Universitat Politècnica de Catalunya

Implementation of FAPEC decorrelation stages for IQ and water column data

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Outline

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Background

- Two strategic projects of DAPCOM Data Services, a spin-off of UPC and UB.
- FAPEC is the data compressor from DAPCOM.

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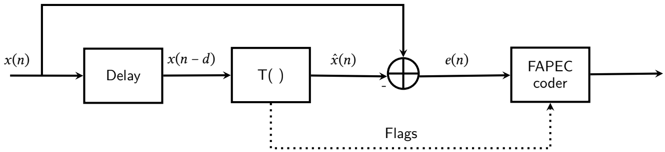
- FAPEC is the data compressor from DAPCOM.
- FAPEC works in a classical 2-stage structure.



Data compression is fundamental in environments where:

- Bandwidth is limited.
- Computing power is limited.

Motivation

Data compression is fundamental in environments where:

- Bandwidth is limited.
- Computing power is limited.

Examples:

- Space.
- Offshore.

Objectives

- Develop a FAPEC stage for IQ and audio data.
- Develop a FAPEC stage for the KMALL format from Kongsberg Maritime.
- Propose a scale invariant metric to evaluate the former stages.

Background & features

- Designed to solve some limitations of the CCSDS compression standards.
- High computing performance.

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- Data chunking $\Longrightarrow$ better robustness to data corruption.
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- High computing performance.
- Data chunking $\Longrightarrow$ better robustness to data corruption.
- Several preprocessing stages for different data types.
- Multithreading support.
- Data encryption using AES.

For a continuous random variable X with a density $f(x)$, its differential entropy is:

$$h(X) = -\int_{-\infty}^{+\infty} f(x) \ln f(x) dx$$

The Normal distribution has maximum entropy. Thus, if G is a gaussian random variable with variance σ^2:

$$h(G) = \ln\left(\sqrt{2\pi e\sigma^2}\right)$$

Negentropy is defined as:

$$J(X) = h(G) - h(X) \geq 0$$

where $G \sim \mathcal{N}(\mu, \sigma^2)$ and X is a random variable with variance σ^2.

Important properties:

- It provides an indicator of normality.
- It is invariant to any linear map.

Outline

Pass-band signal:

$$s(t) = i_s(t) \cdot \cos(2\pi f_0 t) - q_s(t) \cdot \sin(2\pi f_0 t)$$

Data format

Pass-band signal:

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IQ samples: the discrete time samples of $i_s(t)$ and $q_s(t)$ $\equiv$ time series in two channels $\equiv$ stereo audio $\Longrightarrow$ FLAC $\Longrightarrow$ linear predictor.

Requirements

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- Compression ratio must be at least 80% of that from FLAC.
- Compression speed must be better than that of FLAC.

Linear predictor model:

$$\hat{x}(n) = \sum_{i=1}^{Q} h_i x(n-i)$$

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Finding h_i. The Yule-Walker equations:

$$r_x(j) = \sum_{i=1}^{Q} h_i r_x(|i-j|), \quad 1 \leq j \leq Q$$

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The linear system is solved with the Levinson-Durbin algorithm with a complexity $O(Q^2)$.

Short-term autocorrelation:

$$r_x(i) = \sum_{m=0}^{T-1-i} x_N(m)x_N(m+i), \quad i \geq 0$$

$x_N(m)$ is assumed to be WSS and $T \leq N$.

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Prediction errors $e(n) = x(n) - \hat{x}(n)$ and coefficients h_i are sent to the entropy coder.

Additional features:

- Arbitrary number of channels.
- Channel coupling.

Algorithm

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- Tunable period length N.
- Tunable training length T.

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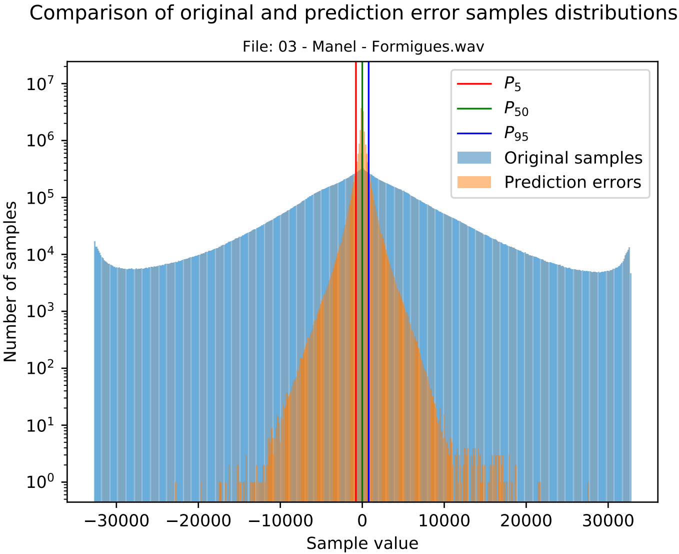
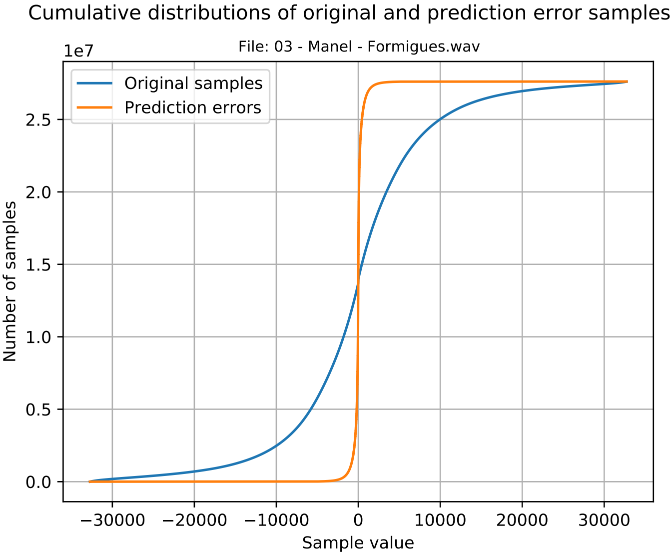
- Arbitrary number of channels.
- Channel coupling.
- Tunable period length N.
- Tunable training length T.
- Lossless or lossy compression.

Input settings:

- Filter order: $Q = 10$.
- Period length: $N = 65536$.
- Training length: $T = 65536$.
- Number of channels: 2.
- No coupling.
- No losses.

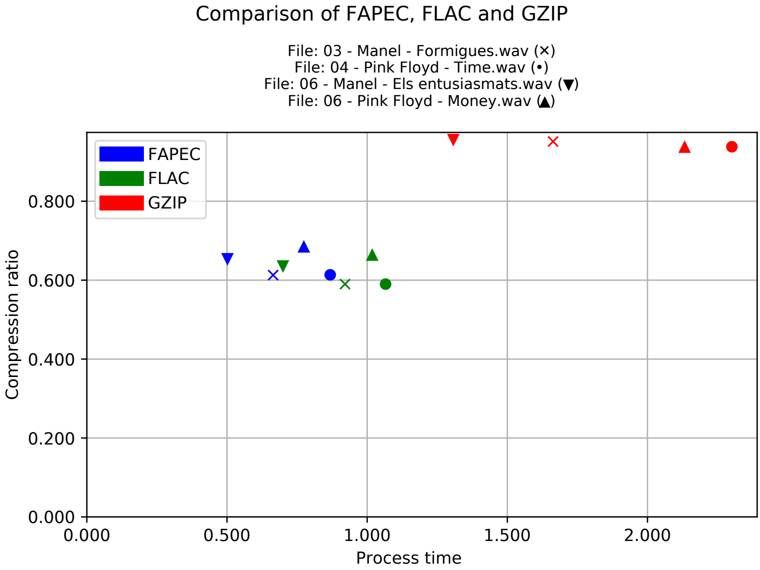

Comparison of original and prediction error samples distributions
File: 03 - Manel - Formigues.wav
P_5
P_{50}
P_{95}
Original samples
Prediction errors
Number of samples
Sample value
10^0
10^1
10^2
10^3
10^4
10^5
10^6
10^7
−30000
−20000
−10000
0
10000
20000
30000


Cumulative distributions of original and prediction error samples
File: 03 - Manel - Formigues.wav
1e7
Original samples
Prediction errors
Number of samples
Sample value
0.0
0.5
1.0
1.5
2.0
2.5
−30000
−20000
−10000
0
10000
20000
30000

Negentropies

Filename	$J(X)$	$J(E)$	$J(E)/J(X)$
03 - Manel - Formigues.wav	0.0018	0.0144	8.0
04 - Pink Floyd - Time.wav	0.0004	0.0238	59.5
06 - Manel - Els entusiasmats.wav	0.0012	0.0098	8.2
06 - Pink Floyd - Money.wav	0.0009	0.0090	10

Negentropy is not proportional to the compression ratio.


Comparison of FAPEC, FLAC and GZIP
File: 03 - Manel - Formigues.wav (×)
File: 04 - Pink Floyd - Time.wav (•)
File: 06 - Manel - Els entusiasmats.wav (▼)
File: 06 - Pink Floyd - Money.wav (▲)
FAPEC
FLAC
GZIP
Compression ratio
0.000
0.200
0.400
0.600
0.800
Process time
0.000
0.500
1.000
1.500
2.000

Euclidean distances for FAPEC, FLAC and Gzip

Filename	FAPEC dist.	FLAC dist.	GZIP dist.
03 - Manel - Formigues.wav	0.9040	1.0938	1.9161
04 - Pink Floyd - Time.wav	1.0630	1.2181	2.4851
06 - Manel - Els entusiasmats.wav	0.8242	0.9453	1.6197
06 - Pink Floyd - Money.wav	1.0333	1.2152	2.3294

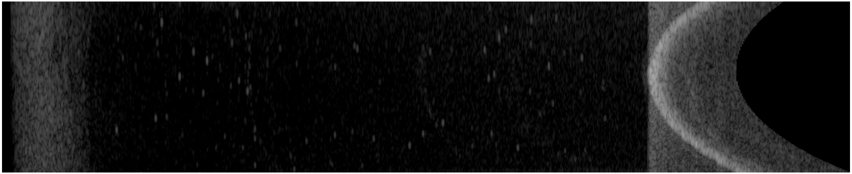
FAPEC is the fastest option.

Outline

Data format

Important definitions:

- **Ping:** A ping is defined as a number of pulses transmitted at approximately the same time.
- **Beam:** Each ping is formed by some pulses in different angles, which we call beams.



Data format

- The KMALL format is the successor of the ALL format.
- It is structured in datagrams.
- Each `.kmall` file contains several datagrams.
- The most important are MRZ and MWC (multibeam).

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- The most important are MRZ and MWC (multibeam).

Structure of a MWC datagram

Header	Partition	CmnPart	TxInfo	SectorData	RxInfo	BeamData
20 [B]	4 [B]	12 [B]	12 [B]	9 x 16 [B]	16 [B]	$N_B \cdot (16 + N_S \cdot (1 + phaseFlag))$ [B]

- Compression ratio shall be better than that of Gzip.
- Compression speed shall be better than that of Gzip.

- Usually files do not contain MRZ an MWC datagrams at the same time.

Data analysis

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- MRZ datagrams are a 92% of the total size.
- MWC datagrams are a 99% of the total size.

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- Usually files do not contain MRZ an MWC datagrams at the same time.
- MRZ datagrams are a 92% of the total size.
- MWC datagrams are a 99% of the total size.
- High correlation between beams.

Samples are predicted from the samples in the same position as those from the previous beam, when possible:

$$E_{i,j} = S_{i,j} - S_{i,j-1}, \qquad 0 \leq i < \min(N_{S_{j-1}}, N_{S_j}), \quad 1 \leq j < N_B$$

Otherwise, the previous sample is used:

$$E_{i,j} = S_{i,j} - S_{i-1,j}, \qquad \min(N_{S_{j-1}}, N_{S_j}) \leq i < N_{S_j}, \quad 1 \leq j < N_B$$

The first beam is treated differently:

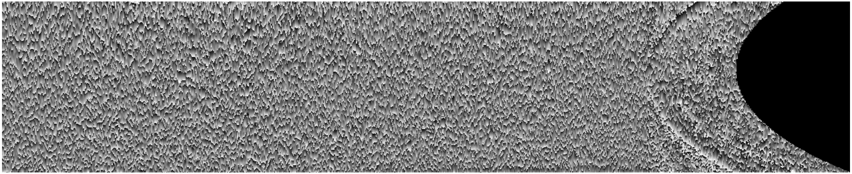
$$E_{i,0} = S_{i,0} - S_{i-1,0}, \qquad 1 \leq i < N_{S_0}$$

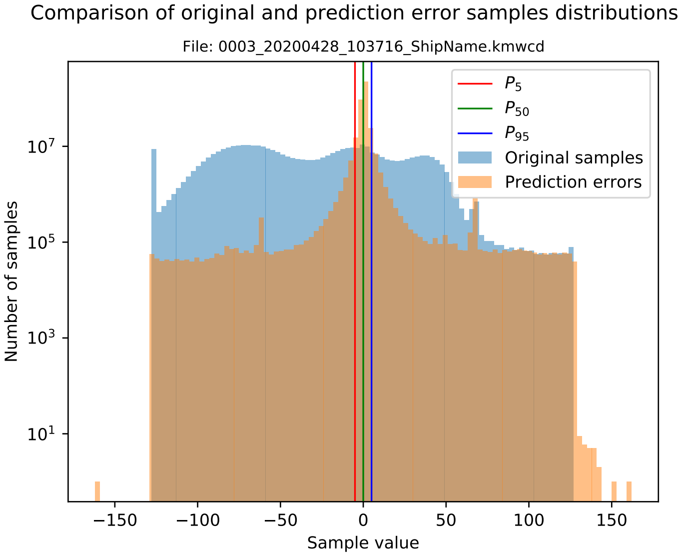
And the first sample in the ping:

$$E_{0,0} = S_{0,0} + 128$$

Phase is not compressible. A simple differential is used:

$$E_{i,j} = S_{i,j} - S_{i-1,j}, \qquad 1 \leq i < N_{S_j}, \quad 1 \leq j < N_B$$




Comparison of original and prediction error samples distributions
File: 0003_20200428_103716_ShipName.kmwcd
P_5
P_{50}
P_{95}
Original samples
Prediction errors
Number of samples
10^7
10^5
10^3
10^1
Sample value
−150
−100
−50
0
50
100
150

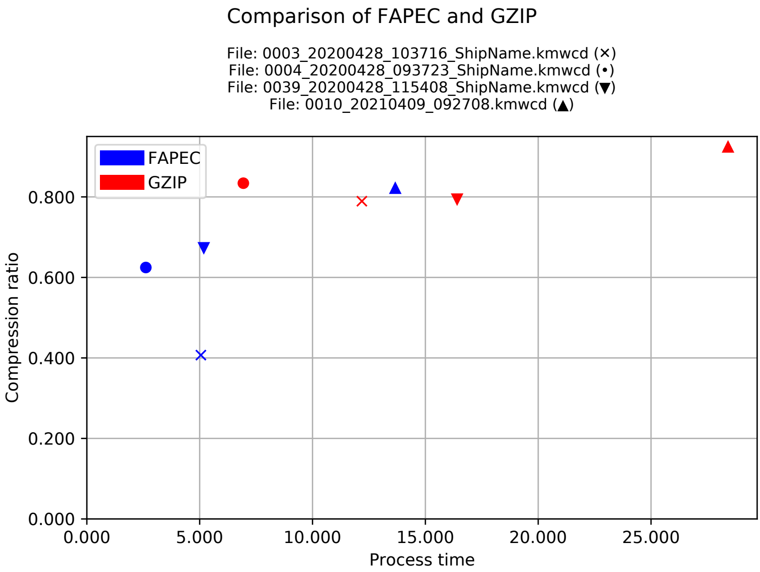
Results

Cumulative distributions of original and prediction error samples
File: 0003_20200428_103716_ShipName.kmwcd
1e8
4.0
3.5
3.0
2.5
2.0
1.5
1.0
0.5
0.0
Number of samples
Original samples
Prediction errors
−150
−100
−50
0
50
100
150
Sample value

Negentropies

Filename	$J(X)$	$J(E)$	$J(E)/J(X)$
0003_20200428_103716_ShipName.kmwcd	0.0004	0.0530	132.5
0004_20200428_093723_ShipName.kmwcd	0.0000	0.0252	-
0039_20200428_115408_ShipName.kmwcd	0.0001	0.0146	146
0010_20210409_092708.kmwcd	0.0001	0.0089	89

Remember that negentropies cannot be compared between different files.



Comparison of FAPEC and GZIP
File: 0003_20200428_103716_ShipName.kmwcd (×)
File: 0004_20200428_093723_ShipName.kmwcd (•)
File: 0039_20200428_115408_ShipName.kmwcd (▼)
File: 0010_20210409_092708.kmwcd (▲)
FAPEC
GZIP
Compression ratio
0.000
0.200
0.400
0.600
0.800
Process time
0.000
5.000
10.000
15.000
20.000
25.000

Euclidean distances for FAPEC and Gzip

Filename	FAPEC dist.	GZIP dist.
0003_20200428_103716_ShipName.kmwcd	5.0696	12.2123
0004_20200428_093723_ShipName.kmwcd	2.6879	6.9850
0039_20200428_115408_ShipName.kmwcd	5.2258	16.4260
0010_20210409_092708.kmwcd	13.6912	28.4271

FAPEC is the best option.

Conclusions

- Wave stage:
  - Linear predictor.
  - A bit worse ratios than those of FLAC.
  - Faster than FLAC.
- KMALL stage:
  - Tailored algorithm which takes advantage of the correlation between beams.
  - Better ratios than those of Gzip.
  - Faster than Gzip.
- Negentropy increases for all the dataset.
- All the goals are fulfilled.

Future work

- Analyze the entropy of each beam to detect zones with low entropy.
- Explore audio encoding algorithms such as TAK to improve the Wave stage.
- Add a new algorithm to the KMALL stage to also compress MRZ datagrams.
- Find a relation between negentropy and FAPEC ratio.

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telecos BCN

Thank you

Negentropy is a particular case of the Kullback–Leibler divergence:

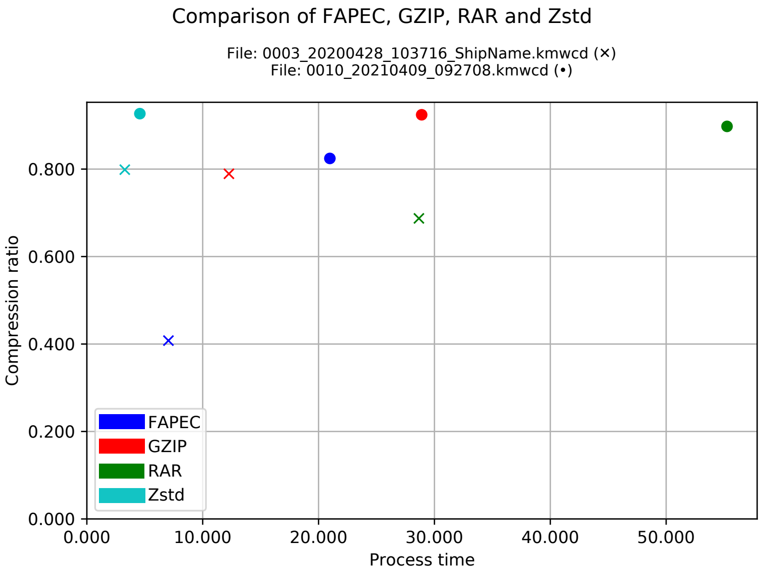
$$J(X) = \int f(x) \ln \frac{f(x)}{\phi(x)} dx$$

As Kullback–Leibler divergence is invariant to any invertible change of coordinates, such is negentropy.

What about IQ data?

- The Wave stage is being deployed in two cubesats constellations from DAPCOM clients.
- Clients have reported that FLAC can be unstable.
- Custom losses for proprietary IQ formats.

Beyond Gzip: RAR & Zstd



Thirty-four shades of KMWCD