A comprehensive framework for analysis and review of super-resolution models in earth observation imagery

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1. Introduction & motivation

Earth Observation data are inherently characterised by a trade-off between spatial resolution and coverage, spectral richness, or revisit frequency, making super-resolution a crucial capability for extracting finer spatial detail from the vast volumes of imagery.

However, the practical adoption of super-resolution (SR) in Earth Observation (EO) remains challenging. Many enhancement methods are developed and validated under pre-defined assumptions, largely due to the scarcity of representative real-world training data, resulting in limited visibility into their trade-offs and potential risks when considered for operational use.

As a result, EO organisations often lack the confidence and decision-oriented guidance needed to determine when, where, and how advanced SR techniques should be integrated into existing processing pipelines without inadvertently introducing risk or disrupting established workflows.

References

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2. Background & limitations

Existing SR approaches for EO are typically developed and evaluated under controlled and/or simplified assumptions. This is largely driven by the scarcity of representative real-world paired low-resolution (LR) and high-resolution (HR) training data, which leads to the widespread use of synthetic degradation models or indirect supervision during model development and benchmarking.

As a result, evaluation practices in EO SR remain predominantly model-centric, focusing on aggregate image-quality metrics, perceptual quality measures, or qualitative visual inspection. While such approaches are effective for comparing algorithmic performance, they provide limited visibility into application-specific trade-offs or operational risks.

This limitation is not confined to a particular modelling paradigm. Through an extensive review of more than 200 research papers, complemented by test-running and inspection of representative implementations, we observe that super-resolution performance is commonly demonstrated under tightly coupled assumptions and context-specific configurations. Many critical choices, such as data preprocessing, and impractical factors, are embedded in code and experimental setup rather than made explicit in reported results.

Consequently, despite rapid methodological progress, existing super-resolution literature offers limited practical guidance for determining how different enhancement strategies should be selected, interpreted, or integrated within real Earth Observation workflows.

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- Wang, X.; Yi, J.; Guo, J.; Song, Y.; Lyu, J.; Xu, J.; Yan, W.; Zhao, J.; Cai, Q.; Min, H. A Review of Image Super-Resolution Approaches Based on Deep Learning and Applications in Remote Sensing. Remote Sens. 2022, 14, 5423. https://doi.org/10.3390/rs14215423
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3. Framework overview

To address these limitations, we propose a decision-driven framework for analysing and reviewing SR methods in EO.

The framework structures evaluation around three complementary activities: Model Exploration, Evidence-Based Comparison, and SR Behaviour Inspection, so that SR assessment supports informed decision-making about applicability, trade-offs, and risk in context, rather than relying on aggregated performance metrics alone.

3.1 Model exploration

Expose assumptions through practical inspection

- Screen and localise candidate SR methods beyond reported results
- Inspect and test runnable implementations to surface implicit assumptions and impractical settings

Outcome

- A clear understanding of a method's assumptions and applicability, to support future evaluation-pool selection

3. Framework overview

3.2 Evidence-based comparison

Compare methods through extensible, multi-metric profiles

- Aggregate multiple quality metrics into a unified comparison space, rather than relying on single headline scores
- Use an extensible representation that allows new metrics to be added without changing the comparison structure
- Compare SR methods based on their overall performance profiles, making strengths, weaknesses, and trade-offs immediately visible

Outcome

- A flexible, interpretable comparison that reveals how different SR methods balance fidelity, enhancement, and artefact risk, supporting informed evaluation-pool decisions

3.3 SR behaviour inspection

Inspect data-level SR behaviour beyond metric summaries

- Represent super-resolution (SR) as an explicit data-in / data-out workflow with controlled processing steps
- Enable consistent execution and inspection across different SR methods using the same inputs and configurations
- Reveal behaviours, artefacts, and sensitivities that are not fully captured by aggregated metric representations

Outcome

- A transparent understanding of how SR methods transform data in practice, complementing radar-chart comparisons with inspection-based insight that supports reliable evaluation decisions

4. Trade-off-based decision support

Decision-oriented evaluation of super-resolution (SR) requires both metric-level trade-off analysis and data-level behaviour inspection. Section 4 demonstrates how these complementary views are combined to support informed judgement about SR suitability.

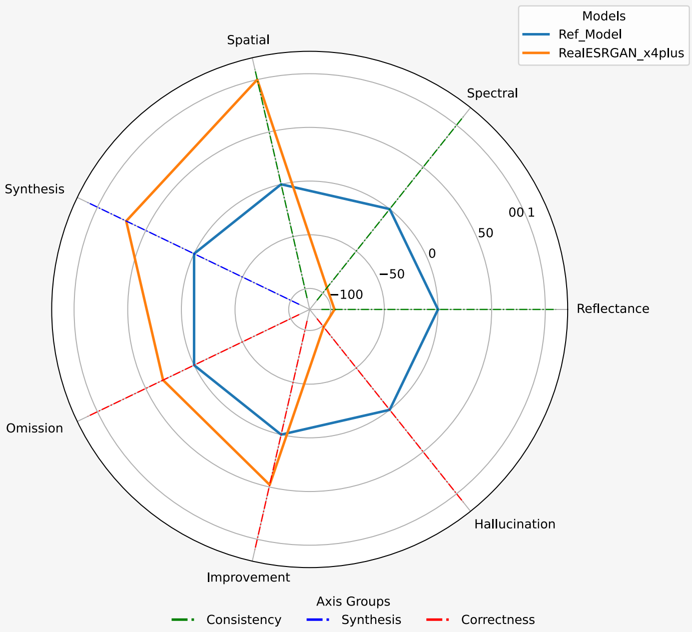
4.1 Evidence-based comparison via radar charts

- To compare super-resolution (SR) methods in a decision-relevant manner, multiple quality metrics must be aggregated into a unified and extensible representation. The radar chart illustrated on the next page fulfils this requirement effectively
- Each axis corresponds to a specific quality aspect, allowing diverse evaluation criteria to be expressed within a single comparison space
- By presenting overall performance profiles, the radar chart makes relative strengths, weaknesses, and trade-offs immediately visible
- Crucially, the representation is extensible: new metrics can be introduced as additional axes without altering the overall structure, supporting evolving evaluation priorities
- Differences in shape and balance reflect how SR methods trade off fidelity preservation, detail enhancement, and artefact risk, enabling evaluators to reason about suitability under different requirements rather than selecting a single “best” model

4. Trade-off-based decision support

4.1 Evidence-based comparison via radar charts

Model – RealESRGAN



Low-resolution

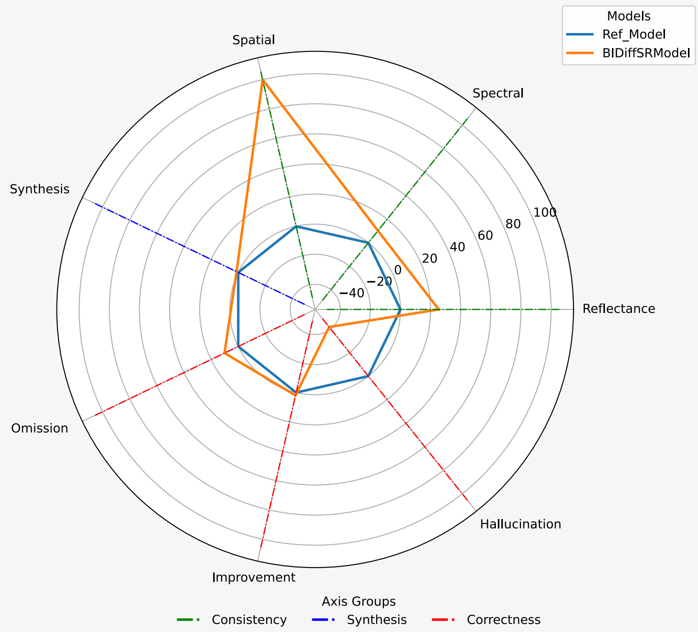
Super-resolution

High-resolution ground truth

4. Trade-off-based decision support

4.1 Evidence-based comparison via radar charts

Model – BIDiffSR



Low-resolution

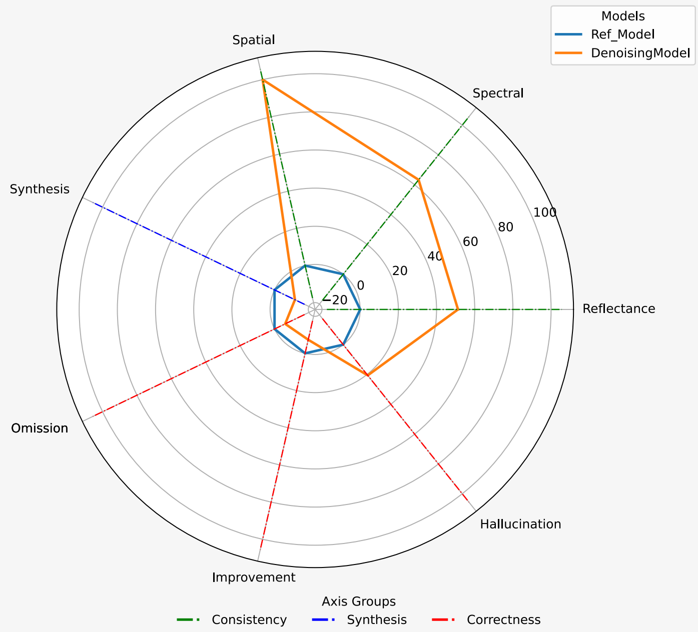
Super-resolution

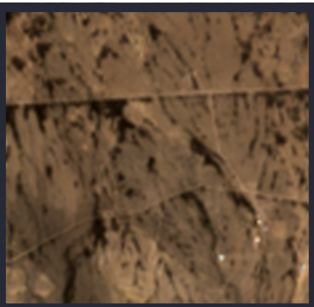
High-resolution ground truth

4. Trade-off-based decision support

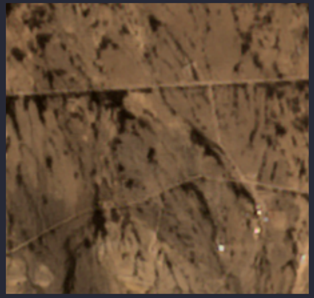
4.1 Evidence-based comparison via radar charts

Model – EDiffSR

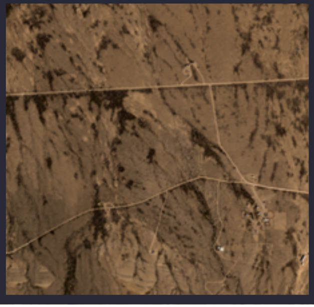




Low-resolution



Super-resolution

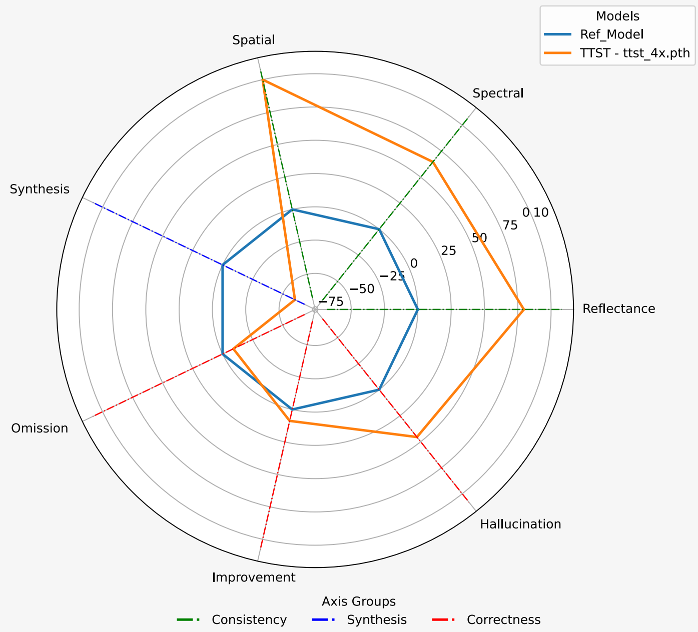


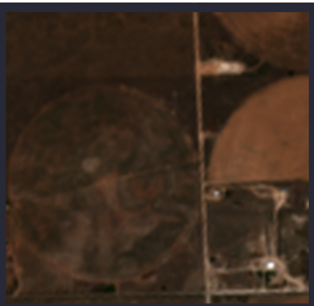
High-resolution ground truth

4. Trade-off-based decision support

4.1 Evidence-based comparison via radar charts

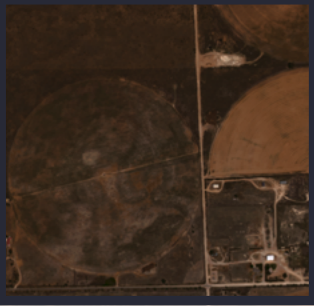
Model – TTST





Low-resolution

Super-resolution



High-resolution ground truth

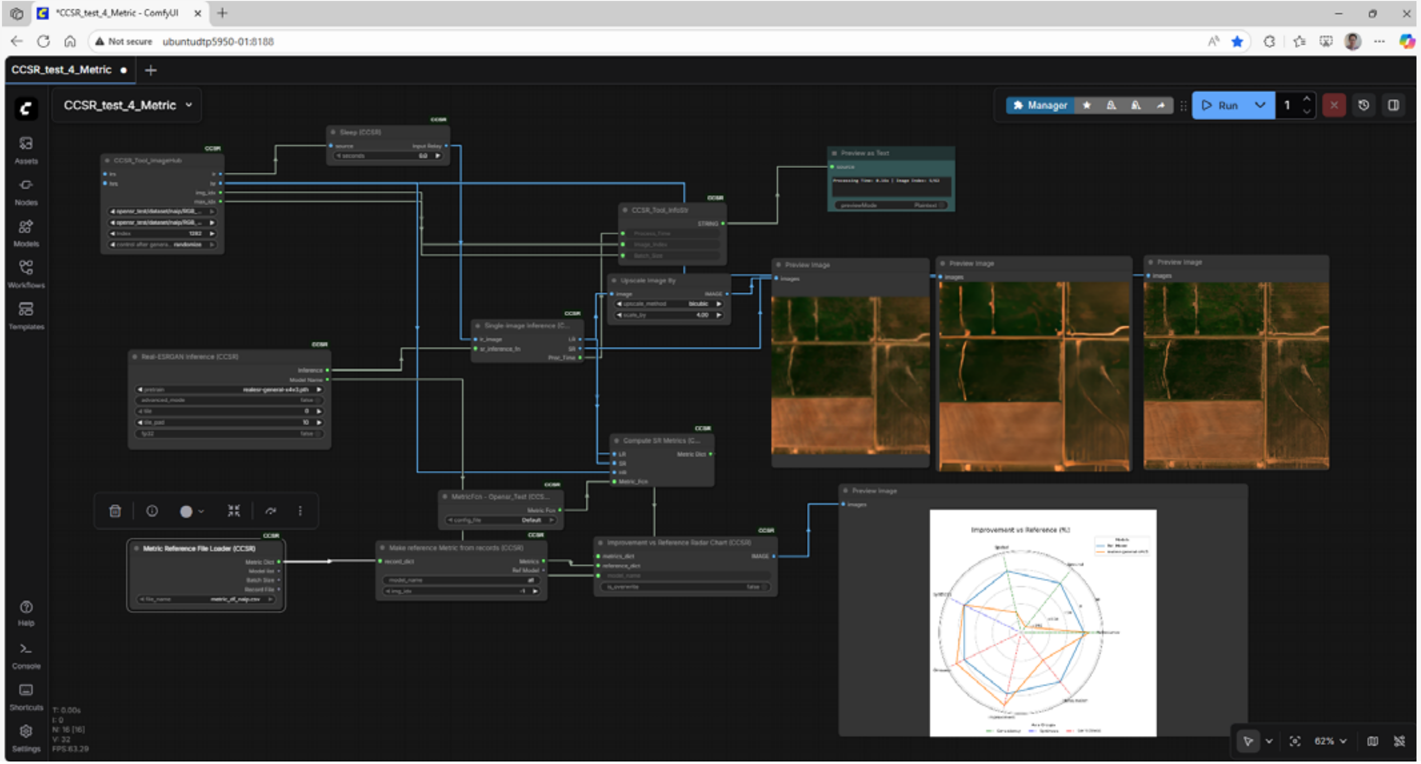
4. Trade-off-based decision support

4.2 SR behaviour inspection beyond metric summaries

- Radar-chart comparisons summarise performance trade-offs but do not fully capture how super-resolution (SR) methods transform data
- To inspect SR behaviour directly, we use a controlled data-in / data-out workflow, illustrated here via a ComfyUI-based implementation
- Executing different SR methods under identical inputs and configurations enables consistent inspection of data-level behaviour, revealing artefacts and sensitivities that may not be evident from aggregated metrics alone
- This behaviour-level view complements radar-chart reasoning by grounding evaluation in observable data transformations
- ComfyUI is used as an example execution environment and is not a requirement of the framework

4. Trade-off-based decision support

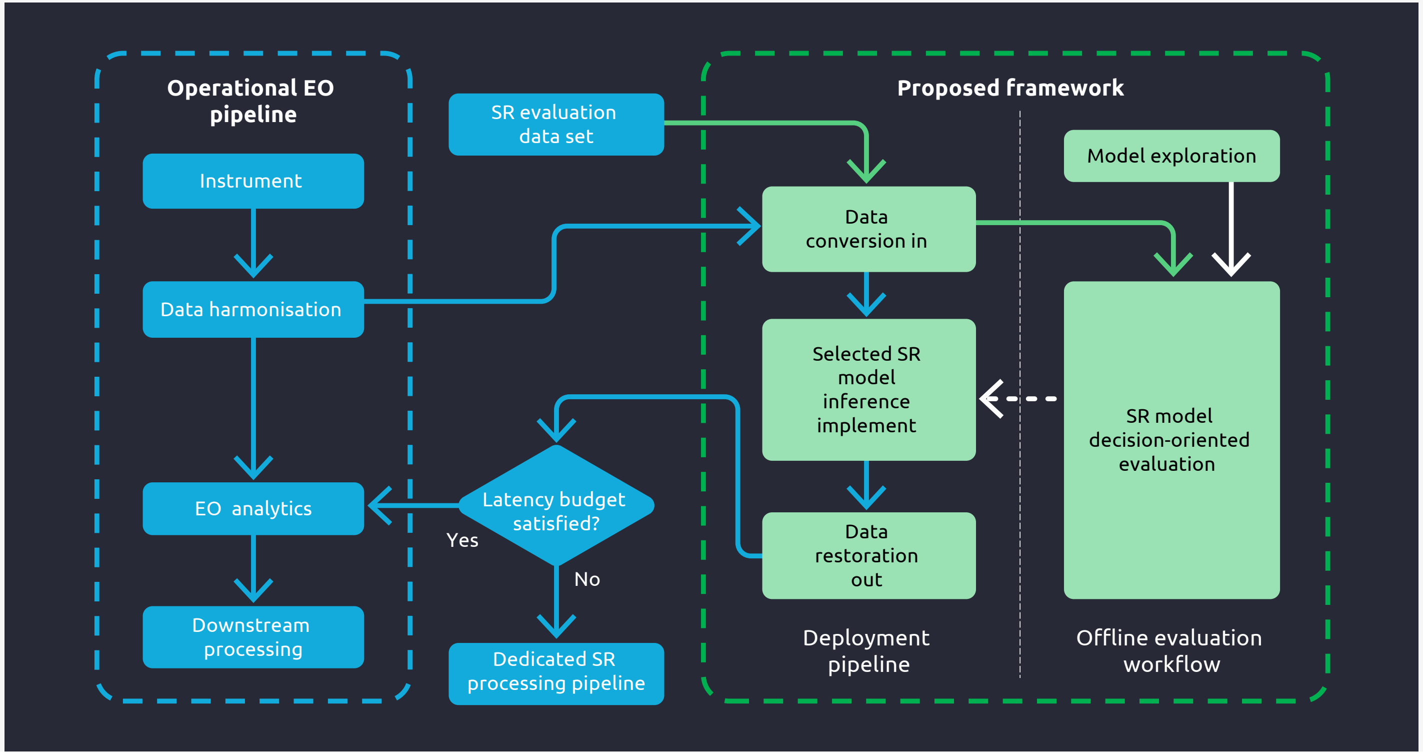
4.2 SR behaviour inspection beyond metric summaries



5. Pipeline integration

- The proposed framework integrates SR into an existing EO pipeline as an optional data-level enhancement applied after data harmonisation, preserving compatibility with downstream EO analytics
- SR model decision-oriented evaluation is performed offline and outside the operational pipeline. Its role is to support SR model selection and configuration, enabling a selected model to be executed seamlessly during deployment. Once configured, SR inference operates purely as a runtime component and does not involve further evaluation logic
- To ensure interoperability between the EO pipeline and SR inference, common Data Conversion In and Data Restoration Out stages are shared across SR models, defining stable data interfaces. These stages are well suited to hardware acceleration (e.g. FPGA), enabling latency reduction without constraining the choice of SR model
- Latency is therefore treated as a system-level deployment consideration, not a property of SR algorithms. SR can be enabled inline when latency budgets permit, bypassed entirely, or offloaded to dedicated processing resource, without disrupting existing EO workflows

5. Pipeline integration



6. Outcomes & implications

This work presents a decision-driven framework for evaluating and integrating super-resolution in earth observation pipelines, addressing the gap between research-level performance reporting and operational use. By structuring evaluation around trade-off analysis and data-level behaviour inspection, the framework enables practitioners to assess enhancement methods in terms that reflect real application constraints rather than isolated metrics.

Separating offline evaluation from runtime execution and embedding super-resolution as an optional pipeline stage supports controlled adoption without disrupting established workflows. This allows enhancement to be introduced, constrained, or bypassed based on application needs, reducing the risk of unintended effects propagating into downstream analytics.

Overall, the framework provides a practical basis for translating advanced super-resolution methods into deployable capabilities, supporting informed decision-making, risk-aware integration, and sustained adaptability in operational earth observation systems.

Let's talk

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