ML-Driven Observational Augmentation: Synthesizing High-Frequency Microwave Imagery of Tropical Cyclones for Enhanced Data Assimilation

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1 BACKGROUND & MOTIVATION

- Data assimilation is central to operational NWP, but its value is constrained by sparse critical observations.
- Passive microwave imagery reveals internal storm structure, eyewalls, rainbands, and precipitation.
- Polar-orbit sampling creates multi-hour temporal gaps and incomplete swaths over tropical cyclones.
- Infrared imagery is abundant and frequent, but primarily senses cloud-top thermal structure.
- We synthesize MW-like imagery from IR to increase effective observational frequency and coverage.

OBSERVATIONAL GAP
Frequent IR → synthetic 85 GHz MW-like imagery

2 OBJECTIVE

Develop an ML-based observational augmentation approach that:

- translates 11 μm TC infrared imagery into synthetic 85 GHz microwave imagery;
- increases temporal and spatial availability for forecasting and DA-oriented evaluation;
- preserves structural information needed for eyewall, rainband, and precipitation analysis.

Scope: downstream forecast utility is tested; direct DA impact remains future work.

3 DATASET & METHOD

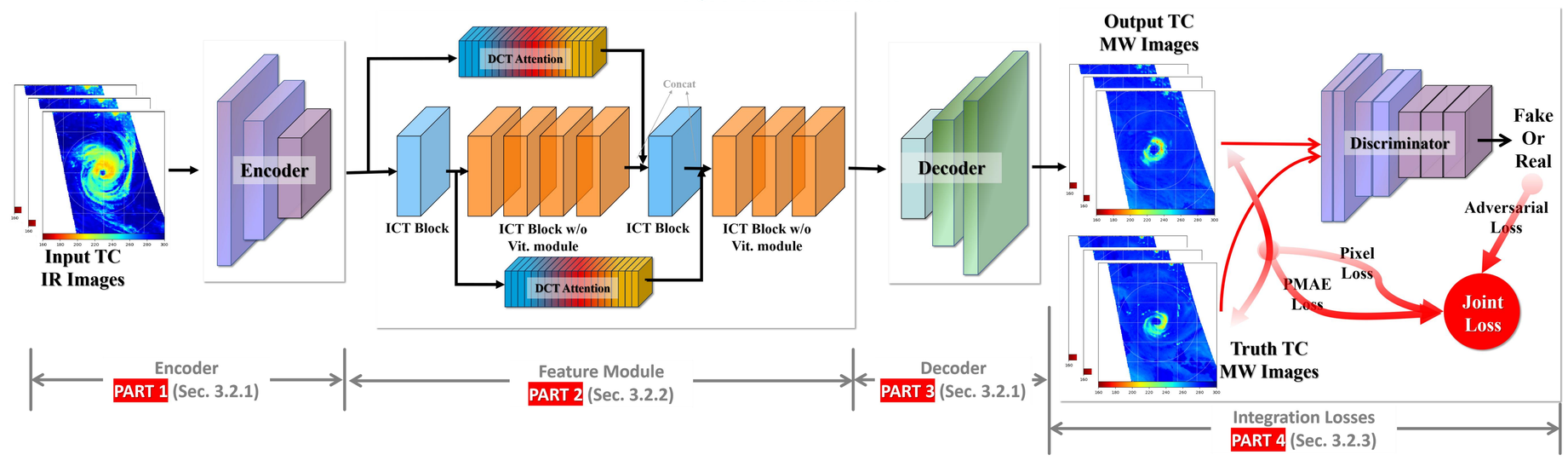
Dataset

- TCIR2MW built by matching NOAA HURSAT-B1 IR and HURSAT-MW observations.
- 9,253 paired IR-MW samples, cropped to 300 x 300 pixels.
- 11 μm IR window channel → 85 GHz MW channel.
- Train / validation / test split: 80% / 10% / 10%.

Method

- TCA-ViT combines an encoder, Feature Module, decoder, and joint loss.
- CNN and Transformer blocks learn local texture and global storm organization.
- DCT channel attention emphasizes informative frequency components.
- Pixel, adversarial, and phase-MAE losses jointly preserve intensity, detail, and geometry.

TCA-ViT framework



Global structure | **ViT blocks** | **Local detail** | **Residual CNN** | **Physical structure** | **Phase loss**

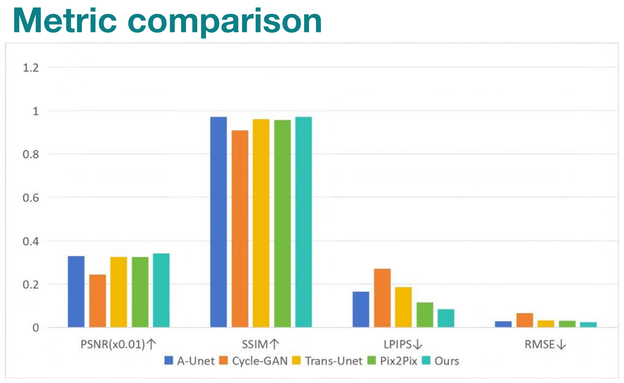
Inference: ~100 ms per image; ~45 ms per image in batch mode in the reported RTX 3090 experiments.

4 RESULTS

Quantitative comparison (test set)

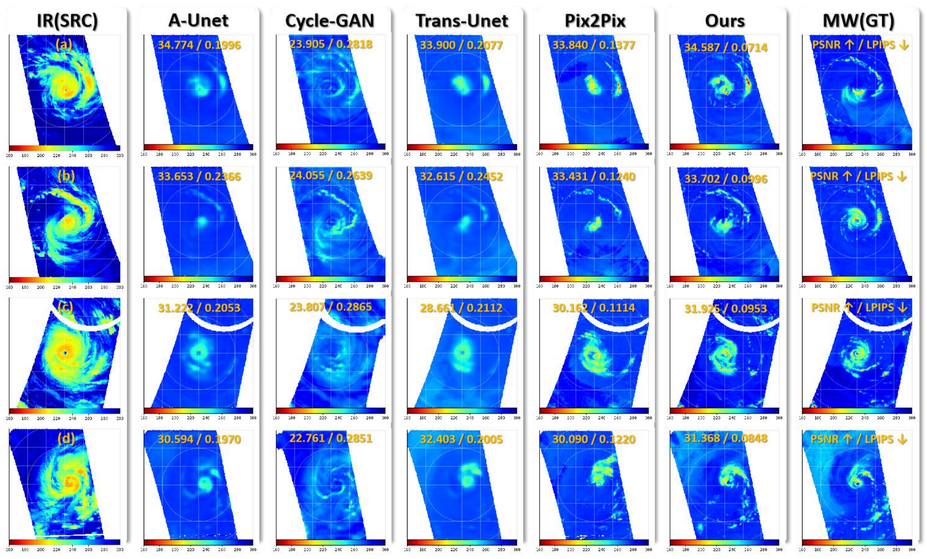
Model	PSNR ↑	SSIM ↑	LPIPS	RMSE
A-Unet	32.94	0.971	0.165	0.028
Cycle-GAN	24.25	0.908	0.269	0.065
Pix2Pix	32.66	0.957	0.115	0.030
Trans-Unet	32.68	0.961	0.185	0.031
TCA-ViT	**34.200**	**0.9715**	**0.0836**	**0.0241**

Metric comparison



- TCA-ViT achieves the strongest overall test-set balance.
- Generated images preserve eyewalls and spiral rainbands.
- Full MW-like outputs can fill regions missing from polar-orbit swaths.

Qualitative comparison (85 GHz MW)



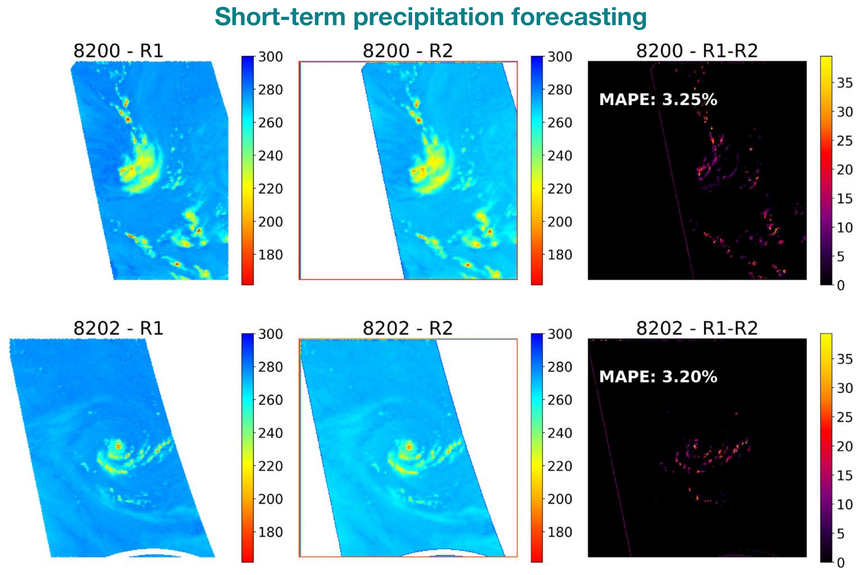
STRUCTURAL FIDELITY

TCA-ViT reconstructs the TC eye and organized rainbands more consistently than the comparison models while retaining realistic microwave intensity patterns.

PSNR 34.2004 dB | SSIM 0.97146 | LPIPS 0.08357 | RMSE 0.02414

5 DOWNSTREAM VALIDATION

Short-term precipitation forecasting



3.24% average MAPE between forecast outputs using real and generated MW

- Generated MW provides comparable support in this downstream task.
- The result supports information retention, not observational equivalence.
- Direct OSE/OSSE or operational DA impact experiments are still required.

6 IMPLICATIONS FOR DATA ASSIMILATION

- Increases the effective frequency of MW-like observations.
- Fills temporal and spatial gaps caused by satellite orbit limitations.
- Provides a fast emulator for DA-oriented observation augmentation studies.
- Enables uncertainty and QC research before operational integration.

7 LIMITATIONS & FUTURE WORK

- Only the 11 μm IR and 85 GHz MW channels are used.
- Physical guidance is loss-based and does not yet model full TC dynamics.
- Rare extremes, regional diversity, and hallucination risk need broader validation.
- Next: multi-band, temporal constraints, confidence metrics, and OSE/OSSE studies.

8 KEY TAKEAWAYS

1. **Synthetic MW from abundant IR can reduce observational scarcity.**
2. **ViT + DCT attention + phase loss preserve storm structure.**
3. **Best test balance: PSNR 34.20, SSIM 0.971, LPIPS 0.084, RMSE 0.024.**
4. **Precipitation validation is promising; operational DA remains to be tested.**

SOURCE PAPER
A data fusion approach to synthesize microwave imagery of tropical cyclones from infrared data using vision transformers
Information Fusion 131 (2026) 104167 | doi.org/10.1016/j.inffus.2026.104167

CODE + DATA
github.com/kleenY/TCIR2MW