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

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OPS-SAT: an in-orbit laboratory

Photo: Lunghammer - TU Graz

- 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…

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
  - Up to 5 frames/s → 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
- Currently being used in several earth observation satellites
- Free evaluation licenses: www.dapcom.es/get-fapec

FAPEC
22.0 Merganser

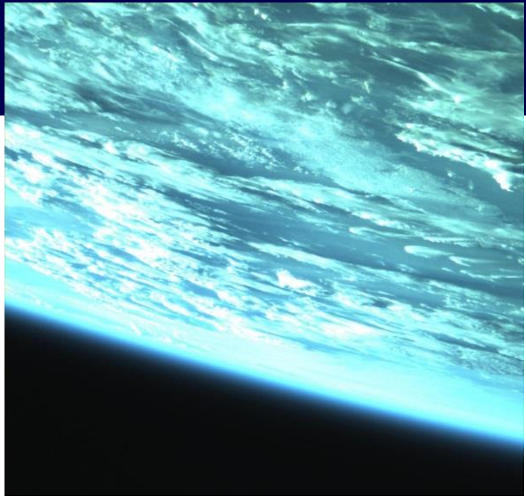
Motivation of this work

- **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
- Cubesats (and "New Space" in general):
  - Typically Linux-based software solutions
  - Agile developments → 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

```
[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...
[29-11-2020 17:00:41]  [1/1] /home/exp1000/toGround/edge/img_msec_1606601765418_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 9.6467) in 0.8 seconds (9.0 MB/s)
[29-11-2020 17:00:41]
[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]
[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)
[29-11-2020 17:00:41] /home/exp100/toGround:
[29-11-2020 17:00:41] -rw-r--r--    1 root     root       806.2K Nov 29 17:00 img_msec_1606601765418_2.fapec
[29-11-2020 17:00:41] -rw-r--r--    1 root     root       782.2K Nov 29 17:00 img_msec_1606638723330_2.fapec
```
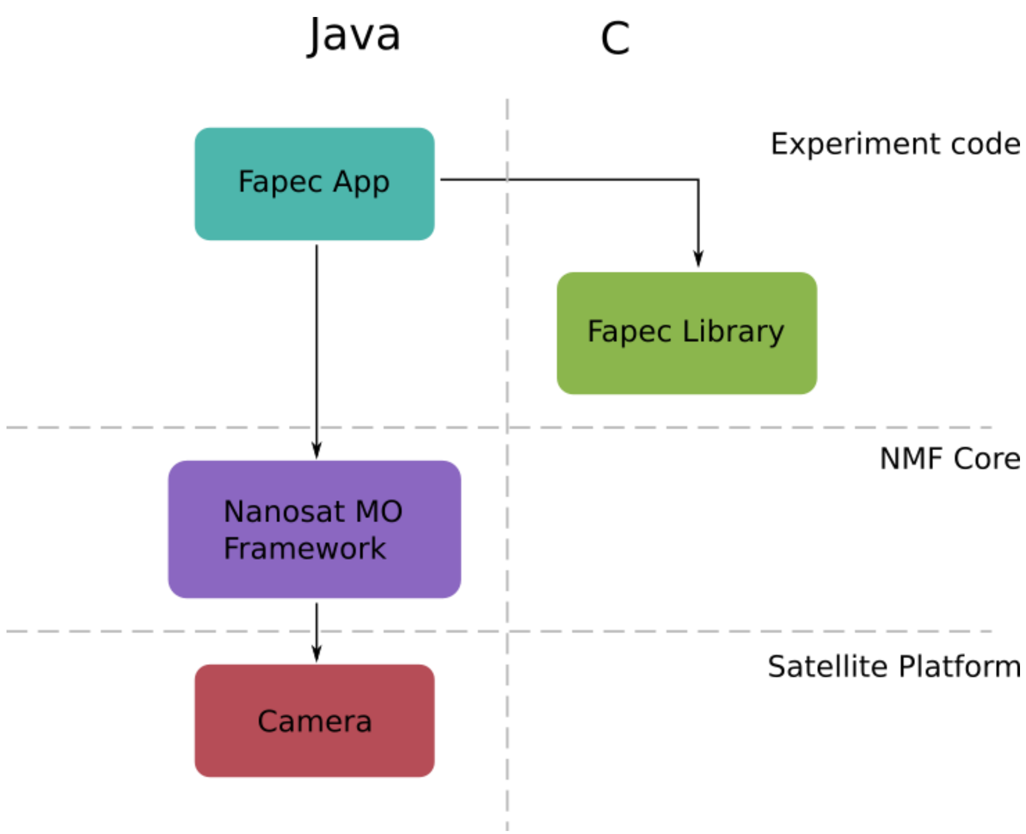
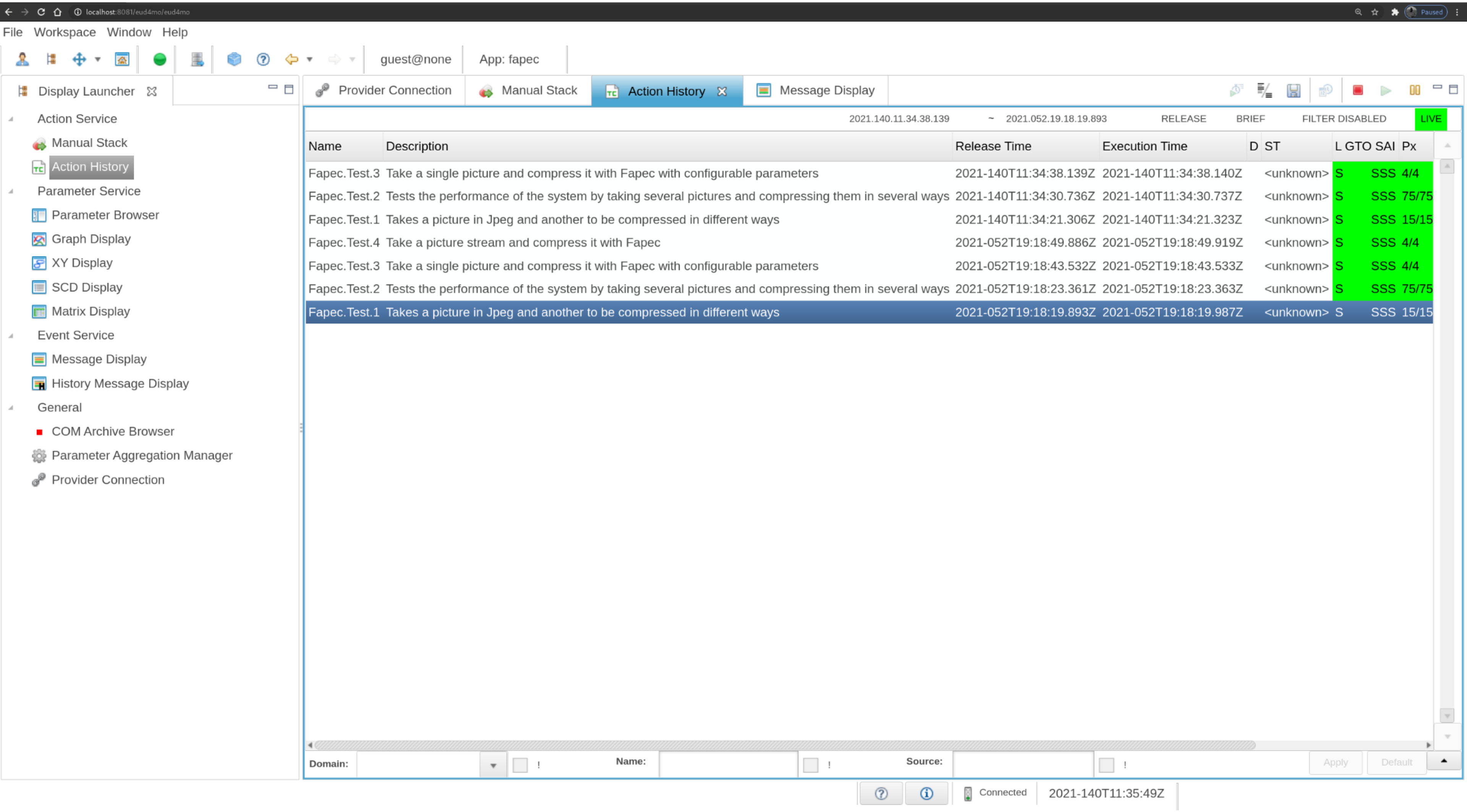

FAPEC in OPS-SAT

- OPS-SAT Experiment #100
  - *In-flight tests of the FAPEC data compression software*
- NMF integration
  - JNI wrapper of FAPEC
  - Load binary library (.so) from Java, invoke camera acquisition methods, invoke FAPEC, store results
  - Several test designs and test cases:
    HPA and CILLIC algorithms,
    comparison with JPEG,
    different quality levels,
    video acquisition…

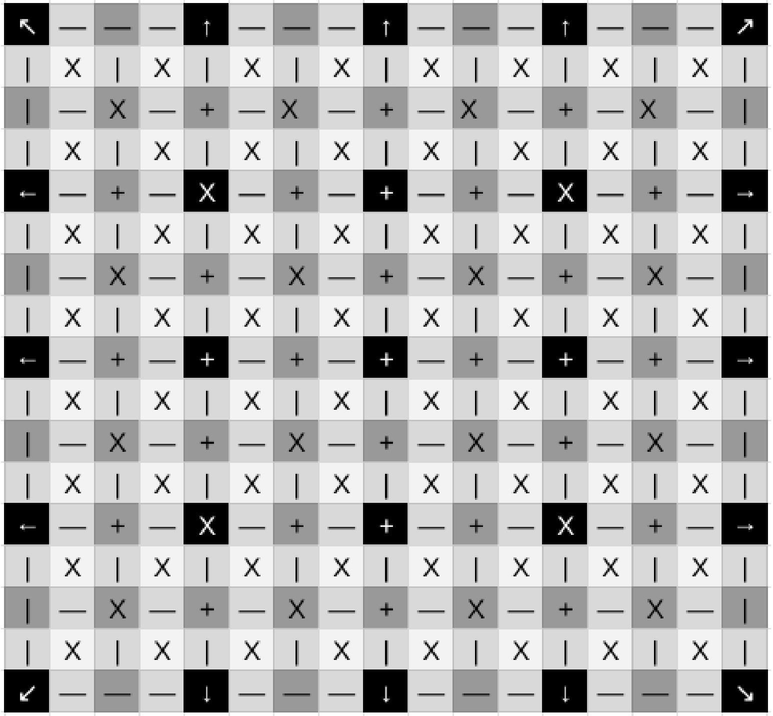


Nanosat Mission operations Framework

- NMF front-end: List of FAPEC tests executed



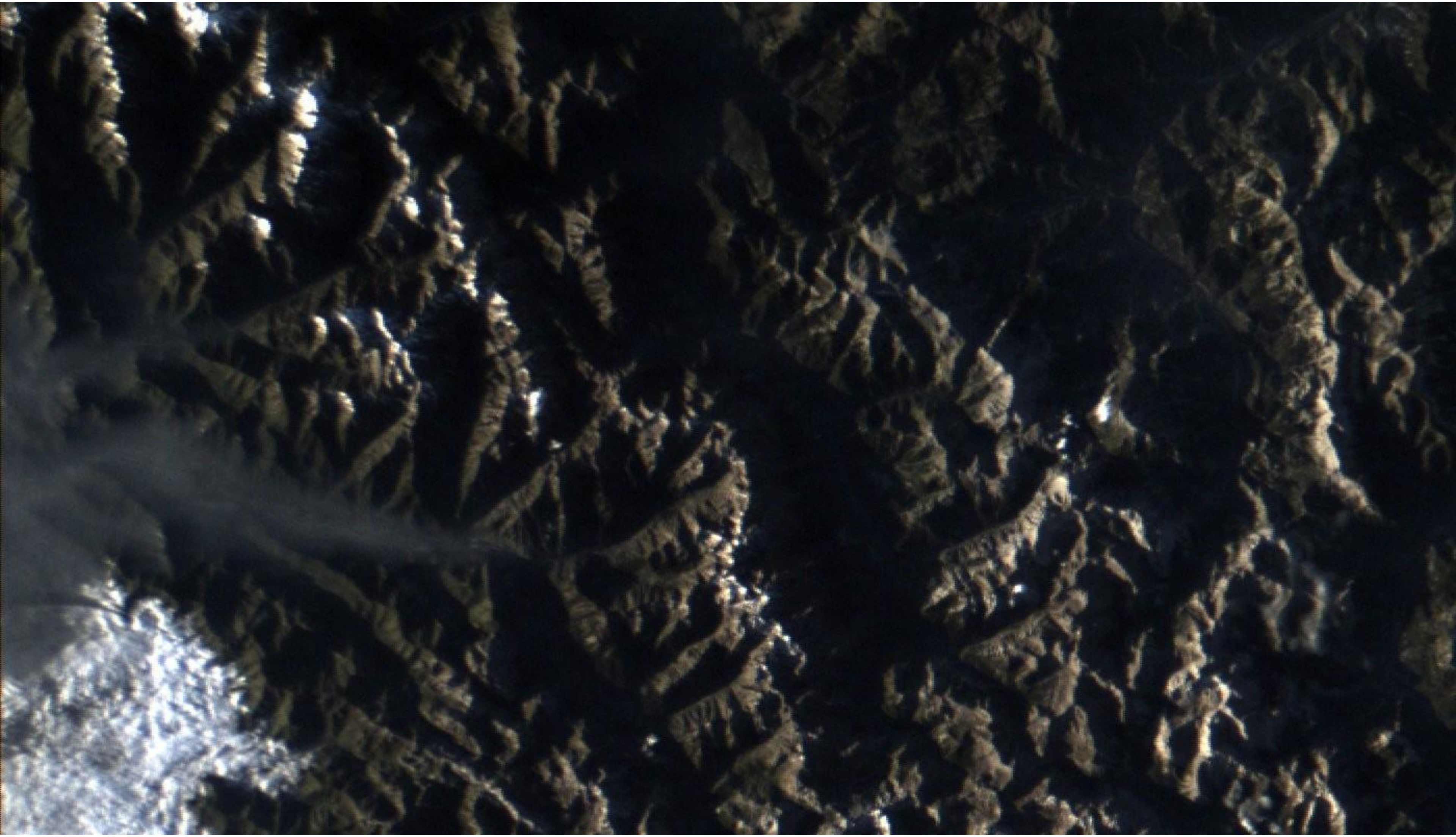
Improvements in the CILLIC algorithm



- 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?

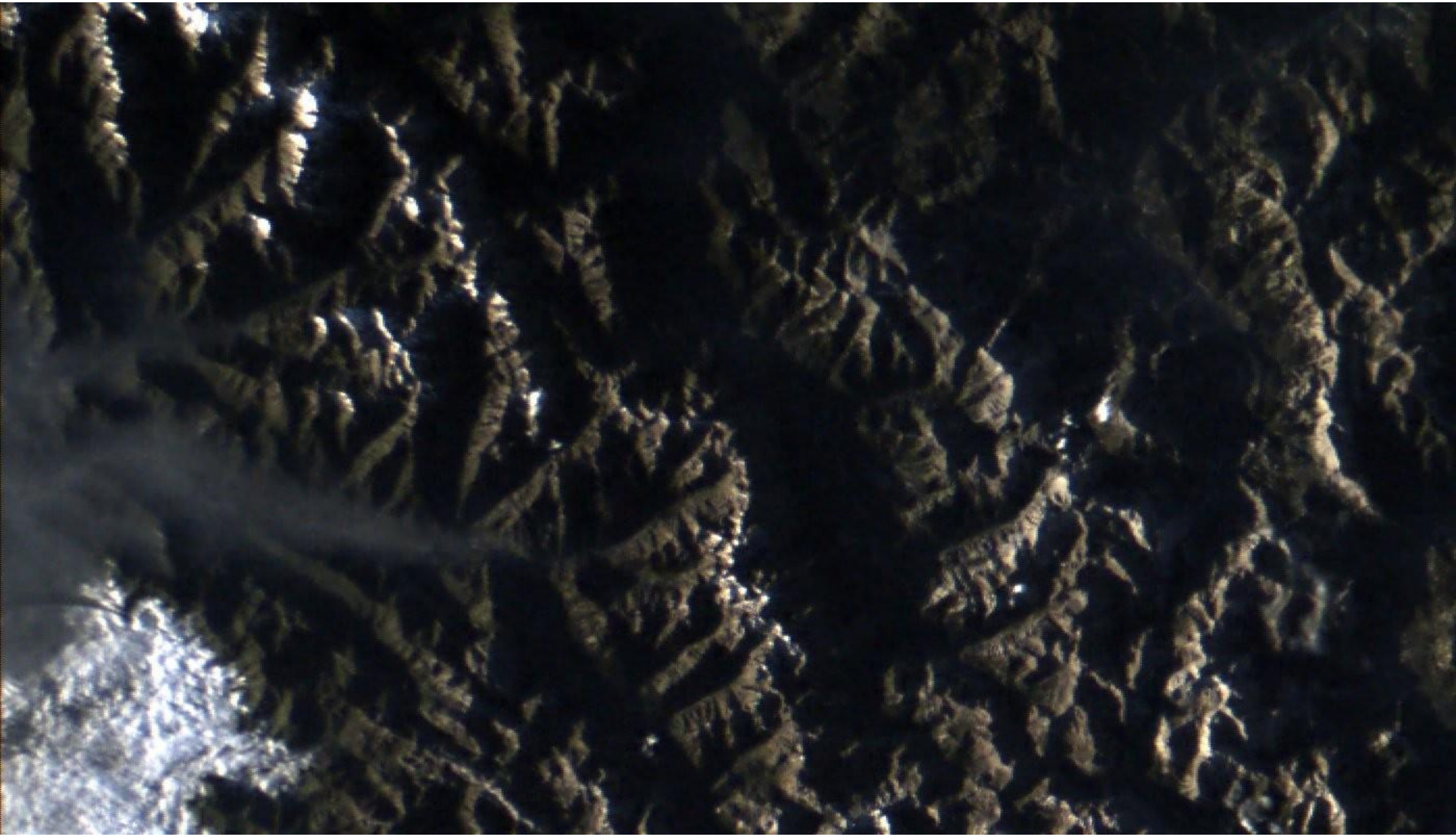
CILLIC tests

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



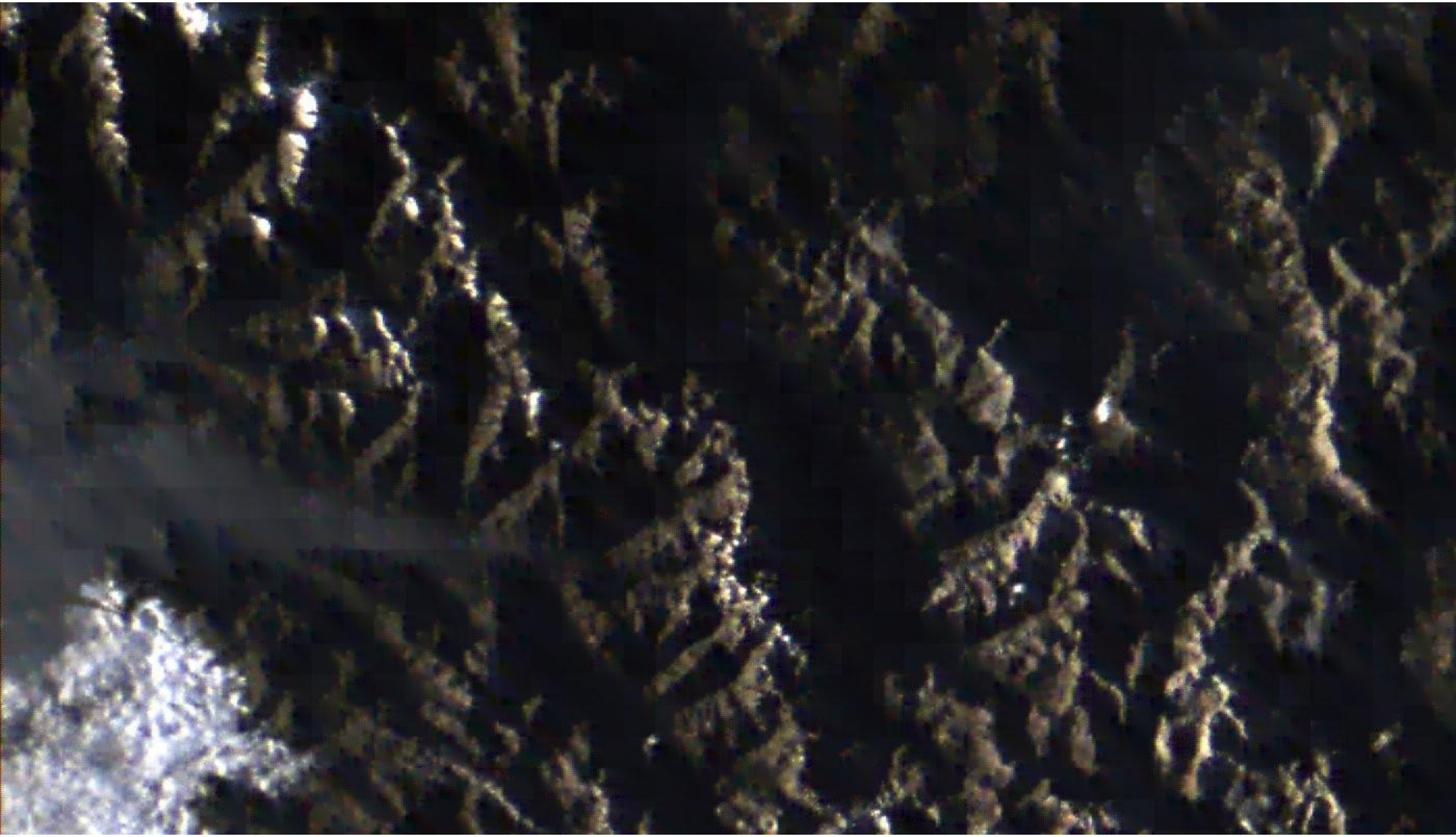
CILLIC tests

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

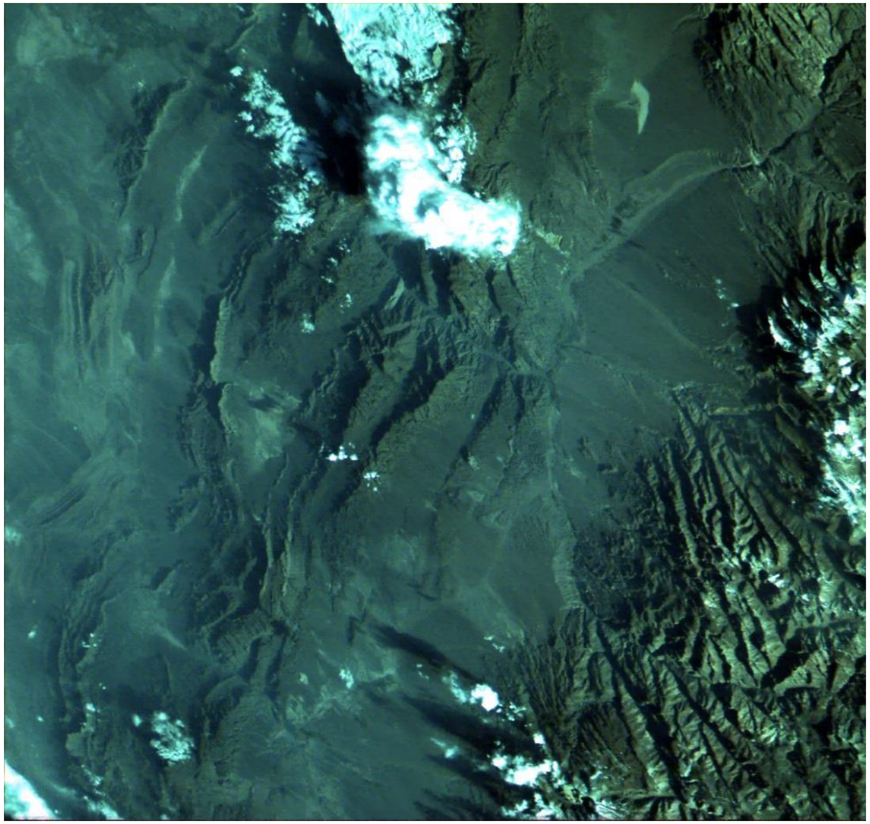


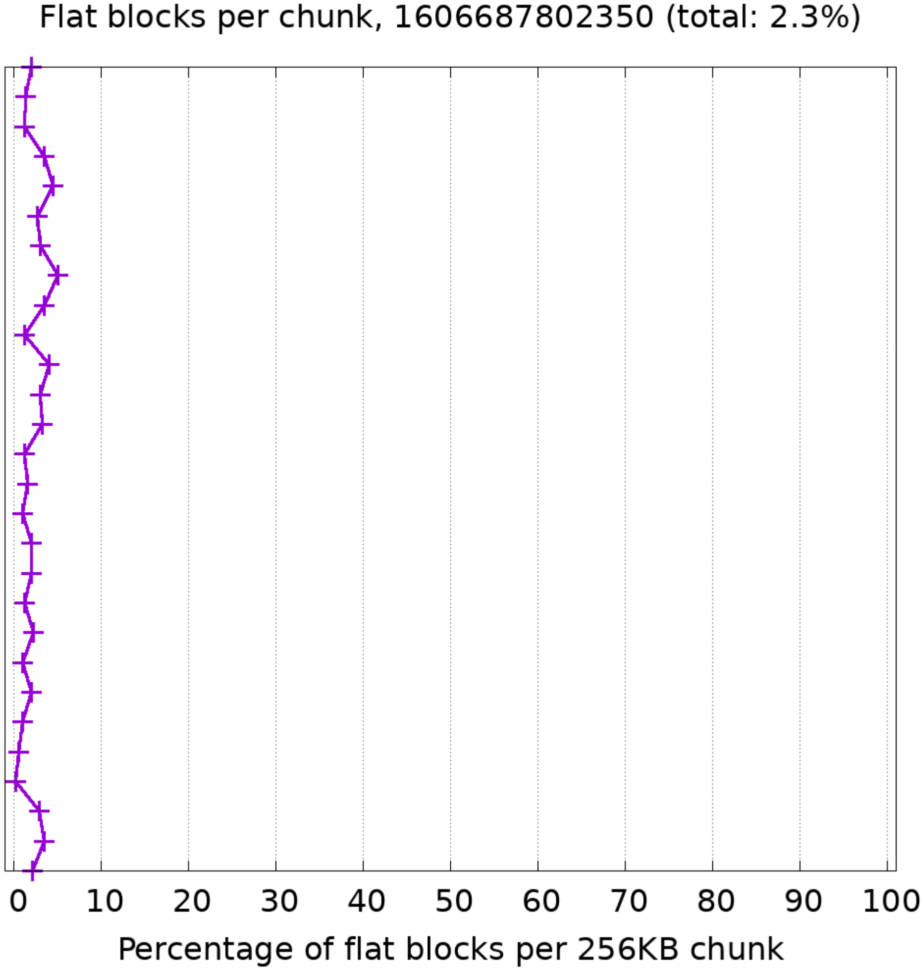
CILLIC tests

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

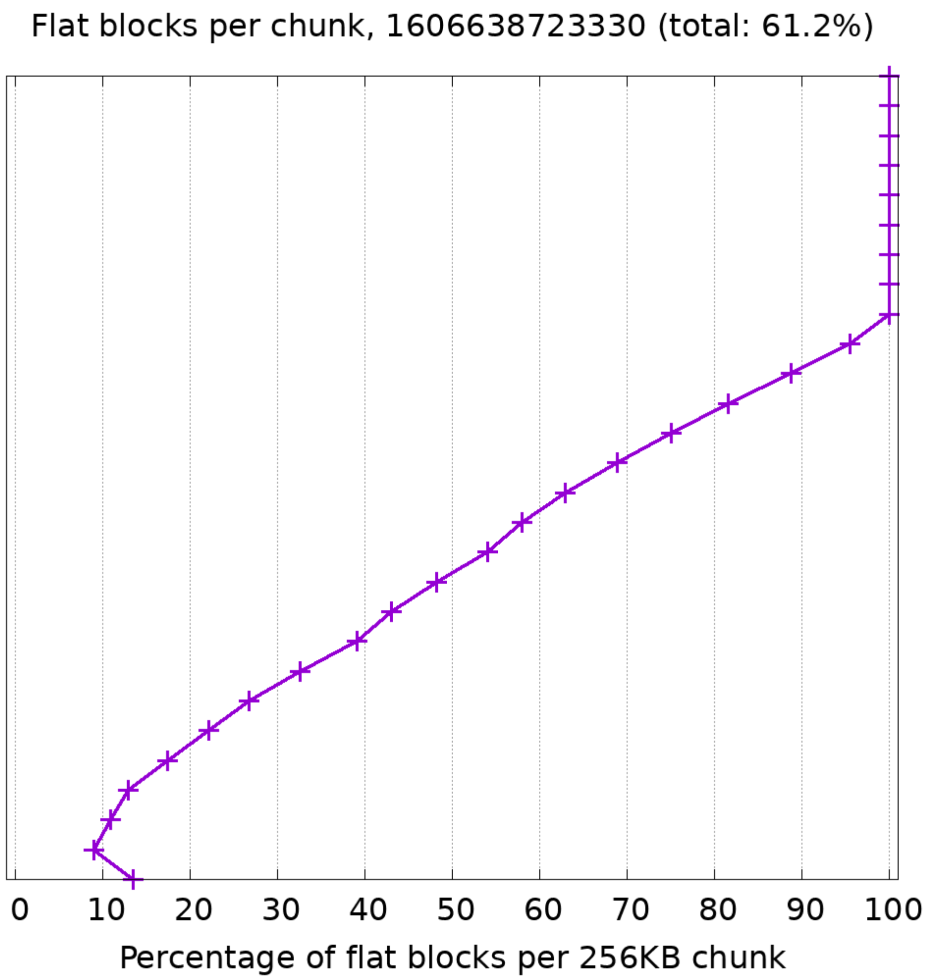


Basic data analysis with CILLIC

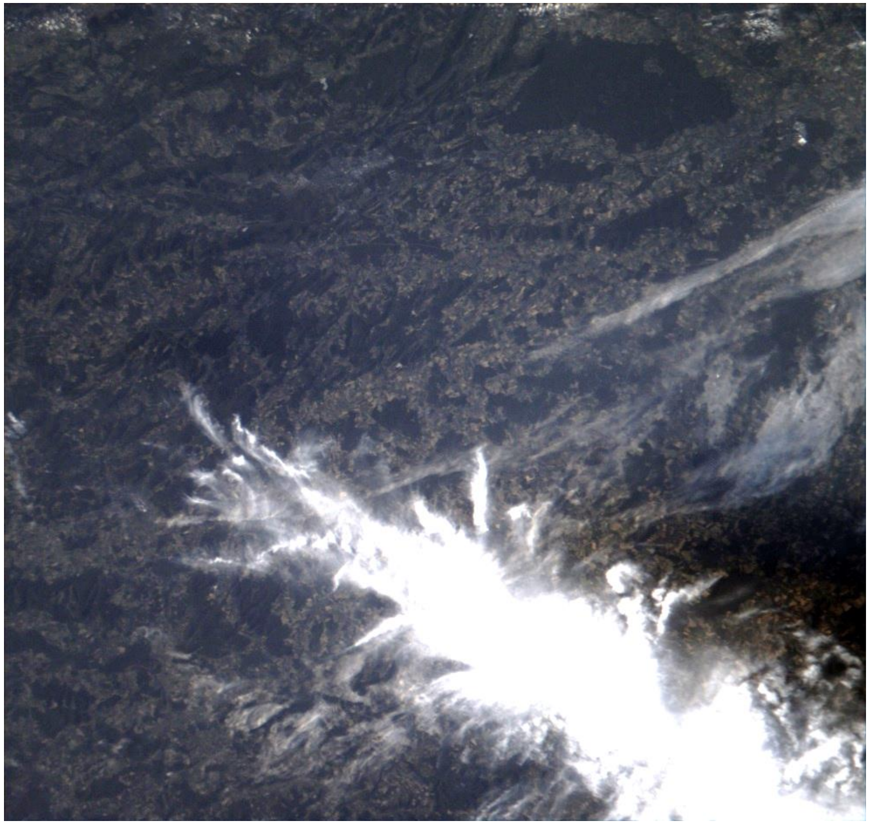


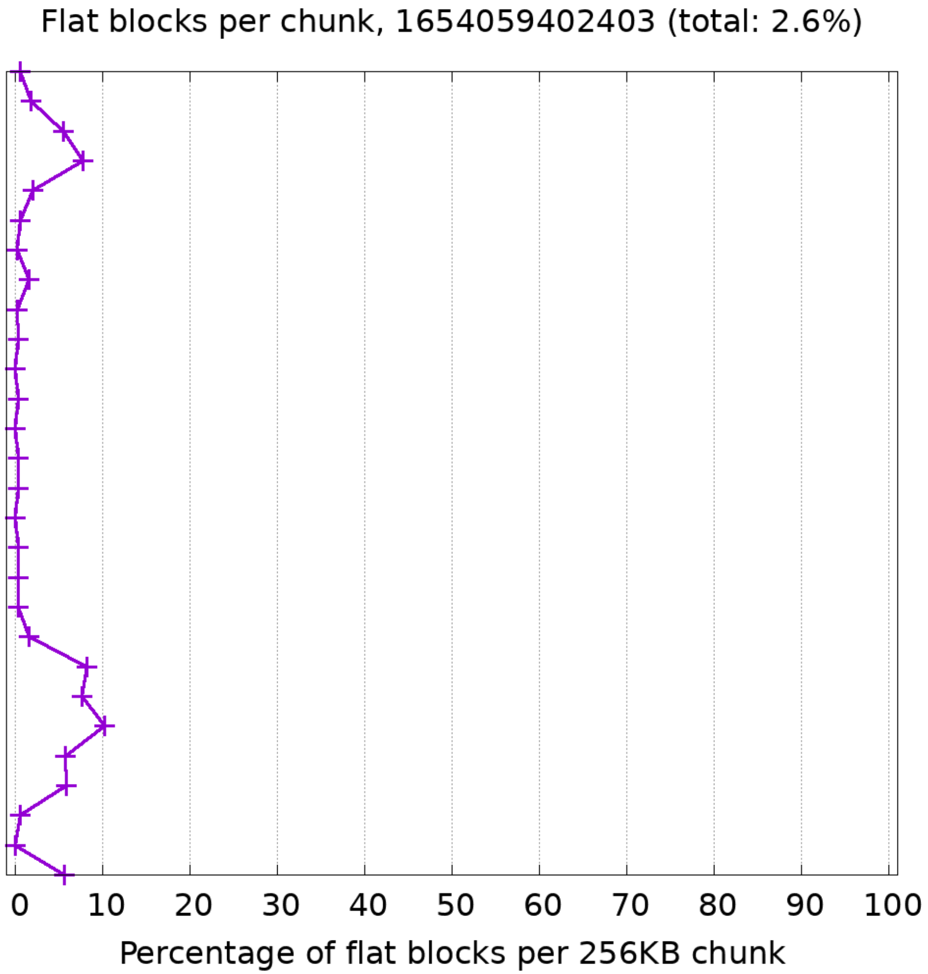


Basic data analysis with CILLIC



Basic data analysis with CILLIC





CILLIC: motion estimation

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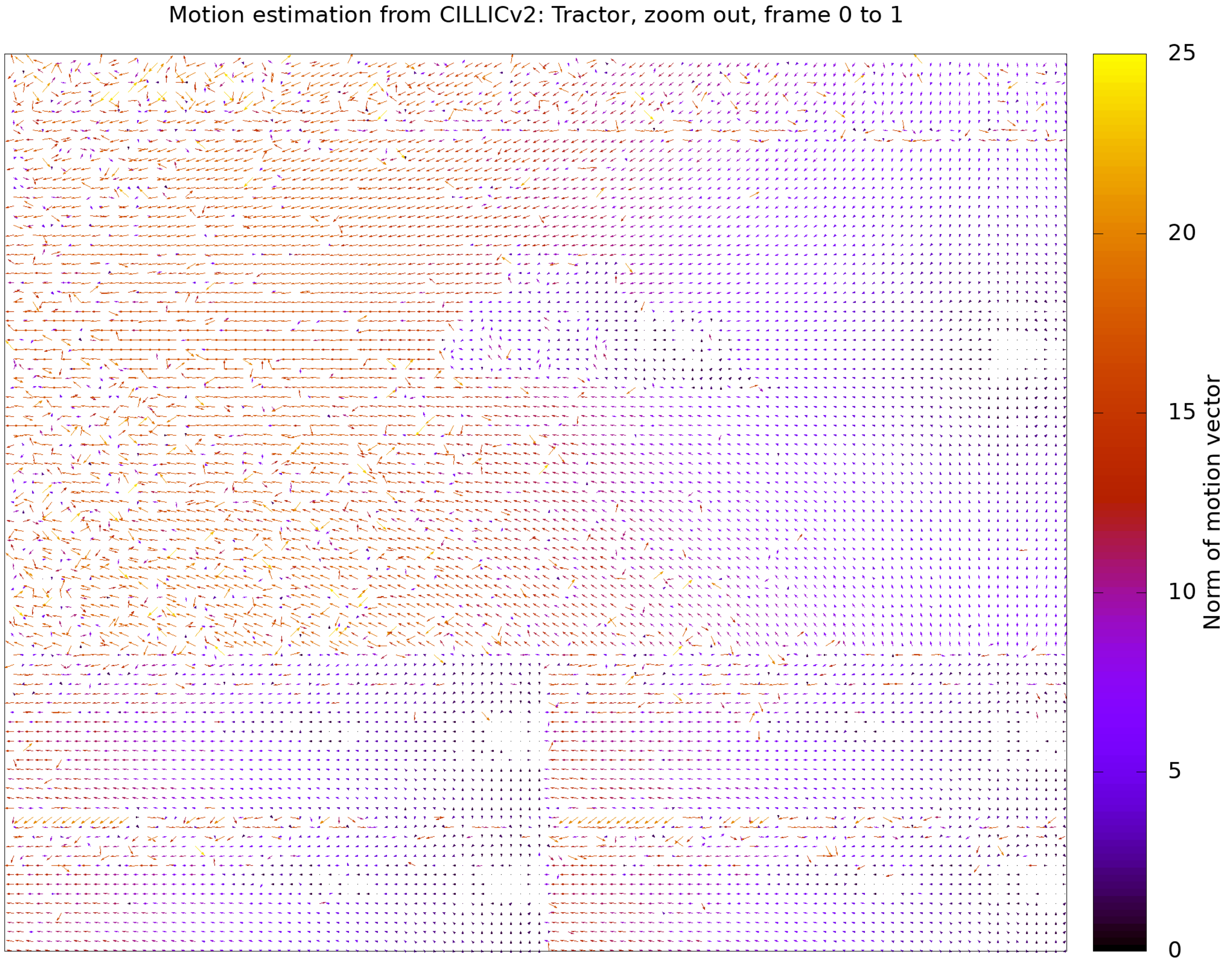
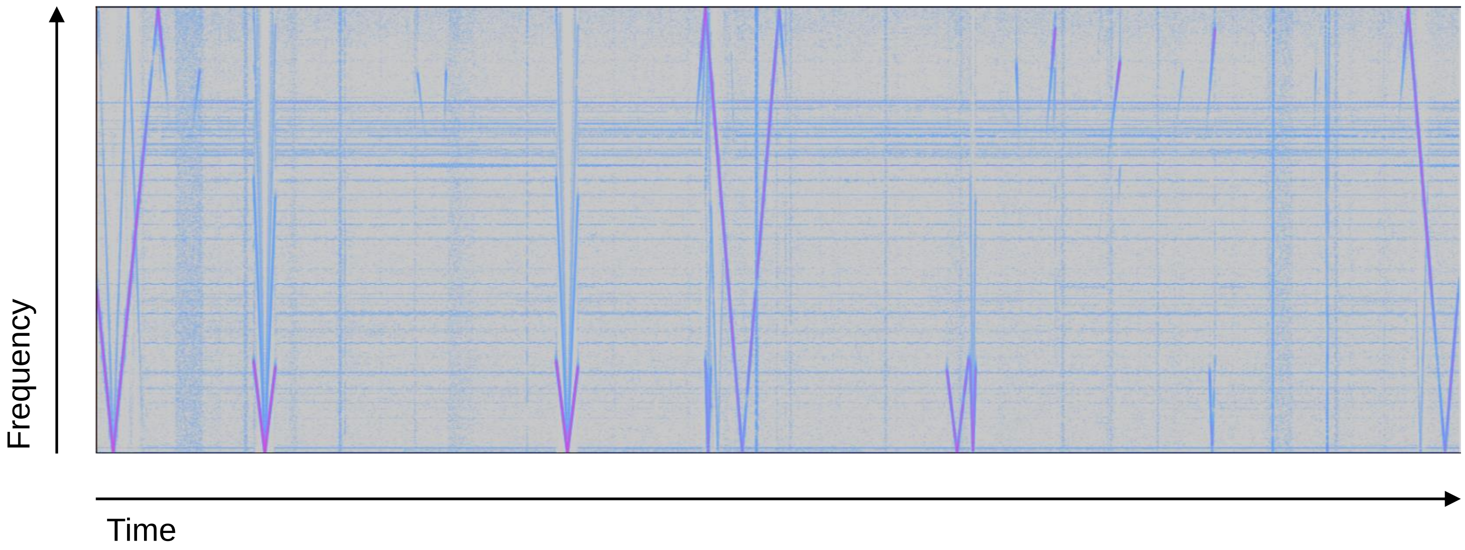


Improvements in the Wave algorithm

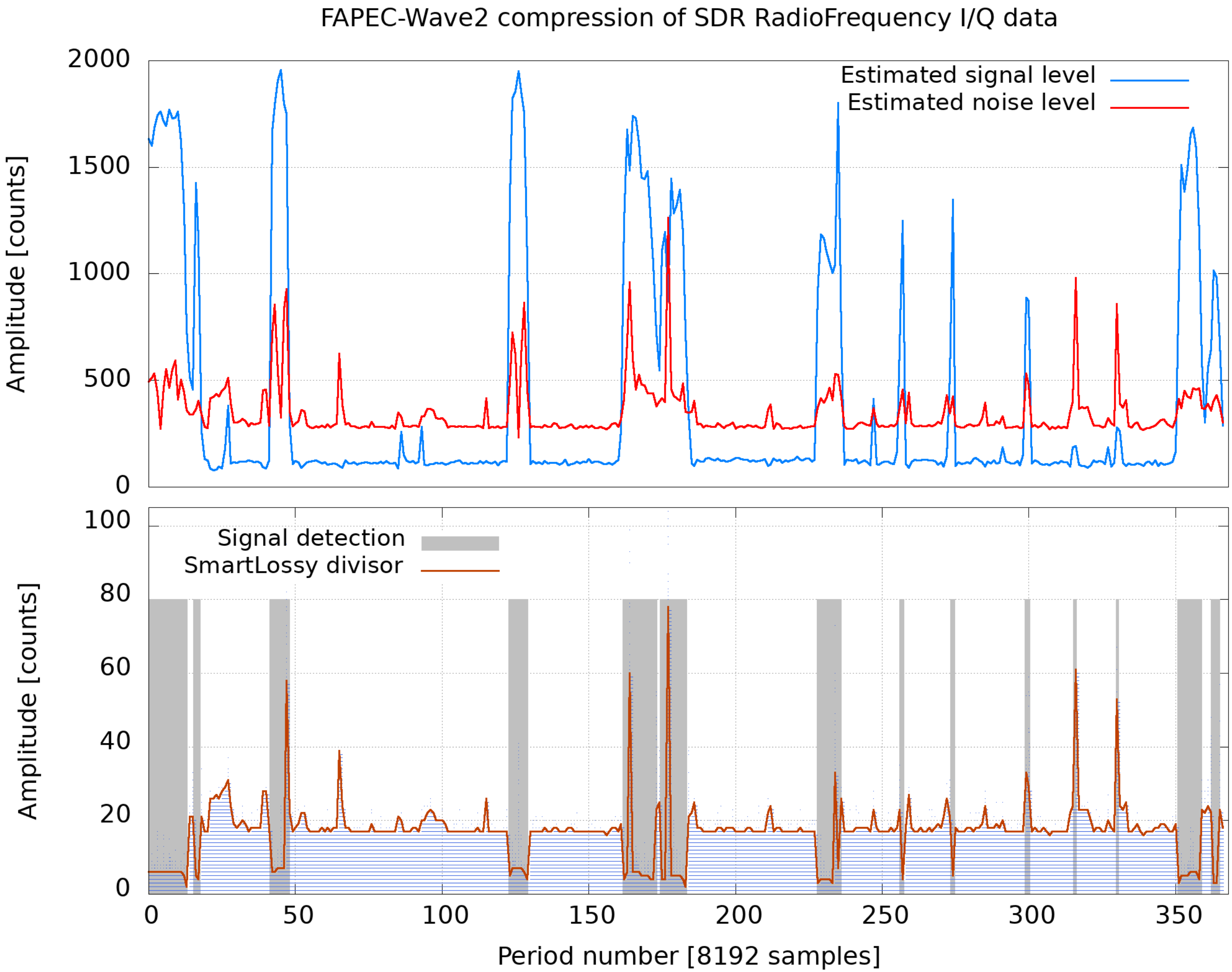
- Same approach as in first version
  - Linear Predictive Coding (LPC) + Levinson-Durbin recursion for coefficients determination
  - Excellent compromise between ratios and speed
  - Up to 32K channels, periods of up to 8M samples, lossless + near-lossless options
- Minor improvements in lossless operation
  - 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

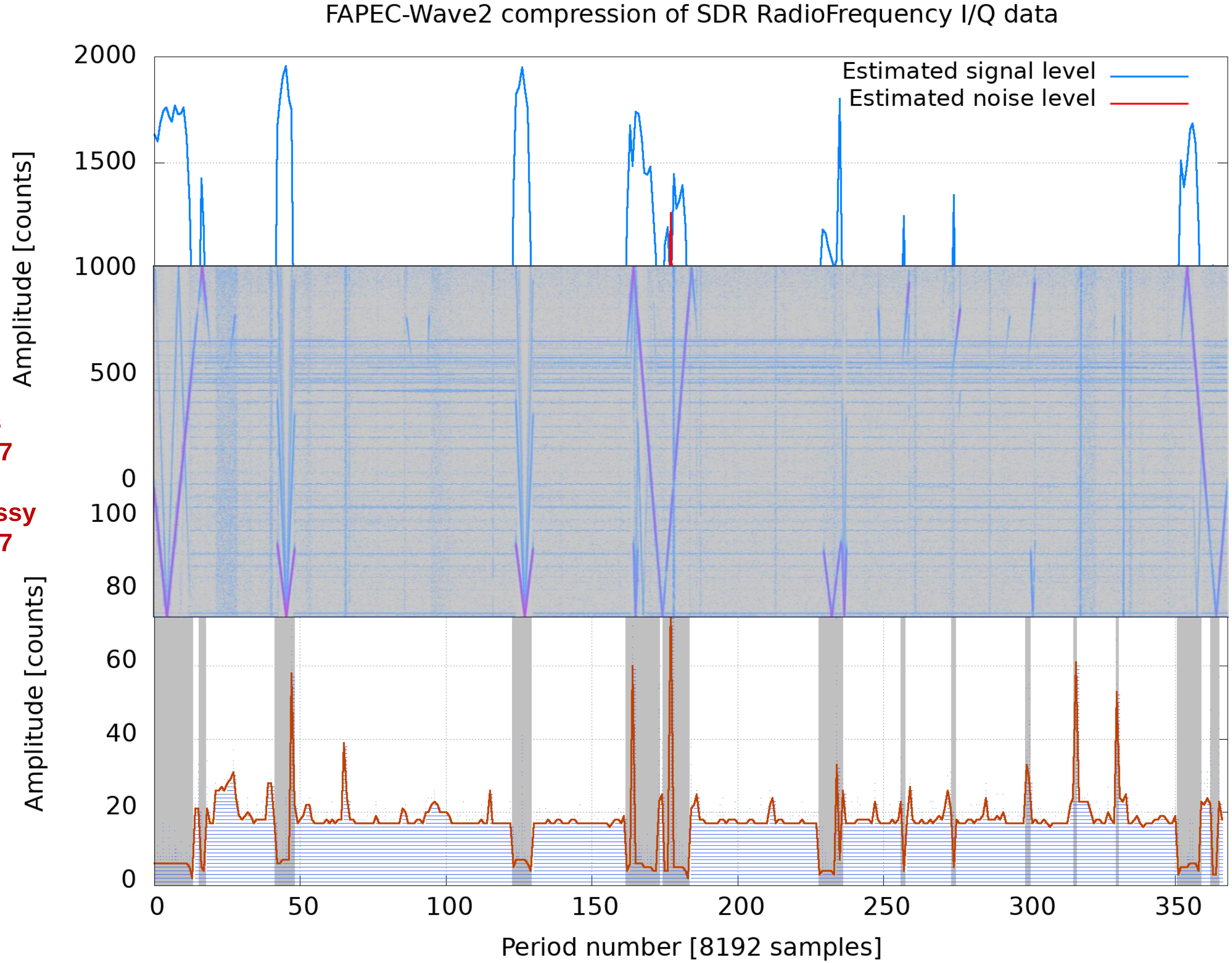
- Spectrogram of a radio-frequency data file from the OPS-SAT SDR receiver
  - Some signals can be seen, including a strong Doppler effect
  - Perhaps “nearby” satellites?



Wave: smart lossy algorithm



Wave: smart lossy algorithm



Lossless ratio: 1.47

Smart lossy ratio: 2.37

Additional tests with Wave: GNSS signals

- One of the challenges is **GNSS data compression**
  - Spread spectrum → signal looks like noise → 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

    → **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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