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>
</tr>
<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>
</tr>
<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>
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<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>
</tr>
<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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<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
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<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>
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<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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<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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<td>RRCOS</td>
<td>Root Raise Cosine</td>
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<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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<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
L, X band RFI

SMAP TA H-pol
1400 MHz

10 GHz GMI
Tb V-pol
(Vertical)

SMAP (Soil Moisture Active Passive) algorithms developed previously under ESTO (Earth Science Technology Office)

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RFI from Geosynchronous Satellites Reflecting from the Surface

The 18 GHz Channel sees significant RFI from surface reflections around CONUS (Continental United States) and Hawaii.

Picture from David W. Draper, [1]
Real Signal Kurtosis (RSK)

Based on Thermal Noise Amplitude Probability Distribution

Sketches of noise and sinusoidal waveforms/PDFs

Figure from [2]

\[ K = 3 \] for Gaussian signal

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

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

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

\[
RSK_I = \frac{\mathbb{E}[(I-\mathbb{E}[I])^4]}{(\mathbb{E}[(I-\mathbb{E}[I])])^2} - 3,
\]
\[
RSK_Q = \frac{\mathbb{E}[(Q-\mathbb{E}[Q])^4]}{(\mathbb{E}[(Q-\mathbb{E}[Q])])^2} - 3
\]

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

\[
RSK = \frac{|RSK_I| + |RSK_Q|}{2}
\]
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

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

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].

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

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Algorithm Simulation and Verification

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

Hardware Verification
- Matlab
- Simulink
- Xilinx
- Matlab
- Python
- AWG
- FPGA Firmware
- ROACH2
- ADC
- Ethernet (10 Gbps)
- 4x
- 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

Xilinx FPGA

DDR RAM

DAC

PowerPC

Main Board

ZDOK Expansion

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

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Modified DSP Architecture at Faster Sampling Rate

Effective Analog of DDC From SMAP DSP Architecture

Equivalent Polyphase Decomposition for Serdes Inputs
Wideband RFI Telemetry - RSK

Moments m1-m4 used to compute Real Kurtosis

Used to produce 3\textsuperscript{rd} and 4\textsuperscript{th} Stokes parameters
Wideband RFI Telemetry - CSK

Moments \( m_1 - m_4 \) used to compute Real Kurtosis

Additional Moments for Complex Kurtosis

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

\[ I, I^2, I^3, I^4 \]
\[ IQ, I^2Q, IQ^2, I^2Q^2 \]
\[ Q, Q^2, Q^3, Q^4 \]

\[ I, I^2, I^3, I^4 \]
\[ IQ, I^2Q, IQ^2, I^2Q^2 \]
\[ Q, Q^2, Q^3, Q^4 \]

\[ I_H I_V + Q_H Q_V \]
\[ I_V Q_H - I_H Q_V \]

H and V Cross-Correlation

Used to produce 3\(^{rd}\) and 4\(^{th}\) 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-bandding 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
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 \( \mathbf{x} \)
- \( \hat{\mathbf{s}} = \mathbf{W}\mathbf{x} \), \( \hat{\mathbf{s}} \) is the estimated independent source

Source vector \( \mathbf{s} \)

\( s_1(n) \)
\( s_2(n) \)
\( s_3(n) \)
\( s_4(n) \)

Observation vector \( \mathbf{x} \)

\( x_1(n) \)
\( x_2(n) \)
\( x_3(n) \)
\( x_4(n) \)

Estimated vector \( \hat{\mathbf{s}} \)

\( \hat{s}_1(n) \)
\( \hat{s}_2(n) \)
\( \hat{s}_3(n) \)
\( \hat{s}_4(n) \)
ICA Algorithm

\[
\begin{bmatrix}
  x_{HI}[0] & x_{HI}[1] & \cdots & x_{HI}[N-1] \\
  x_{HQ}[0] & x_{HQ}[1] & \cdots & x_{HQ}[N-1] \\
  x_{VI}[0] & x_{VI}[1] & \cdots & x_{VI}[N-1] \\
  x_{VQ}[0] & x_{VQ}[1] & \cdots & x_{VQ}[N-1]
\end{bmatrix}
= 
\begin{bmatrix}
a_{00} & a_{01} & a_{02} & a_{03} \\
a_{10} & a_{11} & a_{12} & a_{13} \\
a_{20} & a_{21} & a_{22} & a_{23} \\
a_{30} & a_{31} & a_{32} & a_{33}
\end{bmatrix}
\begin{bmatrix}
  s_{0,0} & s_{0,1} & s_{0,2} & s_{0,3} & \cdots & s_{0,N-1} \\
  s_{1,0} & s_{1,1} & s_{1,2} & s_{1,3} & \cdots & s_{1,N-1} \\
  s_{2,0} & s_{2,1} & s_{2,2} & s_{2,3} & \cdots & s_{2,N-1} \\
  s_{3,0} & s_{3,1} & s_{3,2} & s_{3,3} & \cdots & s_{3,N-1}
\end{bmatrix}
\]

Observations  Mixing Matrix  Independent Components

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, \( \hat{S} \)

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

ICA Input

- Measured \( x \)
- \( \hat{S} = \hat{W}x \)
- Are components \( \hat{s}_i \) in \( \hat{S} \) independent?
  - Yes: Use \( \hat{S} \)
  - No: Update \( \hat{W} \)

ICA Output

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Signal Model

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

\[
x_H(t) = \text{rfi}(t) + w_{g1}(t)
\]

\[
x_V(t) = \text{rfi}(t) e^{-\frac{i \pi}{2}} + w_{g2}(t)
\]

**CW Example:**

\[
x_H(t) = (a \sin(\omega_0 t) + w_2(t)) * h(t)
\]

\[
x_V(t) = (a \sin(\omega_0 t - \pi/2) + w_2(t)) * h(t)
\]
ICA RFI Detection

ICA Output

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

Step 1: Take Kurtosis of each estimated independent component vector

Step 2: Select the kurtosis value that deviated the furthest from 3

ICA Detector Output

\[ \text{max}_k \{ \text{ABS}(\text{RSK}_k - 3) \} \]
Various ICA algorithms are tested [9,10,11,12,13,14,15,16,17]. No ICA pre-processing is done on ‘direct’ data sets.

+2dB INR Gain, Real Signal Kurtosis with FastICA performs just as well as other algorithms for PCW
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

+2dB INR Gain, Complex Signal Kurtosis with Complex ICA Algorithms Performs Best on CW
AUC Results – ICA Performance – Wide Band

Various ICA algorithms are tested [9,10,11,12,13,14,15,16,17]. No ICA pre-processing is done on ‘direct’ data sets.

+2dB INR Gain, Complex Signal Kurtosis with Complex ICA Algorithms Performs Best on Wideband

RSK = Real Signal Kurtosis
CSK = Complex Signal Kurtosis

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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]**
References

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16) Vicente Zarzoso, Institut Universitaire de France , Robust ICA, Matlab Resources, http://www.i3s.unice.fr/~zarzoso/robustica.html