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All-Digital, Spatial Anti-Jam GPS Receivers: Architecture, Implementation, and Initial Performance Results

ION GPS ‘99

Session D6: Military and Commercial Applications Fusion

17 September 1999

System Engineering:	Program Management:	Business Development:
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Agenda

- Motivation for Anti-Jam GPS Receivers
- All-Digital Receiver Architecture
- Spatial Anti-Jam Receiver Architecture
  - RF and Digitization
  - Beamforming Algorithms
  - Interference Detection, DF, and Geolocation
- Beamstar/Iceman Anti-Jam GPS Receiver
  - Architecture
  - C/A Test Results
- Miniaturized Spatial Anti-Jam GPS Receiver
- Summary and Conclusions

Commercial Anti-Jam Requirements

"GPS Risk Assessment Study Final Report",
The Johns Hopkins University Applied Physics Laboratory,
Report No. VS-99-007, January 1999.

"Techniques that can add 40 to 50 dB of additional rejection are possible; inclusion of such capabilities would virtually defeat the jamming threat considered in this study."

"Methods to detect, locate, and prosecute those who intentionally jam GPS signals must be put in place …".

Military Anti-Jam Goals

NAVWAR
Navigation Warfare

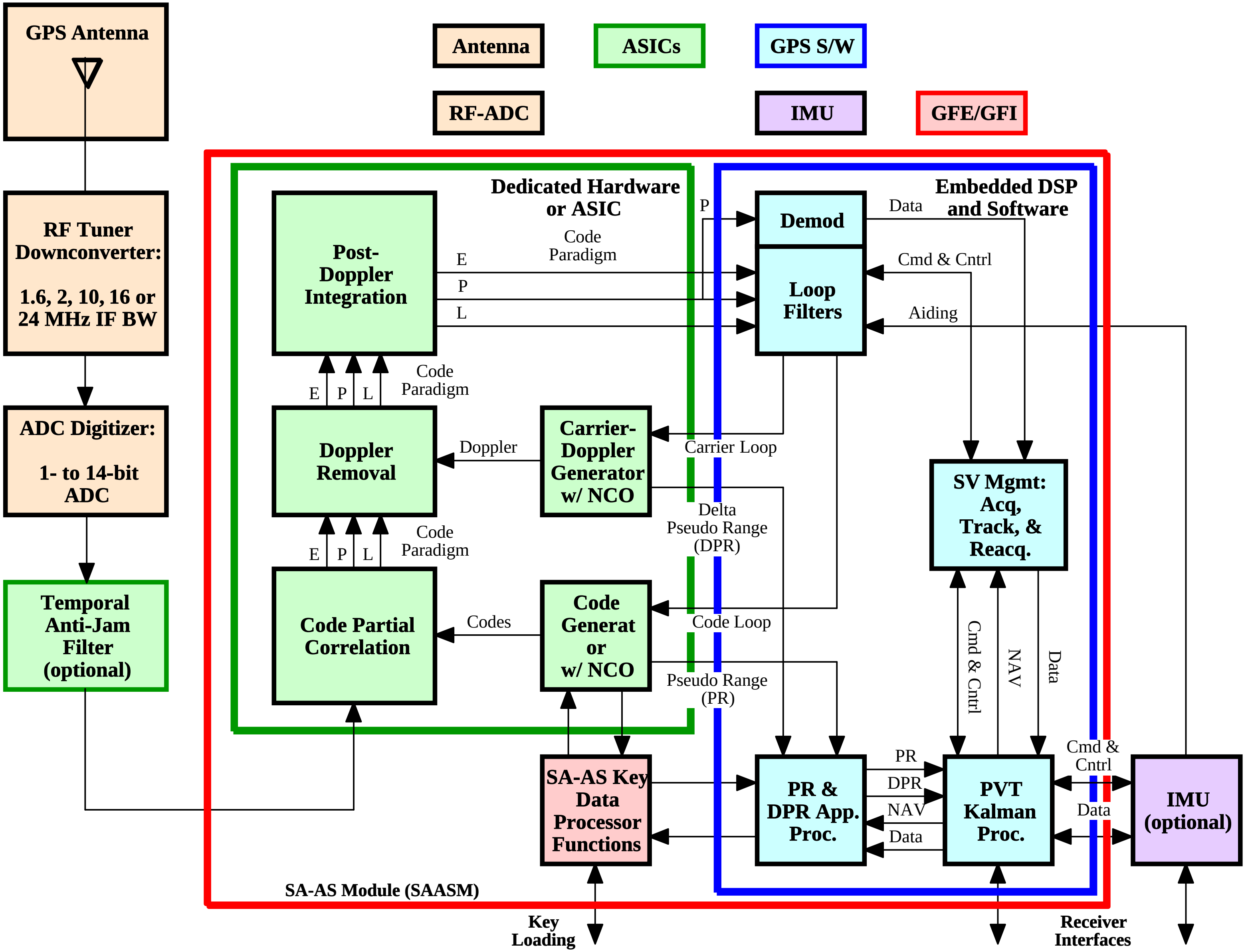
Protect
friendly use of GPS on the battlefields

Prevent
exploitation of satellite navigation by adversaries

Preserve
the ability of civil users to enjoy the benefits of GPS outside areas of conflict

Protection necessitates the development and deployment of both interference mitigation or cancellation for GPS receivers and systems to detect and geolocate jamming sources for the purpose of targeting and elimination

All-Digital GPS Implementation



Antenna
ASICs
GPS S/W
RF-ADC
IMU
GFE/GFI

GPS Antenna

RF Tuner Downconverter:
1.6, 2, 10, 16 or 24 MHz IF BW

ADC Digitizer:
1- to 14-bit ADC

Temporal Anti-Jam Filter (optional)

Dedicated Hardware or ASIC

Post-Doppler Integration

E
P
L

Code Paradigm

Doppler Removal

Doppler

Carrier-Doppler Generator w/ NCO

Code Partial Correlation

Codes

Code Generator w/ NCO

SA-AS Key Data Processor Functions

SA-AS Module (SAASM)

Key Loading

Embedded DSP and Software

P

Demod

Data

Cmd & Cntrl

Loop Filters

Aiding

Carrier Loop

Delta Pseudo Range (DPR)

Code Loop

Pseudo Range (PR)

SV Mgmt: Acq, Track, & Reacq.

Cmd & Cntrl
NAV
Data

PR & DPR App. Proc.

PR
DPR
NAV
Data

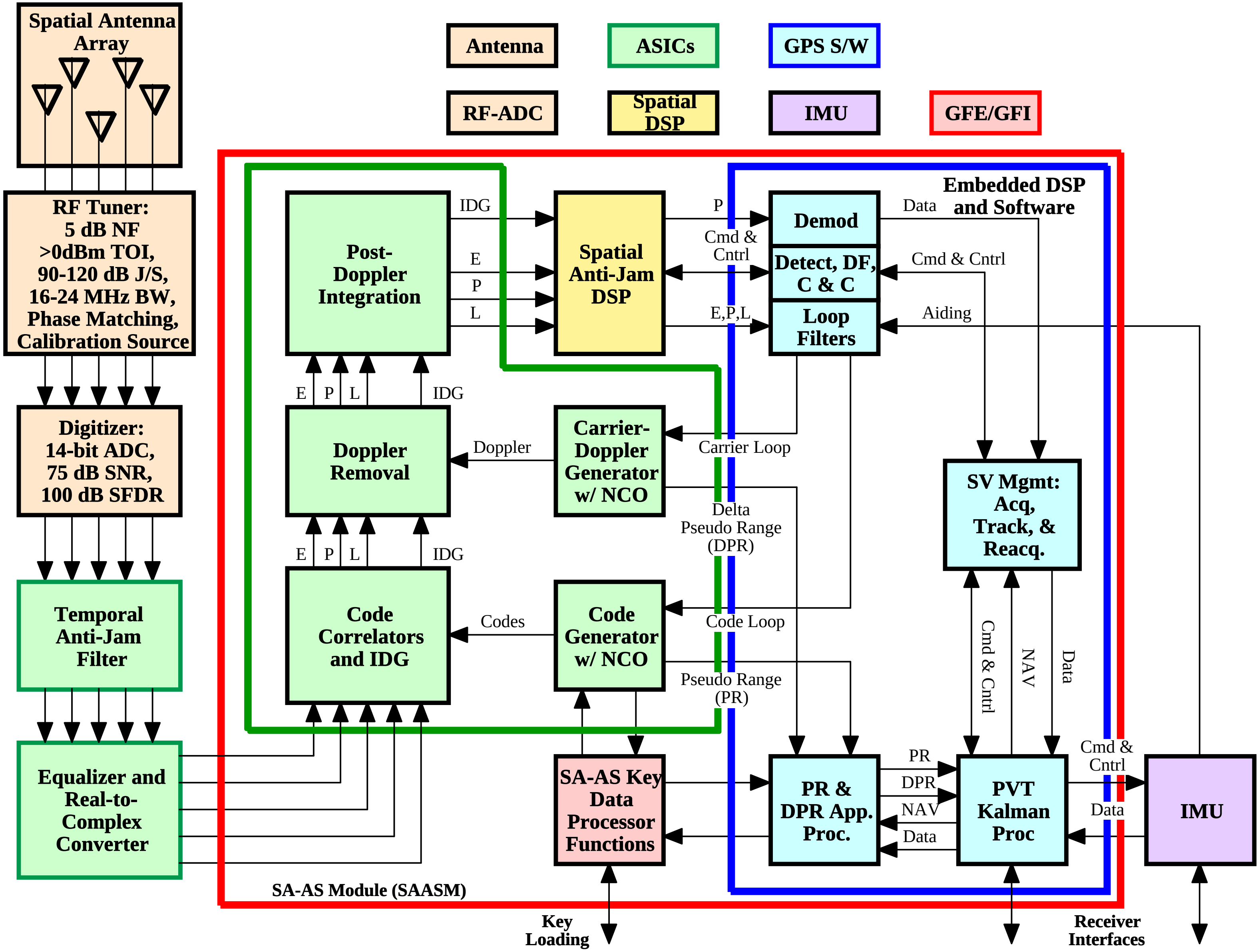
PVT Kalman Proc.

Cmd & Cntrl
Data

IMU (optional)

Receiver Interfaces

All-Digital Spatial Anti-Jam Implementation



Antenna
ASICs
GPS S/W
RF-ADC
Spatial DSP
IMU
GFE/GFI

Spatial Antenna Array

RF Tuner:
5 dB NF
>0dBm TOI,
90-120 dB J/S,
16-24 MHz BW,
Phase Matching,
Calibration Source

Digitizer:
14-bit ADC,
75 dB SNR,
100 dB SFDR

Temporal Anti-Jam Filter

Equalizer and Real-to-Complex Converter

Post-Doppler Integration

Doppler Removal

Code Correlators and IDG

Spatial Anti-Jam DSP

Carrier-Doppler Generator w/ NCO

Code Generator w/ NCO

SA-AS Key Data Processor Functions

Demod

Detect, DF, C & C

Loop Filters

SV Mgmt: Acq, Track, & Reacq.

PR & DPR App. Proc.

PVT Kalman Proc

IMU

Embedded DSP and Software

SA-AS Module (SAASM)

IDG
E
P
L
E P L IDG
E P L IDG
Doppler
Codes
P
Cmd & Cntrl
E,P,L
Data
Cmd & Cntrl
Aiding
Carrier Loop
Delta Pseudo Range (DPR)
Code Loop
Pseudo Range (PR)
Cmd & Cntrl
NAV
Data
PR
DPR
NAV
Data
Cmd & Cntrl
Data

Key Loading

Receiver Interfaces

RF and Digitizer Design Considerations

Code Type	Chip Rate (Mcps)	Band Fs	99% Power Bandwidth	kTB	% BW @173.91 MHz	Shape Factor @ 65 Msps
C/A-Code	1.023	0	10.23 MHz	-103.90 dBm	5.88%	5.35-to-1
P(Y)-Code Mainlobe	10.23	0	16.00 MHz	-101.96 dBm	9.20%	3.06-to-1
L5 Split C/A (est.)	1.023	±5.115 MHz	20.46 MHz	-100.89 dBm	11.76%	2.18-to-1
Lm-Code (est.)	TBD	TBD	24.00 MHz	-100.20 dBm	13.80%	1.71-to-1

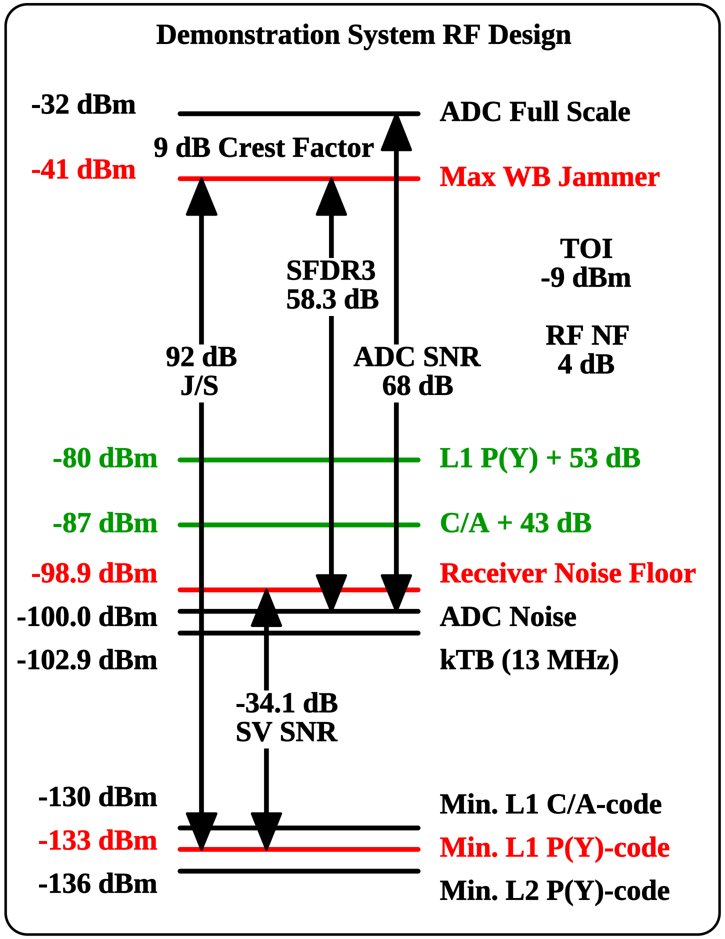
- **Receiver Bandwidth**
  - **Nominally 99% Power**
  - **Thermal Noise Power (kTB)**
- **IF Filter Design**
  - **IF Frequency and Percent Bandwidth**
  - **Materials, Design, Ripple**
- **ADC Selection**
  - **Sample Rate, SNR, SFDR**
- **Instantaneous Dynamic Range**
  - **Resolution below noise floor**
  - **Range above highest jammer power plus peaking factor**
- **Spurious Responses, RF matching, and Passband Ripple**
  - **Second and third order intercept**
  - **Equalization**

Also reference:
D. Moulin, M.N. Solomon, T.M. Hopkinson, P.T. Capozza, J. Psilos , The MITRE Corporation
“High-Performance RF-to-Digital Translators For GPS Anti-Jam Applications”,
Proc. ION GPS-98, Nashville, TN, 15-18 September, 1998, pp. 223-239.

RF and Digitizer Design Maps

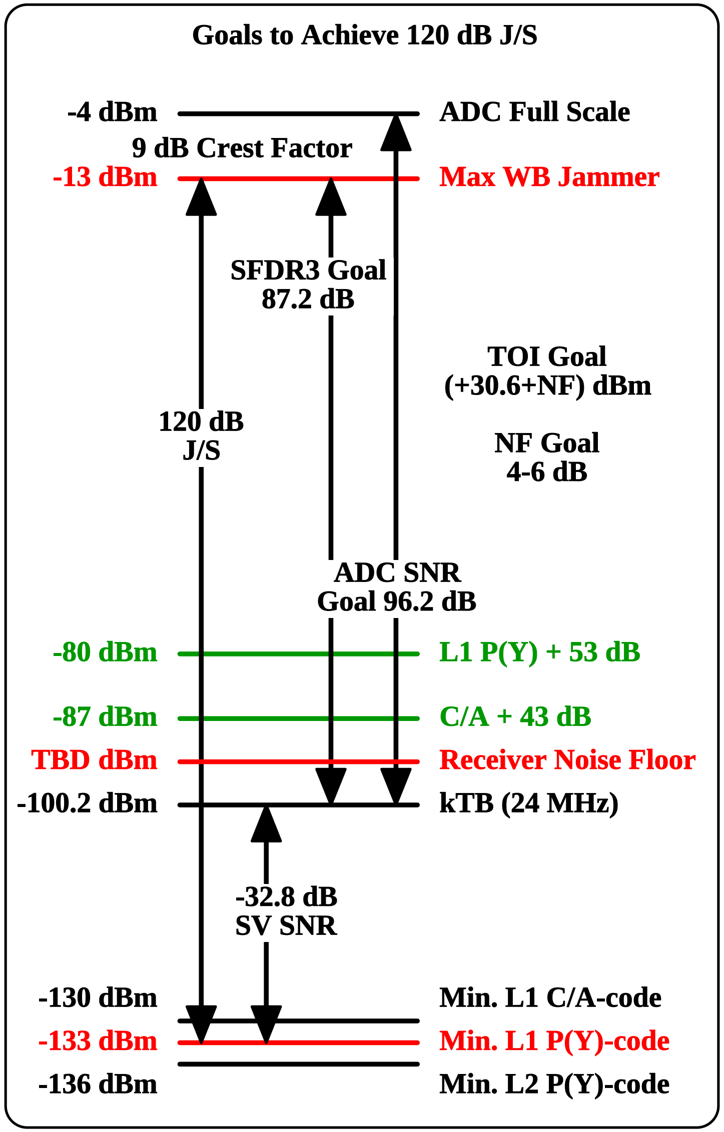
Power levels at the receiver input

- SNR, SIR, Detection Threshold and SINR



Demonstration System RF Design

-32 dBm — ADC Full Scale
9 dB Crest Factor
-41 dBm — Max WB Jammer
SFDR3 58.3 dB
TOI -9 dBm
RF NF 4 dB
92 dB J/S
ADC SNR 68 dB
-80 dBm — L1 P(Y) + 53 dB
-87 dBm — C/A + 43 dB
-98.9 dBm — Receiver Noise Floor
-100.0 dBm — ADC Noise
-102.9 dBm — kTB (13 MHz)
-34.1 dB SV SNR
-130 dBm — Min. L1 C/A-code
-133 dBm — Min. L1 P(Y)-code
-136 dBm — Min. L2 P(Y)-code



Goals to Achieve 120 dB J/S

-4 dBm — ADC Full Scale
9 dB Crest Factor
-13 dBm — Max WB Jammer
SFDR3 Goal 87.2 dB
TOI Goal (+30.6+NF) dBm
120 dB J/S
NF Goal 4-6 dB
ADC SNR Goal 96.2 dB
-80 dBm — L1 P(Y) + 53 dB
-87 dBm — C/A + 43 dB
TBD dBm — Receiver Noise Floor
-100.2 dBm — kTB (24 MHz)
-32.8 dB SV SNR
-130 dBm — Min. L1 C/A-code
-133 dBm — Min. L1 P(Y)-code
-136 dBm — Min. L2 P(Y)-code

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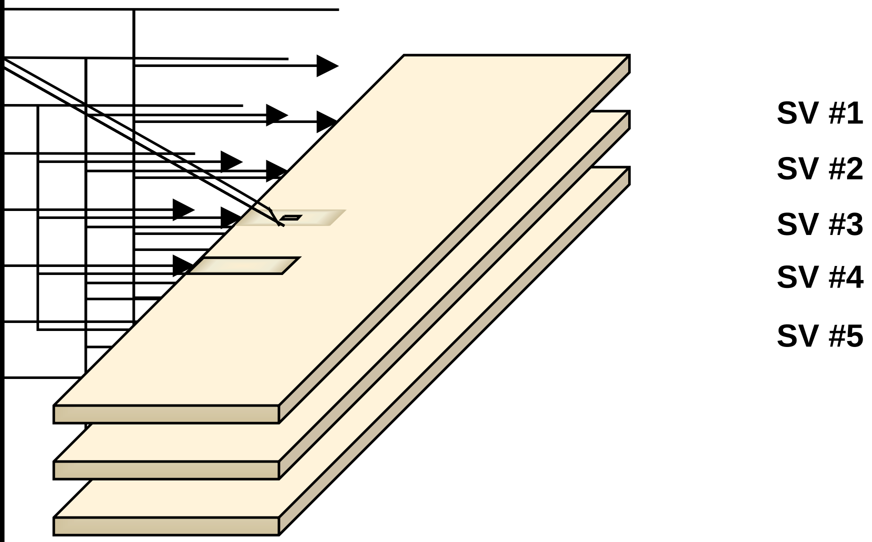
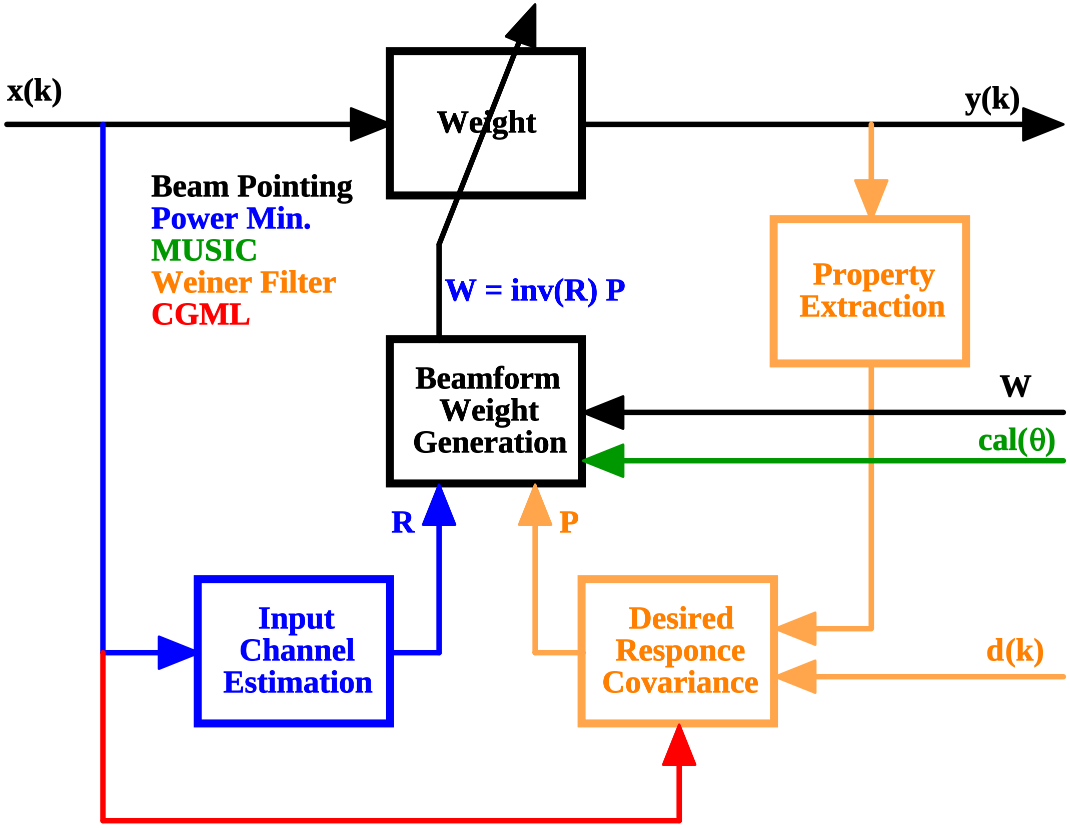
eamforming Structure

One Unique Beamformer per SV
(Digital Hardware/Software)



Spatial Beamforming



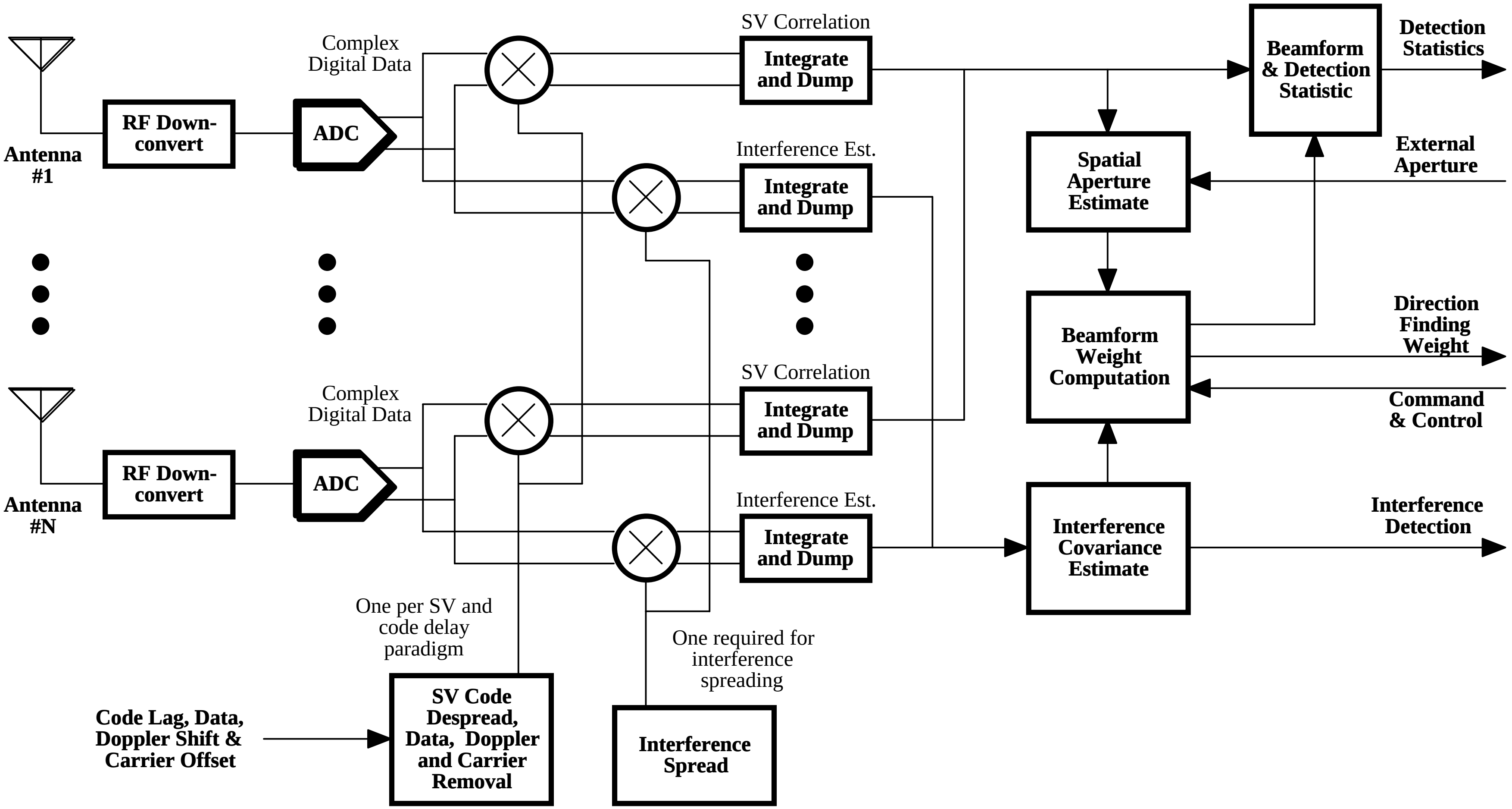
- **A-priori Beam Pointing:** Using the known location of the SVs, platform orientation, and a calibrated antenna array to point a spatial beam with gain to each of desired SVs.
- **Adaptive Power Minimization:** Using least-mean square (LMS) adaptive or environmental whitening algorithms to minimize the pre-correlation receiver signal power; thereby, creating nulls in the direction of interference.
- **Multiple Signal Classification (MUSIC):** Applying the MUSIC algorithm or other Eigenvector technique to determine the AOA of interference and generate spatial nulls to cancel the interference. This technique requires a calibrated antenna array for AOA and beamforming weight generation.
- **Wiener Filter Beamforming:** Optimal spatial beamformer using the inverse of the spatial input data auto-correlation matrix and the a-priori knowledge of the SV location, platform orientation, and a calibrated antenna array.
- **Code-Gated Maximum Likelihood (CGML) Beamforming:** Blind adaptive algorithm to achieve “optimal” spatial. Does not require any knowledge of SV location or platform orientation and does not require the use of a calibrated antenna array.

References:

S. Haykin, Adaptive Filter Theory, 3rd Ed., Prentice-Hall., Upper Saddle River, NJ, 1996.

S.U. Pillai, Array Signal Processing, Springer-Verlag, New York, NY, 1989.

DSSS Beamforming Architecture



Antenna #1

RF Down-convert

ADC

Complex Digital Data

SV Correlation

Integrate and Dump

Interference Est.

Integrate and Dump

Antenna #N

RF Down-convert

ADC

Complex Digital Data

SV Correlation

Integrate and Dump

Interference Est.

Integrate and Dump

One per SV and code delay paradigm

One required for interference spreading

Code Lag, Data, Doppler Shift & Carrier Offset

SV Code Despread, Data, Doppler and Carrier Removal

Interference Spread

Beamform & Detection Statistic

Detection Statistics

Spatial Aperture Estimate

External Aperture

Beamform Weight Computation

Direction Finding Weight

Command & Control

Interference Covariance Estimate

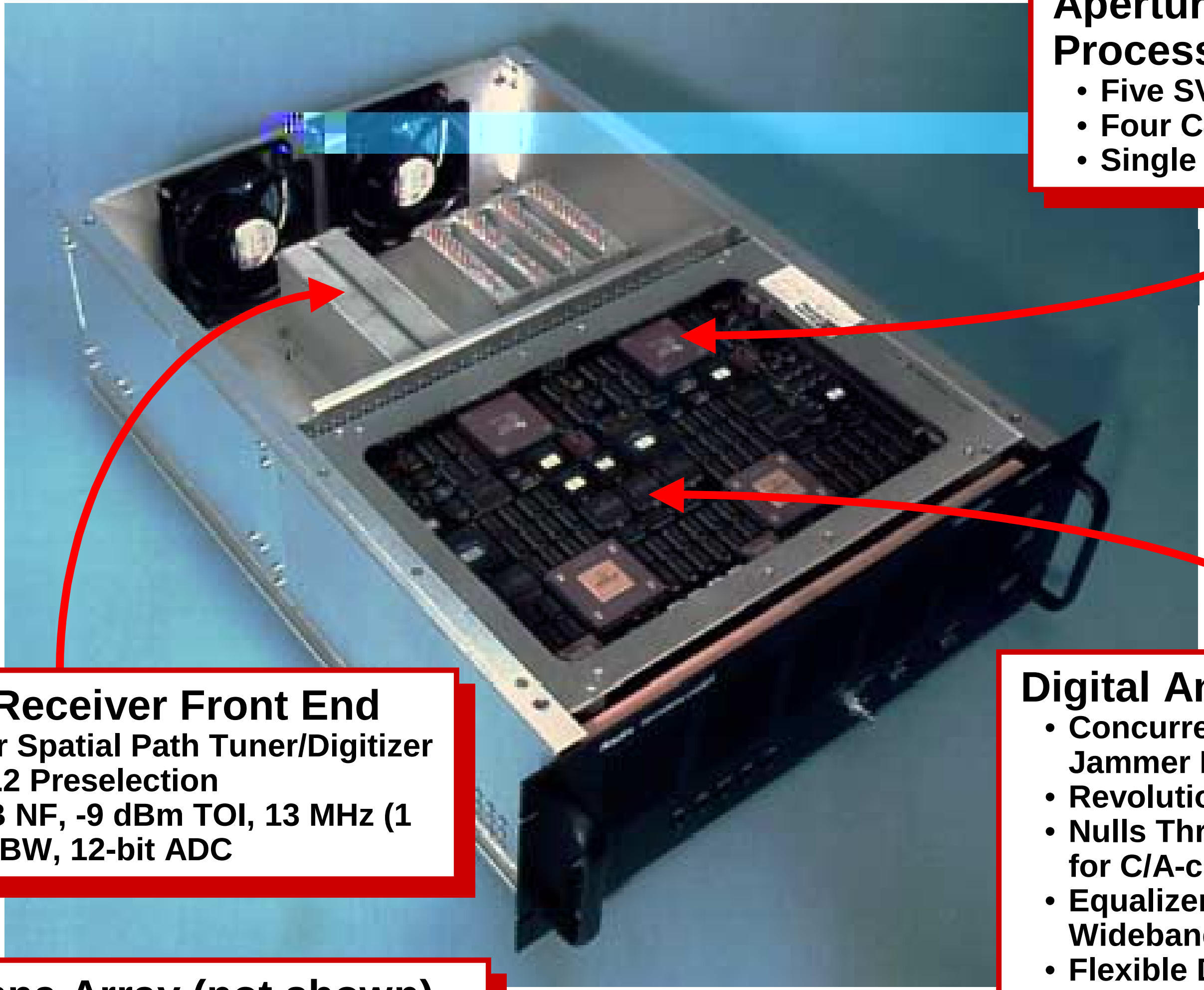
Interference Detection

A. Belouchrani and M.G. Amin, “A Two-Sensor Array Blind Beamformer for Direct Sequence Spread Spectrum Communications”, IEEE Trans. Signal Proc., Vol. 47, No. 8, Aug. 1999, pp. 2191-2199.

Detection, DF, and Geolocation

- Detection
  - Eigenvalues of the interference covariance matrix (trace or minimum to maximum spread)
  - Coincidence of beamformed nulls
- Direction Finding
  - Music-based approaches using signal or noise Eigenvectors
  - Copy-DF super resolution with blind adaptive weights
    - » Radix Copy-Aided Joint Maximum Likelihood (CA-JML) Algorithm, DF both interference and SVs
    - » In-situ antenna/platform calibration using SVs as references
- Geolocation of Interference
  - Multiple lines-of-bearing from multiple sites or a moving platform

Beamstar/Iceman Ant-Jam GPS Receiver



Aperture, GPS & Navigation Processors
- Five SV Acquisition and Tracking
- Four C40 Digital Processors
- Single Kalman Filter

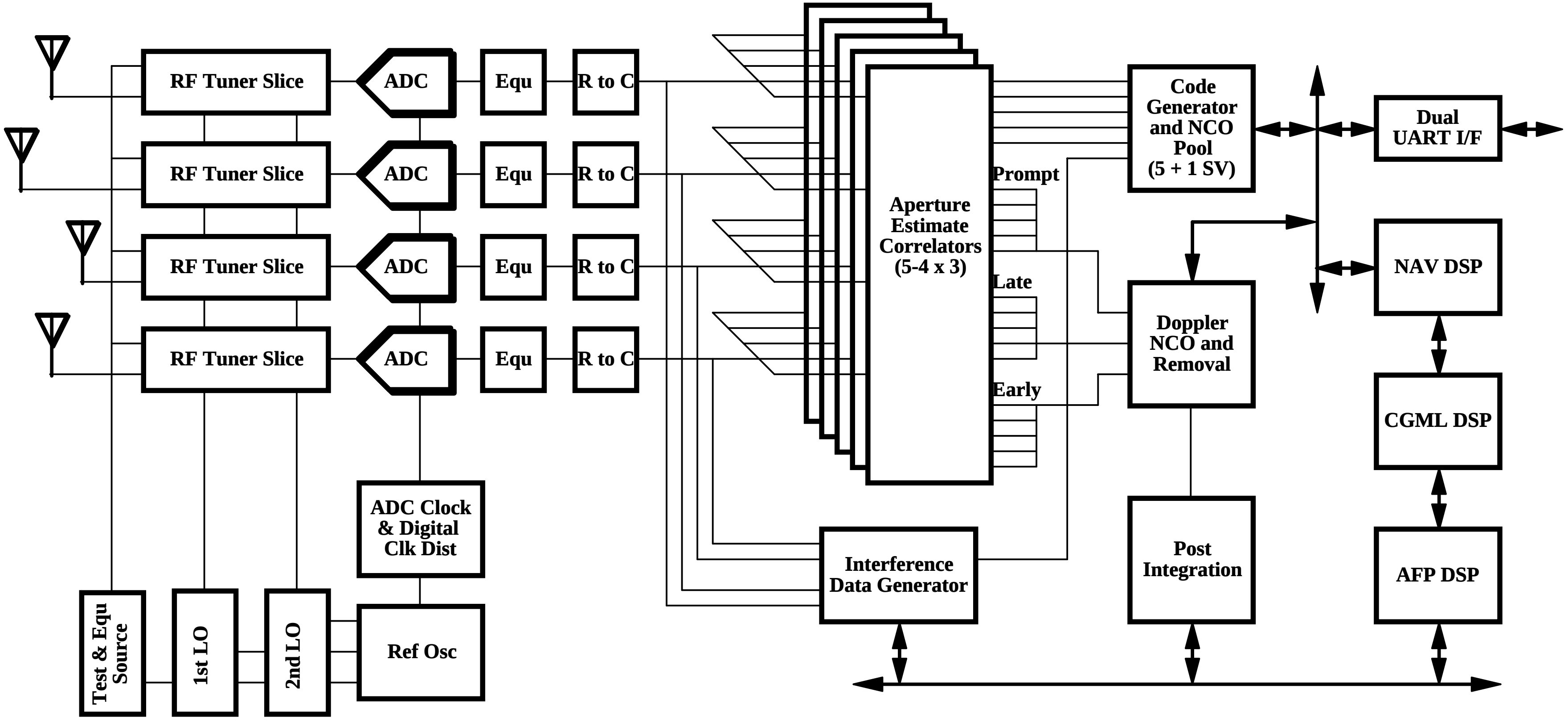
Three Receivers have been constructed
- BEAMSTAR
- ICEMAN
- Radix (IRAD)

GPS Receiver Front End
- Four Spatial Path Tuner/Digitizer
- L1/L2 Preselection
- 4 dB NF, -9 dBm TOI, 13 MHz (1 dB) BW, 12-bit ADC

Digital Anti-Jam Electronics
- Concurrent SV Beamforming and Jammer Null Steering (NB & WB)
- Revolutionary CGML Spatial Filter
- Nulls Three WB Jammers, >80 dB J/S for C/A-code
- Equalizer ASICs Support Deep Nulls for Wideband Jammers
- Flexible Digital Processing Architecture
- Design accommodates future insertion of Temporal Cancellation for Narrowband Jammers

Antenna Array (not shown)
- Four Element TGAT (GFE)
- Enables Digital Beamforming

Architecture Block Diagram



- Discrete Component Demonstration Receivers
  - Dual tuner modules, LC IF filter, 10 MHz reference
  - 12-bit ADC, GC2011 FIR filters, Xilinx correlators & IDG, TMS320C40 DSP

Beamstar/Iceman C/A-code Performance

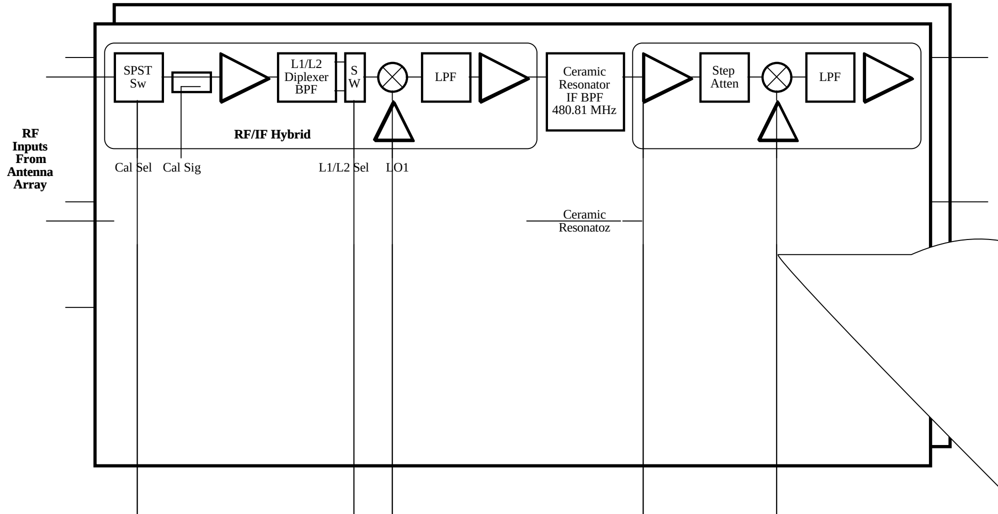
Code Gated Maximum Likelihood Estimation (CGML)
Blind Adaptive Algorithm

Mode	Code	One Jammer	Two Jammers	Three Jammers
Acquisition	C/A	85 dB (1 MHz)	80 dB (ea. 1 MHz)	
Tracking	C/A	90 dB (0.8,20 MHz)	86 dB (ea. 1 MHz)	83 dB (ea. 1 MHz)
Reacquisition	C/A	86 dB (1 MHz)	80 dB (ea. 1 MHz)	80 dB (ea. 1 MHz)

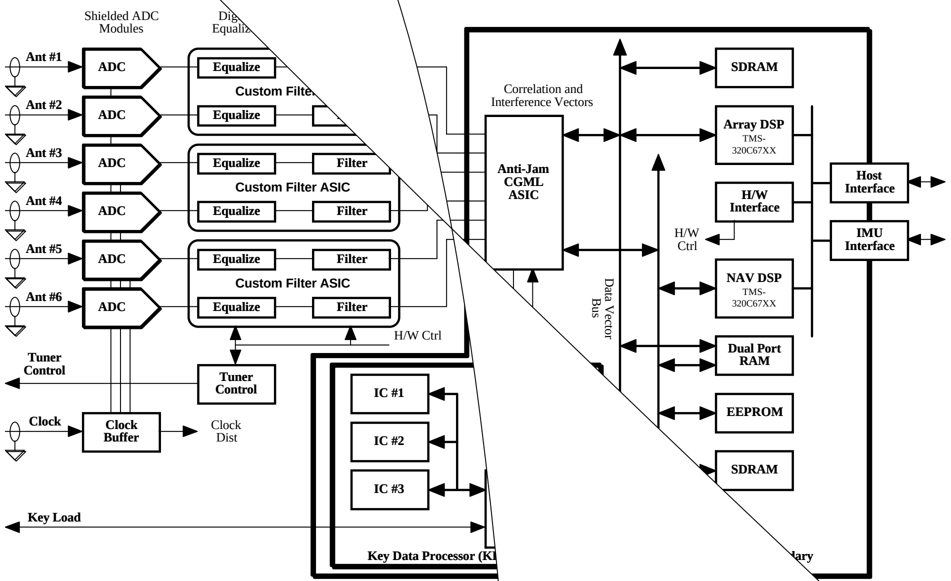
Laboratory simulations using a STR2760 GPS Satellite Simulator,
STR2769 Butler Matrix, and multiple interference signal generators

US Patent 5,694,416, issued 2 December 1997, to Russell K. Johnson, "Direct sequence spread spectrum receiver and antenna array for the simultaneous formation of a beam on a signal source and a null on an interfering jammer."

Miniaturized Anti-Jam GPS Receiver



- RF Design
  - –Downconverter
    - »Two RF/IF hybrids, one IF filter
  - –Synthesizer
    - »Reference oscillator, comp. source, and local oscillators
- igital Design
  - Commercial ADC and DSP
  - vo custom ASICs



Conclusions

- **The BEAMSTAR/ICEMAN technology demonstrated the ability of spatial beamforming to achieve >80 dB J/S C/A code operation**
  - Multipath mitigation may be required for some applications and installations
- **All-Digital, Software Processing Receiver**
  - The architecture is readily scalable, software upgradable, and extensible for a wide range of military and commercial applications for both jamming and interference mitigation as well as the detection, location, and elimination of interference.
- **High performance anti-jam GPS receivers are available**

- **Commercial Anti-Jam GPS Receivers are required today for protection in mission critical and safety of life GPS applications**
  - Airport terminal control areas, maritime shipping ports and waterways, DGPS reference stations, time/frequency references for data and voice communications

Acknowledgments and Support

- Support for this work was provided by the Air Force Research Laboratory (AFRL) through Phase I and Phase II Small Business Innovative Research (SBIR) programs:
  - Beamforming for Satellite Timing and Ranging (BEAMSTAR)
    AFRL/MNGN, Eglin Air Force Base, FL 32542-6810
    Contract No. F08630-94-C-0061
    COTR: Capt. Christopher Rabourn and Mr. Eddie Gibbs
  - Interference Cancellation and Excision for Missile Augmented Navigation (ICEMAN)
    AFRL/VSDD, Kirtland Air Force Base, Albuquerque, NM 87117-5776.
    Contract No. F29601-94-C-0148
    COTR: Dr. Sandra Slivinsky

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