Estimating Explosion Yields Using Fourier Neural Operators and Long-Range Infrasound Observations

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INTRODUCTION AND MAIN RESULTS

This poster presents a physics-informed Bayesian framework—powered by a fast Fourier Neural Operator surrogate—uses IMS infrasound to estimate explosive yield under realistic (gravity-wave) atmospheric variability for CTBT decision support.
On decade-scale Hukkakero events (IS37, 321 km), we achieve ~4 dB TL MAE and ~4 ms inference, recover yields in the 15–30 t range with tight 95% credible intervals via MLE+MCMC, enabling reliable yield estimations.

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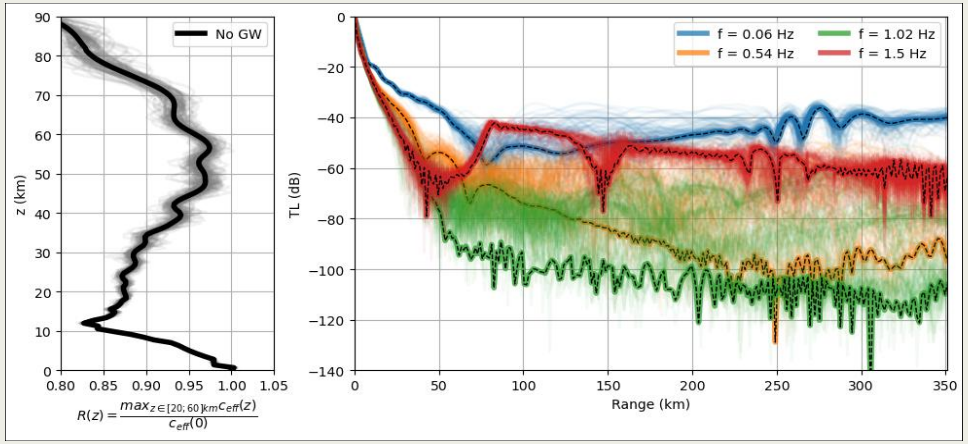
Problem & Motivation

We aim to characterize explosive yield from IMS infrasound so that CTBT analysts can decide whether an event is consistent with non-nuclear activity or merits escalation. As a controlled case, we use the long-running Hukkakero chemical explosions in Finland—reliably recorded at IS37 **(≈321 km)**—whose yields **W** are in the **15–30** t range.

The main obstacle is atmospheric variability, especially gravity-wave–driven wind/temperature fluctuations in the stratosphere that refract sound ducts and alter effective celerity, making propagation both uncertain and expensive to simulate numerically due to **statistical dispersion**. Our approach combines a fast, physics-informed surrogate for propagation with a Bayesian inference scheme that turns station recordings into yield estimates with credible intervals. The scientific question is straightforward: **can we reliably separate nuclear-scale from non-nuclear-scale yields under realistic atmospheric variability using Bayesian analysis of infrasound?**

Dataset

We synthesize a training corpus of **~20,000** effective-celerity profiles **a** representing ten years of Hukkakero-like conditions, with and without **gravity-wave perturbations.** For each profile, a normal-mode solver (FLOWS) provides 1D transmission loss **u** across **25 frequencies between 0.06 and 1.5 Hz** and ranges from **1 to 351** km.



Hukkakero #96 (19 Aug 2022). Gravity-wave perturbations drive strong dispersion in transmission-loss across selected frequencies, with gains up to ~20 dB; the bold black curve is the no-GW baseline.

Methodology

❶ Surrogate **F**ourier **N**eural **O**perator for infrasound propagation

A one-dimensional, eight-layer **FNO** (~3 M parameters) learns the mapping from atmosphere to TL and achieves **≈4 dB** MAE while evaluating a full TL field in **~4 ms** (256 ranges **r** × 25 frequencies **f**).

$$u = R(v_l \circ \cdots \circ v_0)Pa \text{ with } v_{l+1} = \sigma\Big(\mathcal{F}^{-1}(\mathcal{F}(K_{l+1}).\mathcal{F}(v_l)) + W_{l+1}v_l\Big)$$

❷Yield estimation with **M**aximum **L**ikelihood **E**stimation and **M**arkov **C**hain **M**onte-**C**arlo

Source parameters comes from numerical fits, which parameterize Reed or Friedlander spectra. For a candidate yield, we use the surrogate to obtain TL-shaped near-source spectra (~ 2 km) and define a likelihood from the absolute spectral difference to the corresponding source model. We first locate the maximum via **MLE**, then quantify uncertainty with a simple Metropolis–Hastings sampler (2,000 warm-up, 10,000 draws), which produces stable, narrow posteriors around the expected tens-of-tons range.

$$\mathcal{P}(W|\mathcal{TL}) = \int_{P_{src}(f,r,W)} \rho_{\mathcal{TL}}\Big(P_{FNO} - P_{src}, f, r, GW)w(f)df$$

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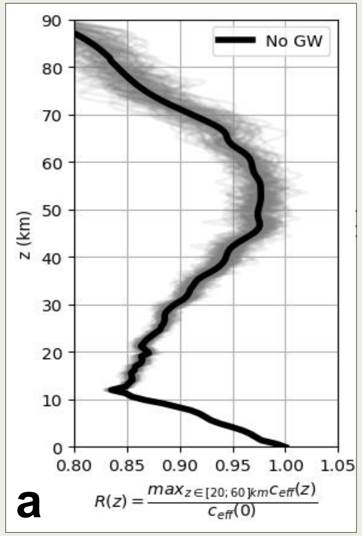
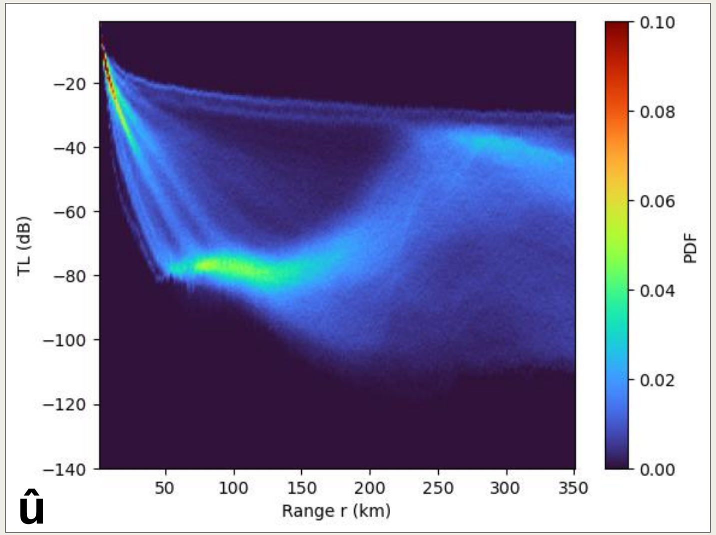
Results for Hukkakero event of 08/19/22

❶ Inference with surrogate FNO for 132 profiles

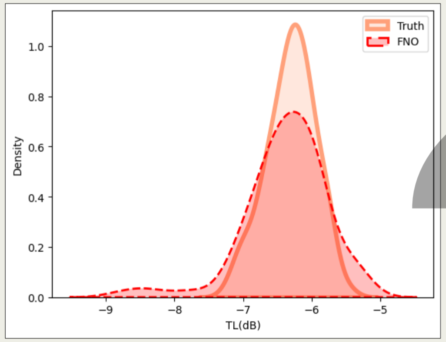


û = FNO(a)

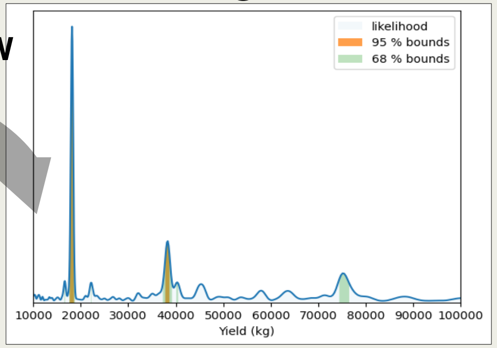


TL PDF û for 131 w/ GW + 1 w/o GW profiles of event 96

❷ MLE + MCMC



Likelihood for each W



Single-frequency TL density and yield likelihood (W = 1–100 t). The Friedlander source model produces multi-modal structure: a dominant peak near ~18 t and a surface-burst alias close to ~36 t (≈2×), reflecting amplitude–duration ambiguity.

Conclusion & Future Directions

Under realistic atmospheric variability, a physics-informed ML surrogate coupled with Bayesian inference reliably estimates yields in the 15–30 t regime from IMS infrasound, providing transparent uncertainty and supporting characterization of non-nuclear and nuclear-scale events for CTBT decision-making. We will extend to 2D waveform propagation and seismo-acoustic coupling, and harden a real-time pipeline with adaptive frequency selection for operational deployment.

References

Dellaportas, P., Roberts, G.O. (2003). **An Introduction to MCMC**. In Spatial Statistics & Computational Methods, LNS 173, Springer. Blom, P.S., Dannemann, F.K., Marcillo, O.E. (2018)**. Bayesian characterization of explosive sources using infrasonic signals**. GJI 215(1):240–251. doi:10.1093/gji/ggy258.
Bertin, M., Millet, C., Bouche, D. (2014). **A low-order reduced model for the long-range propagation of infrasound in the atmosphere**. JASA 136(1):37–52. doi:10.1121/1.4883388.
Lehmann, F., Gatti, F., Bertin, M., Clouteau, D. (2023**). Fourier Neural Operator surrogate model to predict 3D seismic waves propagation**. arXiv:2304.10242.
Li, Z., Kovachki, N., Azizzadenesheli, K., et al. (2021). **Fourier Neural Operator for Parametric PDEs**. ICLR; arXiv:2010.08895.