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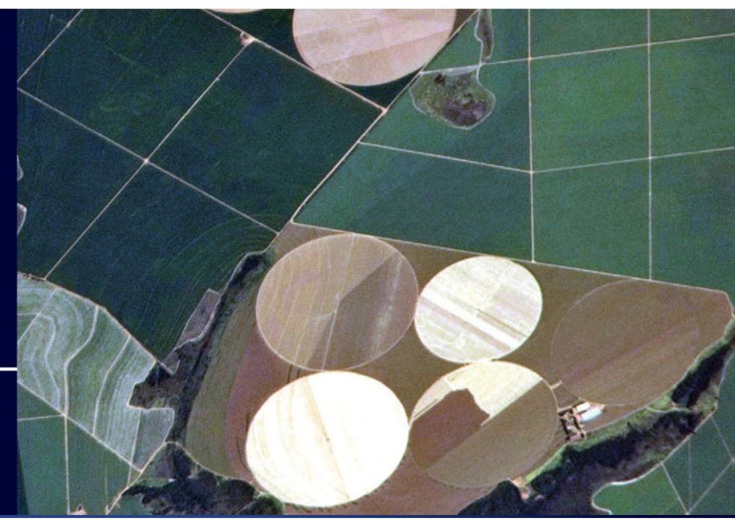
WELCOME TO
PRECISE POSITIONING TECHNIQUES: GNSS ERROR SOURCES & MITIGATION

Monday, December 15, 2014

10 am–11:30 PST
11 am–12:30 pm MST
Noon–1:30 pm CST
1 pm–2:30 pm EST



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WELCOME TO
Precise Positioning Techniques: GNSS Error Sources & Mitigation

Sanjeev Gunawardena
Research Assistant Professor
Autonomy & Navigation
Technology Center
Air Force Institute of Technology

Sunil Bisnath
Associate Professor
Department of Earth and Space
Science and Engineering
York University, Toronto

Sandy Kennedy
Director and Chief Engineer
of Core Cards
NovAtel Inc.

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Moderator: Lori Dearman, Sr. Webinar Producer

Who's In the Audience?

A diverse audience of over 900 professionals registered from 73 countries, 40 states and provinces representing the following industries:

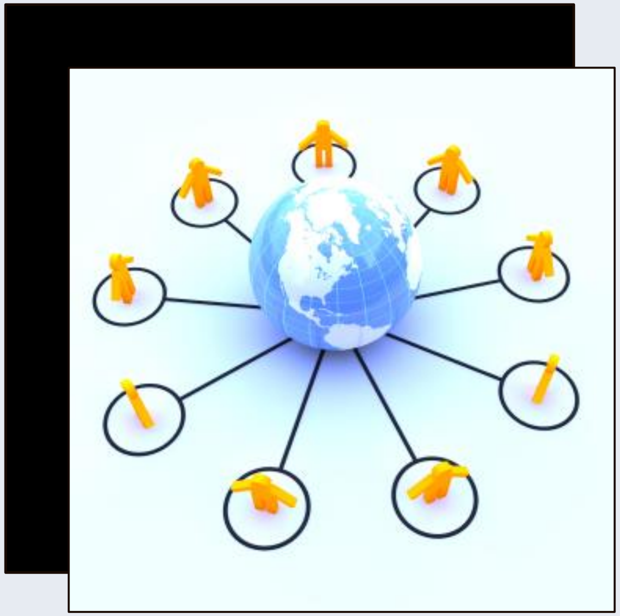
16% GNSS Equipment Manufacturer

25% Professional User

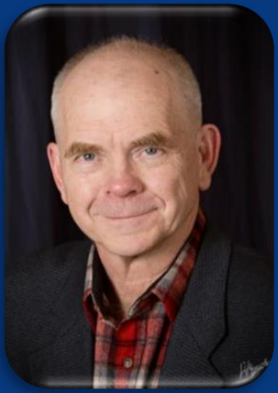
18% System Integrator

14% Product/Application Designer

27% Other



Welcome from *Inside GNSS*



Glen Gibbons

Editor and Publisher
Inside GNSS

A word from the sponsor

Sara Masterson, P. Eng.

New Business Development Manager
NovAtel, Inc

Poll #1

What level of accuracy do you currently achieve with your gnss positioning?

- *Greater than a meter*
- *Less than a meter*
- *Meter*
- *10 centimeters*
- *Less than 10 centimeters*

Today's Speakers

Sanjeev Gunawardena
Research Assistant Professor
Autonomy & Navigation
Technology Center
Air Force Institute of Technology

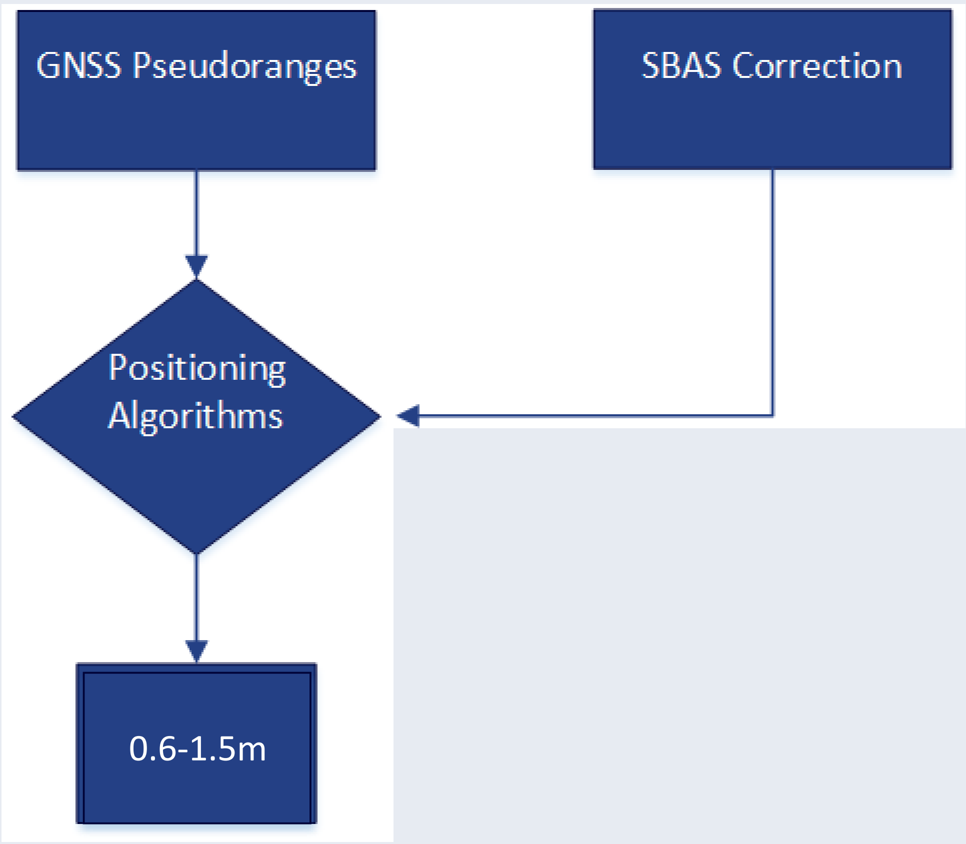
Sunil Bisnath
Associate Professor
Department of Earth and Space
Science and Engineering
York University, Toronto

Sandy Kennedy
Director and Chief Engineer
of Core Cards
NovAtel Inc.

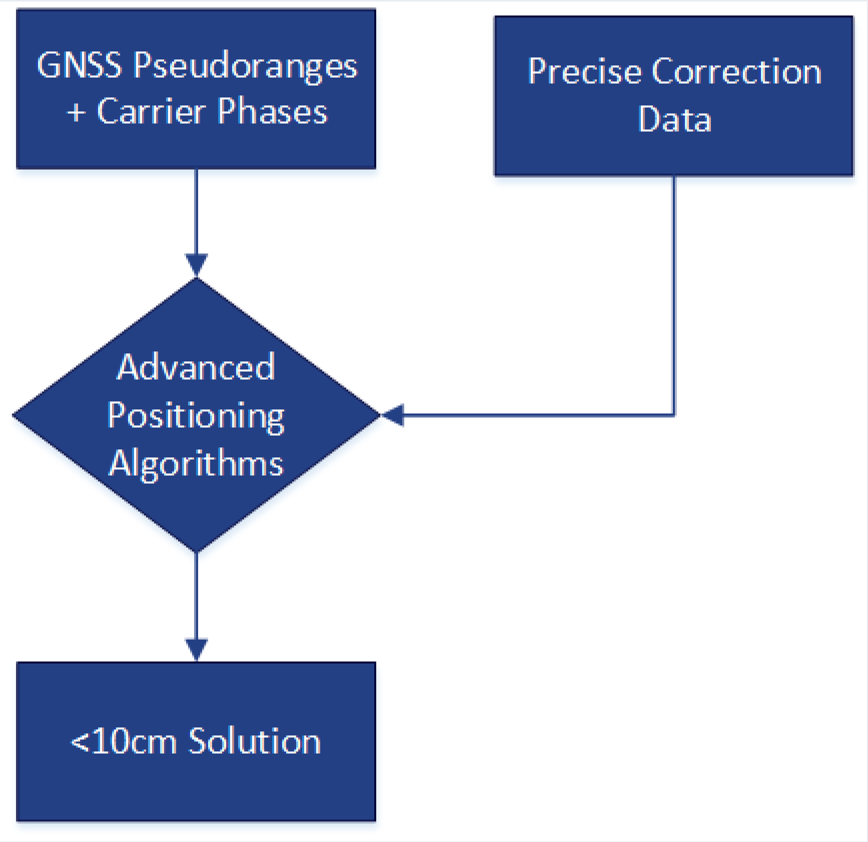
Precise GNSS Positioning

Sandy Kennedy
Director, Core Receiver Cards
NovAtel Inc.

General Standalone GNSS Positioning



Precise GNSS Positioning



The Enablers

- <10cm accuracy has been possible for over 10 years, why is there more interest now?
- The Enablers:
  - Easily accessible correction data
  - Advanced positioning algorithms

Correction Data

THEN

- Your own base receiver
- Radio link, limited to 3 km, affected by terrain
- Competition for radio channels
- Long delays (days) for precise orbits and clocks

NOW

- RTK correction services in most cities, broadcast over cellular frequencies
- Base station files available for post-processing (ie CORS)
- Rapid precise clocks and orbits
- Increased quality of corrections delivered over L-band/MSS

Improved Algorithms

RTK

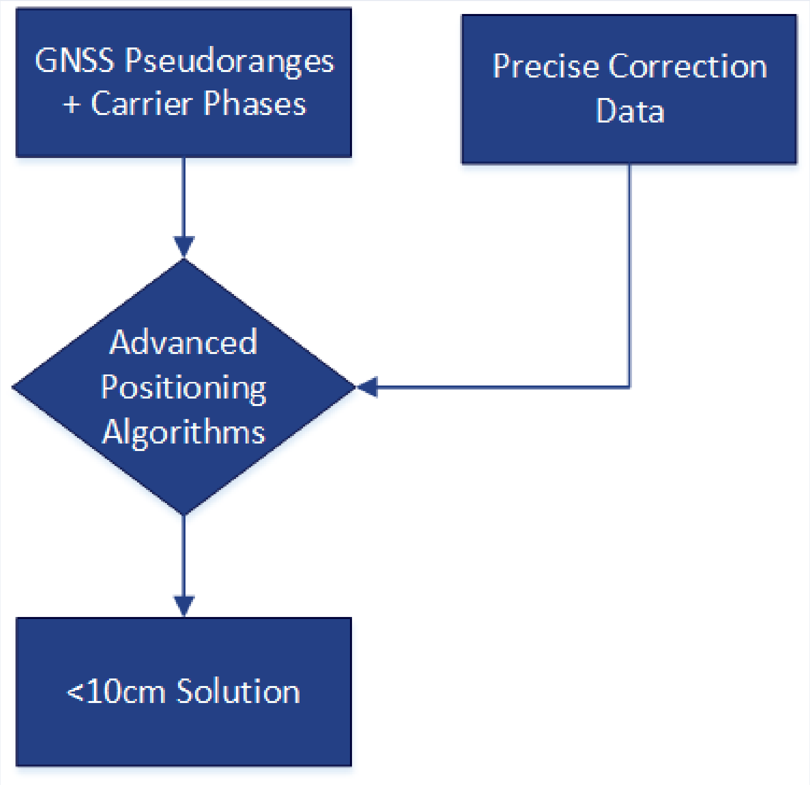
- Faster fixes over longer baselines
- Network RTK or single base station
- Reliable quality indicators

PPP

- Has come a long way!
- Popular in post-processing first, now real time
- <10cm kinematic, real-time acheivable

Corrections + Algorithms – Let's Go!

- When your focus shifts from having a meter level position to a cm level position
  - You require good quality, precise measurements
  - Trade off decisions on antenna and receiver design may change



GNSS Antenna and Receiver Design Considerations for High Accuracy Applications

Disclaimer: The views expressed in this presentation are those of the author, and do not reflect the official policy or position of the United States Air Force, Department of Defense, or U.S. Government.

Sanjeev Gunawardena
Research Assistant Professor
Air Force Institute of Technology

OVERVIEW

- Primer on GNSS Antenna and Receiver Design
  - GPS signal link budget and S/N_0
  - GNSS antennas
  - Receiver architecture
  - Baseband signal processing
- How Range Measurements are Computed
  - Pseudorange
  - Accumulated Doppler Range
  - Carrierphase
- Considerations for High Accuracy GNSS
  - Relationship between bandwidth and measurement accuracy
  - Multipath mitigation
  - Front-end component effects
  - Signal deformation

GPS-SPS Link Budget, S/N_0, and C/N_0

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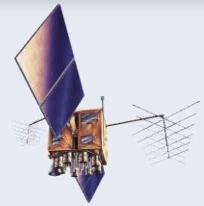
GPS Signal

Radiated Power	14 dBW (25 W)
SV Antenna Gain (avg.)	+11 dB
Free Space Loss: $PD = \frac{P_t}{4\pi R^2} \left(\text{Watts}/\text{Meter} \right)$ $R \sim 22{,}700 km$	-158 dB
Atmospheric Loss:	-2 dB
Pwr. incident on Isotropic Antenna: $\frac{\boldsymbol{\lambda}^2}{\boldsymbol{4\pi}}$	-25 dB
Receive Antenna Gain	+1 dB
Received Signal Power: min. L1 C/A [GPS IS-200]	-159 dBW



GPS Receiver

Thermal Noise

$$n_0(t) \sim N(0, \sigma_{n_0}^2)$$

$$\sigma_{n_0}^2 = k_B T_0 B$$

k_B : Boltzmann's constant

1.38×10^{-23} [Joules / Kelvin]

T_0 : Ambient Temperature [Kelvin]

Example: for B=24 MHz, and T=295K:

$\sigma_{n_0}^2 = -130\ dBW$

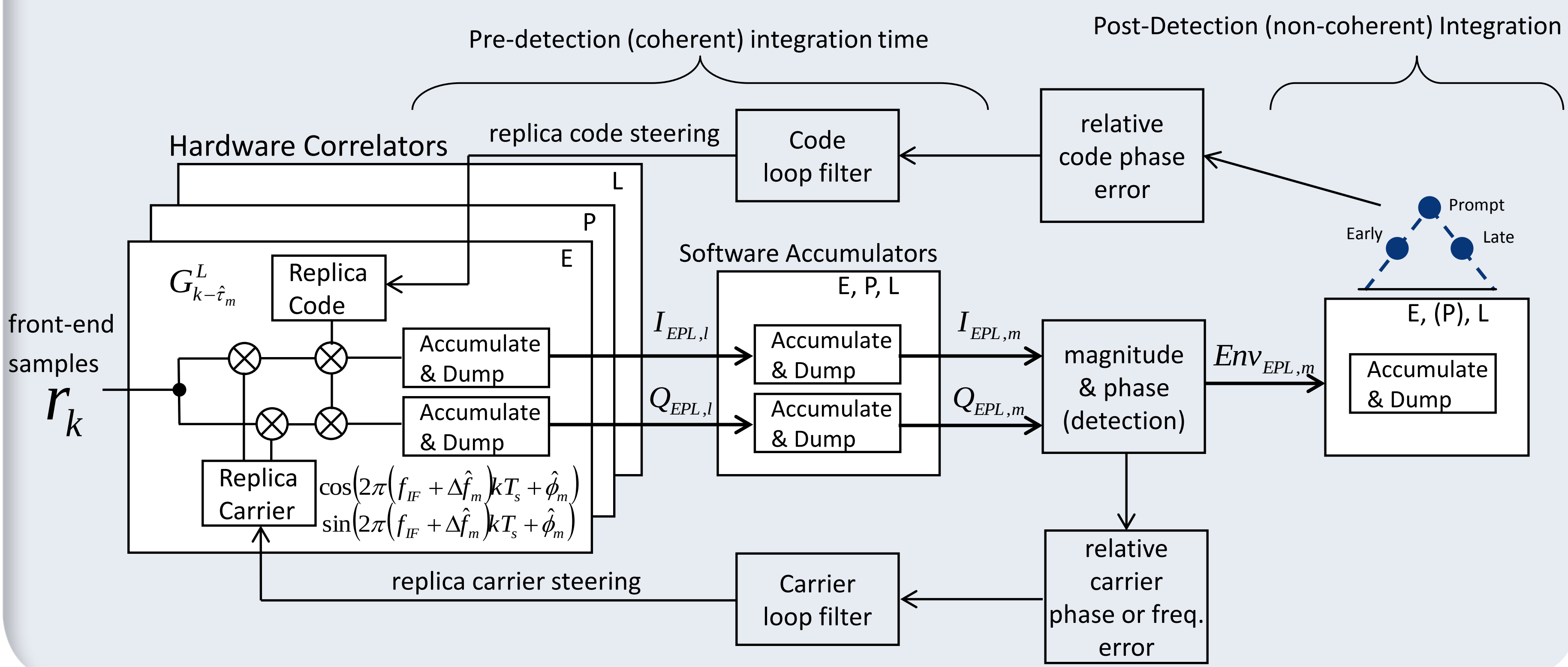
S/N_0 = -159-(-130) = -29 dB

*C/N_0 = S/N_0*B = -29+10Log(B) = 43.8 dB-Hz*

Received GNSS Signals are ~1000 times below the noise floor!

Correlation Processing and Signal Tracking

- A GNSS receiver never actually 'sees' the signal. It can only estimate signal parameters relative to its replica using correlation
  - Signal's code phase error relative to replica code
  - Signal carrier frequency or phase error relative to replica carrier
- Steering commands used to keep the replicas aligned to the signal are used to form range measurements



Generic GNSS Receiver Architecture

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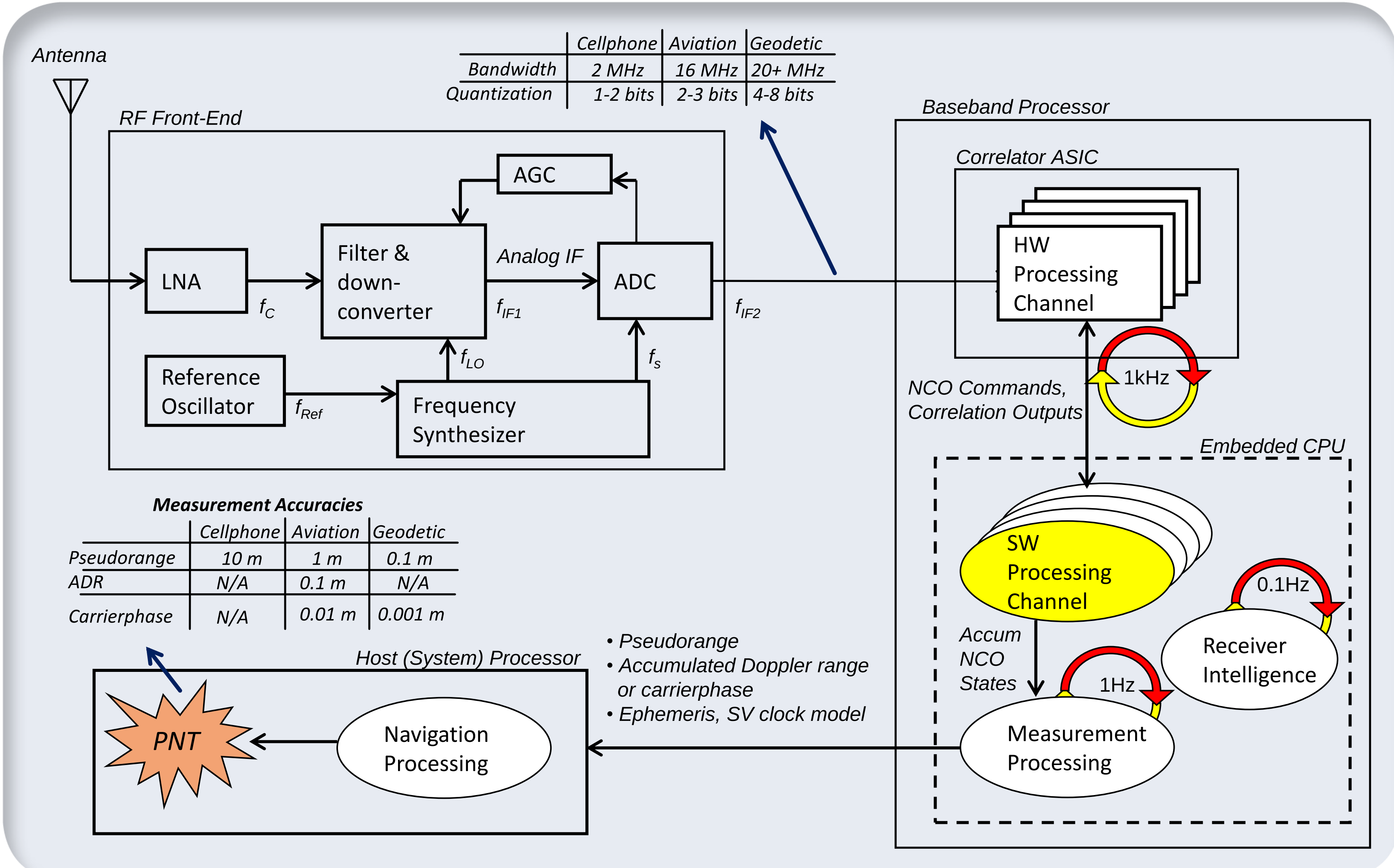


	Cellphone	Aviation	Geodetic
Bandwidth	2 MHz	16 MHz	20+ MHz
Quantization	1-2 bits	2-3 bits	4-8 bits

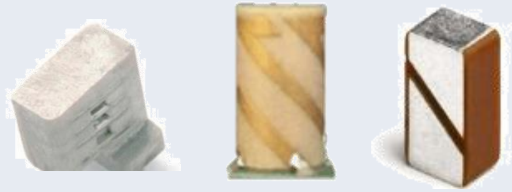
Measurement Accuracies

	Cellphone	Aviation	Geodetic
Pseudorange	10 m	1 m	0.1 m
ADR	N/A	0.1 m	N/A
Carrierphase	N/A	0.01 m	0.001 m

GNSS Antennas

- Mass Market/Cellphone
  - Single Frequency (centered between GPS L1 and GLONASS L1 bands)
  - Size and cost are highest priority
  - Designs: helical SMT (linearly polarized), quadrifilar or chip (RHCP)
  - Size: <2 cm, Cost: <$ 3
- Aviation/Machine Control
  - Single or dual frequency
    - L1/L2 for high-accuracy industrial
    - L1/L5 for aviation
  - Patch antenna design with built-in diplexer and LNA
  - Low-elevation cutoff using planer designs and absorber materials
  - Phase center stability controlled by design
  - Size: ~10 cm, Cost: $20-300
- Geodetic/Reference Station
  - Supports multiple GNSS bands
  - Supports PPP network bands (e.g. TerraStar)
  - Similar design criteria as high-end Aviation/Machine control antennas
  - Excellent phase center stability over azimuth and GNSS bands
  - Choke ring or other 'external' multipath limiting features
  - Qualification tested
  - Size: ~30 cm, Cost $2,500-7,000

Helical SMT, Quadrifilar, and Chip Antennas



Source: www.gsm-modem.de/M2M/m2m-componets/gps-helical-antenna/

Source: Garmin

Source: NovAtel

Measurements from a GNSS Receiver

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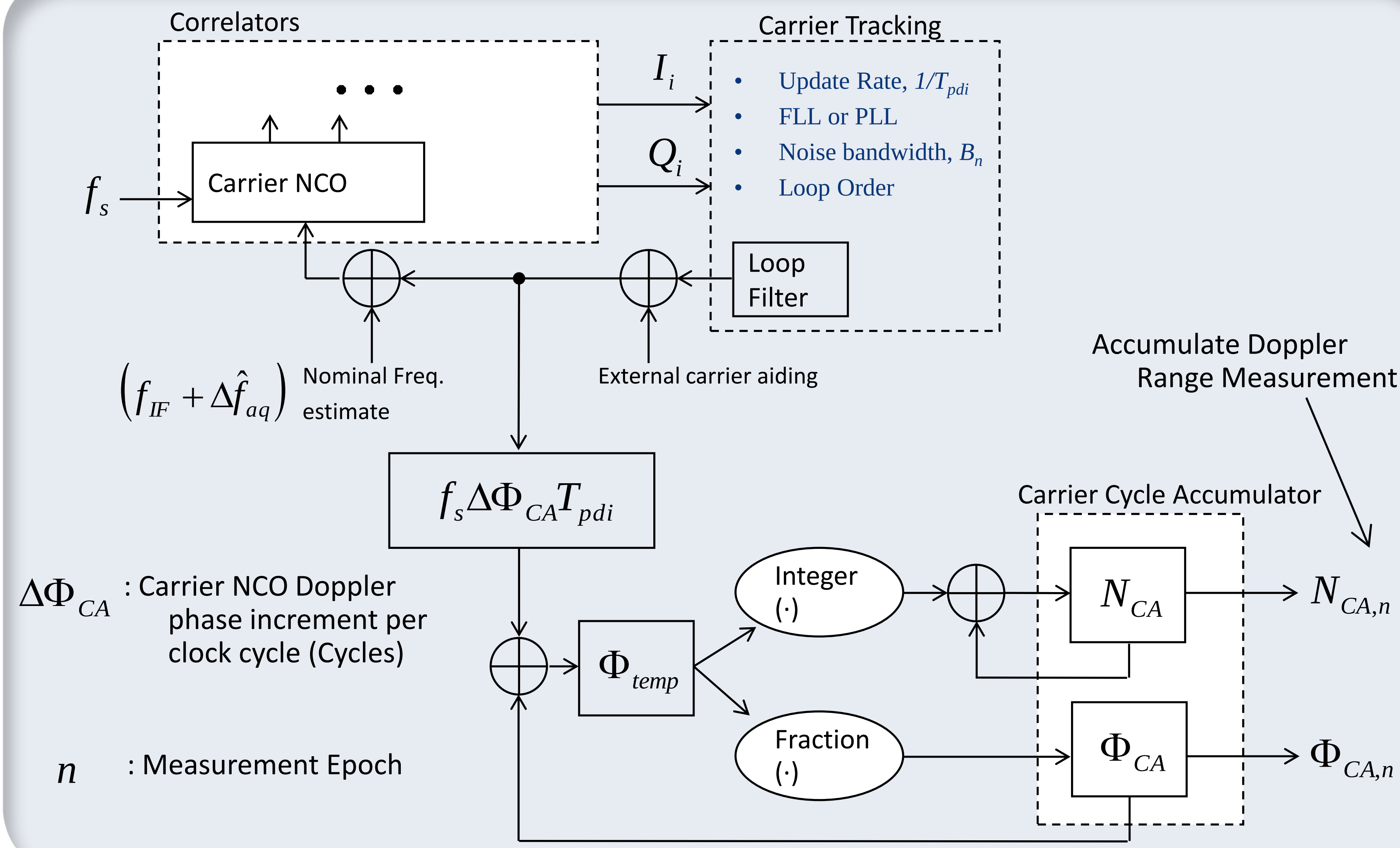
- Desired Measurements:
  - Absolute LOS range to each visible satellite
  - Precise LOS velocity to each visible satellite
- What you get instead:
  - Pseudorange to each visible satellite
    - Noisy (1-10 meters error)
    - Absolute and unambiguous range measurement
    - Has a range bias common to all measurements of all visible satellites
  - Accumulated (integrated) Doppler Frequency Range
    - Receiver tracking carrier in frequency-locked mode
    - Robust against high dynamics, interference, multipath fading and iono scintillation
    - Decimeter-level noise
    - Relative range measurement
  - Accumulated Doppler Phase Range (a.k.a. CarrierPhase)
    - Receiver tracking carrier in phase-locked mode
    - More susceptible to loss-of-lock
    - Slips cycles can occur when tracking loop can't keep up with dynamics
    - Millimeter-level noise
    - Relative range measurement. Contains integer cycle ambiguity ($N\lambda$)

Carrier Cycle Accumulator



Pseudorange Measurement

Pseudorange to satellite *i* at measurement epoch *n*:

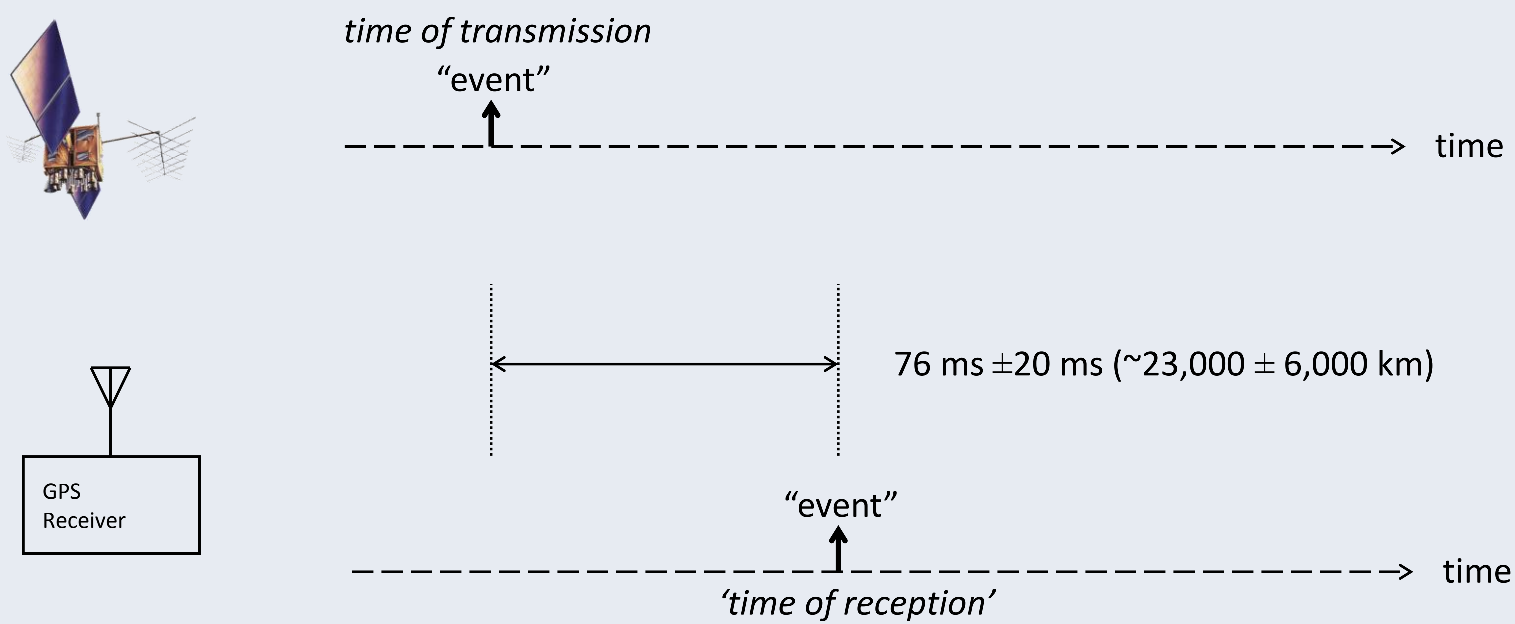
$$\rho_{i,n} = c\left[t_{R,n} - t_{T,i,n}\right] \text{ (m)}$$

Where:

t_R: Time of reception (derived from receiver clock)

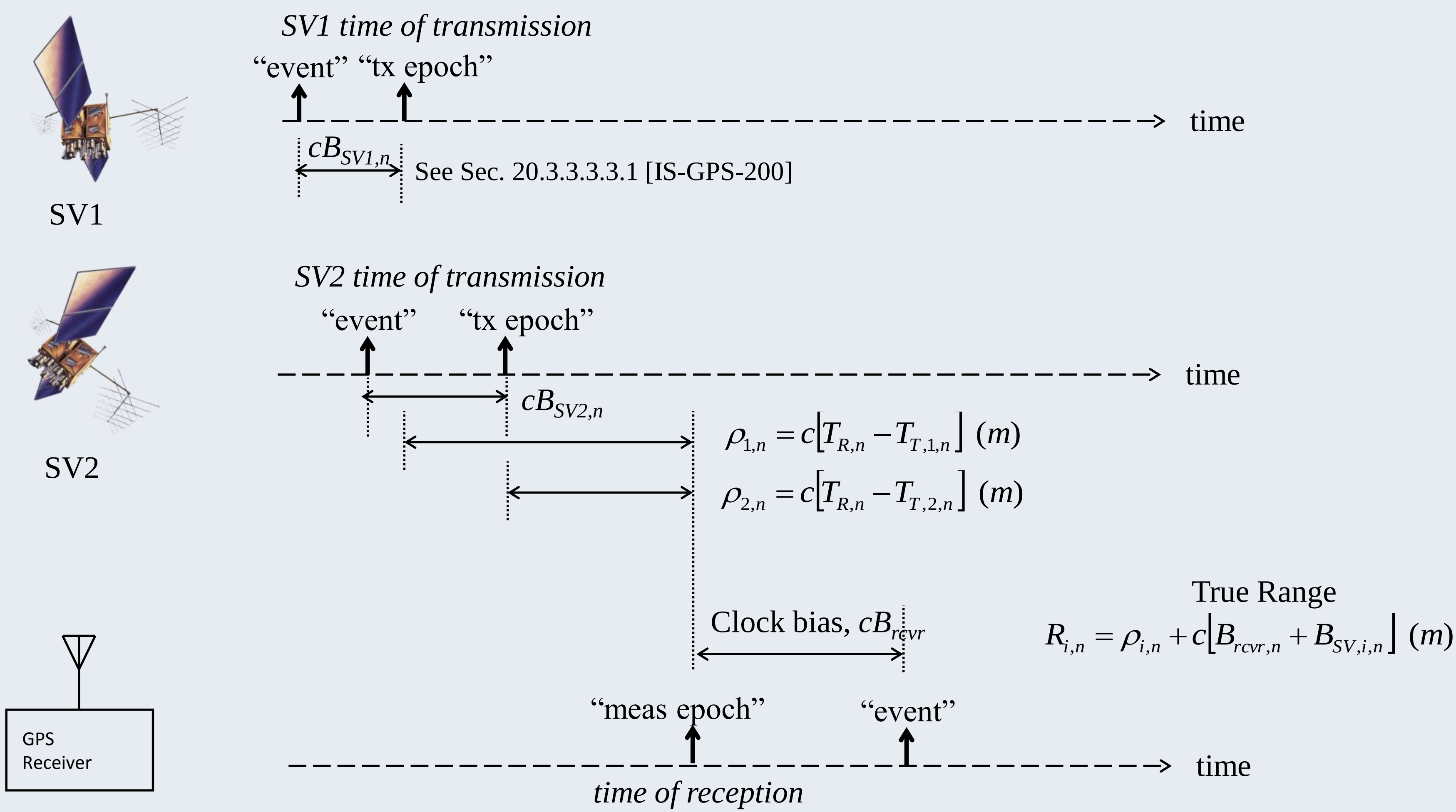
t_T: Time of transmission

c : speed of light (2.99792458 x 10^8 m/s)

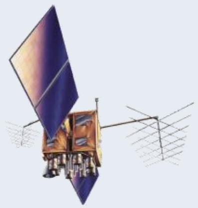


Pseudorange Measurement (contd.)

Pseudorange versus True Range



Computing Time of Transmission



Measurement Processor:

"give me a measurement NOW!"

Start of GPS week

meas. epoch

time

time of transmission

From Decoded Navigation Message*

1-week Z Count (0-403,199)

\+

6-sec Subframe bit offset (0 – 299)

\+

20 ms bit C/A code cycle offset (0 – 19)

\+

From Code NCO Updates

0.98 μs C/A code chip offset (0 – 1022)

\+

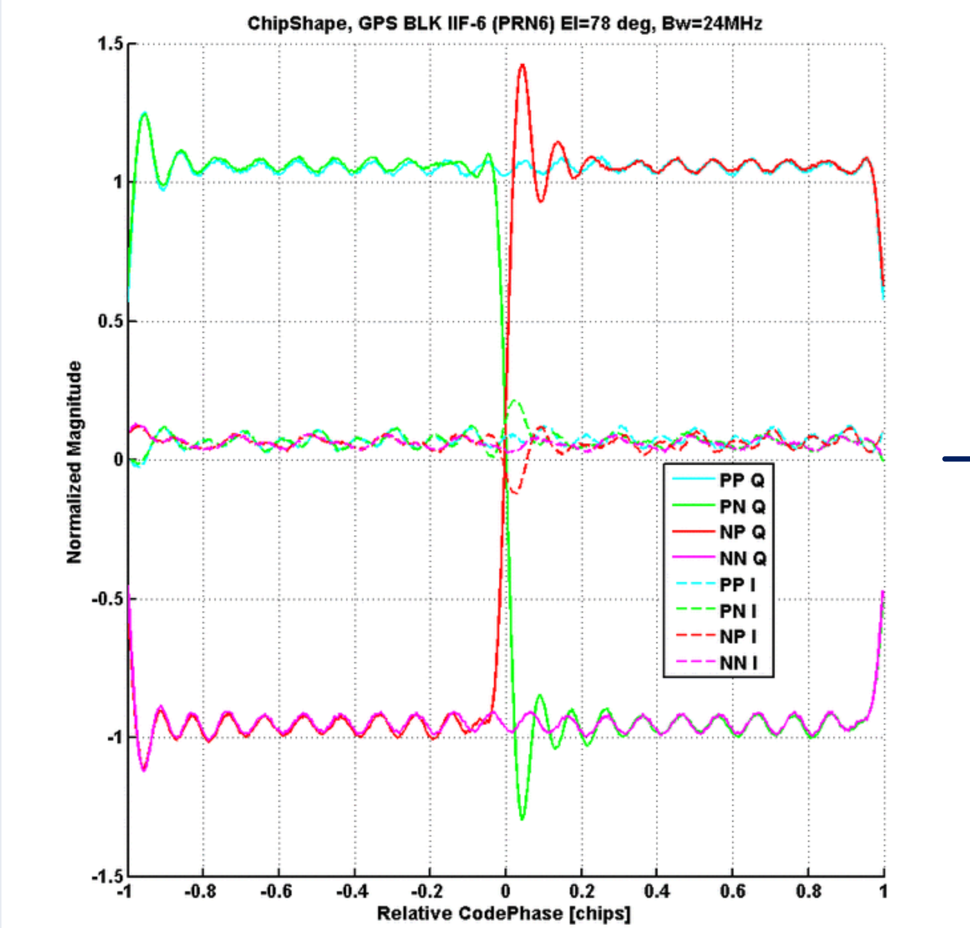
<0.98 μs Fractional chip offset (0 – <1)

Code Accumulator

** Refer to IS-GPS-200*

Front-End Bandwidth & Measurement Accuracy

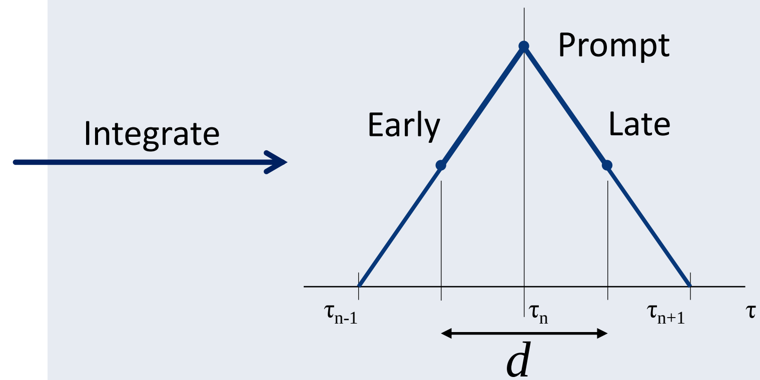
Chip Shapes of Actual GPS-SPS Signals



Time is estimated from chip transition zero crossings*

Sharp edges ↔ precise measurements

* In practice, the receiver implements an early-minus-late discriminator function



Pseudorange Measurement Accuracy

$$\sigma_{tDLL,chips} \cong \sqrt{\frac{B_n}{2C/N_0}\left(\frac{1}{B_{fe}T_c}\right)\left[1+\frac{1}{T_{pdi}\,C/N_0}\right]} \quad D \le \frac{R_c}{B_{fe}}$$

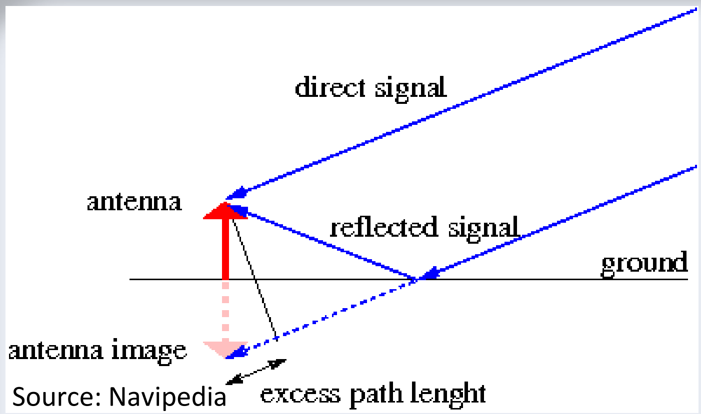
R_c: code chipping rate T_c: chip period

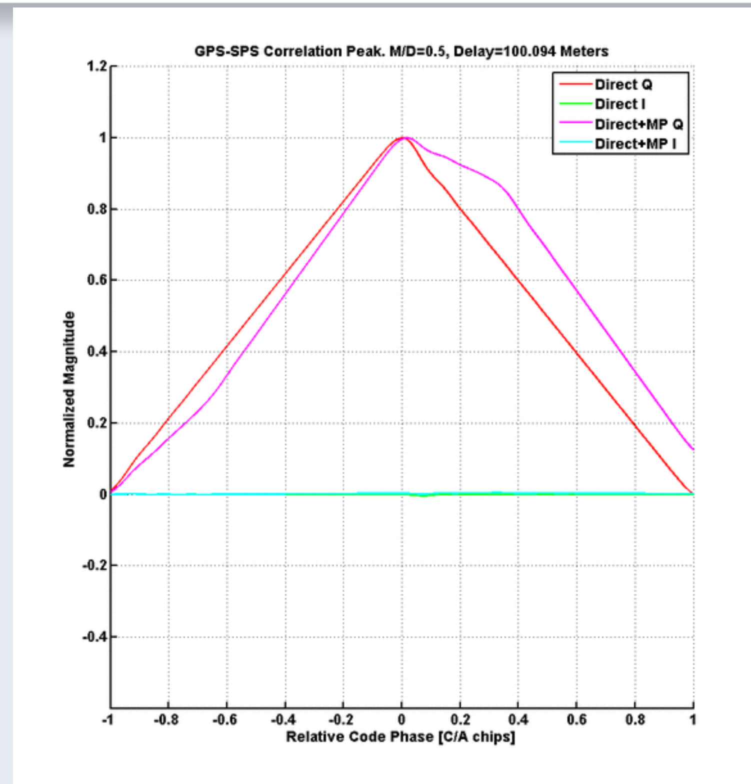
B_{fe}: front-end bandwidth B_n: loop noise bandwidth

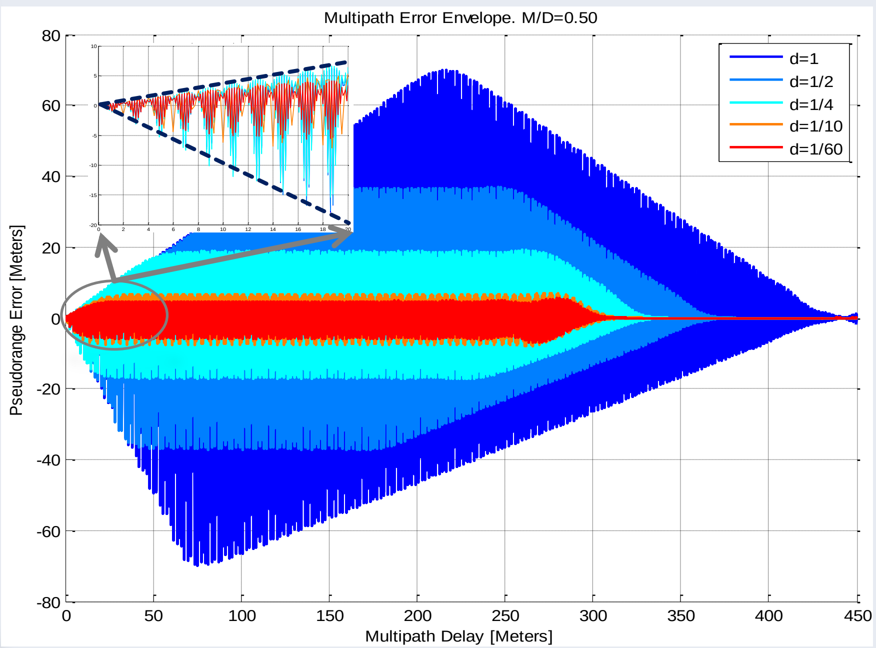
T_{pdi}: pre-detection integration time

- P. Fenton, J. Jones, "The Theory and Performance of NovAtel Inc.'s Vision Correlator," ION GNSS 2005
- S. Gunawardena, "A Universal Software Receiver Toolbox for Education and Research," InsideGNSS, July/August 2014.

Multipath

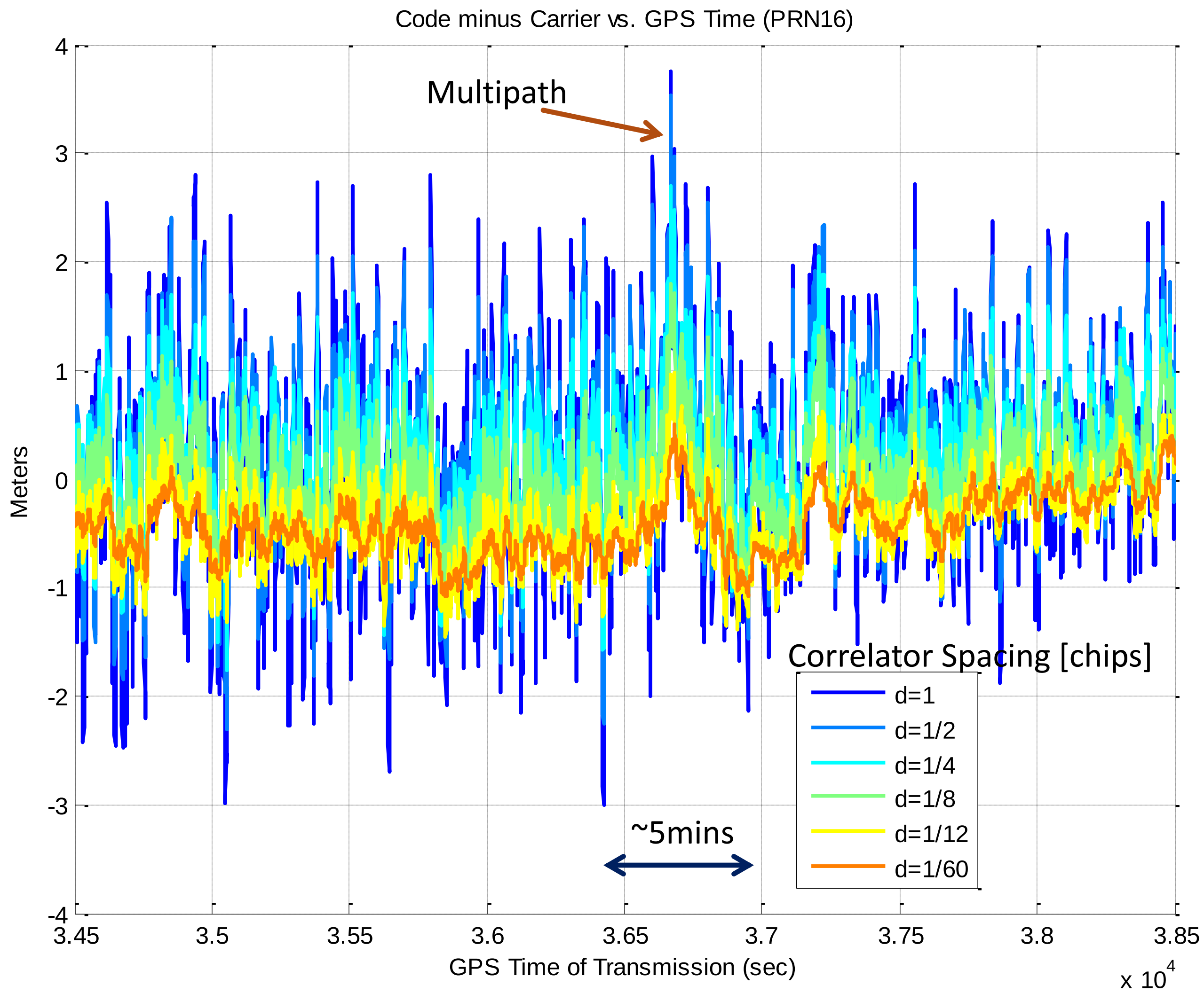






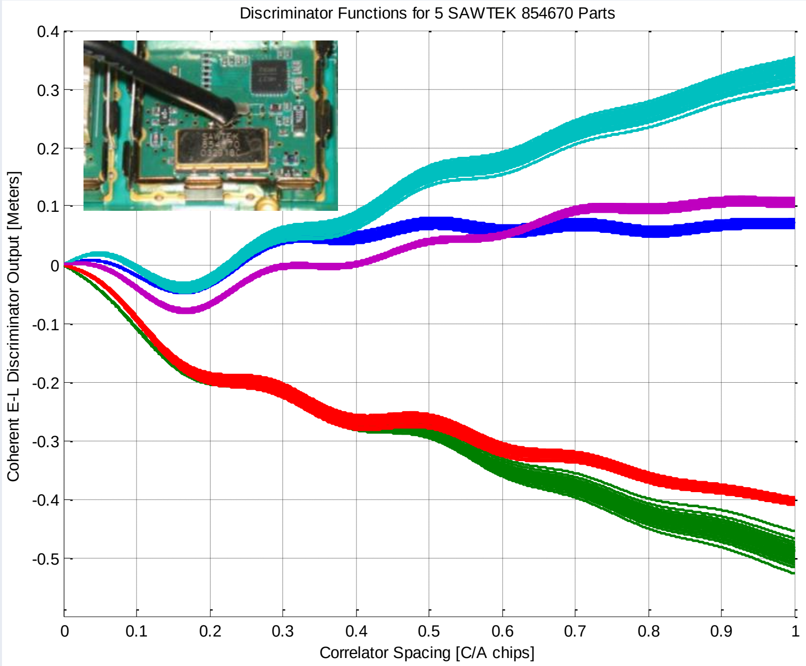
- Narrowing correlator spacing reduces the effect of correlation peak distortion due to multipath
- Also reduces code measurement error since thermal noise on E and L become correlated (but reduces tracking threshold)
- To reduce EL spacing, need sufficient bandwidth to prevent top-rounding of correlation function
- More advanced techniques in use: double-delta, MEDLL, NovAtel Vision™ Correlator
- Mitigating short-delay multipath (<3m) is still challenging

Example: Correlator Spacing, Pseudorange Accuracy & Multipath Mitigation Performance

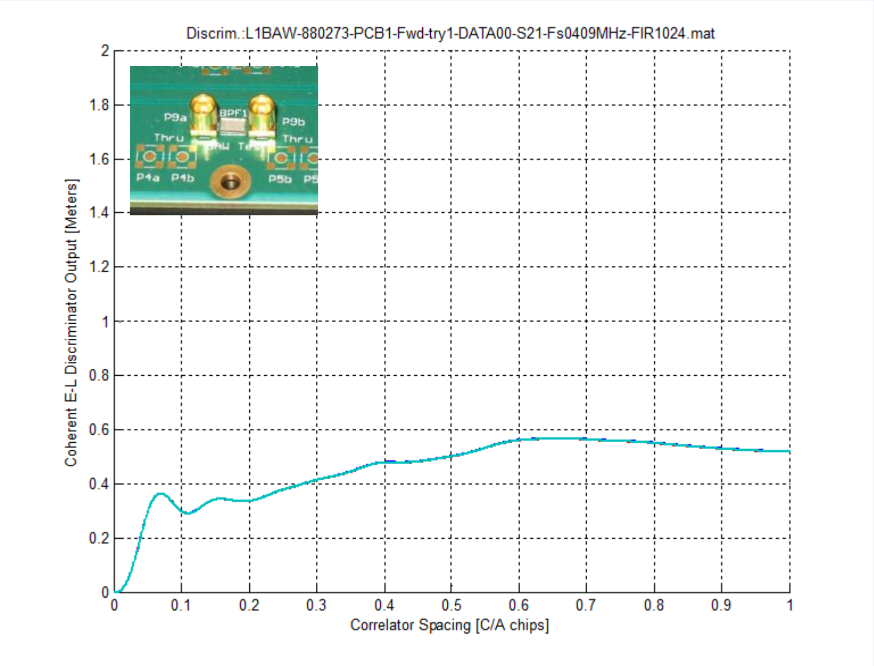


Front-End Component Effects

Surface Acoustic Wave (SAW) IF Filter



Block Acoustic Wave (BAW) RF Filter



Pseudorange Variations:

~15 cm @ 0.1 chip, ~35 cm @ 0.3 chip

~20 cm @ 0.1 chip, ~70 cm @ 0.3 chip

- Impacts precision time/time transfer receivers and FDMA signals (GLONASS)
- Geodetic-grade receivers perform in-system calibration for GLONASS FDMA
- IF SAW filters can induce cm-level inter-PRN pseudorange biases

Signal Deformation

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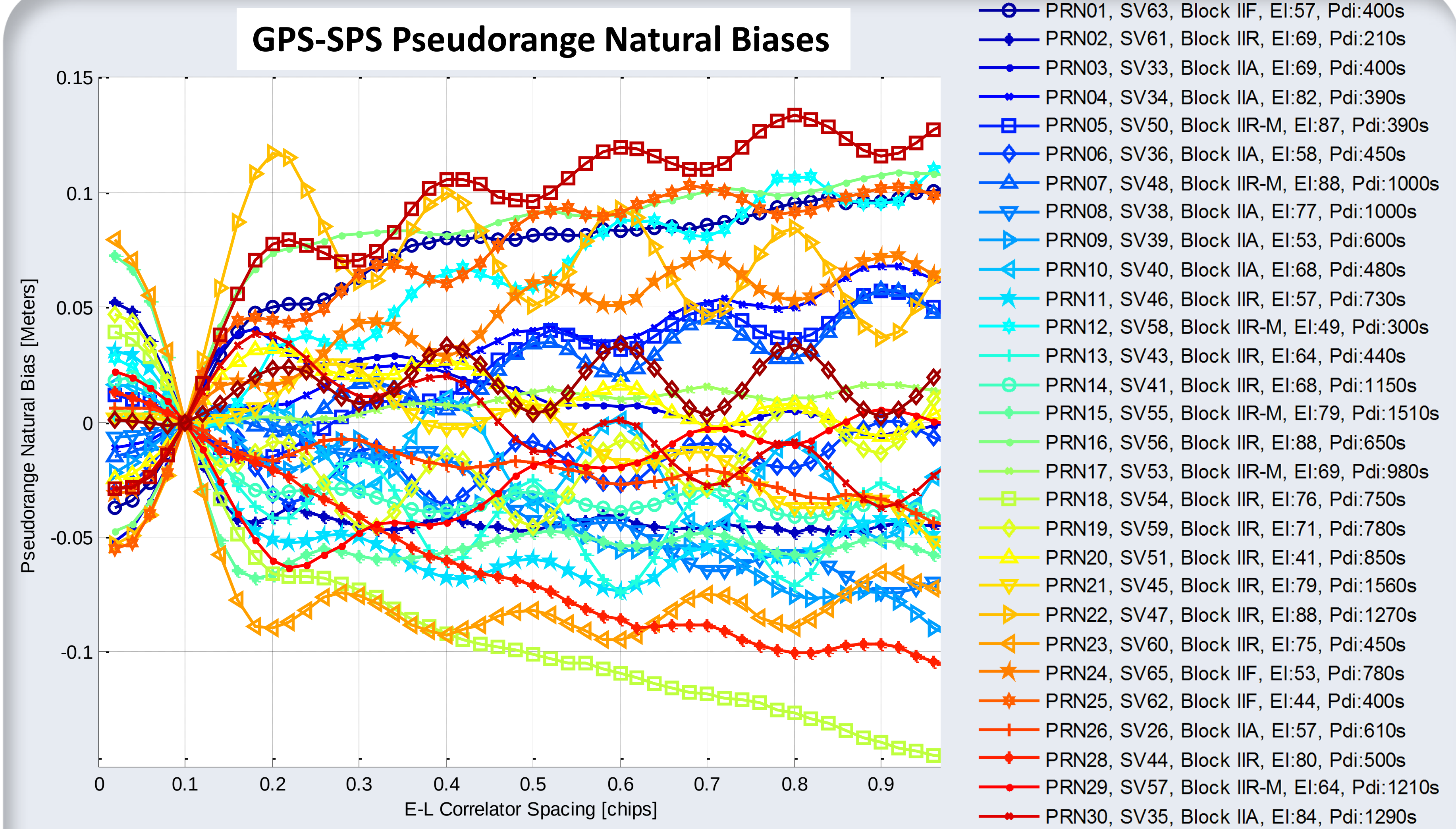


cm-level errors for differential GPS users using dissimilar receivers

Antenna and Front-End Comparison

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

Baseband Processing Comparison

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 Vision™ Correlator	Narrow-correlator Double-delta correlator Vision™ Correlator
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 (e.g. NovAtel Vision™ correlator)	Interference and signal deformation monitoring
Typical Implementation (2014)	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

Ask the Experts – Part 1

Sanjeev Gunawardena
Research Assistant Professor
Autonomy & Navigation Technology Center
Air Force Institute of Technology

Sunil Bisnath
Associate Professor
Department of Earth and Space Science and Engineering
York University, Toronto

Sandy Kennedy
Director and Chief Engineer of Core Cards
NovAtel Inc.

Poll #2

What accuracy would you like to get in the future?

- *Greater than a meter*
- *Less than a meter*
- *Meter*
- *10 centimeters*
- *Less than 10 centimeters*

Software processing requirements for precise positioning

Sunil Bisnath
Associate Professor
York University

Drivers of GNSS Performance

Performance

Quality and types of measurements	Antenna Receiver
Error modeling	Long list
Positioning mode	Point positioning Relative positioning DGNSS RTK / Network RTK PPP

Requirements for Standard Positioning

- Continuous L1 C/A-code measurements …
- From minimum of 4 GPS (GNSS) satellites …
- To compute user 3D position and receiver timing error.
- Perhaps: use of L1 carrier phase + filtering
- Quality of L1 C/A-code measurements: ~1 m + noise

Mode of operation for ~99% of users

Requirements for Precise Positioning

- Receiver
- Additional infrastructure
- Communication link
- Measurement corrections
- Data processing

Receiver Requirements

- High-performance (geodetic)
- L1 C/A-code tracking (+ L1 P(Y)-code) + L1 carrier-phase
- + L2 P(Y)-code + L2 carrier-phase
- P(Y)-code tracking at 10s cm + noise
- Carrier-phase tracking at mms + noise

Infrastructure Requirements

- A second receiver, or …
- Working within a network of receivers and receiving additional GNSS signals and corrections, or …
- Receiving additional corrections

Major Error Sources

Generation:

- Orbit errors
- Clock errors
- Phase wind-up
- Phase center offset
- Phase center variation
- Equipment delays

Transmission:

- Ionospheric refraction
- Tropospheric refraction

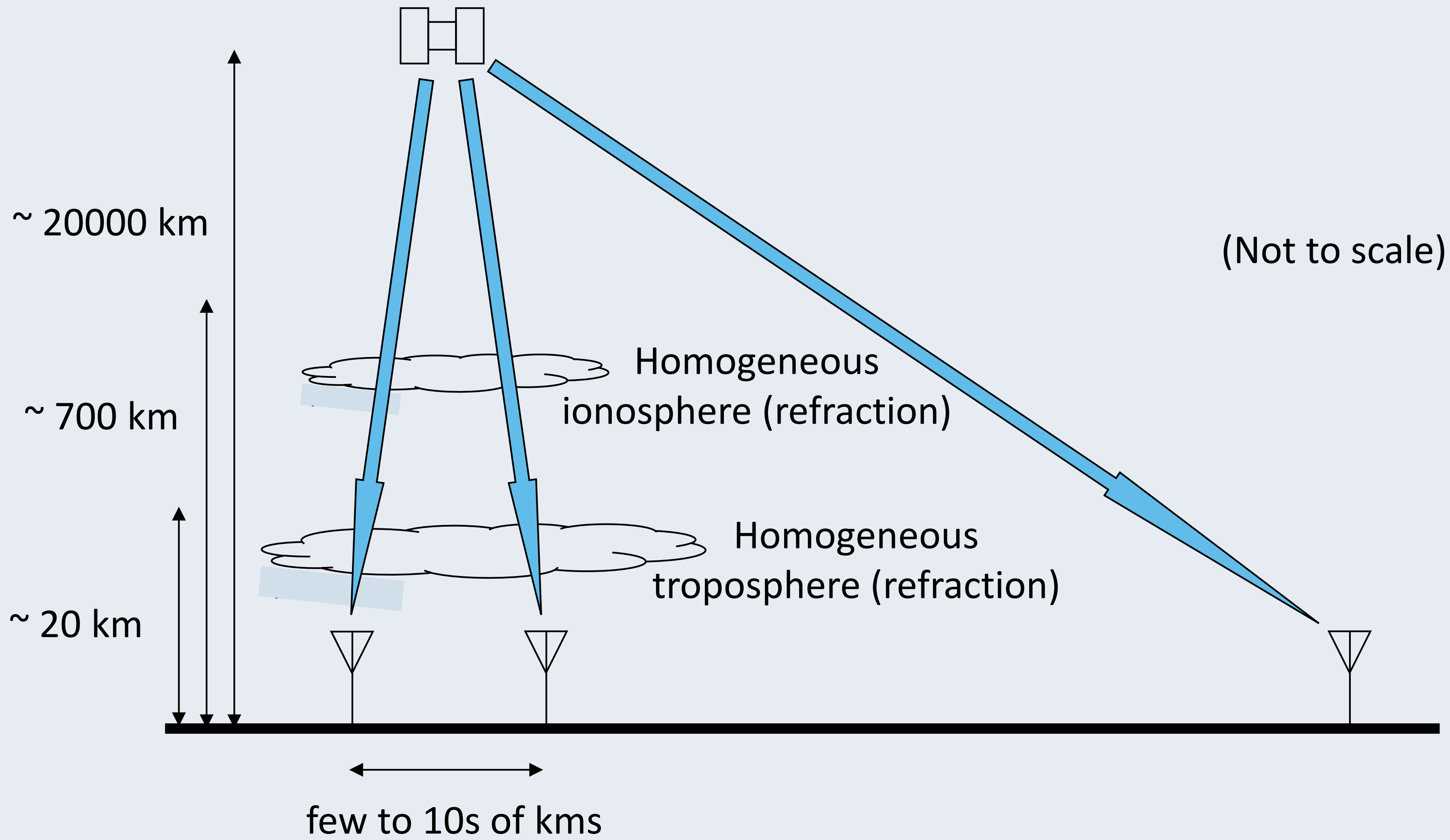
Reception:

- Multipath
- Phase center offset
- Phase center variation
- Phase wind-up
- Solid Earth tides
- Ocean loading
- Equipment delays
- Receiver noise

Error Magnitudes (inTypical PPP Processing)

Effect	Magnitude	Domain	Mitigation method	Residual error
Ionosphere	10s m	range	linear combination	mm
Troposphere	few m	range	modelling; estimation	dm - mm
Relativistic	10 m	range	modelling	mm
Sat phase centre; variation	m - cm	pos; range	modelling	mm
Code multipath; noise	1 m	range	filtering	dm - mm
Solid Earth tide	20 cm	position	modelling	mm
Phase wind-up (iono-free)	10 cm	range	modelling	mm
Ocean loading	5 cm	position	modelling	mm
Satellite orbits; clocks	few cm	pos; range	filtering	cm - mm
Phase multipath; noise	1 cm	range	filtering	cm - mm
Rcv phase centre; variation	cm - mm	pos; range	modelling	mm

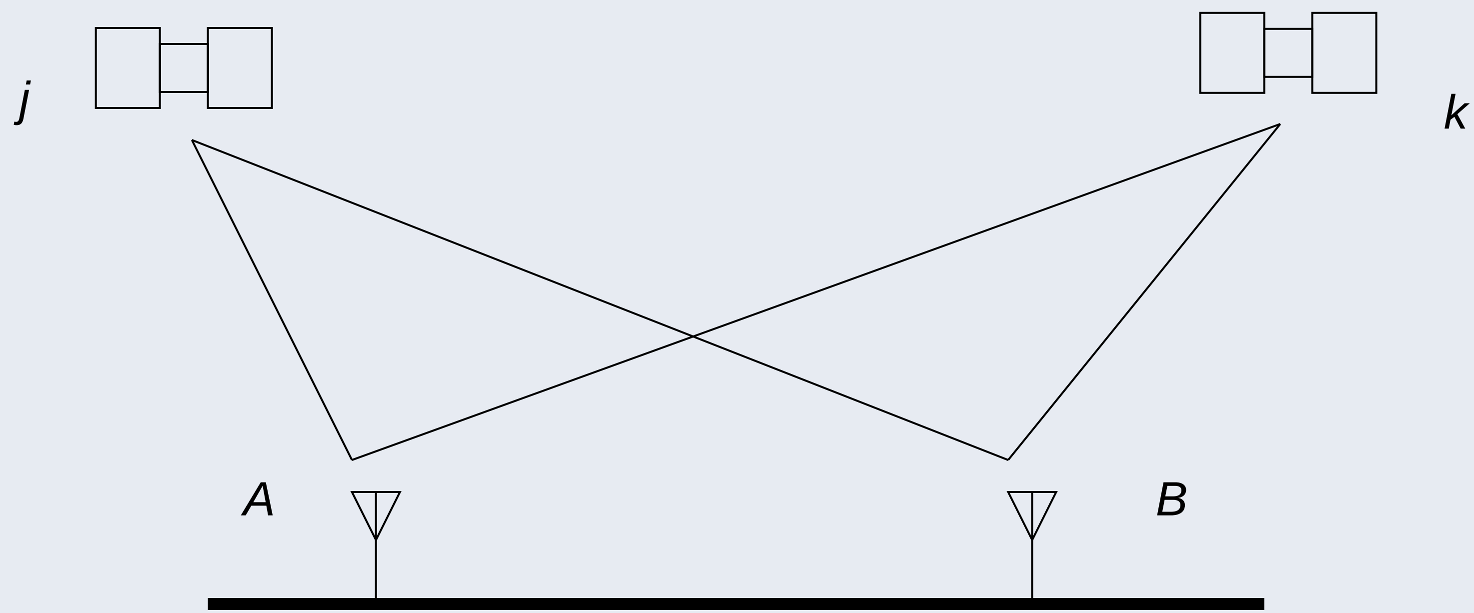
Spatial Decorrelation of Errors – Atmospheric Refraction Example



Relative Positioning

- Double-difference:

  Mathematical differencing of simultaneous measurements from two satellites *j* and *k*, and from two receivers *A* and *B*



Carrier-Phase Integer Ambiguity Resolution

1. Generation of potential integer ambiguity candidates:
   - Is “guess” integer ambiguity for double-difference satellite pair
   - More candidates → higher probability of correct ambiguity
   - Fewer candidates → faster search

2. Identification of optimum ambiguity candidate:
   - Criterion typically integer candidate which minimizes sum of square of residuals (least-squares criterion), as optimum candidate should “best” fit data

3. Validation (or verification) of selected ambiguities:
   - Assessment of correctness of integers obtained

Relative Position Accuracies

- Relative positioning accuracy varies depending on:
  - Length of data set (longer time spans better)
  - Single-frequency vs dual-frequency data (single-frequency greatly limited)
  - s/w: modeling of errors; ambiguity resolution

- Performance range:
  - mm-cm-level $\rightarrow$ Static relative positioning with many hours of data over hundreds to thousands of kms
  - Few cm-level $\rightarrow$ Kinematic relative positioning with seconds of data over a few kms -> *baseline RTK (Real-Time Kinematic)*

Network RTK Station Configuration

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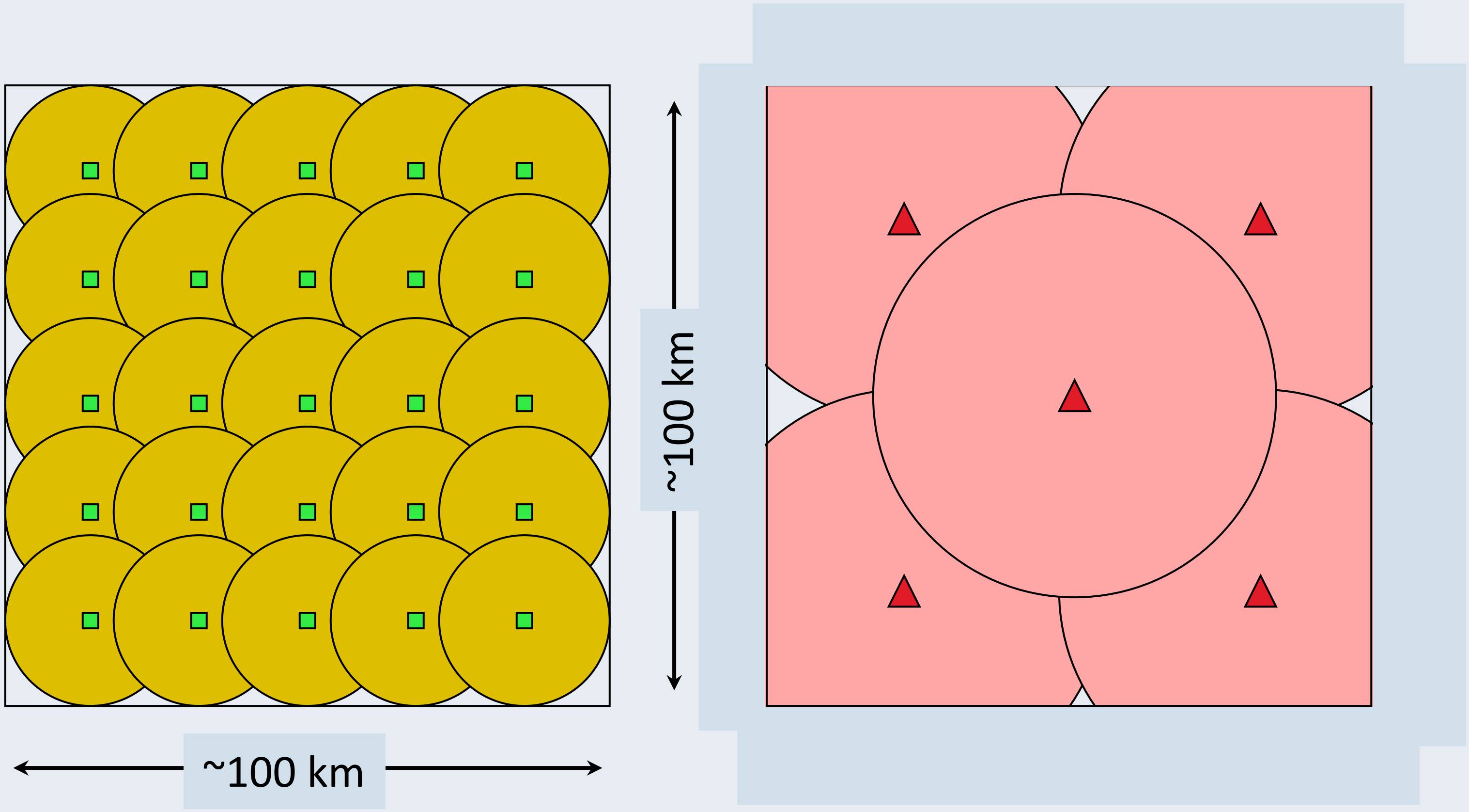
- RTK: ~25-30 reference stations per 10 000^2 km
- Network RTK: ~5-10 reference stations per 10 000^2 km



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

+

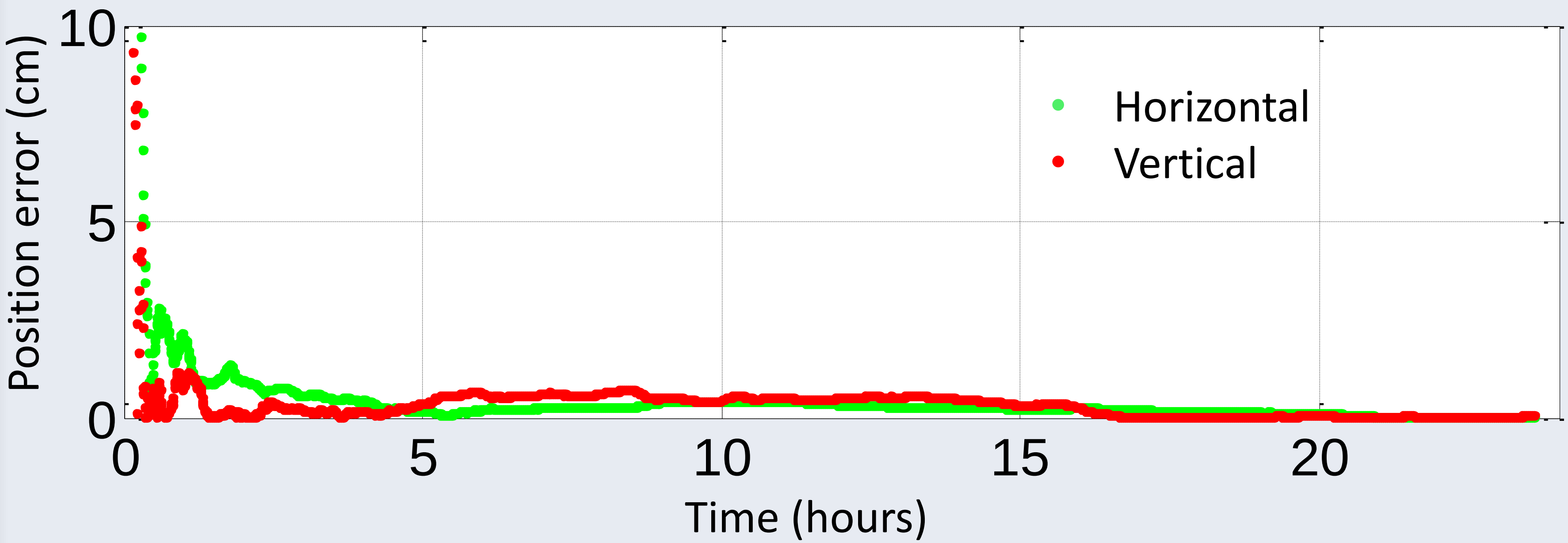
Additional error modeling

=

dm- to mm-level user position estimate

Standard PPP Positioning Performance

- A good, static GPS PPP solution over 24 hours



- Characteristic PPP initial convergence period
- Solution very sensitive to quality of measurements

Current Status and Near-Future

- RTK / network RTK mature technology $\rightarrow$ *industry standard*
- PPP is standard for high-precision, remote operation
- Infrastructure and usage continue to grow
- New GNSS signals enhancing RTK and PPP performance
  - Most network RTK services are now GPS+GLONASS
  - GPS+GLONASS PPP reduces convergence period
- Fast PPP re-convergence and PPP-AR is being commercialized
- Fast RTK-like initialization for PPP is still a goal

Practical Example

Precise Positioning Use Case

Sandy Kennedy
Director, Core Receiver Cards
NovAtel Inc.

Precision Agriculture

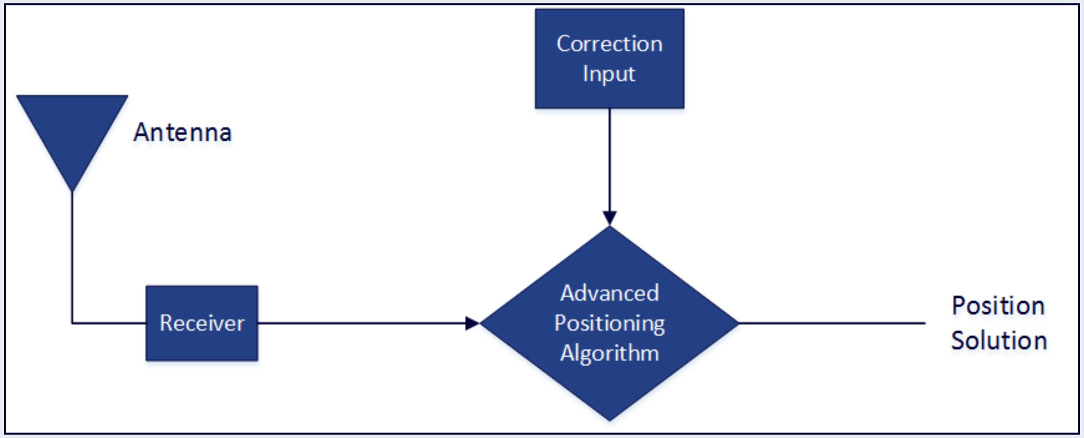
- Positioning Accuracy Requirement:
  - <10 cm
- Correction Source:
  - TerraStar-D
- Algorithm Deployed:
  - Precise Point Positioning

- Rationale for Choice:
  - Meets accuracy requirement
  - Primarily open sky, means good line of sight to geostationary satellite providing corrections
  - No extreme maneuvers (i.e. no barrel rolls), so should have a continuous solution

GNSS Measurement Source

- Antenna
  - Needs to be able to receive correction signal and GPS/GLO L1/L2
  - Front door to the receiver

- Receiver:
  - Capable of tracking TerraStar-D correction signal
  - GPS/GLO L1 and L2 capable
  - Minimized multipath via Pulse Aperture Correlator technology
  - PPP engine on board

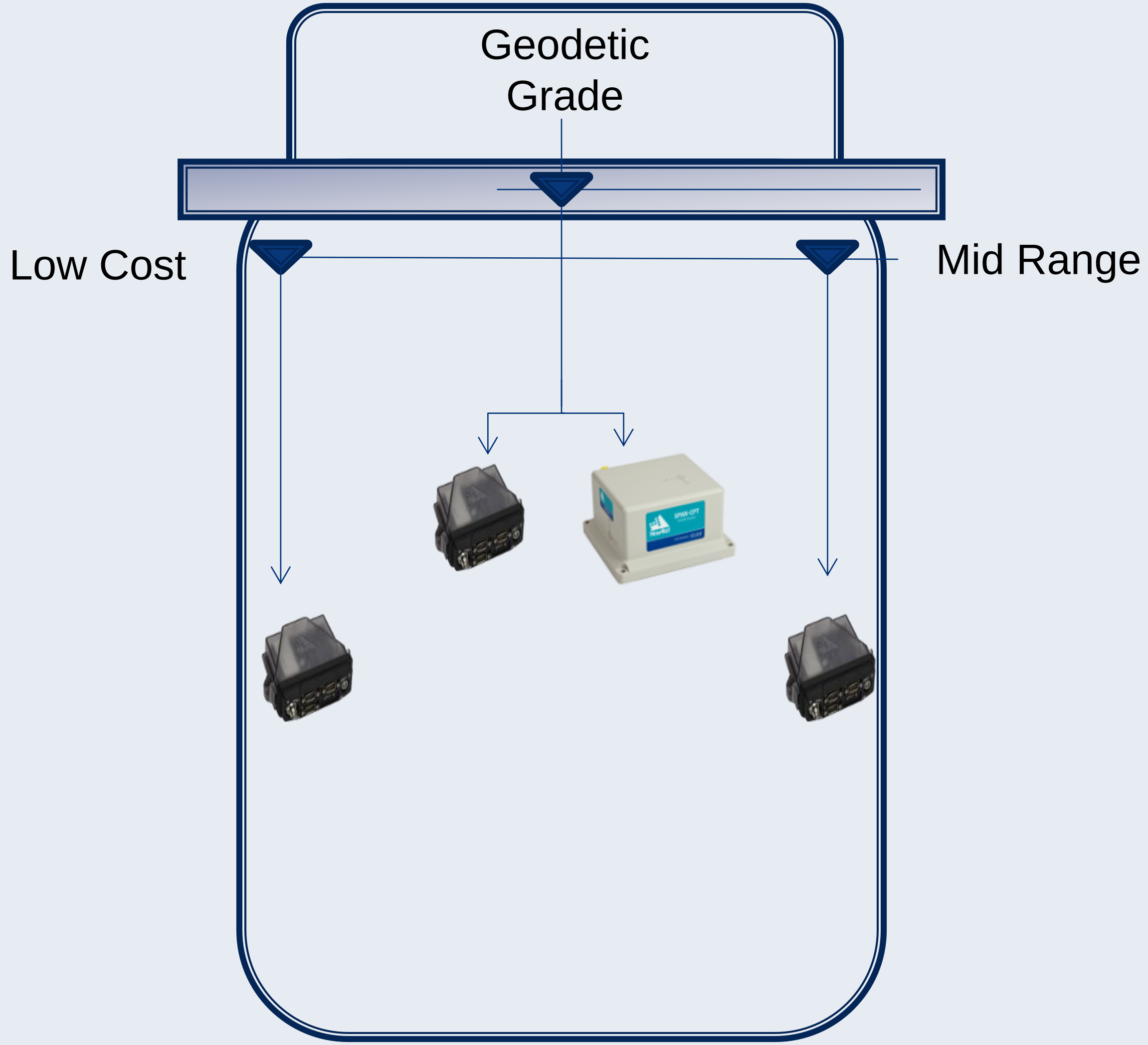


Antenna Choice

- Antennas are often taken for granted
- Often viewed as a cost saving opportunity

- 3 antenna choices
  - Top quality, “geodetic grade” antenna
  - Mid-range antenna, still good quality but some design compromises
  - Low-cost antenna that claims to support all necessary frequencies:
    - Correction signal = 1525-1550 MHZ
    - GPS L1 = 1575.42 MHz
    - GPS L2 = 1227.60 MHz
    - GLO L1 = 1601.66 MHz (centre)
    - GLO L2 = 1245.73 MHz (centre)

Test Van Setup



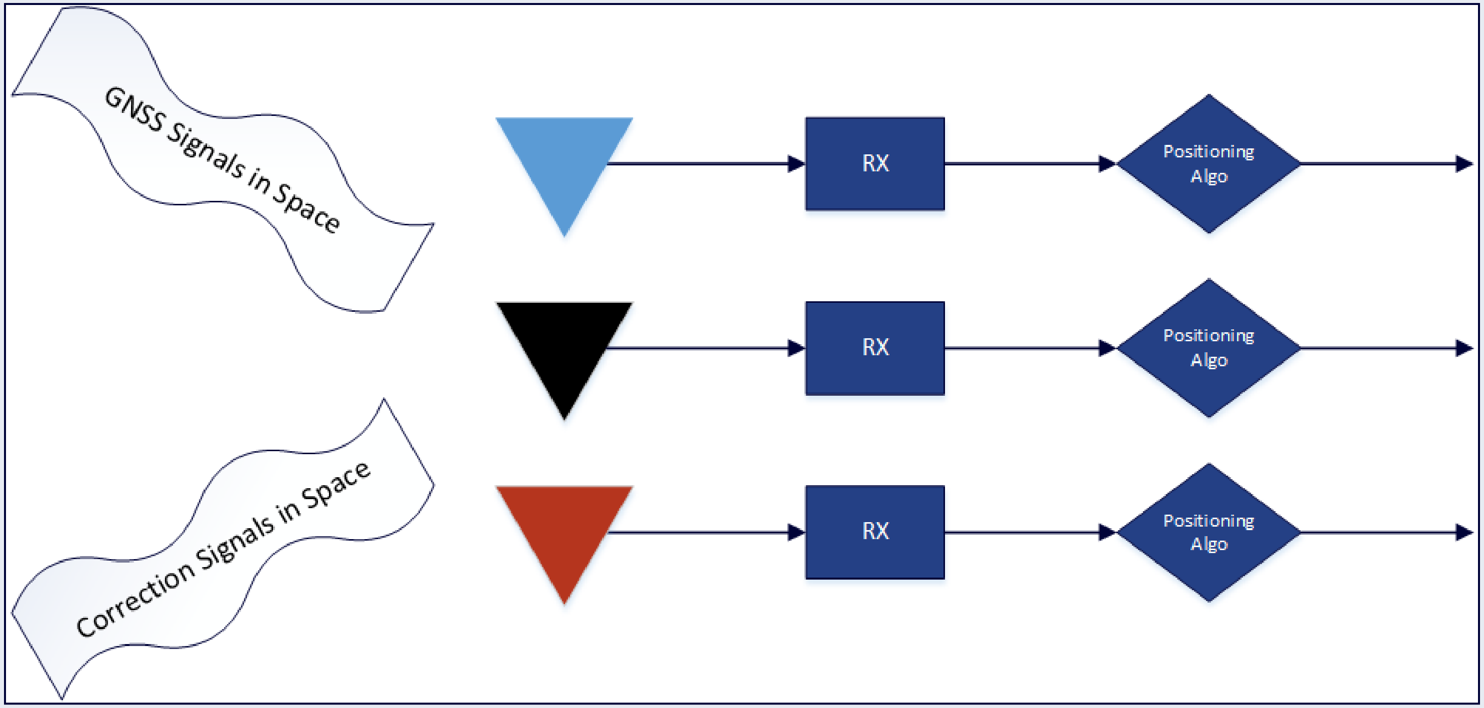
Position Error Computation

- Reference system:
  - SPAN GNSS/INS with own antenna, post processed for best accuracy solution
  - Provides attitude
  - Measured offset vectors (lever arms) between reference antenna and test antennae
- Position errors measured by moving the reference solution to each Unit Under Test location and differencing the reference and UUT trajectories
- Drove a route with a good clear sky view

Recap Test Setup

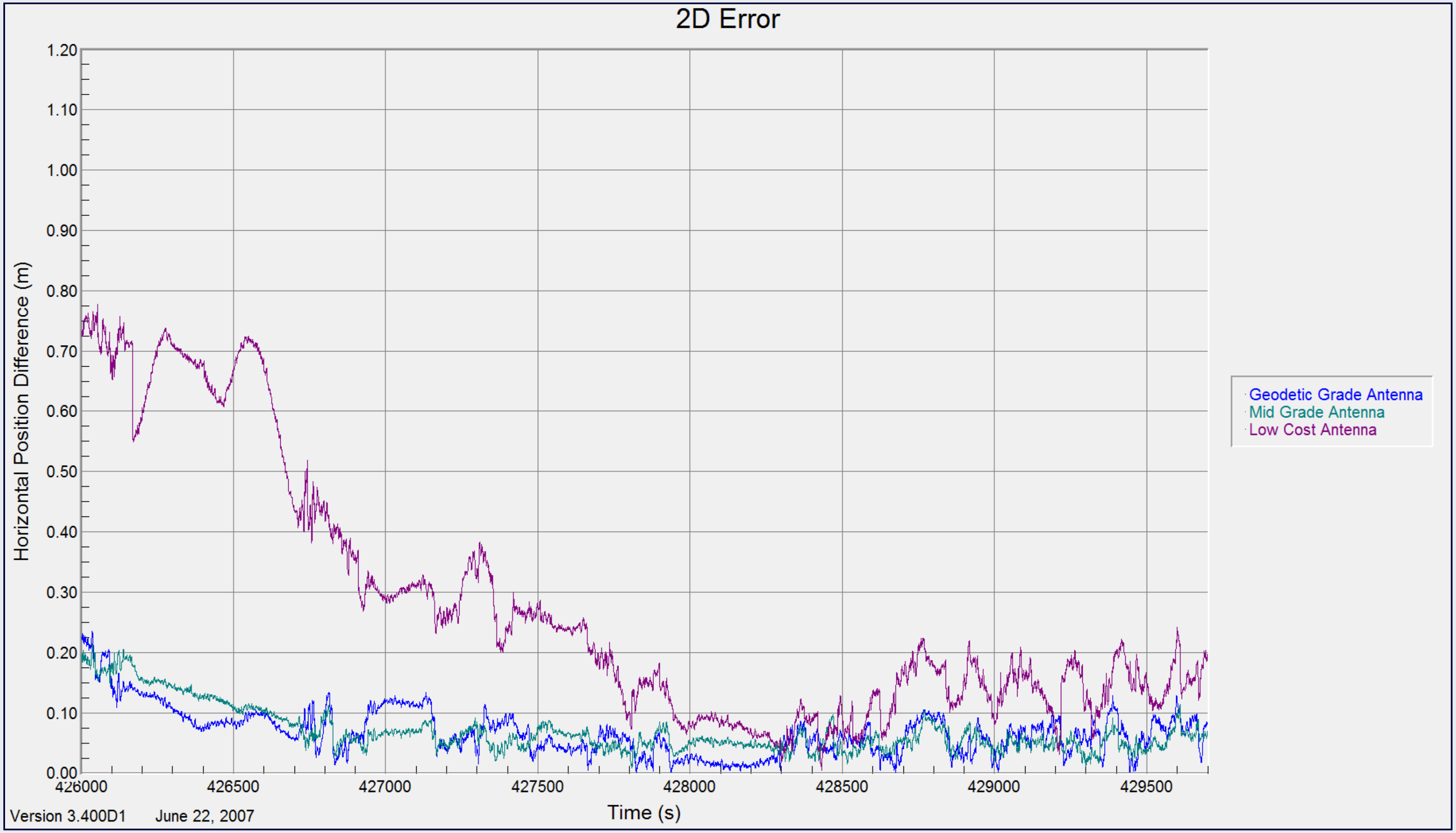
- Same signals in space
- Same receiver model
- Same algorithm

- Only difference is the antenna



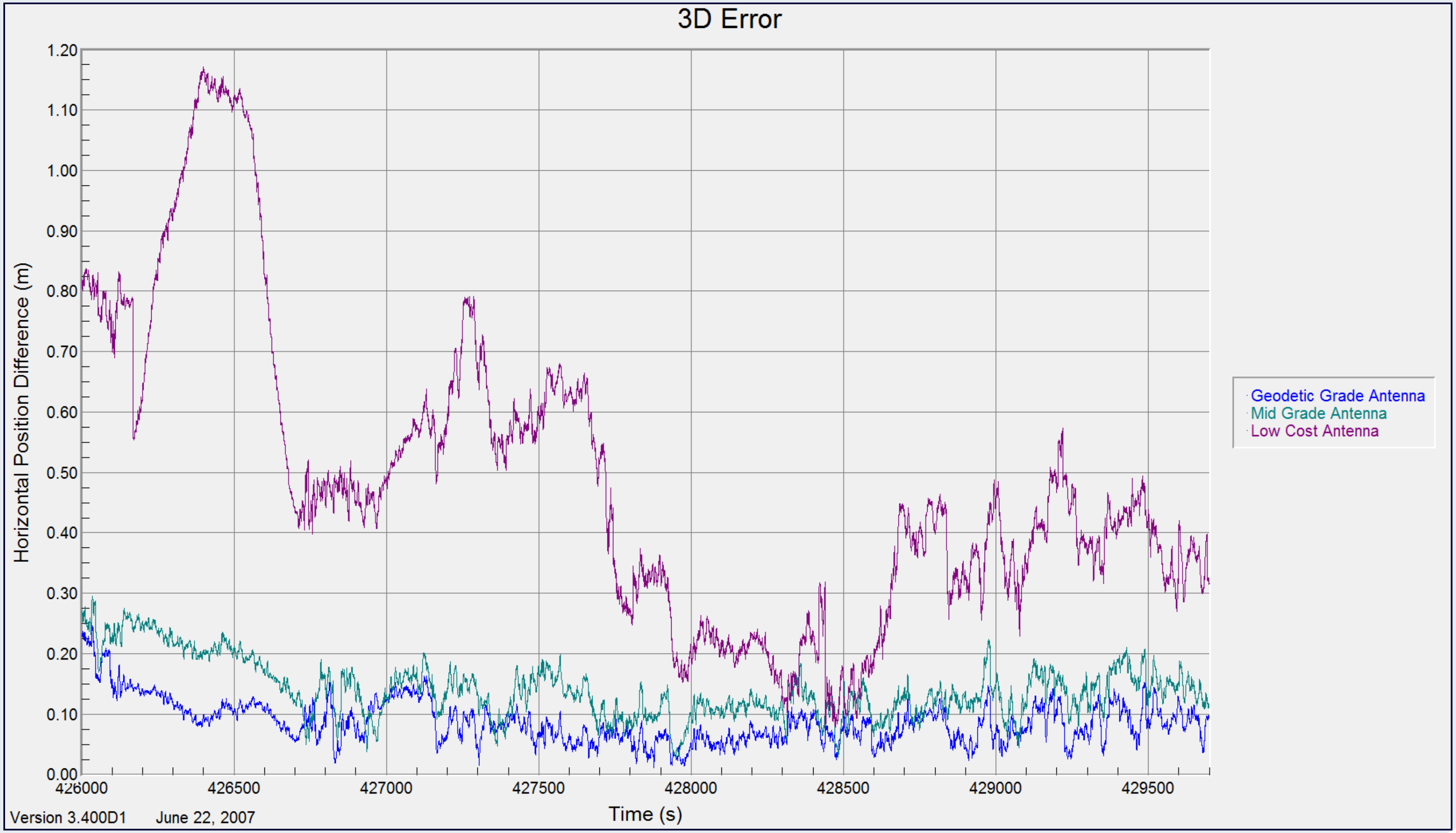
Positioning Errors

2D Error



Positioning Errors

3D Error

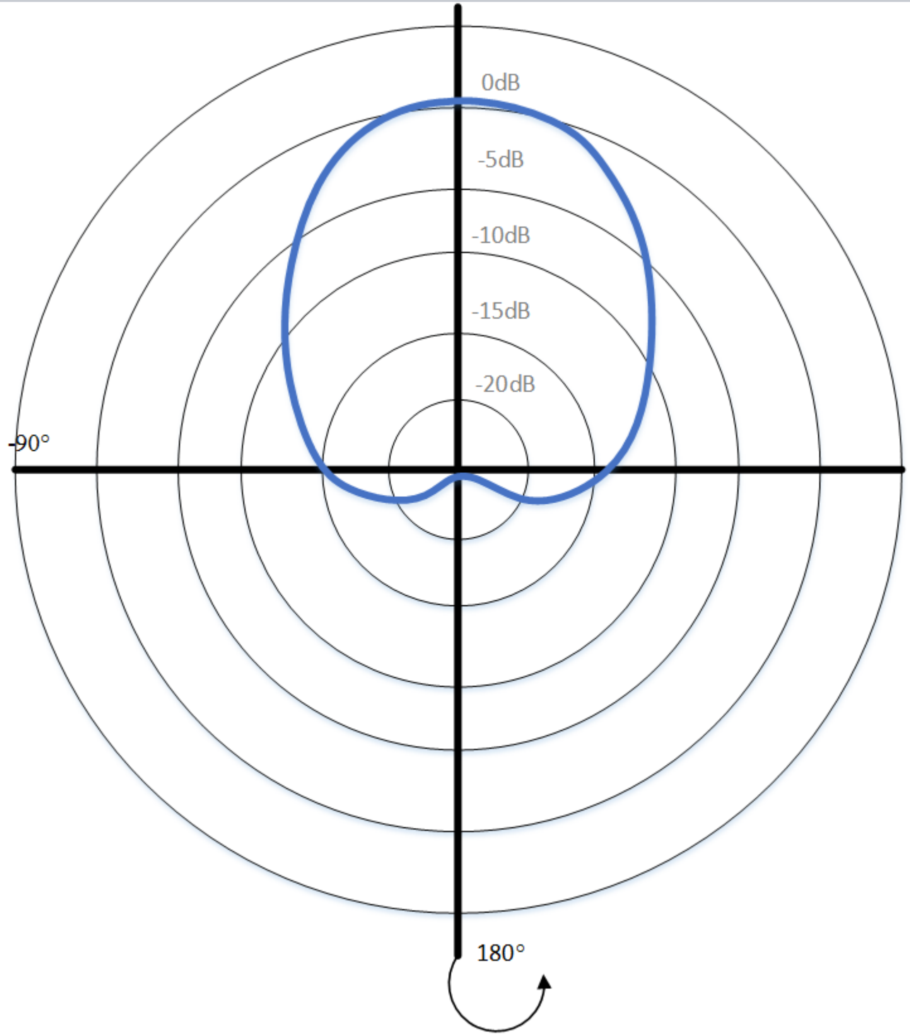


What Happened?

- Troubleshooting eliminate usual suspects
  - Subscription issue?
  - Pigeon sitting on one antenna?

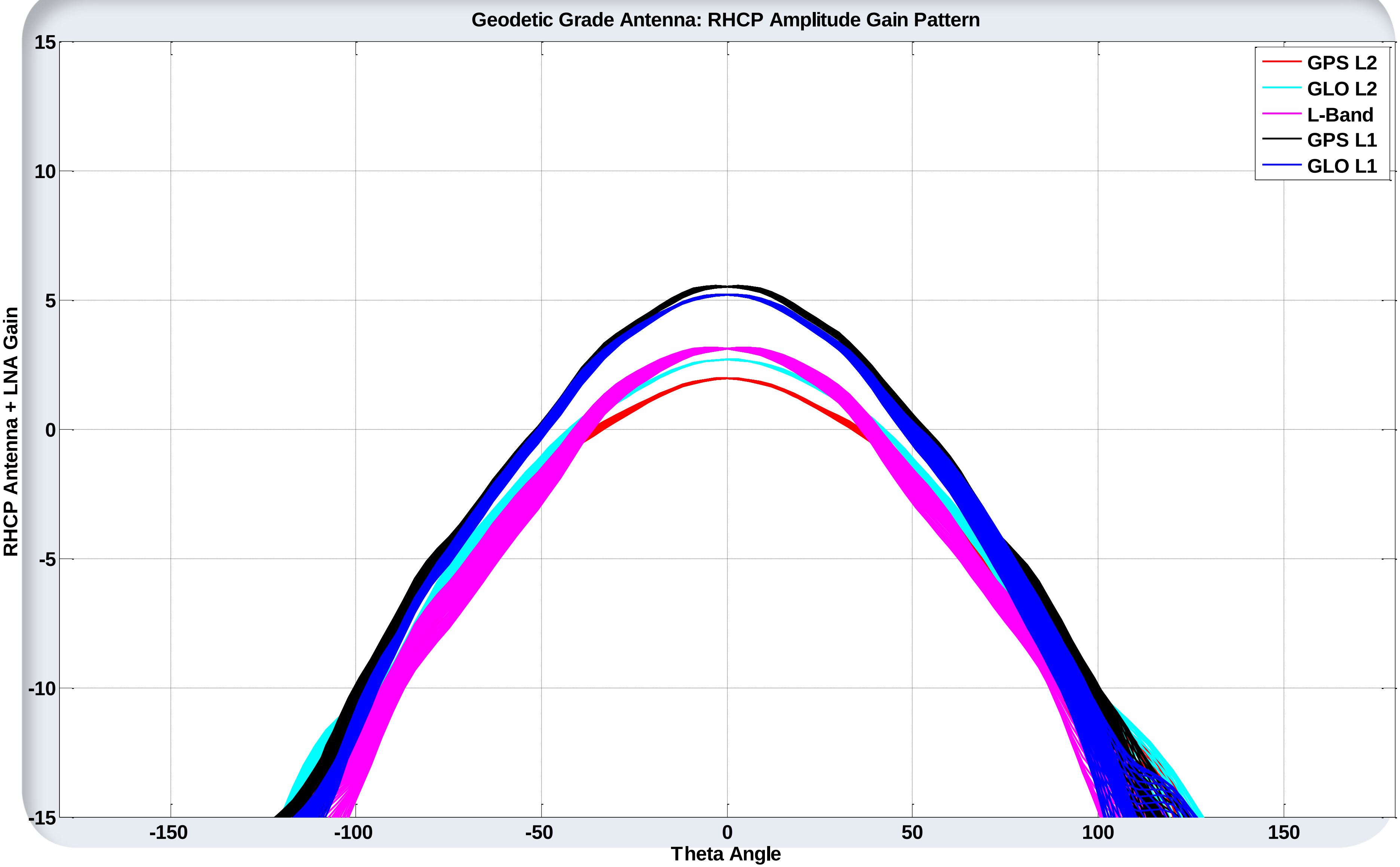
- Root cause:
  - Antenna Performance
  - What does frequency support really mean?

Ideal Antenna Gain Pattern

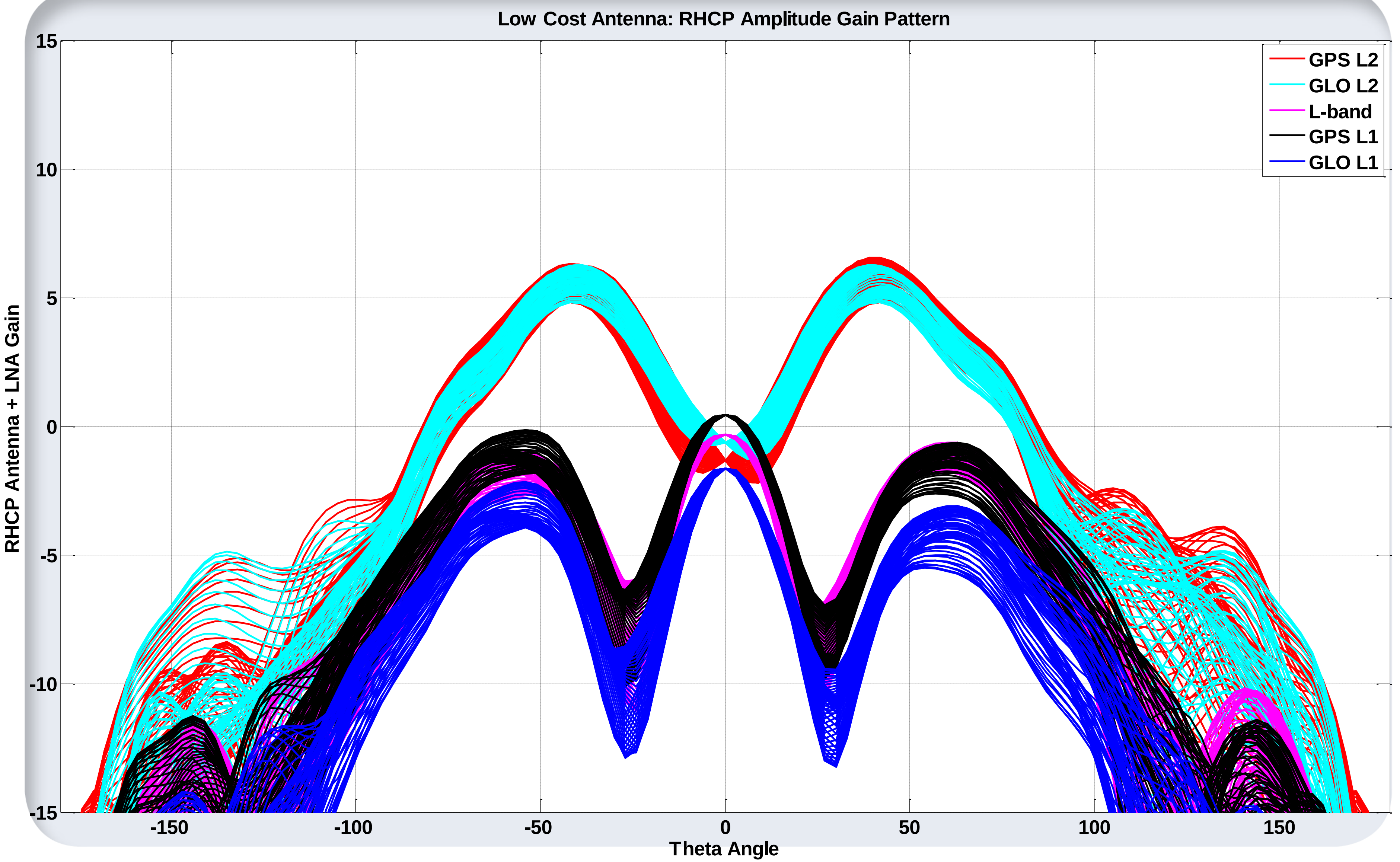


Ideal antenna gain pattern is described by rotating this cross section around the zenith axis

Geodetic Grade Antenna Gain Pattern



Low Cost Antenna Gain Pattern



Conclusion

- Know your measurement chain!
- Maintain signal quality at each component
- Trade off where you can, but don't sacrifice the fundamentals

- Enjoy your <10cm positioning!

Next Steps

Visit www.insidegnss.com/webinars for:

- PDF of Presentations
- Bibliography

To contact today's panel, email:

info@insidegnss.com

Poll #3

What additional functionality would you like to have in your GNSS? (Select up to two)

- Higher accuracy
- Greater availability/robustness
- Greater redundancy
- Greater integrity

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Ask the Experts – Part 2

Sanjeev Gunawardena
Research Assistant Professor
Autonomy & Navigation
Technology Center
Air Force Institute of Technology

Sunil Bisnath
Associate Professor
Department of Earth and Space
Science and Engineering
York University, Toronto

Sandy Kennedy
Director and Chief Engineer
of Core Cards
NovAtel Inc.

Inside GNSS @ www.insidegnss.com/
NovAtel @ www.Novatel.com

A word from the sponsor

Sara Masterson, P. Eng.

New Business
Development Manager
NovAtel, Inc

NovAtel @ www.Novatel.com