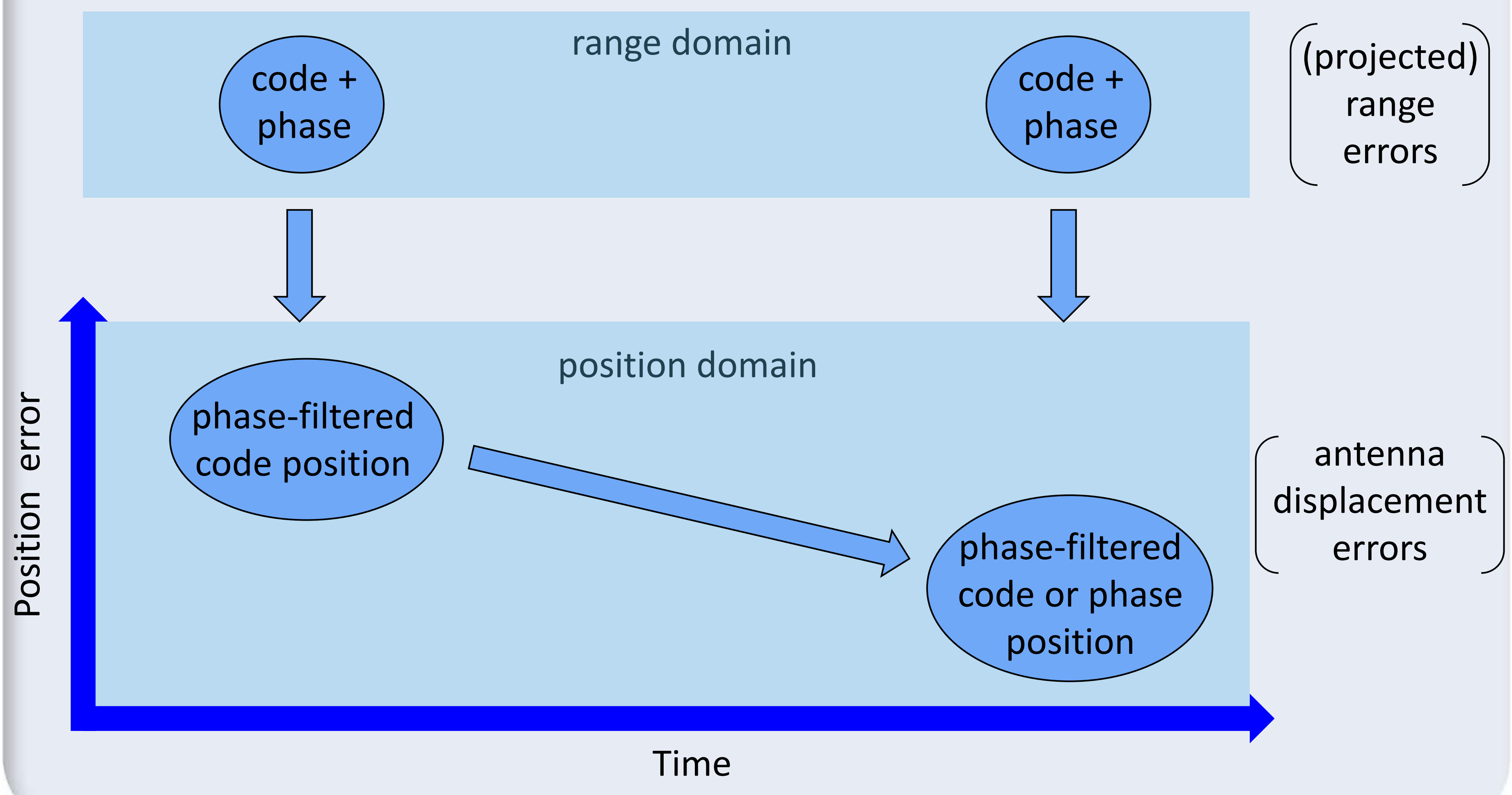
ASPECT	PPP	RTK / NETWORK RTK
Coverage	Global	Local / regional
Range limitation	None	Baseline / network
Positioning accuracy	dm - mm	cm - mm
User hardware	Single geodetic receiver	Single geodetic receiver
Infrastructure	Global CORS network	Single CORS / regional CORS network
Corrections	GPS orbits and clocks	Single CORS measurements / CORS measurements; orbit and atmospheric corrections
Communications	Satellite; Internet; post-processing	Radio / cellular
Major limitation	Convergence period	Range

- A good, static GPS PPP positioning solution over 24 hours

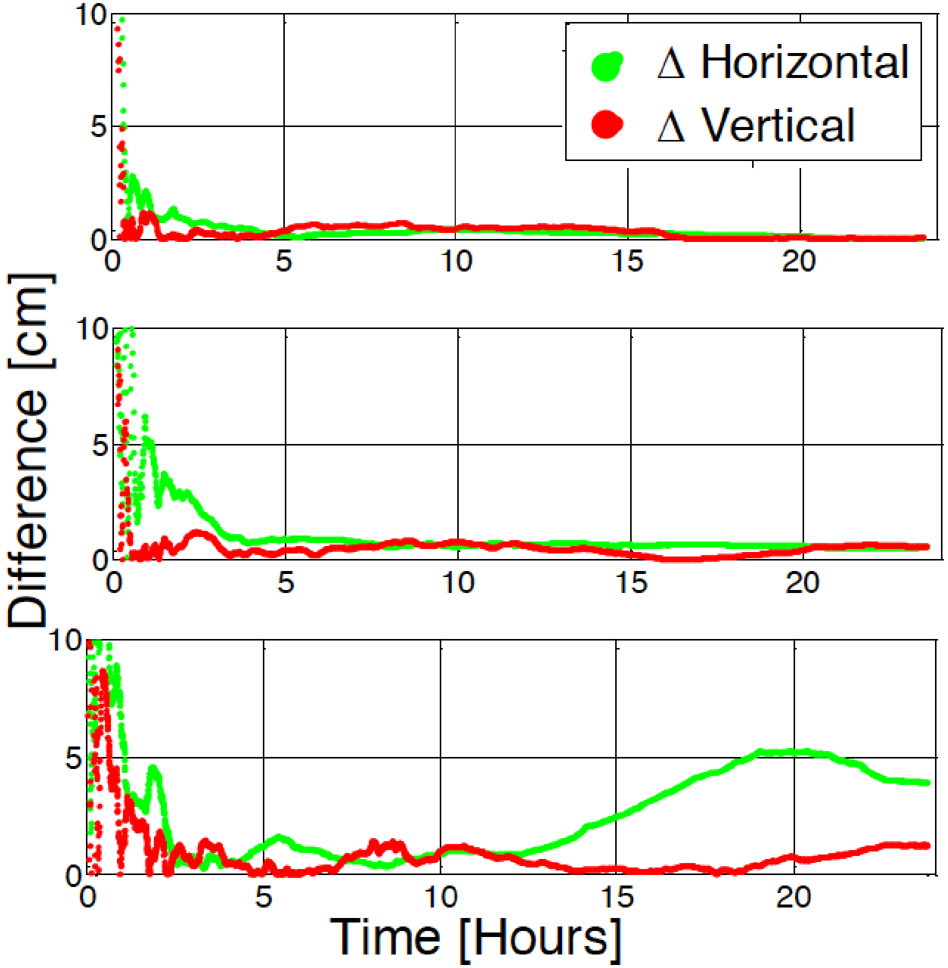


- Characteristic PPP initial convergence period
- Solution very stable post-convergence
- Solution gap requires re-convergence as shown

REASON FOR PPP SOLUTION CONVERGENCE



24 hour static solutions



Site : RIGA, ***RIGA*** Above average convergence

Statistic (mm)	2D	Up	3D
Bias	3	3	4
std dev	2	5	5
rms	4	6	7

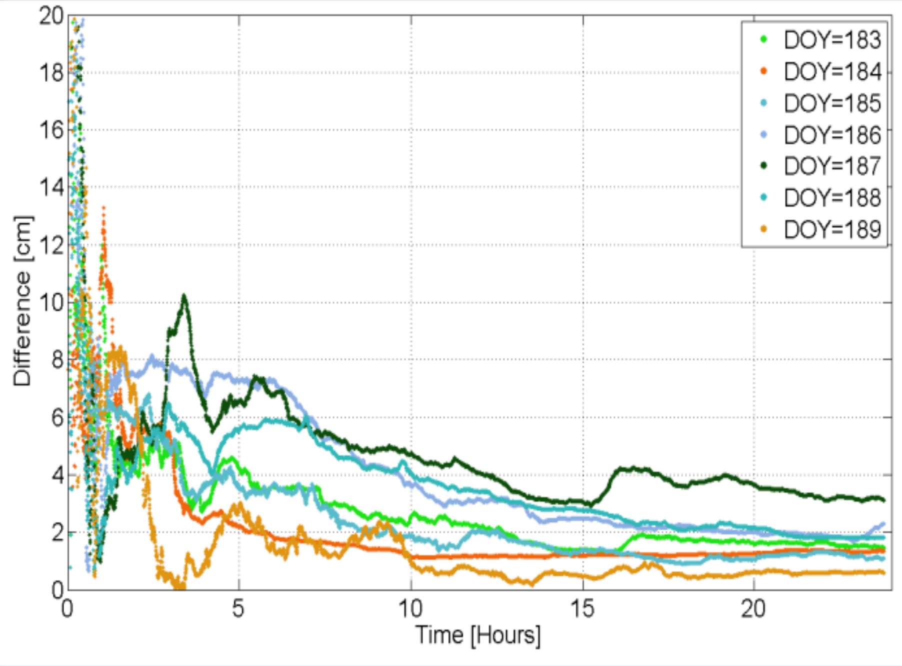
Site : CONT, ***Concepcion*** Typical convergence

Statistic (mm)	2D	Up	3D
Bias	9	-11	14
std dev	2	2	3
rms	9	11	14

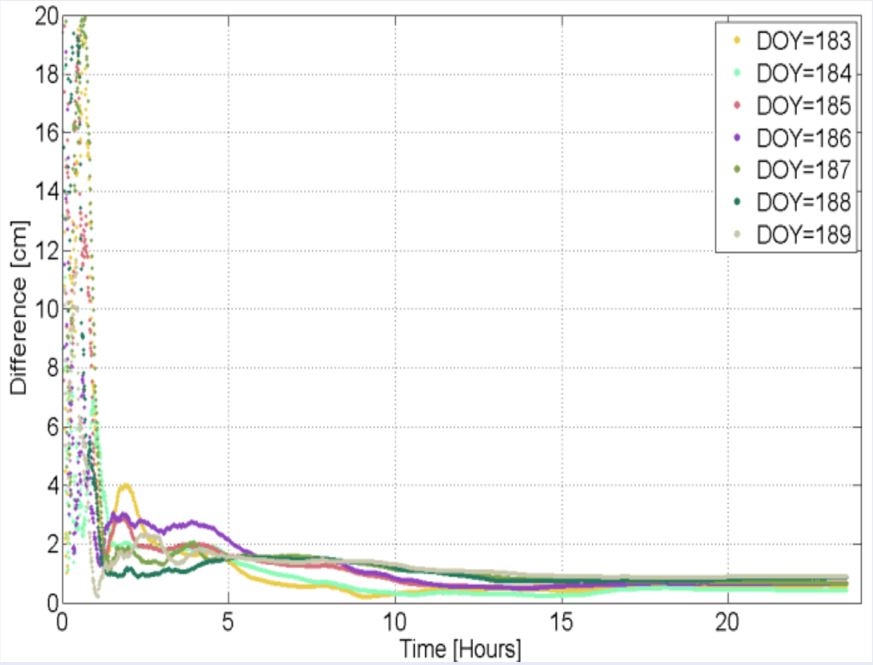
Site : POVE, ***Porto Velho*** Poor convergence

Statistic (mm)	2D	Up	3D
Bias	29	-1	29
std dev	10	10	14
rms	31	26	32

DAILY VARIATIONS IN RATES OF CONVERGENCE



AZU1
Azusa, California

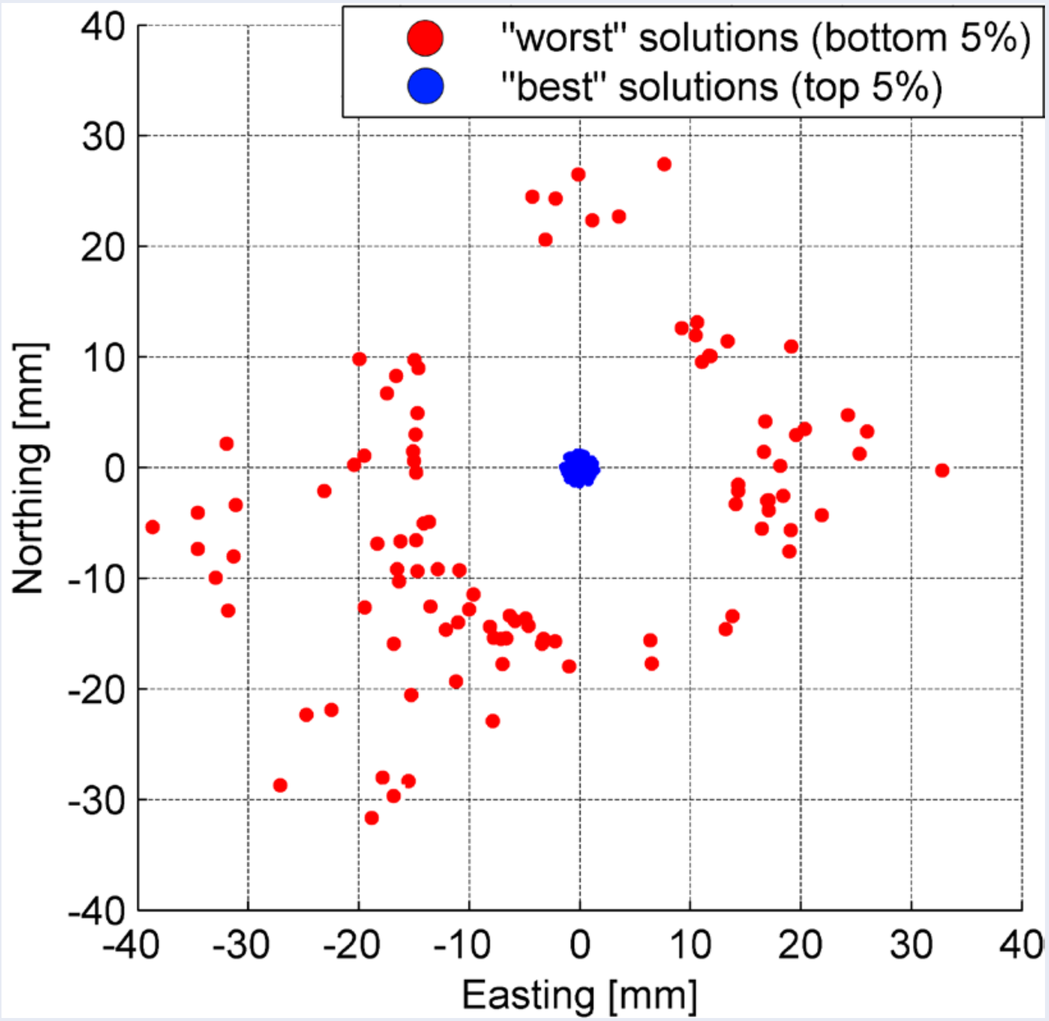


WHC1
Whitter College, California

stations < 10 km apart

(static processing)

DAILY HORIZONTAL PPP ACCURACY



- 1 week, 300 global IGS stations
- Daily position error
- Static processing

- Potential benefits of ambiguity resolution:
  - (Greatly) reduced convergence period
  - Higher positional accuracy
  - More consistent solutions
  - All resulting in more robust processing technique
- Initial attempts at fixed PPP through modeling of small satellite and receiver time mis-synchronization biases resulted in over-parameterization of model:

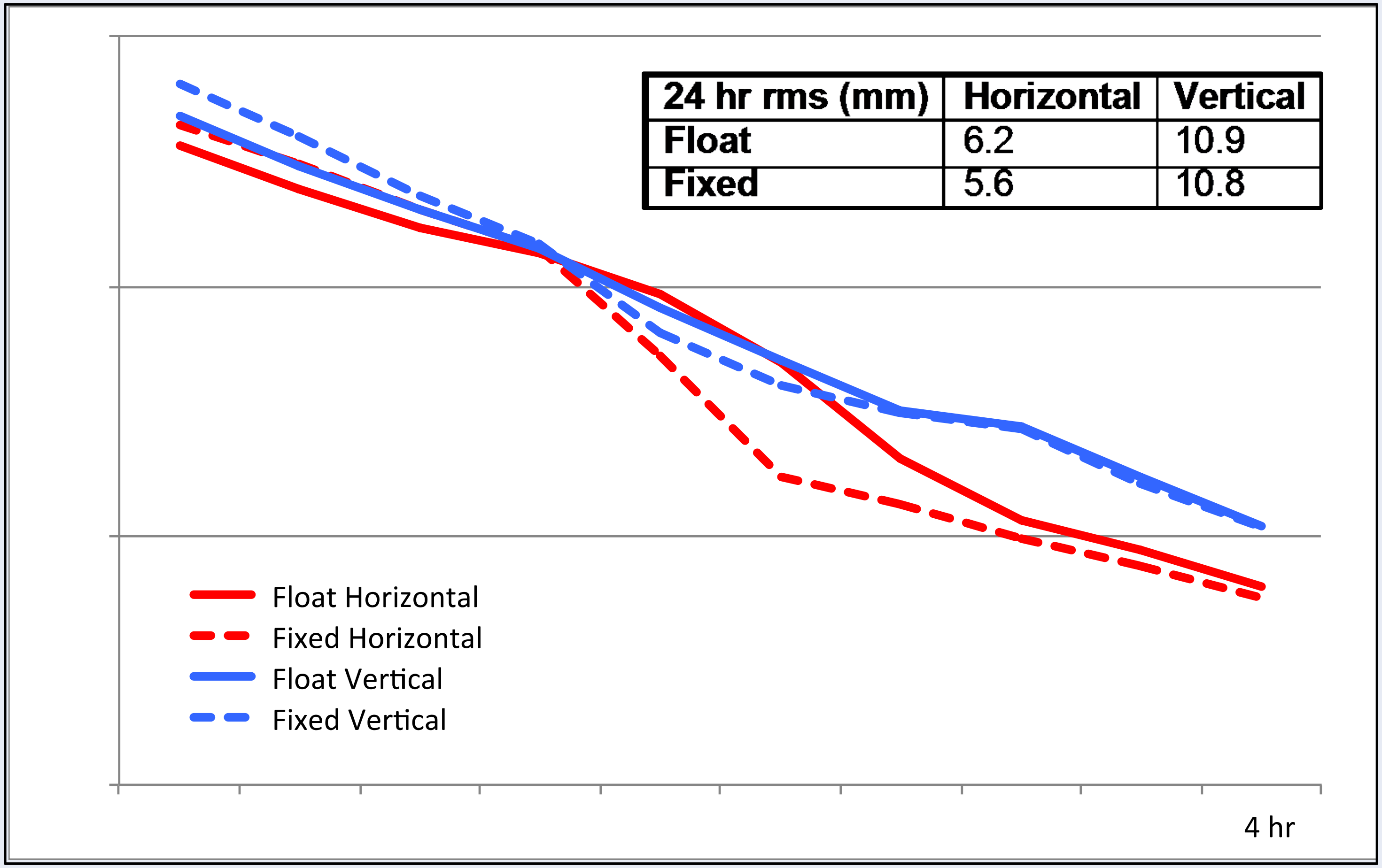
$$P_3 = \rho + T + c(dt^r - dt^s) + b^r_{P3} - b^s_{P3} + \varepsilon_{P3}$$

$$L_3 = \rho + T + c(dt^r - dt^s) + b^r_{L3} - b^s_{L3} - \lambda_3 N_3 + \varepsilon_{L3}$$

- *So question is: How to resolved PPP ambiguities – with no or limited assumptions about timing biases?*

- A few methods nominally equivalent approaches have been developed to resolve PPP ambiguities, e.g.:
  - Decoupled clocks (NRCan)
  - Integer clocks (CNES)
  - Uncalibrated hardware delays (GFZ / Wuhan / Nottingham)
- 'Decoupled clock model' and 'Integer clocks' re-parameterize observation equations to isolate code biases from ambiguity estimates
  - (In principle) permits ambiguity resolution
  - Phase ambiguity moved to phase clock parameters
  - Ionosphere-free wavelength amplified with widelane
- 'Uncalibrated hardware delays' computes offsets relative to IGS clocks to access integer ambiguities via single difference
- All require additional satellite bias products for users, computed from global network solution

PPP-AR RESULTS



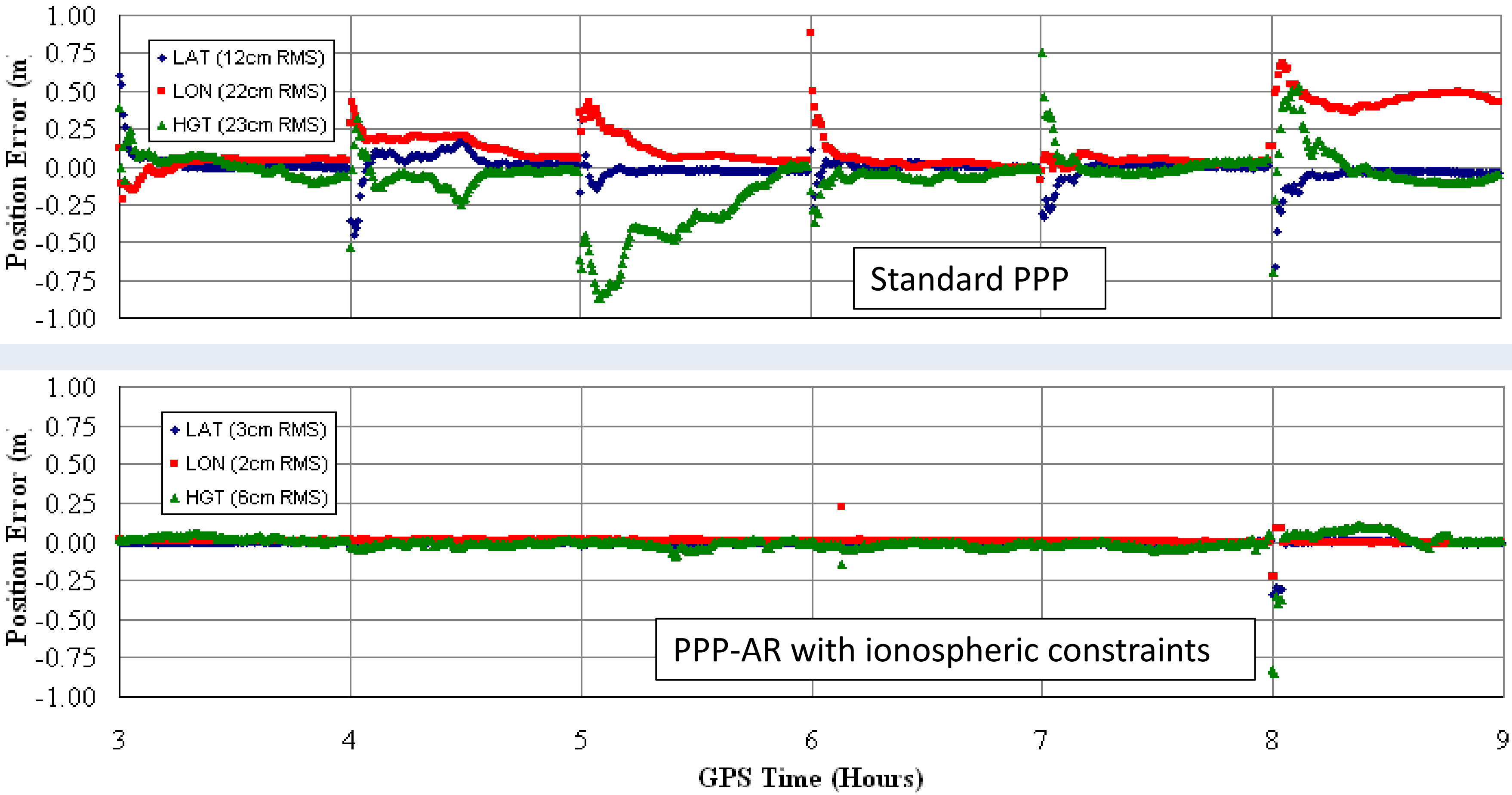
24 hr rms (mm)	Horizontal	Vertical
Float	6.2	10.9
Fixed	5.6	10.8

PPP-AR WITH IONOSPHERIC CONTRAINTS

- Instead of ionospheric-free code and phase, use undifferenced four observables
- Ionospheric parameter is corrupted by biases
- Carry-out implicit differencing to estimate relative ionosphere
- Same way ambiguities are differenced in decoupled clock model to isolate their relative integer character

- Ionosphere parameter can provide constraint on ambiguity resolution when, e.g., loss of lock, data gap, etc. is experienced
- When all ambiguities are reset, should provide rapid *re-convergence* of solution

PPP-AR RE-CONVERGENCE – IONO CONSTRAINTS



Ask the Experts – Part 1

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NovAtel, Inc

Poll #2

Performance wise (accuracy, integrity) which one do you think is true?

- GPS + GLONASS PPP is equivalent to GPS-only PPP.
- GPS + GLONASS PPP is better than GPS-only PPP.
- GPS + GLONASS PPP is worse than GPS-only PPP.
- It is not that simple.

High Accuracy GNSS

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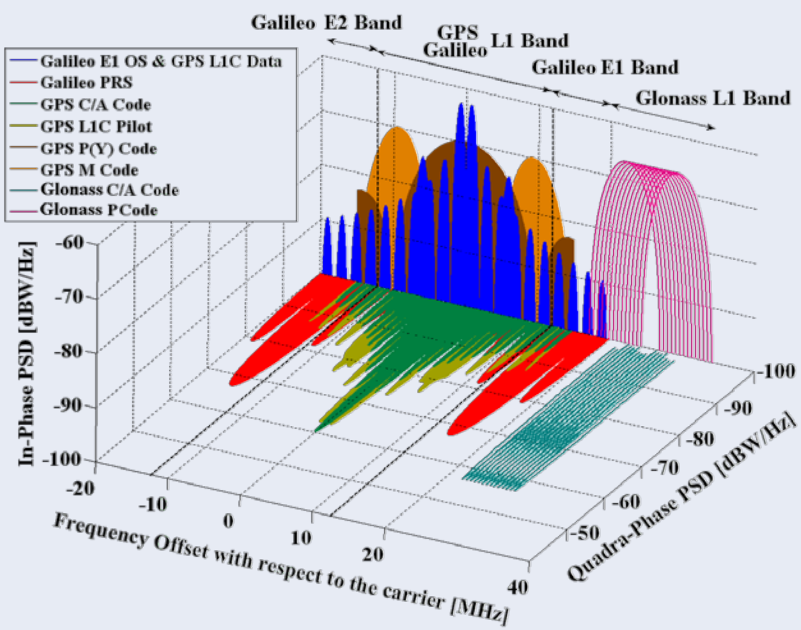
products, services, or the suitability of any products referenced herein
for any particular purpose

Sanjeev Gunawardena
Research Assistant Professor
Air Force Institute of Technology

GLONASS Signals on L1
1598.0625 – 1604.2500 MHz

- Contains standard precision (SP) and high precision (HP) services using FDMA modulation
- L1 center frequency for channel *k*: $f_c=1602+k\times0.5625$ [MHz] where $k=-7, -6, \ldots, 4$ (1598.0625 – 1604.2500)
- P Code: Rc=5.11 Mcps, 33,554,432 chips long, 25-bit LFSR, repeats every second [Kaplan & Hegarty].
- Receiver inter-channel biases due to FDMA represents challenge for receiver designers
- Front-end group delay for each channel must be determined and measurements calibrated accordingly



www.navipedia.net/images/b/b6/GLONASS_Sig_Plan_Fig_3.png

GNSS System	GLONASS	GLONASS
Service Name	C/A Code	P Code
Centre Frequency	(1598.0625-1605.375) MHz ± 0.511 MHz	
Frequency Band	L1	L1
Access Technique	FDMA	FDMA
Spreading modulation	BPSK(0.511)	BPSK(5.11)
Sub-carrier frequency	-	-
Code frequency	0.511 MHz	5.11 MHz
Signal Component	Data	Data
Primary PRN Code length	511	N/A
Code Family	M-sequences	N/A
Meander sequence	100 Hz	N/A
Data rate	50 bps	N/A
Minimum Received Power [dBW]	-161 dBW	N/A
Elevation	5°	N/A

Source:
www.navipedia.net/index.php/GLONASS_Signal_Plan

Relevant public ICD:
- ICD L1, L2 (ed. 5.1 2008)

Also read: U. Roßbach, Positioning and Navigation Using the Russian Satellite System GLONASS, 2001

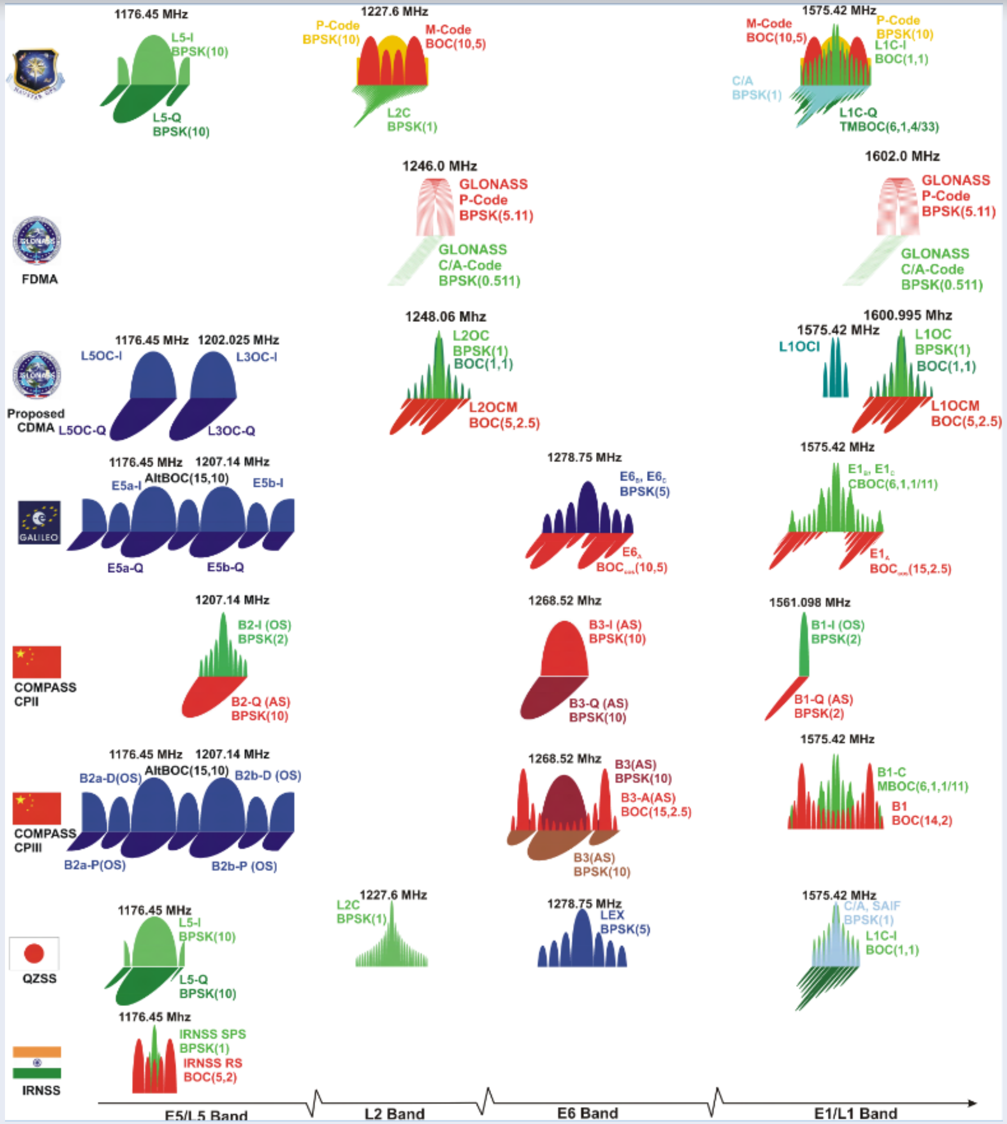
GLONASS Inter-Channel Bias Compensation Techniques

Increasing cost and complexity

Technique	Pros	Cons
One-time factory calibration of nominal biases	Simple, supports mass production	Not sufficient for high-accuracy applications
Factory calibration as a function of temperature. Store calibration values in memory	Suitable for medium-volume cost-sensitive GPS/GLONASS receivers	Requires front-end temperature sensing. Longer and more complex calibration procedure.
Integrated closed-loop calibration using built-in 'group delay meter'	Continuous dynamic estimation of inter-channel biases using group delay measurements	Works primarily for self-contained receivers (i.e. no detached antenna). High cost and complexity.

GNSS 'Spectral Landscape' Present & Future

InsideGNSS
GPS | GALILEO | GLONASS | BEIDOU
NovAtel



Ref: www.navipedia.net/images/c/cf/GNSS_All_Signals.png

GNSS PPP

Sunil Bisnath
Associate Professor
York University

BENEFITS AND ISSUES ARISING IN GNSS PPP

BENEFITS:

- Measurement sensitive technique →
- More measurements **+** varied geometry **=** improved positioning

ISSUES:

- Different spatial reference systems for different systems
- Different temporal reference systems for different systems
- GLONASS is FDMA, while all other systems are CDMA
- Managing various equipment biases within and between systems

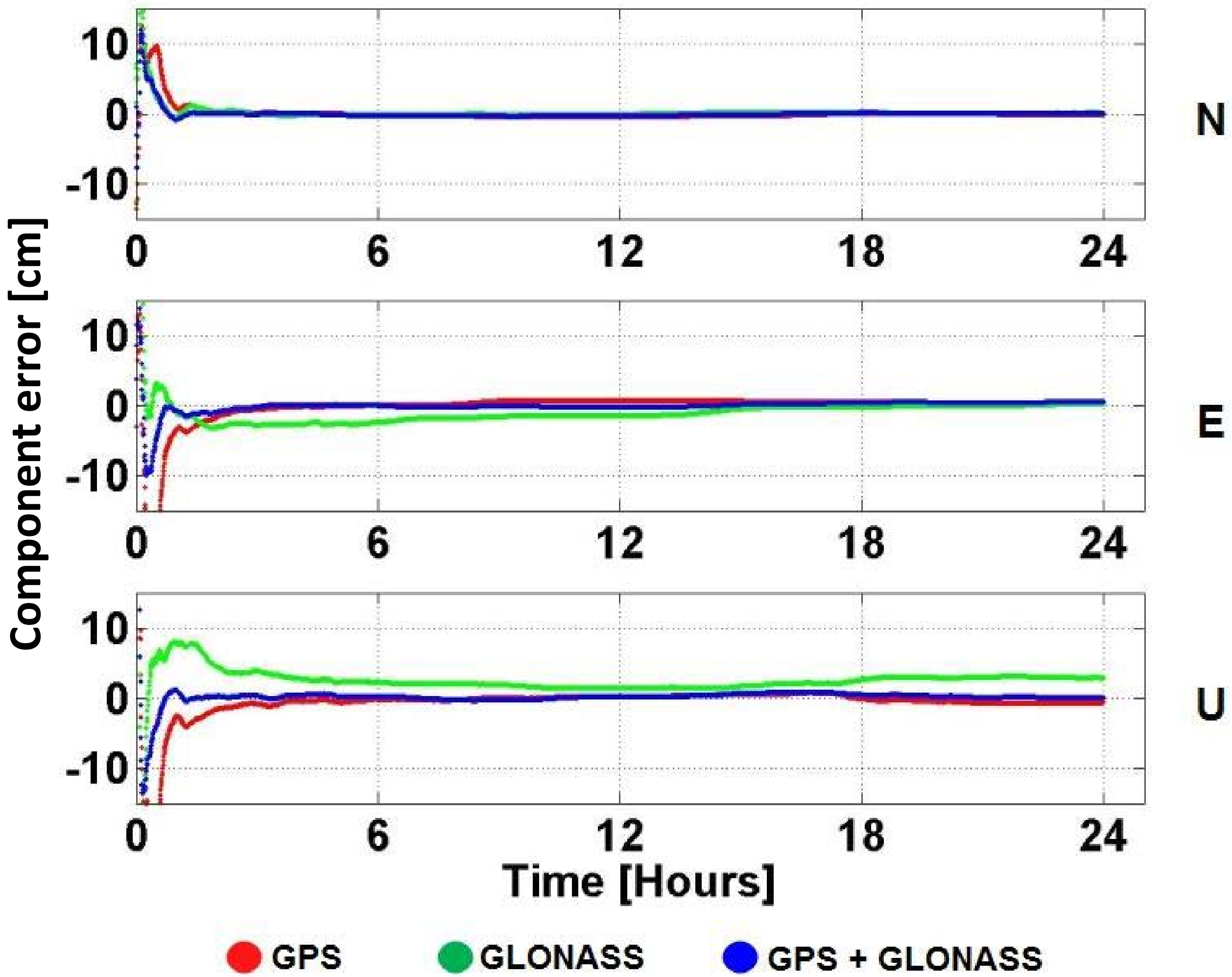
EQUIPMENT DELAYS

- Popular terms: “hardware biases” or “hardware delays” or “instrumental delays”, referring to errors introduced in the equipment (circuitry and electronics)
- Satellite instrumental delays and receiver instrumental delays

- Some delays estimated by tracking network
- Others modeled as an additional term added to code and phase observation equations
- Often implied modeling: added to receiver noise / SV hardware delay / multipath term

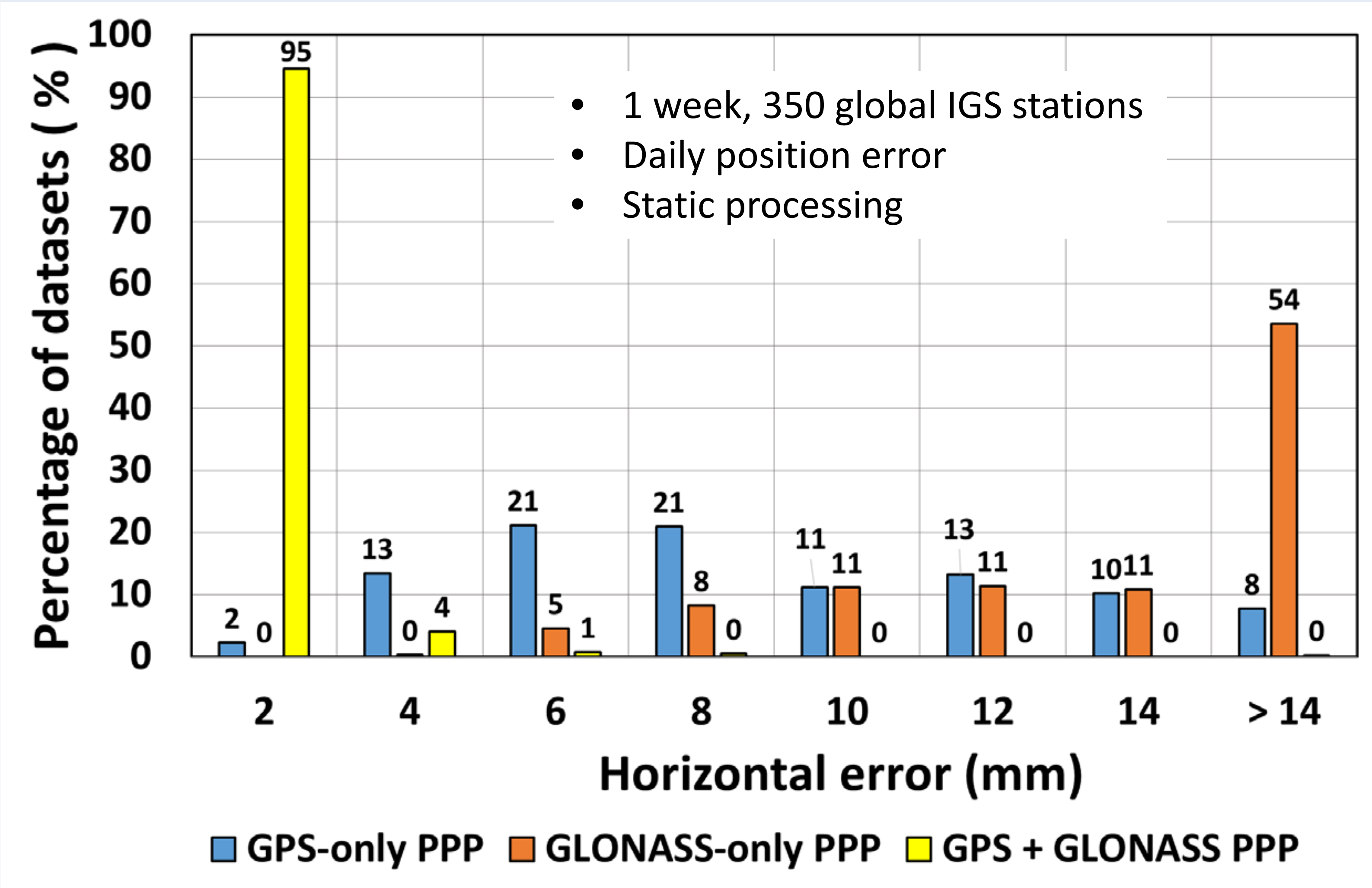
DCB Differential Code Bias	P2–P1
DPB Differential Phase Bias	L2–L1
RCB Relative Code Bias	P1–C1, P2–C2
RPB Relative Phase Bias	L1(P)–L1(C), L2(P)–L2(C)
CPB Code-Phase Bias	C1–L1(C), P1–L1(P), etc.

GPS + GLONASS PPP: CONVERENCE AND STABILITY



(static processing)

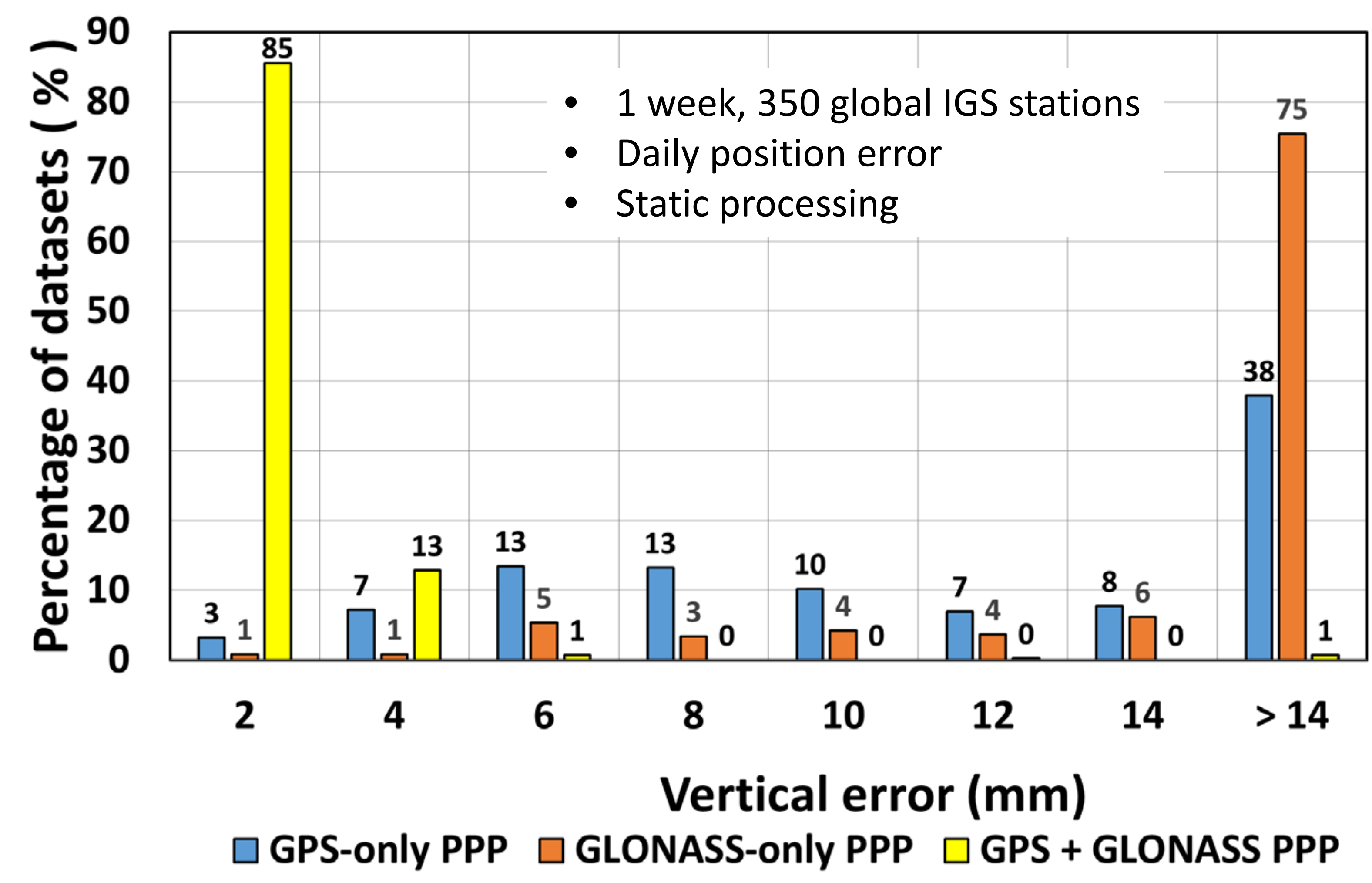
GPS + GLONASS PPP – HORIZONTAL ACCURACY

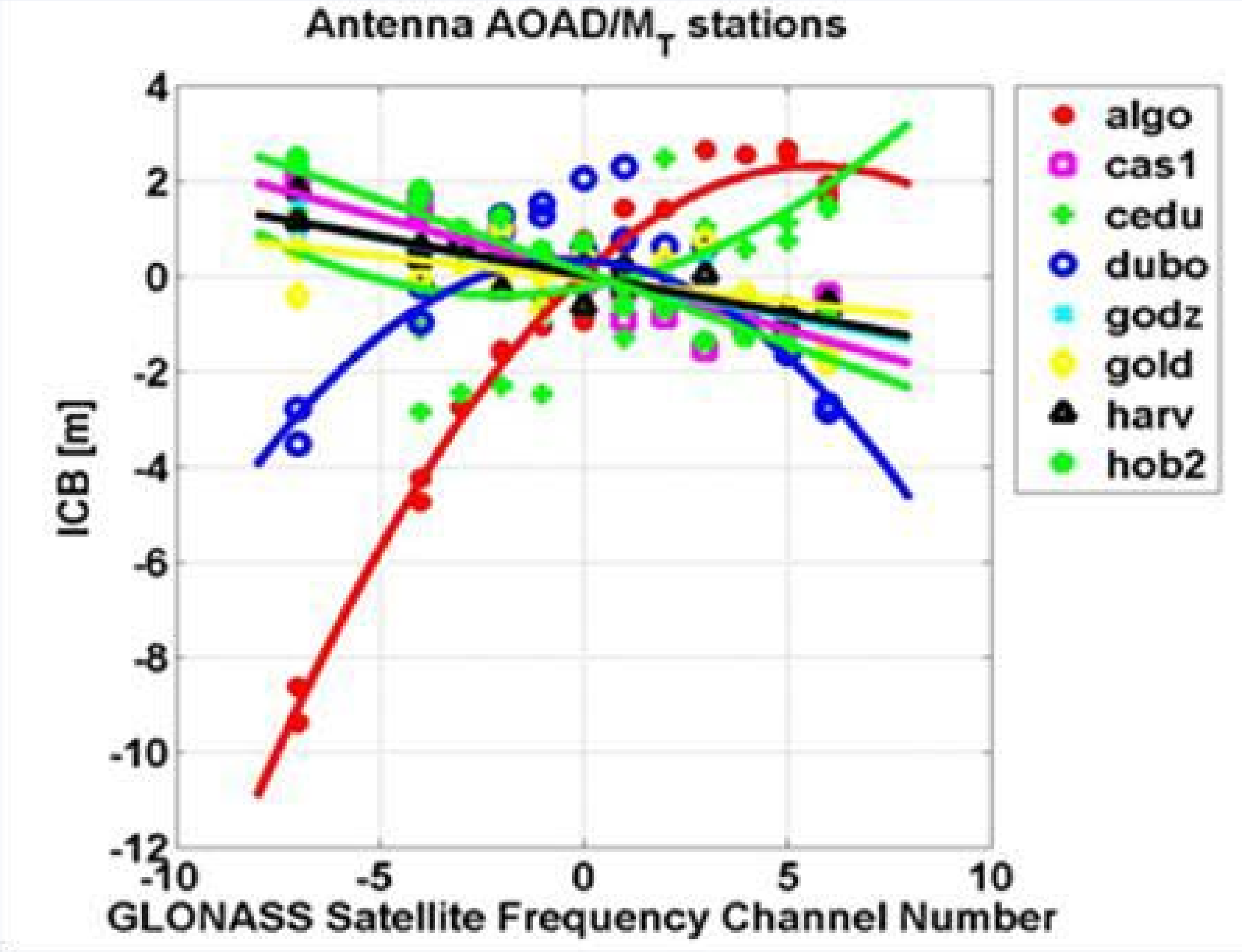


GPS + GLONASS PPP – VERTICAL ACCURACY

InsideGNSS

NovAtel





- Pseudorange ICBs
- 8 stations
- Same antenna types
- Different receiver types and firmware versions

GNSS PPP IN NEAR-FUTURE

- **New GNSS signals enhancing PPP (and RTK) performance**
  - Most network RTK services are now GPS+GLONASS
  - GPS+GLONASS PPP with AR and fast re-convergence commercially available

- ***Fast RTK-like initialization for PPP is still goal***
  - Integration of PPP and network RTK processing
  - Early GPS+GLONASS+BEIDOU+GALILEO PPP results show further improvements
  - Triple-frequency GPS PPP-AR simulations show very fast convergence

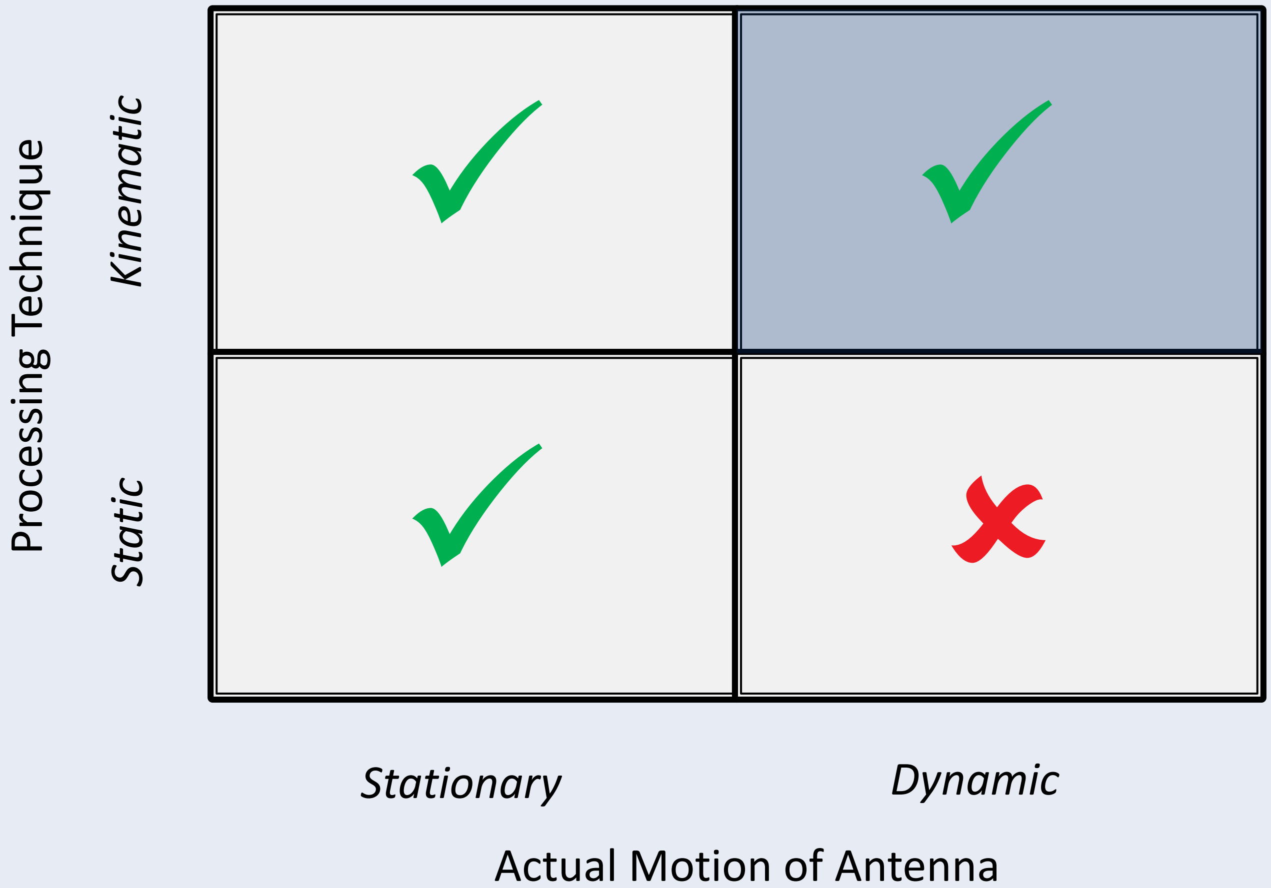
Thomas Morley

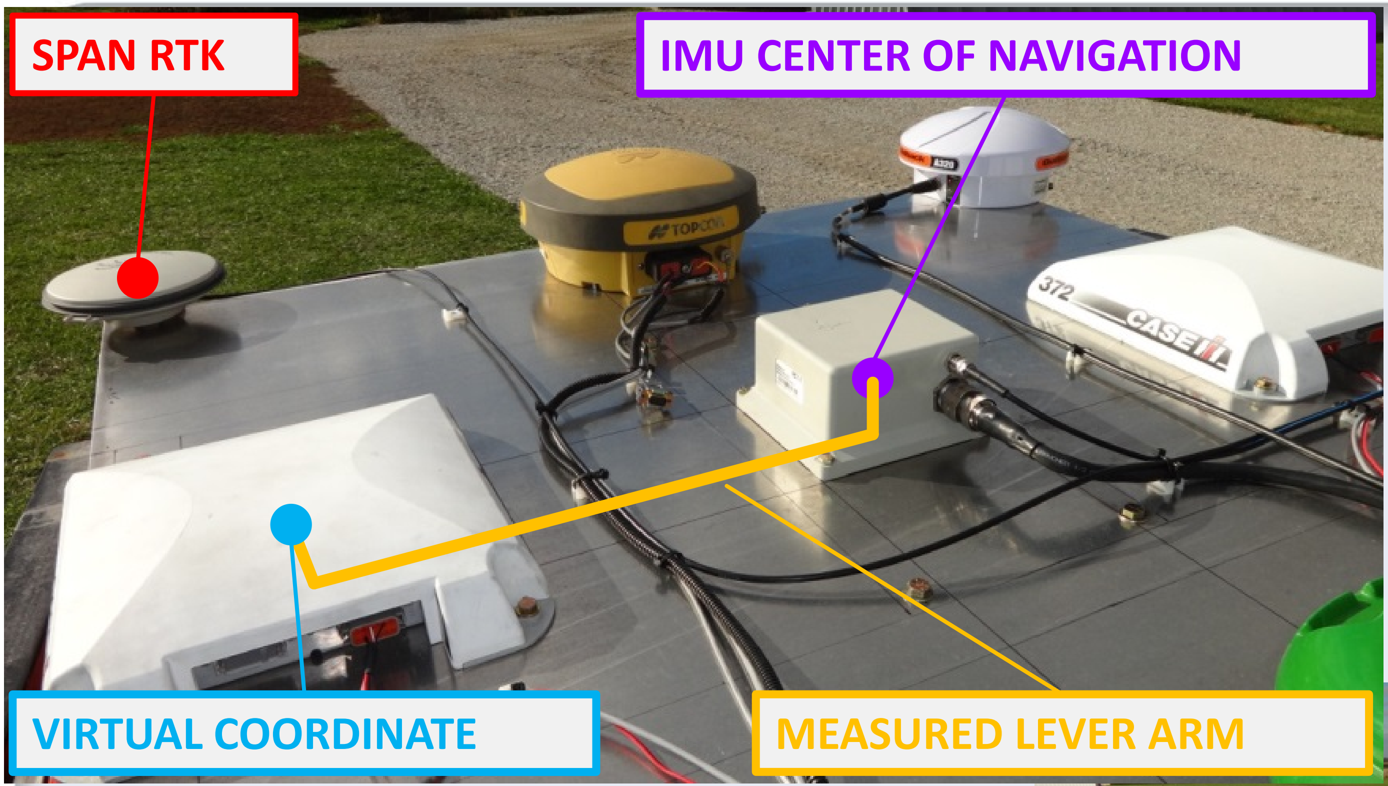
Real World Evaluation of PPP

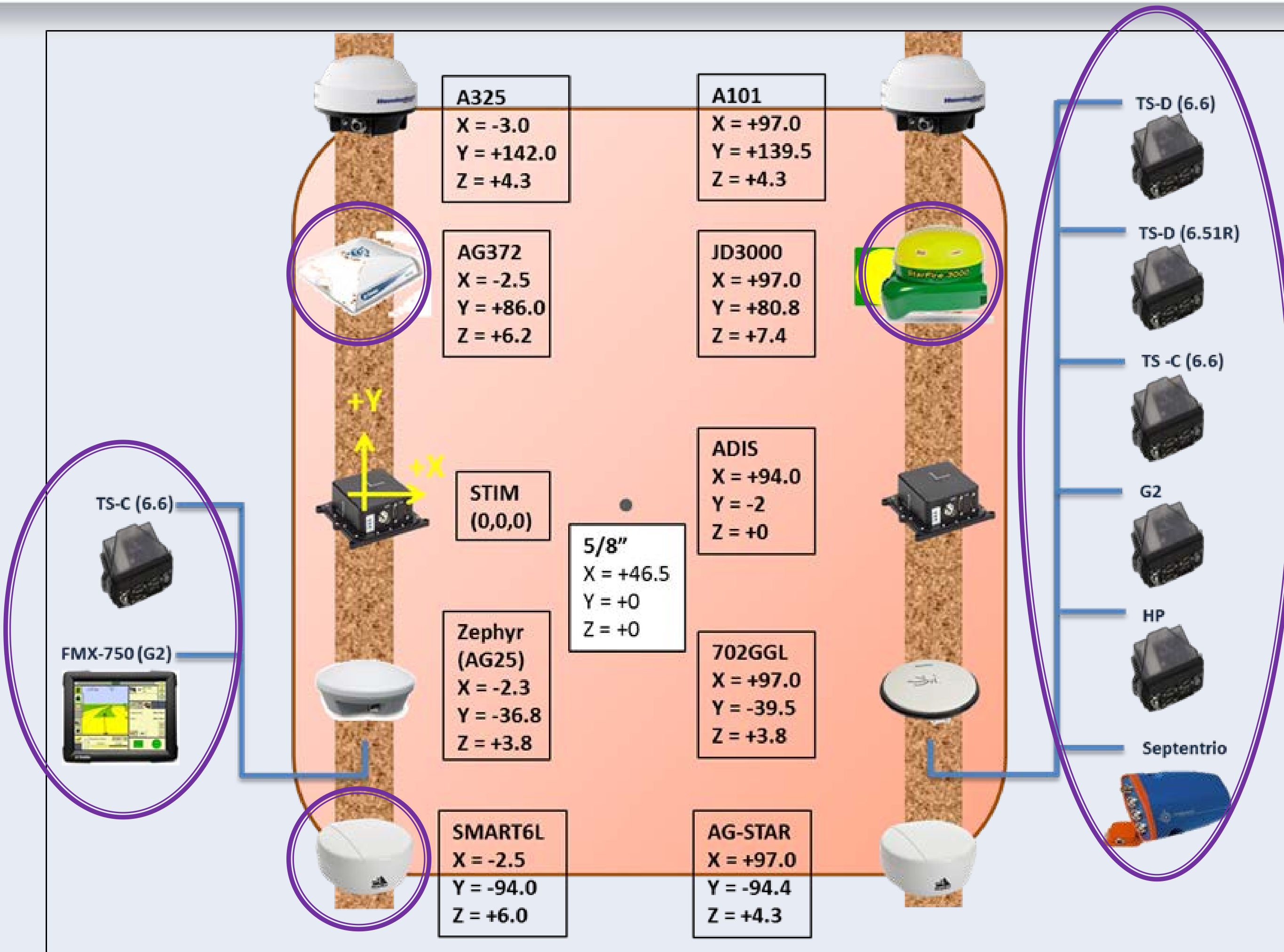
Outline

- Actual antenna motion versus processing technique
- Dynamic evaluation methodology
- Real-world results – dynamic antennas
  - Open sky conditions
  - Operation near trees
    - Partial obstructions
  - Operation near and through a 625m long tunnel
    - Complete obstruction for 30 seconds

Actual Motion and Processing Technique

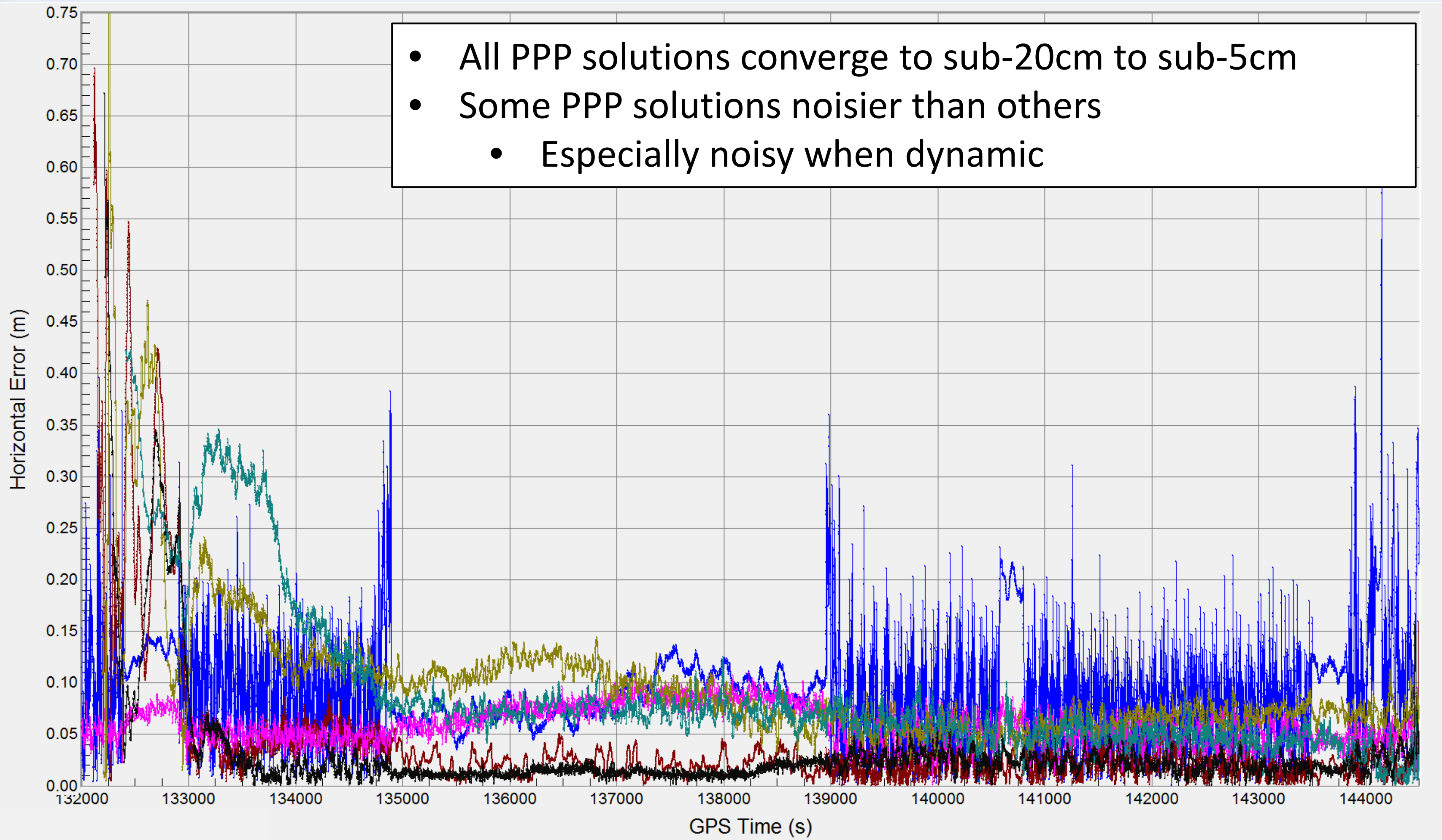



SPAN RTK
IMU CENTER OF NAVIGATION
VIRTUAL COORDINATE
MEASURED LEVER ARM

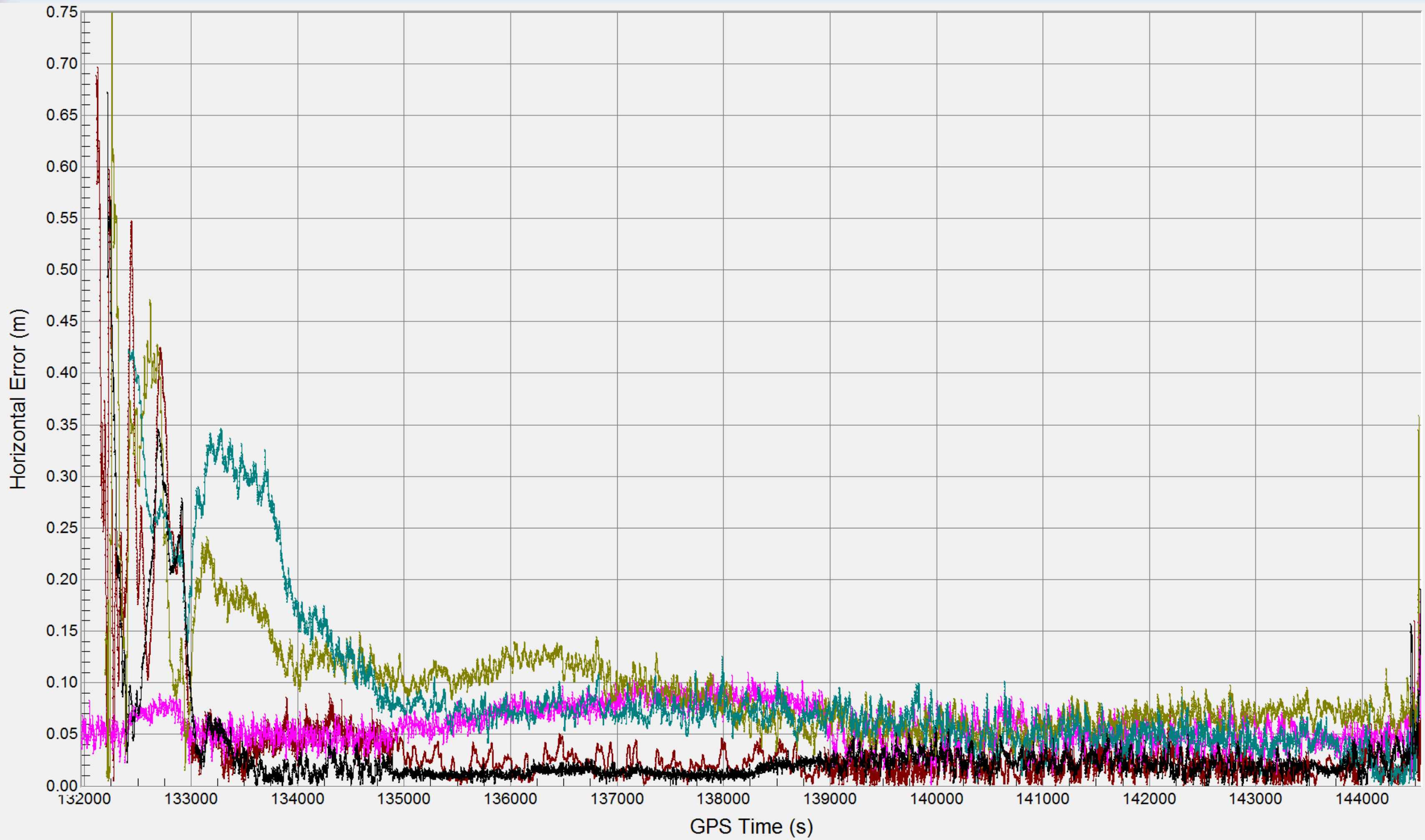


Note: All Z measurements are from top of wood to ARP

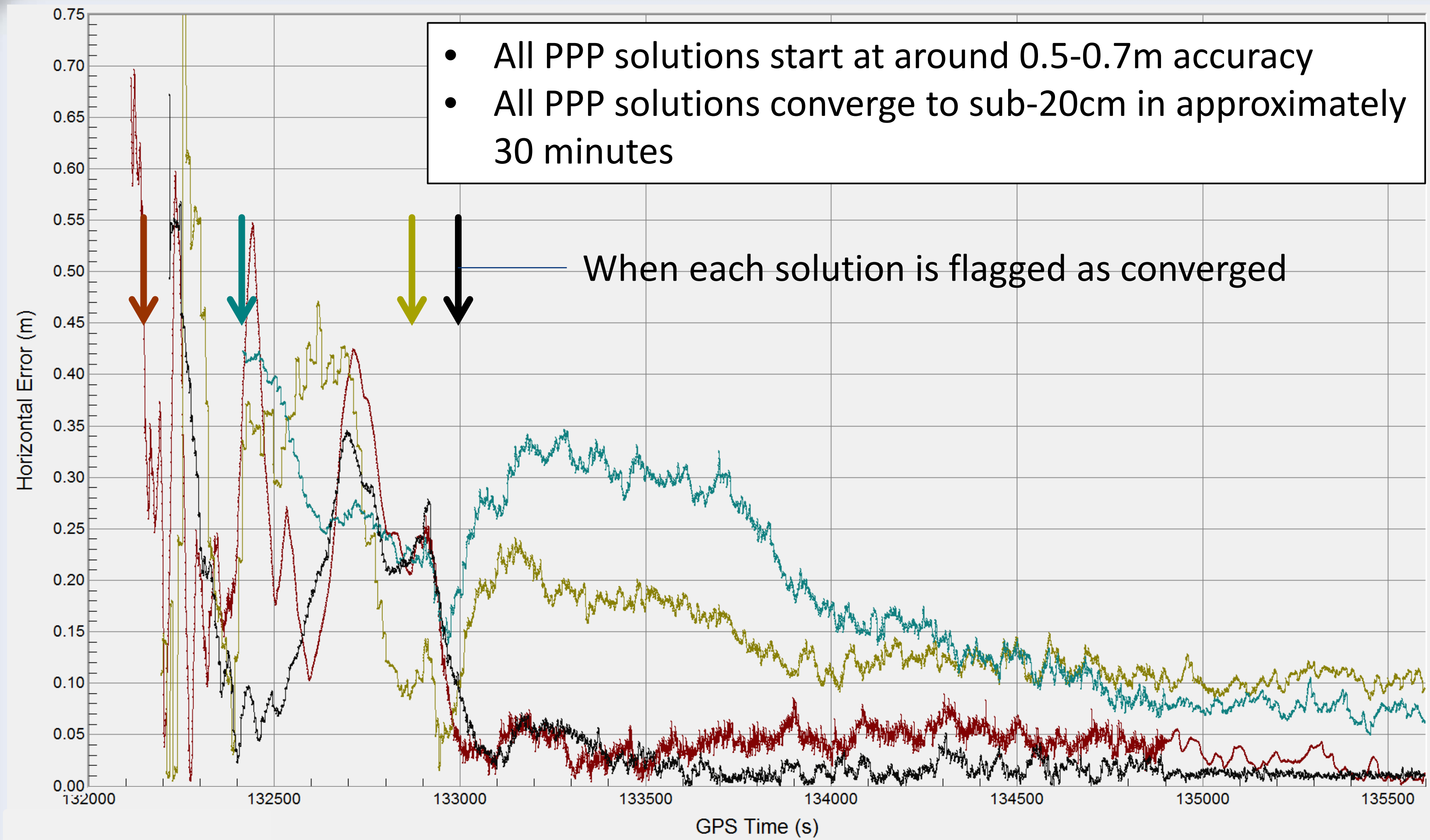
Dynamic Evaluation – Machine Trajectory (Benign)



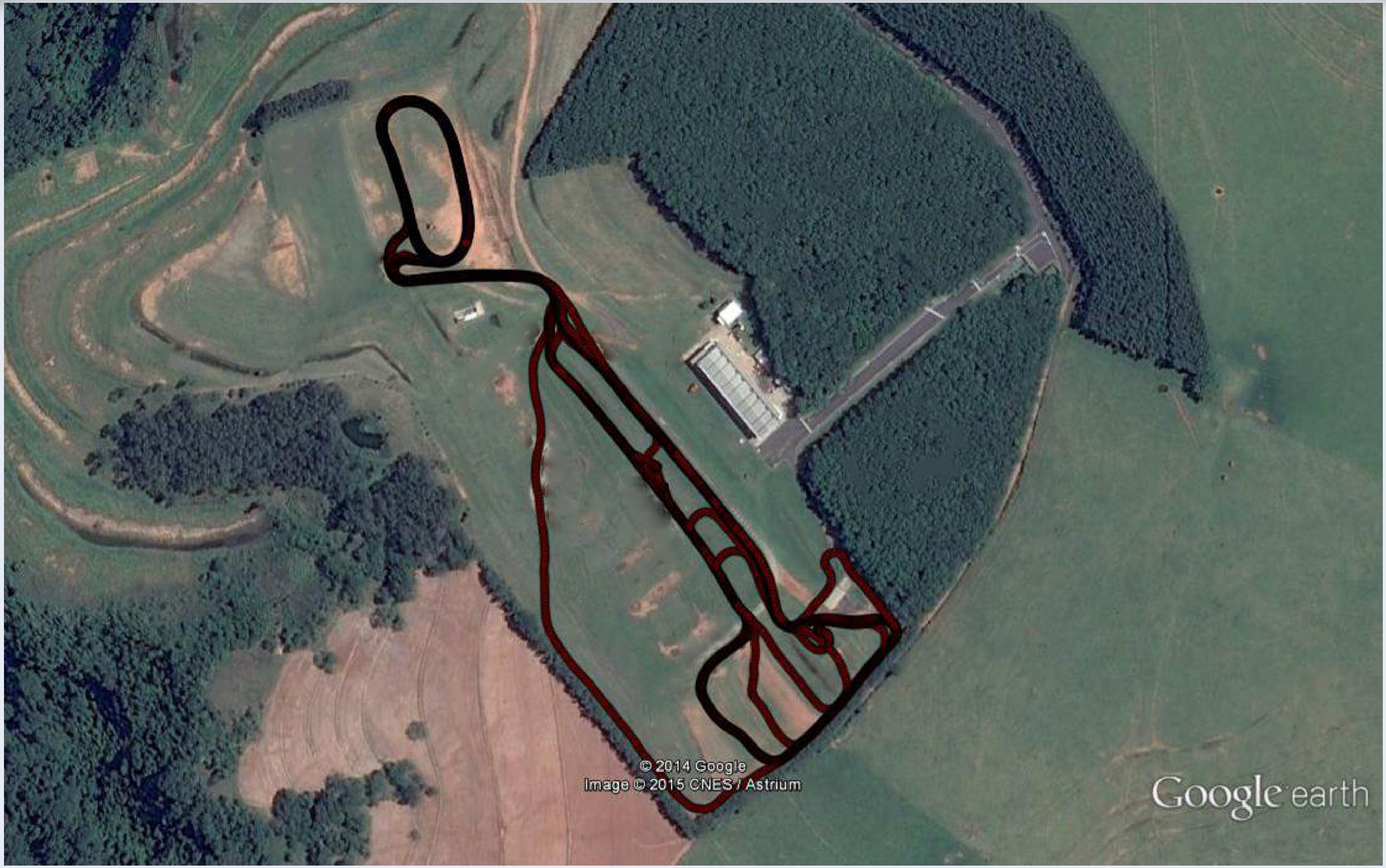
- All PPP solutions converge to sub-20cm to sub-5cm
- Some PPP solutions noisier than others
  - Especially noisy when dynamic


0.75
0.70
0.65
0.60
0.55
0.50
0.45
0.40
0.35
0.30
0.25
0.20
0.15
0.10
0.05
0.00
Horizontal Error (m)
132000
133000
134000
135000
136000
137000
138000
139000
140000
141000
142000
143000
144000
GPS Time (s)

Dynamic Evaluation – First Hour Showing Convergence

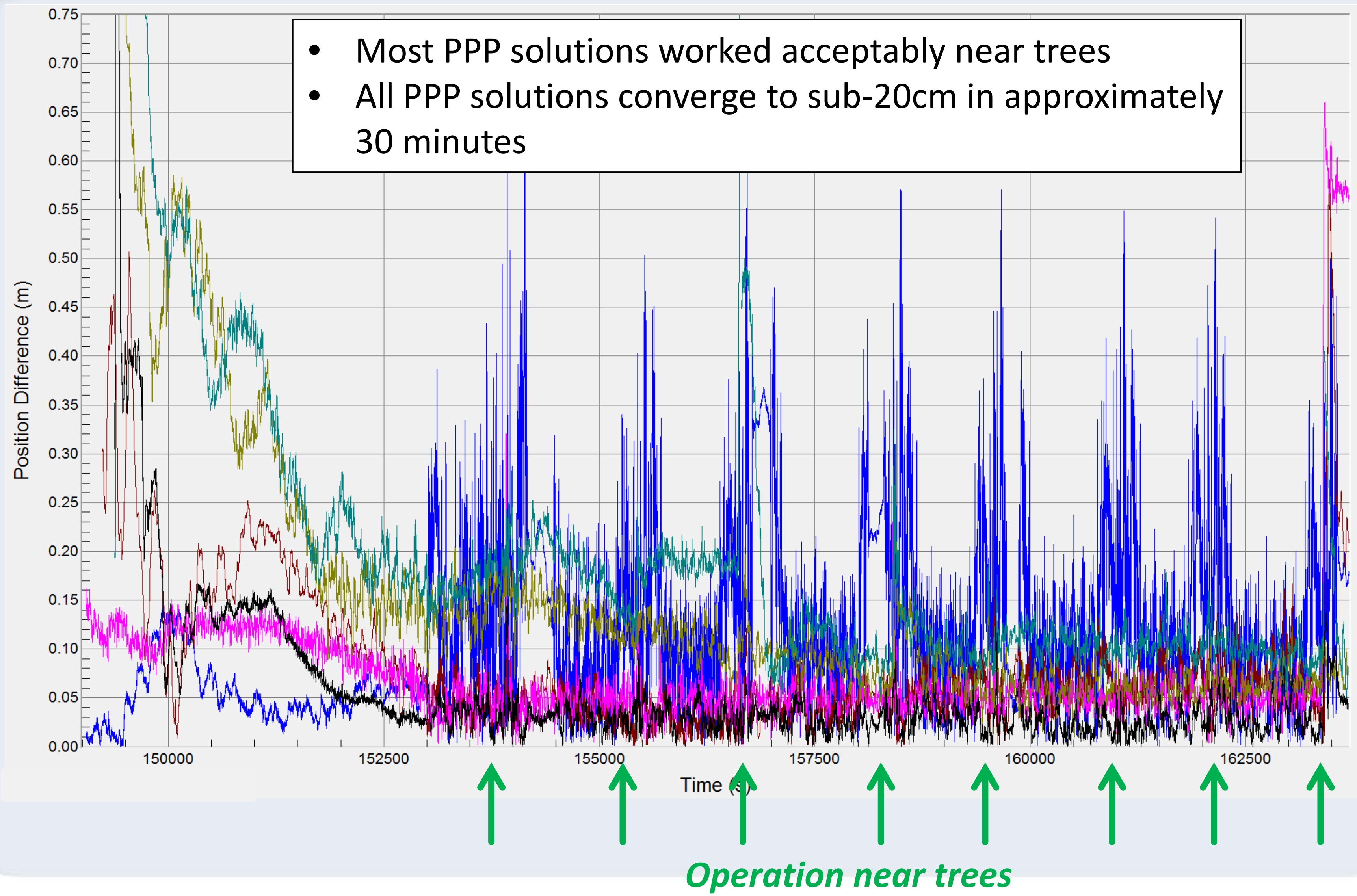


Dynamic Evaluation – Machine Trajectory (Not So Benign)

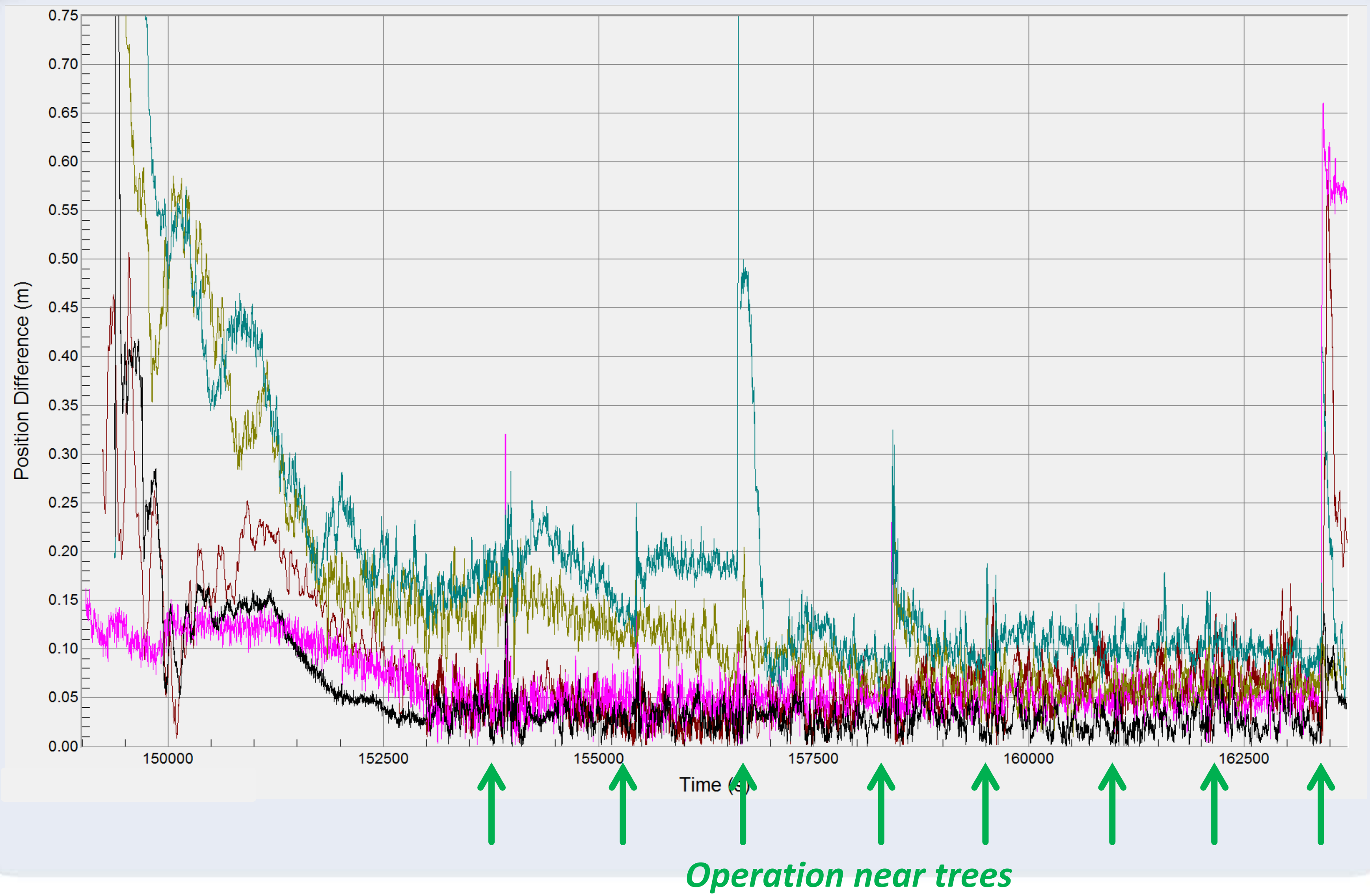


Dynamic Evaluation – Horizontal Errors (Not So Benign)

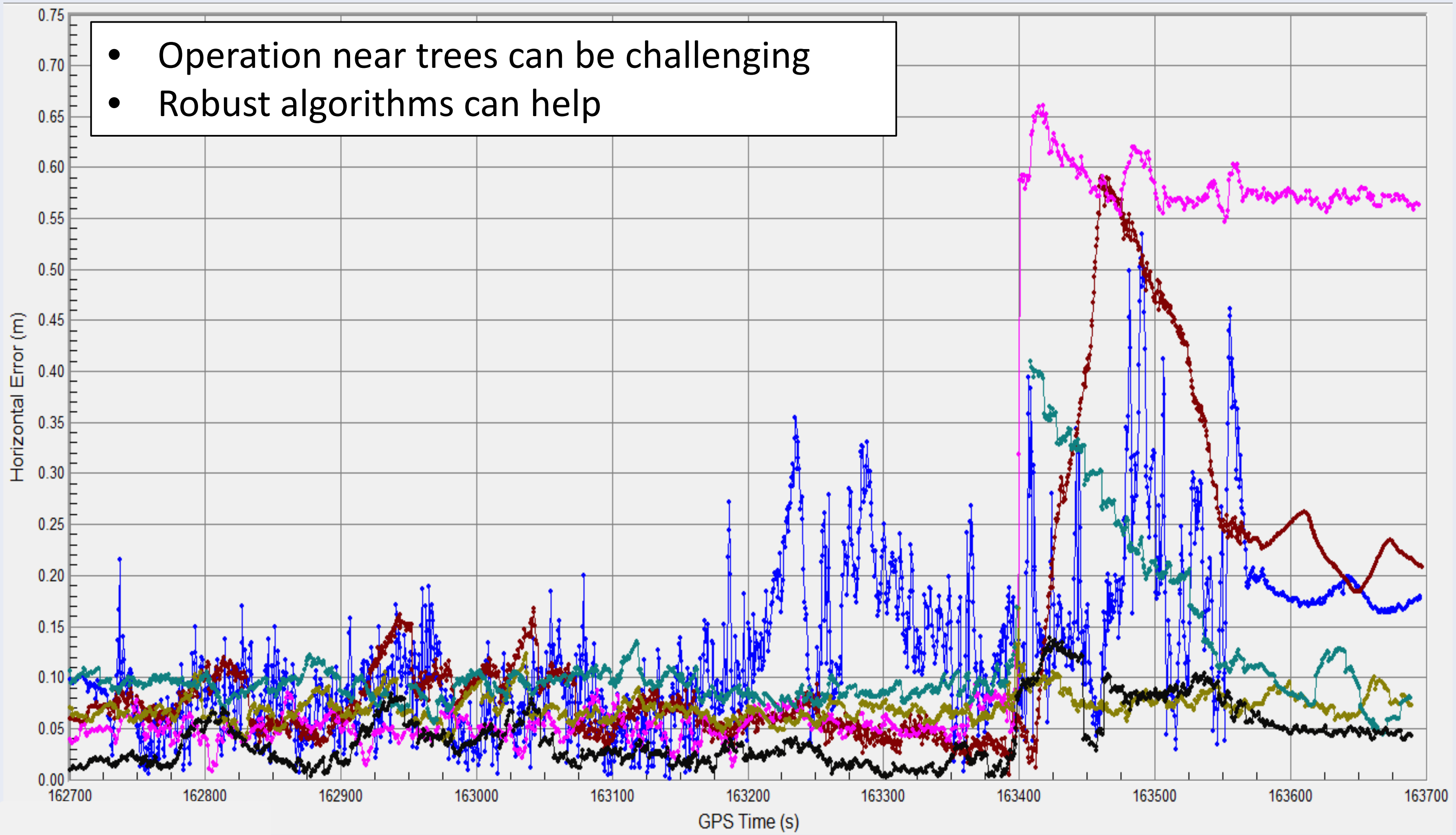
- Most PPP solutions worked acceptably near trees
- All PPP solutions converge to sub-20cm in approximately 30 minutes



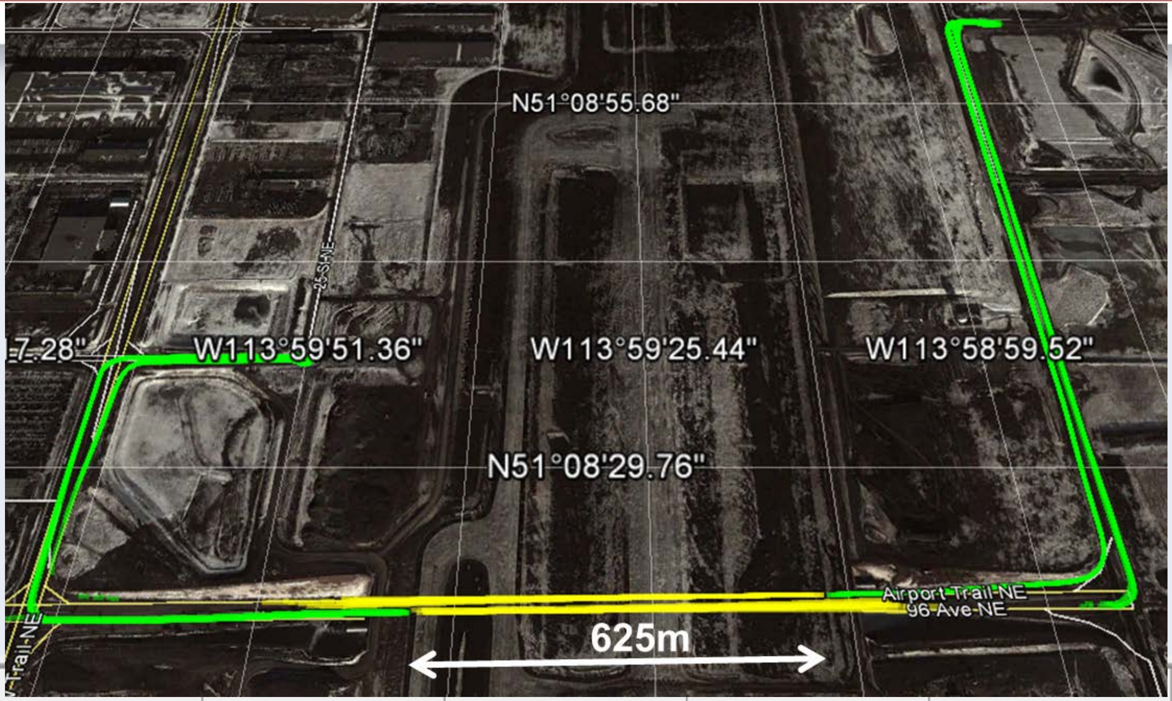
Dynamic Evaluation – Horizontal Errors (Not So Benign)

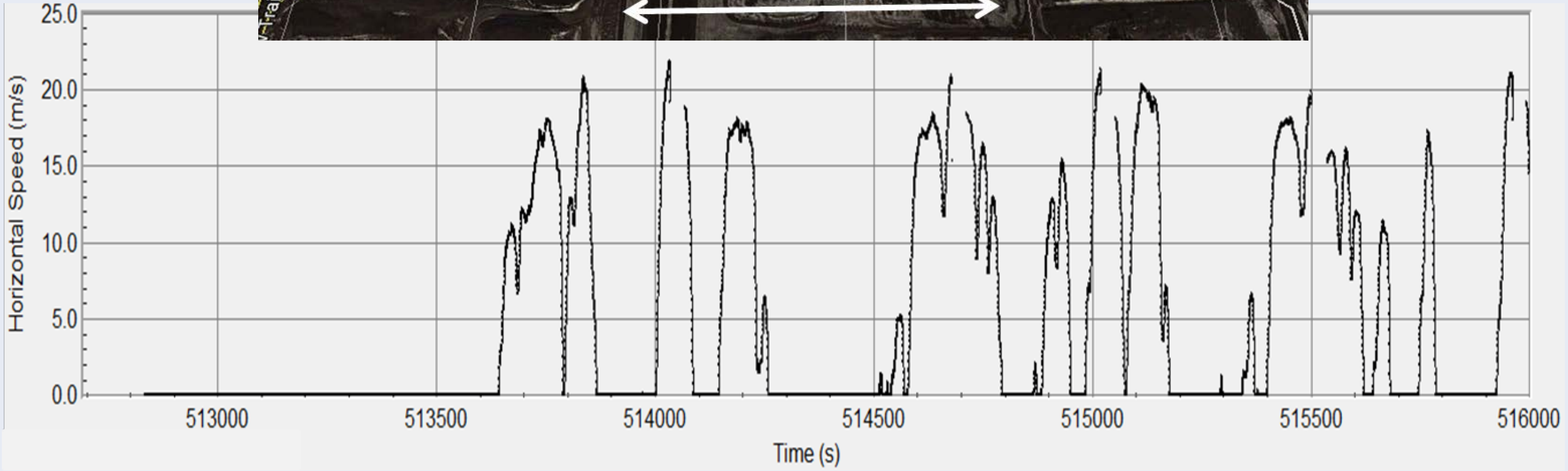


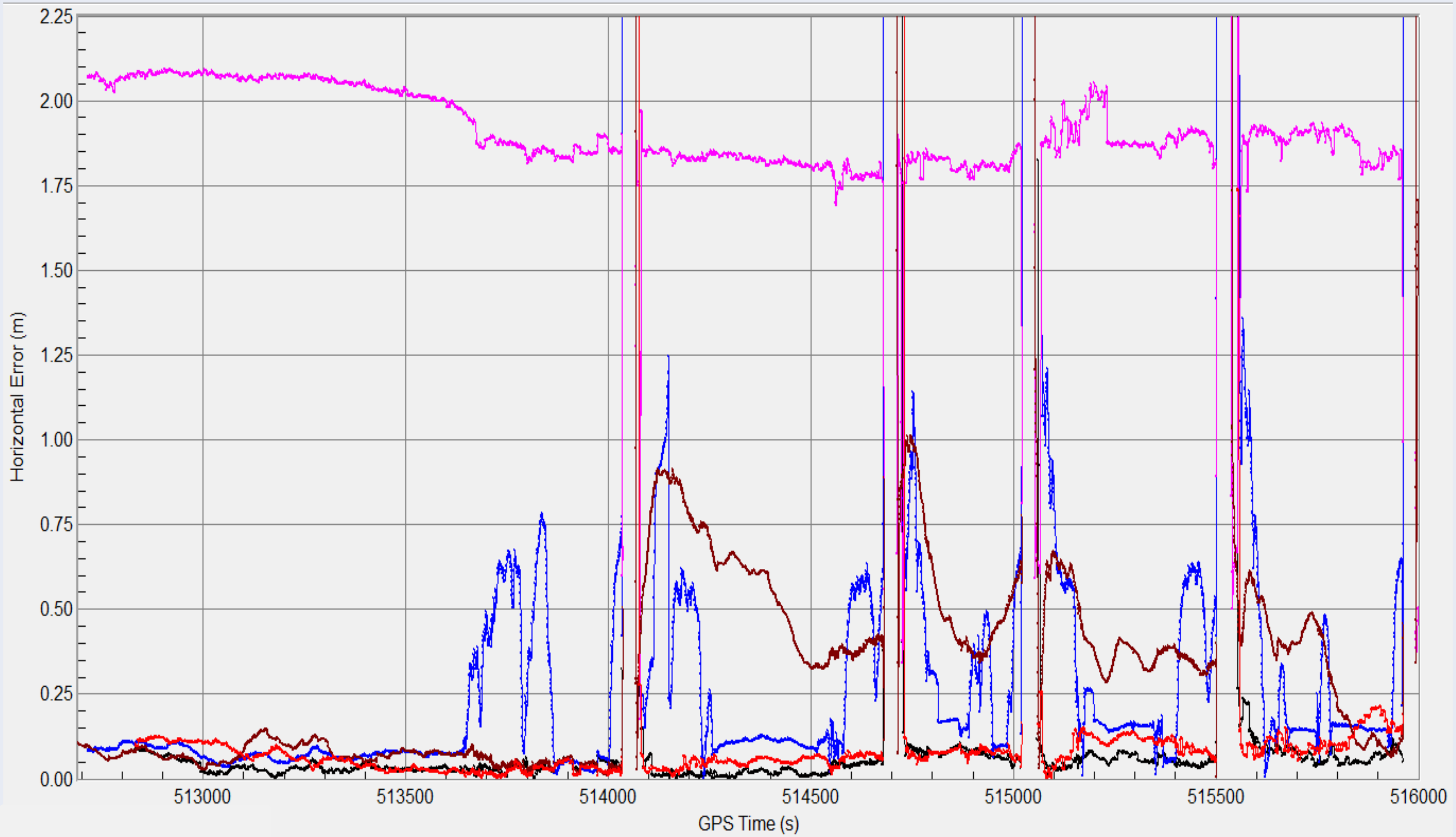
Dynamic Evaluation – Horizontal Errors (Not So Benign)



Dynamic Evaluation – Horizontal Speed (Tunnel)







2.25
2.00
1.75
1.50
1.25
1.00
0.75
0.50
0.25
0.00
Horizontal Error (m)
513000
513500
514000
514500
515000
515500
516000
GPS Time (s)

Conclusions

- Initial PPP convergence to dm accuracy can take tens of minutes
- Rapid reconvergence can occur with some flavors or implementations of PPP
- Dynamic performance of PPP is typically quite good
  - Based on many days of testing in real-world conditions
  - 6-8 different PPP solutions evaluated concurrently
  - Some solutions noisier than others, especially when dynamic
  - Most solutions can provide a reliable decimeter-level solution
  - Operation near trees can be challenging
  - Reconvergence performance can vary considerably after signal tracking disruption

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- Ensuring your success.
- Thanks for participating in today's webinar.

Poll #3

Based on what you have heard today, in my applications I plan to:

- Consider replacing a meter level solution with PPP
- Consider replacing RTK with PPP
- I have no need for PPP
- Continue to use both RTK and PPP
- Not sure. I will wait.

Ask the Experts – Part 2

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Thank you!

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