Latent Field Reduction of Earth Observation Foundation Model

Advances in Representation Learning for Earth Observation

Lars Uebbing[1], **Harald L. Joakimsen**[1], **Theodor J. L. Forgaard**[2], **Michael C. Kampffmeyer**[1,2], **Kristoffer K. Wickstrøm**[1], **Sébastien Lefèvre**[1,3], **Arnt-Børre Salberg**[2], **Robert Jenssen**[1,2,4]

[1]UiT The Arctic University of Norway, [2]Norwegian Computing Center [3]University of South Brittany, [4]University of Copenhagen

Earth Observation Foundation Model

- **FM4CS**: Foundational Model for Climate and Society, encodes satellite images into 768-dimensional latent vectors v using a ViT architecture.
- **Data**: Sentinel-3 SLSTR daily measurements over Norway (2018), 4 optical + 2 thermal bands, 2–3 km resolution.
- **Latent Field**: Latent vectors form a spatially resolved, abstract vector field $v(x)$ of satellite data across the region.

(Reference 1)

Latent Vector Field Embedding

- **Idea**: Analyze latent field via dimensionality reduction of vectors v.
- **Problem:** Traditional methods treat vectors as point cloud → ignore domain and continuity of underlying structure.
- **Solution:** Treat vectors as samples from a continuous field and find embedding $u(x)$ of the field in a lower dimensional vector space using Graph Kernel Operators (GKO).

Graph Kernel Operator

- **Graph construction**:
  - Sample set of random latent vectors $v(x_i)$ as node features.
  - Nearest neighbors connected by edges.
  - Edges equipped with attributes containing positional encoding of nodes.

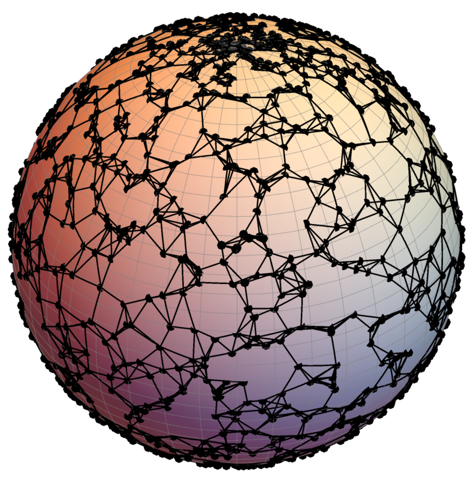


Figure 1: Visualization of graph, constructed using discrete latent vector field realizations for GKO-based dimensionality reduction.

- **Architecture**
  - Lifting: Single linear layer P projects nodes into a intermediate dimensional vector space H

$$Pv(x_i) = h_i \in H. \qquad (1)$$

  - Message-Passing: Information from neighboring nodes is iteratively passed

$$h_i^{(t+1)} = \sigma\left(Wh_i^{(t)} + \sum_{j:(i,j)\in E(i,j)} K_{ij} h_j^{(t)}\right), \qquad (2)$$

    using a kernel matrix K_{ij} that is predicted based on edge attributes.
  - Final node features $h^{(T)}$ are projected into low-dimensional space with using a linear layer Q

$$Qh_i^{(T)} = \hat{u}(x_i) \qquad (3)$$

(Reference 2)

Experiments

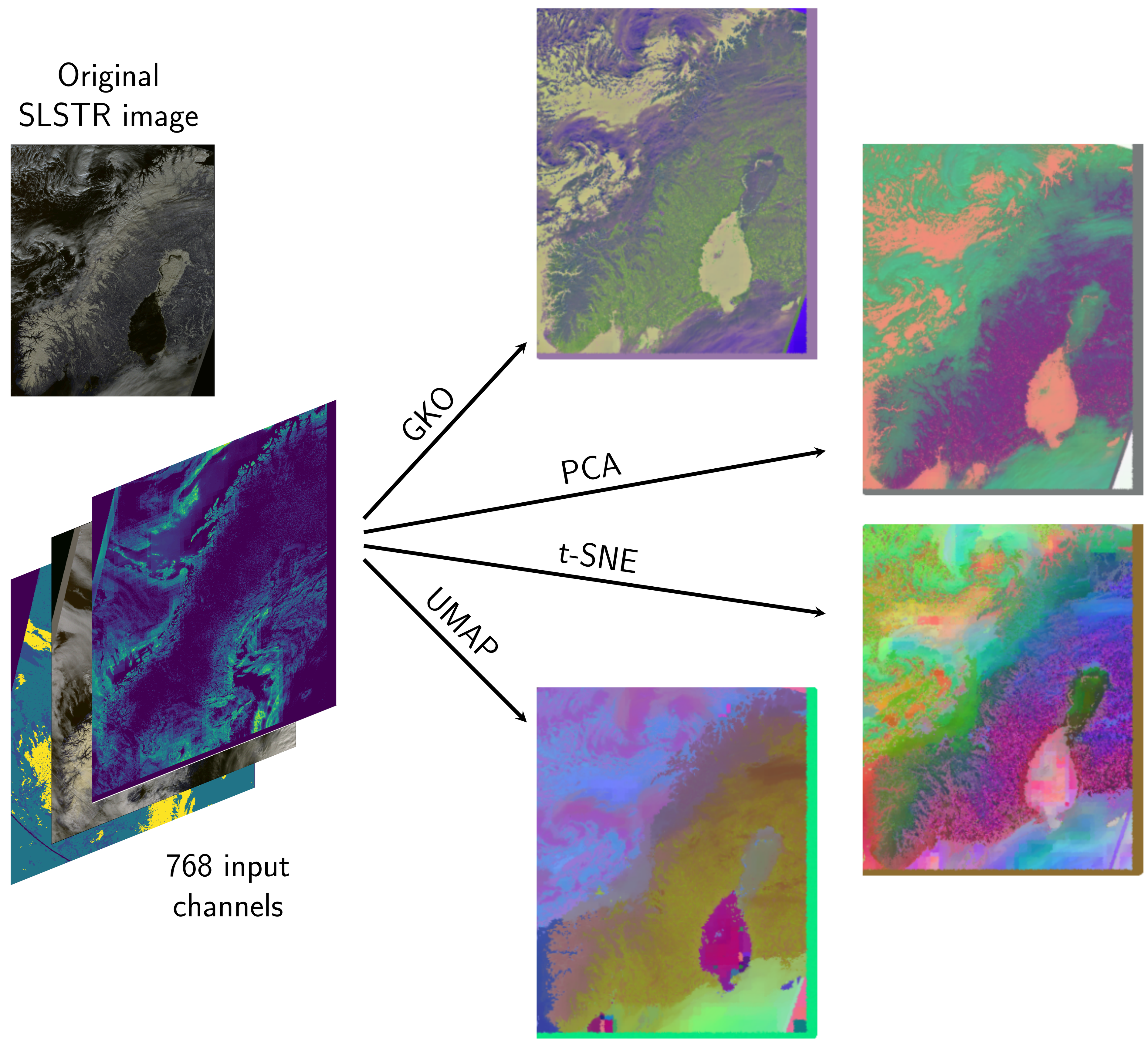
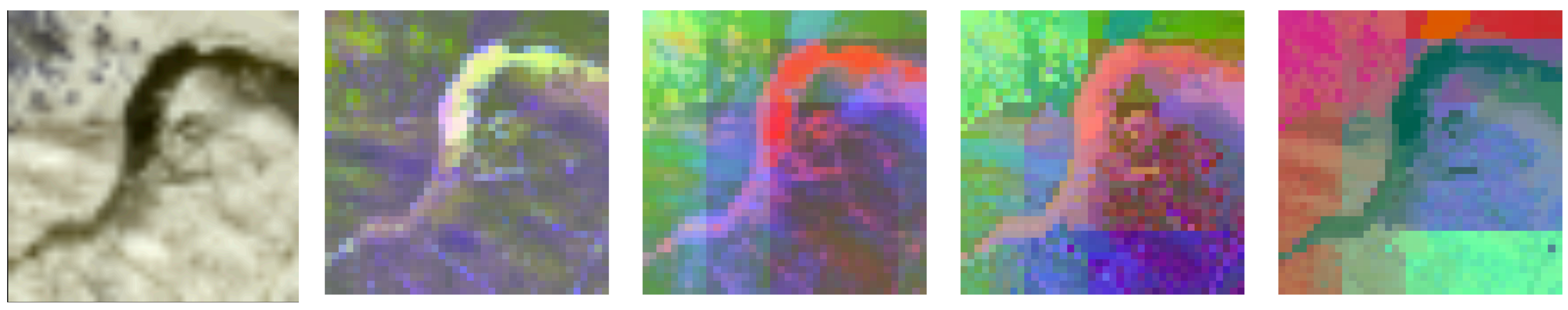


Figure 2: 100,000 randomly sampled vectors from FM4CS' latent space representation of Scandinavia for 01.04.2018 are reduced from 768 to 3 dimensions. For comparison, this is done using our GKO method, as well as classical methods (PCA, t-SNE, UMAP). Results are displayed by interpreting each of the 3 dimensions as an RGB color-channel.



(a) SLSTR (b) GKO (c) PCA (d) t-SNE (e) UMAP

Figure 3: Dimensionality reduction for densely sampled 1600 latent vectors for a small region, representing a "zoom" into a small region of interest. Plots compare (3a) the original SLSTR image and (3b–3e) reduction for the same samples across methods.

Main Results

- **Conceptual Advantage:**
  - Traditional methods view data as point cloud; GKO view vectors as discrete realizations of a continuous field. This guarantees **continuous embeddings**.
  - Due to its graph structure and positional encodings, GKO-based dimensionality reduction is **domain-aware**.
- **Practical Observations:**
  - GKO method is efficient and scalable.
  - Resulting images are closer to original SLSTR images → increases interpretability.
  - Traditional methods contain artifacts due to overclustering and underlying image-patch structure; GKO is the only method to overcome these issues.

Visual Intelligence projects are financially supported by the Research Council of Norway, through its Centre for Research-based Innovation funding scheme (grant no. 309439), and Consortium Partners.

References 1
FM4CS presentation:
https://nr.no/en/publication/10255345/

References 2
Z. Li, et al., *Neural Operator: Graph Kernel Network for Partial Differential Equations, arXiv preprint arXiv:2003.03485*, 2020. [Online]. Available: https://arxiv.org/abs/2003.03485

VISUAL INTELLIGENCE

sfi Centre for Research-based Innovation
The Research Council of Norway

UiT The Arctic University of Norway