







Image and Radio-Frequency data compression for OPS-SAT using FAPEC

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On-Board Payload Data Compression workshop VIII

Athens, 28-30 September 2022

OPS-SAT: an in-orbit laboratory

- = Technology demonstration cubesat by ESA
 - MityARM 5CSX (dual core Cortex-A9, 800 MHz)
 - Camera (Bayer R-G-G-B Colour Filter Array)
 - Software Defined Radio (SDR)
 - Fine ADCS
 - ି GPS
 - S-Band (≤ 1 Mbps), X-Band (≤ 50 Mbps), UHF, Optical receiver
 - NMF: Nanosat Mission Operations (MO) Framework (Java!)
 - Launched 18-Dec-2019, 515 km polar orbit
- = Over 100 experiments registered
 - ் AI, ML, Attitude, RF...
 - One of them is FAPEC data compression

= THANKS, ESA!

- Excellent opportunity to easily test technology in orbit
- Negligible paperwork, OPS-SAT team always willing to help
- Wishing for an OPS-SAT 2 mission...



Photo: Lunghammer - TU Graz



OPS-SAT: an in-orbit laboratory

= OPS-SAT camera

- 2048 x 1944 x 12-bit (raw image size: 8 MB)
- 4 "bands" (Red, Green, Green, Blue)
- JPEG can be used, requiring onboard Bayer demosaicing
- \odot Up to 5 frames/s \rightarrow up to 320 Mbps raw throughput

= Software Defined Radio

- 12-bit in-phase & quadrature (I&Q) radio frequency data
- Some tests at 1.5 Msamples/s → 48 Mbps

= Nanosat Mission operations Framework (NMF)

- New concept of on-board mission operations aiming at simple deployments and experiments
- Java-based framework
- "Apps" from experimenters, deployed (uploaded) there as packages
- Access to the several devices on board
- Either executed from ground during contacts or scheduled
- = Also: Linux-based shell environment

The FAPEC data compressor

Versatile data compression solution (onboard + onground applications)

- = FAPEC entropy coding core (outlier-resilient)
- Suite of pre-processing stages including images (greyscale, multi/hyperspectral) and wave data (e.g. audio or RF), lossless and near-lossless
- = Fast, multi-thread, encryption
- = Basic data analysis capabilities
- = ANSI C software implementation
- = CLI + C/Python/Java API
- E Currently being used in several earth observation satellites
- Free evaluation licenses: www.dapcom.es/get-fapec



Motivation of this work

= **ESA OSIP Call**: OPS-SAT Experiments Campaign

© Call for proposals of additional experiments and developments for OPS-SAT

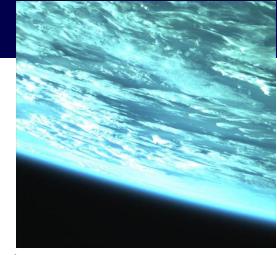
■ FAPEC image and RF compression:

- © CILLIC and Wave algorithms already available as of FAPEC 22.0
- Some (modest) limitations identified: ratios, lossy quality, speed
- Add support for video compression
- Add extra features: "Thumbnails" or basic data analysis to support downlink decisions
- E Cubesats (and "New Space" in general):
 - Typically Linux-based software solutions
 - \Rightarrow Agile developments \rightarrow use COTS and ready-to-use software as much as possible
 - ➢ Zip, JPEG, JPEG2K, PNG, etc. → memory and CPU usage, limitations (e.g.: 16-bit hyperspectral images?)

Improve image and RF decorrelation algorithms for FAPEC Provide a "de facto" standard for data compression in cubesats

FAPEC in OPS-SAT

- = FAPEC being used on-board OPS-SAT since 2020!
 - CILLIC lossy image compression invoked from CLI
 - Lots of images (and "videos") downloaded
 - Ratios around 10, very good image quality



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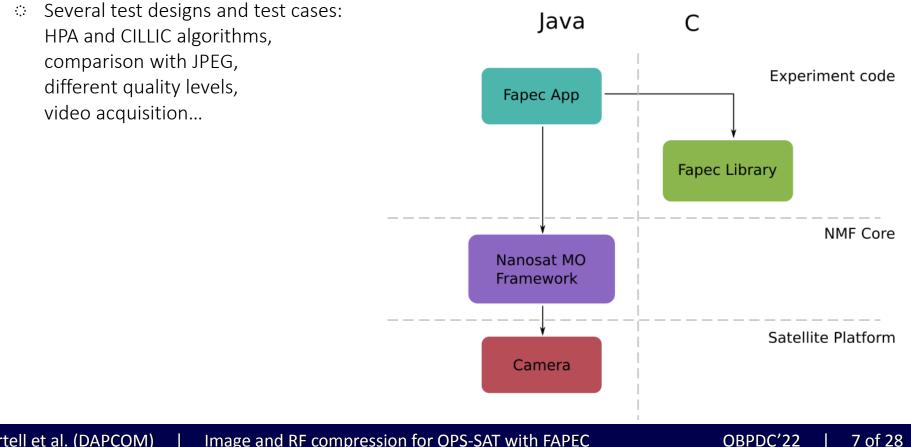
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[29-11-2020 17:00:26] COMMAND Uplink to SEPP: for f in /home/exp1000/toGround/edge/*.ims rgb; do
 c='/home/exp100/fapec -q -chunk 512K -mt 1 -dtype 16 -cillic 2048 1944 1 x10 12 4 -lev 5
    -ow -o /home/exp100/toGround/'$(basename ${f%.*}.fapec); eval '$c $f >> /home/exp100/f.log'; done
[29-11-2020 17:00:33] DATA: START
[29-11-2020 17:00:33] DATA: STOP
[29-11-2020 17:00:34] COMMAND Uplink to SEPP: cat /home/exp100/f.log; ls -larthR /home/exp100/toGround
[29-11-2020 17:00:41] DATA: START
[29-11-2020 17:00:41]
[29-11-2020 17:00:41] FAPEC Archiver - 20.0.0 Beta r2280 (2020-11-15)
[29-11-2020 17:00:41] (c) 2013-2020 DAPCOM Data Services S.L. - http://www.dapcom.es
[29-11-2020 17:00:41] 32/32 bit LE Restricted license for:
[29-11-2020 17:00:41] ESA OPS-SAT
[29-11-2020 17:00:41]
[29-11-2020 17:00:41] Compressing 1 file into /home/exp100/toGround/img msec 1606601765418 2.fapec...
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[29-11-2020 17:00:41]
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[29-11-2020 17:00:41] FAPEC Archiver - 20.0.0 Beta r2280 (2020-11-15)
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[29-11-2020 17:00:41] ESA OPS-SAT
[29-11-2020 17:00:41]
[29-11-2020 17:00:41] Compressing 1 file into /home/exp100/toGround/img msec 1606638723330 2.fapec...
[29-11-2020 17:00:41] [1/1] /home/exp1000/toGround/edge/img msec 1606638723330 2.ims rgb (7.6 MB)...
[29-11-2020 17:00:41]
[29-11-2020 17:00:41] Done: 7.6 MB compressed to 0.8 MB (ratio 9.9437) in 0.8 seconds (9.3 MB/s)
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                                                         806.2K Nov 29 17:00 img msec 1606601765418 2.fapec
                                               root
[29-11-2020 17:00:41] -rw-r--r--
                                                         782.2K Nov 29 17:00 img msec 1606638723330 2.fapec
                                   1 root
                                               root
```

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Image and RF compression for OPS-SAT with FAPEC

FAPEC in OPS-SAT

- **OPS-SAT Experiment #100** Ξ
 - In-flight tests of the FAPEC data compression software $\langle \cdot \rangle$
- NMF integration Ξ
 - JNI wrapper of FAPEC \vdots
 - Load binary library (.so) from Java, invoke camera acquisition methods, invoke FAPEC, store results \vdots



Nanosat Mission operations Framework

= NMF front-end: List of FAPEC tests executed

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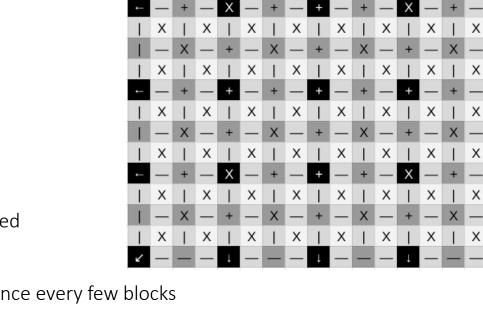
Improvements in the CILLIC algorithm

= Larger blocks: 17 x 17 pixels

- More SIMD friendly
- Thumbnails: 1/289th resolution

= Different pixel types

- 9 x 9 "lattice" pixels (types 1 and 2)
- 208 internal pixels
- = Spatial and spectral decorrelators
 - Interpolation and inter-block estimators
 - Simplistic inter-band decorrelator, for speed
- = Multi-band adaptiveness:
 - Determine best inter-band decorrelator once every few blocks
- Near-lossless and lossy options:
 - Revised approach to achieve higher ratios and better quality
- Flat blocks:
 - Smaller variations than quantization step
- = Misalignment / motion estimation:
 - Brute force for now, to be vastly optimized. Hill Climbing algorithm?



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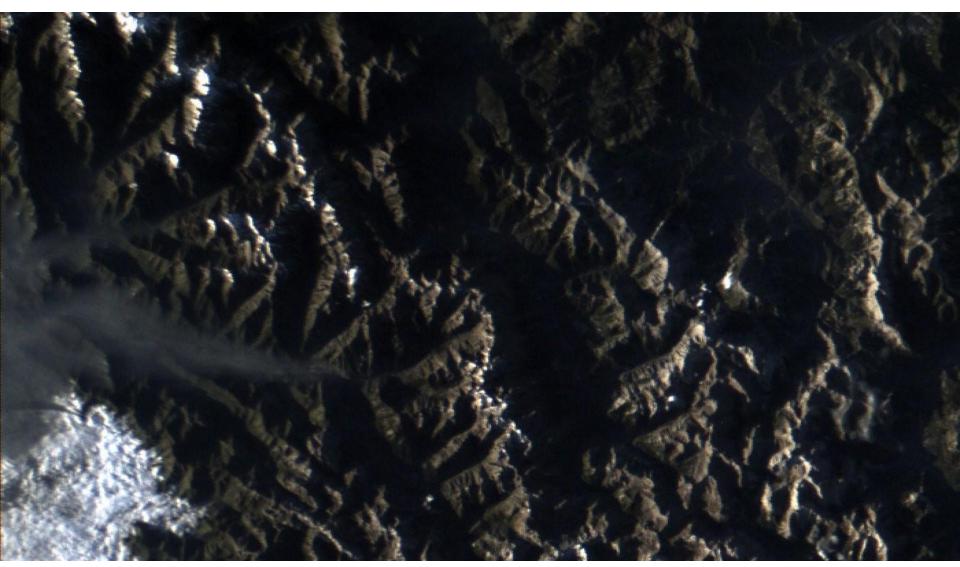
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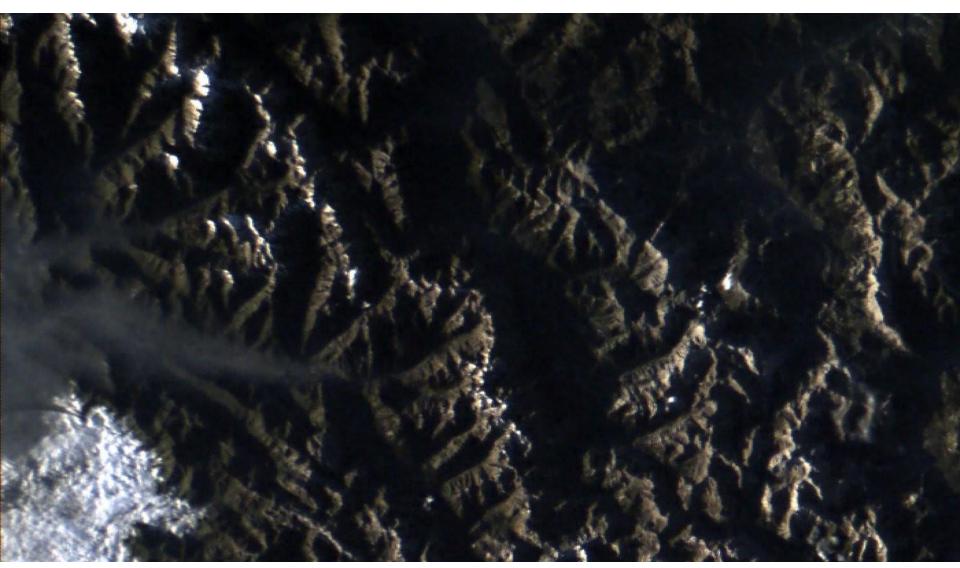
CILLIC tests

= Lossless: ratio 2.0 (small zoom-in: 1400 x 800 pixels, debayered with ImageJ)



CILLIC tests

■ Near-lossless level 12: ratio 14, PSNR 41 dB

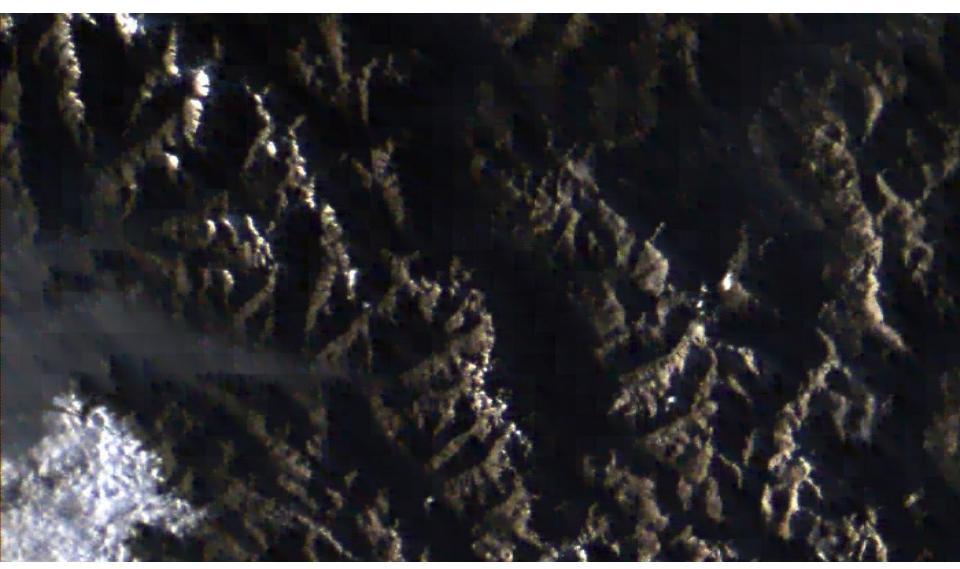


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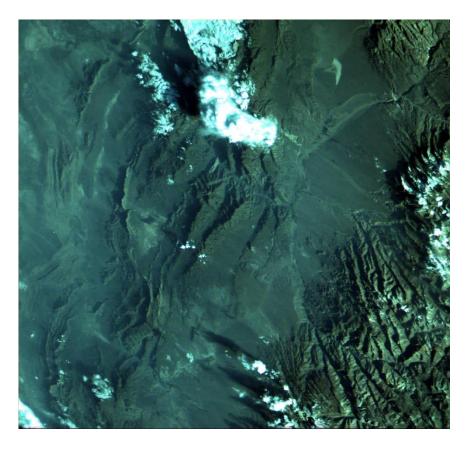
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CILLIC tests

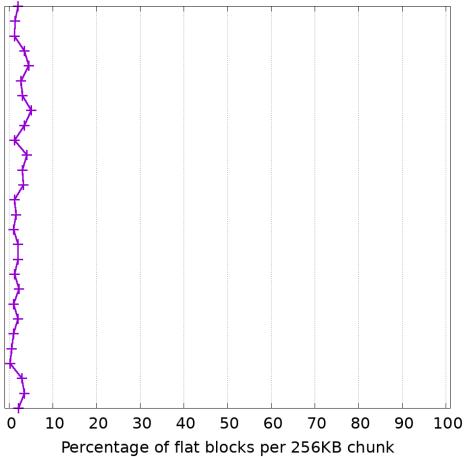
■ Near-lossless level 16: ratio 42, PSNR 34 dB



Basic data analysis with CILLIC



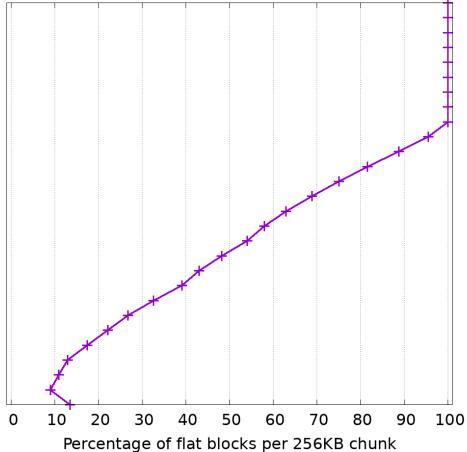
Flat blocks per chunk, 1606687802350 (total: 2.3%)



Basic data analysis with CILLIC



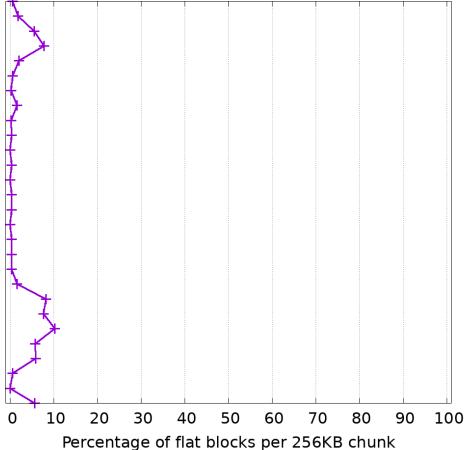
Flat blocks per chunk, 1606638723330 (total: 61.2%)



Basic data analysis with CILLIC



Flat blocks per chunk, 1654059402403 (total: 2.6%)



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Motion estimation from CILLICv2: Tractor, moving left, frame 0 to 1

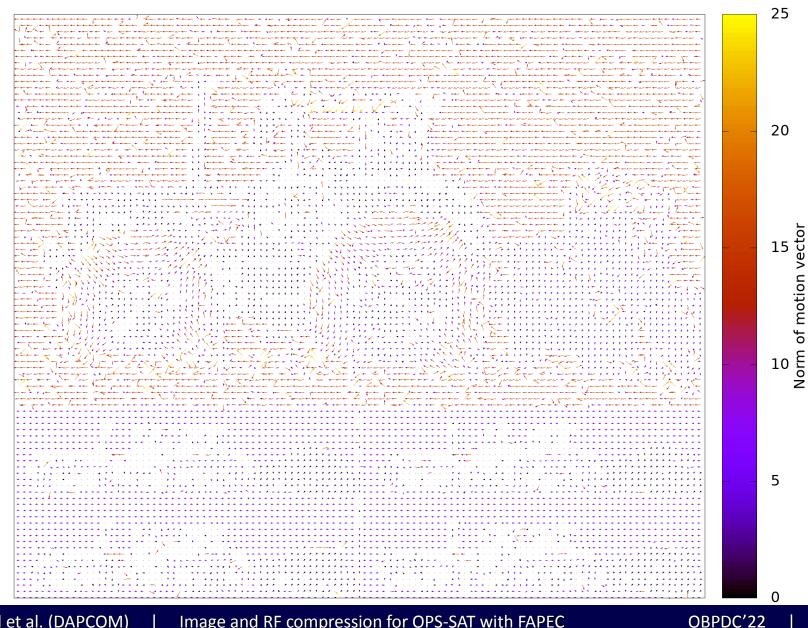


Image and RF compression for OPS-SAT with FAPEC

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Motion estimation from CILLICv2: Tractor, zoom out, frame 0 to 1

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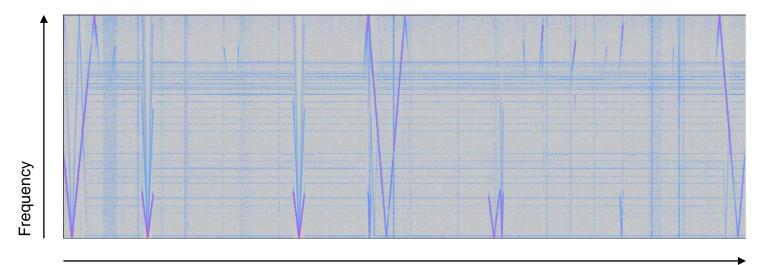
Improvements in the Wave algorithm

≡ Same approach as in first version

- Linear Predictive Coding (LPC) + Levinson-Durbin recursion for coefficients determination
- Excellent compromise between ratios and speed
- Up to 32K channels, periods of up to 8M samples, lossless + near-lossless options
- Minor improvements in lossless operation
 - Higher LPC order: Up to 16
 - Adaptive LPC order for each period of samples
- Remarkably: "smart lossy" algorithm
 - Detect presence of signals in the RF data files
 - Automatically set the loss level for each period
 - Simplistic (fast) option using information from Levinson-Durbin recursion, then adjusting loss level (LPC residuals quantization) according to estimated signal/noise levels
 - Rigorous (slow) approach:
 Welch method + Akaike Information Criterion, to estimate noise power;
 Neyman-Pearson detector with different probability levels of false alarm, for signal detection

Wave: smart lossy algorithm

- Spectrogram of a radio-frequency data file from the OPS-SAT SDR receiver
 - Some signals can be seen, including a strong Doppler effect
 - Perhaps "nearby" satellites?



Time

Wave: smart lossy algorithm

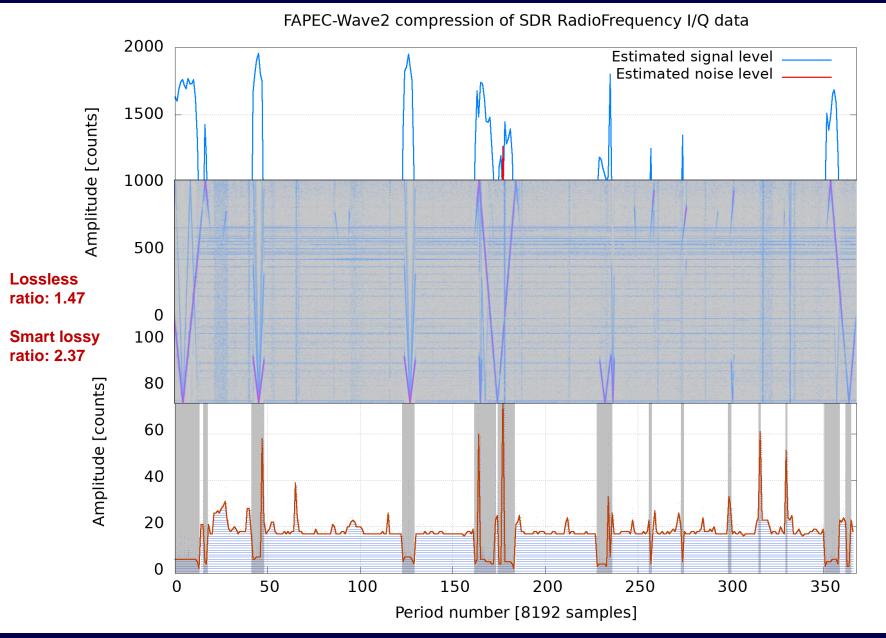
FAPEC-Wave2 compression of SDR RadioFrequency I/Q data 2000 Estimated signal level Estimated noise level 1500 Amplitude [counts] 1000 500 0 100 Signal detection SmartLossy divisor 80 Amplitude [counts] 60 40 20 0 0 50 100 150 200 250 300 350

Period number [8192 samples]

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Wave: smart lossy algorithm



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Image and RF compression for OPS-SAT with FAPEC

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Additional tests with Wave: GNSS signals

- One of the challenges is **GNSS data compression**
 - Spread spectrum \rightarrow signal looks like noise \rightarrow may not be detected by our "smart lossy" algorithms
 - © Can we compress SDR data files with GNSS signals with losses?
- = Preliminary evaluation of GNSS signal detection with **GNSS-SDR** software
 - Quite difficult (very complete!) software package, specially regarding its configuration
 - Some tests on OPS-SAT SDR data files:
 GPS signals detected, but not really conclusive (perhaps problematic due to high Doppler?)



- Took other (ground-based) SDR data files with the same format:
 Galileo signals persistently detected
- Tested FAPEC-Wave with near-lossless compression:
 Lossless → ratio 1.8
 Near-lossless with quite high loss → ratio 7, Galileo signals still consistently detected!
- → We can configure the smart-lossy approach in a conservative manner to ensure usability of GNSS signals while still achieving high ratios

Conclusions

■ OPS-SAT:

- Unique in-orbit laboratory
- © Colour camera, SDR receiver, high-performance ARM processor, Linux, Java/NMF...

≡ FAPEC:

- · Versatility, portability, ease of use and high performance: confirmed once more with OPS-SAT
- Compressing OPS-SAT images seamlessly since 2020
- Java-based NMF tests
- Excellent option for small satellites (specially cubesats)

= CILLIC:

- Significant improvements in lossy compression (quality, high ratios)
- Good progress towards video compression
- Fast detection of "flat blocks" (or "Regions Of non-Interest")

■ Wave:

- Nearly optimum solution for radio-frequency data compression
- Lossless + near-lossless + "smart lossy"
- Estimation of noise and signal levels and/or signal detection

Conclusions

On-board data analysis capabilities

- Identification of (portions of) image and RF data files with useful/useless information
- Optimization of downlink (beyond compression): avoid unnecessary downloads

ightarrow Continuous optical/RF monitoring, download of just interesting files

- = Forthcoming work:
 - Improve spectral decorrelator of CILLIC: usage of inter-band shifts found identification and correction of sub-pixel artefacts
 - Optimize motion estimator of CILLIC conclude video compression support
 - ☺ Fine tune "smart lossy" options of Wave











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On-Board Payload Data Compression workshop VIII