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

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<table>
<thead>
<tr>
<th>Acronym</th>
<th>Definition</th>
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</thead>
<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>
</tr>
<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>
</tr>
<tr>
<td>CW</td>
<td>Continuous Wave</td>
</tr>
<tr>
<td>dB</td>
<td>Decibel</td>
</tr>
<tr>
<td>DDC</td>
<td>Digital Down Converter</td>
</tr>
<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>
</tr>
<tr>
<td>ESTO</td>
<td>Earth Science Technology Office</td>
</tr>
<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>
</tr>
<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>
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<tbody>
<tr>
<td>GSFC</td>
<td>Goddard Space Flight Center</td>
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<tr>
<td>H</td>
<td>Horrizontal</td>
</tr>
<tr>
<td>ICA</td>
<td>Independent Component Analysis</td>
</tr>
<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>
</tr>
<tr>
<td>QPSK</td>
<td>Quadrature Phase Shift Keying</td>
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<tr>
<td>RADAR</td>
<td>RAdio Detection And Ranging</td>
</tr>
<tr>
<td>RF</td>
<td>Radio Frequency</td>
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<tr>
<td>RFI</td>
<td>Radio Frequency Interference</td>
</tr>
<tr>
<td>ROACH</td>
<td>Reconfigurable Open Architecture Computing Hardware</td>
</tr>
<tr>
<td>ROC</td>
<td>Receiver Operating Characteristic</td>
</tr>
<tr>
<td>RRCOS</td>
<td>Root Raise Cosine</td>
</tr>
<tr>
<td>RSK</td>
<td>Real Signal Kurtosis</td>
</tr>
<tr>
<td>SB</td>
<td>Sub Band</td>
</tr>
<tr>
<td>SERDES</td>
<td>Serializer / Deserializer</td>
</tr>
<tr>
<td>SMAP</td>
<td>Soil Moisture Active Passive</td>
</tr>
<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 TA H-pol filtered

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]

GMI data
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
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].

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

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

Hardware Verification
- Noise + RFI Test Signals
- AWG
- FPGA Firmware
- ROACH2
- ADC
- Ethernet (10 Gbps)
- Algorithms
- 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
- PowerPC
- Main Board
- ZDOK Expansion
- 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

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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

Inherent Duality Between Serdes and DSP Polyphase Decomposition

Re{c(t)} = \cos(2\pi f_m n / F_s)

Im{c(t)} = -\sin(2\pi f_m n / F_s)

x(n) x_0(n) x_Q(n) 4 h_0, h_4, h_8, ...

Z^{-1} ...

x_i(n) x_0(n)

x(n)

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Wideband RFI Telemetry - RSK

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

I

$I, I^2, I^3, I^4$

H

Q

$Q, Q^2, Q^3, Q^4$

I

$I, I^2, I^3, I^4$

V

Q

$Q, Q^2, Q^3, Q^4$

3

$I_H I_V + Q_H Q_V$

4

$I_V Q_H - I_H Q_V$

H and V Cross-Correlation

Used to produce 3$^{rd}$ and 4$^{th}$ Stokes parameters

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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

Used to produce $3^{rd}$ and $4^{th}$ Stokes parameters

H and V Cross-Correlation

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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 \(\text{AUC} = 0.5\) detector does not work
  - When \(\text{AUC} = 1\) 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 reverts 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
ICA Algorithm

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

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, \( \hat{S} \)

\[
\begin{align*}
x &= As \\
W &= A^{-1} \\
s &= \hat{W}x
\end{align*}
\]
Signal Model

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

\[ x_H(t) = rfi(t) + wgn_1(t) \]
\[ x_V(t) = rfi(t) e^{-\left(\frac{i\pi}{2}\right)} + wgn_2(t) \]

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

ICA Output

\[ s_0[0], s_0[1], ..., s_0[N-1] \]

\[ s_1[0], s_1[1], ..., s_1[N-1] \]

\[ s_2[0], s_2[1], ..., s_2[N-1] \]

\[ s_3[0], s_3[1], ..., s_3[N-1] \]

Step 1: Take Kurtosis of each estimated independent component vector

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

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

ICA Detector Output

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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.

RSK = Real Signal Kurtosis
CSK = Complex Signal Kurtosis
Various ICA algorithms are tested [9,10,11,12,13,14,15,16,17]. No ICA pre-processing is done on ‘direct’ data sets.
AUC Results – ICA Performance – Wide Band

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

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]**
References

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13) Mike Novey and T. Adali, "Complex Fixed-Point ICA Algorithm for Separation of QAM Sources using Gaussian Mixture Model" in IEEE Conf. ICASSP 2007
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