Generative Models for Satellite Image Analysis

Learning with little or complex data

Valentine Bellet, Mathieu Fauvel, Jordi Inglada, Sivia Valero-Valbuena, Yoël Zerah

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Outline

Plan

Context

Land Cover Classification

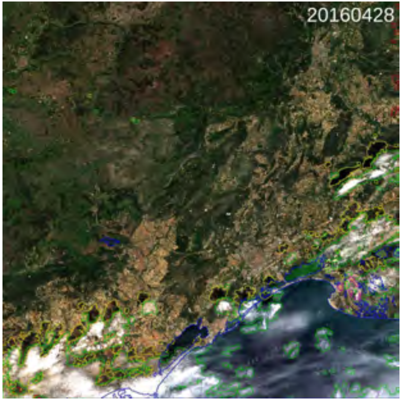
Physic constraint auto-encoder

Conclusion and perspectives

Chair *Learning with little or complex data* (Prof. Nicolas Dobigeon - IRIT-INPT)

- Themes
  - AI and physical models
  - Learning from noisy data
  - Multi-source & -scale time series
- Members - CESBIO:
  - Mathieu Fauvel, INRAe
  - Jordi Inglada, CNES
  - Julien Michel, CNES
  - Silvia Valero, UT3
- ANITI Ressources
  - 2 PhD (Region & CNES): Y. Zérah & V. Bellet
  - 2 Ms
  - 1 engineer (CS-Group)

CESBIO's IA activities



Information extraction from EO imagery

- Land cover/use mapping
- Bio/geo-physical variable estimation
- Change detection and dynamic analysis

Hybrid IA

- Physical modeling
- Data Science / Machine Learning

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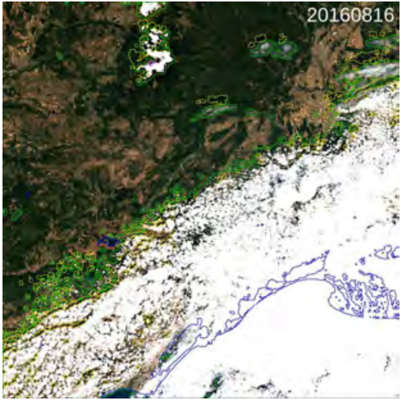

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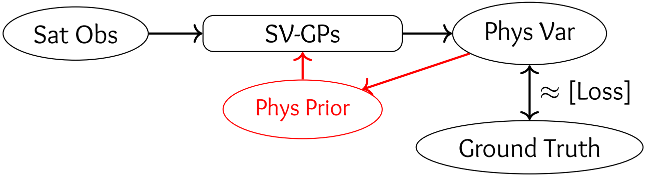
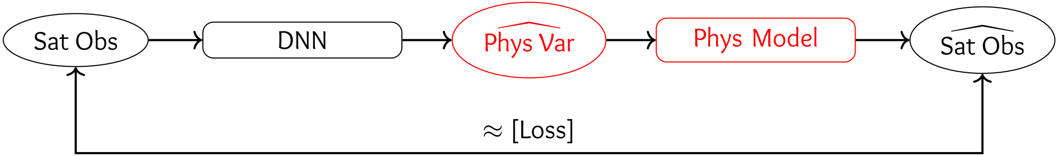
Contribution to ANITI

- **Valentine Bellet**, *Artificial intelligence for ecosystem monitoring*

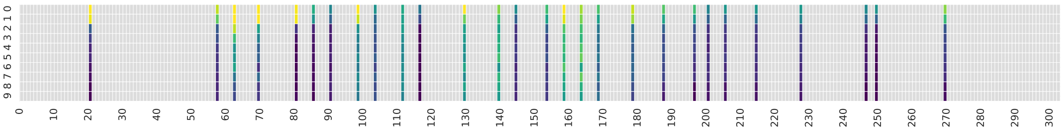


- **Yoël Zerah**, *Generative Models for Mapping Land Cover Changes with Time Series of Satellite Images*

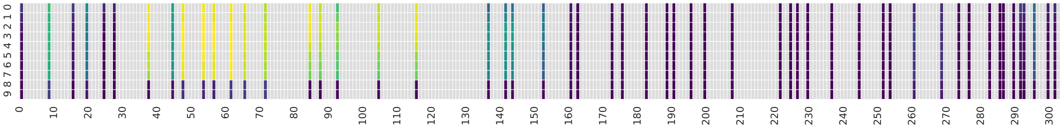


Plan

Model 1/2 - Structured latent representation



$$\mathbf{Z} = \mathbf{B}\left[\mathbf{X}^* + \mathbf{P}\right]\boldsymbol{\Gamma}$$



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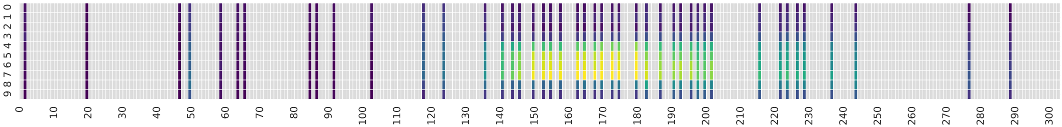
Model 1/2 - Structured latent representation



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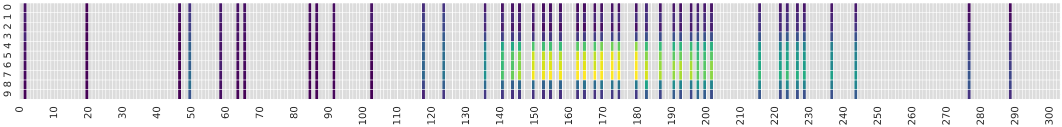

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- Temporal embedding

$$\hat{x}_\ell(r) = \sum_{j=1}^{T} \frac{K(r, t_j) m_j}{\sum_{j'=1}^{T} K(r, t_{j'}) m_{j'}} x_\ell^*(t_j)$$

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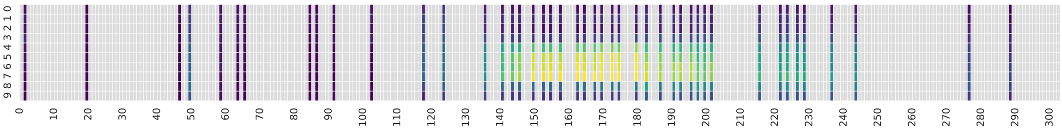

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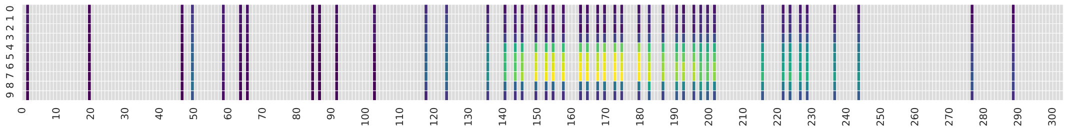

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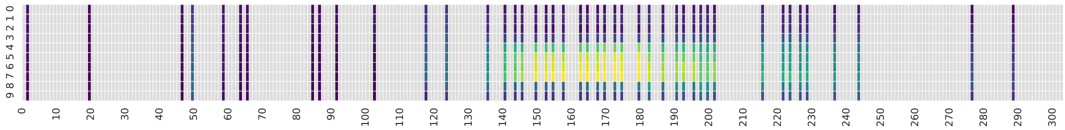

$$Z = B\left[X^* + P\right]\Gamma$$

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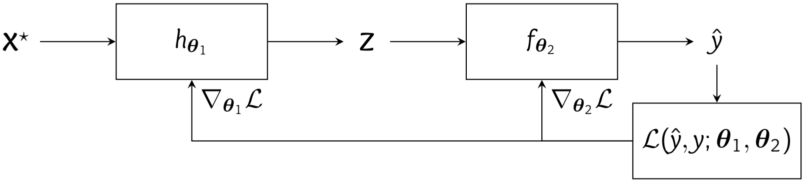
$$\hat{x}_\ell(r) = \sum_{j=1}^{T} \frac{K(r, t_j)m_j}{\sum_{j'=1}^{T} K(r, t_{j'})m_{j'}} x^*_\ell(t_j)$$

$$||Z^i - Z^j||_F^2 = ||B(X^{i*}\Gamma^i - X^{j*}\Gamma^j)||_F^2 + ||B(P^i\Gamma^i - P^j\Gamma^j)||_F^2 + 2\left\langle B(X^{i*}\Gamma^i - X^{j*}\Gamma^j), B(P^i\Gamma^i - P^j\Gamma^j)\right\rangle_F$$



- Optimize a lower bound of the log-likelihood (ELBO) [HMG15]

$$\mathcal{E}(q) = \sum_{i=1}^{N} \mathbb{E}_{q'(g(\mathbf{Z}^i)|\boldsymbol{\theta}^v, \boldsymbol{\theta})}\left[\log p\left(y^i | g(\mathbf{Z}^i)\right)\right] - \mathrm{KL}\left[q\left(g(\mathbf{Z}_u)|\boldsymbol{\theta}^v\right) \| \, p\left(g(\mathbf{Z}_u)|\boldsymbol{\theta}\right)\right],$$

with

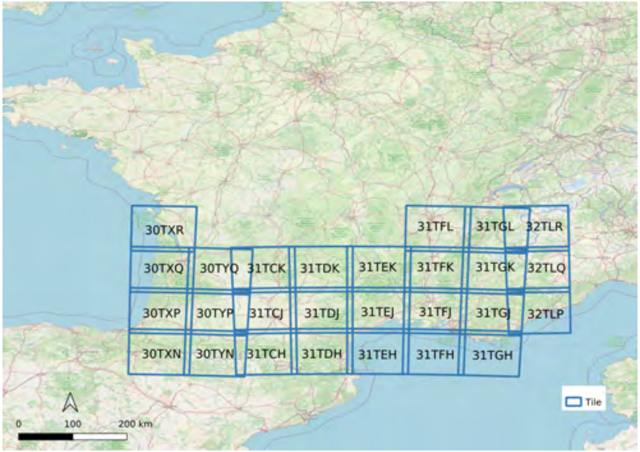
$$q\left(g(\mathbf{Z}_u)|\boldsymbol{\theta}^v\right) \sim \mathcal{N}_M\left(\mathbf{m}, \mathbf{S}\right)$$
$$q'\left(g(\mathbf{Z}^i)|\boldsymbol{\theta}^v, \boldsymbol{\theta}\right) \sim \mathcal{N}_1\left(g(\mathbf{Z}^i)|\, \mathbf{k}_{Mi}^\top \mathbf{K}_{MM}^{-1}\mathbf{m}, k(\mathbf{Z}^i, \mathbf{Z}^i) - \mathbf{k}_{Mi}^\top \mathbf{K}_{MM}^{-1}\left(\mathbf{K}_{MM} - \mathbf{S}\right)\mathbf{K}_{MM}^{-1}\mathbf{k}_{Mi}\right)$$

- Expectation approximate with MC sampling and reparametrisation trick

Data set

- All S2 acquisitions between [01-2018, 12-2018]
- 10 bands + 3 spectral indices
- $T = 303$ & $D = 13$
- 23 land cover classes
  - Training: 4000 pixels/class
  - Validation: 1000 pixels/class
  - Test: 10,000 pixels/class
  - 9 random (train, val, test) sets

Training	*Validation*	*Test*
92 000	23 000	230 000



Results

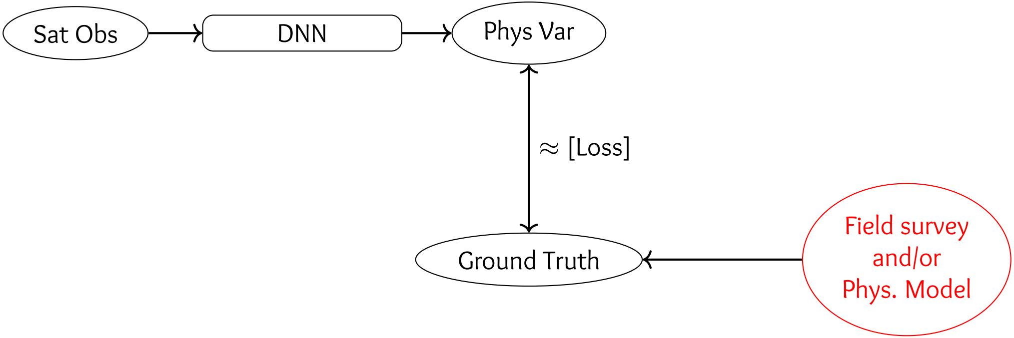
	mTAN-MLP	**mTAN-SVGP**	linInter-SVGP	linInter-RF
OA (%)	71.5	**77.4 (0.2)**	67.3 (0.4)	65.4 (0.4)
Time (s)	1207	**1317.4**	336.6	54.6

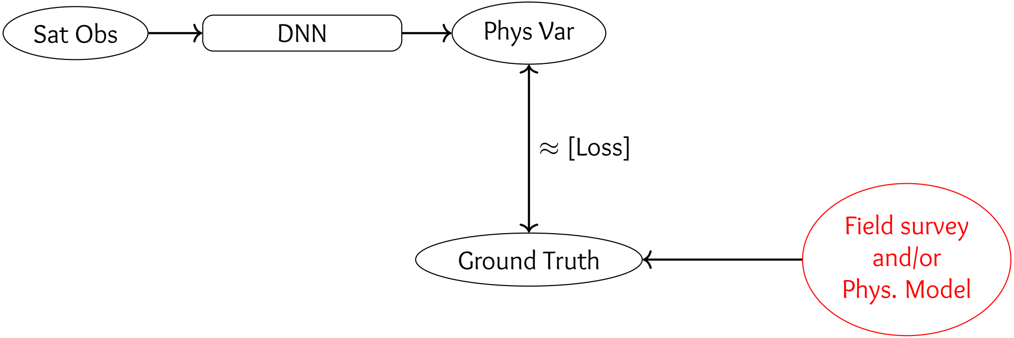
- Publications:

  - Valentine Bellet, Mathieu Fauvel, and Jordi Inglada. "Land Cover Classification with Gaussian Processes using spatio-spectro-temporal features." In: *IEEE Transactions on Geoscience and Remote Sensing* (Jan. 2023). DOI: 10.1109/TGRS.2023.3234527. URL: https://hal.science/hal-03781332
  - Valentine Bellet et al. "End-to-end Learning for Land Cover Classification using Irregular and Unaligned SITS by Combining Attention-Based Interpolation with Sparse Variational Gaussian Processes." working paper or preprint. July 2023. URL: https://hal.science/hal-04112115

Plan

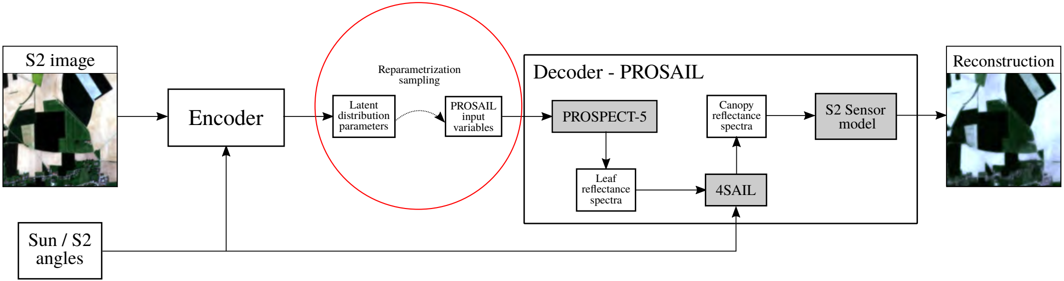
Physically aware ML





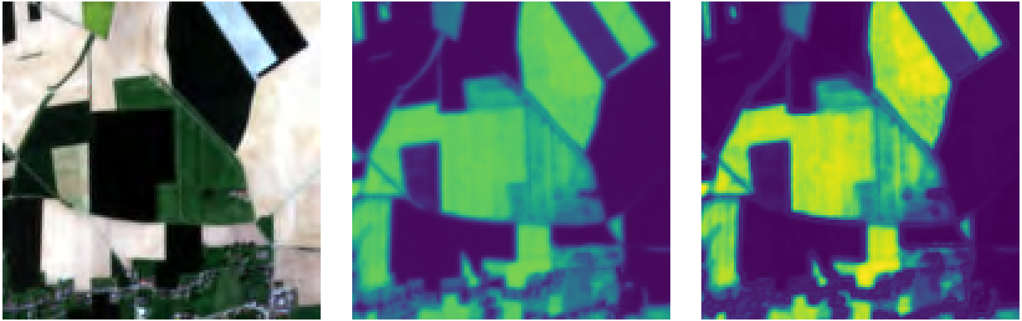
- Distribution of GT biased
- *Use the physical model as the decoder in a AE framework*: no GT needed for training.

Prosail-VAE



- Variational AE with *constrained Prior*
  - Truncated Gaussian
  - Auto-regressive
- Yoël Zérah, Silvia Valero, and Jordi Inglada. "Physics-Driven Probabilistic Deep Learning for the Inversion of Physical Models With Application to Phenological Parameter Retrieval From Satellite Times Series." In: *IEEE Transactions on Geoscience and Remote Sensing* 61 (June 2023). DOI: 10.1109/TGRS.2023.3284992. URL: https://hal.science/hal-03837736

RMSE	LAI BelSAR 2018	LAI Barrax 2018	LAI Barrax 2021	LAI Wytham 2018	LAI ALL	CCC Barrax 2018	CCC Barrax 2021	CCC Wytham 2018	CCC ALL
MLP-Reg	**1.22**	1.43	**0.48**	1.77	1.24	83.92	84.53	101.35	88.08
Prosail-VAE	1.30	**1.42**	0.72	**1.21**	**1.16**	**27.60**	**20.51**	**80.78**	**42.33**



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Take away

Conclusions

Generative Models for Satellite Image Analysis

- More robust to noisy data
- More robust to limited (no) training data
- More accurate

Perspectives

ANITI 2.0 - RELEO

- More data source
- Richer prior distribution
- Meteo & Agro model
- Essential Biodivisity/Climate variables
- Industrial Chair

Bibliography I

[1] Valentine Bellet, Mathieu Fauvel, and Jordi Inglada. "Land Cover Classification with Gaussian Processes using spatio-spectro-temporal features." In: *IEEE Transactions on Geoscience and Remote Sensing* (Jan. 2023). DOI: 10.1109/TGRS.2023.3234527. URL: https://hal.science/hal-03781332.

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[3] James Hensman, Alex Matthews, and Zoubin Ghahramani. "Scalable Variational Gaussian Process Classification." In: *In Proceedings of the 18th International Conference on Artificial Intelligence and Statistics*. 2015, pp. 351–360.

[4] Yoël Zérah, Silvia Valero, and Jordi Inglada. "Physics-Driven Probabilistic Deep Learning for the Inversion of Physical Models With Application to Phenological Parameter Retrieval From Satellite Times Series." In: *IEEE Transactions on Geoscience and Remote Sensing* 61 (June 2023). DOI: 10.1109/TGRS.2023.3284992. URL: https://hal.science/hal-03837736.