# Correction of TanDEM-X InSAR DEM Penetration Bias Using Physics-Informed Neural Networks: A Case Study of the Greenland Ice Sheet

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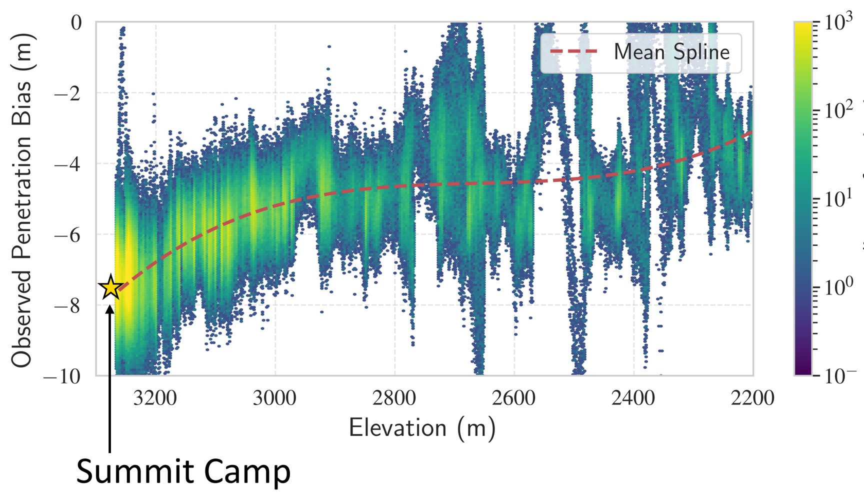
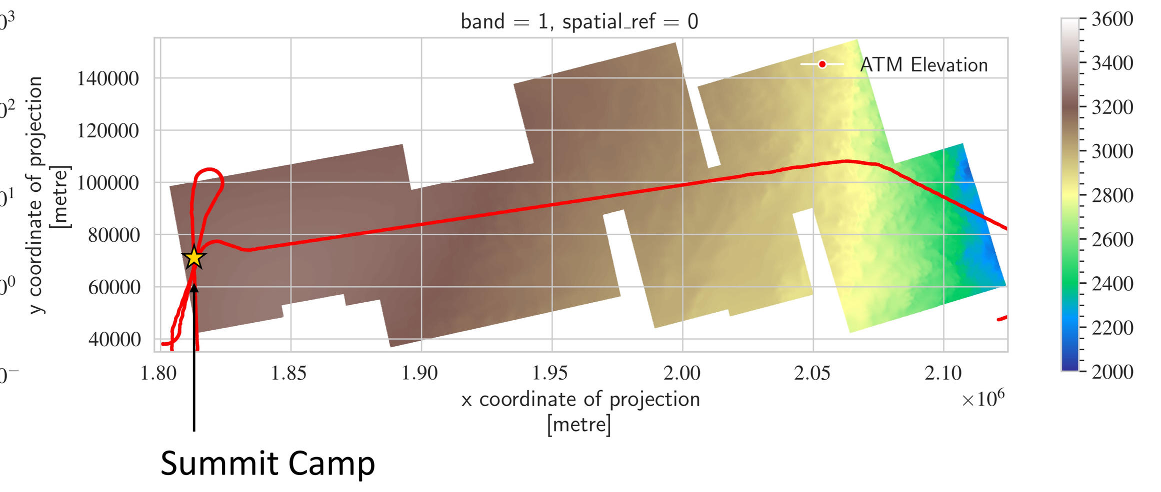
## Study Area and Dataset

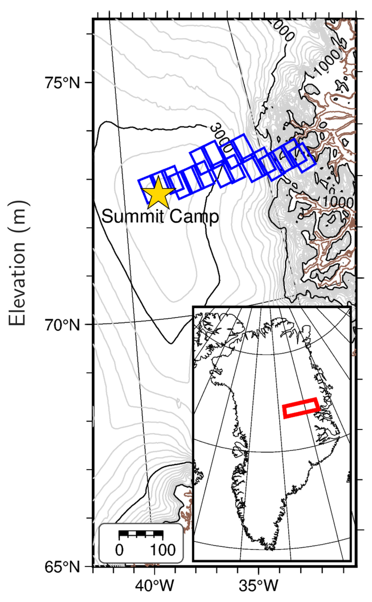
- **Motivation**: Compensating for InSAR elevation biases caused by penetration over ice sheets.

$$p_{\text{bias}} = DEM_{InSAR} - DEM_{Ref}$$

- **Location:** Greenland, from summit to east cost.
- **Dataset:** TanDEM-X SAR scenes (Jan–Mar 2017) and NASA IceBridge ATM LiDAR (Mar 2017).



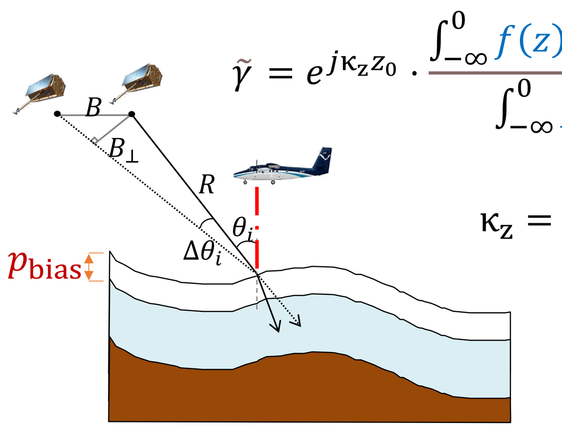




## Estimation of Penetration Bias

### Physical Modeling[1]:

- Utilize a vertical scattering distribution $f(z)$ (e.g., Exponential, Weibull) to model InSAR volume decorrelation and coherence.
- Invert the InSAR Phase Center Depth $\angle\gamma$ to estimate penetration depth.

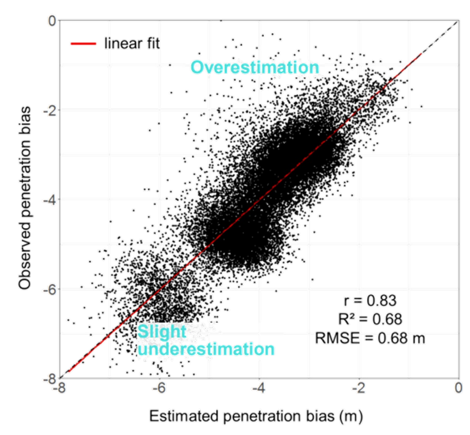



$$\tilde{\gamma} = e^{j\kappa_z z_0} \cdot \frac{\int_{-\infty}^{0} f(z) \cdot e^{-j\cdot\kappa_z z}\, dz}{\int_{-\infty}^{0} f(z)\, dz}$$

$$\kappa_z = \frac{4\pi}{\lambda} \frac{\Delta\theta_i}{\sin\theta_i}$$

### Linear Regression/ML[2] :

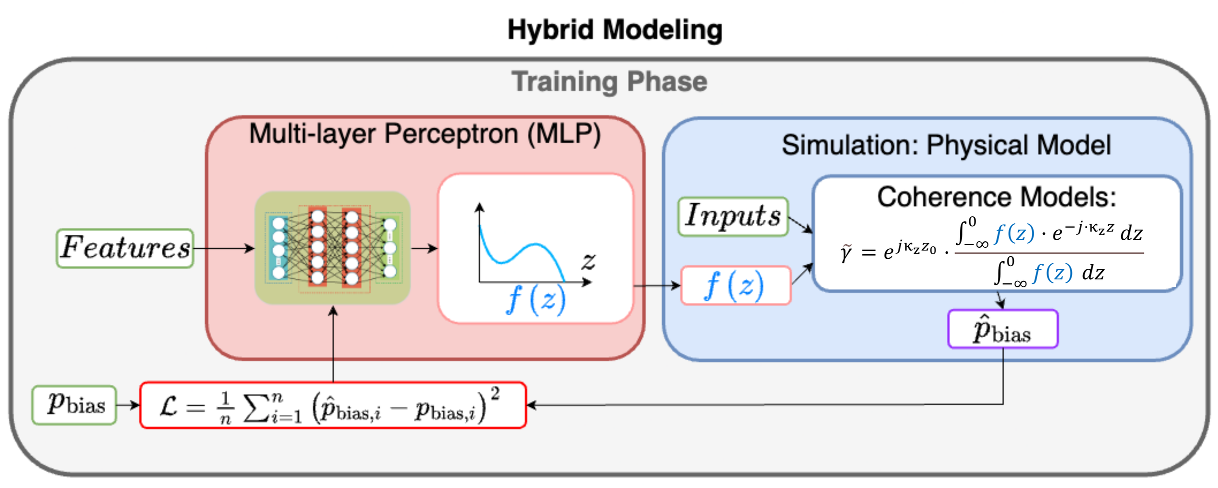
- Applies statistical linear regression models to adjust measured values and minimize bias.
- Implements correction functions across all scenes to correct elevation estimates.

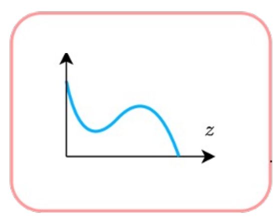



## Methodology: Hybrid Method (Physics-informed Neural Networks)

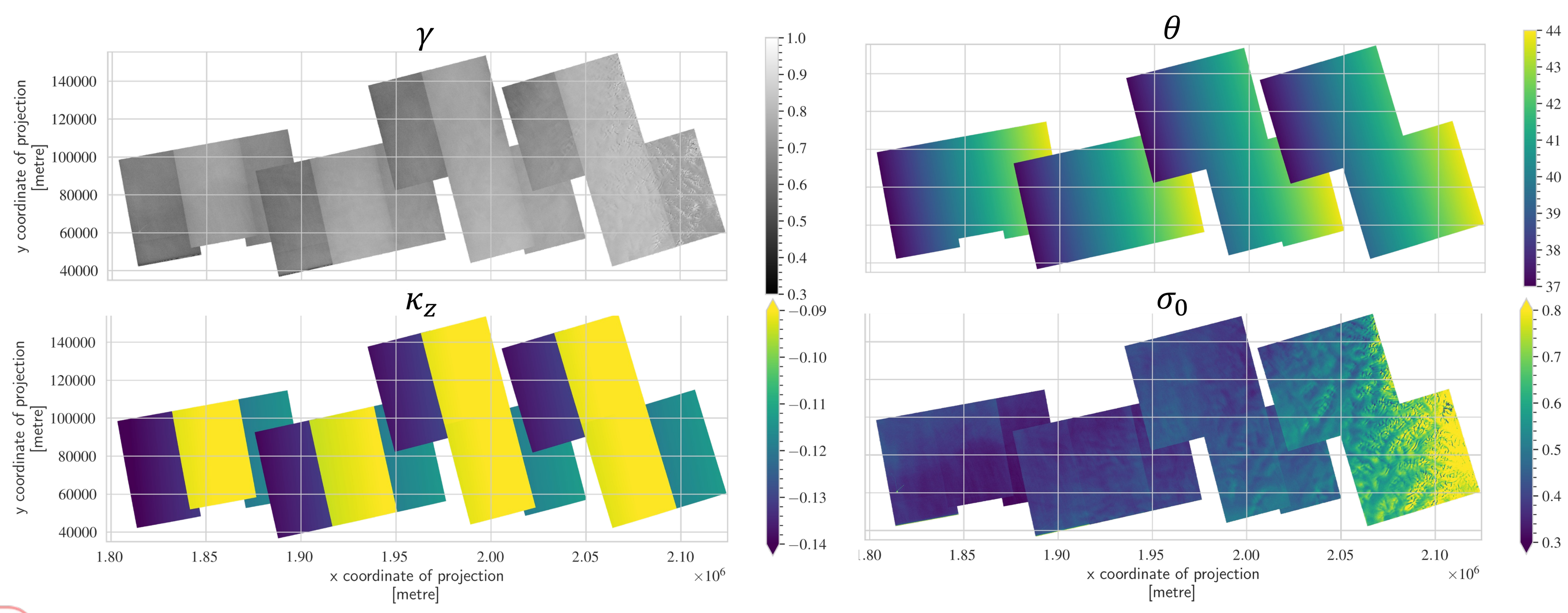
### Hybrid Method (Physics-informed Neural Networks):

- Combines ML with physical modeling for enhanced bias correction.
- Input features include interferometric coherence and other SAR-derived metrics.
- Learn a scattering distribution (e.g., Exponential, Weibull) to compensate for the underlying assumptions of the physical model.



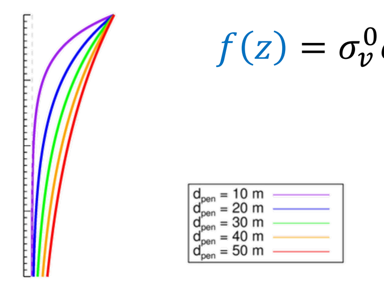



Input Features



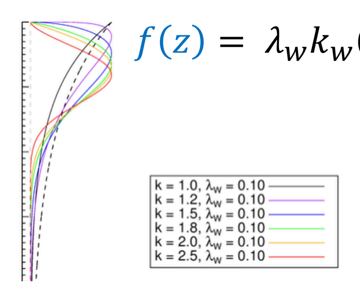

**Exp. Profile**

$$f(z) = \sigma_v^0 e^{\frac{2z}{d_{\text{pen}}}}$$



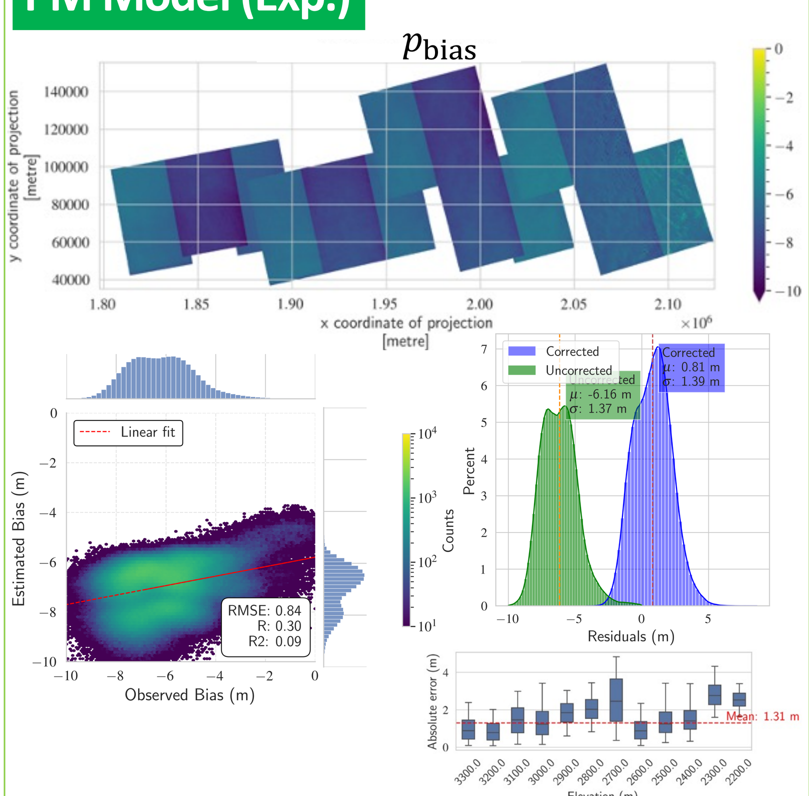
**Weibull Profile**

$$f(z) = \lambda_w k_w (\lambda_w z)^{k_w - 1} e^{-(\lambda_w z)^{k_w}}$$



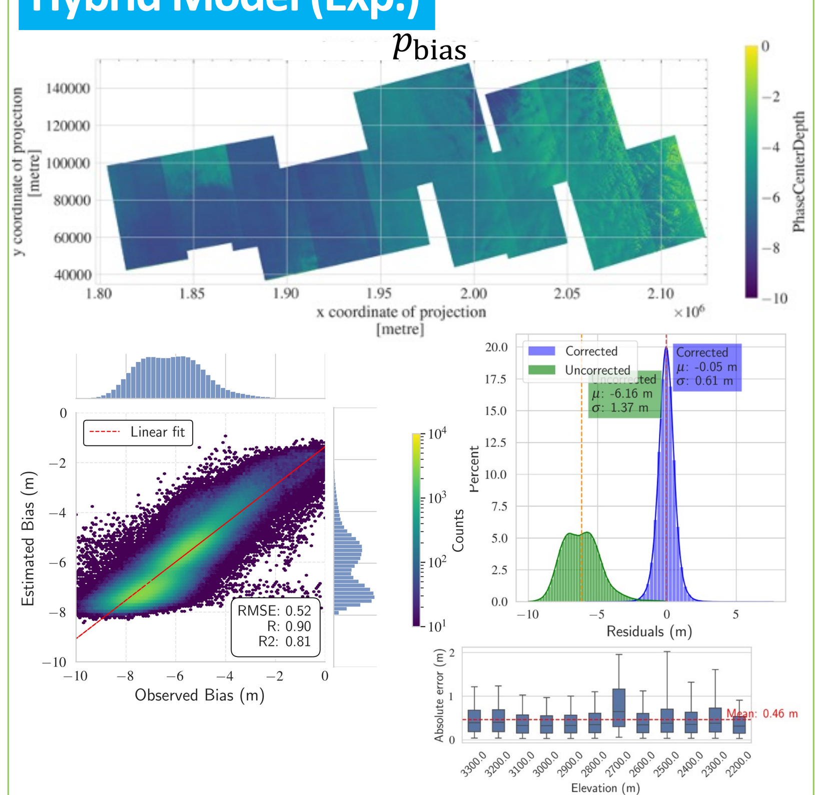
## Results

### PM Model (Exp.)



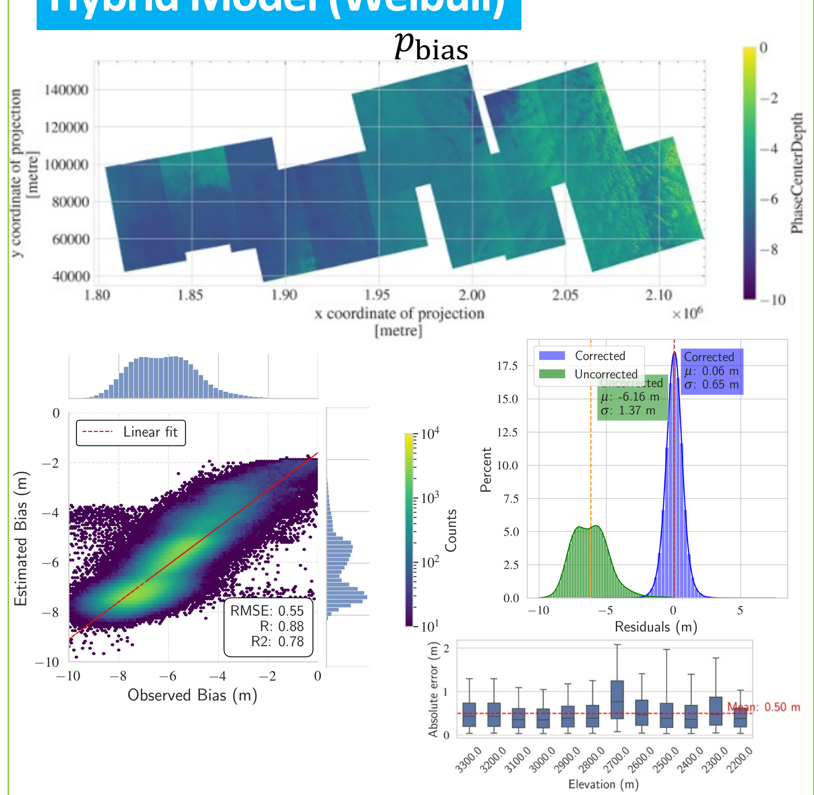

- **Pros**: Easy to understand and provides consistent results across different InSAR geometries.
- **Cons**: Uses only the direct relationship between InSAR coherence $\gamma$ and penetration bias, based on simplified assumptions of $f(z)$.

### Hybrid Model (Exp.)




- **Pros**: Combines strengths from PM and ML approaches for robustness/accuracy with limited labeled data.
- **Cons**: Complex to develop and implement.

### Hybrid Model (Weibull)




- **Pros**: More flexible with two parameters to learn.
- **Cons**: Requires additional work to tune it.

## Benefit of Terrabyte

- **High-Performance Computing for PhD Research:**
- It allows running multiple simulations for the hybrid modeling approach in parallel with changing optimization parameters. This significantly reduces computational time:
  - From one week using local institute infrastructure.
  - To only a few hours on Terrabyte's HPC capabilities.
- **GPU Usage for Hybrid Modeling Development:**
- It accelerates the training process for a hybrid modeling approach by:
  - Leveraging GPU power for faster neural network computation.
  - Effectively handling large datasets, reducing bottlenecks during training.
  - To only a few hours on Terrabyte's HPC capabilities.
- **Impact on PhD Workflow:**
- Enables quicker experimentation—an essential component for promptly achieving research milestones.

## Conclusion

- **Enhanced DEM Accuracy:**
  - Corrected DEMs exhibit higher precision and reliability.
- **Penetration Bias Reduction:**
  - Achieved MAE of approximately 0.5 meters across different elevation ranges.
- **Effectiveness of Physics-Informed ML:**
  - Successfully corrects biases even with an unbalanced training dataset.
  - Delivers superior overall performance with limited training data.

[1] S. Abdullahi, B. Wessel, M. Huber, A. Wendleder, A. Roth, and C. Kuenzer, "Estimating Penetration-Related X-Band InSAR Elevation Bias: A Study over the Greenland Ice Sheet," *Remote Sensing*, vol. 11, no. 24, Art. no. 24, Jan. 2019, doi: 10.3390/rs11242903.
[2] G. Fischer, K. P. Papathanassiou, and I. Hajnsek, "Modeling and compensation of the penetration bias in InSAR DEMs of ice sheets at different frequencies new," *IEEE Journal of Selected Topics in Applied Earth Observations and Remote Sensing*, vol. 13, pp. 2698–2707, 2020, doi: 10.1109/JSTARS.2020.2992530.

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