Enjeux et défis des techniques de compression pour les données de simulation massives

CORESA 2021

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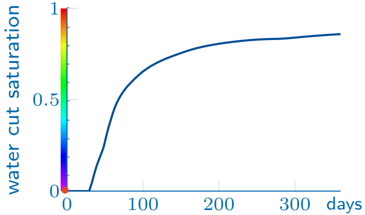
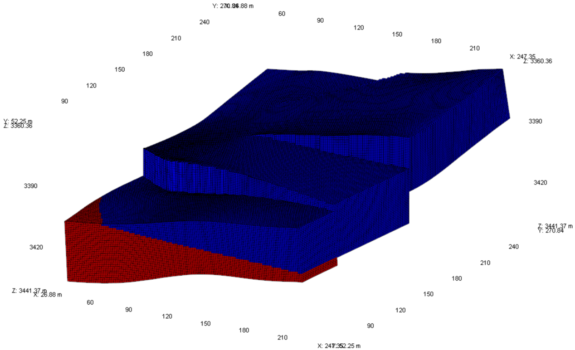
Plan



Simulation output

Compression in simulation: what for?



Flow simulation in a reservoir

On standard multimedia data

- A pervasive and transparent paradigm
  - A world of streaming and evanescent binary abstractions (Deeflix, Netzer, SpotS, OCify)
- Three most common types of objects
  - Audio (essentially 1D)
  - Image (essentially 2D)
  - Video (essentially 2D+1D)
- Mostly meant for (human) interpretation
  - Knowledge of the human sensory system
  - Wide audience for testing ("all users")
  - Little need for post-processing*
- Reasonably well-structured data
  - Audio: even sampling
  - Image: cartesian pixel grid (mostly)
  - Video: audio+image at regular frame rates (24/25 fps)

On data-intensive scientific discovery

- So-called "fourth paradigm" (Hey, Tolle, Tansley, 2009)
  - Three different ones: empirical, theoretical, computational science (no drama)
- Tentative layers of "scientific data" object abstraction:
  - Instrumental (sensors, recording devices, IoT)
  - Computational (modeling, simulation, avatar, metaverse)
  - Inferential (statistical model, data science, machine/deep learning)
- Mostly meant for (reality) understanding
  - Often outside human sight range
  - Sharing in relatively small scientific communities
  - Important postprocessing or workflows for further data exploitation
- Unreasonably ill-structured data
  - Many in-house or ad-hoc storage structures (e.g. HDF, CDF)
  - Not sufficiently used for *imposing* pervasive "formats" (nor well documented)
    - *"The nice thing about standards is that you have so many to choose from; furthermore, if you do not like any of them, you can just wait for next year's model." (Attributed to A. S. Tanenbaum)*

Reminders on compression principles

- What makes sense can be shrunk: redundacy versus relevancy
  - Part is predictable (resolution)
  - Part is forgetable (precision)
- Main actions
  - Transform data to enhance the useful (cosine, wavelet, companding)
  - Discard (or reorder) information from useful to less useful
  - Encode binary streams in sensible ways
- Goals
  - Lossless, lossy
  - Quasi-lossless, lossless to lossy, progressive (in resolution or precision)
  - Efficiency, usability

On incentives for compression

- Multimedia data
  - Necessary standardization (mp3: 1991; jpeg: 1992; mpeg4: 1998*)
  - Small-to-medium size (fits on a "drive")
  - Many objective/subjective models and metrics
  - In one equation: $I - \hat{I} = i$ (integer)
- Data-intensive science
  - Storage and HPC inflation
  - Bigger size (sometimes fit on several drives*)
  - Way less objective/subjective models and metrics
  - In a second equation: $4F - \widehat{4F} = 4F$ (quadruple-precision floating-point)

Illustrations and figures

Geophysics in 2012: 2-3 months to sort (byte-swapping*)

Computations to train largest NLP models: increased 300,000 times in 6 years (April 2021)

GPT-4: 100 trillion parameters, “five hundred times" larger than GPT-3

Microscopy (TEM, SEM): 50 Tb/sample, thousands of cell slices (biology*)

CERN Large Hadron Collider: 90+25 petabytes/year (physics)

SKA (Square Kilometre Array: 300 petabytes/year in 2023

HL-LHC (High Luminosity-Large Hadron Collider): 1 exabyte in 2026

Illustrations and figures: simulation

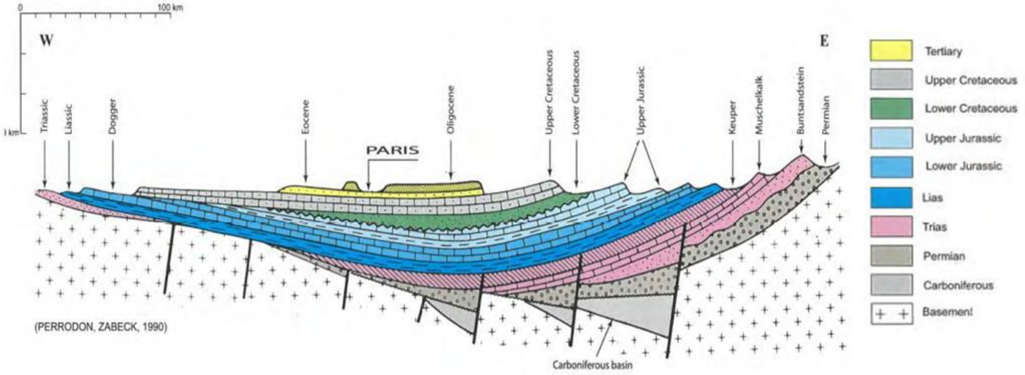
Climatology: "[Coupled Model Intercomparison Project (CIMP6)] entire project is estimated to release about 20 to 40 petabytes of data from more than 20 climate models"

Quite often, massive simulations produce

- more data than we can store*
- more quickly than we can write
- more data than they can share*
- more data than we can pay for (material, energetic, legal)

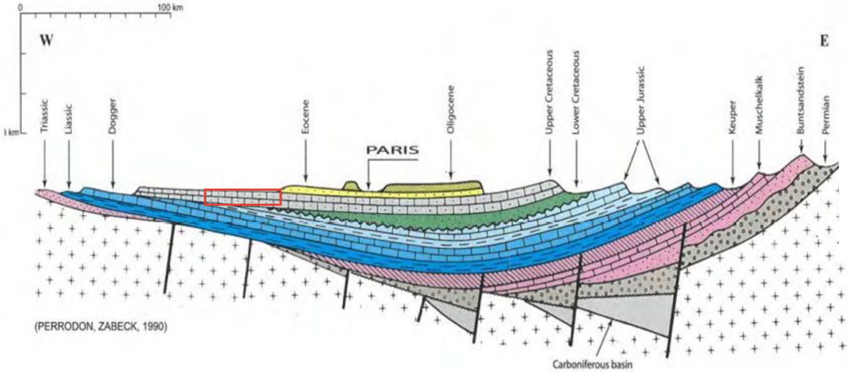
Geological data

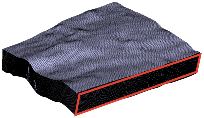
Section of sedimentary basin



Geological data

Section of sedimentary basin

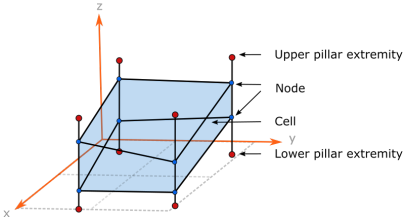


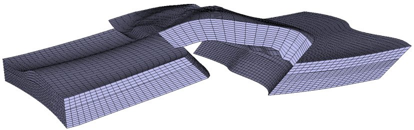


Geological data model

Structure: Corner Point Grid format (CPG)

Pillar extremities	$2D$	(x, y, z) coordinates
Node altitudes	$1D$	relative
Cell activity	$3D$	(boolean/cell)
Properties	$3D$	
Categorical (low dynamic)		(discrete-integer/cell)





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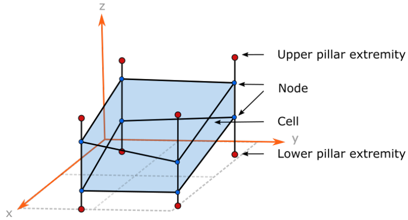

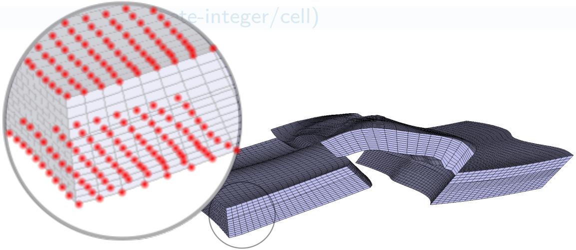

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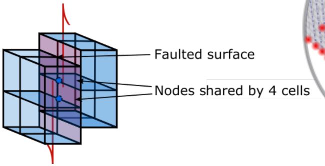

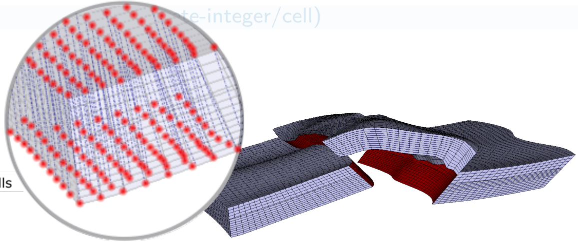

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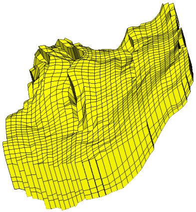

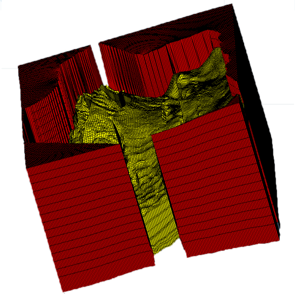

Geological data model

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Pillar extremities	$2D$	(x, y, z) coordinates
Node altitudes	$1D$	relative
Cell activity	$3D$	(boolean/cell)
Properties ($\mathbb{R}$)	$3D$	(floating-point/cell)
Categorical (low dynamic)		(discrete-integer/cell)

Geological data model

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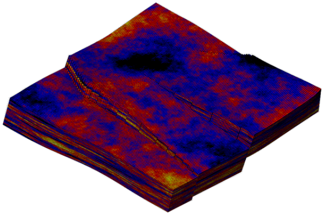
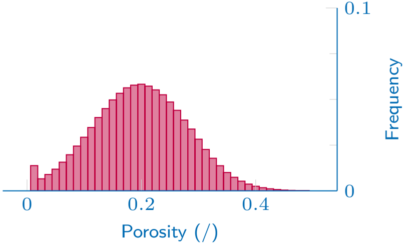
Porosity (high dynamic)		
Categorical (low dynamic)		(discrete-integer/cell)





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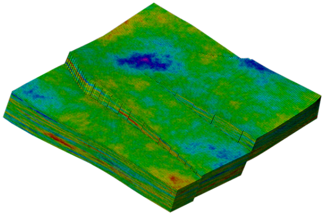
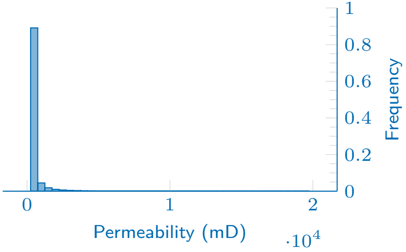
Node altitudes	$1D$	relative
Cell activity	$3D$	(boolean/cell)
Properties ($\mathbb{R}$)	$3D$	(floating-point/cell)
Permeability (high dynamic)		
Categorical (low dynamic)		(discrete-integer/cell)





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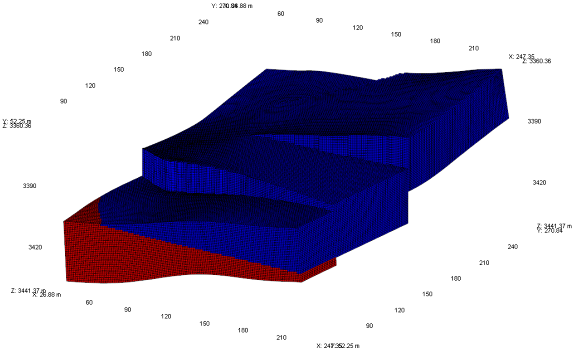
Issues, compressed

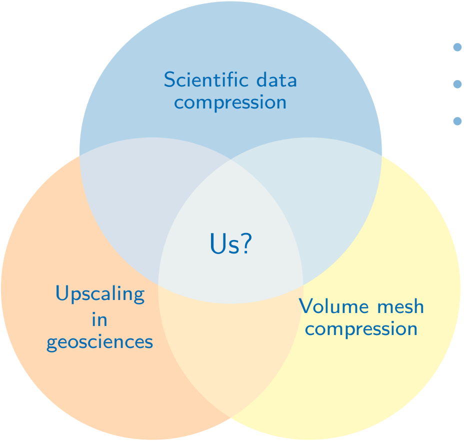


72 hours simulation on an average scientific laptop

A compact state-of-the-start (them and us)

- Cappello, 2019
- Lindstrom, 2014
- Baker, 2019

- Durlofsky, 2012
- Li, 2000
- Qi, 2009



A compact state-of-the-start (them and us)

Toward solutions

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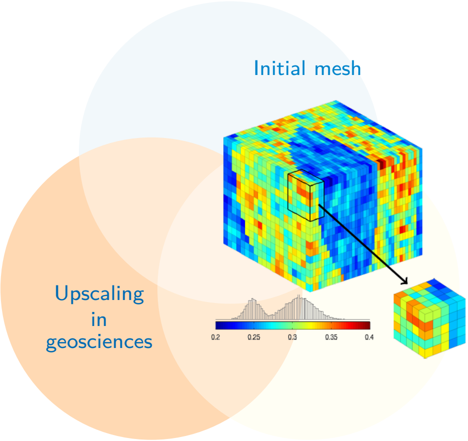

- Developed for simulation
- Not for storage

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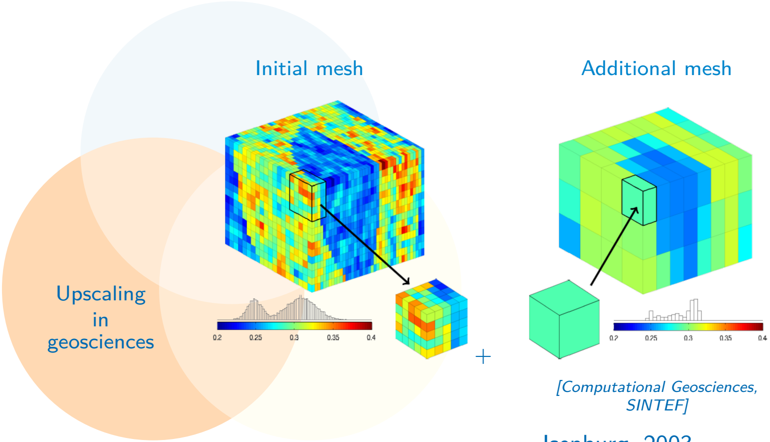

[Computational Geosciences, SINTEF]

- Isenburg, 2003
- Krivograd, 2008
- Lindstrom, 2008

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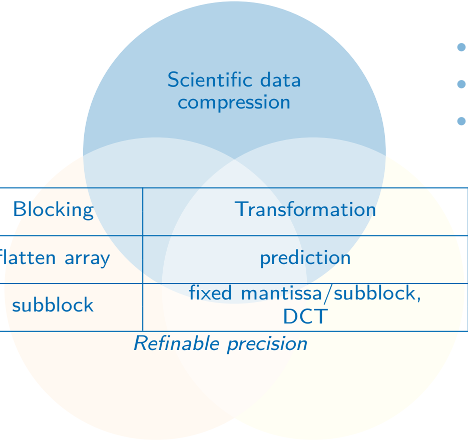

	Preprocess	Blocking	Transformation	Quantization	Encoding
SZ	float to int	flatten array	prediction	uniform	Huffman
ZFP		subblock	fixed mantissa/subblock, DCT	Zerotree	

A compact state-of-the-start (them and us)

Toward solutions

Scientific data compression

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Refinable precision

HexaShrink	float to int		Dyadic wavelet	Zerotree	

Refinable resolution & precision

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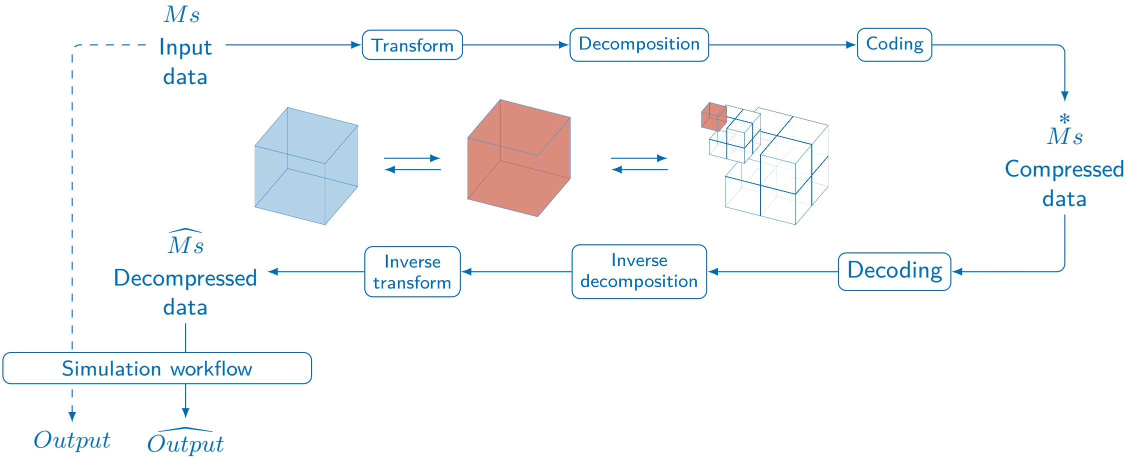
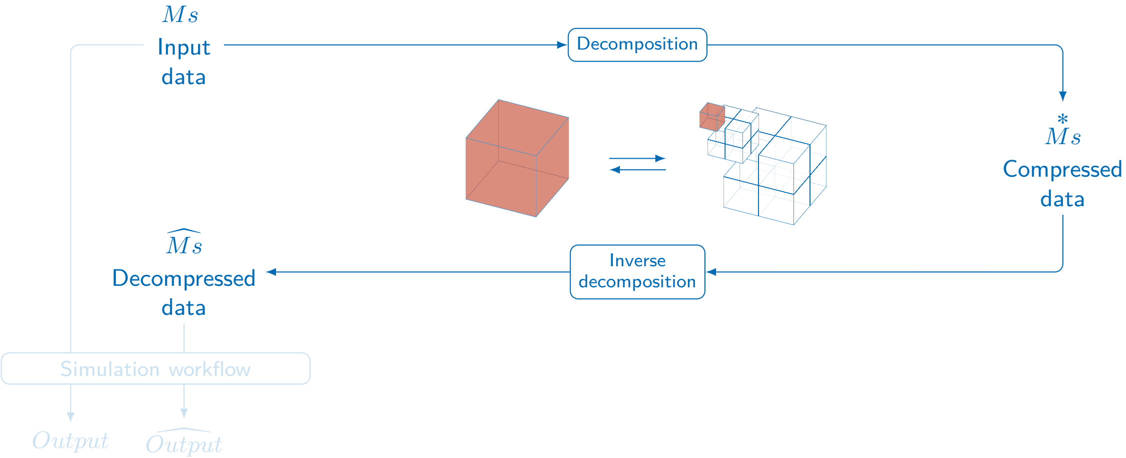
Refinable resolution & precision

Generic simulation workflow



HexaShrink (HS) multiresolution decomposition

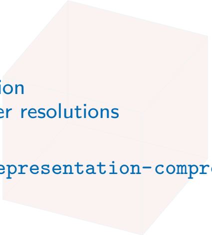
Workflow



HexaShrink (HS) multiresolution decomposition

Structure		
Pillar extremities	Surface points	$2D$ morphological wavelet
Node altitudes	$1D$ data	Non linear $1D$ wavelet
Cell activity	$3D$ data (boolean)	
Properties	$3D$ data	$3D$ wavelet

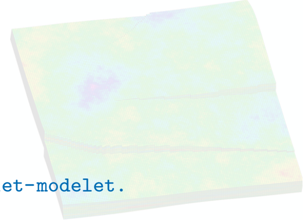
Initial data



Motivations:

- Structure & faults preservation
- Properties coherency at lower resolutions

`http://www.laurent-duval.eu/opus-hexashrink-multiscale-mesh-representation-compression-wavelet-modelet.html`



Initial mesh

HexaShrink (HS) multiresolution decomposition

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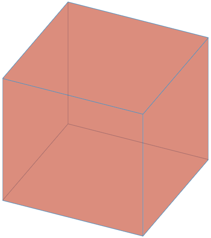

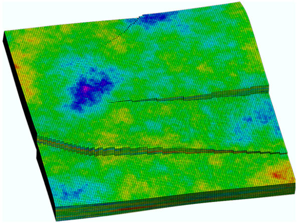

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An.

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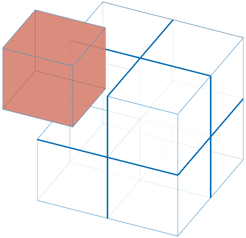

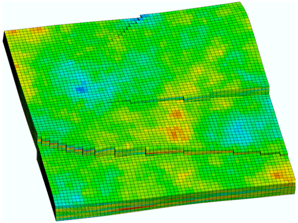

Generated from Analysis (An.) output

HexaShrink (HS) multiresolution decomposition

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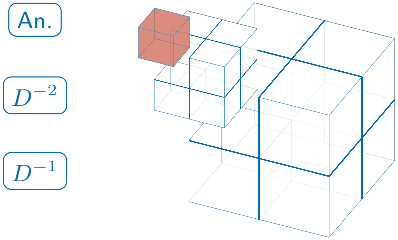

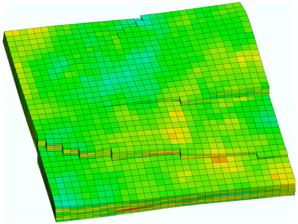

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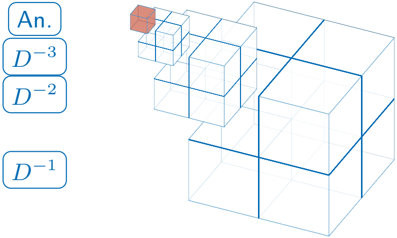
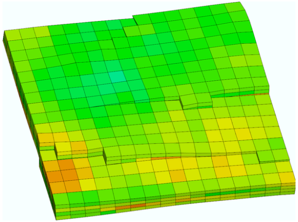
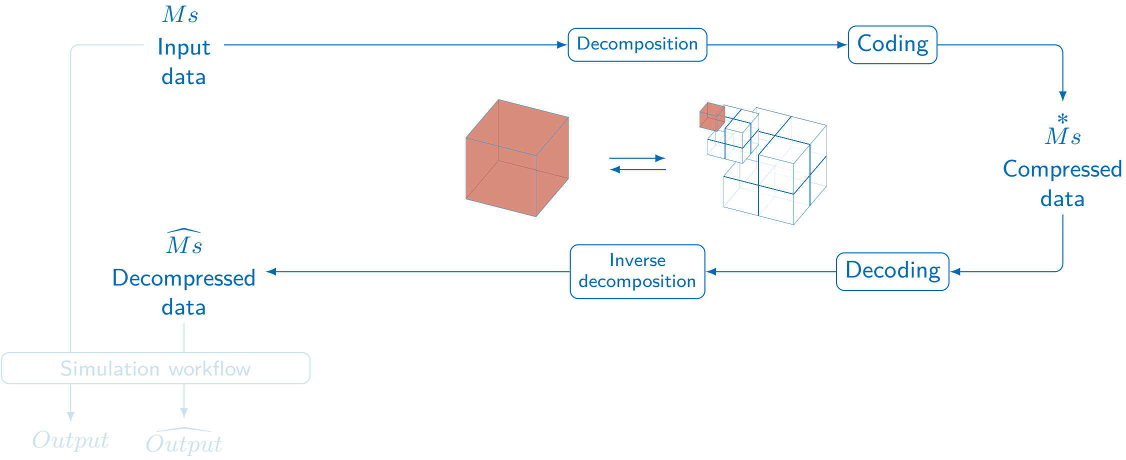




Generated from Analysis (An.) output

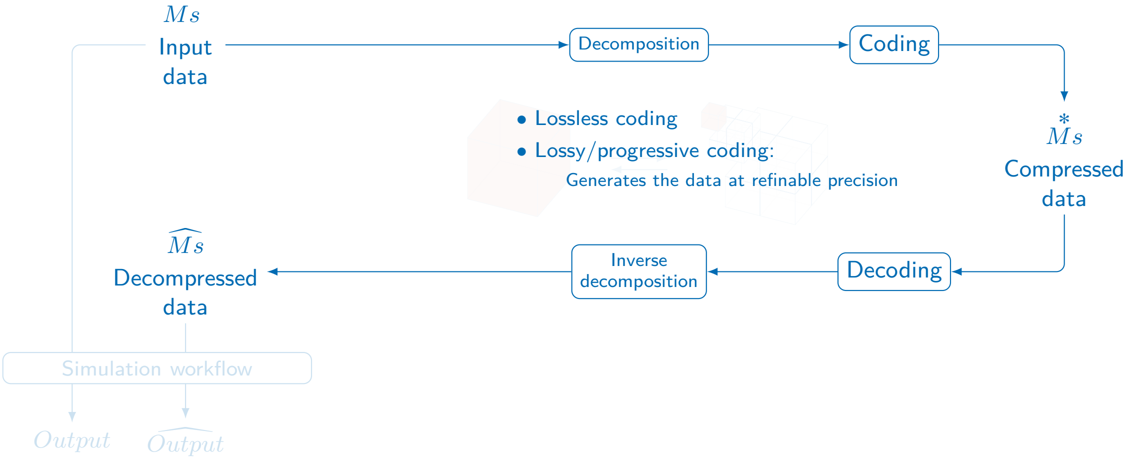
HexaShrink coding

Compression steps



HexaShrink coding

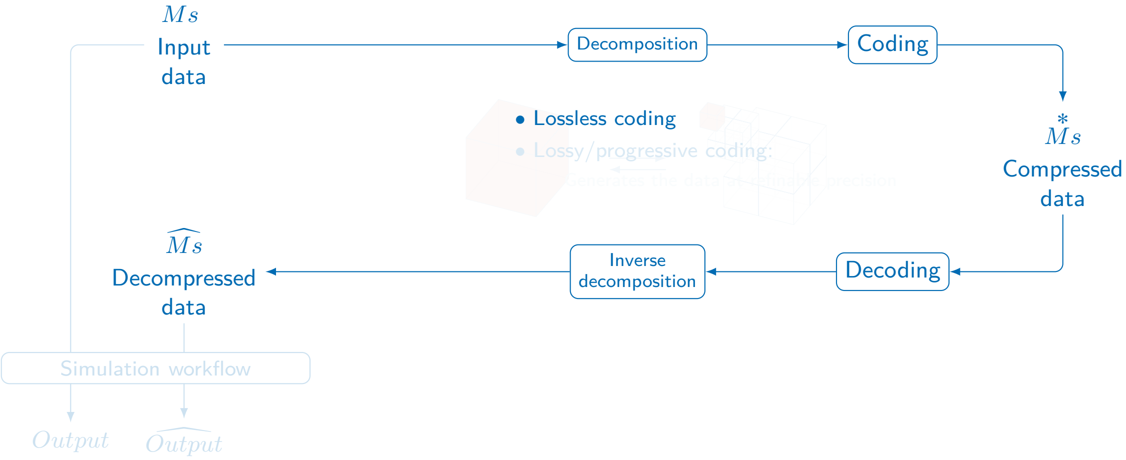
Compression steps



- Lossless coding
- Lossy/progressive coding:
  Generates the data at refinable precision

HexaShrink coding

Compression steps



HexaShrink lossless

Compression steps

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Original data

HexaShrink lossless

Compression steps

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

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6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Original data

HexaShrink lossless

Compression steps

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4	13	21	28	-1	-9	-2	-4
5	22	22	16	-5	2	1	-1
10	6	12	18	-1	-2	2	8
14	10	6	15	-1	2	-1	-16
-2	-6	3	3	-5	9	-6	-1
-6	1	3	3	5	7	2	0
-6	-7	16	-2	8	2	5	1
-2	-6	0	-5	7	-5	-4	1

1 decomposition level

HexaShrink lossless

Compression steps

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

4	13	21	28	-1	-9	-2	-4
5	22	22	16	-5	2	1	-1
10	6	12	18	-1	-2	2	8
14	10	6	15	-1	2	-1	-16
-2	-6	3	3	-5	9	-6	-1
-6	1	3	3	5	7	2	0
-6	-7	16	-2	8	2	5	1
-2	-6	0	-5	7	-5	-4	1

1 decomposition level

HexaShrink lossless

Compression steps

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

11	22	-13	-1	-1	-9	-2	-4
10	13	4	-7	-5	2	1	-1
-5	6	9	-12	-1	-2	2	8
-5	5	-1	4	-1	2	-1	-16
-2	-6	3	3	-5	9	-6	-1
-6	1	3	3	5	7	2	0
-6	-7	16	-2	8	2	5	1
-2	-6	0	-5	7	-5	-4	1

2 decomposition levels

HexaShrink lossless

Compression steps

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

11	22	-13	-1	-1	-9	-2	-4
10	13	4	-7	-5	2	1	-1
-5	6	9	-12	-1	-2	2	8
-5	5	-1	4	-1	2	-1	-16
-2	-6	3	3	-5	9	-6	-1
-6	1	3	3	5	7	2	0
-6	-7	16	-2	8	2	5	1
-2	-6	0	-5	7	-5	-4	1

2 decomposition levels

HexaShrink lossless

Compression steps

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

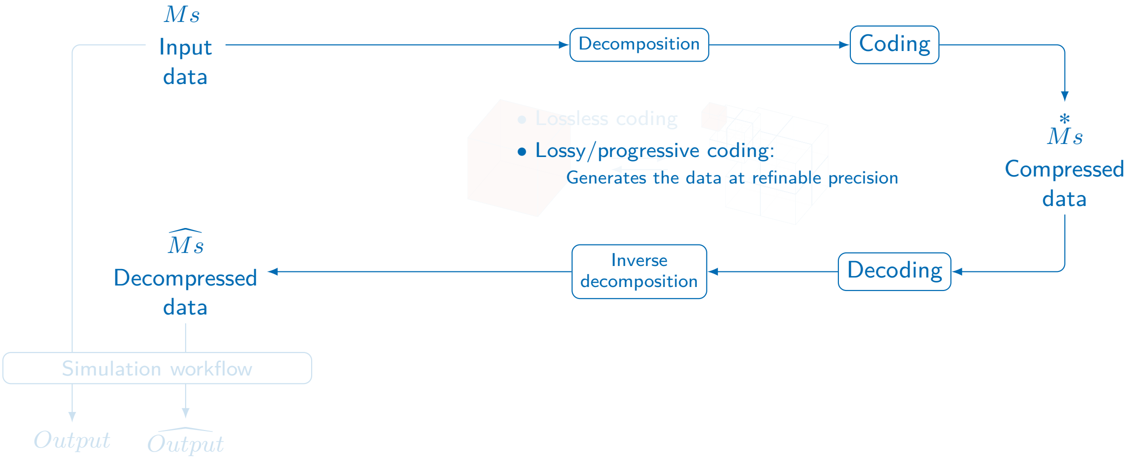
11	22	-13	-1	-1	-9	-2	-4
10	13	4	-7	-5	2	1	-1
-5	6	9	-12	-1	-2	2	8
-5	5	-1	4	-1	2	-1	-16
-2	-6	3	3	-5	9	-6	-1
-6	1	3	3	5	7	2	0
-6	-7	16	-2	8	2	5	1
-2	-6	0	-5	7	-5	-4	1

2 decomposition levels

Subbands coding
with generic lossless methods

HexaShrink lossy

Compression steps



HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

11	22	-13	-1	-1	-9	-2	-4
10	13	4	-7	-5	2	1	-1
-5	6	9	-12	-1	-2	2	8
-5	5	-1	4	-1	2	-1	-16
-2	-6	3	3	-5	9	-6	-1
-6	1	3	3	5	7	2	0
-6	-7	16	-2	8	2	5	1
-2	-6	0	-5	7	-5	-4	1

		11
Most Significant Bit	4	0
	3	1
5 MSB_Z	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

5 MSB$_Z$

Res. 0

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

10	22	-12	0	0	-8	-2	-4
10	12	4	-6	-4	2	0	0
-4	6	8	-12	0	-2	2	8
-4	4	0	4	0	2	0	-16
-2	-6	2	2	-4	8	-6	0
-6	0	2	2	4	6	2	0
-6	-6	16	-2	8	2	4	0
-2	-6	0	-4	6	-4	-4	0

4 MSB$_Z$

		10
Most Significant Bit	4	0
	3	1
4 MSB$_Z$	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

10	22	-12	0	0	-8	-2	-4
10	12	4	-6	-4	2	0	0
-4	6	8	-12	0	-2	2	8
-4	4	0	4	0	2	0	-16
-2	-6	2	2	-4	8	-6	0
-6	0	2	2	4	6	2	0
-6	-6	16	-2	8	2	4	0
-2	-6	0	-4	6	-4	-4	0

		10
Most Significant Bit	4	0
	3	1
4 MSB_Z	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

8	20	-12	0	0	-8	0	-4
8	12	4	-4	-4	0	0	0
-4	4	8	-12	0	0	0	8
-4	4	0	4	0	0	0	-16
0	-4	0	0	-4	8	-4	0
-4	0	0	0	4	4	0	0
-4	-4	16	0	8	0	4	0
0	-4	0	-4	4	-4	-4	0

		8
Most Significant Bit	4	0
	3	1
3 MSB_Z	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

3 MSB_Z

0	0	2	10	12	20	25	31
0	0	6	22	16	16	27	29
0	1	23	21	20	20	14	18
1	11	21	23	20	20	14	18
0	0	0	3	17	15	18	14
3	11	7	11	3	5	22	18
10	12	5	9	3	9	2	18
12	18	17	13	5	7	10	26

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

8	20	-12	0	0	-8	0	-4
8	12	4	-4	-4	0	0	0
-4	4	8	-12	0	0	0	8
-4	4	0	4	0	0	0	-16
0	-4	0	0	-4	8	-4	0
-4	0	0	0	4	4	0	0
-4	-4	16	0	8	0	4	0
0	-4	0	-4	4	-4	-4	0

		8
Most Significant Bit	4	0
	3	1
3 MSB_Z	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

Res. 0

5 $\mathrm{MSB}_{\mathcal{Z}}$

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 $\mathrm{MSB}_{\mathcal{Z}}$

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

3 $\mathrm{MSB}_{\mathcal{Z}}$

0	0	2	10	12	20	25	31
0	0	6	22	16	16	27	29
0	1	23	21	20	20	14	18
1	11	21	23	20	20	14	18
0	0	0	3	17	15	18	14
3	11	7	11	3	5	22	18
10	12	5	9	3	9	2	18
12	18	17	13	5	7	10	26

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

8	16	-8	0	0	-8	0	0
8	8	0	0	0	0	0	0
0	0	8	-8	0	0	0	8
0	0	0	0	0	0	0	-16
0	0	0	0	0	8	0	0
0	0	0	0	0	0	0	0
0	0	16	0	8	0	0	0
0	0	0	0	0	0	0	0

		8
Most Significant Bit	4	0
	3	1
2 $\mathrm{MSB}_{\mathcal{Z}}$	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

3 MSB_Z

0	0	2	10	12	20	25	31
0	0	6	22	16	16	27	29
0	1	23	21	20	20	14	18
1	11	21	23	20	20	14	18
0	0	0	3	17	15	18	14
3	11	7	11	3	5	22	18
10	12	5	9	3	9	2	18
12	18	17	13	5	7	10	26

2 MSB_Z

0	0	0	12	2	14	18	30
0	4	4	24	6	10	22	26
0	2	22	22	16	16	12	20
2	10	22	22	16	16	12	20
0	0	0	6	8	8	8	8
0	12	6	14	0	0	16	16
6	14	4	8	0	10	0	16
14	22	16	12	2	6	8	24

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

8	16	-8	0	0	-8	0	0
8	8	0	0	0	0	0	0
0	0	8	-8	0	0	0	8
0	0	0	0	0	0	0	-16
0	0	0	0	0	8	0	0
0	0	0	0	0	0	0	0
0	0	16	0	8	0	0	0
0	0	0	0	0	0	0	0

		8
Most Significant Bit	4	0
	3	1
2 MSB_Z	2	0
	1	1
Least Significant Bit	0	1

HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

3 MSB_Z

0	0	2	10	12	20	25	31
0	0	6	22	16	16	27	29
0	1	23	21	20	20	14	18
1	11	21	23	20	20	14	18
0	0	0	3	17	15	18	14
3	11	7	11	3	5	22	18
10	12	5	9	3	9	2	18
12	18	17	13	5	7	10	26

2 MSB_Z

0	0	0	12	2	14	18	30
0	4	4	24	6	10	22	26
0	2	22	22	16	16	12	20
2	10	22	22	16	16	12	20
0	0	0	6	8	8	8	8
0	12	6	14	0	0	16	16
6	14	4	8	0	10	0	16
14	22	16	12	2	6	8	24

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

Sig	Sig	Sig	0	0	Sig	0	0
Sig	Sig	0	0	0	0	0	0
0	0	Sig	Sig	0	0	0	Sig
0	0	0	0	0	0	0	Sig
0	0	0	0	0	Sig	0	0
0	0	0	0	0	0	0	0
0	0	Sig	0	0	0	0	0
0	0	0	0	0	0	0	0

Progressive coding with Zerotree:

- EZW (Shapiro, J., 1993)
- SPIHT (Said, A., Pearlman, W., 1996)

HexaShrink lossy/progressive

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

3 MSB_Z

0	0	2	10	12	20	25	31
0	0	6	22	16	16	27	29
0	1	23	21	20	20	14	18
1	11	21	23	20	20	14	18
0	0	0	3	17	15	18	14
3	11	7	11	3	5	22	18
10	12	5	9	3	9	2	18
12	18	17	13	5	7	10	26

2 MSB_Z

0	0	0	12	2	14	18	30
0	4	4	24	6	10	22	26
0	2	22	22	16	16	12	20
2	10	22	22	16	16	12	20
0	0	0	6	8	8	8	8
0	12	6	14	0	0	16	16
6	14	4	8	0	10	0	16
14	22	16	12	2	6	8	24

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

Sig	Sig	Sig		0	Sig		
Sig	Sig		0	0	0		
		Sig	Sig			0	Sig
	0	0				0	Sig
				0	Sig	0	0
				0	0	0	0
		Sig	0	0	0		
		0	0	0	0		

Progressive coding with Zerotree:

- EZW (Shapiro, J., 1993)
- SPIHT (Said, A., Pearlman, W., 1996)

HexaShrink lossy/progressive

Compression steps

Res. 0

5 MSB_Z

2	5	8	12	20	25	27	31
6	4	9	22	20	19	25	28
1	3	25	20	24	22	17	18
4	11	21	23	20	20	14	15
8	5	2	3	22	18	21	13
10	15	8	11	4	5	22	15
15	12	7	8	4	7	5	20
13	17	15	11	6	5	9	25

4 MSB_Z

0	4	6	12	16	21	25	30
4	3	8	22	17	16	24	27
0	3	24	21	22	21	16	18
3	11	21	24	19	20	14	16
6	4	2	3	19	17	20	14
8	14	9	12	3	5	22	16
14	13	7	10	4	8	4	20
13	18	16	13	6	6	10	26

3 MSB_Z

0	0	2	10	12	20	25	31
0	0	6	22	16	16	27	29
0	1	23	21	20	20	14	18
1	11	21	23	20	20	14	18
0	0	0	3	17	15	18	14
3	11	7	11	3	5	22	18
10	12	5	9	3	9	2	18
12	18	17	13	5	7	10	26

2 MSB_Z

0	0	0	12	2	14	18	30
0	4	4	24	6	10	22	26
0	2	22	22	16	16	12	20
2	10	22	22	16	16	12	20
0	0	0	6	8	8	8	8
0	12	6	14	0	0	16	16
6	14	4	8	0	10	0	16
14	22	16	12	2	6	8	24

Res. -1

4	13	21	28
5	22	22	16
10	6	12	18
14	10	6	15

Res. -2

11	22
10	13

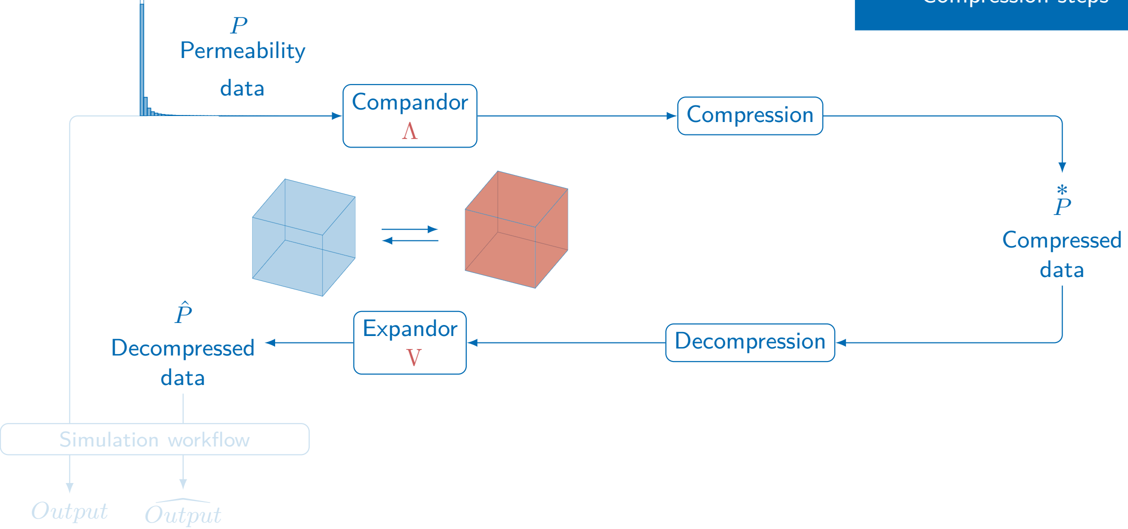
Sig	Sig	Sig	Ztr	0	Sig		
Sig	Sig	Ztr	0	0	0		
Ztr	Ztr	Sig	Sig			0	Sig
Ztr	0	0	Ztr			0	Sig
				0	Sig	0	0
				0	0	0	0
		Sig	0	0	0		
		0	0	0	0		

Progressive coding with Zerotree:

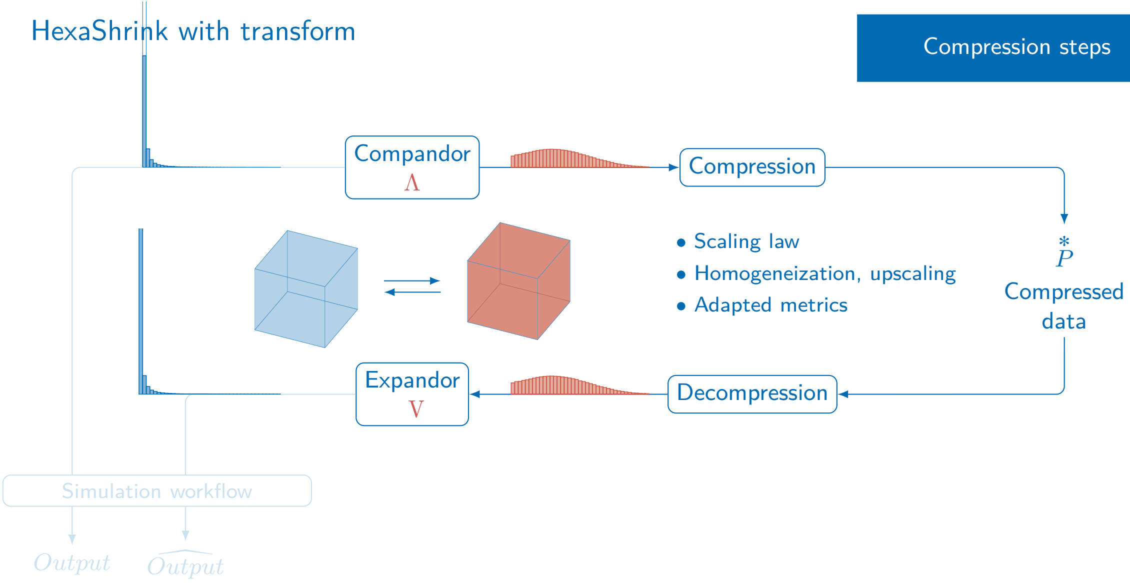
- EZW (Shapiro, J., 1993)
- SPIHT (Said, A., Pearlman, W., 1996)

HexaShrink with transform

Compression steps



HexaShrink with transform



Transform and metrics

Compandor

$$\Lambda_{nbits}(P) = round\left(\frac{\lambda(P) - \lambda(\min P)}{\lambda(\max P) - \lambda(\min P)} \times (2^{nbits} - 1)\right),$$

$$with \quad \lambda(P) = \log(P+1),$$

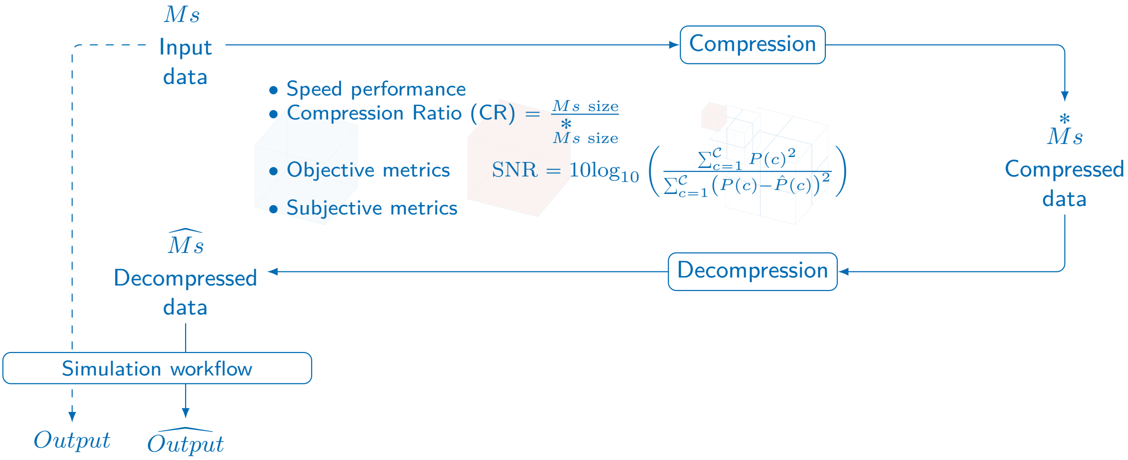
Expandor

$$\hat{P} = \mathrm{V}_{nbits}(\Lambda_{nbits}(P)) = \Upsilon\left(\frac{\Lambda_{nbits}(P)}{(2^{nbits} - 1)} \times (\lambda(\max P) - \lambda(\min P)) + \lambda(\min P)\right),$$

$$with \quad \Upsilon(P) = \exp(P) - 1.$$

$Output$ $\widehat{Output}$

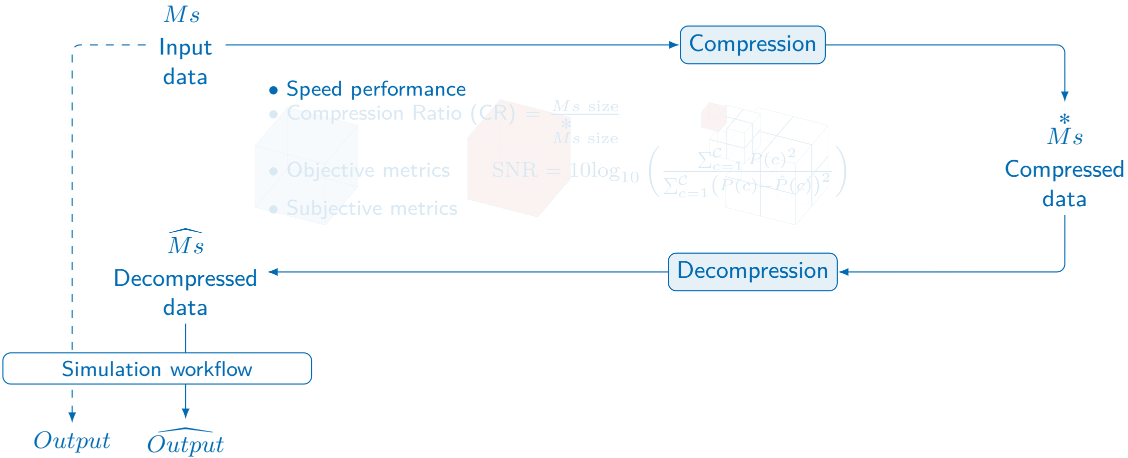
Evaluation criteria



- Speed performance
- Compression Ratio (CR) $= \frac{Ms \text{ size}}{\overset{*}{Ms} \text{ size}}$
- Objective metrics $\quad \mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} P(c)^2}{\sum_{c=1}^{\mathcal{C}}\left(P(c)-\hat{P}(c)\right)^2}\right)$
- Subjective metrics

Evaluation criteria

Compression steps

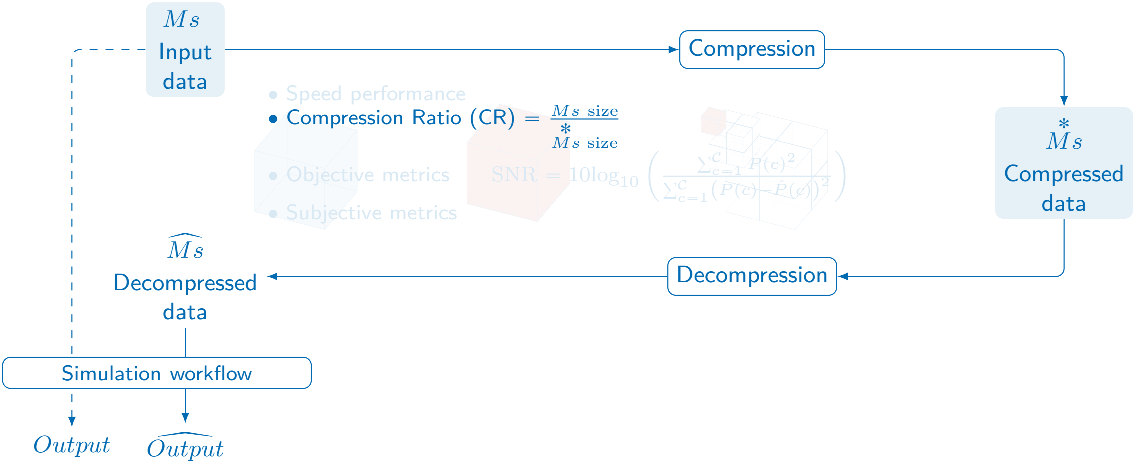


- Speed performance
- Compression Ratio (CR) $= \frac{Ms \text{ size}}{\overset{*}{Ms} \text{ size}}$
- Objective metrics $\mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{C} P(c)^2}{\sum_{c=1}^{C}(P(c)-\hat{P}(c))^2}\right)$
- Subjective metrics

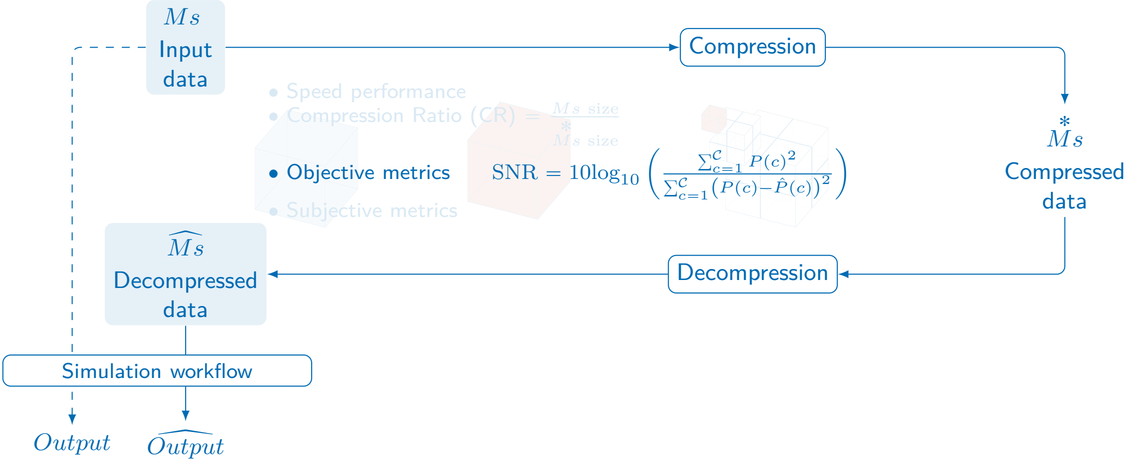
Evaluation criteria

Compression steps

- Speed performance
- Compression Ratio (CR) $= \frac{Ms \text{ size}}{\overset{*}{M}s \text{ size}}$
- Objective metrics $\quad \mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{C} P(c)^2}{\sum_{c=1}^{C}(P(c)-\hat{P}(c))^2}\right)$
- Subjective metrics

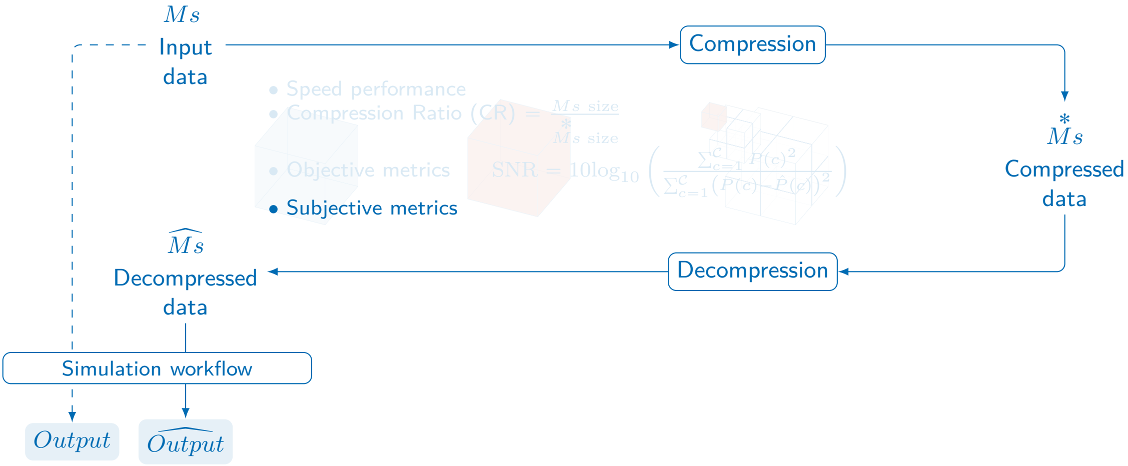


Evaluation criteria



- Speed performance
- Compression Ratio (CR) $= \frac{Ms \text{ size}}{\overset{*}{Ms} \text{ size}}$
- Objective metrics $\quad \text{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} P(c)^2}{\sum_{c=1}^{\mathcal{C}}\left(P(c)-\hat{P}(c)\right)^2}\right)$
- Subjective metrics

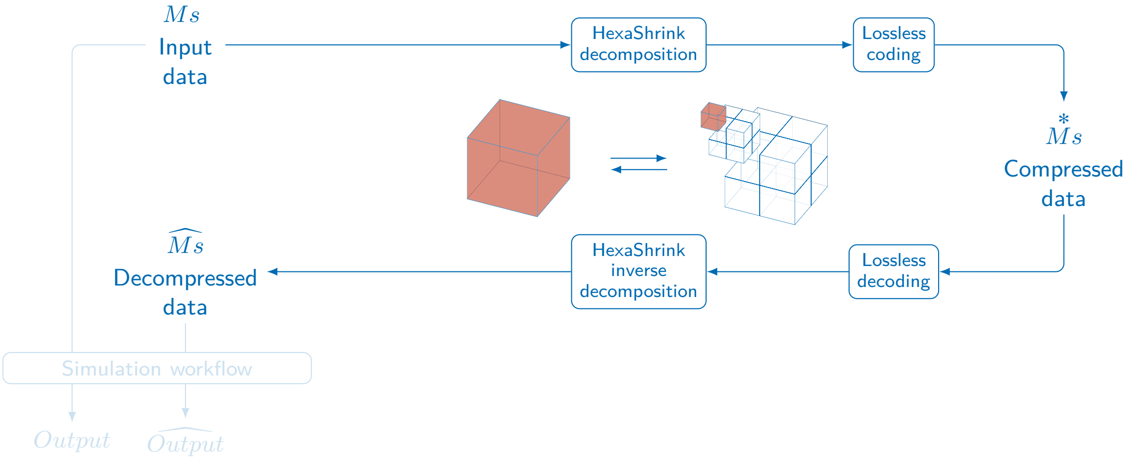
Evaluation criteria



- Speed performance
- Compression Ratio (CR) $= \frac{Ms \text{ size}}{\overset{*}{M}s \text{ size}}$
- Objective metrics $\quad \mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{C} P(c)^2}{\sum_{c=1}^{C}(P(c)-\hat{P}(c))^2}\right)$
- Subjective metrics

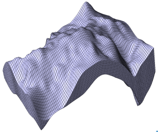
HexaShrink lossless

Compression (objective)



Benchmark

Compression (objective)

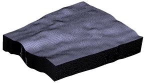


#1

~~faults~~

93,600.00 cells

4.62 MB

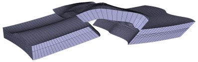


#2

~~faults~~

1,000,000.00 cells

42.46 MB

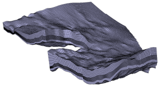


#3

faults

36,816.00 cells

1.46 MB

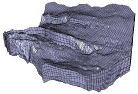


#4

faults

210,000.00 cells

7.88 MB

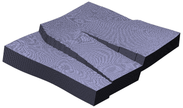


#5

faults

450,576.00 cells

22.73 MB

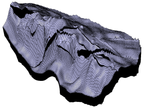


#6

faults

524,288.00 cells

64.27 MB

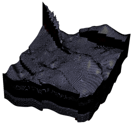


#7

faults

6,577,325.00 cells

274.57 MB



#8

faults

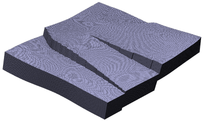
13,947,600.00 cells

580.94 MB

HexaShrink lossless performance

Compression (objective)

On mesh$_{\#6}$



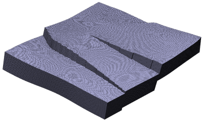
Features		Compression ratio			
Faults	File Size	Level	gzip (1992)	bzip2 (1996)	LZMA (1998)
		none	1.88	2.25	3.04
Yes	64.27 MB	1.00	2.70	3.17	3.71
		2.00–6.00	2.84–2.86	3.39–3.42	3.90–3.93

Observations:

- Lossless coders provide good performance
- HexaShrink improves further compression rate
- Less significant improvements above two levels

HexaShrink lossless performance

On mesh$_{\#6}$



Features		Compression ratio			
Faults	File Size	Level	gzip (1992)	bzip2 (1996)	LZMA (1998)
Yes	64.27 MB	none	1.88	2.25	3.04
		1.00	2.70	3.17	3.71
		2.00–6.00	2.84–2.86	3.39–3.42	3.90–3.93

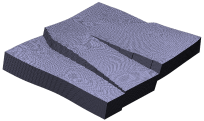
Observations:

- Lossless coders provide good performance
- HexaShrink improves further compression rate
- Less significant improvements above two levels

HexaShrink lossless performance

Compression (objective)

On mesh$_{\#6}$



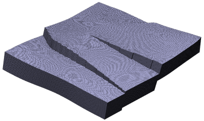
Features		Compression ratio			
Faults	File Size	Level	gzip (1992)	bzip2 (1996)	LZMA (1998)
Yes	64.27 MB	none	1.88	2.25	3.04
		1.00	2.70	3.17	3.71
		2.00–6.00	2.84–2.86	3.39–3.42	3.90–3.93

Observations:

- Lossless coders provide good performance
- HexaShrink improves further compression rate
- Less significant improvements above two levels

HexaShrink lossless performance

On mesh$_{\#6}$



Features		Compression ratio			
Faults	File Size	Level	gzip (1992)	bzip2 (1996)	LZMA (1998)
Yes	64.27 MB	none	1.88	2.25	3.04
		1.00	2.70	3.17	3.71
		2.00–6.00	2.84–2.86	3.39–3.42	3.90–3.93

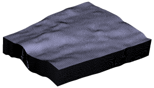
Observations:

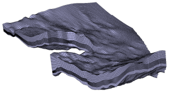
- Lossless coders provide good performance
- HexaShrink improves further compression rate
- Less significant improvements above two levels

HexaShrink lossless performance

Compression (objective)

On all meshes



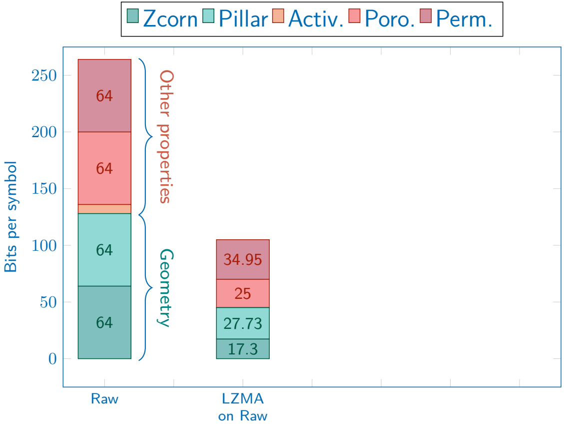


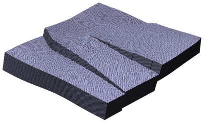
Mesh	Features: Faults	Features: File Size	Compression ratio: Level	gzip (1992)	bzip2 (1996)	LZMA (1998)
1	No	4.62 MB	none	3.73	4.98	6.43
			1	5.62	6.07	7.52
			2.00–4.00	5.67	6.12–6.13	7.42–7.44
2	No	42.46 MB	none	3.23	8.41	10.12
			1	6.49	10.82	11.81
			2.00–6.00	7.48–7.58	12.75–13.03	13.35
3	Yes	1.46 MB	none	2.67	2.99	3.63
			1	3.88	4.70	5.24
			2.00–4.00	4.03–4.05	4.92–4.93	5.47–5.48
4	Yes	7.88 MB	none	1.83	1.89	2.21
			1	2.64	3.06	3.48
			2.00–4.00	2.76	3.22–3.23	3.64–3.65
5	Yes	22.73 MB	none	2.46	2.55	3.33
			1	3.14	2.83	3.71
			2.00–4.00	3.25–3.26	2.91–2.92	3.80–3.81
6	Yes	64.27 MB	none	1.88	2.25	3.04
			1	2.70	3.17	3.71
			2.00–6.00	2.84–2.86	3.39–3.42	3.90–3.93
7	Yes	274.57 MB	none	2.31	2.25	3.04
			1	3.31	3.53	4.44
			2.00–6.00	4.14–4.24	4.48–4.68	5.54–5.73
8	Yes	580.94 MB	none	3.20	5.98	12.52
			1	5.42	7.07	8.90
			2.00–7.00	5.80–6.72	7.63–10.12	9.05–10.23

HexaShrink lossless performance

In-depth analysis for *LZMA*

Compression (objective)





LZMA efficiency on all components

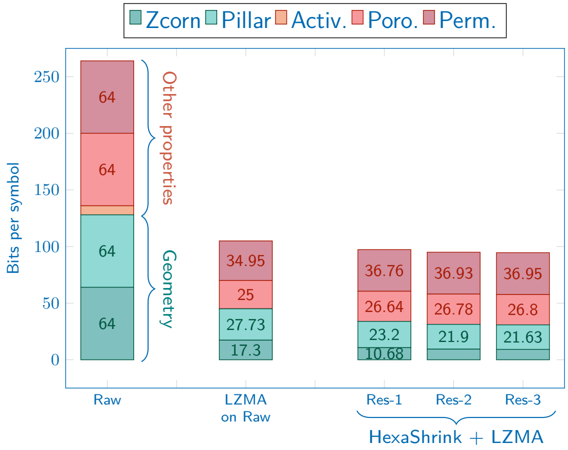
With Hexashrink decomposition:

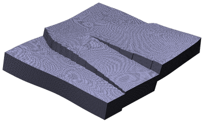
- Geometry
  - Efficient
- Other properties

HexaShrink lossless performance

In-depth analysis for *LZMA*

Compression (objective)





LZMA efficiency on all components

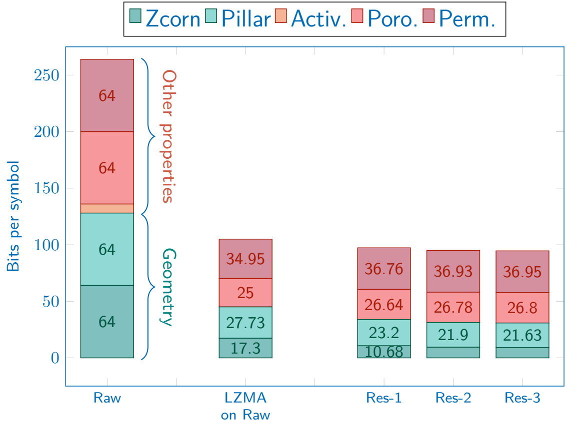
With Hexashrink decomposition:

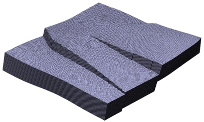
- Geometry
  - Efficient
- Other properties
  - Limited

HexaShrink lossless performance

In-depth analysis for *LZMA*

Compression (objective)





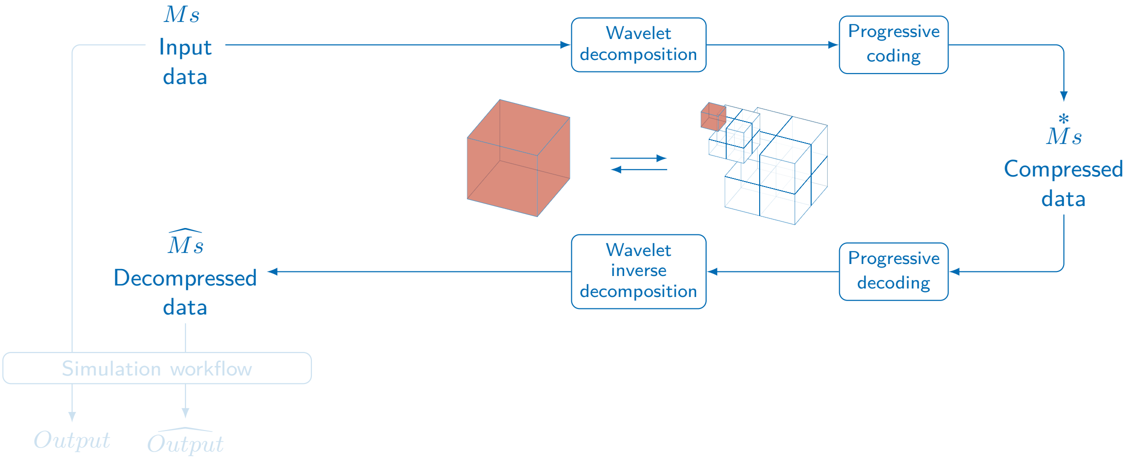
LZMA efficiency on all components

With Hexashrink decomposition:

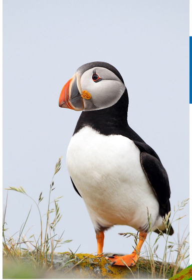
- Geometry
- Other properties

Let us explore refinable precision!

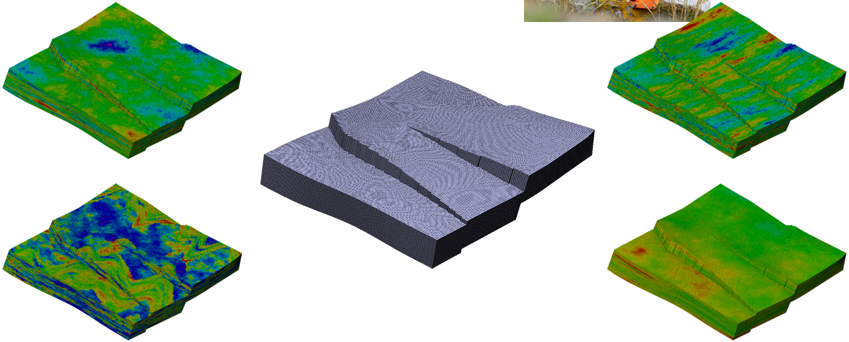
HexaShrink lossy/progressive performance



HexaShrink lossy/progressive performance on Lundi

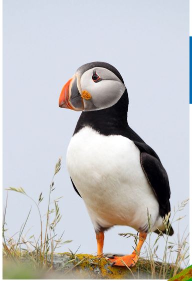


Four property environnements (SPE10, Christie, M. 2001)

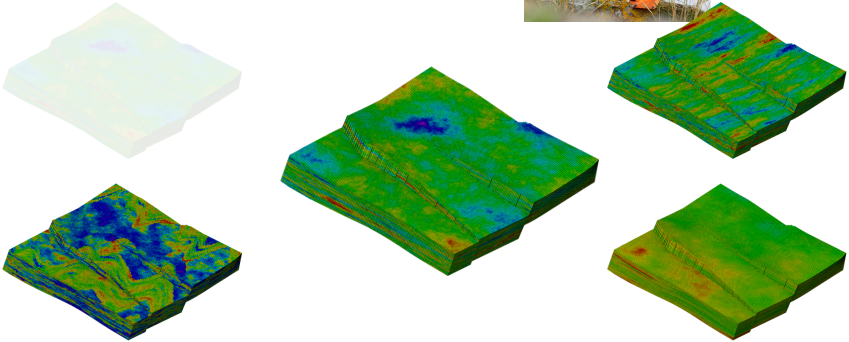


HexaShrink lossy/progressive performance on Lundi

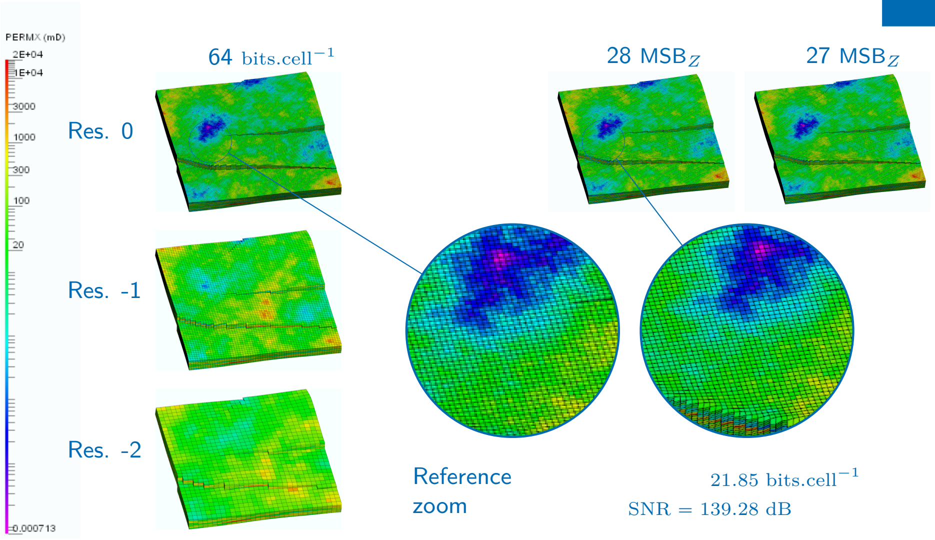
Compression (subjective)



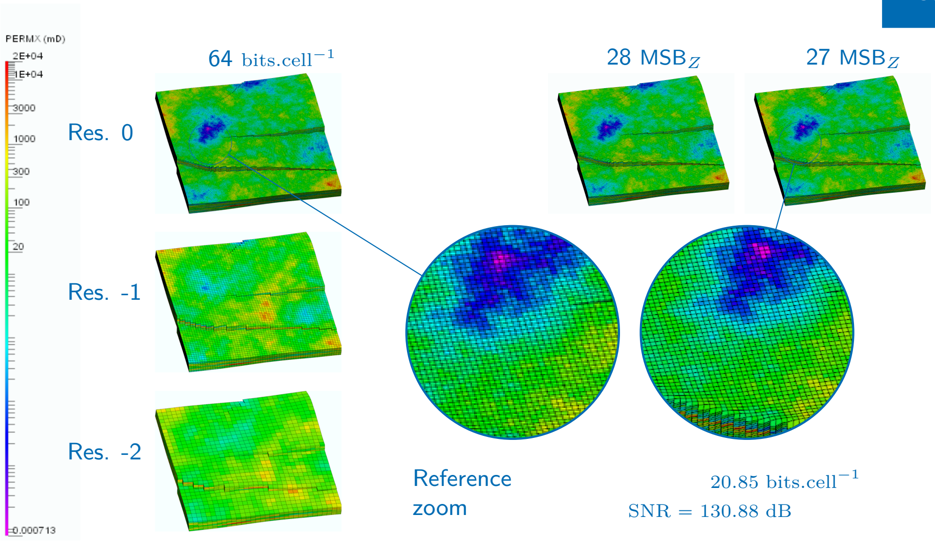
Four property environnements (SPE10, Christie, M. 2001)



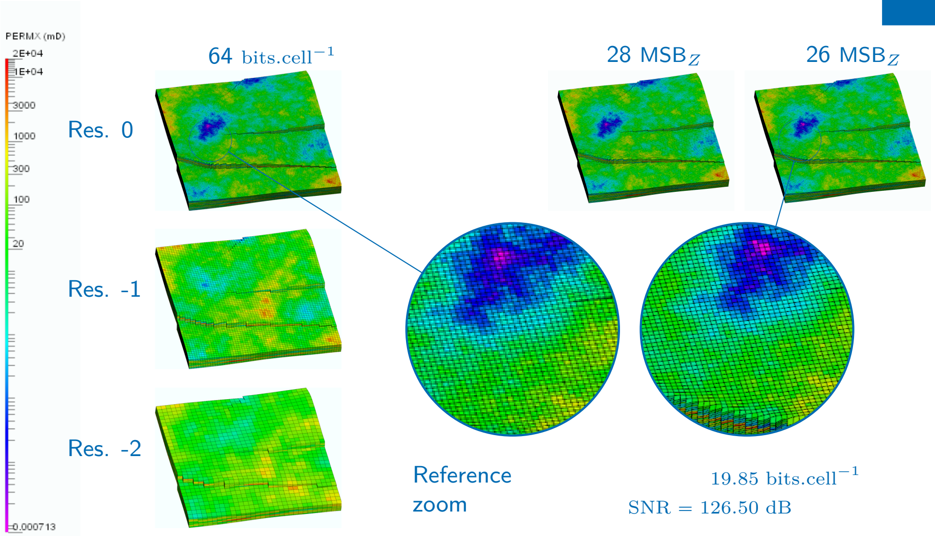
HexaShrink lossy/progressive: visual results



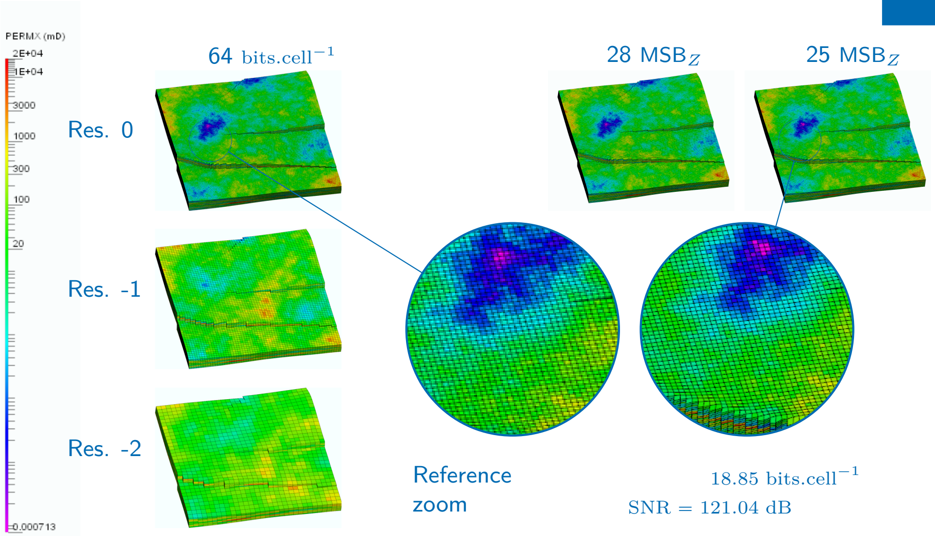
HexaShrink lossy/progressive: visual results



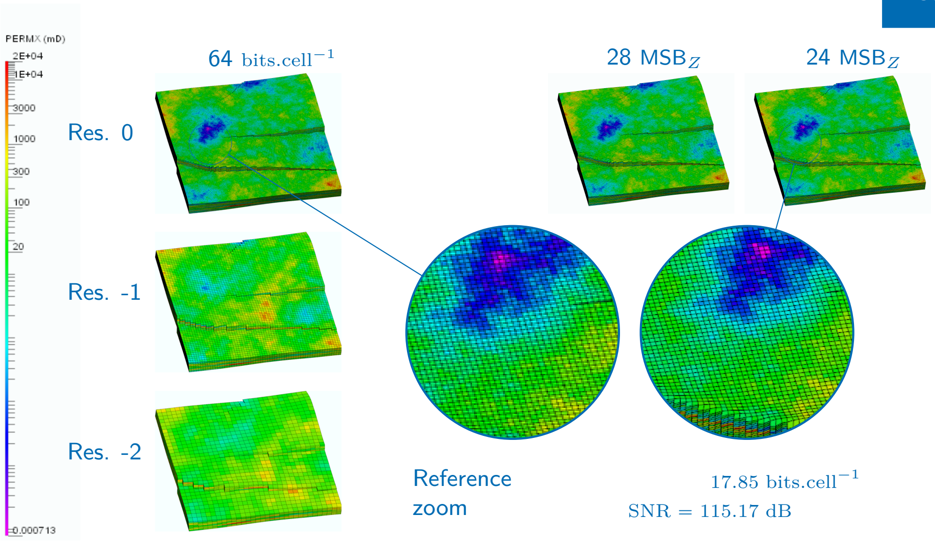
HexaShrink lossy/progressive: visual results



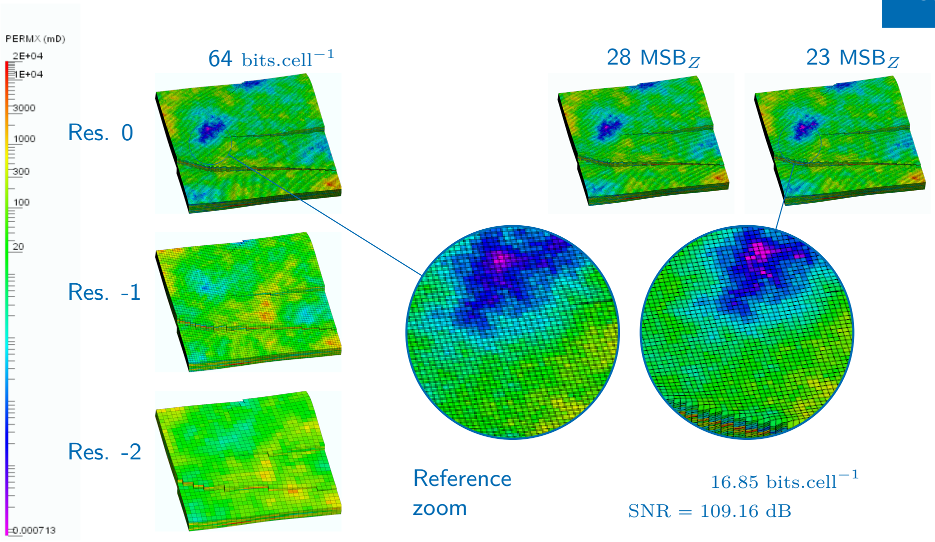
HexaShrink lossy/progressive: visual results



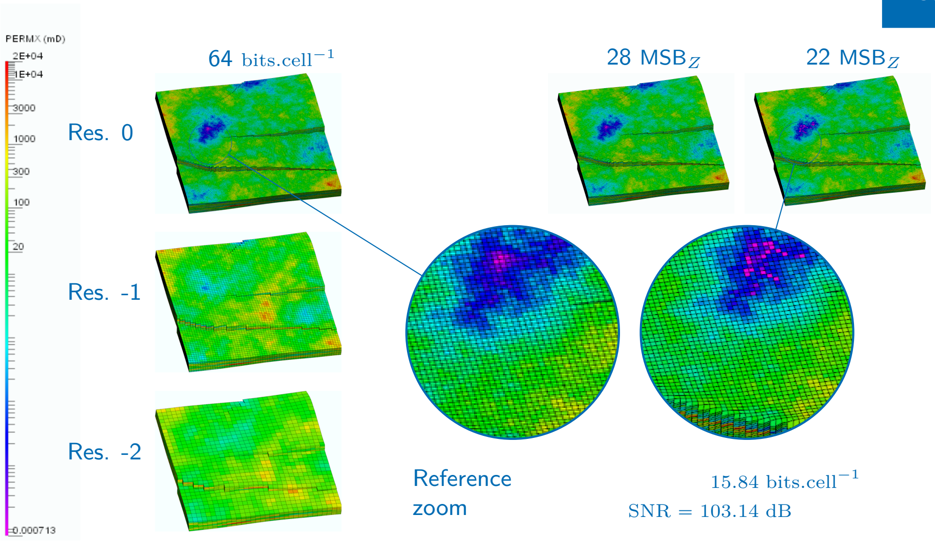
HexaShrink lossy/progressive: visual results



HexaShrink lossy/progressive: visual results

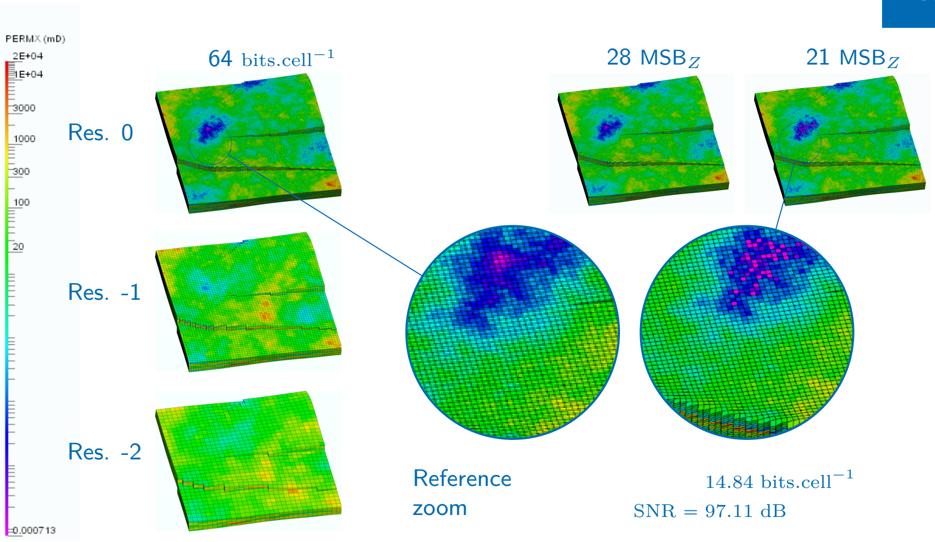


HexaShrink lossy/progressive: visual results



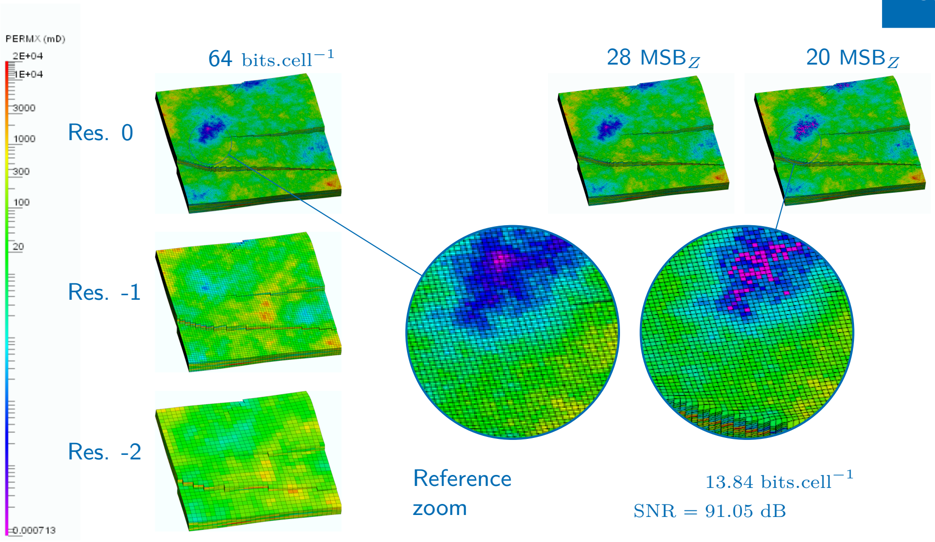
HexaShrink lossy/progressive: visual results

Compression (subjective)

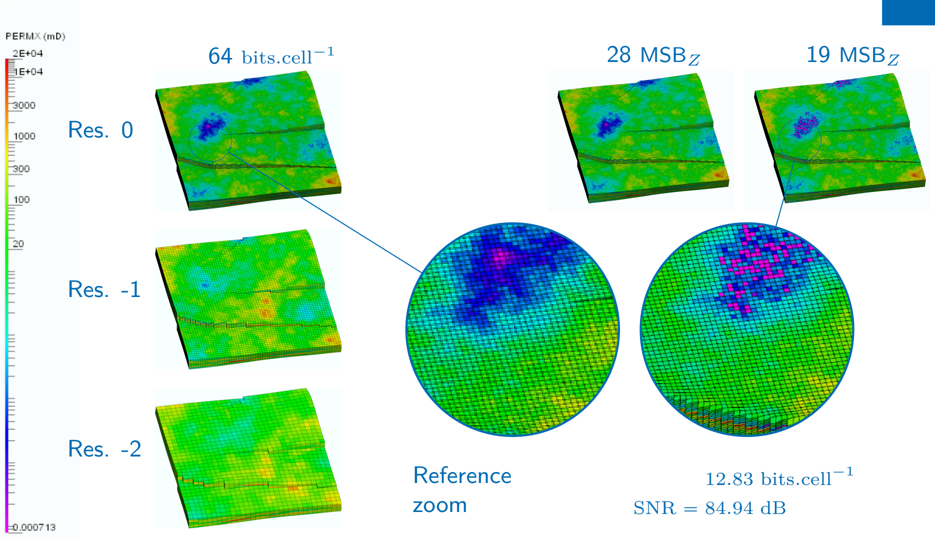


HexaShrink lossy/progressive: visual results

Compression (subjective)

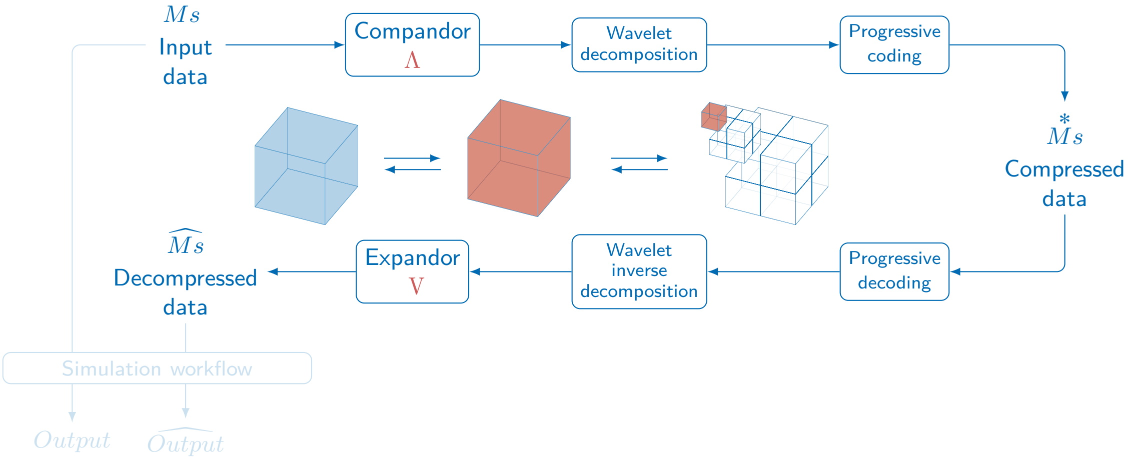


HexaShrink lossy/progressive: visual results

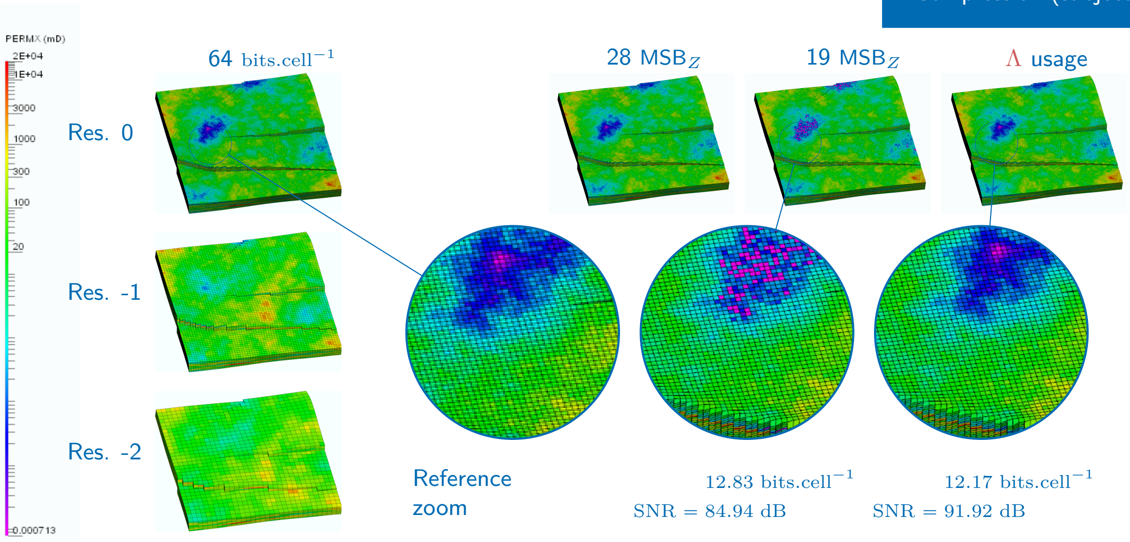


HexaShrink lossy/progressive with companding: visual results

Compression (subjective)



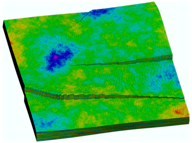
6.0 Compandor effect: visual results

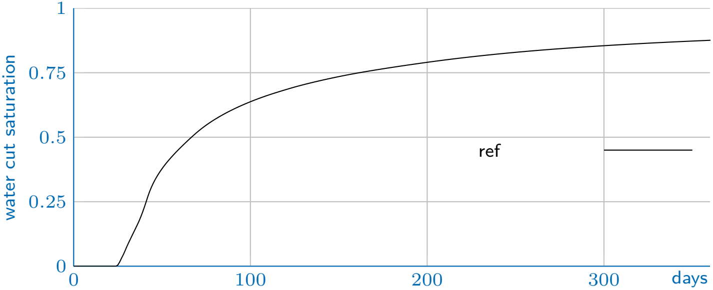


Simulation: fidelity versus resolution (HexaShrink)

Simulation (subjective)

Raw

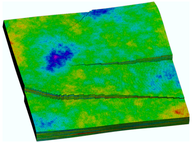


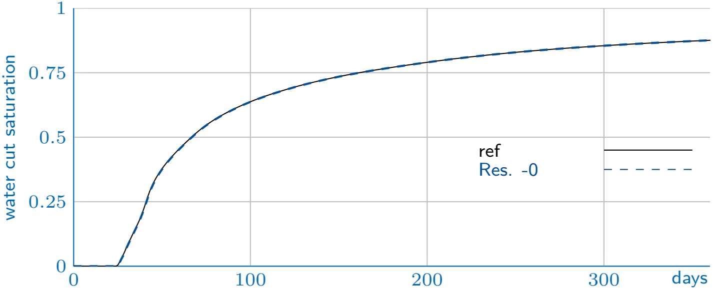


Simulation: fidelity versus resolution (HexaShrink)

Simulation (subjective)

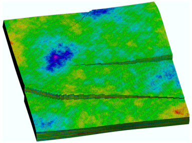
Res. -0
$\approx$ 72 hours



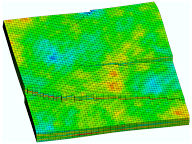


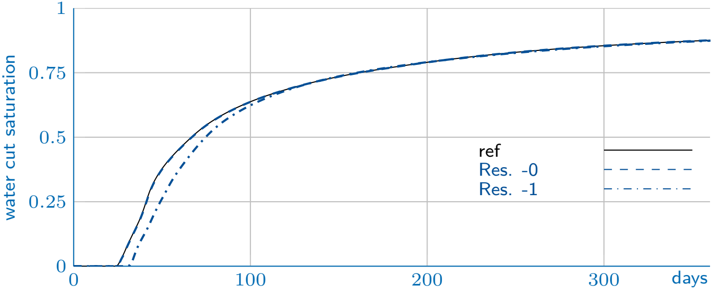
Simulation: fidelity versus resolution (HexaShrink)

Res. -0
≈ 72 hours



Res. -1
≈ 4 hours

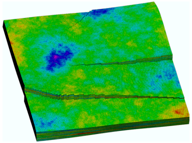




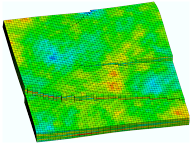
Simulation: fidelity versus resolution (HexaShrink)

Simulation (subjective)

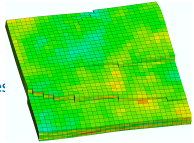
Res. -0
≈ 72 hours

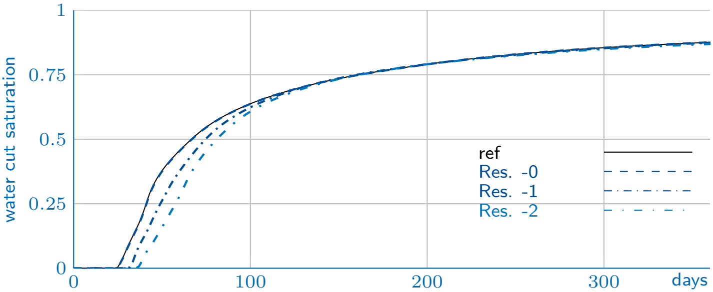


Res. -1
≈ 4 hours



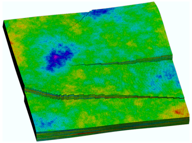
Res. -2
≈ 20 minutes





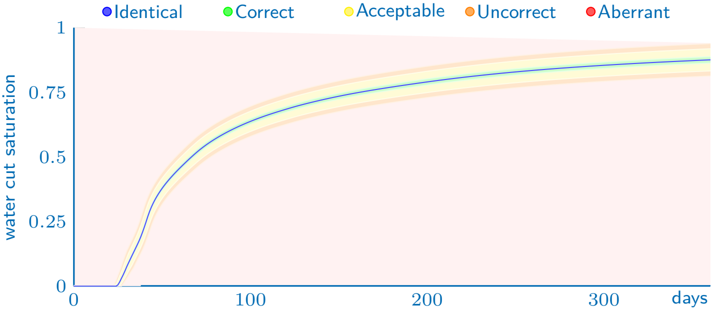
Simulation: fidelity versus resolution (HexaShrink)

Res. -0



Res. -1

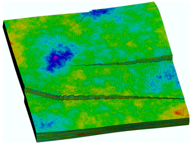
Res. -2



Simulation: accuracy versus precision

Simulation (subjective)

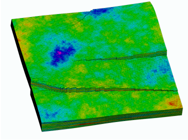
Res. 0



Res. -1

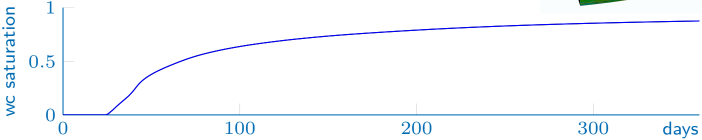
Res. -2

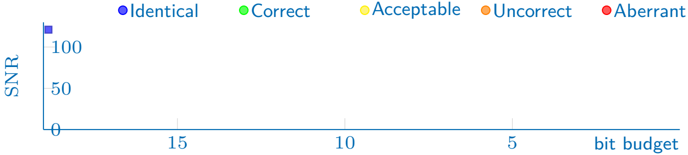
25 MSB_Z



18.85 bits.cell^{-1}

SNR = 121.04 dB

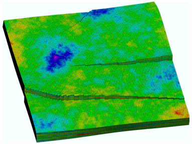




Simulation: accuracy versus precision

Simulation (subjective)

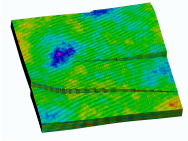
Res. 0



Res. -1

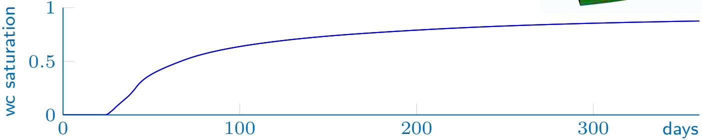
Res. -2

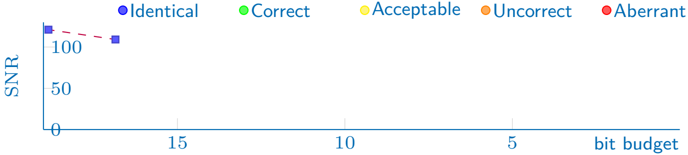
23 MSB_Z



16.85 bits.cell^{-1}

SNR = 109.16 dB



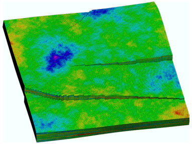


Simulation: accuracy versus precision

Simulation (subjective)

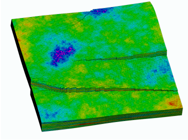
21 MSB_Z

Res. 0



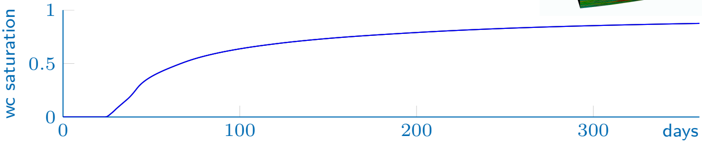
Res. -1

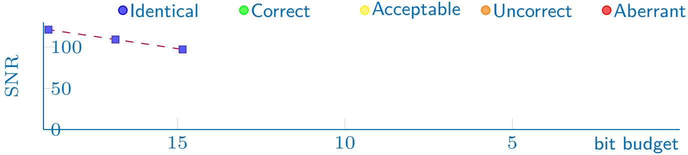
Res. -2



14.84 bits.cell^{-1}

SNR = 97.11 dB

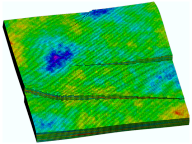




Simulation: accuracy versus precision

Simulation (subjective)

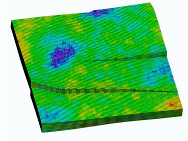
Res. 0



Res. -1

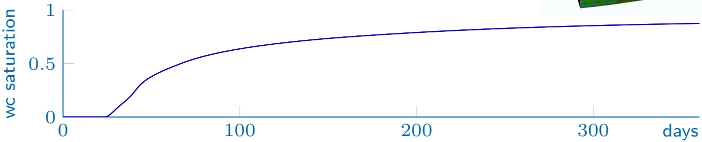
Res. -2

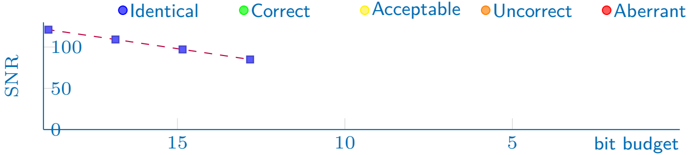
19 MSB_Z



12.83 bits.cell^{-1}

SNR = 84.94 dB

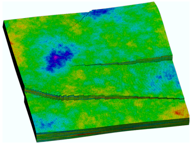




Simulation: accuracy versus precision

Simulation (subjective)

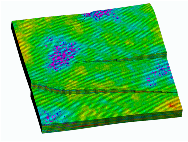
Res. 0



Res. -1

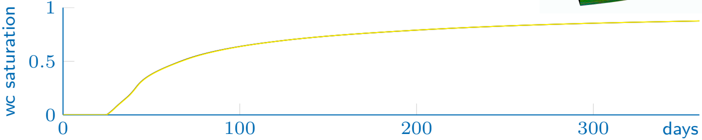
Res. -2

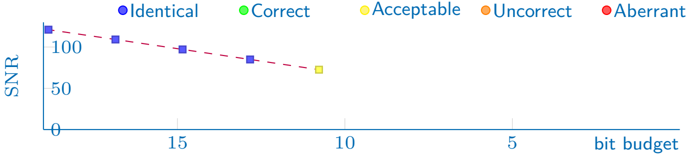
17 MSB_Z



10.77 bits.cell^{-1}

SNR $= 72.54$ dB

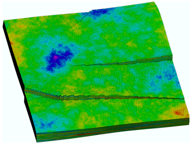




Simulation: accuracy versus precision

Simulation (subjective)

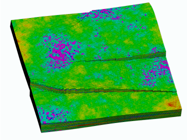
Res. 0



Res. -1

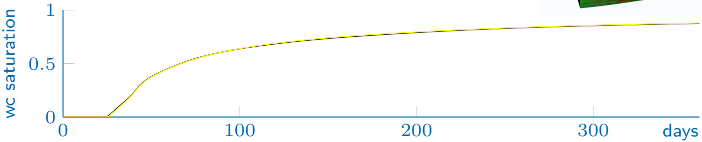
Res. -2

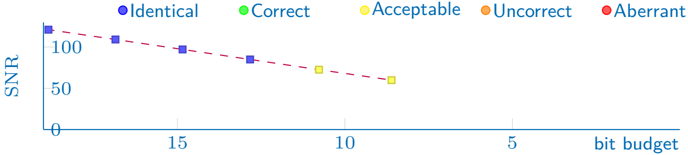
15 MSB_Z



8.60 bits.cell^{-1}

SNR = 59.89 dB

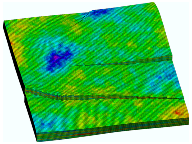




Simulation: accuracy versus precision

Simulation (subjective)

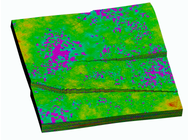
Res. 0



Res. -1

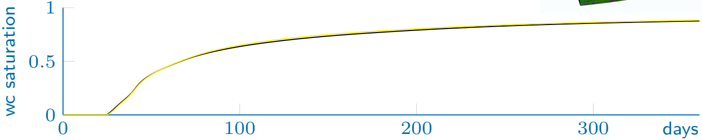
Res. -2

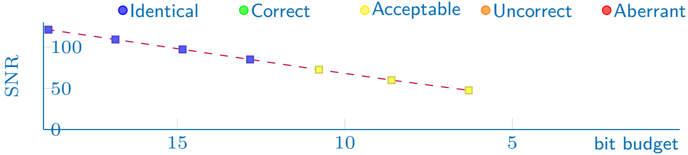
13 MSB_Z



6.30 bits.cell^{-1}

SNR = 47.54 dB

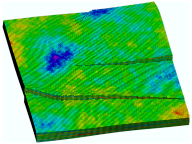




Simulation: accuracy versus precision

Simulation (subjective)

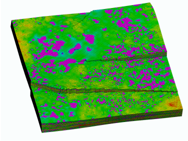
Res. 0



Res. -1

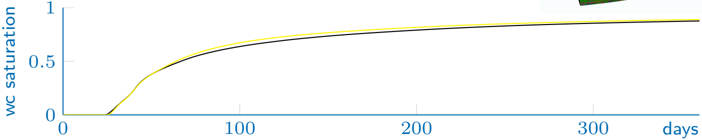
Res. -2

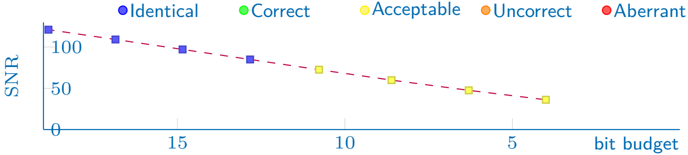
11 MSB_Z



4.00 bits.cell^{-1}

SNR $= 36.10$ dB

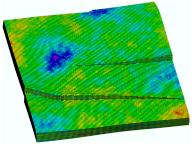




Simulation: accuracy versus precision

Simulation (subjective)

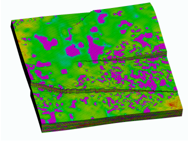
Res. 0



Res. -1

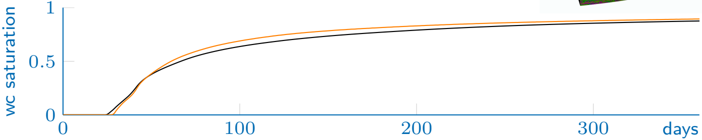
Res. -2

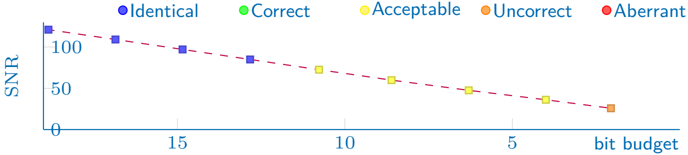
9 MSB_Z



2.05 bits.cell^{-1}

SNR $= 25.82$ dB

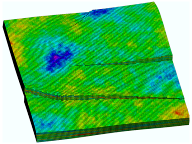




Simulation: accuracy versus precision

Simulation (subjective)

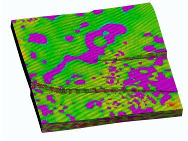
Res. 0



Res. -1

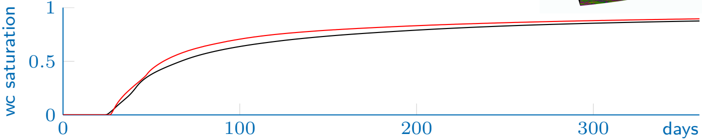
Res. -2

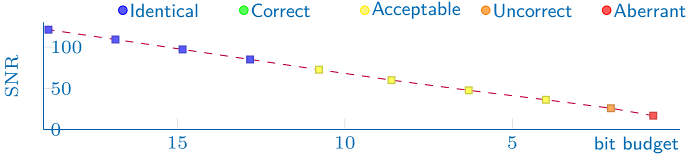
7 MSB_Z



0.79 bits.cell^{-1}

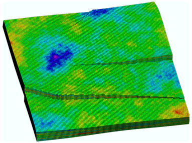
SNR $= 16.91$ dB





Simulation: accuracy versus precision

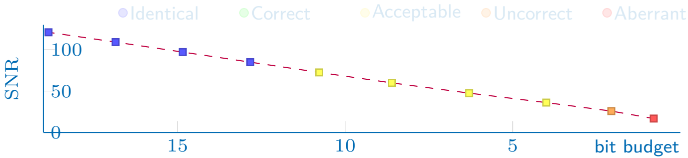
Res. 0



Res. -1

Res. -2

Is SNR suitable for simulation?

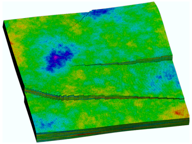


Simulation-adapted metrics: is SNR valid?

Simulation (better adapted metri

$$\mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} P(c)^2}{\sum_{c=1}^{\mathcal{C}}\left(P(c)-\hat{P}(c)\right)^2}\right)$$

Res. 0

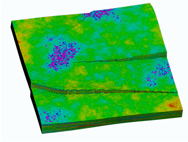


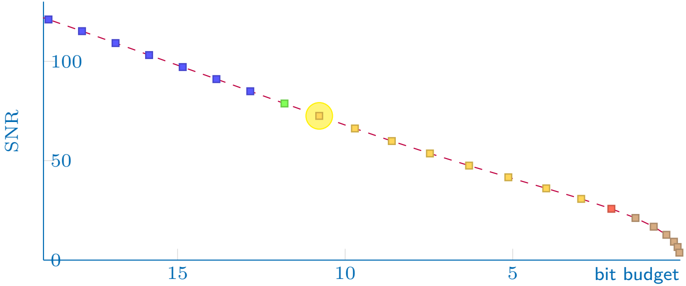
Res. -1

Res. -2

10.77 bits.cell^{-1}

$\mathrm{SNR} = 72.54$ dB



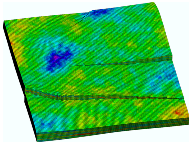


Simulation-adapted metrics: is SNR valid?

Simulation (better adapted metri

$$\mathrm{SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} P(c)^2}{\sum_{c=1}^{\mathcal{C}}\left(P(c)-\hat{P}(c)\right)^2}\right)$$

Res. 0

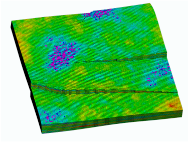


Res. -1

Res. -2

10.77 bits.cell^{-1}

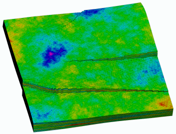
SNR $= 72.54$ dB

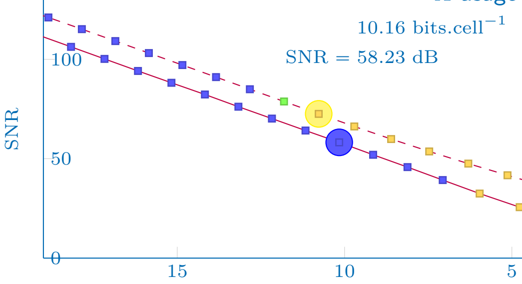


Λ usage

10.16 bits.cell^{-1}

SNR $= 58.23$ dB



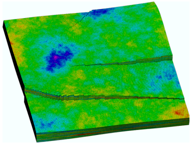


Simulation-adapted metrics: is SNR valid?

Simulation (better adapted metri

$$\Lambda\text{-SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} \Lambda_{P(c)}^2}{\sum_{c=1}^{\mathcal{C}}\left(\Lambda_{P(c)} - \Lambda_{\hat{P}(c)}\right)^2}\right)$$

Res. 0

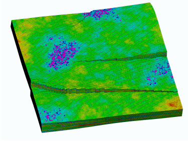


Res. -1

Res. -2

10.77 bits.cell^{-1}

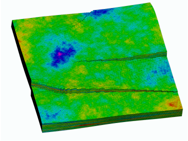
Λ-SNR = 33.14 dB

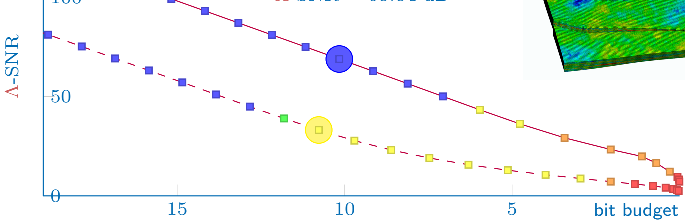


Λ usage

10.16 bits.cell^{-1}

Λ-SNR = 68.84 dB



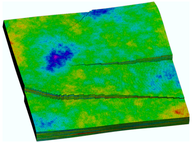


Simulation-adapted metrics: is SNR valid?

Simulation (better adapted metri

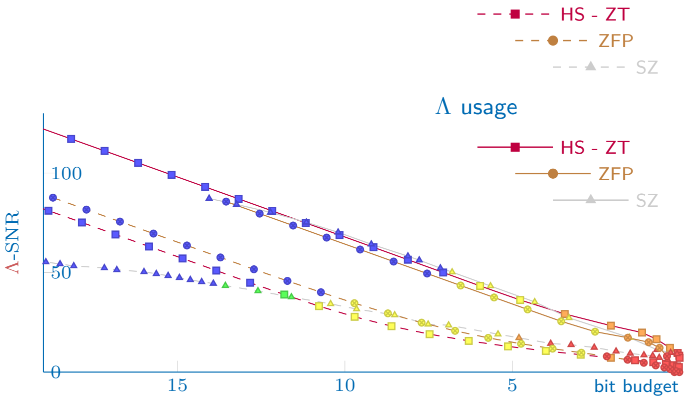
$$\Lambda\text{-SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} \Lambda_{P(c)}^2}{\sum_{c=1}^{\mathcal{C}}\left(\Lambda_{P(c)}-\Lambda_{\hat{P}(c)}\right)^2}\right)$$

Res. 0



Res. -1

Res. -2

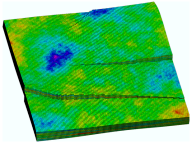


Simulation-adapted metrics: is SNR valid?

Simulation (better adapted metri

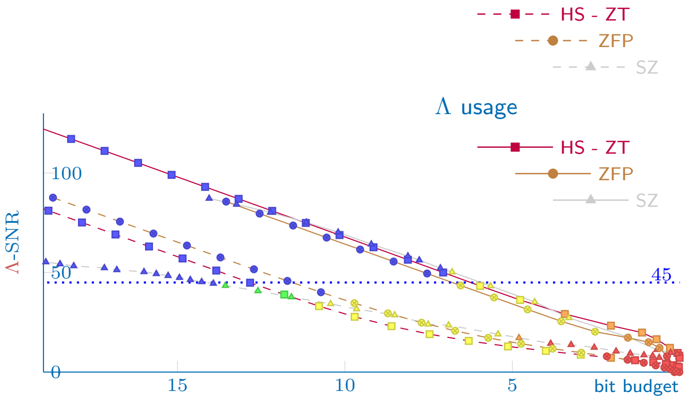
$$\Lambda\text{-SNR} = 10\log_{10}\left(\frac{\sum_{c=1}^{\mathcal{C}} \Lambda_{P(c)}^2}{\sum_{c=1}^{\mathcal{C}}\left(\Lambda_{P(c)} - \Lambda_{\hat{P}(c)}\right)^2}\right)$$

Res. 0



Res. -1

Res. -2



On compression challenges in simulation

- Demanding domains
  - Compression close to the workflow
  - Integrate physical laws or proxies
  - Devevelop pertinent metrics
  - Require solid benchmarking
- Different needs
  - Compress once, decompress many
  - Data and energy efficient algorithms
  - Random access: by the slice or by the block
  - and many more

On compression opportunities in simulation

- A lot of opportunities for DSP/compression people (from digital twins to Metaverse)
  - Visualization, storage, transfer, memory footprint, checkpointing restart, *in situ* analysis...
  - Energetic, economic, ecological
- Some people in simulation
  - may not know well what compression can do (mesh inflation)
  - may have excessive expectation when they know more (all mesh random access)
- Toward CaaS: Compression as a Service
  - Not the best in end-to-end quality, adapted to the overall workflow
  - With added value: old and new references
    - Natarajan, B. K., Filtering Random Noise from Deterministic Simals via Data Compression, 1995
    - Sabeti, E., Song, P. X. K., Hero, A. O., Data Discovery Using Lossless Compression-Based Sparse Representation, 2021

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