Navigation Accuracy and Interference Rejection for an Adaptive GPS Antenna Array

David S. De Lorenzo, Jason Rife, Per Enge
Stanford University GPS Lab

Dennis Akos
University of Colorado

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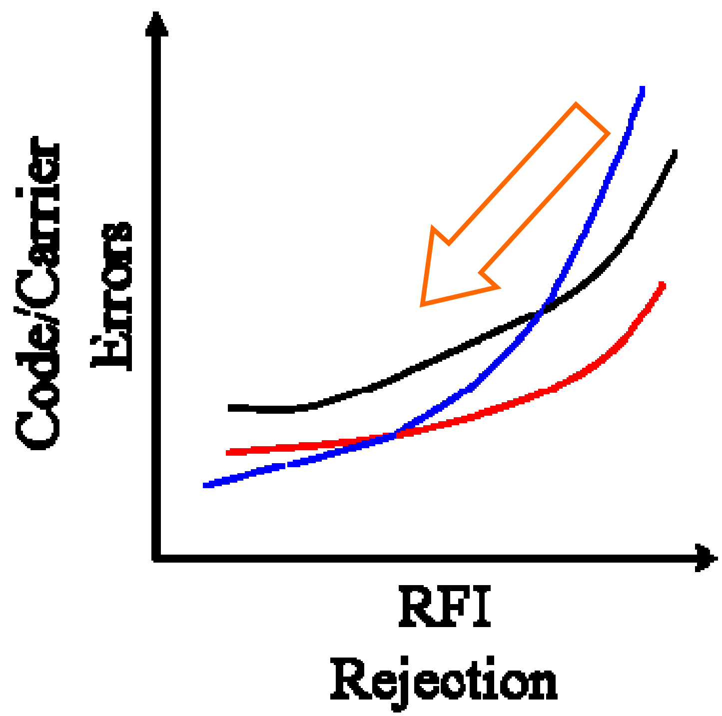
Constrained Adaptive Processing

- JPALS has stringent limits on pseudorange & carrier-phase errors
  - Required to meet carrier-landing accuracy limits.
- GPS antennas introduce distortion on received signals
  - Apparent as deterministic pseudorange and carrier phase biases
  - Dependent on the incoming signal line-of-sight.
- JPALS will likely require multi-element STAP algorithms to improve C/No under jamming & RFI conditions.
- STAP algorithms can introduce additional pseudorange and carrier phase biases.

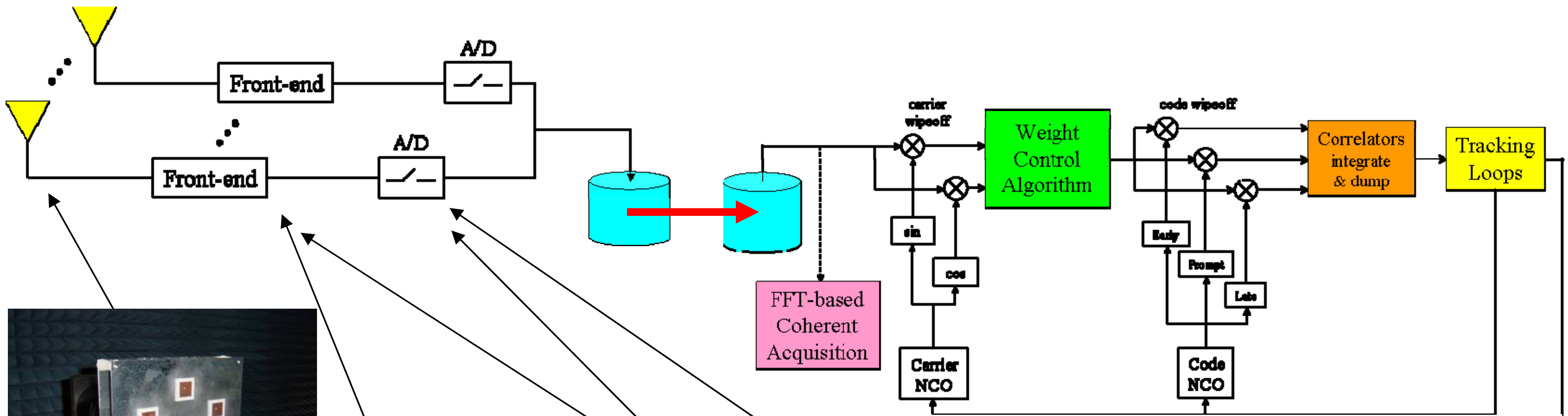
Goal: Through temporal & spatial constraints on a STAP algorithm, move down & left in the trade space, to a point where deterministic pseudorange & carrier phase corrections based on signal LOS can be applied.

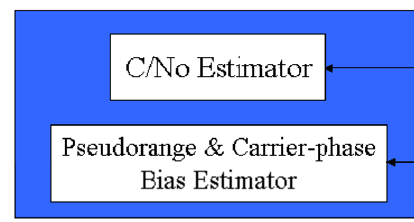


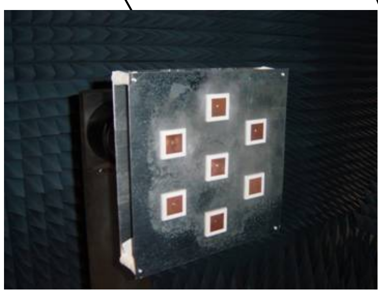
Outline

- Software tools for signal simulation & tracking
  - Signal simulator
    - C/A or P-code signal generator that includes antenna distortion effects
  - Software receiver
    - Tracks a wide range of GNSS signals – GPS C/A & P-code, Galileo L1 & E6
    - Includes multi-antenna and space-time adaptive signal processing
- Verification of software receiver & multi-signal tracking performance
- Research methodology:
  - Characterize biases vs. RFI rejection
  - Evaluate different compensation schemes
- Preliminary results
  - FRPA vs. CRPA biases and interference rejection

Stanford HW & SW Development







7-element array
rectangular patch antennas manufactured at Stanford University

Analog front-end
4-channel GP2015 with 10 MHz common clock

HP Vector Signal Analyzer

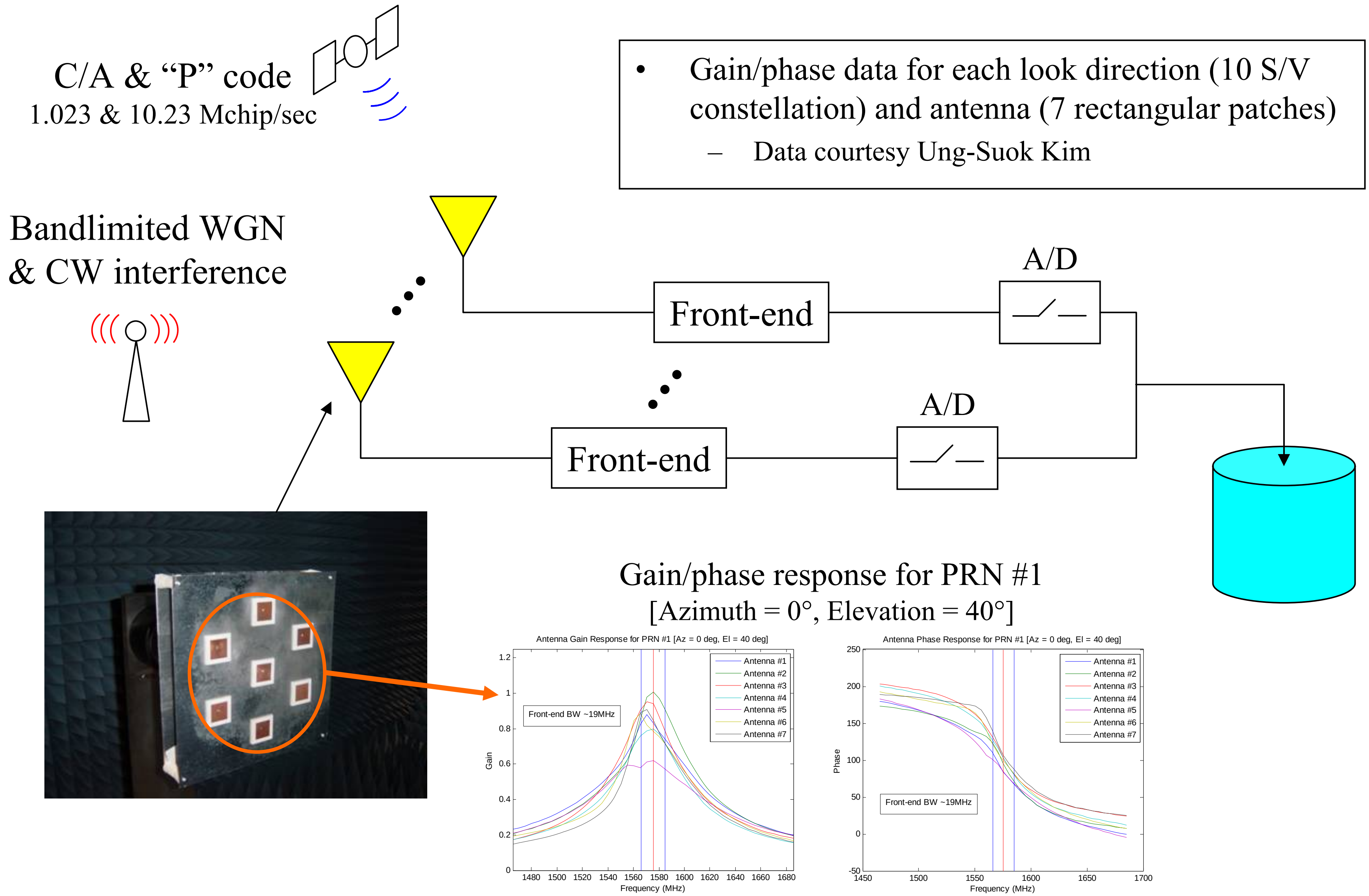
Data collection computer
(2) ICS-650 cards sampling at 5-65 MHz and 12-bit A/D resolution

Software Receiver
all-in view, multi-signal GNSS receiver with STAP array processing

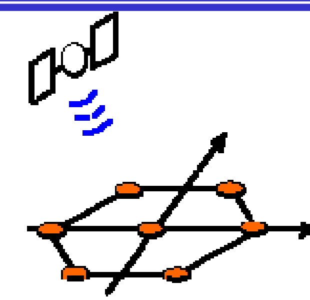
2m high-gain dish

* Possibility of including data from OSU's multi-element antenna array.

Software-Based Signal Simulator



Signal Generation at Intermediate Freq.

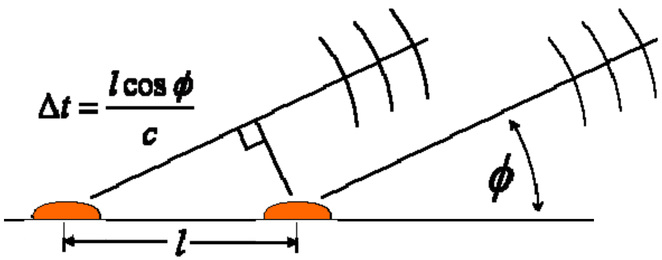


- Received signal at master element:

$$\sqrt{2P_S}\cdot D(t-\tau)\cdot x(t-\tau)\cdot\cos\left[2\pi\left(f_{L1}+f_D\right)t+\theta\right]$$

- Mixing signal:

$$\sqrt{2}\cdot\cos\left[2\pi\left(f_{L1}-f_{IF}\right)t\right]$$



- Signal after LPF:

$$\sqrt{P_S}\cdot D(t-\tau)\cdot x(t-\tau)\cdot\cos\left[2\pi\left(f_{IF}+f_D\right)t+\theta\right]$$

- Received signal at subsidiary element:

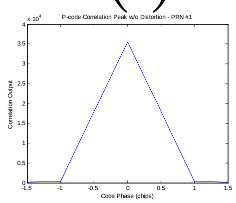
$$\sqrt{2P_S}\cdot D(t+\Delta t-\tau)\cdot x(t+\Delta t-\tau)\cdot\cos\left[2\pi\left(f_{L1}+f_D\right)(t+\Delta t)+\theta\right]$$

- Signal after mixing & LPF:

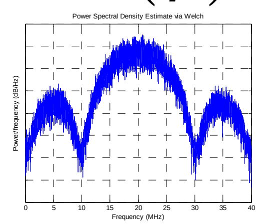
$$\sqrt{P_S}\cdot D(t+\Delta t-\tau)\cdot x(t+\Delta t-\tau)\cdot\cos\left[2\pi\left(f_{IF}+f_D\right)t+\theta+2\pi\left(f_{L1}+f_D\right)\Delta t\right]$$

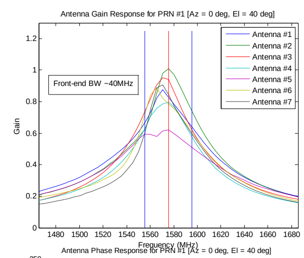
Signal Generation w/ Antenna Distortion

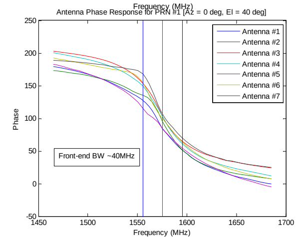
$s(t) \rightarrow$ fft $\rightarrow S(f)$



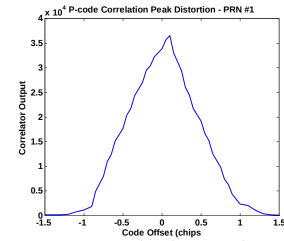
Autocorrelation of *s(t)*







$\otimes \rightarrow fft^{-1} \rightarrow s_{out}(t)$



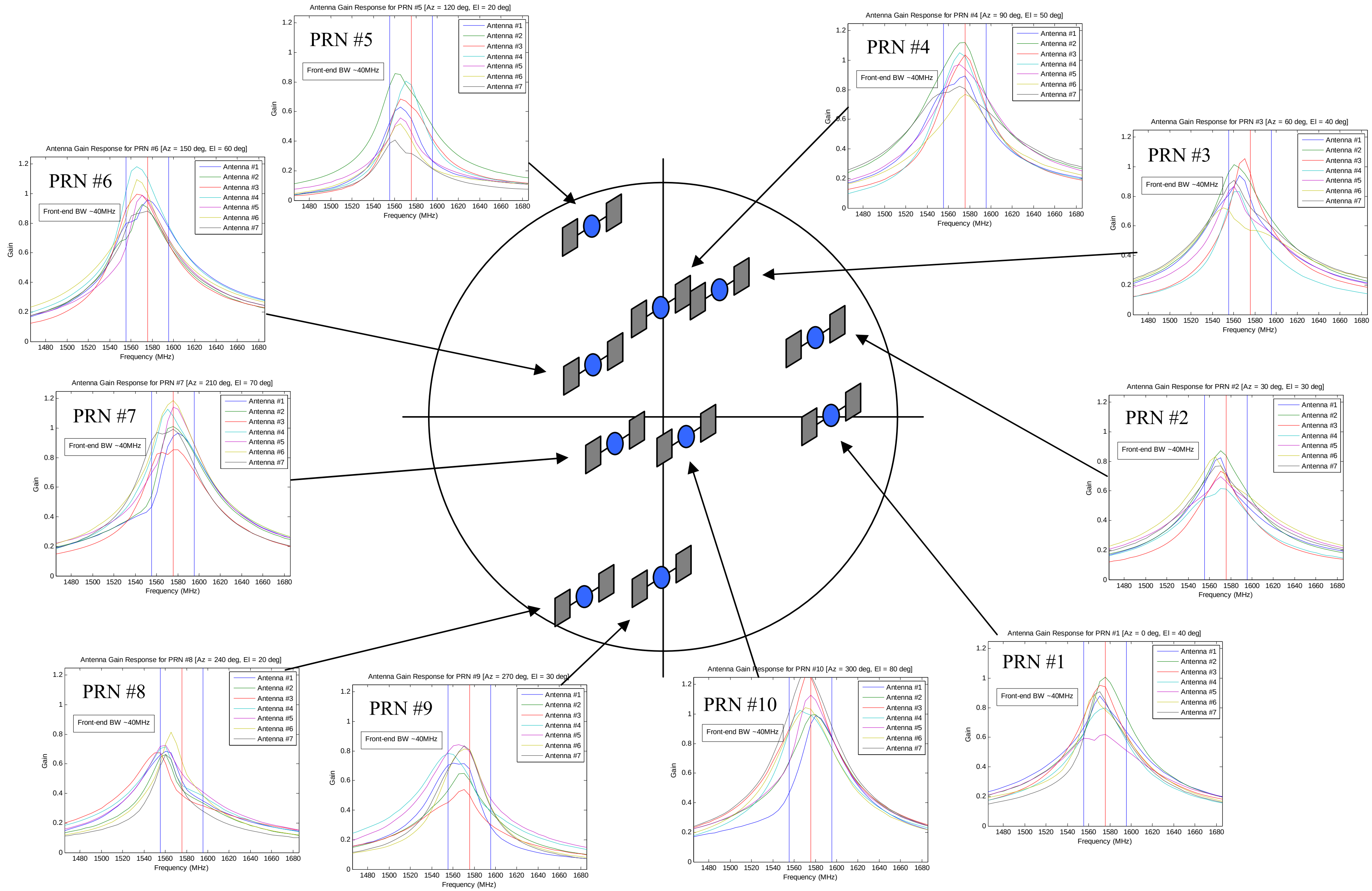
Autocorrelation of $s_{out}(t)$

Gain/phase distortion data available from HFSS simulation

- Verified by comparison to anechoic chamber testing
- Data courtesy Ung-Suok Kim

$s(t)$ and gain/phase data are antenna & S/V specific

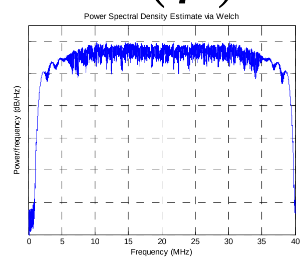
Standard Satellite Constellation



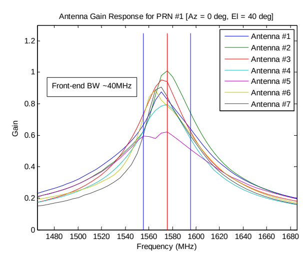
Wideband Jammer Signal Generation at IF

$$j(t) \longrightarrow \boxed{fft} \longrightarrow J(f)$$

- For each jammer – six swept sinusoids cover frequency band from ~0 Hz to ~$f_s/2$
- Amplitude scaled as needed to achieve desired J/S ratio



$$\otimes \longrightarrow \boxed{fft^{-1}} \longrightarrow j_{out}(t)$$

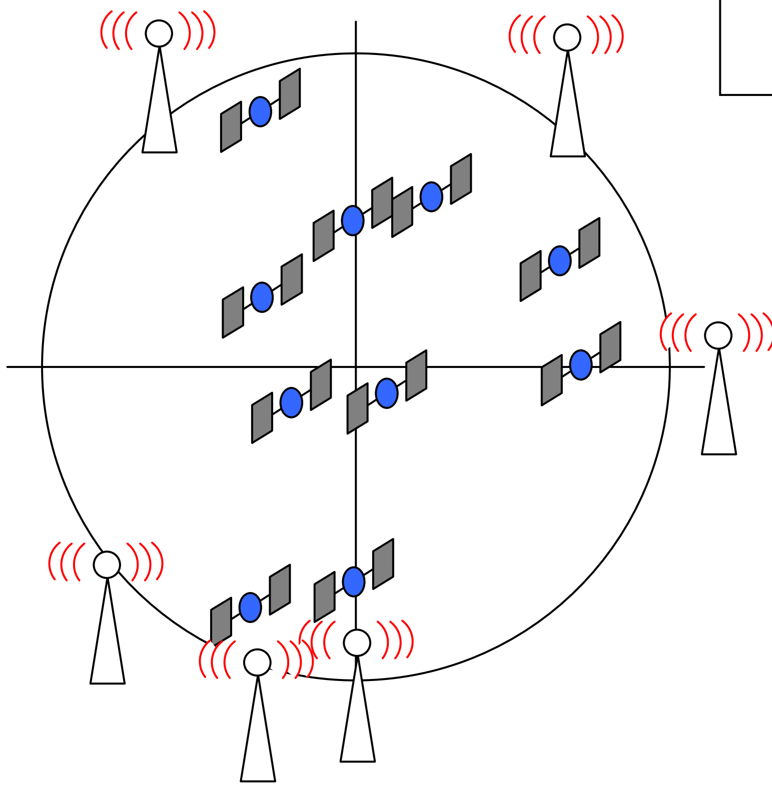


Gain/phase distortion data are currently not available $\Longrightarrow$ $j(t) \equiv j_{out}(t)$

$$\sqrt{2P_J} \cdot \sum_i \cos\left[2\pi\left(f_{IF} + f_{J_i}\right)t + f_J'(t+\Delta t)^2 + 2\pi\left(f_{L1} + f_{J_i}\right)\Delta t\right]$$

Satellite & RFI Constellation

PRN	Azimuth	Elevation
1	0	40
2	30	30
3	60	40
4	90	50
5	120	20
6	150	60
7	210	70
8	240	20
9	270	30
10	300	80



Bandlimited WGN and/or CW interference

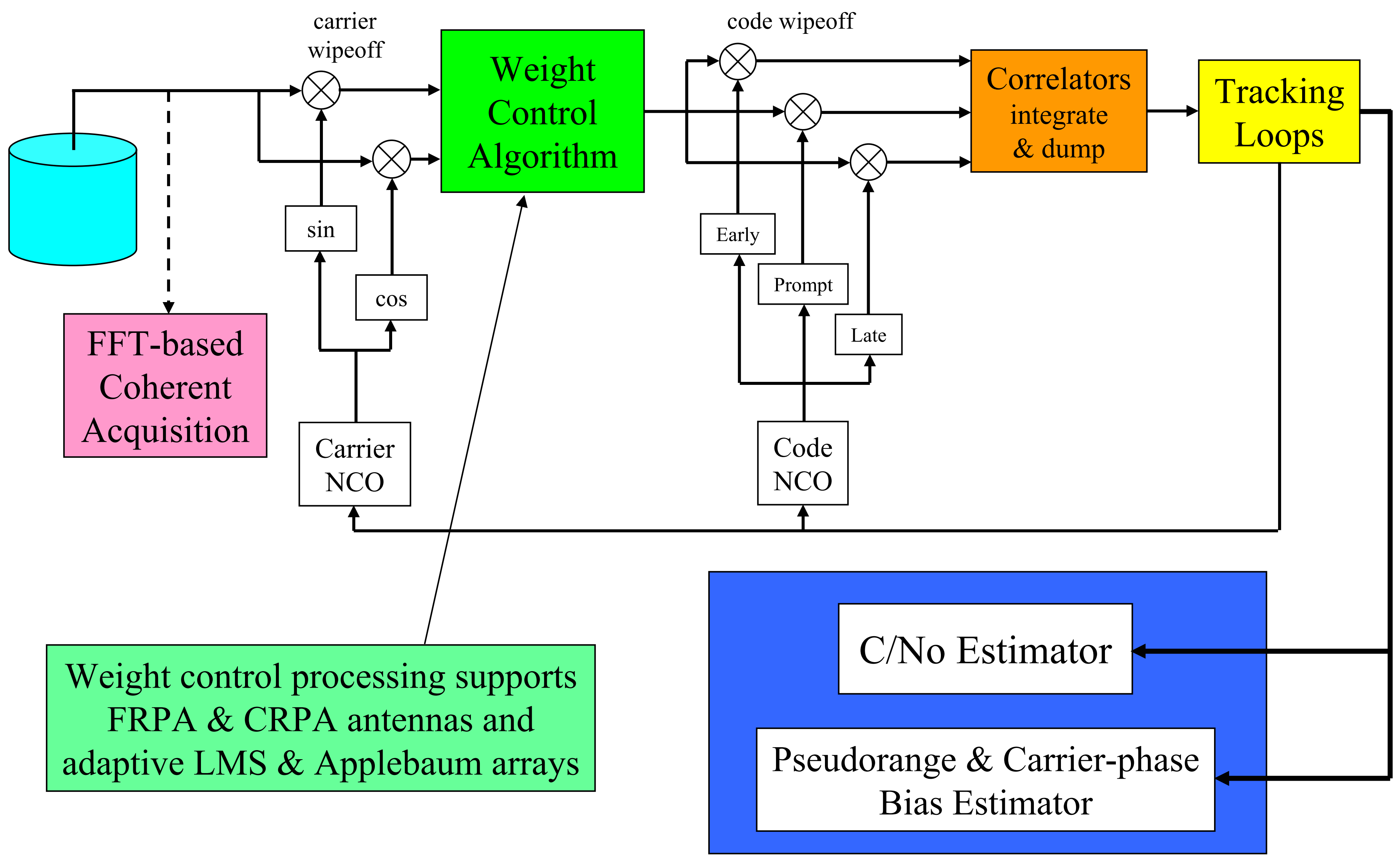
RFI	Azimuth	Elevation
1	0	0
2	45	0
3	120	0
4	225	0
5	250	0
6	270	10

Multi-signal Software GNSS Receiver

- Software Receiver tracks a wide range of GNSS signals, runs in MATLAB
  - GPS C/A and pseudo-P-codes
  - Galileo L1-B/C and E6-B/C codes
- Includes multi-antenna and space-time adaptive signal processing
- Supports arbitrary sampling frequency, intermediate frequency, data format, etc.
  - The ideal s/w rcvr is fast, flexible, & uncomplicated

You can have 2 out of 3!!

Software Receiver Block Diagram



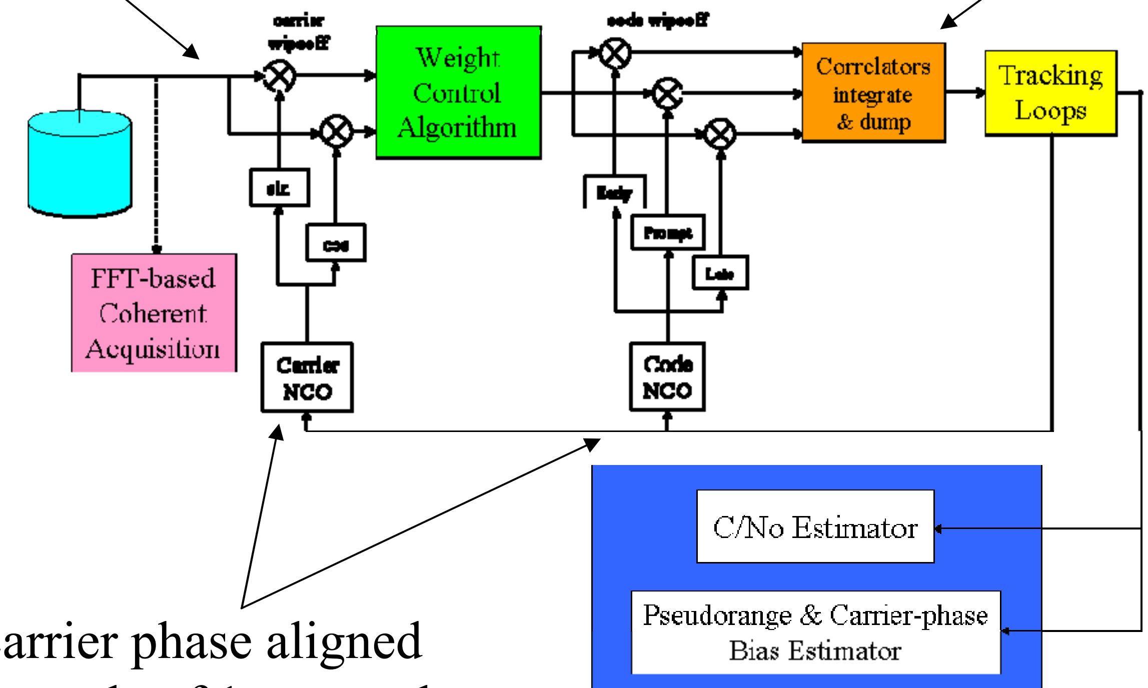
Software Receiver Flow Chart

Discrete operation from stored data → sample indexing & alignment

For each tracking channel: 1ms sample buffer aligned w/ start of spreading code

This loop runs on a 1ms schedule

Noncoherent or coherent integration depends on nav. data bit alignment

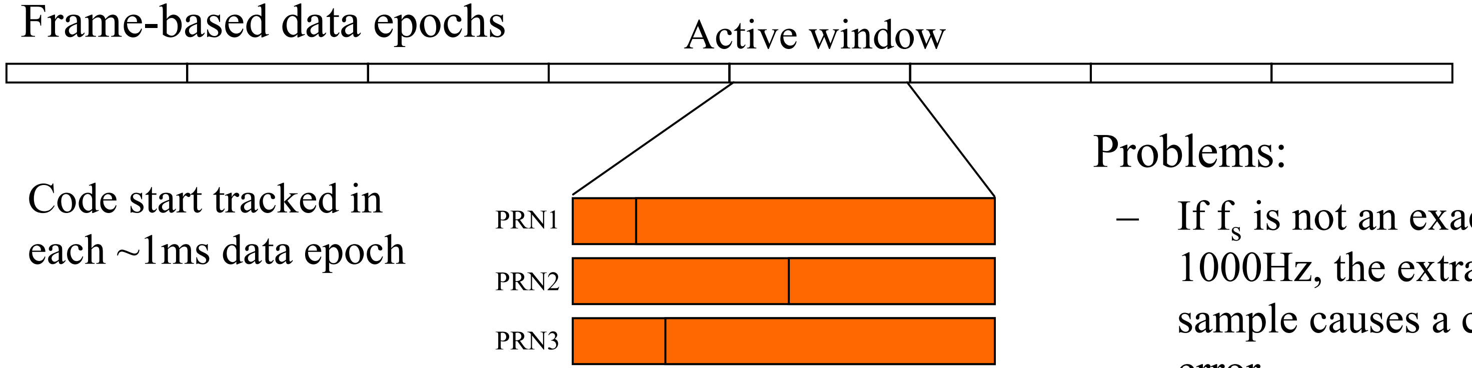


The devil is in the details

Code/carrier phase aligned w/ first sample of 1ms epoch

Epoch-based Tracking of GNSS Codes

Frame-based data epochs



Code start tracked in each ~1ms data epoch

Problems:

- If f_s is not an exact multiple of 1000Hz, the extra fractional sample causes a code-phase ramp error
- Approaching/receding satellites will cause code wrap (phase skew), leading to dropped sample epochs

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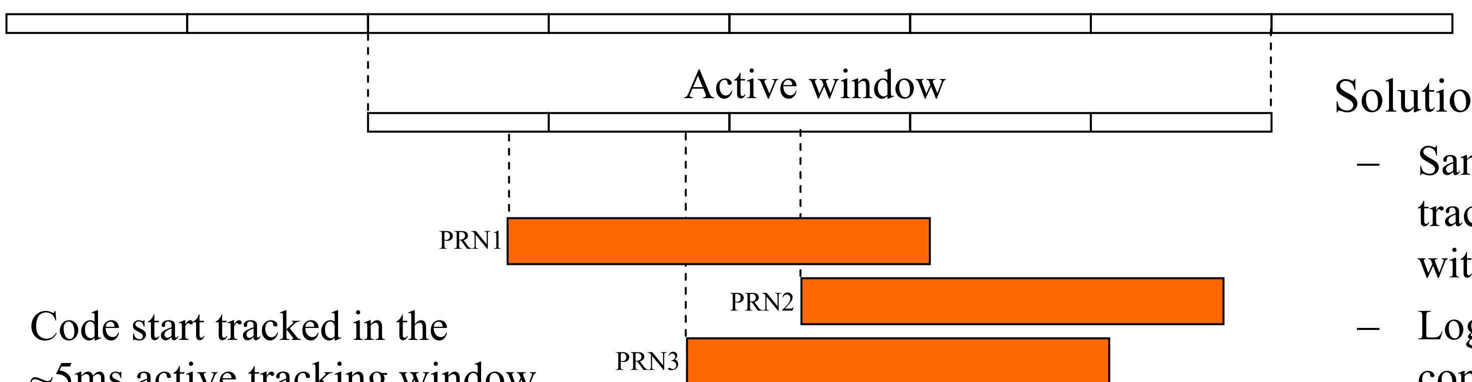
Multi-epoch tracking window



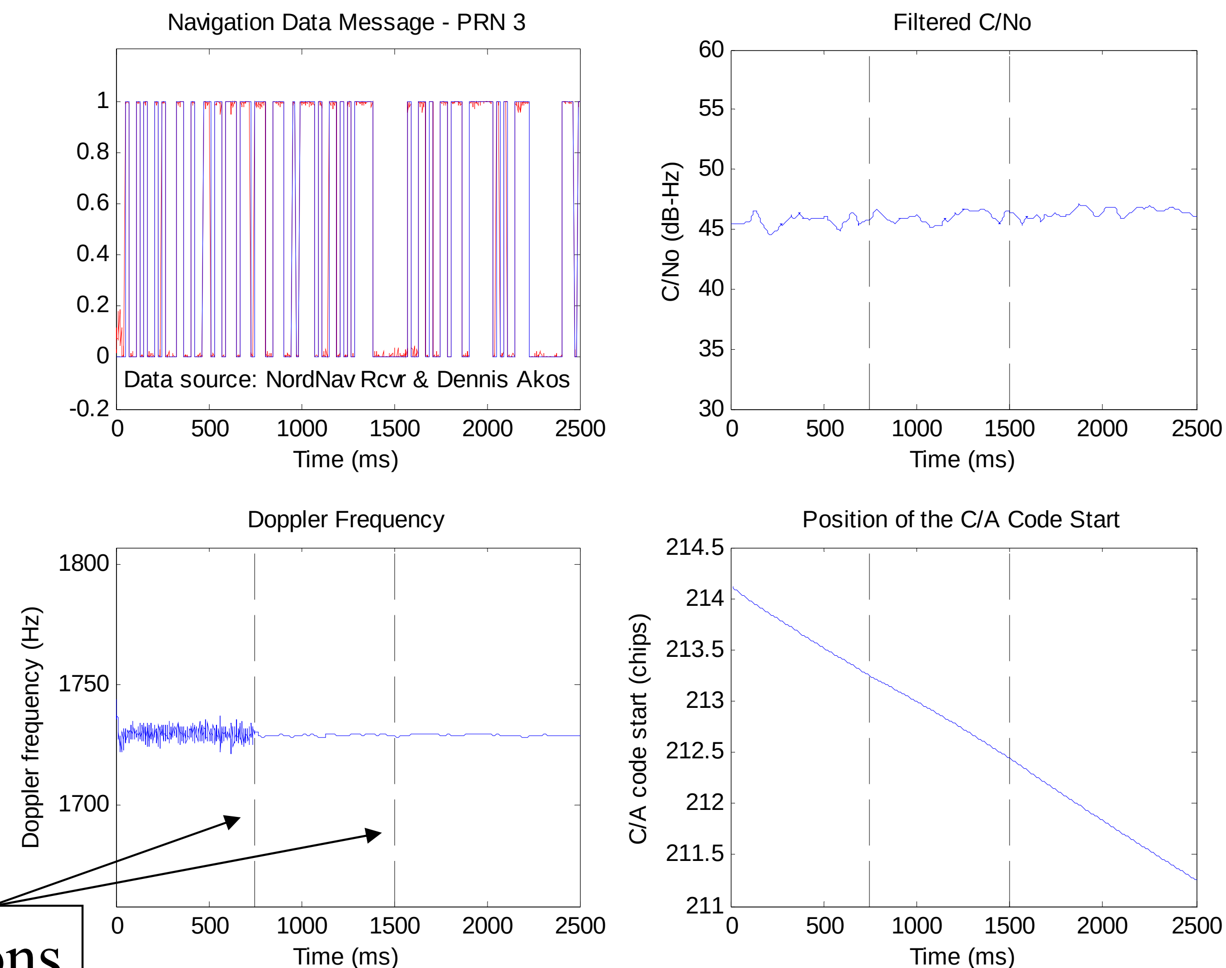
Code start tracked in the ~5ms active tracking window

Solutions:

- Sample index for each tracked PRN aligns with 0 code phase
- Logic is used to control sample index over-run or under-run

S/W Rcvr Verification:
GPS C/A Code Tracking – Real Data

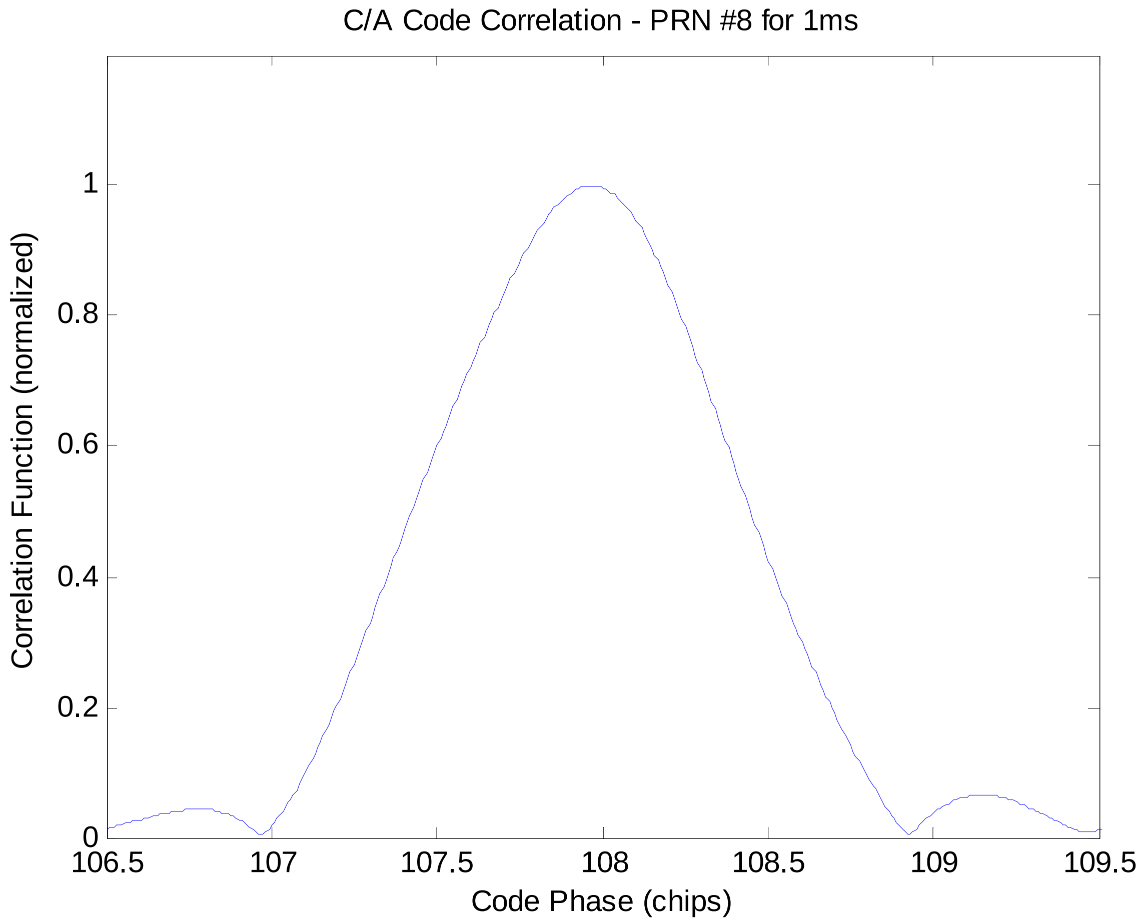
- All-in-view tracking of GPS C/A code signals
- Software receiver is a combination of in-house code and structures from Kai Borre of Aalborg University



Tracking mode transitions

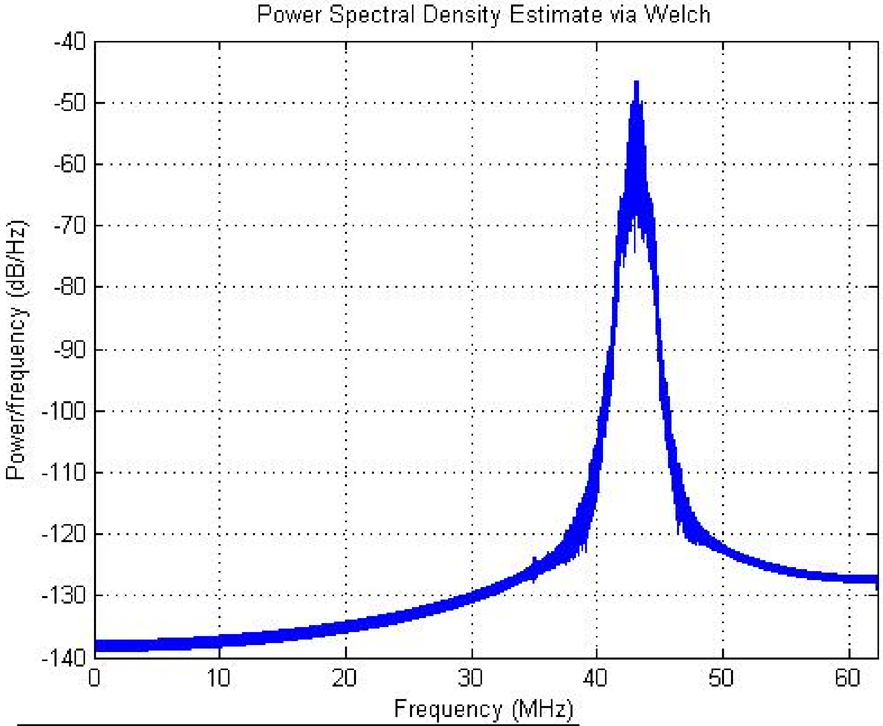
S/W Rcvr Verification:
C/A Code Acquisition – High-Gain Data

- Acquisition of GPS C/A code signal collected with SRI Dish
  - f_S = 124.5 MHz
  - f_{IF} = 43.08 MHz
  - Data courtesy Grace Gao of the Stanford GPS Lab

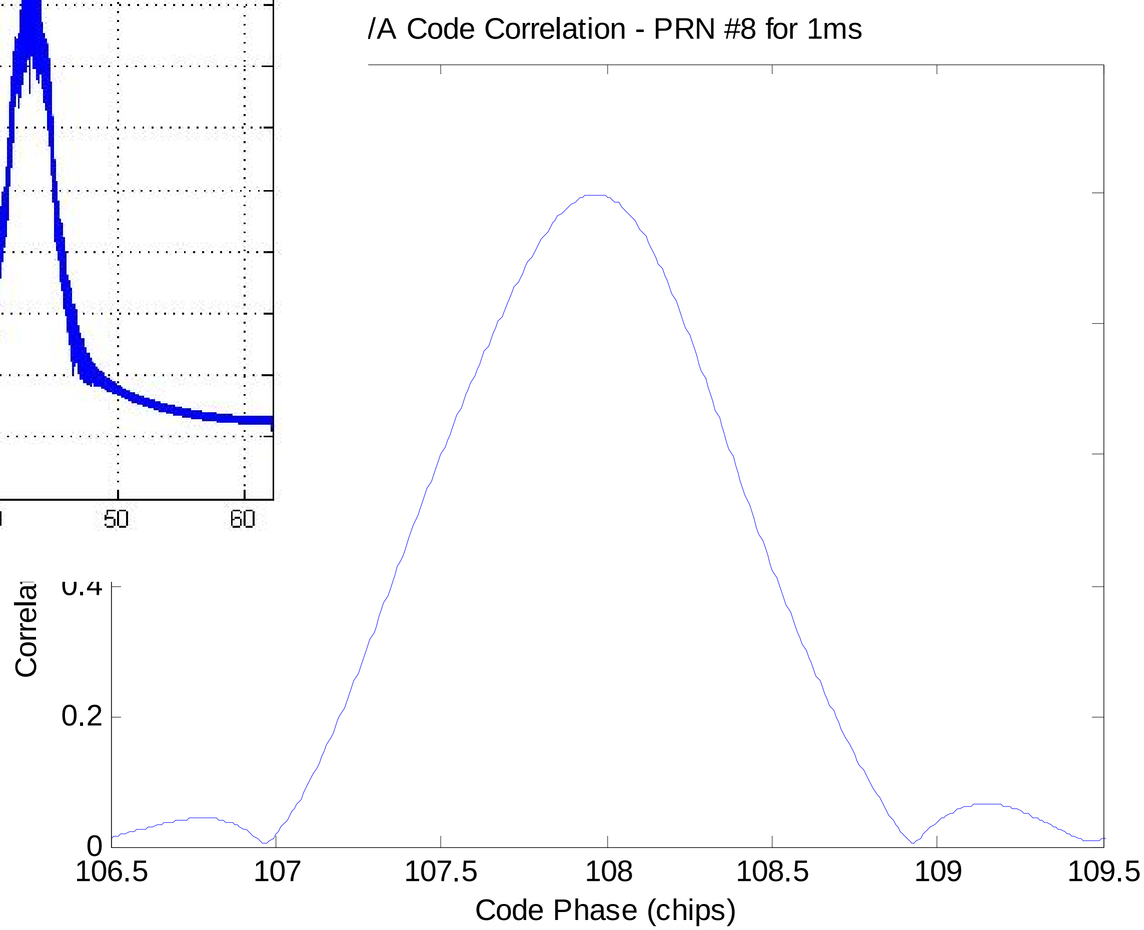


Why is the correlation peak rounded?

S/W Rcvr Verification:
C/A Code Acquisition – High-Gain Data

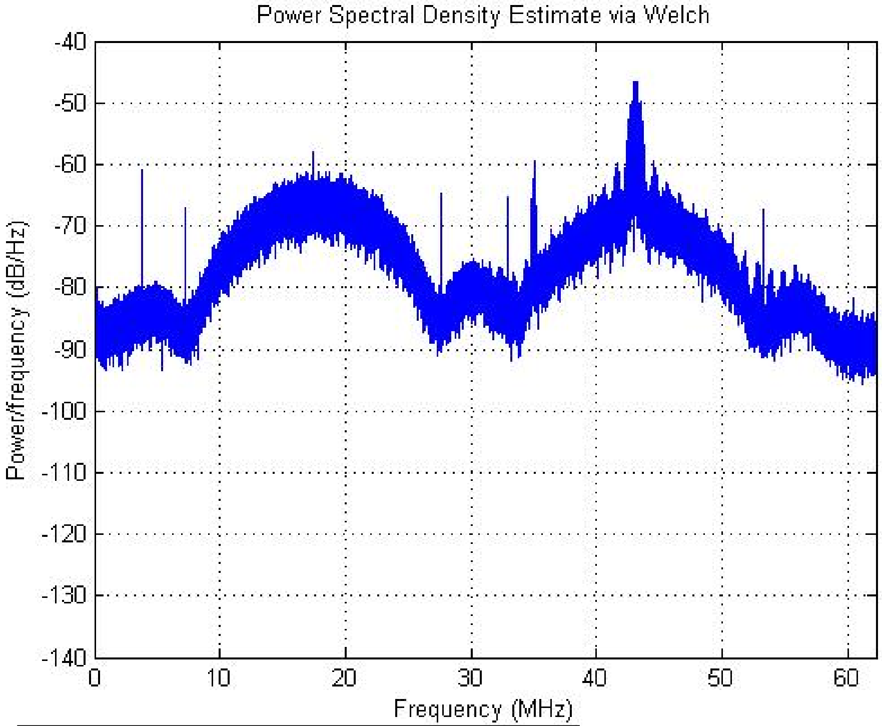


signal collected with

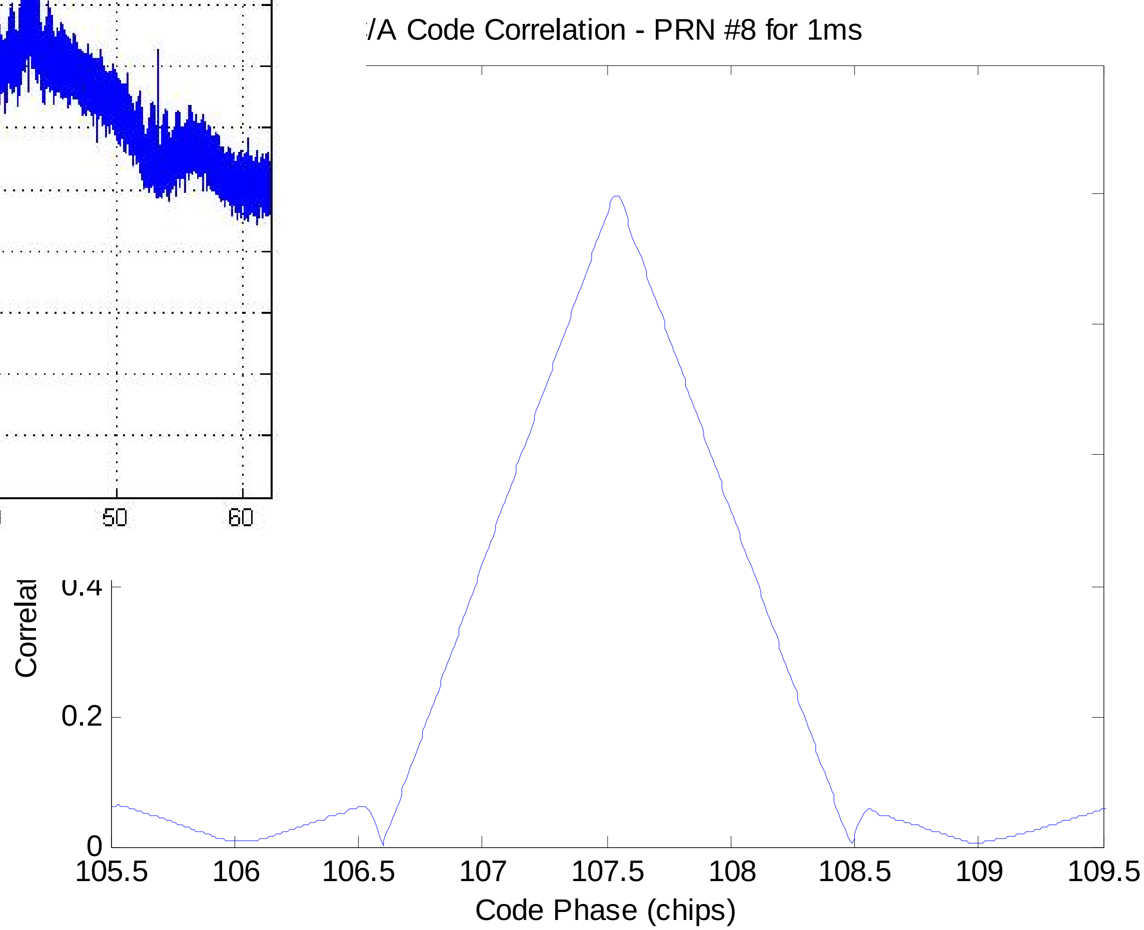


A band-pass filter was applied to the data before processing.

S/W Rcvr Verification: C/A Code Acquisition – High-Gain Data

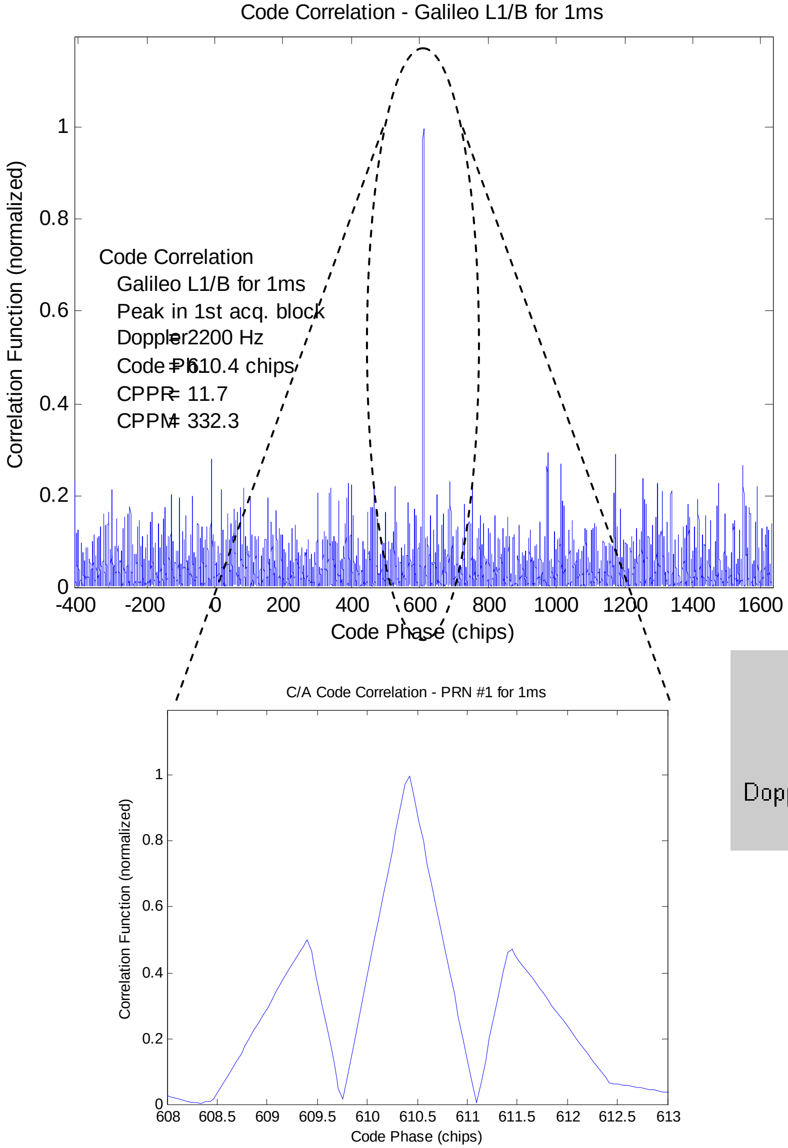


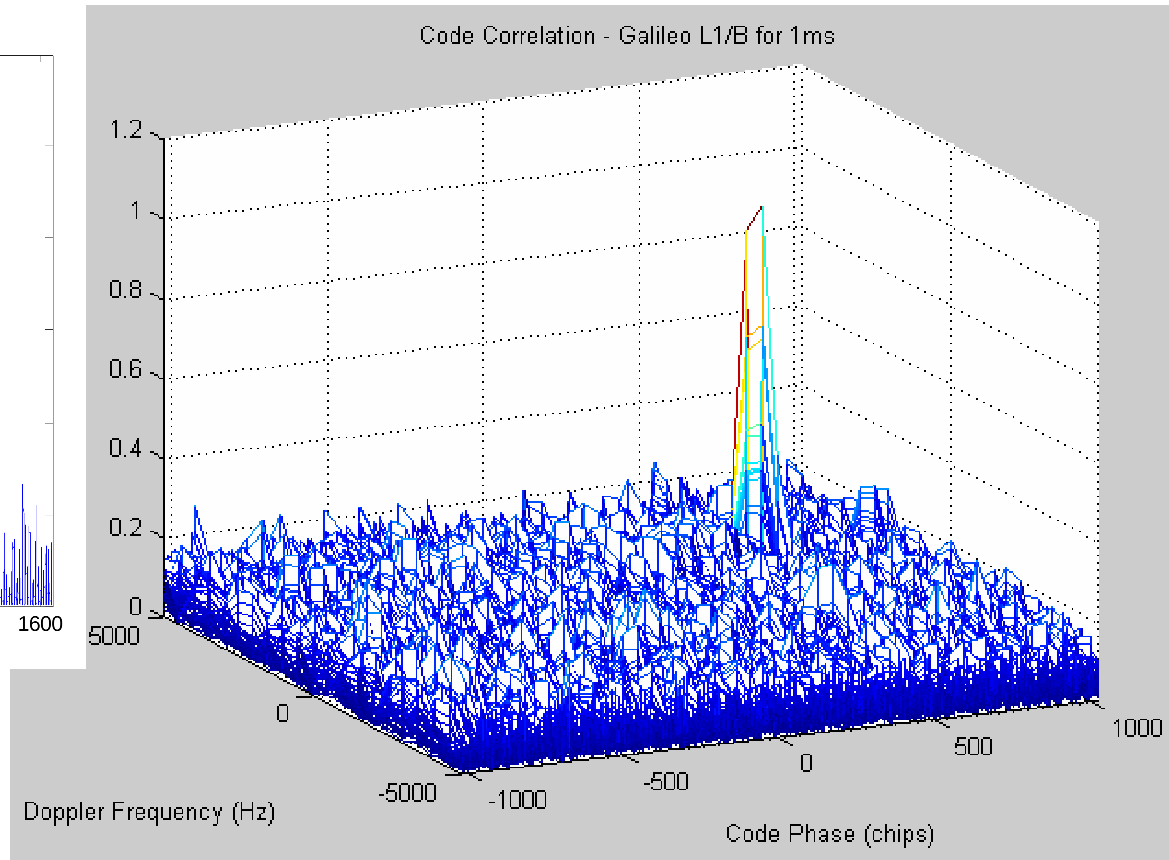
: signal collected with



This is the correlation to unfiltered data.

S/W Rcvr Verification:
Galileo L1/B Code Acquisition – Real Data

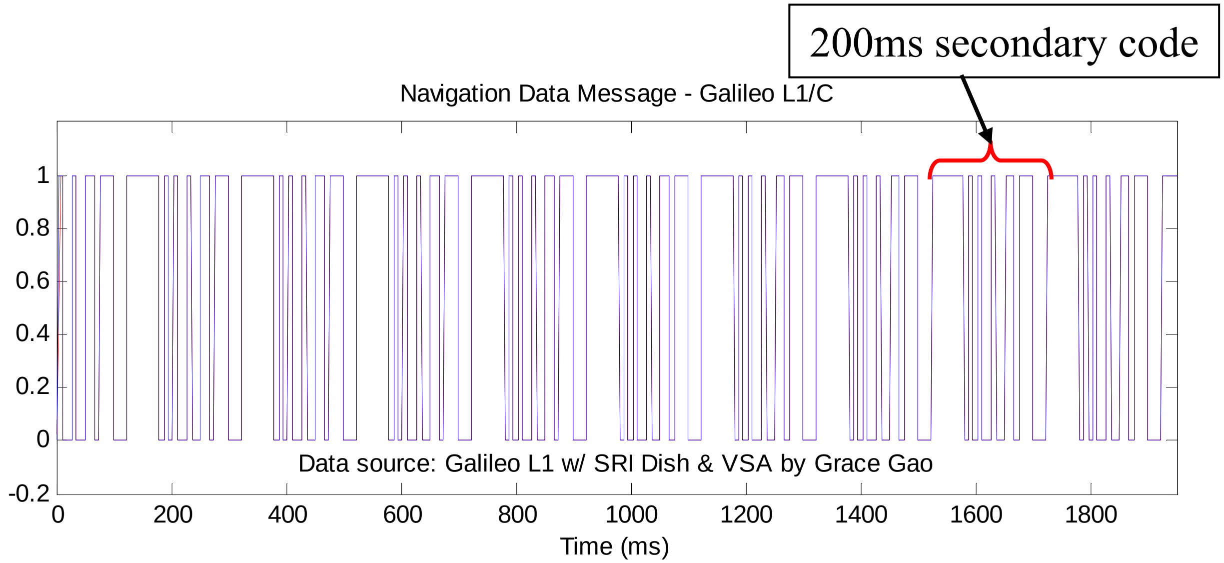


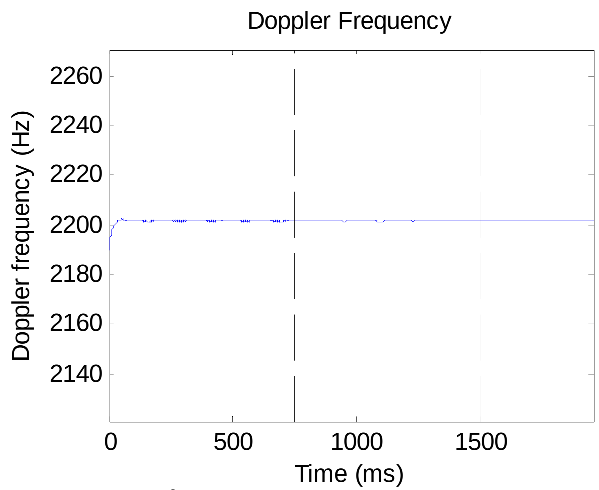


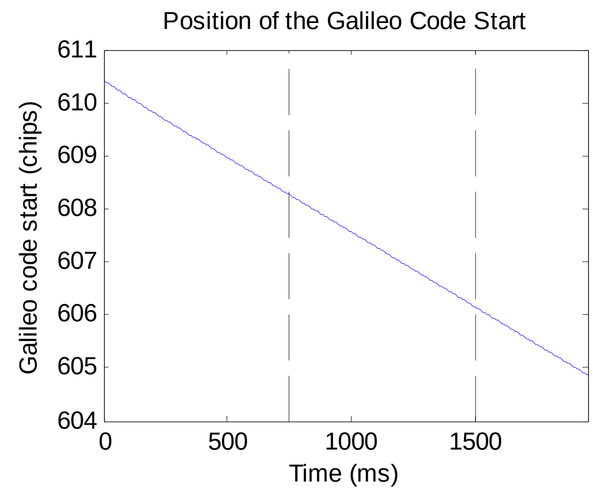
– Galileo L1-B/C and E6-B/C codes determined by Grace Gao of the Stanford GPS Lab

S/W Rcvr Verification:
Galileo L1/C Code Tracking – Real Data

- Tracking of Galileo L1/C BOC(1,1) pilot signal
- No modification to s/w rcvr except new code generators
- Galileo L1-B/C and E6-B/C codes determined by Grace Gao of the Stanford GPS Lab

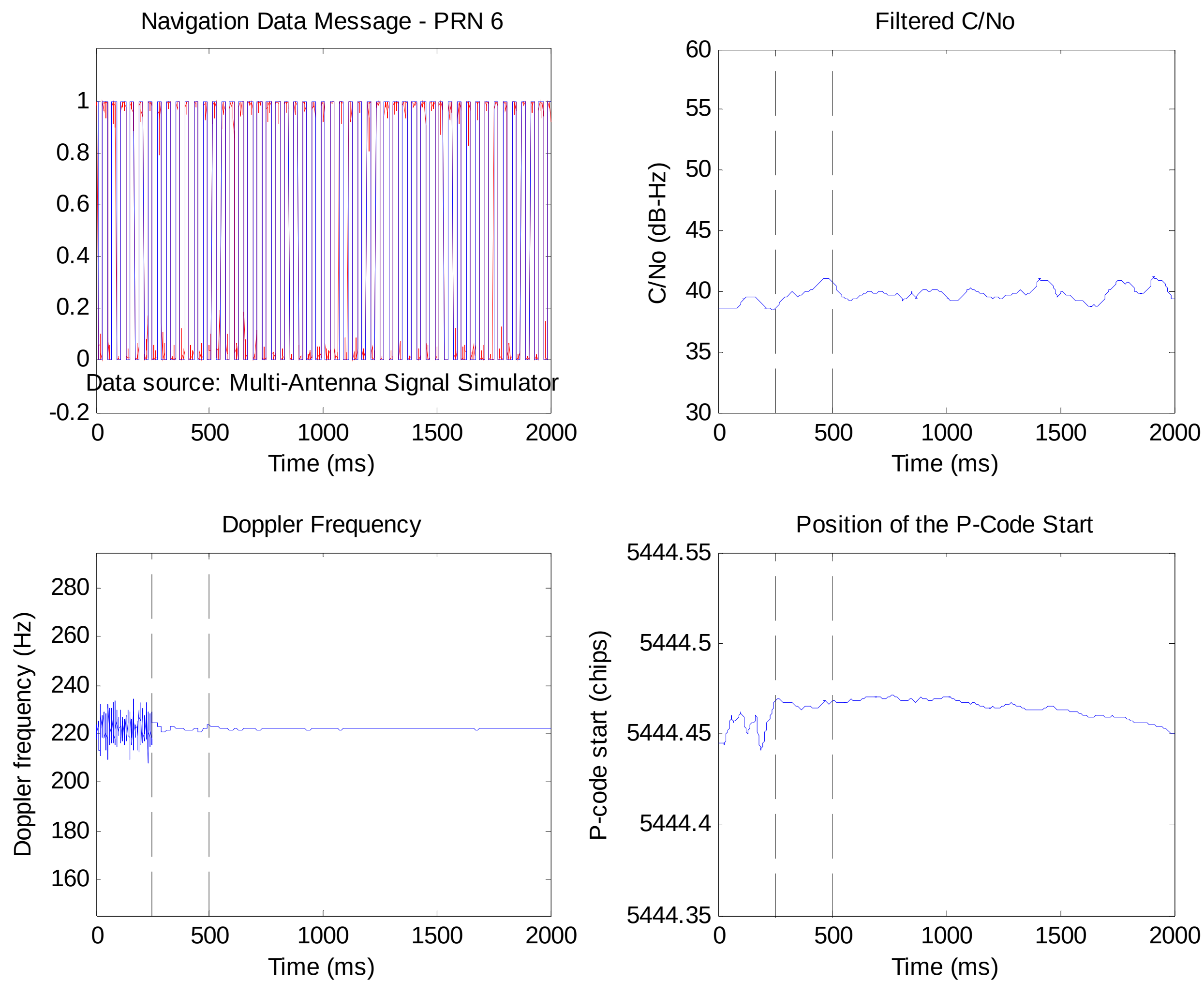






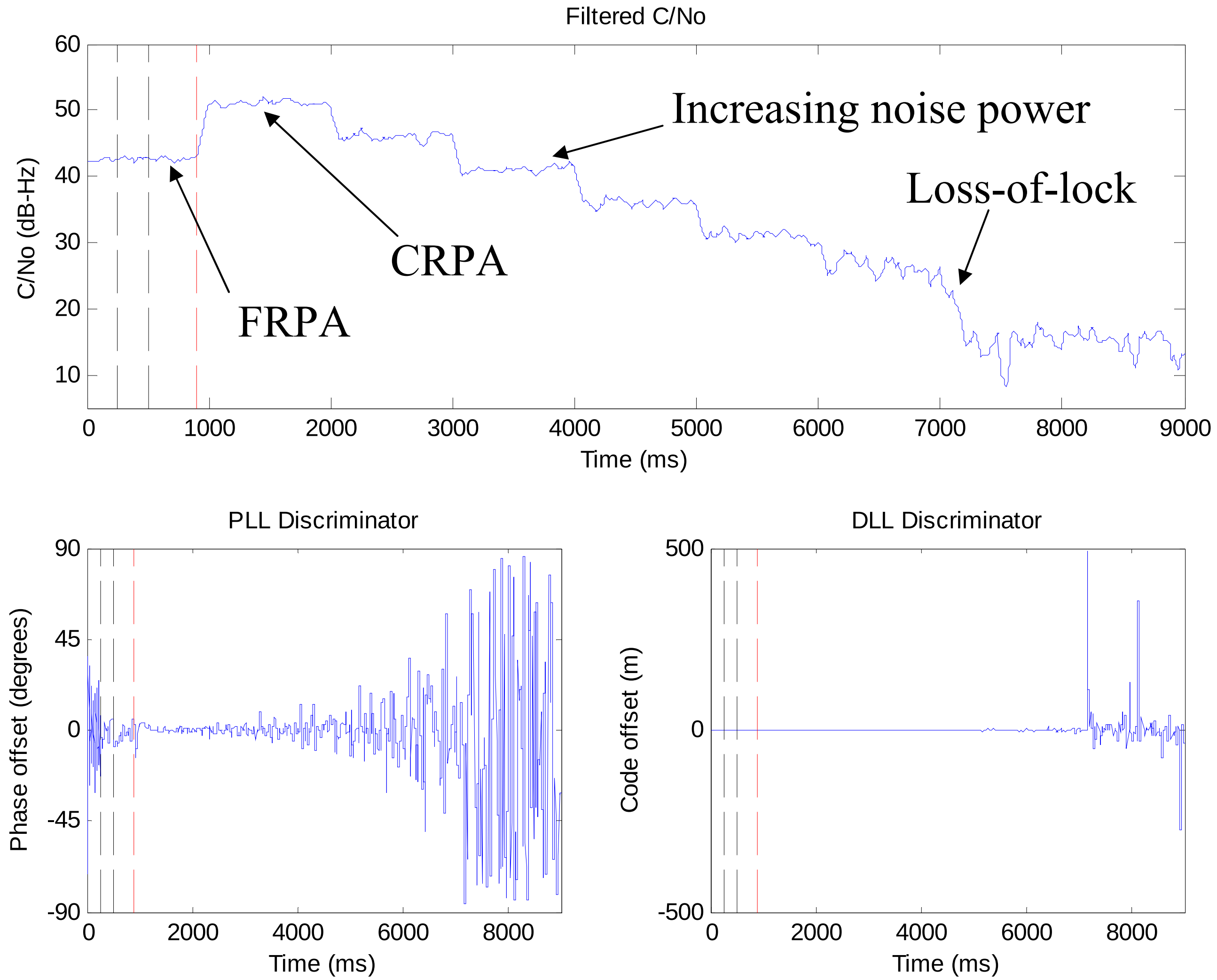
S/W Rcvr Verification:
GPS P-Code Tracking – Simulated Data

- GPS pseudo-P-code signals, 10.23 Mchips/sec
- Signals have sufficient BW to elucidate effects due to differential antenna gain and phase responses
  - f_S = 80 MHz
  - f_{IF} = 20 MHz



S/W Rcvr Verification: CRPA Processing – Simulated Data

- 7-element CRPA with gradually decreasing C/No
- No special receiver processing for low C/No
- Loss-of-lock below C/No of ~25 dB-Hz

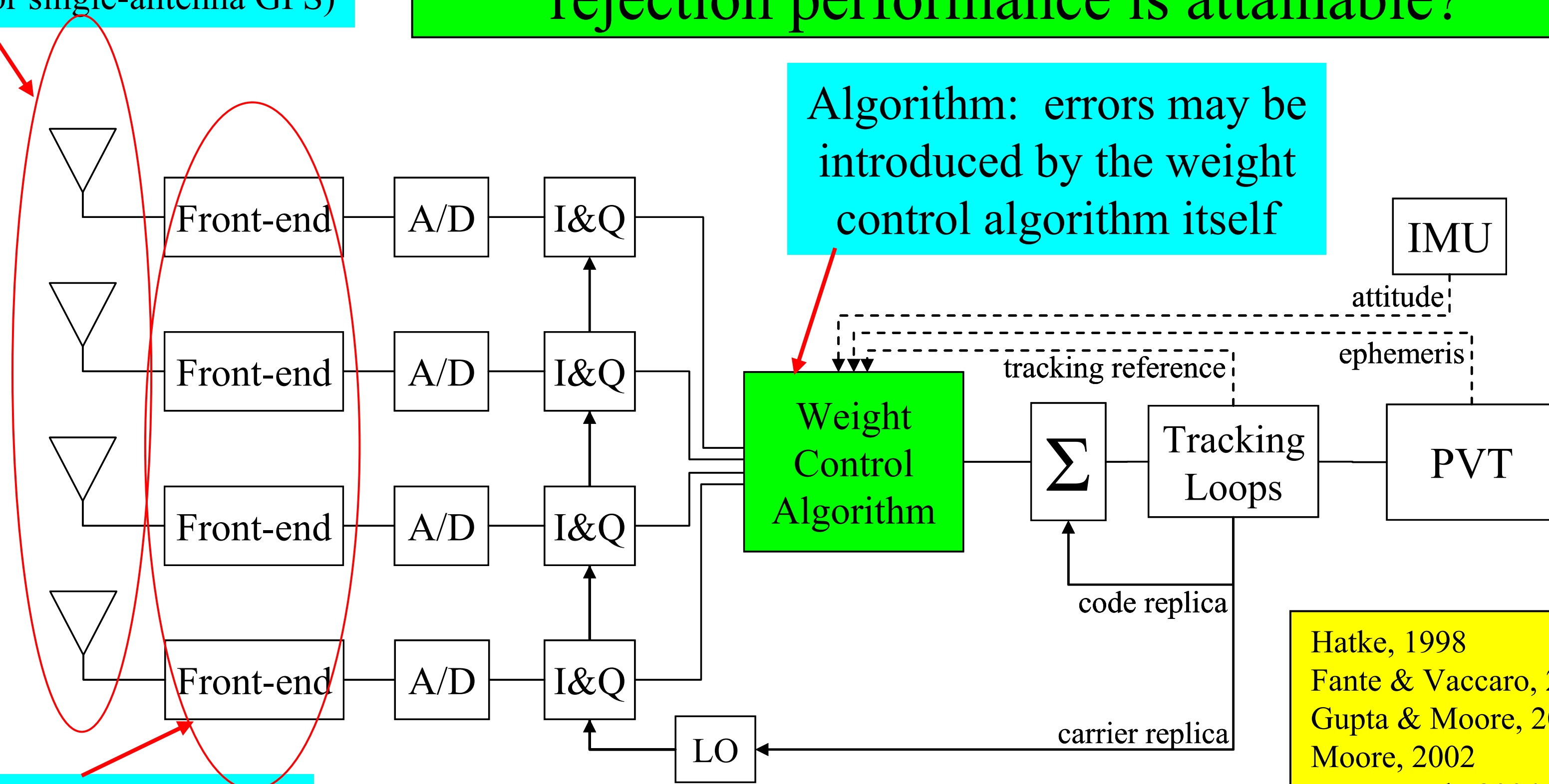


Navigation Errors due to Multi-Antenna Arrays

Non-common-mode: errors are a function of satellite # →az/el-dependent
(also present for single-antenna GPS)

Do errors introduce a pseudorange or carrier-phase bias? What RFI or noise rejection performance is attainable?

Algorithm: errors may be introduced by the weight control algorithm itself



Common-mode: errors are shared by all signals on a particular antenna channel

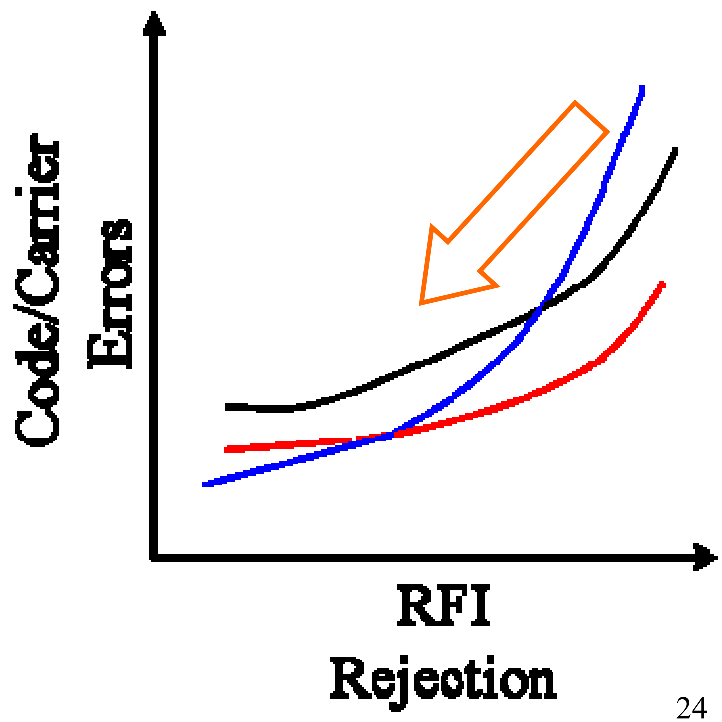
Pseudorange/Carrier-phase errors →

Hatke, 1998
Fante & Vaccaro, 2000
Gupta & Moore, 2001
Moore, 2002
Fante, et.al., 2004
McGraw, et.al., 2004
Hatke & Phuong, 2004
Kim, et.al., 2004
Kim, 2005

Methodology – Biases vs. RFI Rejection

- Develop adaptive algorithms that balance noise/RFI rejection against pseudorange & carrier-phase errors – through constraints on weight adjustment
  - End-to-end: from signal reception through the receiver tracking loops to the pseudorange and carrier phase estimates

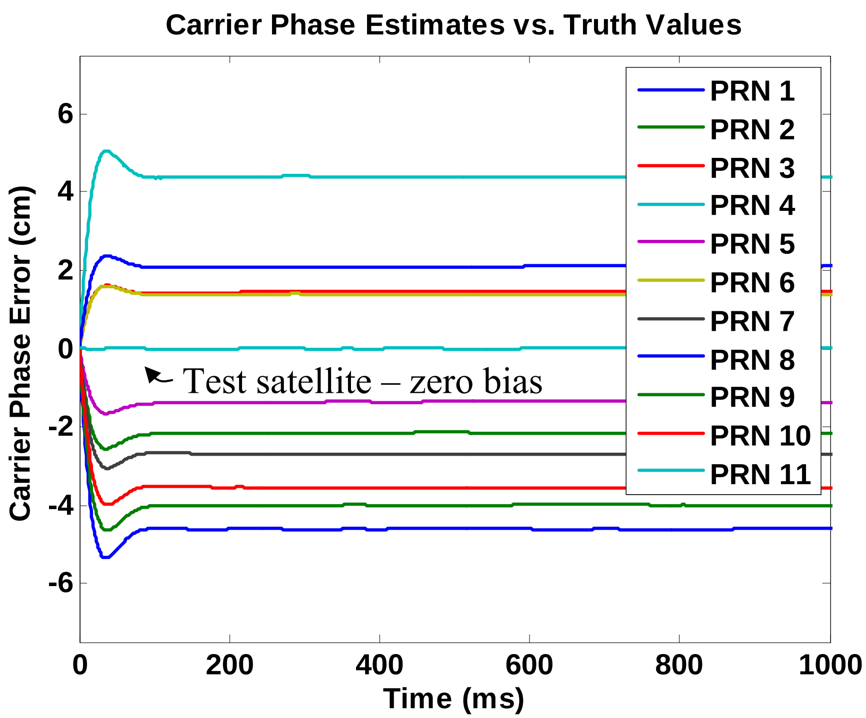
Goal: Through temporal & spatial constraints on a STAP algorithm, move down & left in the trade space, to a point where deterministic pseudorange & carrier phase corrections based on signal LOS can be applied.



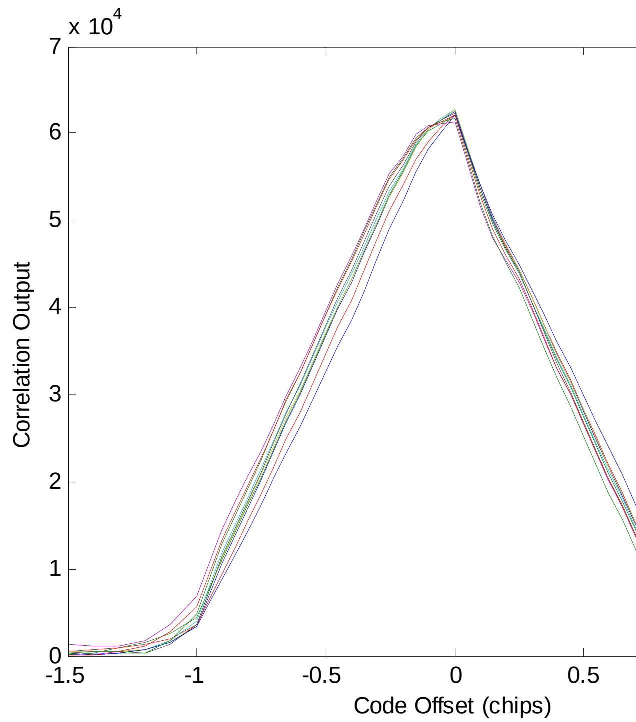
Preliminary Results: GPS P-Code w/ Antenna Distortion

- Simulated data **and** complete visibility of tracking output allow comparison between predicted and true pseudorange and carrier phase values

Carrier phase biases



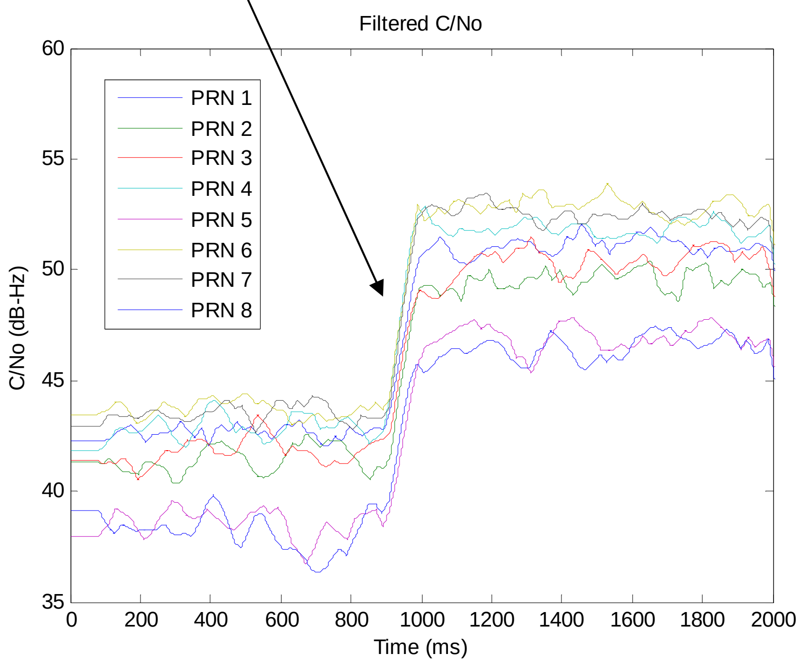
Pseudorange bias – distortion of P-code correlation peak

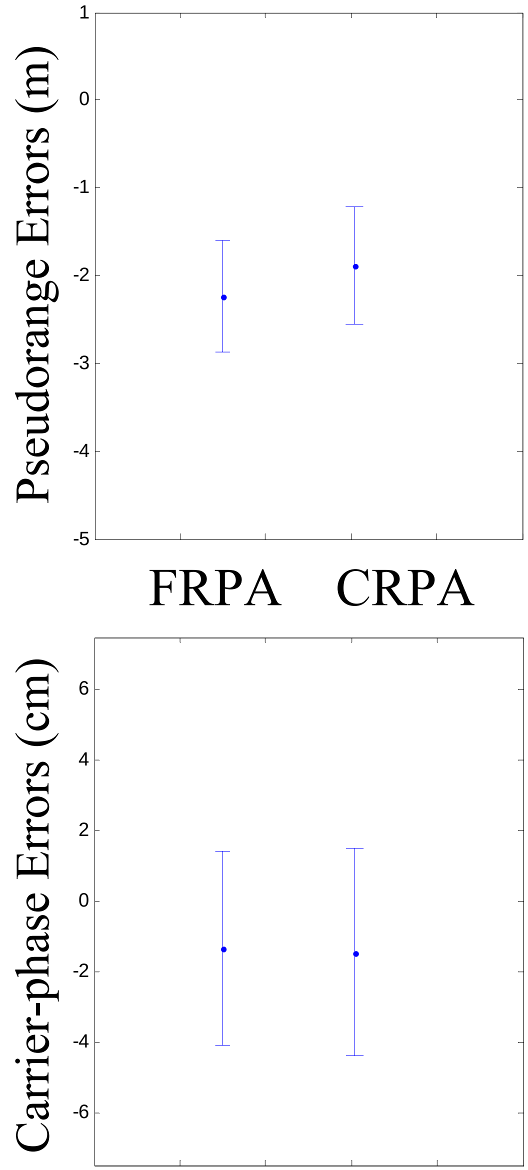


PRN	Code Bias (m)
1	-1.8
2	-2.0
3	-1.3
4	-2.2
5	-2.8
6	-1.9
7	-2.4
8	-0.5
9	-3.0
10	-2.7

Preliminary Results:
FRPA vs. CRPA Processing – no RFI

- Code/carrier errors are not affected by deterministic array processing
- C/No enjoys healthy boost under these conditions





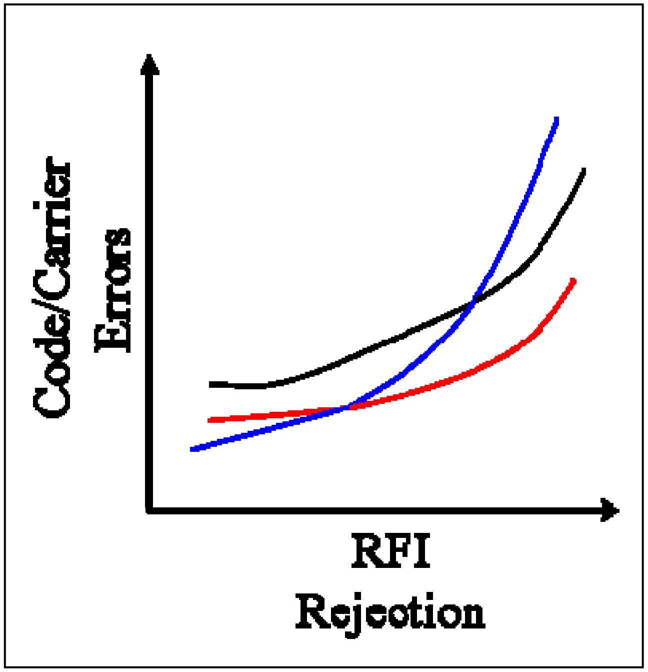
Future Work – Exploring the Trade Space

1. Simulate signals with desired characteristics (C/No, J/S ratio, antenna distortion, etc.)
2. Track with Software Receiver (FRPA, CRPA, LMS, Applebaum processing)
3. Characterize C/No vs. pseudorange and carrier phase biases for various scenarios
4. Apply compensation schemes

	FRPA	CRPA	LMS	Applebaum
J/S level				
C/No				
Distortion				
Temporal Constraints				
Spatial Constraints				

Conclusions

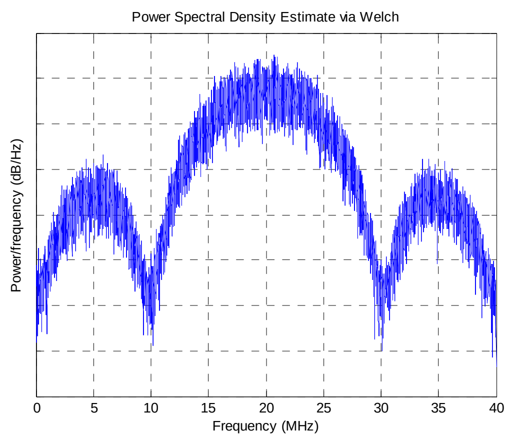
- Signal simulator captures parameters of interest
  - Broadband RFI, antenna gain/phase variation based on detailed characterization models
- Software receiver supports adaptive algorithms and estimation of pseudorange & carrier phase errors
- Methodology is yielding data about tradeoffs between RFI rejection and code/carrier estimation errors
- Tools will support implementation and testing of antenna compensation schemes

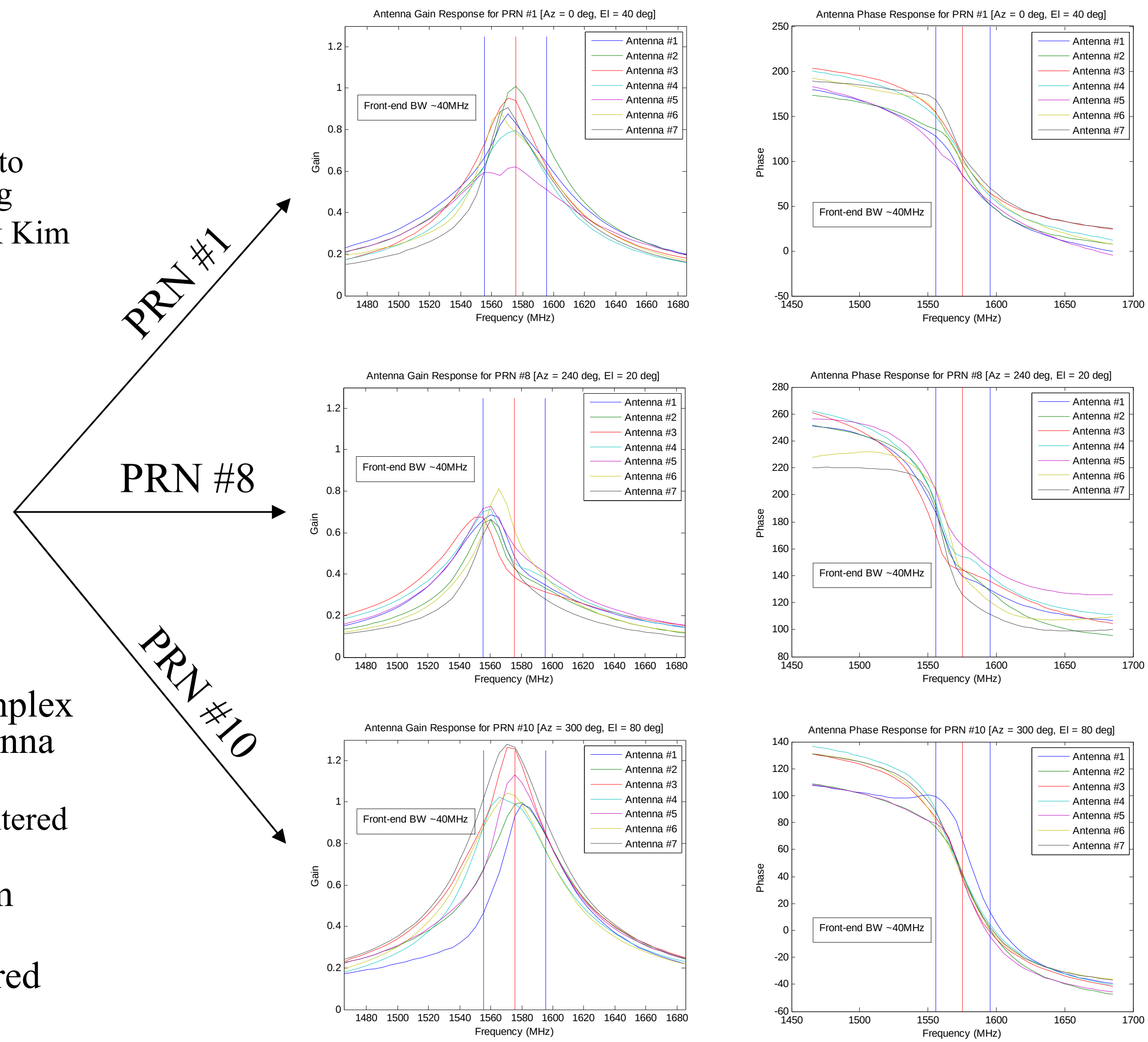


Backup

Antenna Distortion Effects (2)

- Gain/phase distortion data available from HFSS simulation
  - Verified by comparison to anechoic chamber testing
  - Data courtesy Ung-Suok Kim

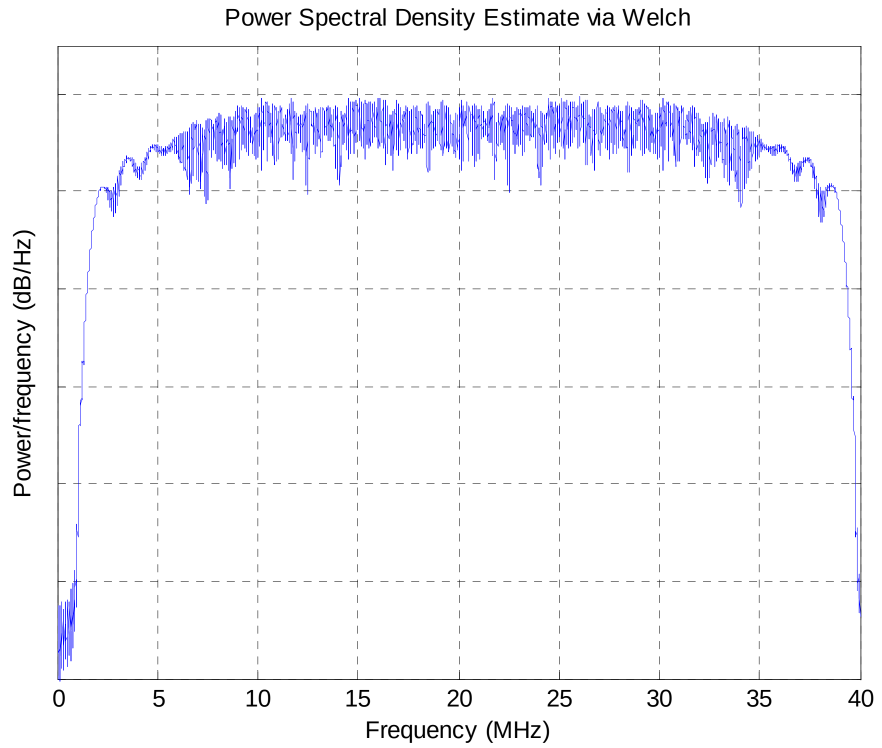




- Fourier transform of complex signal multiplied by antenna response characteristics
  - Gain/phase data re-centered at IF
- Inverse Fourier transform back to time domain
- Real-valued samples stored to disk

Wideband Jammer Signal Generation at IF

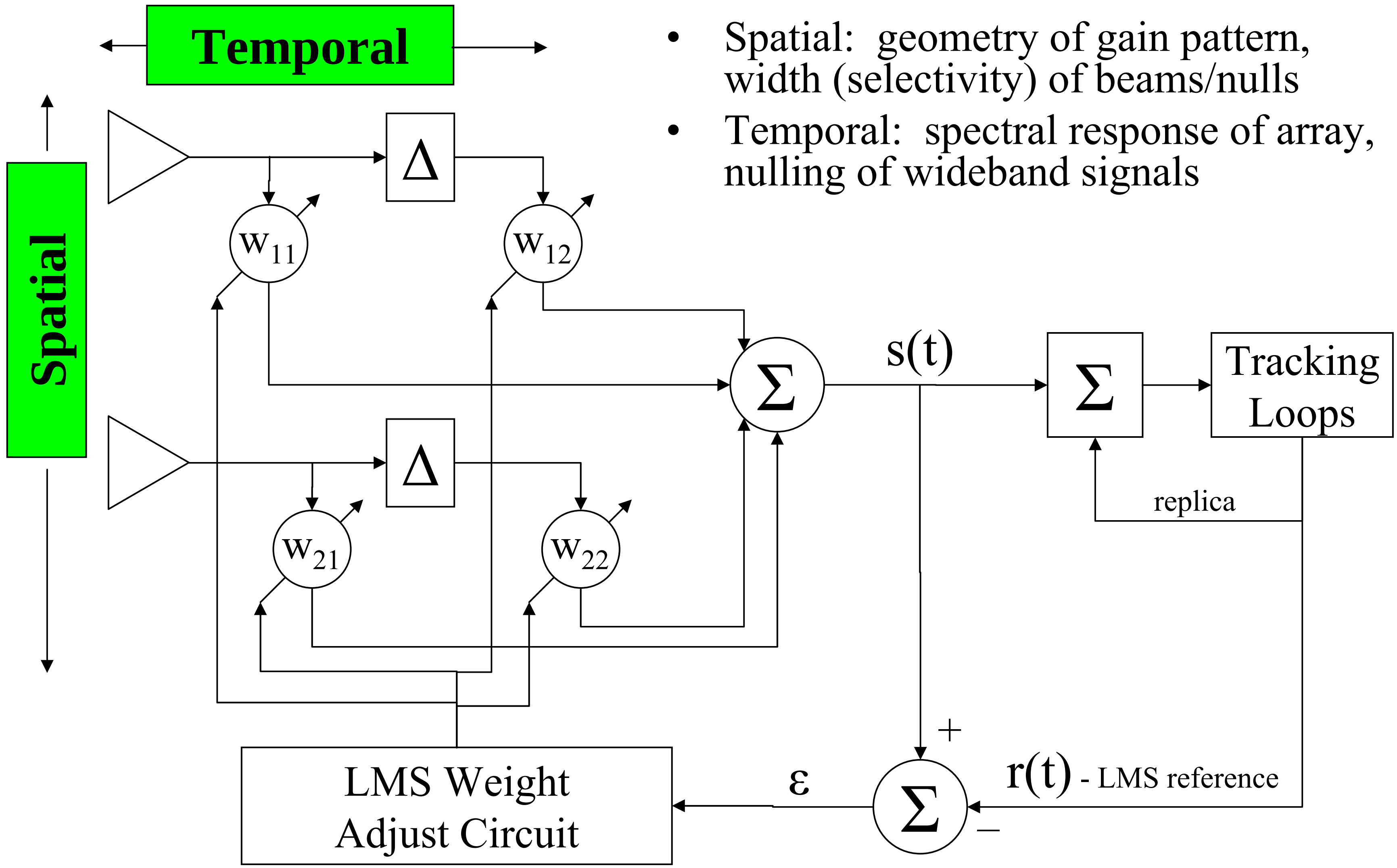
- For each jammer – six swept sinusoids cover frequency band from ~0 Hz to ~$f_s/2$
  - Pseudo-random center frequencies
  - For f_s = 80 MHz and f_{IF} = 20 MHz, each wave covers 10 MHz
- Amplitude scaled as needed to achieve desired J/S ratio



$$\sqrt{2P_J} \cdot \sum_i \cos\left[2\pi\left(f_{IF} + f_{J_i}\right)t + f_J'\left(t + \Delta t\right)^2 + 2\pi\left(f_{L1} + f_{J_i}\right)\Delta t\right]$$

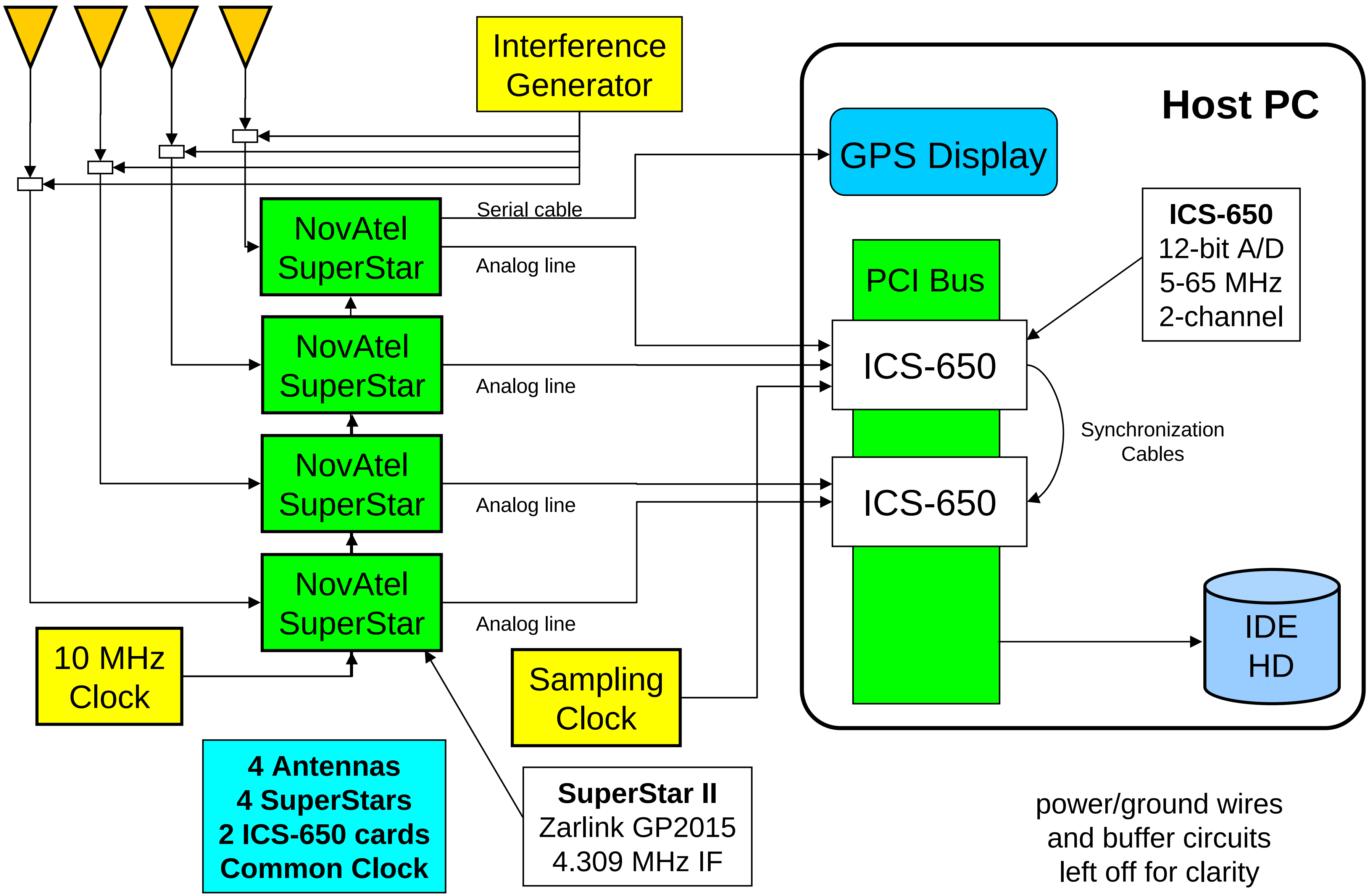
Spatial & Temporal D.O.F

- Spatial: geometry of gain pattern, width (selectivity) of beams/nulls
- Temporal: spectral response of array, nulling of wideband signals

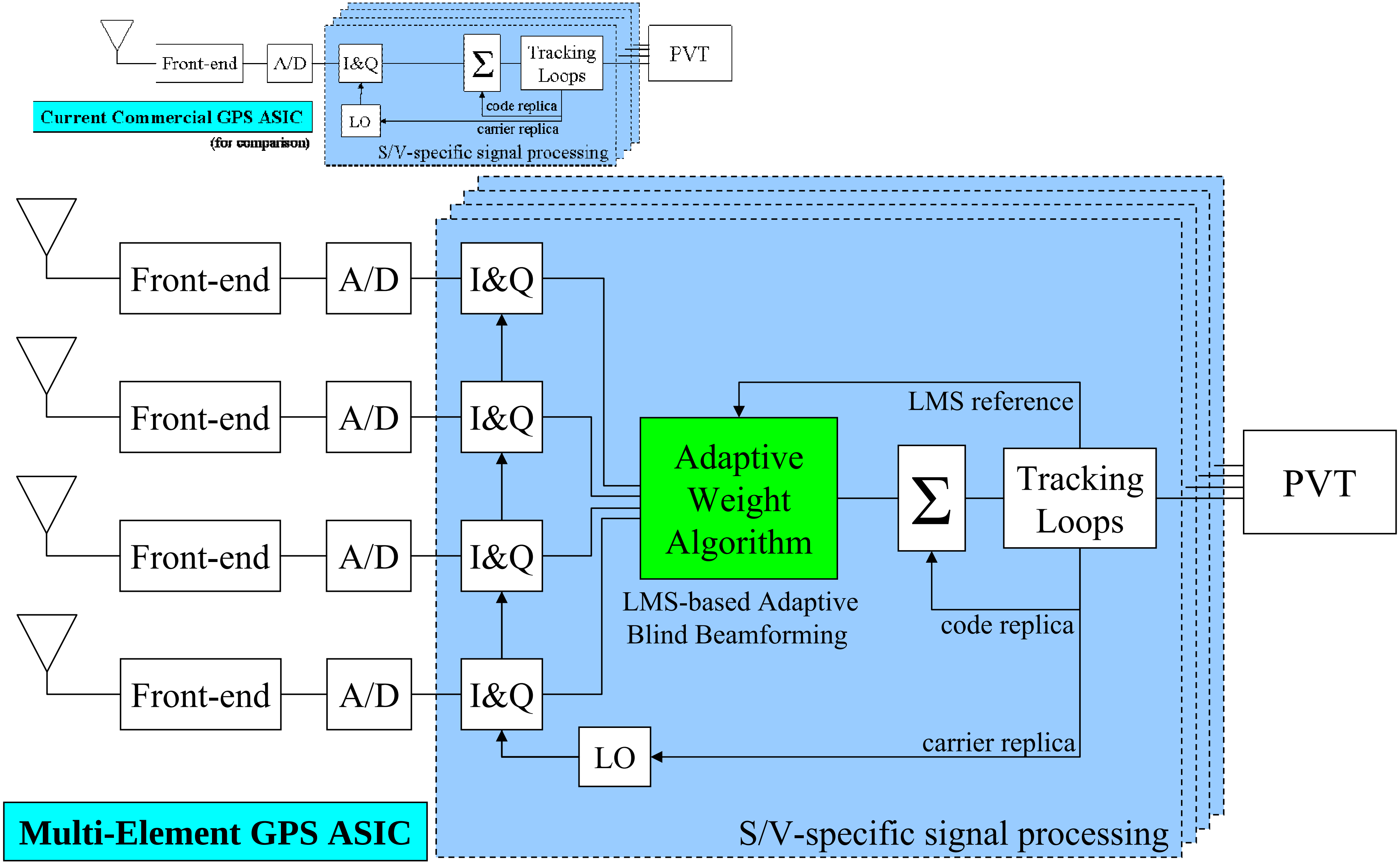


from Widrow & Stearns, Adaptive Signal Processing (1985)

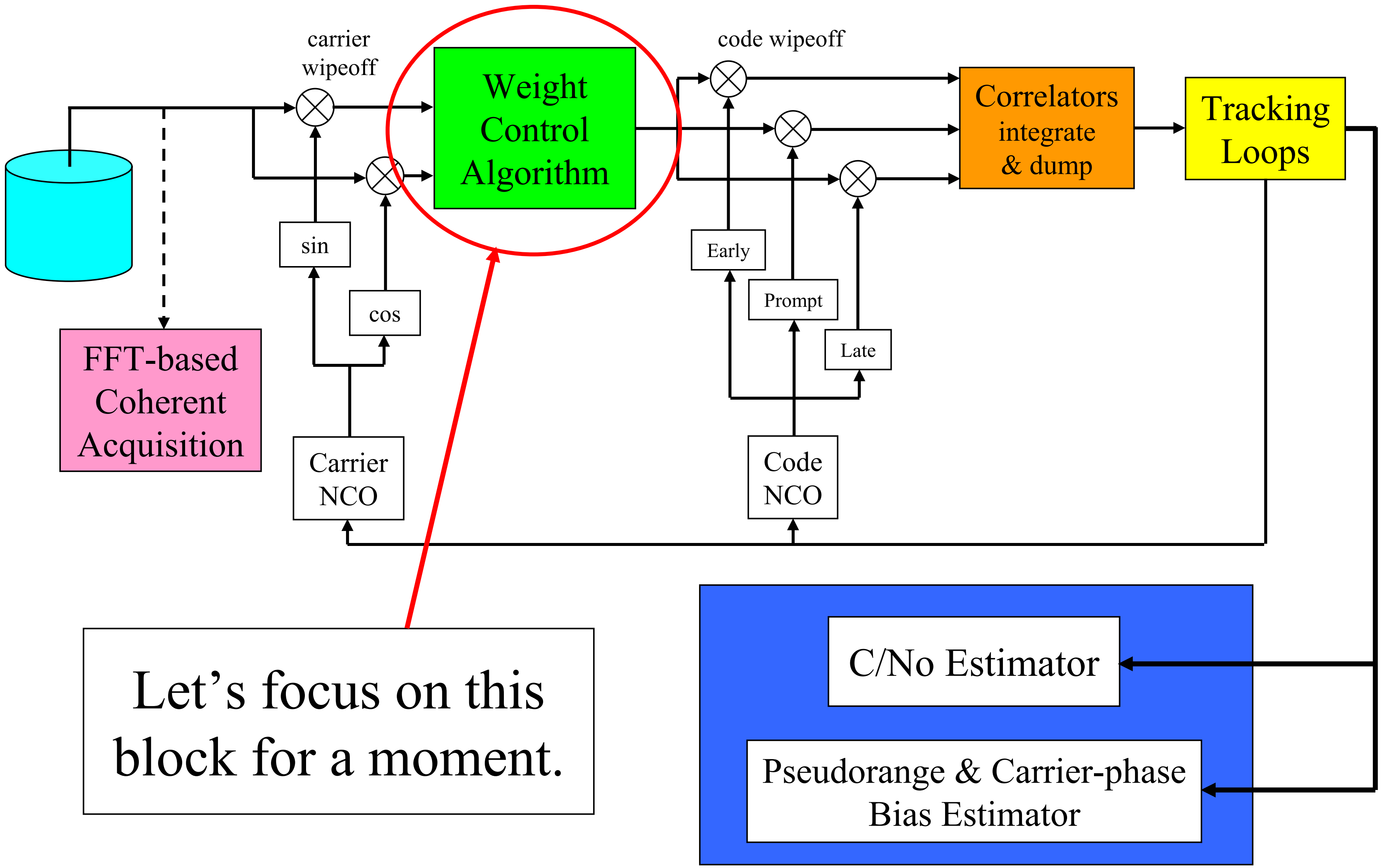
4-Channel Test Hardware – Schematic



Proposed 1st-gen Hardware Implementation

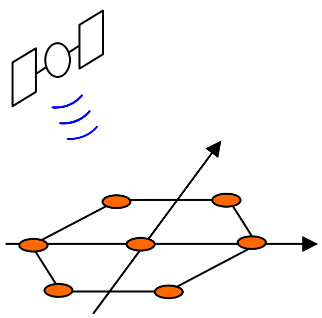


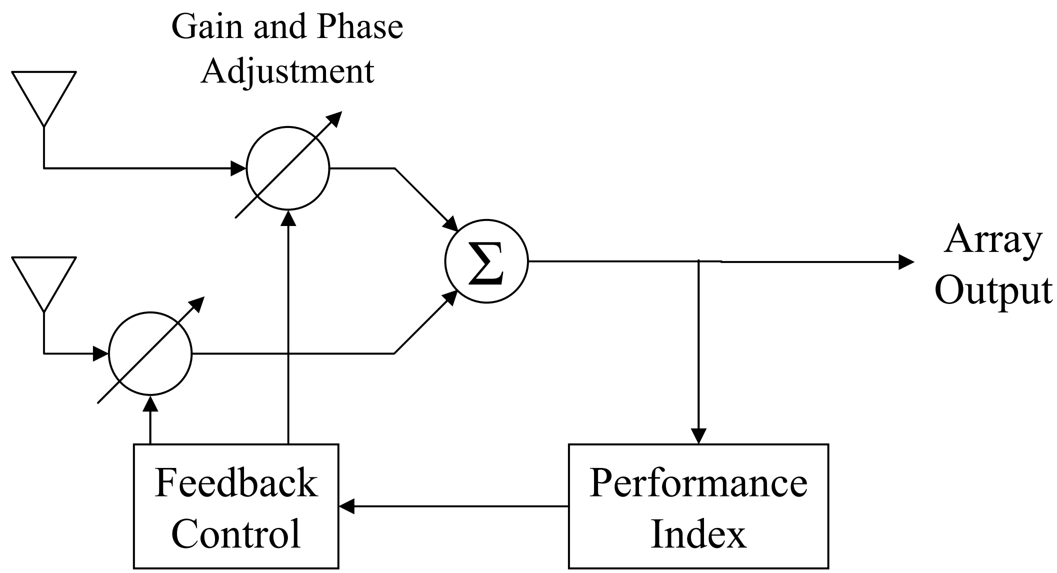
Software Receiver Block Diagram



Generic Adaptive Antenna Array

- Using feedback to optimize some performance index





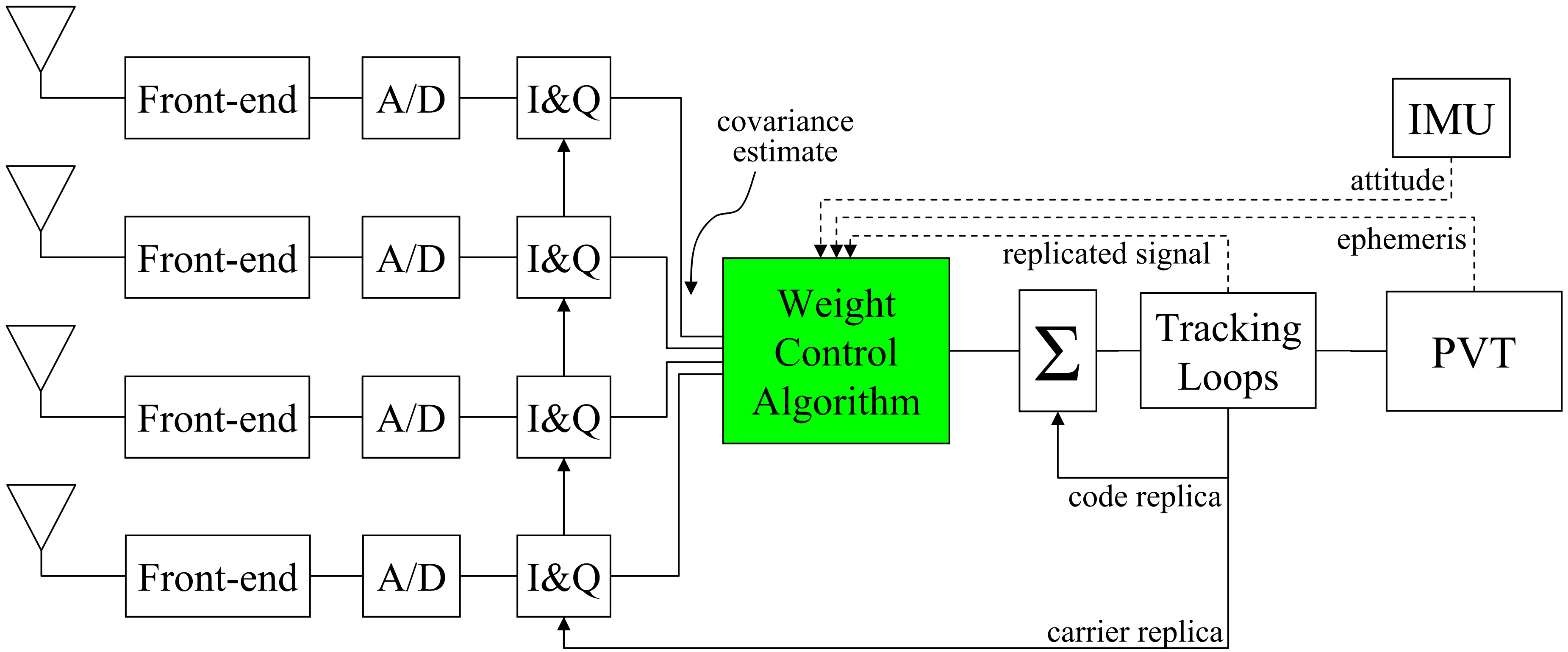
from Compton, Adaptive Antennas (1988)

Optimization Criteria

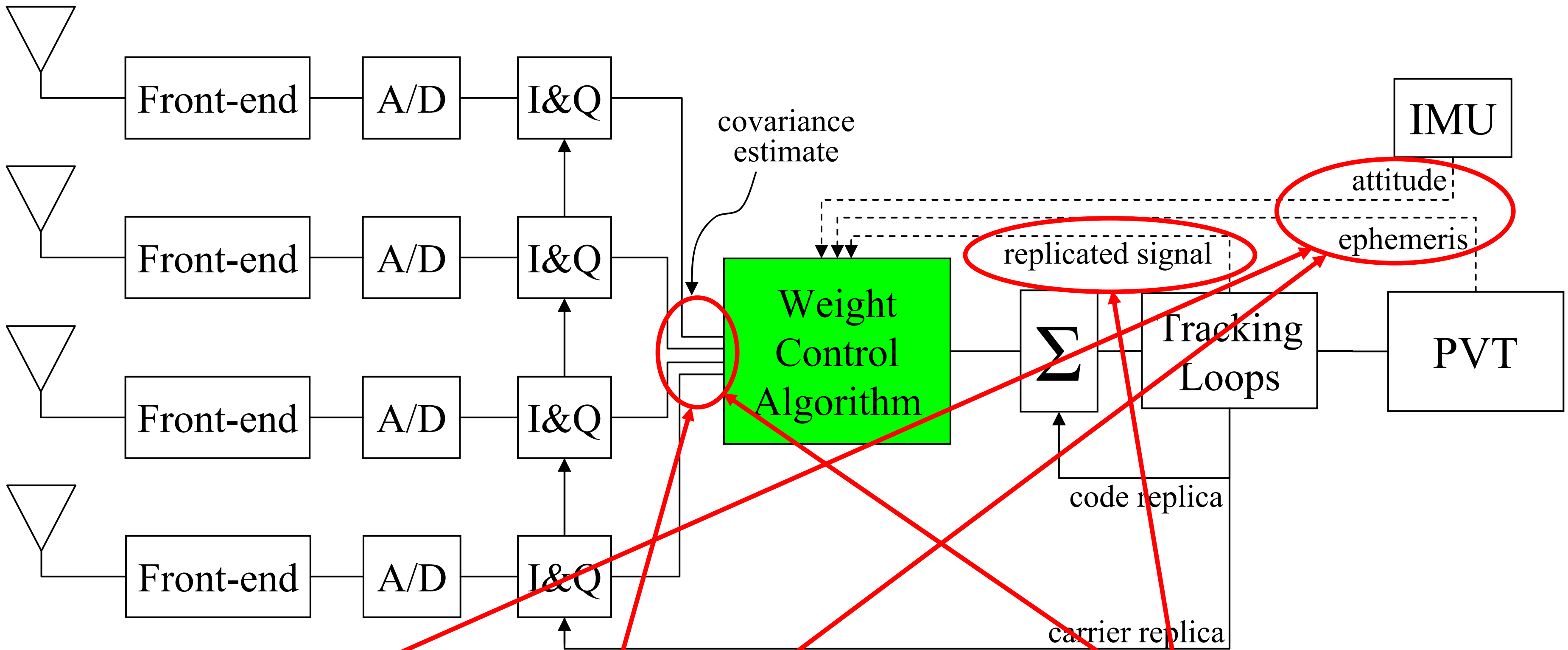
Maximize SINR at the array output (e.g., Applebaum, 1976; Frost, 1972)

Minimize MSE between the actual array output and the ideal array output (e.g., Widrow, et. al., 1967)

Adaptive Array Processing for GPS



Adaptive Array Processing for GPS

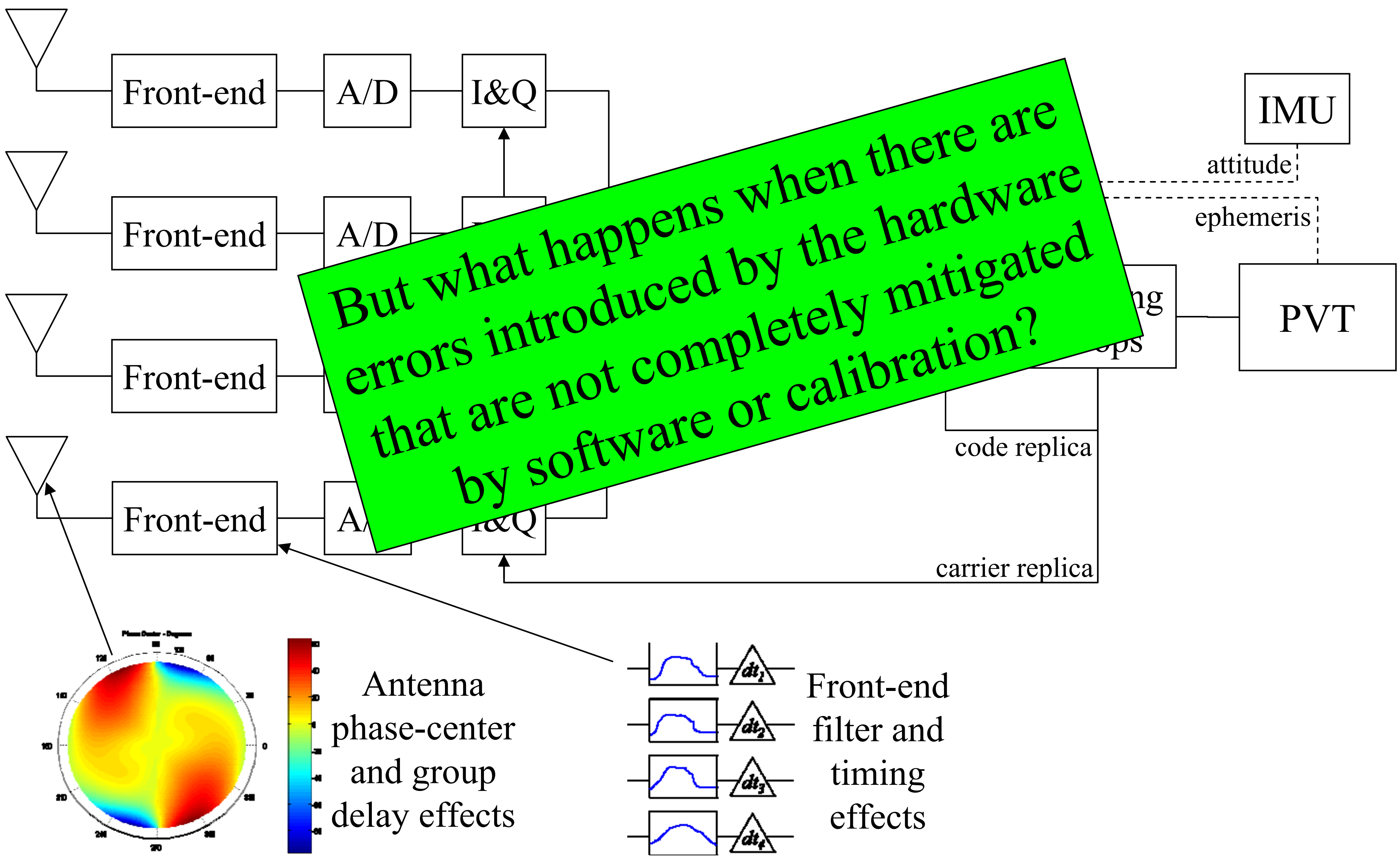


Deterministic CRPA: signal arrival and platform/array orientation

Adaptive w/ minimum MSE, e.g. Widrow LMS: ideal array output reference signal and SINR metric
e.g., Gecan & Zoltowski, 1995

Adaptive w/ maximum SINR, e.g. Applebaum: signal arrival, platform/array orientation, and SINR metric
e.g., Hatke, 1998; Nicholson, et al., 1998; Fante & Vaccaro, 2000; Gupta & Moore, 2001;Hatke & Phuong, 2004; Fante, et al., 2004

Adaptive Array Processing for GPS



But what happens when there are errors introduced by the hardware that are not completely mitigated by software or calibration?