Complex Signal Kurtosis and Independent Component Analysis for Wideband Radio Frequency Interference Detection

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To be presented by Adam Schoenwald at Coexisting with Radio Frequency Interference, Socorro NM, October 17-20, 2016
# Acronym List

<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tbody>
<tr>
<td>ABS()</td>
<td>Absolute Value</td>
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<tr>
<td>AS&amp;D</td>
<td>ASRC Federal Space and Defense</td>
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<tr>
<td>AUC</td>
<td>Area Under Curve</td>
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<tr>
<td>CERBM</td>
<td>Complex Entropy Rate Bound Minimization</td>
</tr>
<tr>
<td>CONUS</td>
<td>Continental United States</td>
</tr>
<tr>
<td>CQAMSYM</td>
<td>Complex Quadrature Amplitude Modulation</td>
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<tr>
<td>CSK</td>
<td>Complex Signal Kurtosis</td>
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<tr>
<td>CW</td>
<td>Continuous Wave</td>
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<tr>
<td>dB</td>
<td>Decibel</td>
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<tr>
<td>DDC</td>
<td>Digital Down Converter</td>
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<tr>
<td>DSP</td>
<td>Digital Signal Processing</td>
</tr>
<tr>
<td>DVB-S2</td>
<td>Digital Video Broadcasting - Satellite - Second Generation</td>
</tr>
<tr>
<td>ERBM</td>
<td>Entropy Rate Bound Minimization</td>
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<tr>
<td>ESTO</td>
<td>Earth Science Technology Office</td>
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<tr>
<td>FB</td>
<td>Full Band</td>
</tr>
<tr>
<td>FPGA</td>
<td>Field Programmable Gate Array</td>
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<tr>
<td>Gbps</td>
<td>Billions of Bits per Second</td>
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<tr>
<td>GMI</td>
<td>GPM Microwave Imager</td>
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<tr>
<td>GPM</td>
<td>Global Precipitation Measurement</td>
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<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
</tr>
<tr>
<td>H</td>
<td>Horrizontal</td>
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<tr>
<td>ICA</td>
<td>Independent Component Analysis</td>
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<tr>
<td>INR</td>
<td>Interference to Noise Ratio</td>
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<tr>
<td>NASA</td>
<td>National Aeronautics and Space Administration</td>
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<tr>
<td>NCCFASTICA</td>
<td>Non Circular Complex Fast ICA</td>
</tr>
<tr>
<td>PI</td>
<td>Principal Investigator</td>
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<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying)</td>
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<tr>
<td>RADAR</td>
<td>RAdio Detection And Ranging</td>
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<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
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<tr>
<td>ROACH</td>
<td>Reconfigurable Open Architecture Computing Hardware</td>
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<tr>
<td>ROC</td>
<td>Receiver Operating Characteristic</td>
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<tr>
<td>RRCOS</td>
<td>Root Raise Cosine</td>
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<tr>
<td>RSK</td>
<td>Real Signal Kurtosis</td>
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<tr>
<td>SB</td>
<td>Sub Band</td>
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<tr>
<td>SERDES</td>
<td>Serializer / Deserializer</td>
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<tr>
<td>SMAP</td>
<td>Soil Moisture Active Passive</td>
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<tr>
<td>V</td>
<td>Vertical</td>
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Motivation

• Unmitigated RFI (Radio Frequency Interference) can cause errors in science measurements
  – L- and C-Band: soil moisture measurements over land
  – L-, C- and X-band: ocean salinity, sea surface temperature, wind speed direction
  – K band: water vapor, liquid water

• Approach
  – RF front end development for 18 GHz (K band)
    • These allocations are known to be corrupted by direct broadcast services
  – Digital back end to allow sophisticated RFI detection and mitigation techniques
SMAP TA H-pol
1400 MHz

SMAP TA H-pol filtered

10 GHz GMI
Tb V-pol
(Vertical)

SMAP (Soil Moisture Active Passive) algorithms developed previously under ESTO (Earth Science Technology Office)
The 18 GHz Channel sees significant RFI from surface reflections around CONUS (Continental United States) and Hawaii.
Real Signal Kurtosis (RSK)

Based on Thermal Noise Amplitude Probability Distribution

Sketches of noise and sinusoidal waveforms/PDFs

Figure from [2]

\[ K \equiv \frac{E[(x - \bar{x})^4]}{E[(x - \bar{x})^2]^2} = \frac{m_4 - 4m_1m_3 + 6m_1^2m_2 - 3m_1^4}{m_2^2 - 2m_2m_1^2 + m_1^4} \]

\[ \sigma_K = \sqrt{\frac{24}{B \tau}} \]

RSK [2] is used on SMAP [3] to help flag measurements that are contaminated with RFI

K = 3 for Gaussian signal
Real Signal Kurtosis (RSK)

Given a complex baseband signal \( z(n) = I(n) + jQ(n) \), the fourth standardized moment is computed independently for both the real and imaginary vectors, I and Q, as was used in SMAP[3].

\[
\text{RSK}_I = \frac{\mathbb{E}[(I - \mathbb{E}[I])^4]}{(\mathbb{E}[(I - \mathbb{E}[I])]^2)} - 3, \quad \text{RSK}_Q = \frac{\mathbb{E}[(Q - \mathbb{E}[Q])^4]}{(\mathbb{E}[(Q - \mathbb{E}[Q])]^2)} - 3
\]

The test statistic, RSK [2,3] (Real Signal Kurtosis), is then defined as

\[
\text{RSK} = \frac{|\text{RSK}_I| + |\text{RSK}_Q|}{2}
\]
Complex Signal Kurtosis

Complex signal kurtosis (CSK) [4] is used to improve ability of the digital radiometer to detect RFI. It makes use of additional information in complex signals.

Given a complex baseband signal $z(n) = I(n) + jQ(n)$, moments $\alpha_{\ell,m}$ of $z(n)$ are defined as

$$\alpha_{\ell,m} = \mathbb{E}[(z - \mathbb{E}[z])^\ell (z - \mathbb{E}[z])^{*m}], \ell, m \in \mathbb{R} \geq 0$$

With $\sigma^2 = \alpha_{1,1}$, Standardized moments $q_{\ell,m}$ can then be found as

$$q_{\ell,m} = \frac{\alpha_{\ell,m}}{\sigma^{\ell+m}}$$

Leading to the CSK (Complex Signal Kurtosis) RFI test statistic used [4].

$$C_K = \frac{q_{2;2} - 2 - |q_{2;0}|^2}{1 + \frac{1}{2} |q_{2;0}|^2}$$

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Algorithm Simulation and Verification

Simulation
- Noise + RFI Test Signals
- Python Algorithms
- Performance Evaluation

Hardware Verification
- ROACH2
  - ADC
  - Ethernet (10 Gbps)
- AWG
  - FPGA Firmware
- Matlab Simulink Xilinx
  - Matlab Python
- Performance Evaluation

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ROACH2 Implementation of RFI Detection Algorithms

- As a base line, a modified version of the Soil Moisture Active Passive Mission (SMAP) digital signal processing architecture was implemented in the Reconfigurable Open Architecture Computing Hardware (ROACH2) with a bandwidth of 24 MHz and verified using test signals generated. [5,6]
- This architecture provided outputs for the real and complex kurtosis statistical computations at 24 MHz
- The architecture was then implemented and verified at 200 MHz bandwidth in the ROACH2
- The real and complex kurtosis were also computed using outputs from the 200 MHz bandwidth architecture
ROACH2 Hardware Description

Two 4x 10 Gigabit Ethernet Cards

2 (1 Gigabit) Ethernet Ports to FPGA and PowerPC

PowerPC

Main Board

ZDOK Expansion

DDR RAM

Xilinx FPGA

DAC

ADC
SMAP Modified DSP Architecture at Faster Sampling Rate

- The FPGA clock speed was increased from 96 MHz to 200 MHz (ratio of 1 : 2.08)
- The ADC sampling rate was increased from 96 MHz to 800 MHz (ratio of 1 : 8.33)
  - Two ADCs clocked at 800 MSPS each
  - Each channel has a 1 : 4 SERDES (Serializer/Deserializer) reception
    - The FPGA reads four samples from each channel every clock cycle
- The DSP (Digital Signal Processing) algorithm had to be parallelized to handle the data throughput
  - A SERDES block natively implements the first stage of a polyphase decomposition
  - The down-sampling is now performed before modulation and filtering, but the entire system input / output is identical
**Modified DSP Architecture at Faster Sampling Rate**

**Effective Analog of DDC From SMAP DSP Architecture**

\[
\text{Re}(c(t)) = \cos(2\pi f_m n / F_s) \\
\text{Im}(c(t)) = -\sin(2\pi f_m n / F_s)
\]

**Equivalent Polyphase Decomposition for Serdes Inputs**

**Inherent Duality Between Serdes and DSP Polyphase Decomposition**

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Wideband RFI Telemetry - RSK

Moments $m_1$-$m_4$ used to compute Real Kurtosis

Used to produce 3rd and 4th Stokes parameters

H and V Cross-Correlation
Wideband RFI Telemetry - CSK

Moments m1-m4 used to compute Real Kurtosis

Additional Moments for Complex Kurtosis

• +4 moments per Polarization [6]
• Extension on moments for real kurtosis

I, I^2, I^3, I^4
IQ, I^2Q, I^2Q^2
Q, Q^2, Q^3, Q^4

I, I^2, I^3, I^4
IQ, I^2Q, I^2Q^2
Q, Q^2, Q^3, Q^4

IH, IV, QH, QV
IHQH, QH, QV
H and V Cross-Correlation

Used to produce 3rd and 4th Stokes parameters

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ROC Curves and AUC

- Each point on an ROC curve can be represented by the set \{FAR, PD\}
  - \{False alarm Rate, Probability of Detection\}
- ROC curves will generate from (0,0) to (1,1) by varying the threshold
- Poor detectors are close to the 1:1 line
- Better detectors show higher PD and smaller FAR
- **Figure of Merit = Area Under Curve (AUC)**
  - \(0.5 \leq \text{AUC} \leq 1\)
  - When AUC = 0.5 detector does not work
  - When AUC = 1 the detector works perfectly

ROC curve example, from [7].
Simulation Results

Smaller duty cycles are easier to detect; sub-bandning improves detection [6].

CW Modulation
CSK is outperforming RSK
Simulation Results

Wide Band revers to QPSK with a RRCOS filter simulating a DVB-S2 Channel,
- Band occupancy = 0.0375 Fs, Carrier = 0.175 Fs
- Using Monte Carlo Simulations, INR is swept is for different types of RFI modulations.
- Algorithms are compared by looking at INR when AUC = 0.75.
- CSK shows improved detection over RSK.
- PCW is easiest to detect. Wideband is hardest to detect [6].
AUC Results: Kurtosis As Detector

Kurtosis yields poor detector for CW and Wide Band RFI

Kurtosis yields good detection for PCW (Such as RADAR)
Sub-banding Verification with Chirp

• 200 MHz BW
Channelized Complex Kurtosis

Visual Verification of channelization.

Deviation away from 0 means interference is detected.
Hardware Results

Sub banding decreased detection on wide band RFI

Sub banding improved detection on narrow band RFI
Independent Component Analysis

- ICA [8] uses higher order statistics to perform blind source separation
- This suggests it may be useful for separating RFI from Gaussian noise in the radiometry context.
- We assume noise and RFI are statistically independent sources, mixing is linear, sources are non-Gaussian
- Mixture model: \( \mathbf{x} = \mathbf{A}\mathbf{s} \), observe \( \mathbf{x} \)
- \( \hat{s} = \mathbf{Wx} \), \( \hat{s} \) is the estimated independent source

\[
\begin{align*}
\text{Source vector } \mathbf{s} & : s_1(n) \quad s_2(n) \quad s_3(n) \quad s_4(n) \\
\text{Original sources/signals} & \\
\text{Linear Mixing} & : \mathbf{A} \\
\text{Linear Mixing} & : \mathbf{x} = \mathbf{A}\mathbf{s} \\
\text{Observation vector } \mathbf{x} & : x_1(n) \quad x_2(n) \quad x_3(n) \quad x_4(n) \\
\text{Estimated vector } \hat{\mathbf{s}} & : \hat{s}_1(n) \quad \hat{s}_2(n) \quad \hat{s}_3(n) \quad \hat{s}_4(n) \\
\text{Estimated sources/signals} &
\end{align*}
\]
ICA Algorithm

\[
\begin{bmatrix}
  x_{HI}[0] & x_{HI}[1] & \ldots & x_{HI}[N - 1] \\
  x_{HQ}[0] & x_{HQ}[1] & \ldots & x_{HQ}[N - 1] \\
  x_{VI}[0] & x_{VI}[1] & \ldots & x_{VI}[N - 1] \\
  x_{VQ}[0] & x_{VQ}[1] & \ldots & x_{VQ}[N - 1]
\end{bmatrix}
= \begin{bmatrix}
a_{00} & a_{01} & a_{02} & a_{03} \\
a_{10} & a_{11} & a_{12} & a_{13} \\
a_{20} & a_{21} & a_{22} & a_{23} \\
a_{30} & a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
  s_{0,0} \\
  s_{0,1} \\
  s_{0,2} \\
  \vdots \\
  s_{0,N-1}
\end{bmatrix}
\]

Find A matrix to transform X into S

- Actual Signals, S, are mixed by mixing matrix, A, and observed as X
- We pick a matrix, \( \hat{W} \), that gives us back our estimated signals, \( \hat{S} \)

\[
x = AS \\
W = A^{-1} \\
s = \hat{W}x
\]

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Signal Model

- Assumptions
  - Gaussian Noise between H and V polarizations is Independent and Uncorrelated
  - Interference is circularly polarized

\[
x_H(t) = \text{rfi}(t) + \text{wgn}_1(t)
\]
\[
x_V(t) = \text{rfi}(t) e^{-\frac{i\pi}{2}} + \text{wgn}_2(t)
\]

**CW Example:**
\[
x_H(t) = (a \sin(\omega_0 t) + w_2(t)) * h(t)
\]
\[
x_V(t) = (a \sin(\omega_0 t - \pi/2) + w_2(t)) * h(t)
\]

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ICA RFI Detection

ICA Output

\[ s_0[0] \quad s_0[1] \quad \ldots \quad s_0[N - 1] \]
\[ s_1[0] \quad s_1[1] \quad \ldots \quad s_1[N - 1] \]
\[ s_2[0] \quad s_2[1] \quad \ldots \quad s_2[N - 1] \]
\[ s_3[0] \quad s_3[1] \quad \ldots \quad s_3[N - 1] \]

Kurtosis

\[ \text{RSK}_0 \]
\[ \text{RSK}_1 \]
\[ \text{RSK}_2 \]
\[ \text{RSK}_3 \]

\[ \max_k \{\text{ABS}(\text{RSK}_k - 3)\} \]

ICA Detector Output

Step 1: Take Kurtosis of each estimated independent component vector

Step 2: Select the kurtosis value that deviated the furthest from 3
Various ICA algorithms are tested [9,10,11,12,13,14,15,16,17]. No ICA pre-processing is done on ‘direct’ data sets.
Various ICA algorithms are tested [9,10,11,12,13,14,15,16,17]. No ICA pre-processing is done on 'direct' data sets.
Various ICA algorithms are tested [9,10,11,12,13,14,15,16,17]. No ICA pre-processing is done on ‘direct’ data sets.

RSK = Real Signal Kurtosis
CSK = Complex Signal Kurtosis
Conclusions

• CSK provides better detection over RSK
• ICA allowed equivalent detection at about 2dB lower INR when used as a preprocessor for RSK and CSK normality tests
• ICA performance mainly limited due to an underdetermined observation matrix
• May be more suitable to systems with a greater number of observation channels
ICA Algorithms Used

• Fast ICA (FASTICA) [9,15]

• Robust ICA (ROBUSTICA) [10,16]

• Non Circular Complex Fast ICA (NCCFASTICA) [11,17]

• Entropy Rate Bound Minimization (ERBM) [12,17]

• Complex Quadrature Amplitude Modulation (CQAMSYM) [13,17]
  – Mike Novey and T. Adali, "Complex Fixed-Point ICA Algorithm for Separation of QAM Sources using Gaussian Mixture Model" in IEEE Conf. ICASSP 2007

• Complex Entropy Rate Bound Minimization (CERBM) [14,17]

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