Navigation Accuracy and Interference Rejection for an Adaptive GPS Antenna Array

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27 Sept 2006

The authors gratefully acknowledge the support of the JPALS Program Office, and the Naval Air Warfare Center Aircraft Division through contract N00421-05-C-0068.

Joint Precision Approach and Landing System (JPALS)

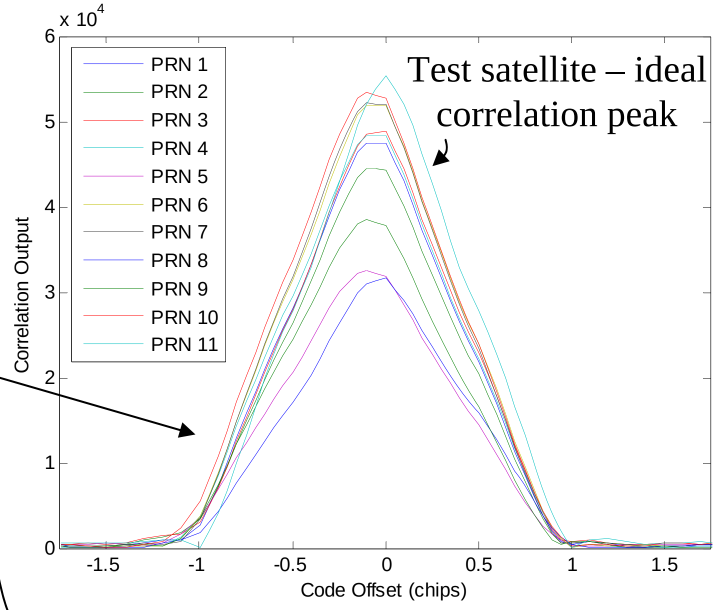
Navigation Accuracy
Interference Rejection
Adaptive GPS Antennas

Antenna Distortion, Code & Carrier Biases

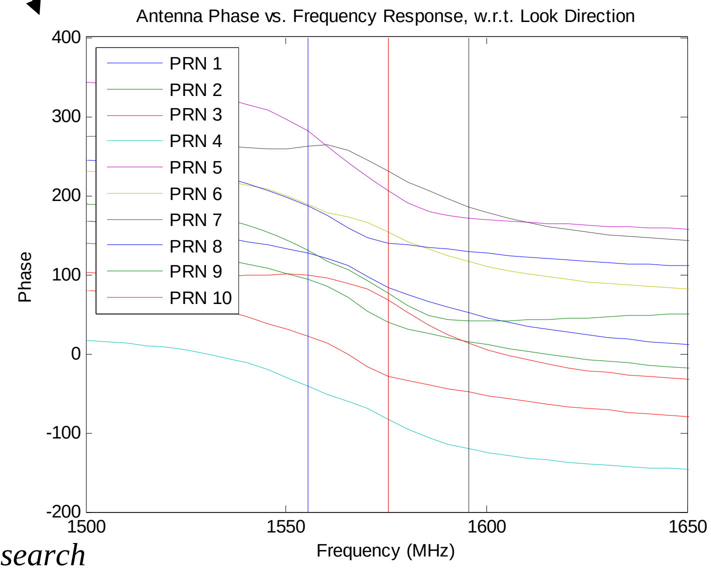
- Antenna gain/phase response varies as a function of incoming signal azimuth, elevation, and frequency
  - Correlation peak distortion
  - Carrier-phase bias
  - Signal attenuation

Pseudorange and carrier-phase biases for the center antenna of a 7-element array, as a function of incoming signal line-of-sight; isotropic signal power of 40 dB-Hz.

PRN	Incoming Signal Line-of-Sight		Pseudorange Bias (m)	Carrier-Phase Bias (deg)	C/No (dB-Hz)
	Az	El			
1	0	40	-2.0	85	37.5
2	30	30	-1.9	42	36.8
3	60	40	-1.5	-27	37.6
4	90	50	-2.3	-83	38.1
5	120	20	-2.8	-154	34.3
6	150	60	-2.2	154	38.7
7	210	70	-2.4	-129	38.9
8	240	20	-0.5	141	33.6
9	270	30	-3.0	76	35.9
10	300	80	-2.7	67	38.8

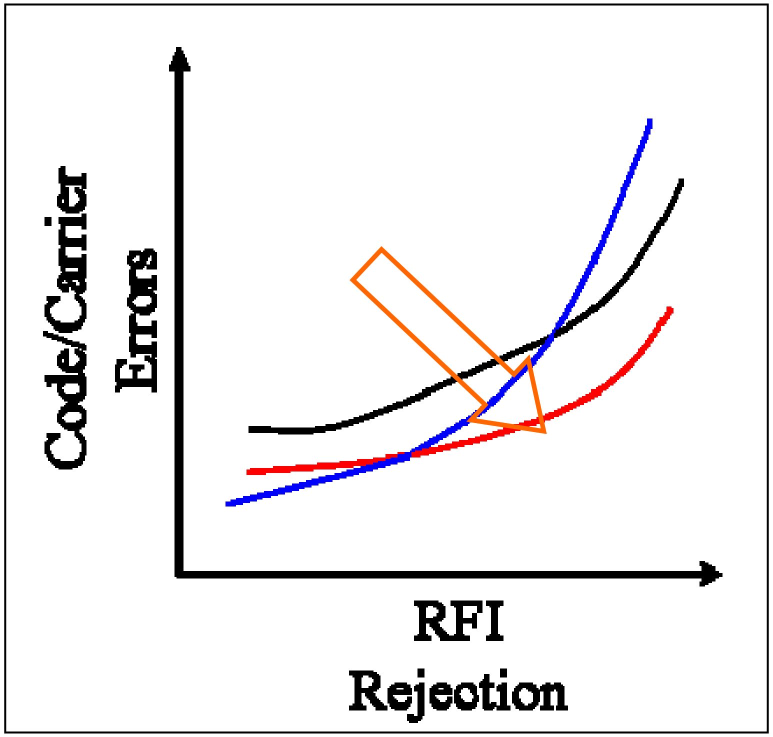


Test satellite – ideal correlation peak



Motivation – Biases vs. RFI Rejection

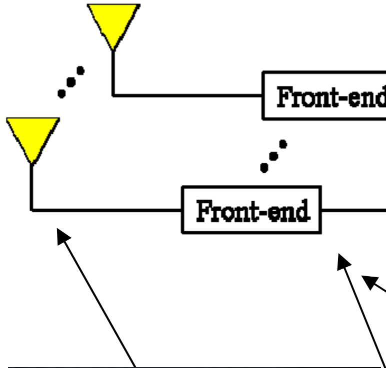
- Antennas:
  - Introduce biases in code-phase and carrier-phase
- Multi-Element Antenna Arrays:
  - Increase C/No
  - Reject RFI
  - Compound biases
- How to calibrate biases for STAP?
- Goal: Evaluate trade-space between RFI and biases

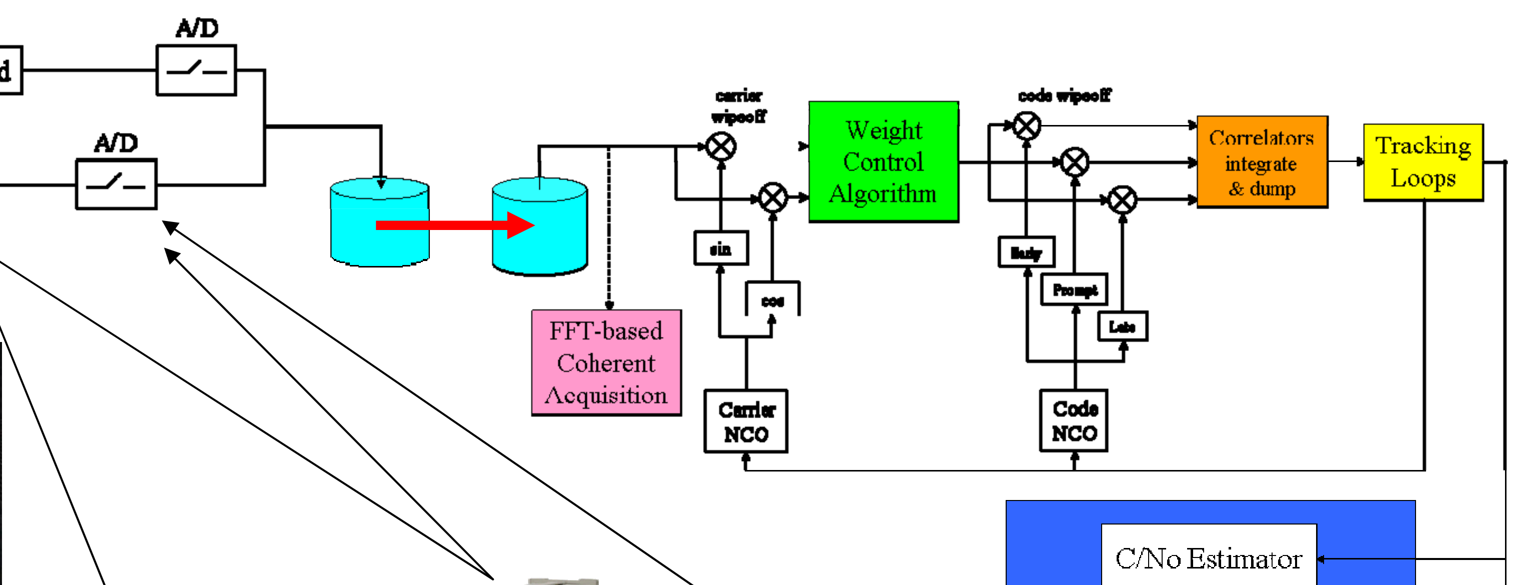


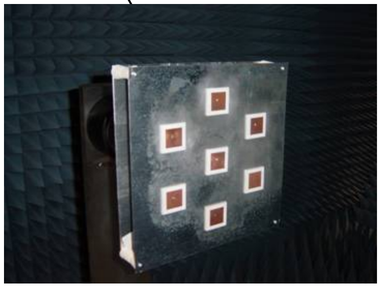
Methodology – Overview

- STAP response depends on signal environment and receiver tracking implementation
- Therefore, we need to estimate bias and noise performance in the context of realistic GPS tracking scenarios
  - End-to-end study
    - Antenna characterization
    - Signal generation
    - Weight adaptation
    - Signal tracking
  - All variables are under direct control, allowing isolation and estimation of parameters of interest

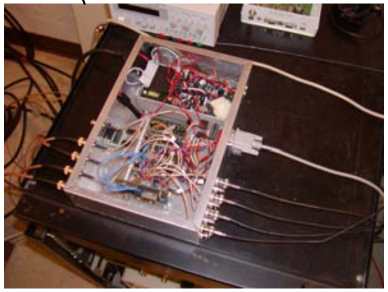
Stanford HW & SW Development





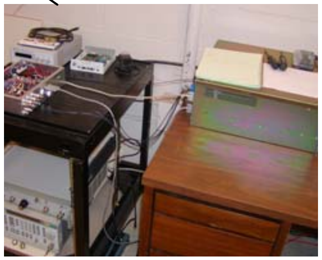


7-element array
rectangular patch
antennas manufactured
at Stanford University



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

HP Vector
Signal
Analyzer



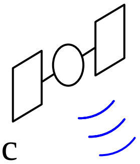
Data collection computer
(2) ICS-650 cards
sampling at 5-65 MHz
and 12-bit A/D resolution

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.

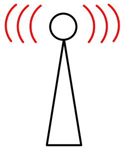
Software-Based Signal Simulator

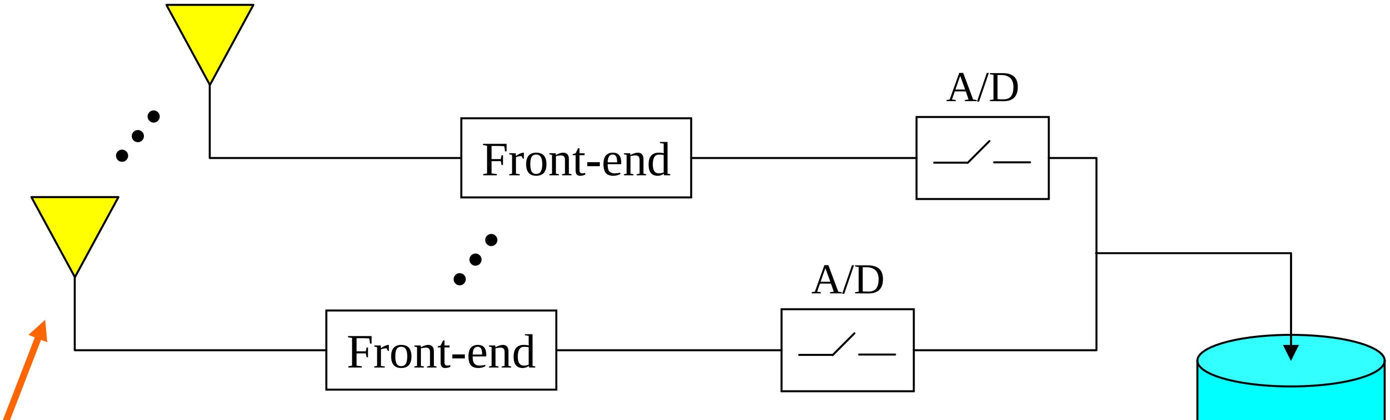


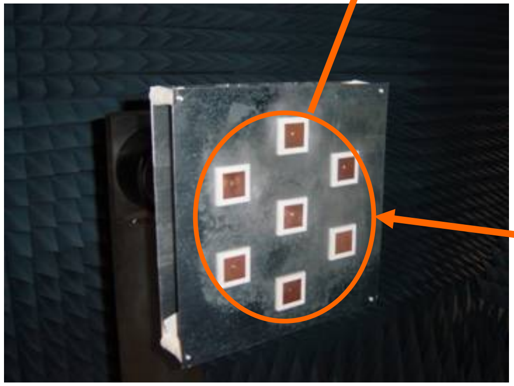
C/A & “P” code
1.023 & 10.23 Mchip/sec

- Gain/phase data for each look direction (10 S/V constellation) and antenna (7 rectangular patches)
  - Data courtesy Ung-Suok Kim

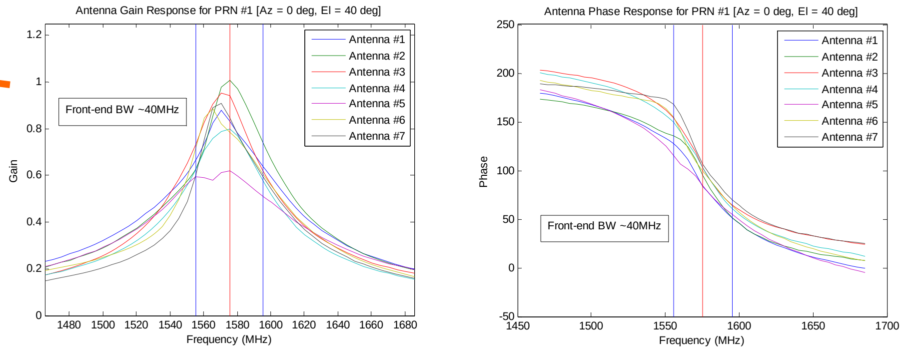
Bandlimited WGN
& CW interference



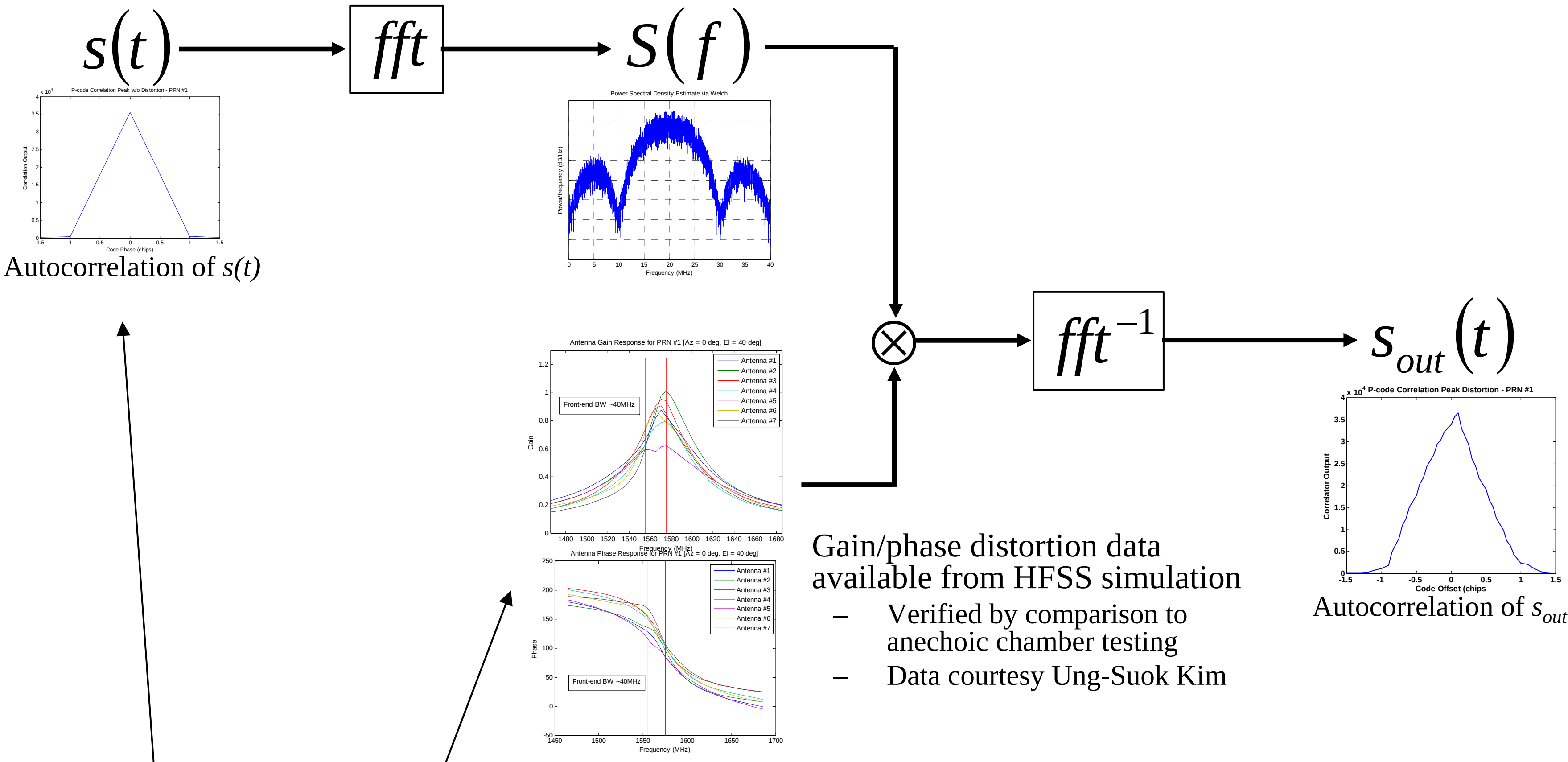




Gain/phase response for PRN #1
[Azimuth = 0°, Elevation = 40°]



Signal Generation w/ Antenna Distortion



Autocorrelation of *s(t)*

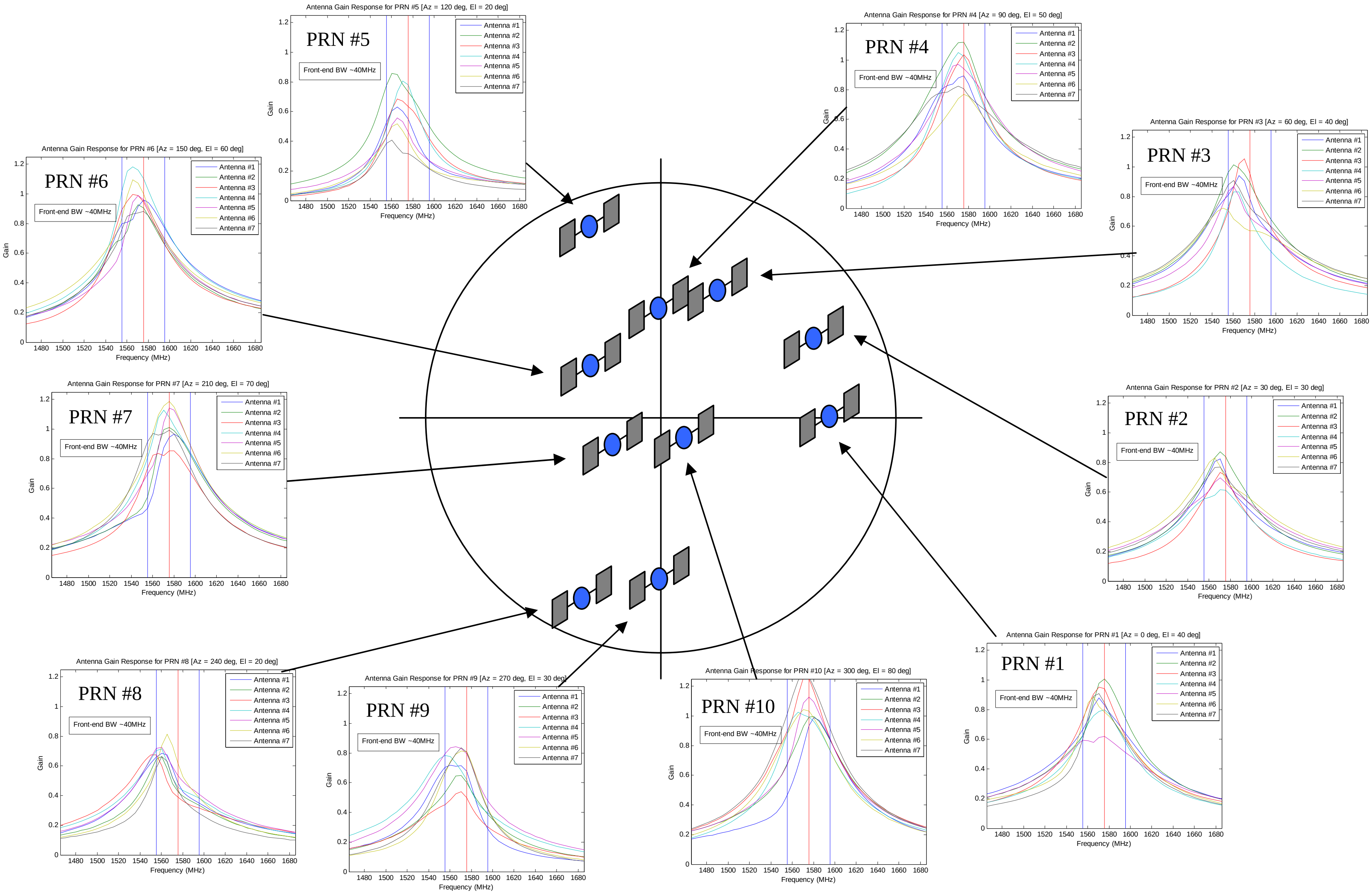
Autocorrelation of $s_{out}(t)$

Gain/phase distortion data available from HFSS simulation

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

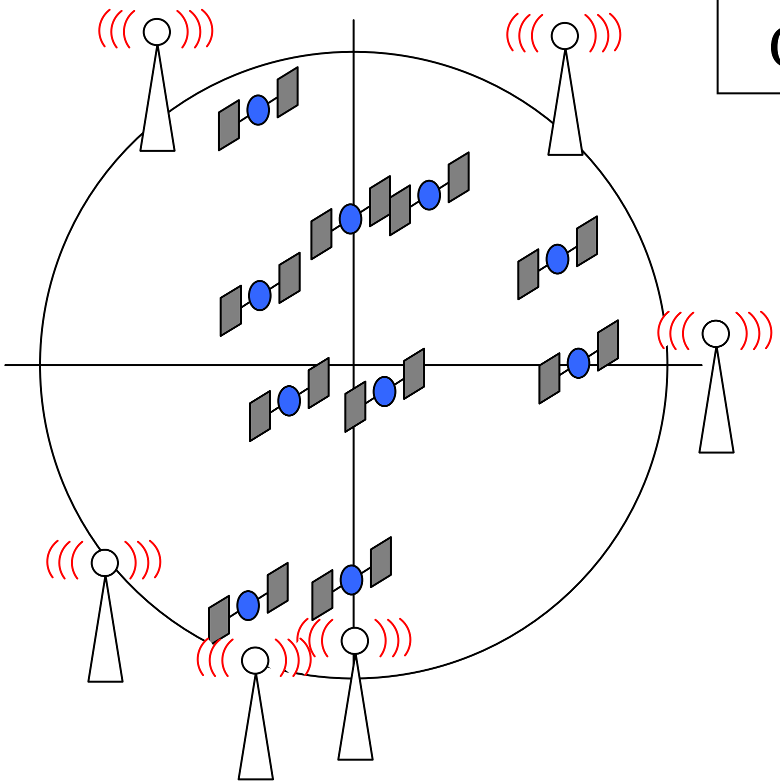
s(t) and gain/phase data are antenna & S/V specific

Standard Satellite Constellation



Satellite & RFI Constellation

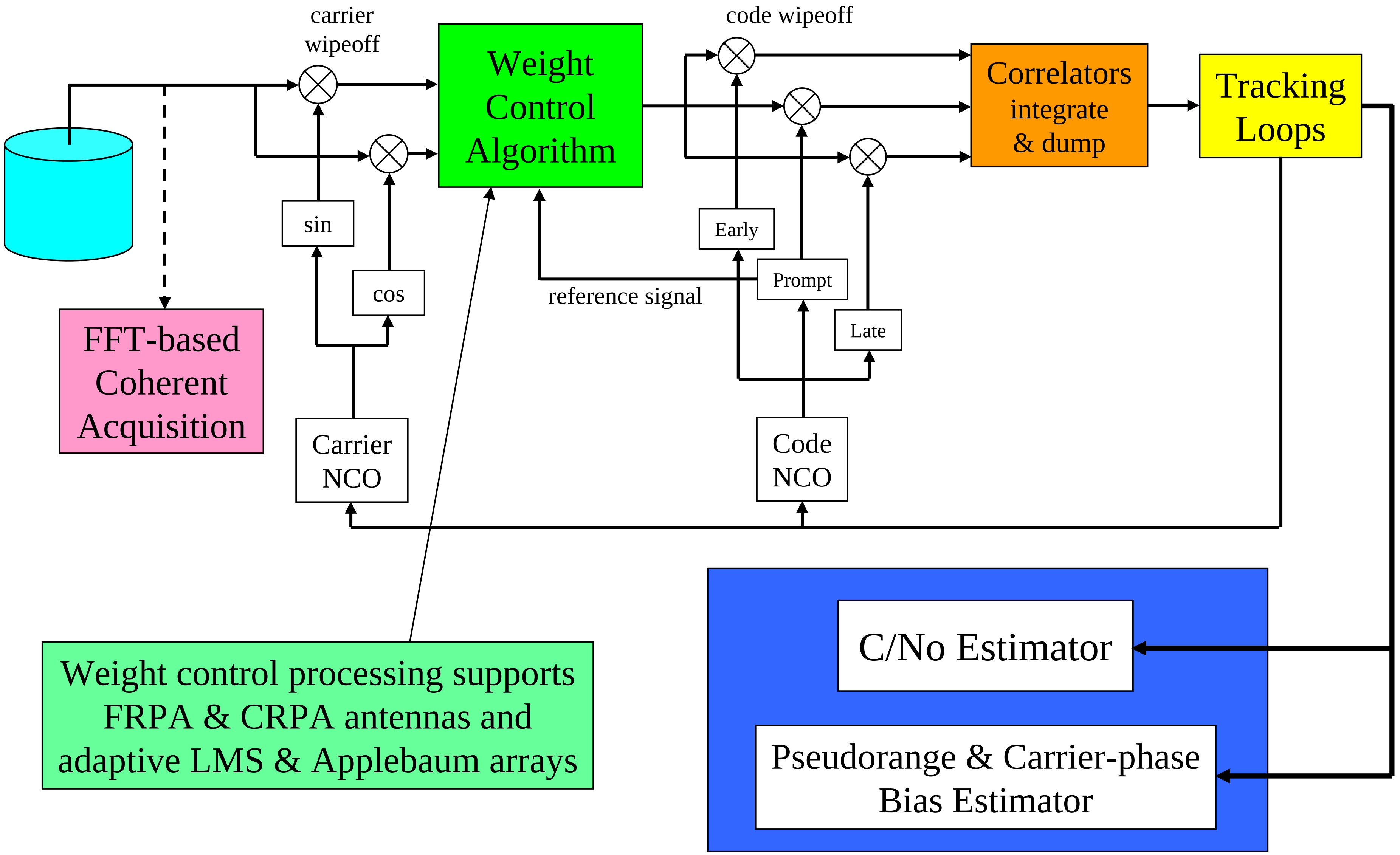
PRN	Azimuth	Elevation
1	0	40
2	30	30
3	60	40
4	90	50
5	120	20
6	150	60
7	210	70
8	240	20
9	270	30
10	300	80



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



carrier wipeoff

Weight Control Algorithm

code wipeoff

Correlators integrate & dump

Tracking Loops

sin

cos

Early

Prompt

Late

reference signal

FFT-based Coherent Acquisition

Carrier NCO

Code NCO

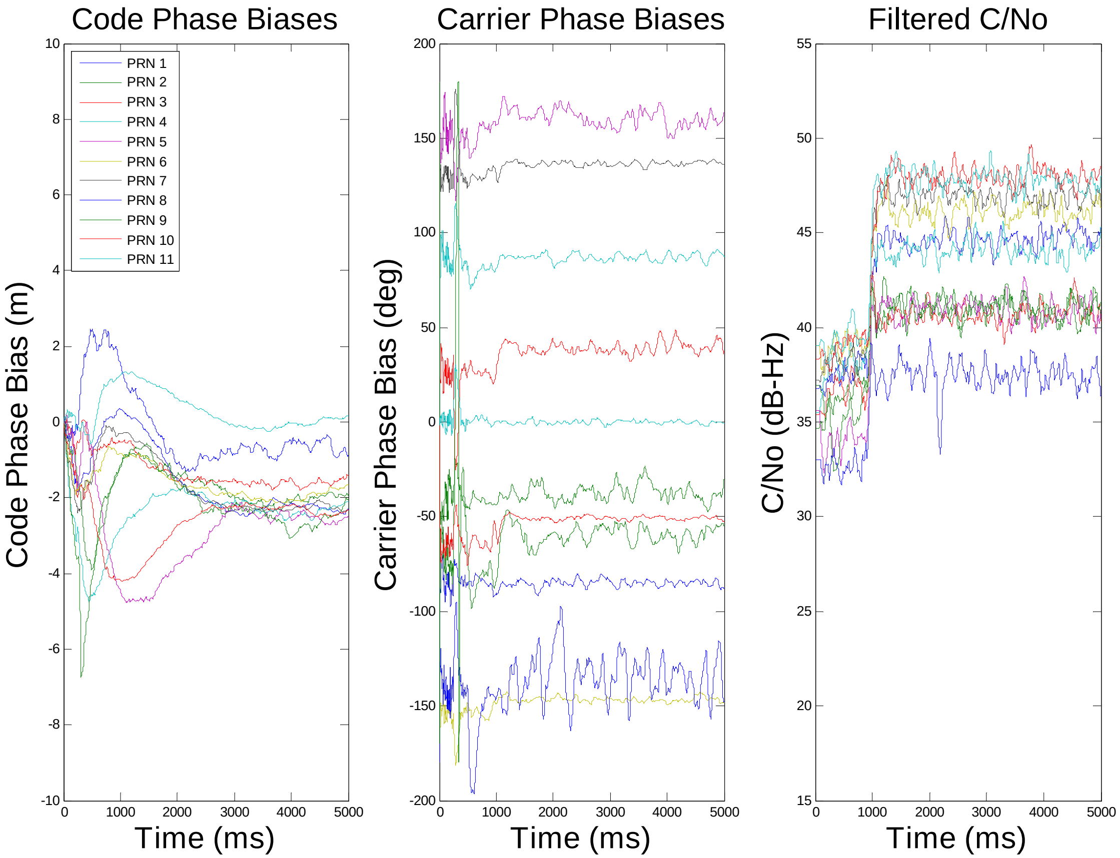
Weight control processing supports FRPA & CRPA antennas and adaptive LMS & Applebaum arrays

C/No Estimator

Pseudorange & Carrier-phase Bias Estimator

SW Receiver Output & Bias Estimation

- Tracking signals containing noise & RFI produces noisy estimates of code- and carrier-phase bias

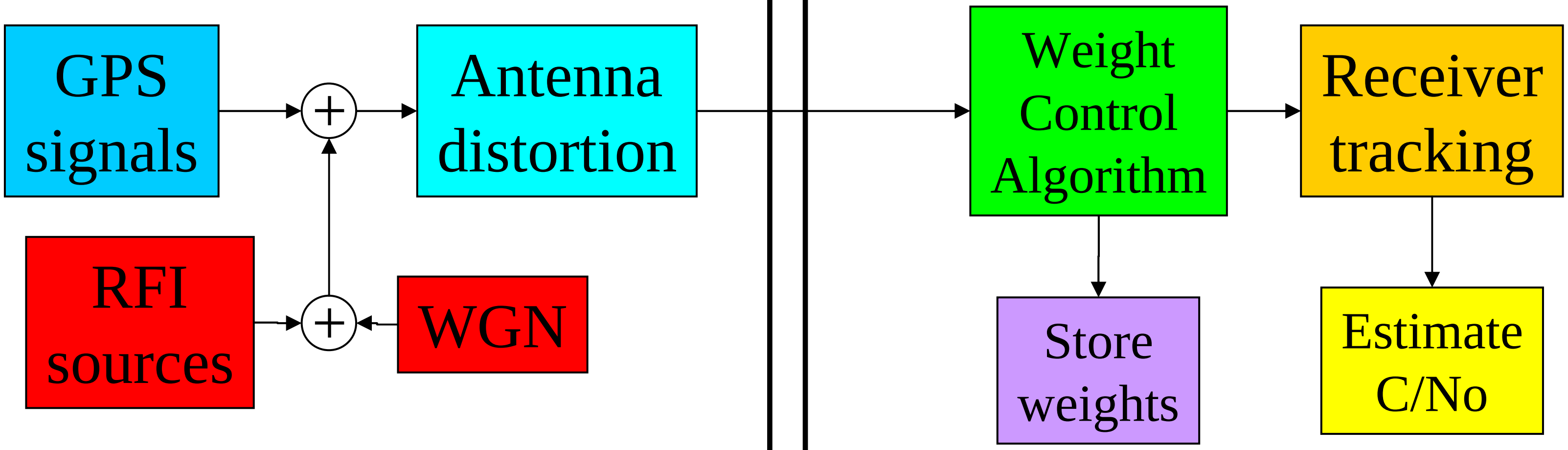


Applebaum-based STAP
C/No = 40 dB-Hz
plus six RFI sources
at J/S = 20dB

Methodology – Step 1 (of 2)

Signal Simulator

Software Receiver



GPS signals

Antenna distortion

RFI sources

WGN

Weight Control Algorithm

Receiver tracking

Store weights

Estimate C/No

- Constellation & array geometry
- P-code sampled at 80 MHz
- Antenna response from HFSS

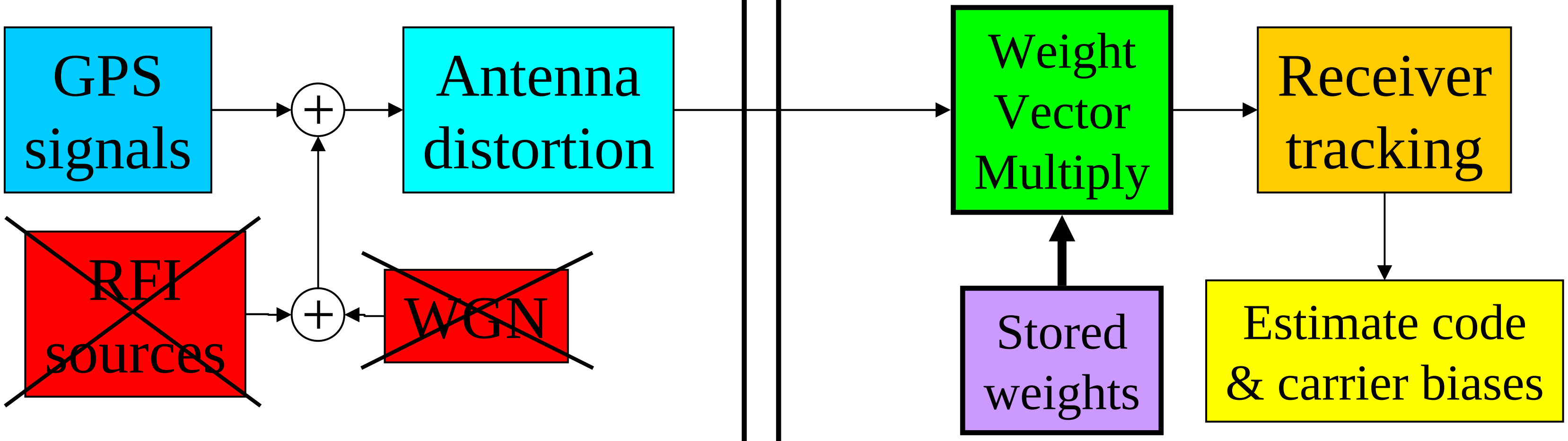
- Standard PLL & DLL
- FRPA, CRPA, & STAP modules
- Spatial & temporal constraints

- Track signals containing RFI & noise
- Save weight vector for STAP algorithms
- Determine noise performance: C/No

Methodology – Step 2 (of 2)

Signal Simulator

Software Receiver



- Constellation & array geometry
- P-code sampled at 80 MHz
- Antenna response from HFSS

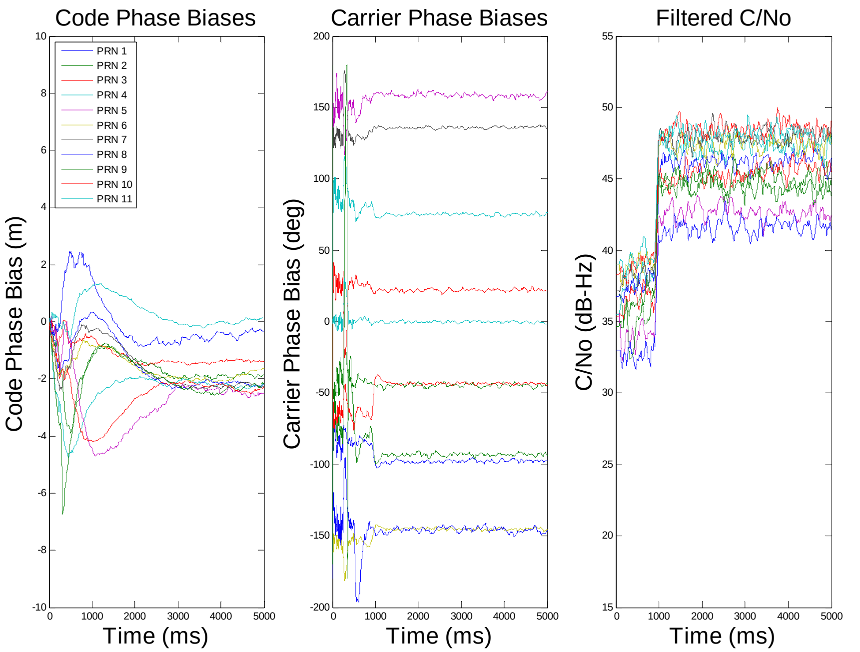
- Standard PLL & DLL
- FRPA, CRPA, & STAP modules
- Spatial & temporal constraints

- Track noise-free signals
- Use stored weight vector for STAP algorithms
- Determine code & carrier biases

Methodology – Tracking Output & Biases

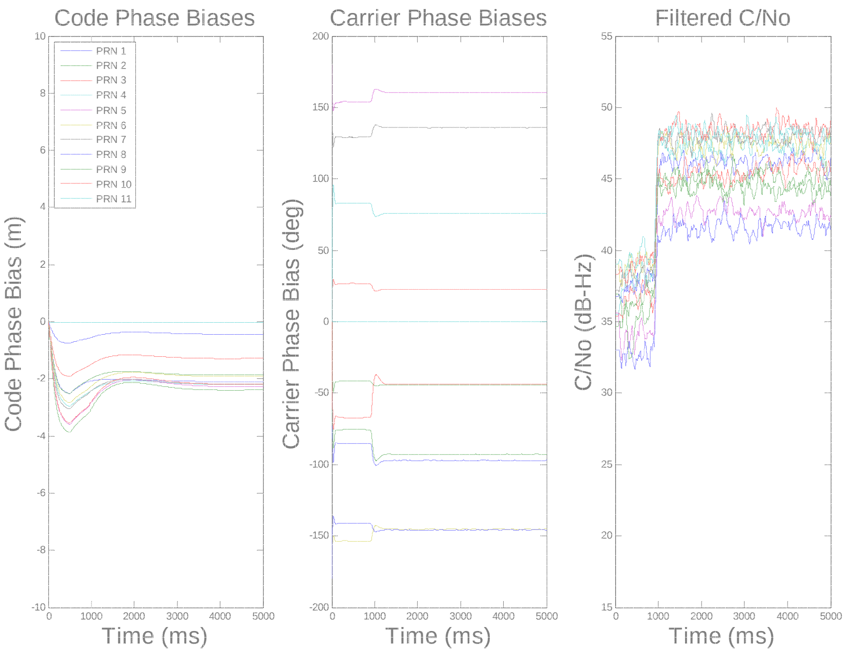
Step 1:

- Track signals containing RFI & noise
- Save weight vector for STAP algorithms
- Determine noise performance: C/No



Step 2:

- Track noise-free signals
- Use stored weight vector for STAP algorithms
- Determine code & carrier biases



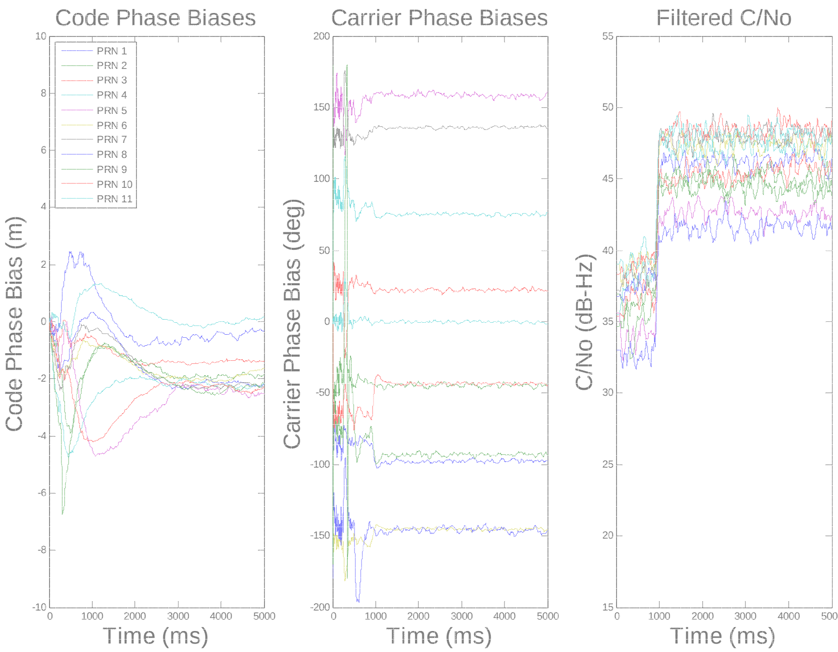
Methodology – Tracking Output & Biases

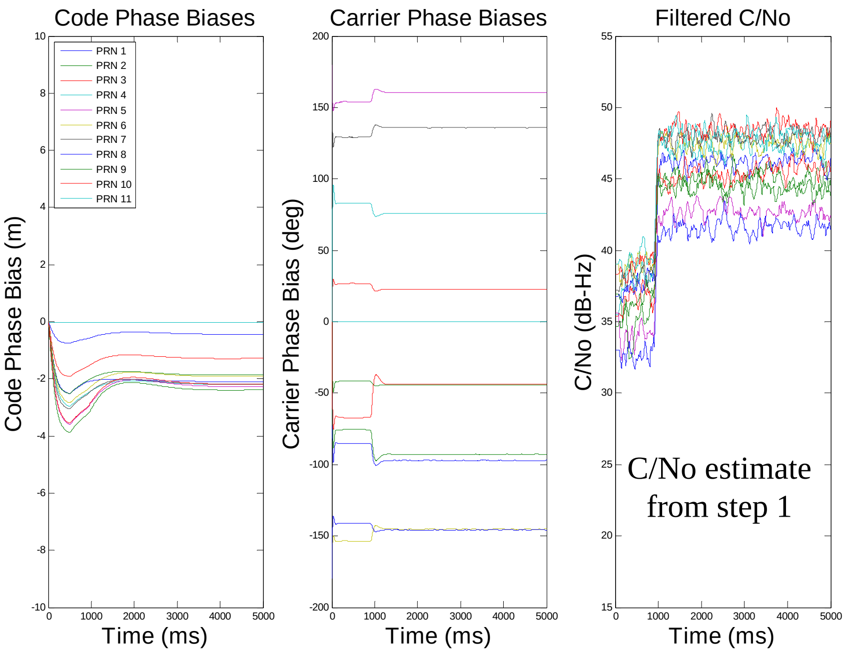
Step 1:

- Track signals containing RFI & noise
- Save weight vector for STAP algorithms
- Determine noise performance: C/No

Step 2:

- Track noise-free signals
- Use stored weight vector for STAP algorithms
- Determine code & carrier biases





C/No estimate from step 1

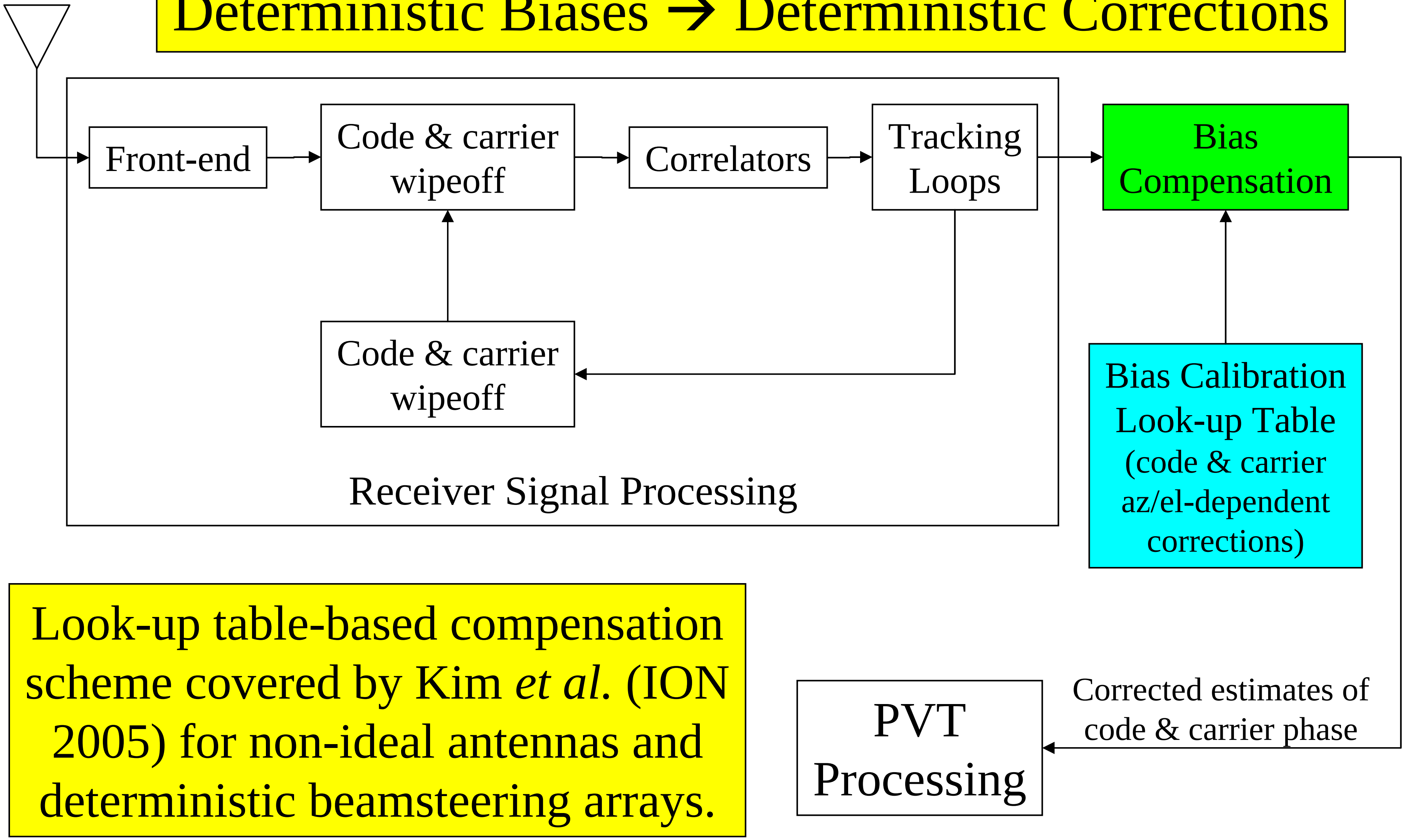
Uncompensated Code & Carrier Biases

- Pseudorange biases ~2m
- Carrier-phase biases uniformly distributed
- 7-element arrays yield ~8.5 dB-Hz improvement in C/No
- Biases unacceptable for high-integrity carrier-phase differential navigation!

Uncompensated pseudorange and carrier-phase biases; isotropic signal power of 40 dB-Hz.				
Averages over 10-satellite constellation	**Single-element FRPA**	**7-element deterministic CRPA**	**Blind-adaptive STAP beam/null steering (LMS-based)**	**Steering-vector STAP beam/null steering (Applebaum-based)**
Pseudorange bias (m)	**2.13**	**1.88**	**1.94**	**1.88**
Carrier-phase bias (deg)	**96**	**96**	**96**	**96**
C/No (dB-Hz)	**37.0**	**45.7**	**45.7**	**45.7**

Pseudorange & Carrier Bias Compensation

Deterministic Biases → Deterministic Corrections



Front-end

Code & carrier wipeoff

Correlators

Tracking Loops

Bias Compensation

Code & carrier wipeoff

Receiver Signal Processing

Bias Calibration Look-up Table (code & carrier az/el-dependent corrections)

PVT Processing

Corrected estimates of code & carrier phase

Look-up table-based compensation scheme covered by Kim *et al*. (ION 2005) for non-ideal antennas and deterministic beamsteering arrays.

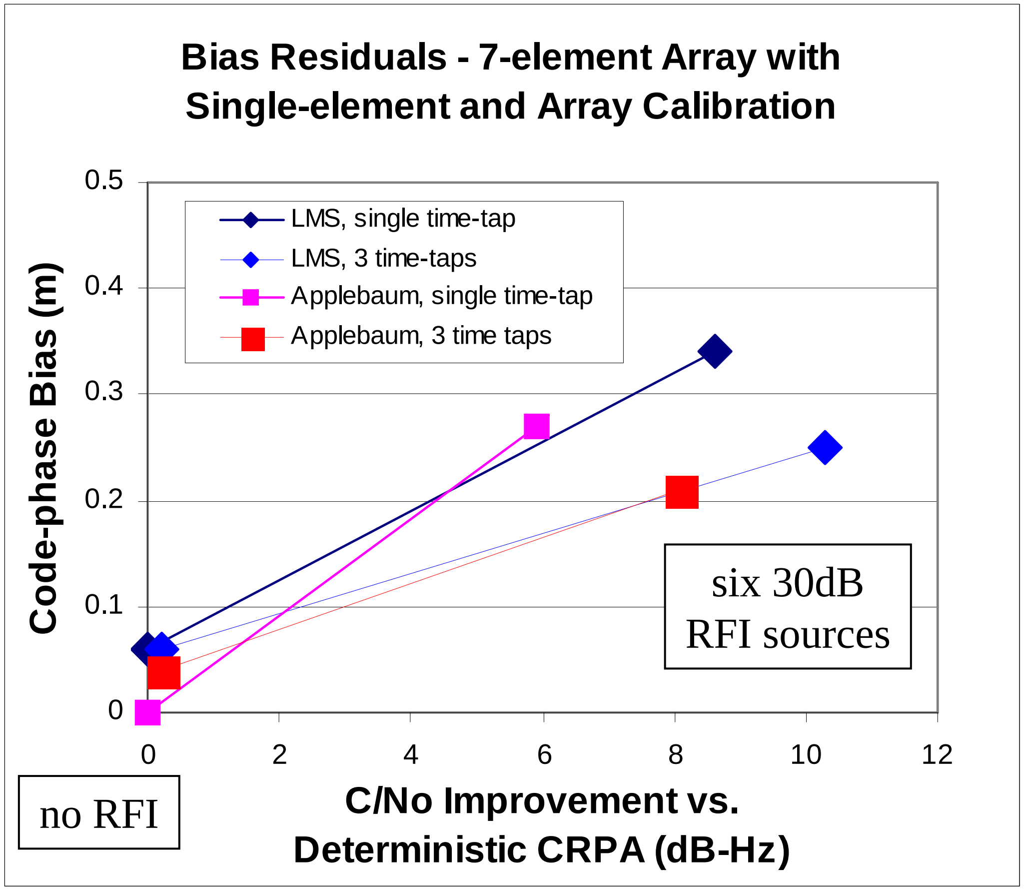
Bias Residuals After Compensation

- Two types of LOS-based (az/el) calibration are possible:
  - Single-Element (FRPA) calibration
  - Multi-Element (CRPA) beamforming calibration
- Best calibration option depends on STAP algorithm

Pseudorange and carrier-phase biases; isotropic signal power of 40 dB-Hz.			
Averages over 10-satellite constellation		**Blind-adaptive STAP beam/null steering (LMS-based)**	**Steering-vector STAP beam/null steering (Applebaum-based)**
Bias residuals w.r.t. single-element FRPA calibration	**Pseudorange bias (m)**	**0.23**	**0.28**
	Carrier-phase bias (deg)	**0.5**	**9.2**
Bias residuals w.r.t. 7-element CRPA calibration	**Pseudorange bias (m)**	**0.06**	**0.00**
	Carrier-phase bias (deg)	**9.3**	**0.0**

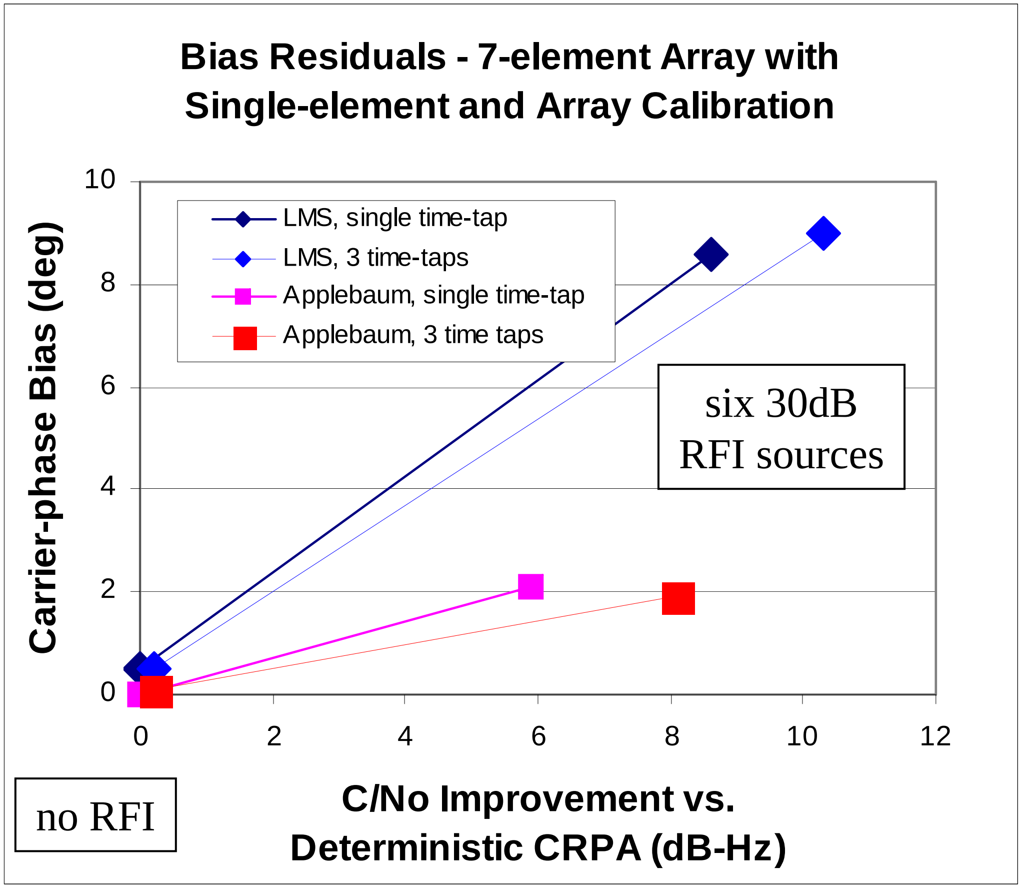
Compensation vs. RFI Tradeoffs (1)

- Two cases considered: No RFI case and 30 dB RFI on six sources
- STAP enables noise rejection at expense of biases
- Code-phase biases equivalent for both STAP algorithms



Compensation vs. RFI Tradeoffs (2)

- Carrier-phase biases lower for Applebaum than for LMS
- Maximum achievable noise rejection better for LMS than for Applebaum



Conclusions

- Deterministic corrections (LOS-based lookup table) will reduce pseudorange and carrier-phase biases in the tracking output
  - Carrier-phase residual is likely livable
  - Code-phase biases appear troubling – need further work

Bias Residuals After Compensation, 7-element Adaptive Array	
Code-phase	**10s of cm**
Carrier-phase	**0-10 deg.**

- As RFI power increases, STAP algorithms become more desirable
- There is a balance between the ability to reject interference and the necessity of limiting errors