A Self-Coherence Based Anti-Jamming GPS Receiver

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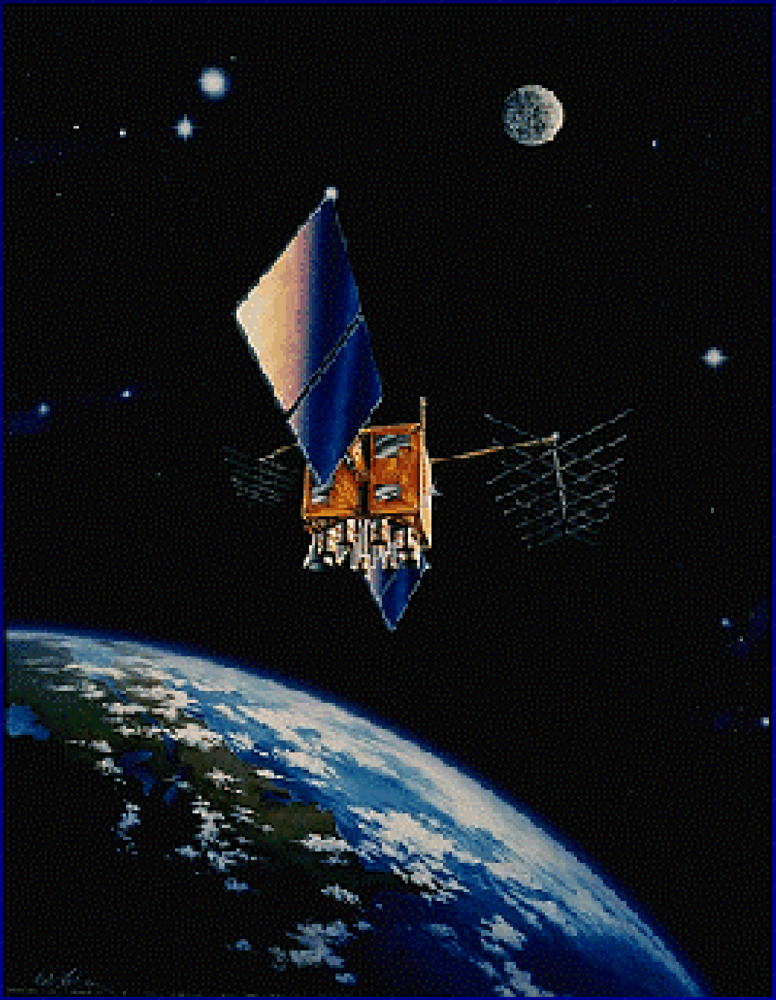
OUTLINE

- GPS overview
- Existing techniques in GPS interference suppression
- Self-coherence based anti-jamming GPS receiver
- Simulation results
- Conclusions

WHAT IS GPS?



- GPS is a satellite-based all-weather navigation system providing precise position, velocity, and timing information.
- Global navigation systems
  - GPS: US
  - GLONASS: Russia
  - Galileo: Europe

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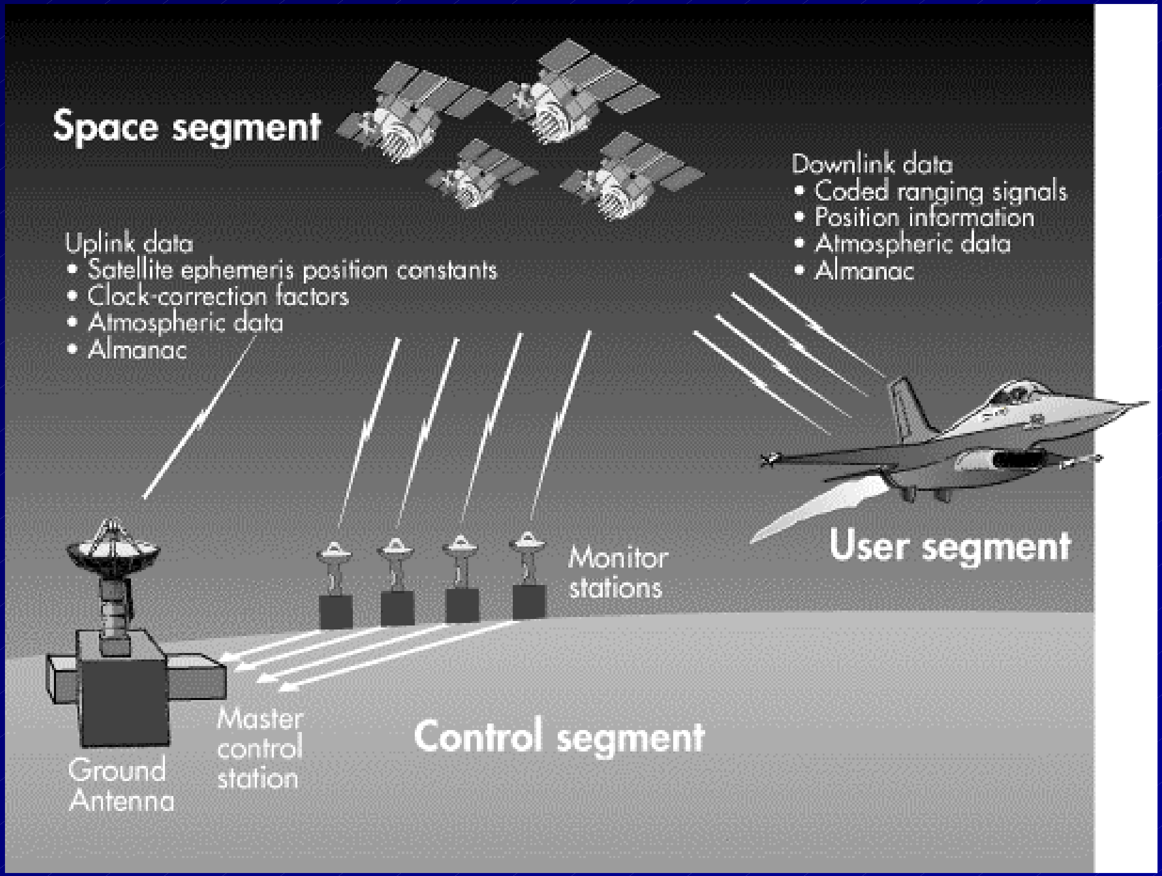
GPS COMPONENTS



- Space segment: satellite constellation
- Control segment: ground stations
- User segment: receivers

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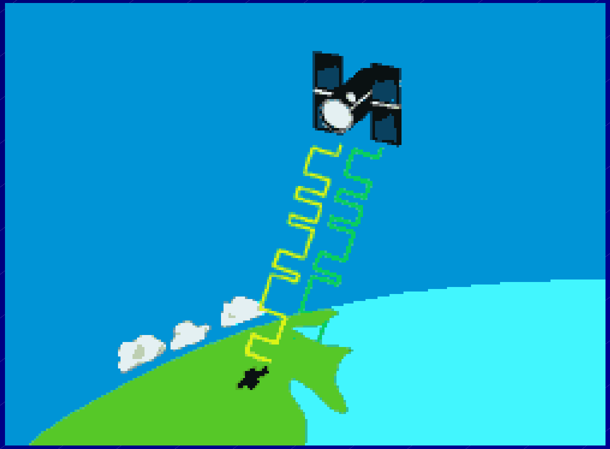
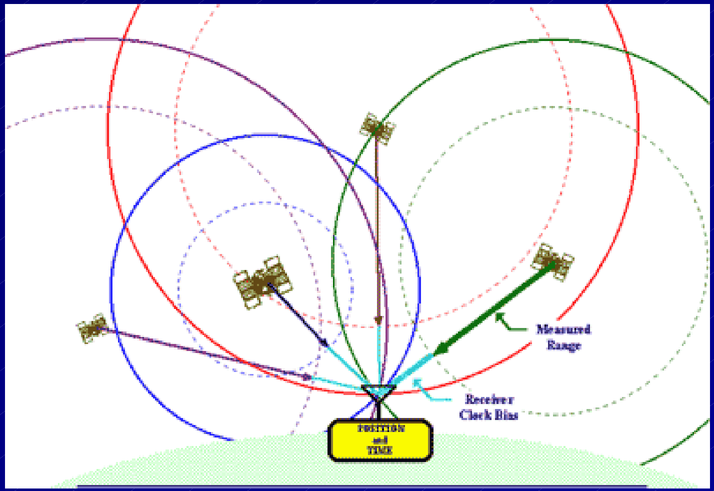
HOW GPS WORKS?

- GPS uses one-way time-of-arrival ranging to determine user position - measure the direct path signal travel time from a satellites to a user's receiving device.



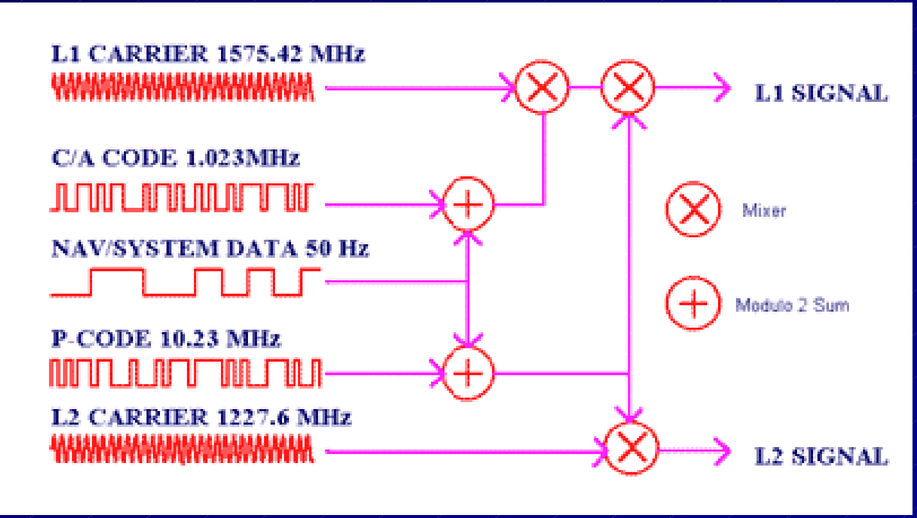
  – Pseudorange: the range from the satellite plus clock offset



- Geolocation of the receiver: the intersection of pseudoranges from a set of satellites (minimum 4).

GPS SIGNAL

GPS employs direct-sequence spread-spectrum (DS-SS) signaling



- Two L-band frequencies:
  - $L1$=1.57542 GHz
  - $L2$=1.2276 GHz
- Two pseudorandom codes
  - Coarse/acquisition (C/A) code: chip rate 1.023 Mchips/sec, BW 2 MHz, repeats every millisec.
  - Precision (P) code: chip rate 10.23 Mchips/sec, BW 20 MHz, repeats about every week (military use).

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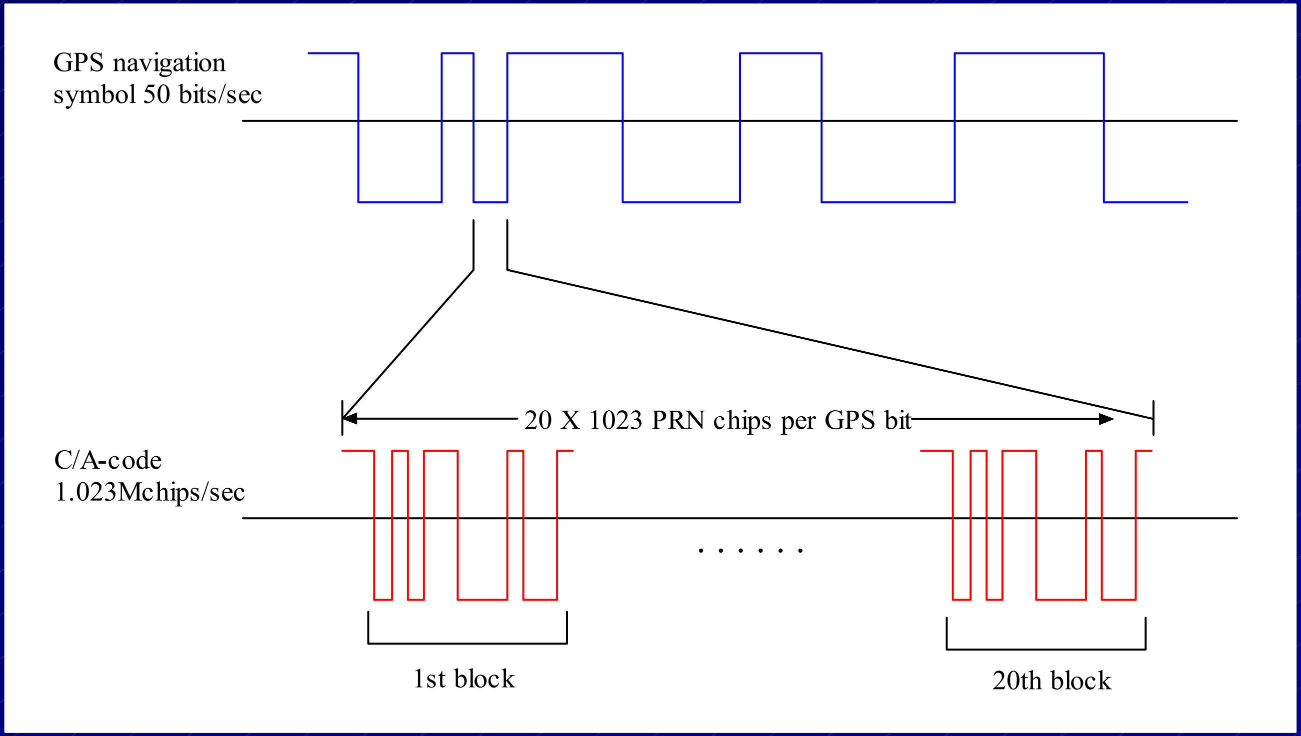
GPS SIGNAL (Cont'd)

- GPS C/A signal waveform:



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CHALLENGES IN GPS

- Two dominant sources of errors in precision GPS:
  - Interference: reduces the SNR of the GPS signal such that the receiver is unable to obtain measurements from the GPS satellite.
  - Multipath: broadens and biases the cross-correlation function.

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GPS AND DSSS SYSTEMS

- Common
  - Both use PN
  - Both require synchronization
    - DSSS: despreading
    - GPS: despreading and pseudorange measurement
- Difference
  - Multipath
    - DSSS: improves system performance due to diversity – constructive ☺
    - GPS: results in erroneous pseudorange measurements – destructive ☹
  - Near-far phenomena
    - DSSS: a severe problem ☹
    - GPS: not a problem ☺

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INTERFERENCE IN GPS

Types of Interference in GPS:

- Additive white Gaussian noise (AWGN)
  - Broadband interference can sometimes be modeled as AWGN
- Continuous wave (CW)
  - A pure tone or narrowband modulated signal.
  - Chirp signal
- Pulsed interference (e.g., radars)
  - Effectively “shoots holes” in the received signal

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EXISTING TECHNIQUES

- Maximum Likelihood Approach

  (Time-delay and carrier-phase estimation)

  - Single-antenna approach
  - Multiple-antenna approach

- Suboptimum Methods

  (Interference Suppression)

  – Space-time adaptive method
  – Time-frequency method
  – Navigation data demodulation

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EXISTING TECHNIQUES

GPS interference suppression

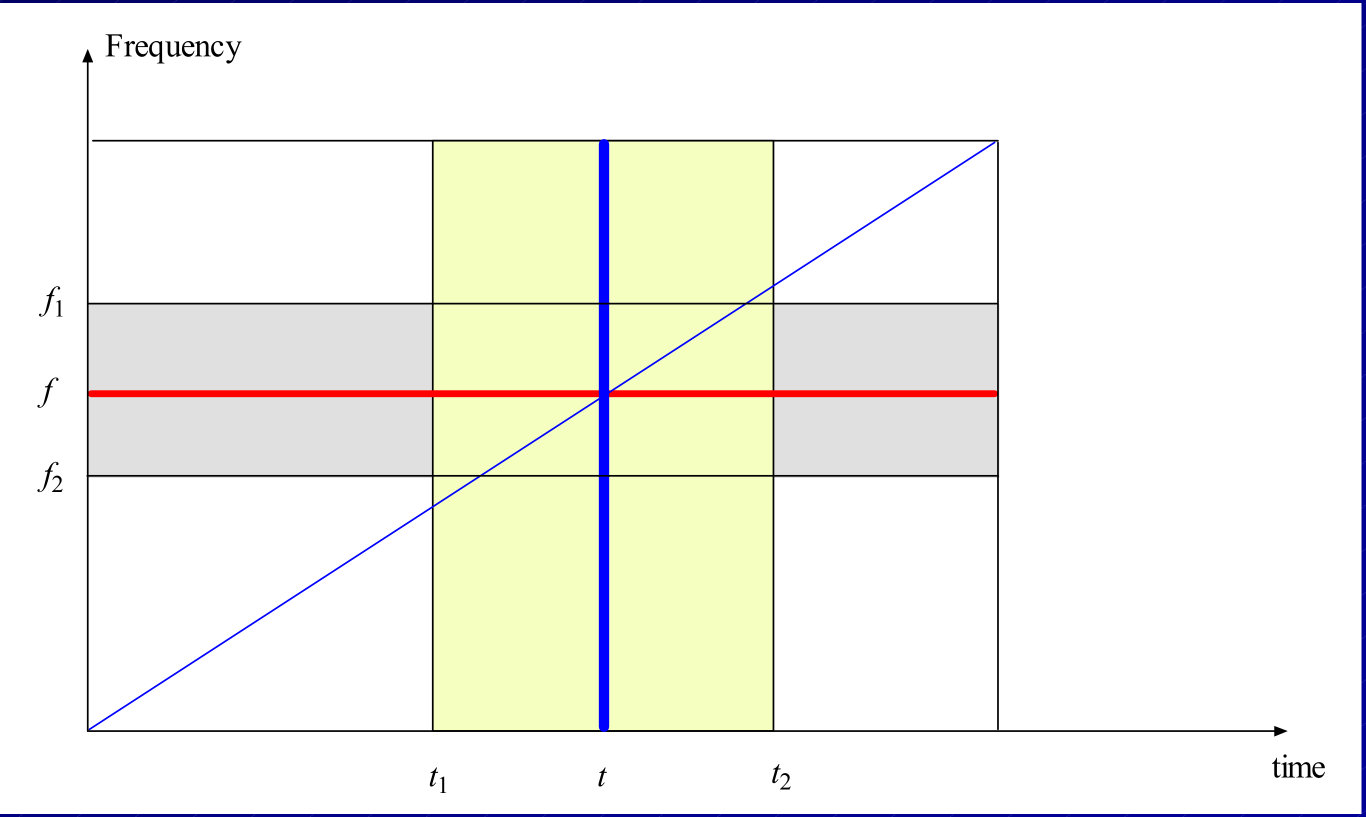
Requires satellite locations
- MMSE
- MSINR
- ML

Assumes bit synchronization
- Spatial-temporal matched filtering

Requires neither
- Self-coherence based anti-jamming approach

Interference Representation

- Time-frequency domain



INTERFERENCE SUPPRESSION IN GPS (Cont'd)

- Spread-spectrum (SS) provides certain protections against interference
  - Receiver fails when the interference to signal ratio exceeds the 30 dB.
- Interference suppression
  - Separate domain: time, space, or frequency
  - Joint domain: time-frequency or space-time
- None of these methods fully utilizes the repetitive feature of the GPS C/A-code.

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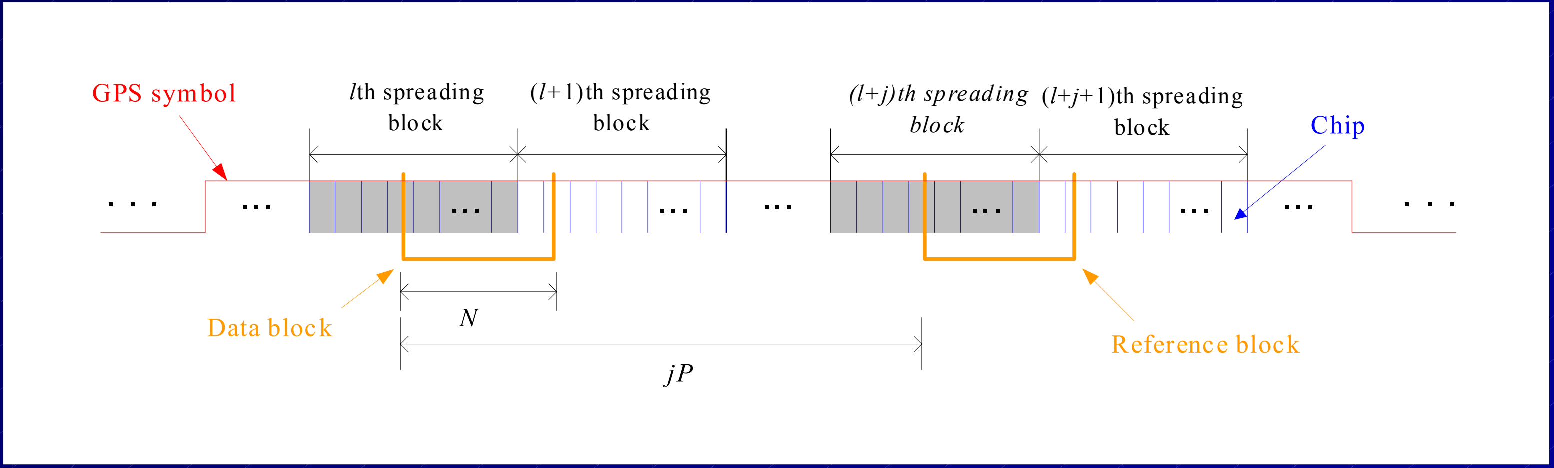
GPS SIGNAL STRUCTURE

Noise-free GPS data structure



- Two blocks of data (N consecutive samples each)
  - Data block
  - Reference block: jP samples apart from data block

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The NOTION OF SELF-COHERENCE

- Self-coherent signal

  The correlation between the signal and its frequency-shifted version is nonzero for some time lag.

- Significance of self-coherence
  - Blindly extract the desired signals in the presence of unknown noise and interference.
  - SCORE algorithm

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SELF-COHERENCE (Cont'd)

- Example:

$$x(t) = as(t) + v(t)$$

  - $s(t)$: self-coherent signal [not $v(t)$]

  Cyclic autocorrelation of $x(t)$

$$R_{xx}^{(\beta)}(\tau) = |a|^2 R_{ss}^{(\beta)}(\tau) + R_{vv}^{(\beta)}(\tau) = |a|^2 R_{ss}^{(\beta)}(\tau)$$

- Frequency shift completely decorrelates the interference component in $x(t)$.

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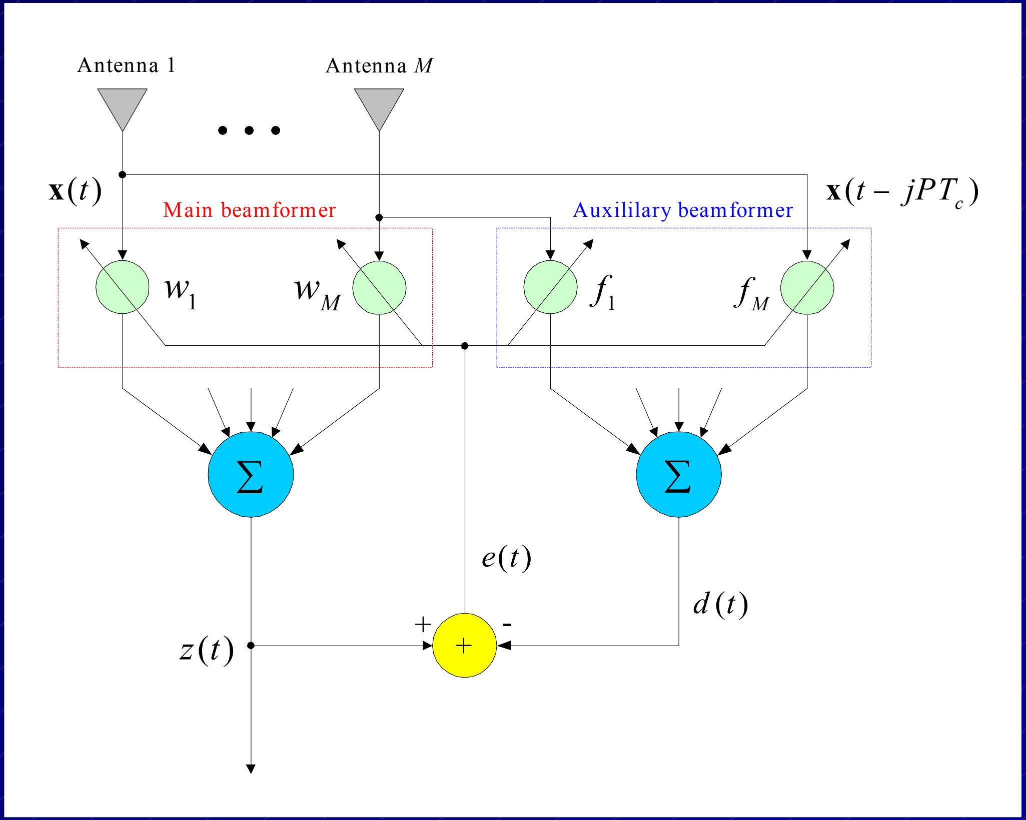
SELF-COHERENCE GPS RECEIVER

Receiver structure



- *M*-antenna array
- Two beamformers
  - **w**: generates output signal
  - **f**: generates reference signal

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SELF-COHERENCE GPS RECEIVER (Cont'd)

- Assumptions:
  - Data block and reference blocks are within the same navigation symbol.
  - Interference does not have the same periodic structure as that of the GPS C/A signals.
- The proposed receiver acts like a pre-processor to suppress interference of all satellites.
  - Conventional multipath mitigation techniques, such as delay lock loop (DLL), can then operate on significantly higher SINR than that encountered at the receiver input.

RECEIVED SIGNAL

- Received signal at the chip-rate in the data block

$$\mathbf{x}(n) = \sum_{q=0}^{Q} s_q(n-\tau_q)\mathbf{a}_q e^{j\phi_q} + u(n)\mathbf{d} + \mathbf{v}(n)$$

  - $S_0(n)$ is direct-path signal
- If the GPS signal, interference, and noise are independent

$$\mathbf{R}_{xx} = E\left\{\mathbf{x}(n)\mathbf{x}^H(n)\right\} = \mathbf{R}_s + \mathbf{R}_u + \mathbf{R}_v$$

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RECEIVED SIGNAL (Cont'd)

- The samples of GPS signal in the reference block have the same values as the corresponding samples in the data block within the same symbol

$$\mathbf{x}(n) = \mathbf{x}(n - jP), \quad 1 \le j < 20$$

- If the GPS signals are the only data components that are correlated when delayed jP samples

$$\mathbf{R}_{xx}^{(P)} = E\left\{\mathbf{x}(n)\mathbf{x}^{H}(n - jP)\right\} = \mathbf{R}_{s}$$

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PROPOSED RECEIVER

- Cost function – SCORE algorithm

$$C(\mathbf{w},\mathbf{f}) = \frac{\left|R_{zd}\right|^2}{R_{zz}R_{dd}} = \frac{\left|\mathbf{w}^H \mathbf{R}_{xx}^{(P)} \mathbf{f}\right|}{\left[\mathbf{w}^H \mathbf{R}_{xx} \mathbf{w}\right]\left[\mathbf{f}^H \mathbf{R}_{xx} \mathbf{f}\right]}$$

$\mathbf{w}$ is obtained by maximizing $C(\mathbf{w},\mathbf{f})$

– Beamformer output: $z(n) = \mathbf{w}^H \mathbf{x}(n)$

– Reference signal: $d(n) = \mathbf{f}^H \mathbf{x}(n - jP)$

– Cross-correlation between $z(n)$ and $d(n)$:

$$R_{zd} = E\left\{z(n)d^H(n)\right\}$$

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PROPOSED RECEIVER (Cont'd)

- Error signal

$$e(n) = z(n) - d(n)$$

Least-squares solution of $\mathbf{f}$

$$\mathbf{f}_{LS} = \mathbf{R}_{xx}^{-1}\mathbf{R}_{xx}^{(P)H}\mathbf{w}$$

- The weight vector $\mathbf{w}$ that maximizes the cost function is the eigenvector corresponding to the largest eigenvalue of the generalized eigenvalue problem

$$\mathbf{R}_{xx}\mathbf{w} = \lambda_{\max}\mathbf{R}_{xx}^{(P)}\mathbf{R}_{xx}^{-1}\mathbf{R}_{xx}^{(P)}\mathbf{w}$$

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Exact Expression

- Define events

$A_1 : x(n)\ \&\ x(n-jP)$ are within the same symbol,

$A_{21} : x(n)\ \&\ x(n-jP)$ are in two symbols with the same sign,

$A_{22} : x(n)\ \&\ x(n-jP)$ are in two symbols with different signs

- The corresponding probabilities are

$$\Pr\{A_1\} = 1 - \frac{jP}{20P}$$

$$\Pr\{A_{21}\} = \Pr\{A_{22}\} = \frac{jP}{40P}$$

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Continue

$$\mathbf{R}_{xx}^{(P)} = E\left\{\mathbf{x}(n)\mathbf{x}^{H}(n-jP)\middle| A_{1}\right\}\Pr\left\{A_{1}\right\}$$

$$+E\left\{\mathbf{x}(n)\mathbf{x}^{H}(n-jP)\middle| A_{21}\right\}\Pr\left\{A_{21}\right\}$$

$$+E\left\{\mathbf{x}(n)\mathbf{x}^{H}(n-jP)\middle| A_{21}\right\}\Pr\left\{A_{21}\right\}$$

$$=\left(1-\frac{jP}{20P}\right)\mathbf{R}_{s}$$

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MODIFIED CROSS-SCORE RECEIVER (Cont'd)

- The cross-SCORE based receiver does not have the ability to mitigate multipath.
- Since multipath often comes from near the horizon while the GPS satellites are located above the horizon, adding constraints to the previous receiver can mitigate multipath entering the receiver from near the horizon.

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MODIFIED CROSS-SCORE RECEIVER (Cont'd)

- Define the matrix containing steering vectors associated equally spaced directions covering solid angle Ω near the horizon

$$\mathbf{B} = \begin{bmatrix} \mathbf{b}(\gamma_1) & \cdots & \mathbf{b}(\gamma_D) \end{bmatrix}$$

- The modified cost function on f

$$\mathbf{f}_{\text{opt}} = \arg\max_{\mathbf{f}} \frac{\mathbf{f}^H \tilde{\mathbf{R}}_{xx} \mathbf{f}}{\mathbf{f}^H \mathbf{R}_{xx} \mathbf{f}}, \text{ subject to } \mathbf{B}^H \mathbf{f} = \mathbf{0}$$

$$\tilde{\mathbf{R}}_{xx} = \mathbf{R}_{xx}^{(P)} \mathbf{R}_{xx}^{-1} \mathbf{R}_{xx}^{(P)H}$$

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MODIFIED CROSS-SCORE RECEIVER (Cont'd)

- Let $\mathbf{A}$ be the matrix that spans the null space of $\mathbf{B}$ such that $\mathbf{B}^H\mathbf{A} = \mathbf{0}$.
- Let α be a vector such that $\mathbf{f} = \mathbf{A}\boldsymbol{\alpha}$.
- Using the vector α, the constrained maximization problem can be transformed into the unconstrained maximization problem as

$$\boldsymbol{\alpha} = \arg\max_{\boldsymbol{\alpha}} \frac{\boldsymbol{\alpha}^H \mathbf{A}^H \tilde{\mathbf{R}}_{xx} \mathbf{A}\boldsymbol{\alpha}}{\boldsymbol{\alpha}^H \mathbf{A}^H \mathbf{R}_{xx} \mathbf{A}\boldsymbol{\alpha}}$$

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MODIFIED CROSS-SCORE RECEIVER (Cont'd)

- Solving the above unconstrained generalized eigenvalue problem lead to α which is given by the eigenvector associated with the largest eigenvalue. The beamformer $\mathbf{f}_{\mathbf{opt}}$ be obtained correspondingly.
- The beamformer $\mathbf{w}_{\mathbf{opt}}$ is then given by

$$\mathbf{w}_{\text{opt}} = \mathbf{R}_{xx}^{-1}\mathbf{R}_{xx}^{(P)}\mathbf{f}_{\text{opt}} = \mathbf{R}_{xx}^{-1}\mathbf{R}_{xx}^{(P)}\mathbf{A}\boldsymbol{\alpha}$$

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IMPLEMENTATION ISSUES

- Sample estimates have to be used instead of the exact ones

$$\hat{\mathbf{R}}_{xx} = \frac{1}{N}\mathbf{X}_N\mathbf{X}_N^H, \qquad \hat{\mathbf{R}}_{xx}^{(P)} = \frac{1}{N}\mathbf{X}_N\mathbf{X}_{N\mathrm{ref}}^H$$

  – Data sample matrix

$$\mathbf{X}_N = \left[\mathbf{x}(n), \quad \cdots, \quad \mathbf{x}(n-(N-1))\right]$$

  – Reference sample matrix

$$\mathbf{X}_{N\mathrm{ref}} = \left[\mathbf{x}(n-jP), \quad \cdots, \quad \mathbf{x}(n-(N-1)-jP)\right]$$

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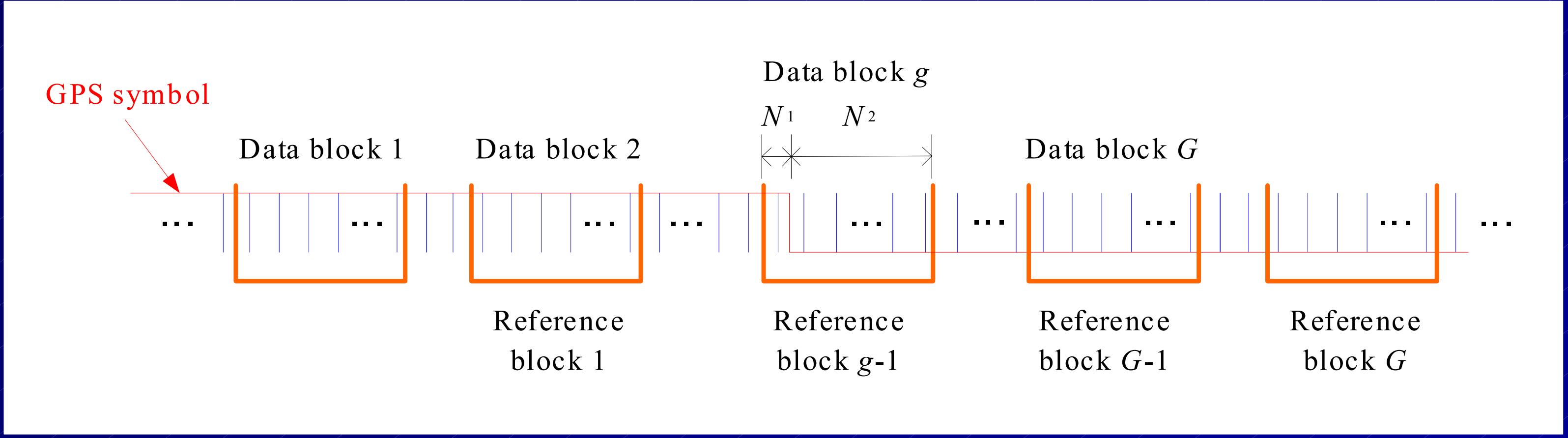
IMPLEMENTATION ISSUES (Cont'd)

- Multiple data and reference blocks can be used to improve the time-averaging:



$$\hat{\mathbf{R}}_{xx} = \frac{1}{G}\sum_{g=1}^{G}\mathbf{X}_N(g)\mathbf{X}_N^H(g)/N$$

$$\hat{\mathbf{R}}_{xx}^{(P)} = \frac{1}{G}\sum_{g=1}^{G}\mathbf{X}_N(g)\mathbf{X}_{Nref}^H(g)/N$$

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COVARIANCE ESTIMATION (Cont'd)

- The expected values of estimates

$$\bar{\hat{\mathbf{R}}}_{xx}^{(P)} = \left(1 - \frac{jP}{20P}\right)\mathbf{R}_s, \text{ one block estimation}$$

$$\bar{\hat{\mathbf{R}}}_{xxG}^{(P)} = \left(1 - \frac{jP}{20P}\right)\mathbf{R}_s, \text{ } G \text{ blocks estimation}$$

- The corresponding variances of estimates

$$\operatorname{var}\left\{\hat{\mathbf{R}}_{xx}^{(P)}\right\} = \frac{M(N+\sigma_v^2)}{N}\mathbf{R}_s + \frac{M(1+\sigma_v^2)}{N}\mathbf{R}_v - \left(\bar{\hat{\mathbf{R}}}_{xx}^{(P)}\right)^2$$

$$\operatorname{var}\left\{\hat{\mathbf{R}}_{xxG}^{(P)}\right\} = \left(1 - 2\frac{jP}{20P} + 2\frac{jP}{20GP}\right)\left[\frac{M(N+\sigma_v^2)}{N}\mathbf{R}_s + \frac{M(1+\sigma_v^2)}{N}\mathbf{R}_v\right] - \left(\bar{\hat{\mathbf{R}}}_{xxG}^{(P)}\right)^2$$

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SIMULATION RESULTS

- Linear uniform array with $M=7$ sensors.
- GPS navigation symbols in BPSK format; C/A-code with processing gain of $P=1023$.
- $N=800$ samples in both the data and reference blocks.
- Jammers are generated as broadband binary signals with the same rate as the C/A-code.
- Multipath signal power is one-fifth of the direct-path signal power.

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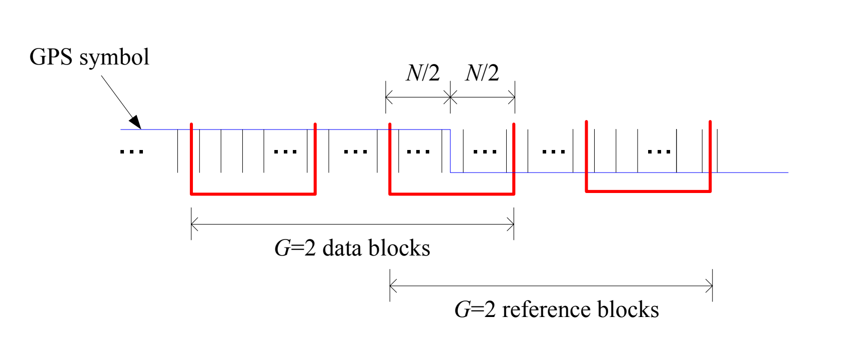
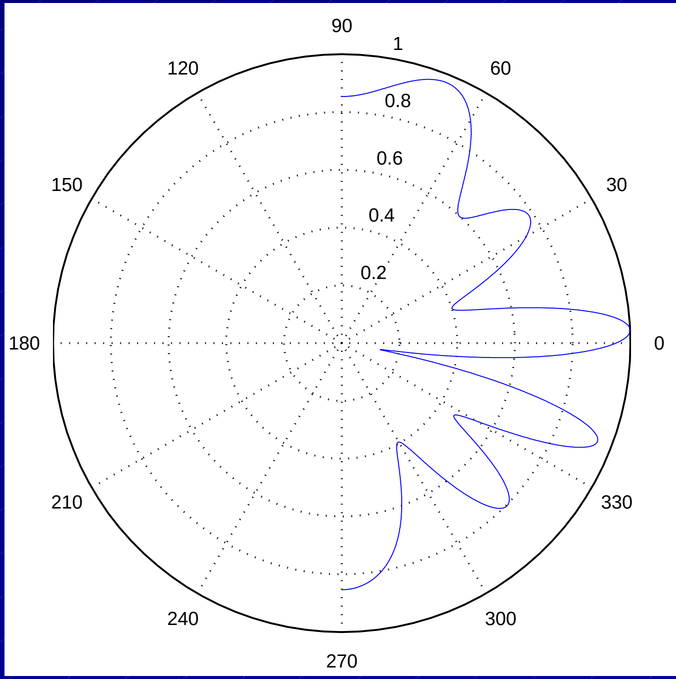
Critical Case

- Beam pattern without interference – evenly split data block (G=2, SNR=-30 dB)





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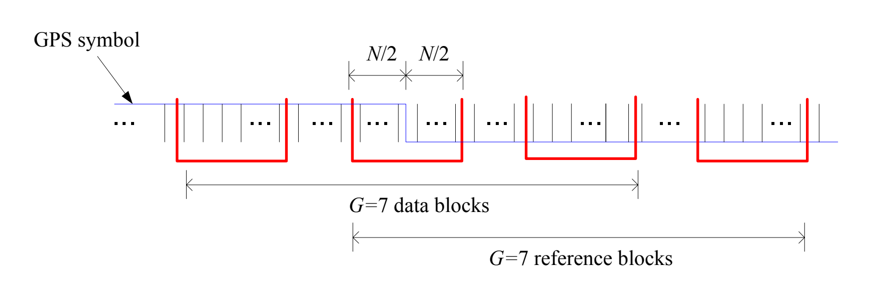
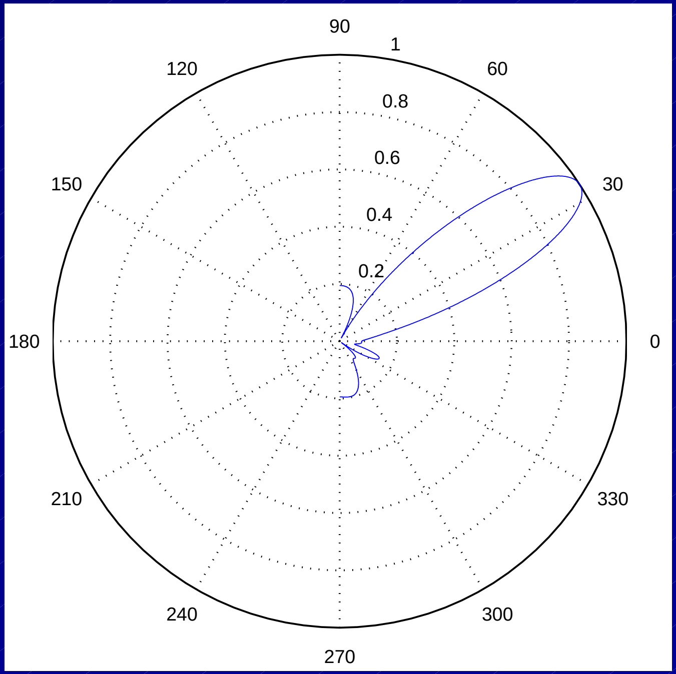
IMPROVED!

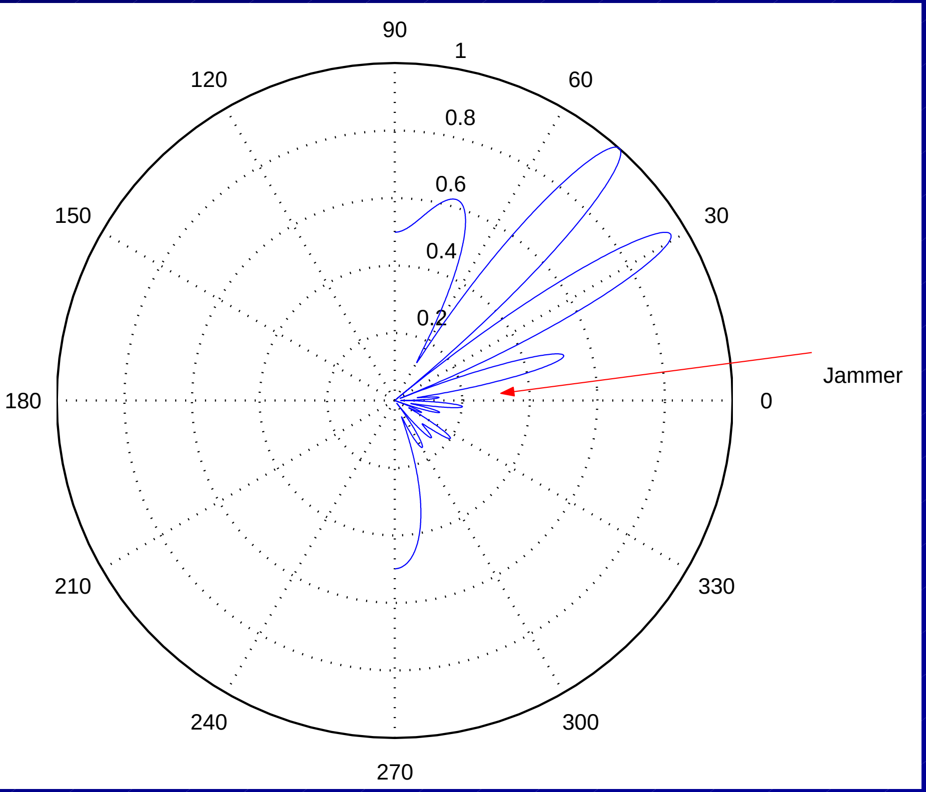
- Beam pattern without interference (G=7, SNR=-30 dB)





FOR ALL SATELLITES

- With multiple satellites in the field of view (M=9, SNR=-30 dB)



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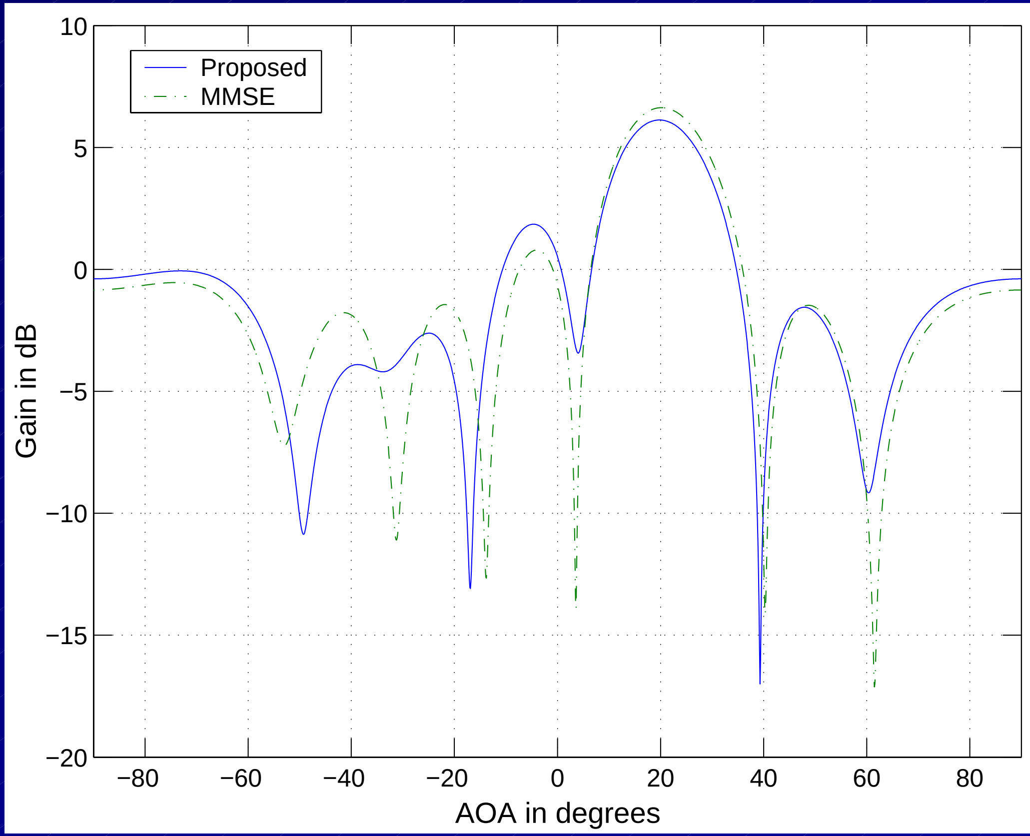
SIMULATION RESULTS (Cont'd)

- Comparison with MMSE method (spatial processing only (SINR=-33 dB, JSR=30 dB)



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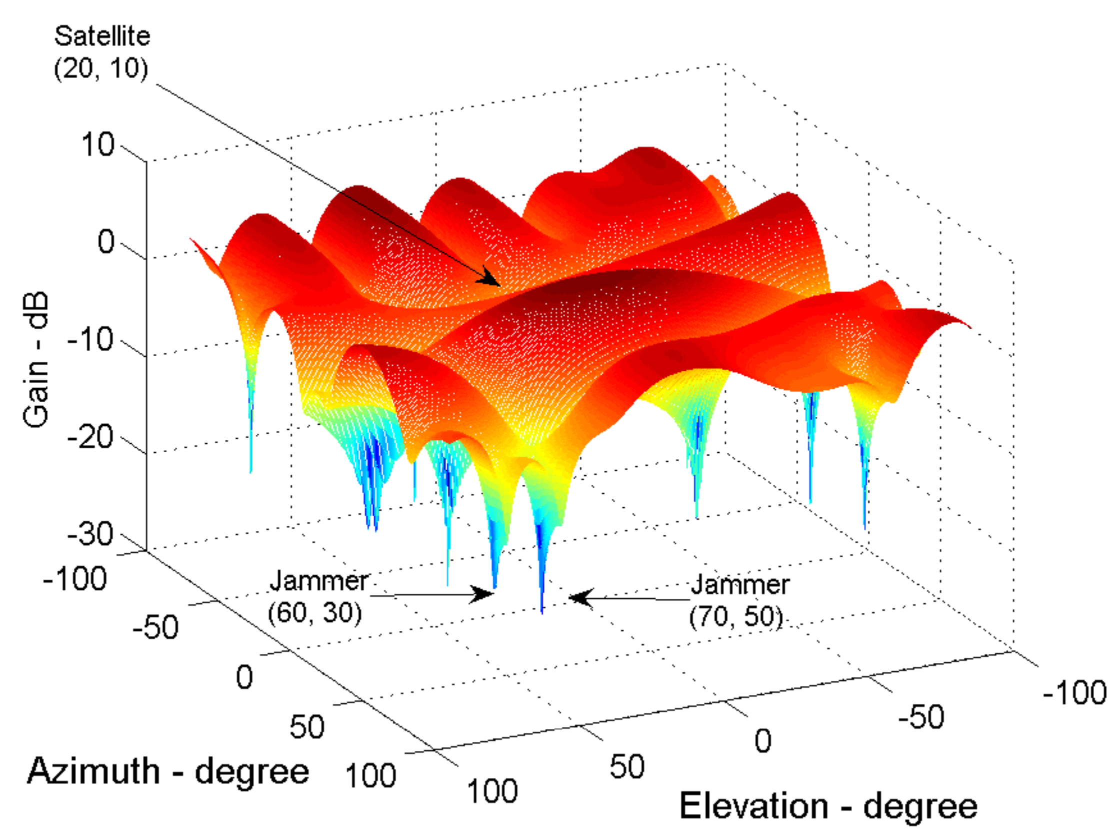
Performance

- Circular array: *M*=7 sensors, SNR=-30 dB and JSR=30 dB.



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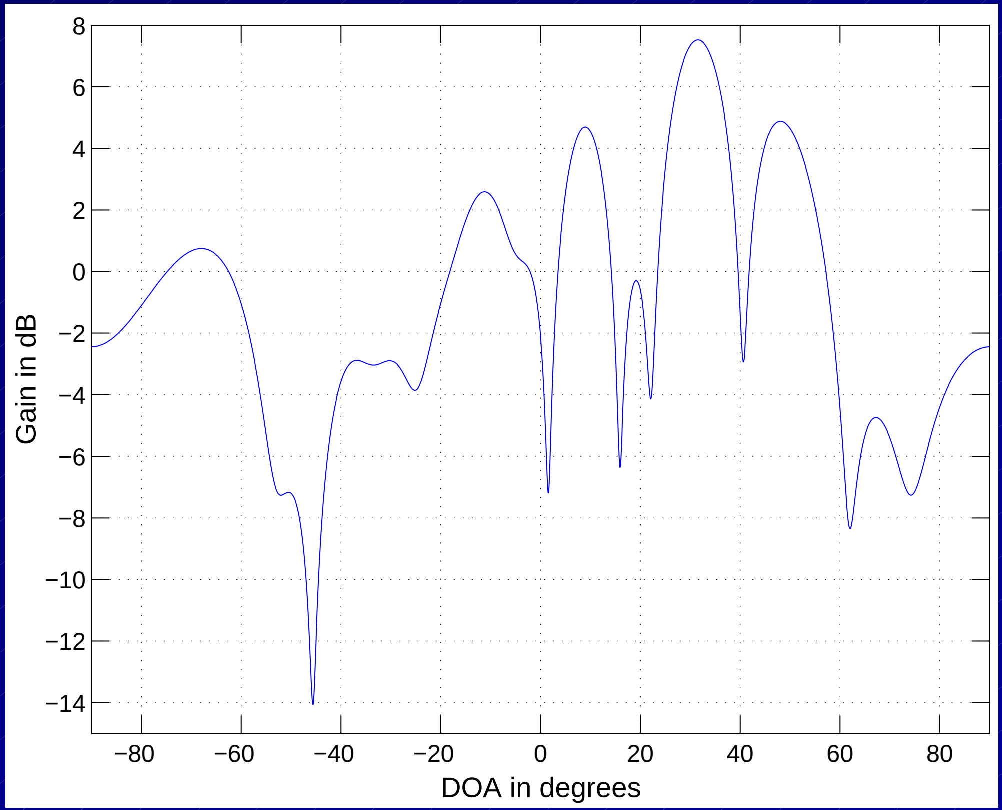
Jammers with Similar Coherence

- Jammers with the same structure as the GPS signals (satellite at 30 degree and two jammers at 10 and 50 degree)



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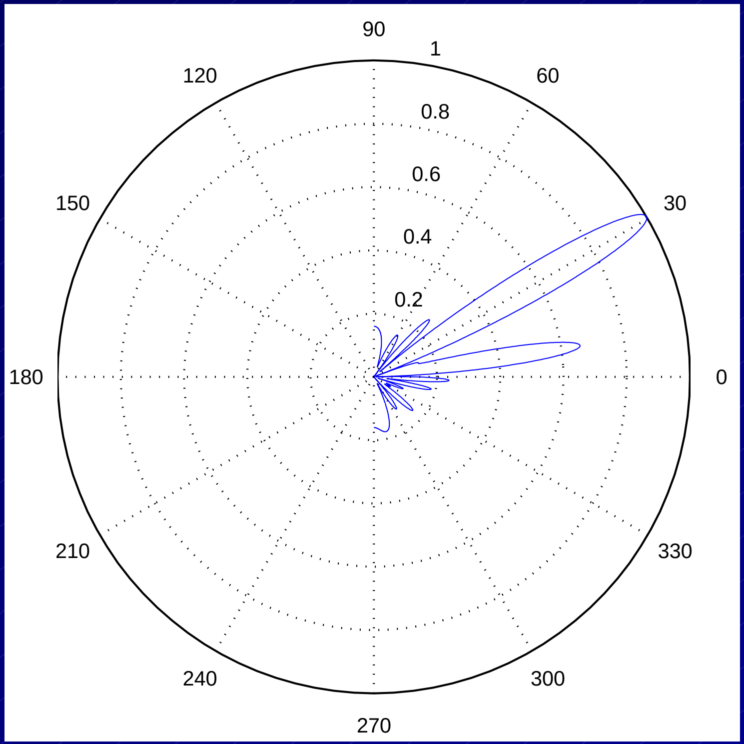
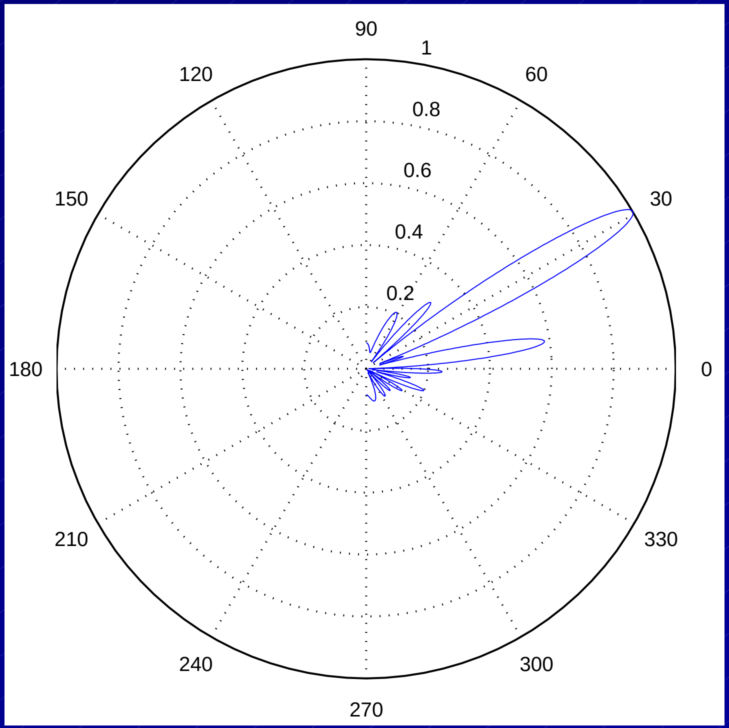
MULTIPATH!

- In the presence of multipath (satellite at 30 degree, one multipath at 8 degrees)



1-chip delay



5-chip delay

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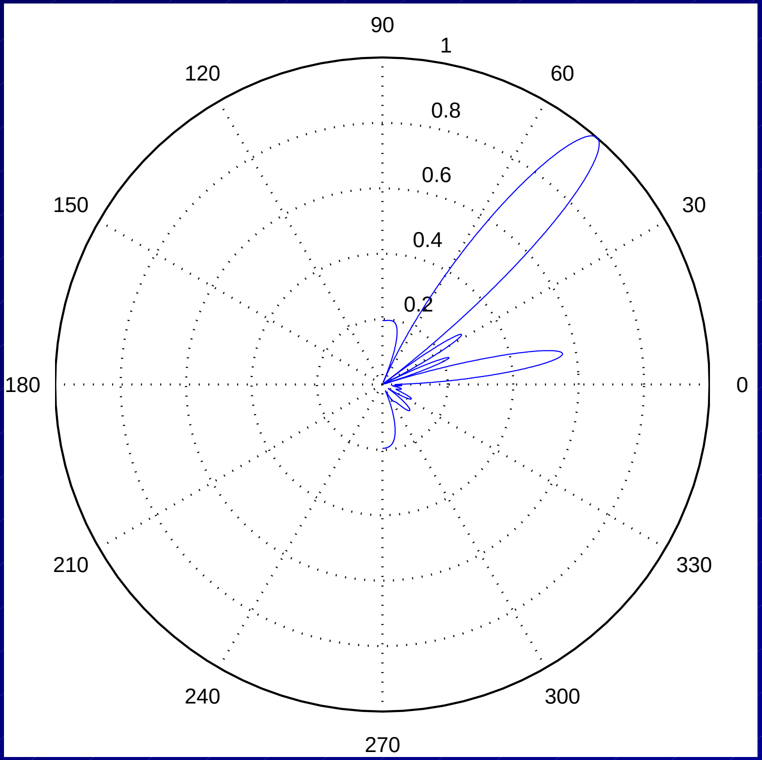
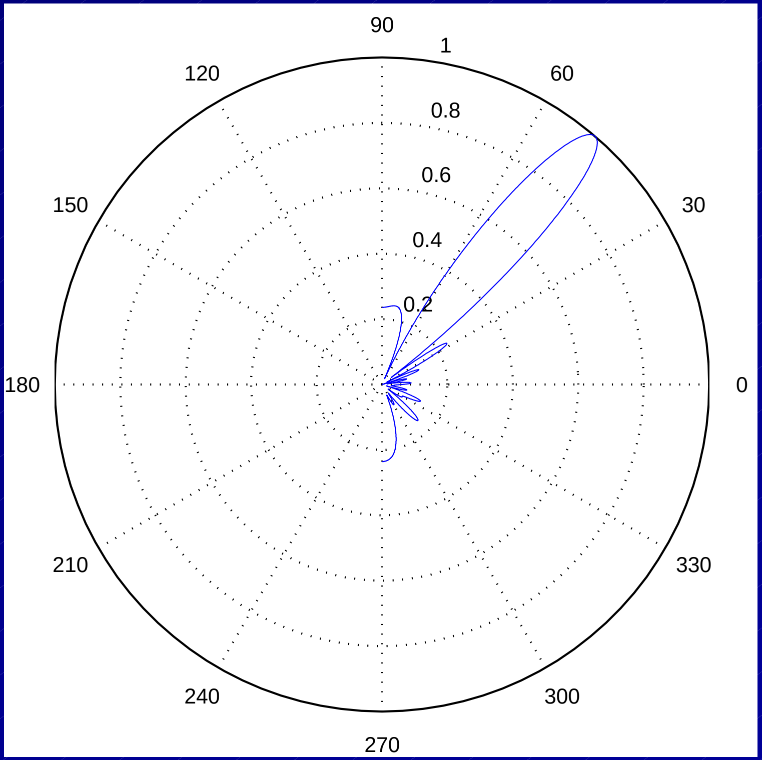
SIMULATION RESULTS (Cont'd)

- Comparison between the original and modified approaches in the presence of multipath (10 degree, SNR = -30 dB, 1/5 power)





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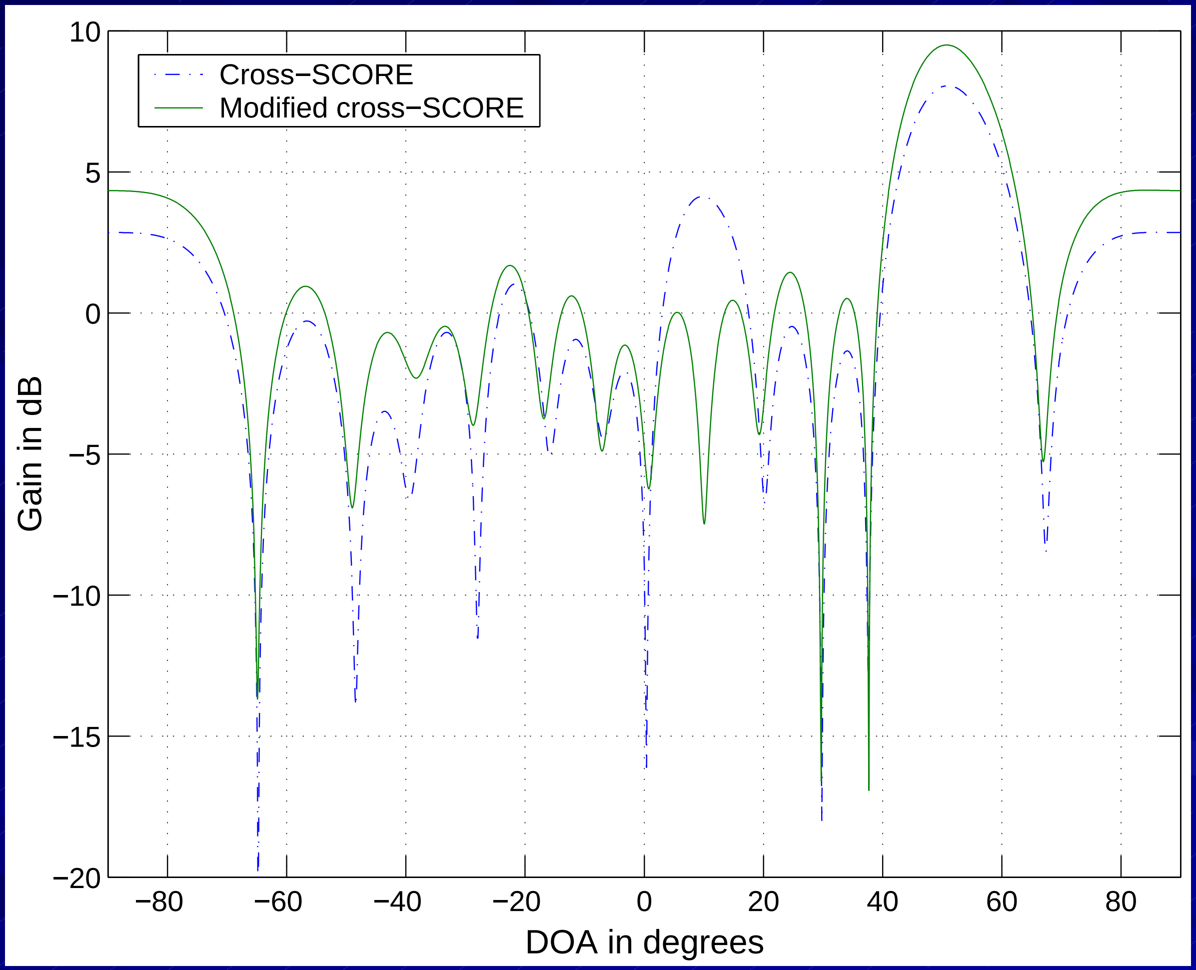

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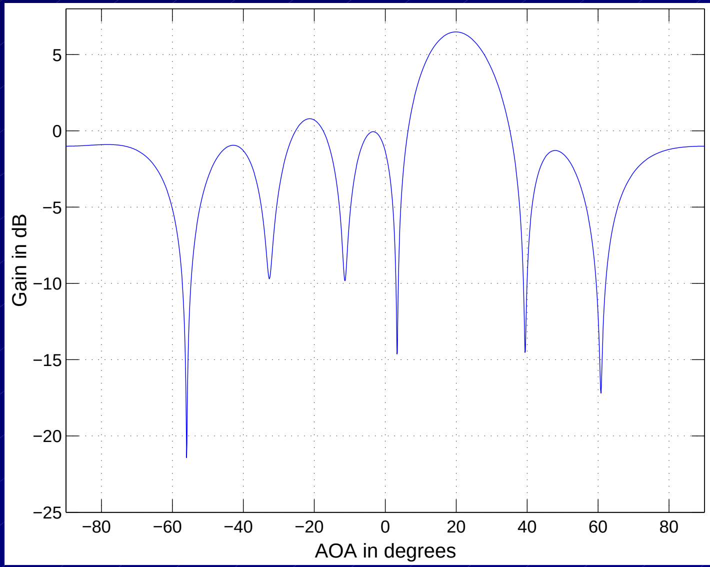
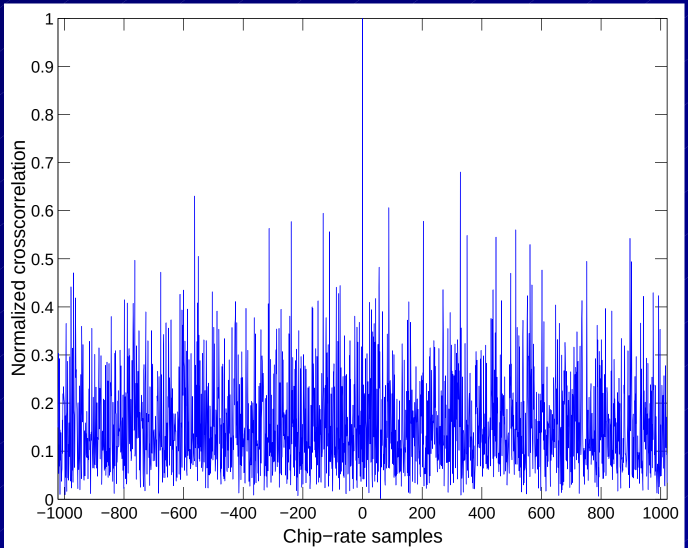
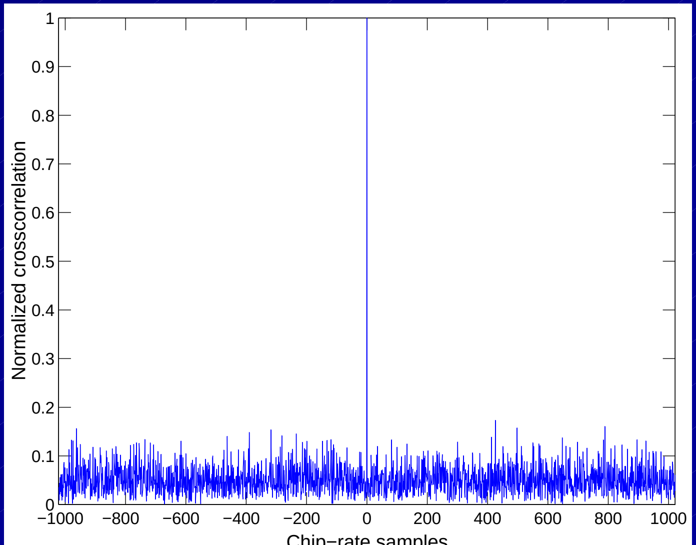
SIMULATION RESULTS (Cont'd)

- Synchronization (SNR=-25 dB, JSR=30 dB)







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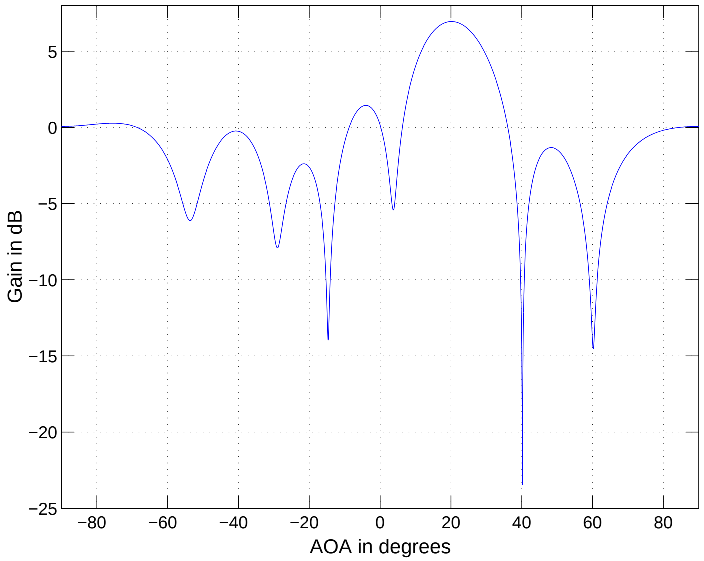
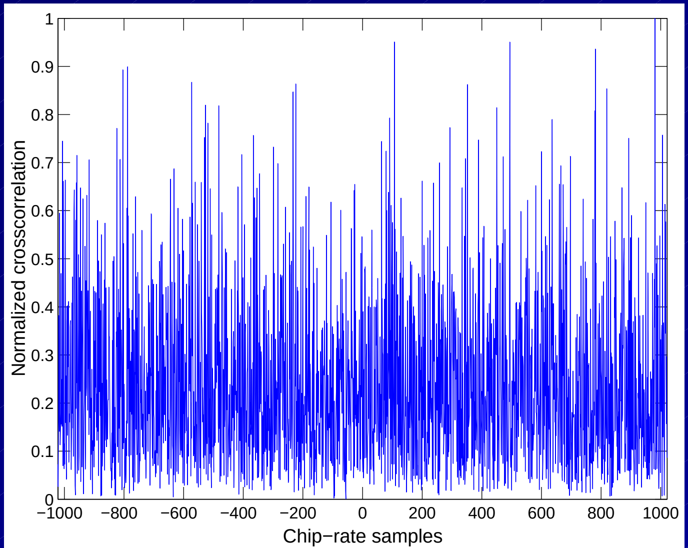
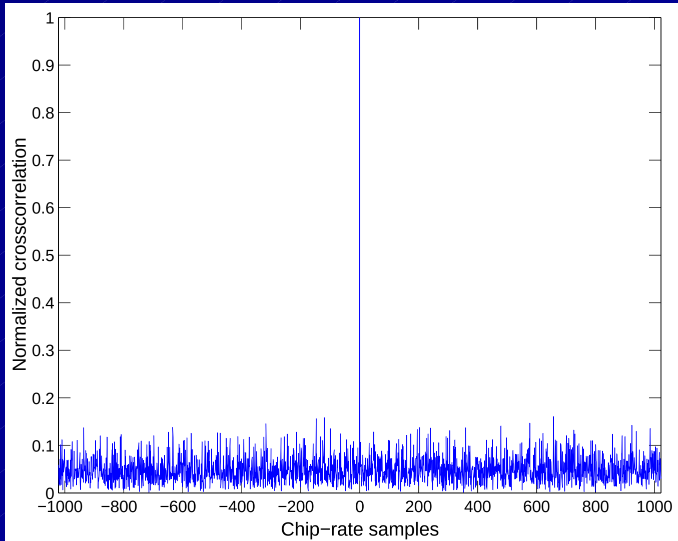
SIMULATION RESULTS (Cont'd)

- Synchronization (SNR=-25 dB, JSR=50 dB)







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CONCLUSIONS

- Presented a novel self-coherence based GPS anti-jam receiver.
- The receiver utilizes the inherent self-coherence feature of the GPS C/A signal.
- The proposed receiver requires neither the knowledge of the transmitted GPS signal nor the location of the satellite.
- The proposed receiver is able to suppress a large class of interference as long as the interferers do not have the same periodic structure as the C/A signal.

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