# The Necessity of Infrasound Stations for Comprehensive Monitoring in Indonesia

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## INTRODUCTION AND MAIN RESULTS

This study evaluates the need for an infrasound station in Indonesia, identifying Ujung Kulon, West Java, as a one potential site. Currently dependent on foreign IMS data, Indonesia lacks independent capacity to monitor detailed events.

Results show a permanent infrasound facility would significantly strengthen the national Early Warning System, complement seismic networks, and improve forecasting of volcanic eruptions, tsunamis, and atmospheric disturbances.

A distributed array model is proposed for installation, ensuring wider coverage, higher sensitivity, and reduced ambient noise. Establishing this infrastructure not only enhances disaster preparedness and climate monitoring but also reinforces Indonesia’s role in CTBTO’s global verification network.

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# The Necessity of Infrasound Stations for Comprehensive Monitoring in Indonesia

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## Abstract

This study assesses the need for an infrasound station facility in Indonesia, with Ujung Kulon, West Java as one of the potential sites. Indonesia relies on infrasound data from nearby countries limiting independent monitoring of detail events.

Data from IMS stations like I06AU, I39PW and others provide insights, however, are insufficient for comprehensive monitoring.

As a potential site for the initial installation, an infrasound station at Ujung Kulon could enhance Indonesia's national Early Warning System (EWS), complement the seismic network, and improve disaster forecasting and climate monitoring

A temporary infrasound station was installed by BMKG in Palangkaraya, Kalimantan in 2004 with support from DASE/CEA, but it is no longer operational, highlighting the need for permanent infrastructure.

This study proposed a distributed infrasound array model for the initial station installation, which would eventually expand to strategically selected places throughout Indonesia. This array design optimizes data collecting by assuring wider coverage, increasing signal detection sensitivity and minimizing noise interference from ambient factors.

Infrasound technology is useful for detecting low-frequency acoustic waves from volcanic eruptions, tsunamis and atmospheric disturbances, often overlooked by seismic systems. Establishing in-country infrasound stations will strengthen Indonesia's monitoring capacity, enhance disaster preparedness and contribute to global networks.

## Methods

- Array Modeling: Triangular & concentric ring arrays.
- Optimization: Maximize sensitivity, ensure coverage, avoid noise.
- Integration: Combine infrasound with seismic & volcano data
- Validation: Compare baseline vs optimized network

## Data

- Seismic catalog BMKG
- Geological data Indoneisan Geological Agency
- Infrasound Array Data (IMS) and Hypothetical/optimized station locations for sensitivity tests.
- Noise models (Ambient noise level and Seasonal variation in atmospheric noise)

## Results

- Integrating infrasound array beamforming with Indonesian seismic hazard data, we identified optimal sites for station deployment.
- Co-locating stations with seismic nodes in Sumatra, Java (including Ujung Kulon), Bali, and Sulawesi ensures broad coverage, while additional arrays in Banda/Maluku and Papua extend monitoring to eastern tectonics and submarine volcanoes.
- **Ujung Kulon (West Java)** emerges as a strong candidate due to its proximity to high seismic and volcanic activity zones.
- Analysis suggests at least 4–5 stations are needed for nationwide coverage.
- Concentric-ring arrays perform best in high-noise environments, whereas triangular arrays are efficient in remote, low-noise areas

## Conclusion

- A minimum of 4–5 infrasound stations is needed across Indonesia (Sumatra, Sulawesi, Banda/Maluku, Papua, and southern regions) to achieve comprehensive coverage of seismic and volcanic monitoring.
- The integration of infrasound and seismic networks strengthens Indonesia's ability to detect, validate, and respond to geophysical events across tectonic boundaries and volcanic arcs.
- Infrasound stations provide independent data to validate and enhance Early Warning Systems (EWS).

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# Indonesia's Hazard Context and Monitoring Challenges

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## Hazard Context and Monitoring Gaps

- Located on the Pacific Ring of Fire, with complex plate convergence (Eurasian, Indo-Australian, Pacific, Philippine Sea).
- Over 130 active volcanoes and frequent shallow earthquakes.
- Major eruptions (Krakatoa 1883, Anak Krakatau 2018) triggered destructive tsunamis.
- High tsunami risk along subduction zones: Sunda Trench, Banda Arc, Molucca Sea Plate.
- Atmospheric hazards: ENSO events, tropical cyclones, and equatorial convection.
- Seismic networks alone cannot detect atmospheric or tsunami-related acoustic signals.
- Infrasound stations would complement existing networks and strengthen Early Warning Systems.

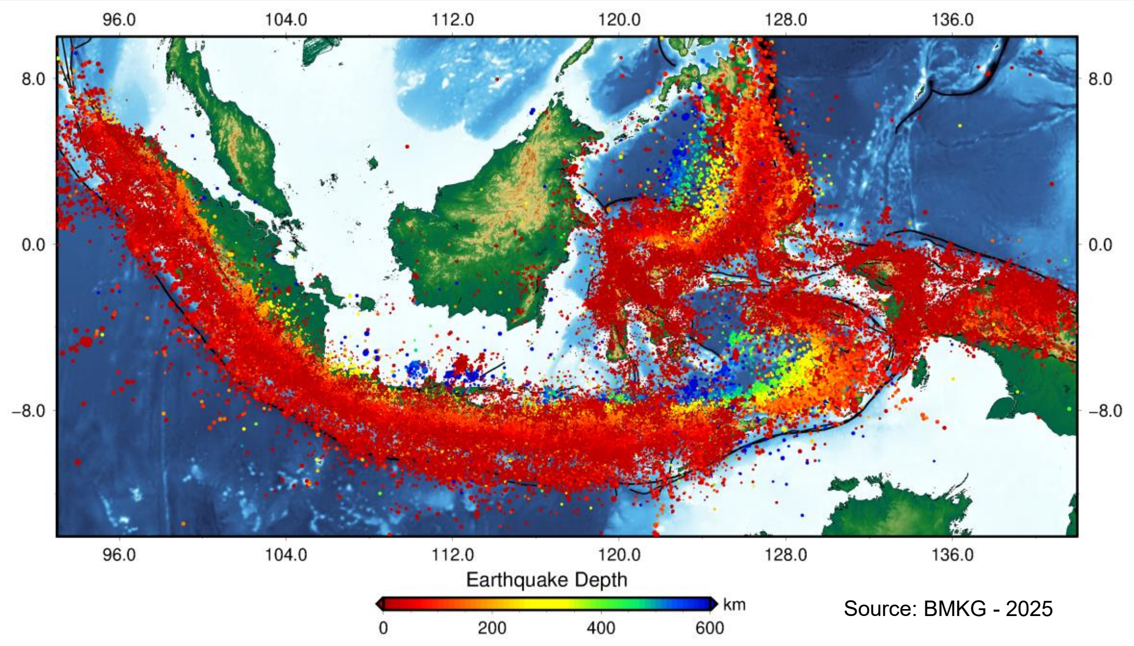


*Fig 1. Seismicity Indonesia 2009 – 2024 source BMKG and IMS data (2025)*

## Challenges in Early Warning and Monitoring

- Reliance on foreign IMS stations limits independent monitoring.
- Low resolution for detecting local events.
- Palangkaraya (2004) and Sukabumi temporary station were no longer operational.
- Critical gaps in the national Early Warning System (EWS).
- Limited verification of volcanic, tsunami, and atmospheric signals.
- Infrasound stations provide independent data to validate and enhance EWS.

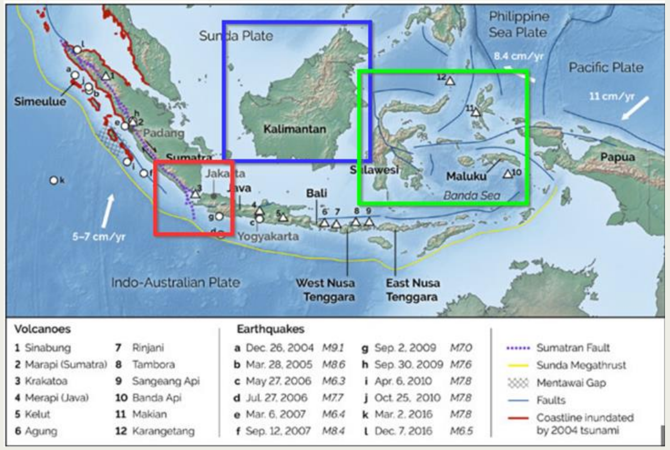


*Fig 2 . Volcano distribution in Indonesia McCaffrey, R. (2009).*

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# Methodology: Array Processing for Infrasound Detection

## Signal detection

$$y(t) = \sum_{i=1}^{N} S\,(t-\tau_i) + n_i(t)$$

Where:
- N= number of sensor in array
- S(t)= the actual infrasound signal
- $\tau\_i$ = time delay of the signal reaching i<sup>th</sup> sensor (depends on distance and wave direction
- $n\_i\,(t)$ = noise at the i[th] sensor

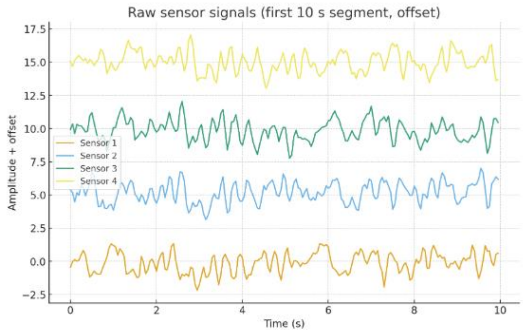
## Array gain/ sensitivity improvement

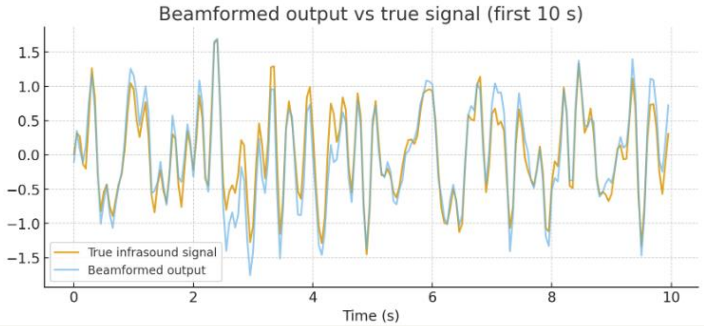
$$SNR_{array} = SNR_{single} x\,\sqrt{N}$$

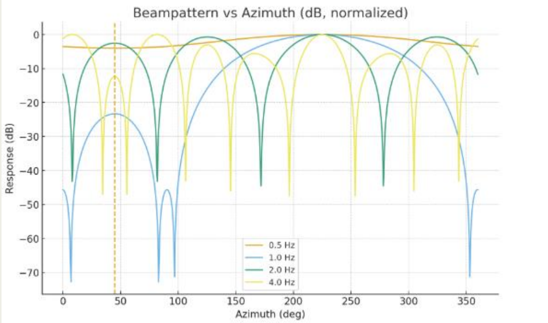
Where:

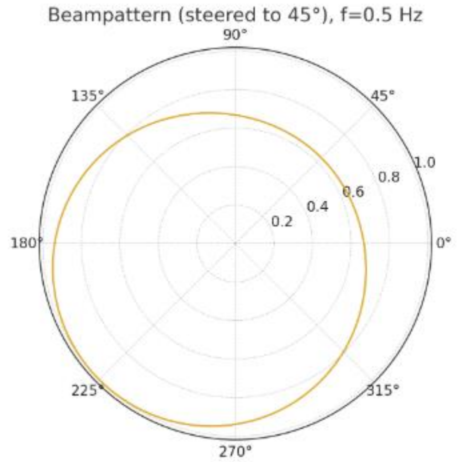
- $SNR$_single = signal-to-noise for single sensor
- N= number of sensor in the array.

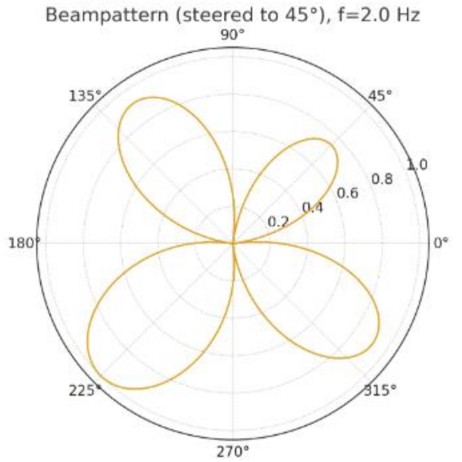
This shows that adding more sensor improves the detection of weak signals and reduce noise

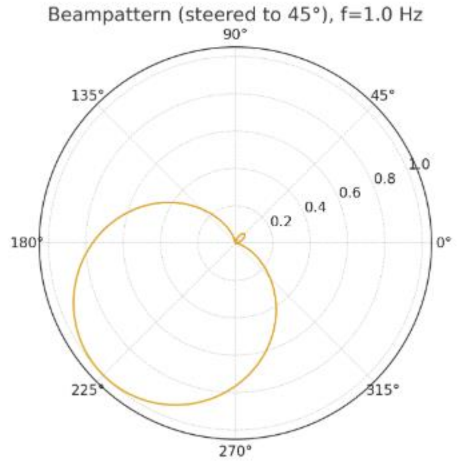


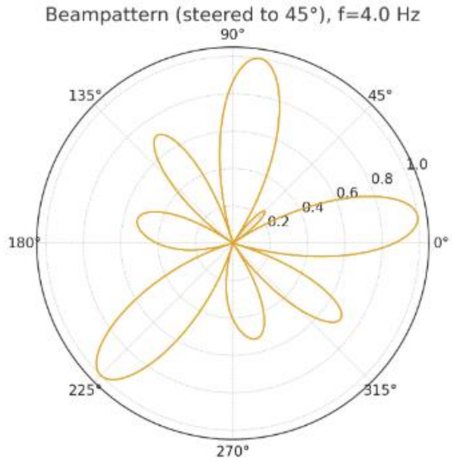



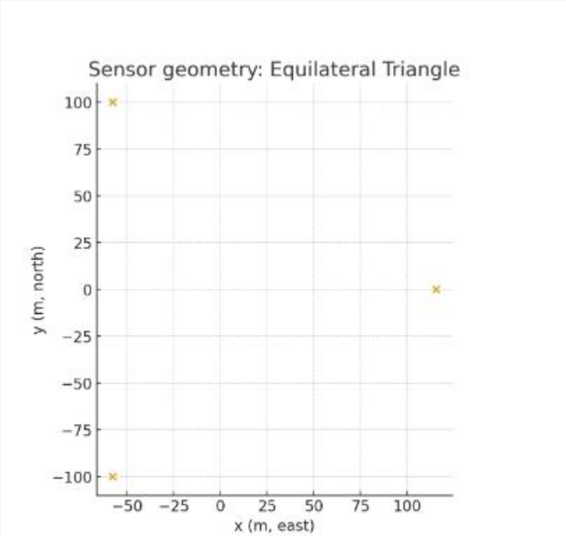



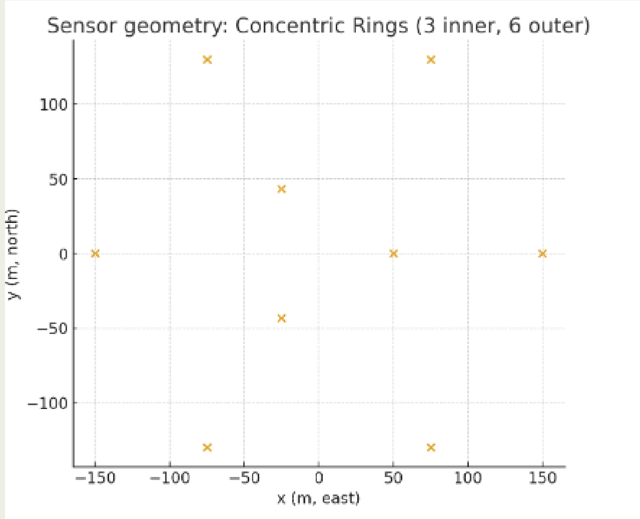



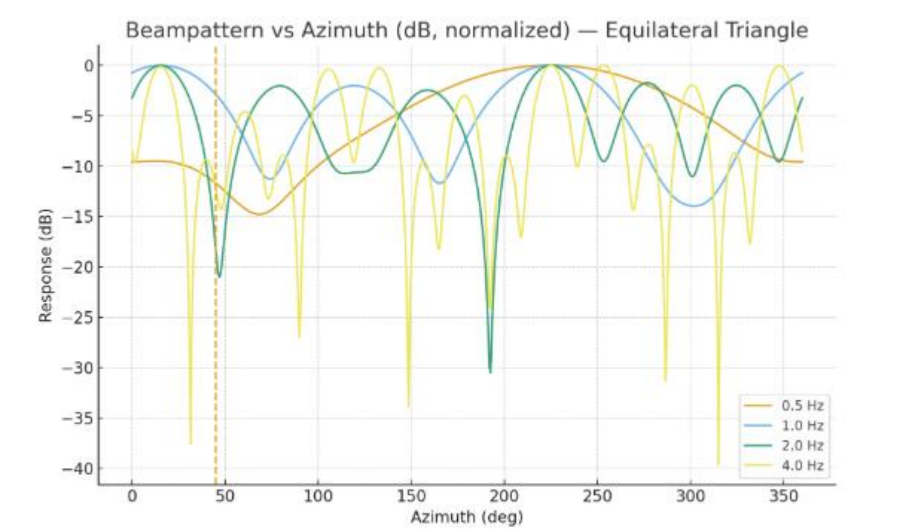

- 4 sensors in a 100×100 m array.
- A broadband (0.5–5 Hz) infrasound wave propagates across them.
- Each sensor sees a delayed version of the wave + 1/f (“pink”) background noise, similar to atmospheric turbulence.
- A beamforming step aligns and averages the signals, recovering the source wave.

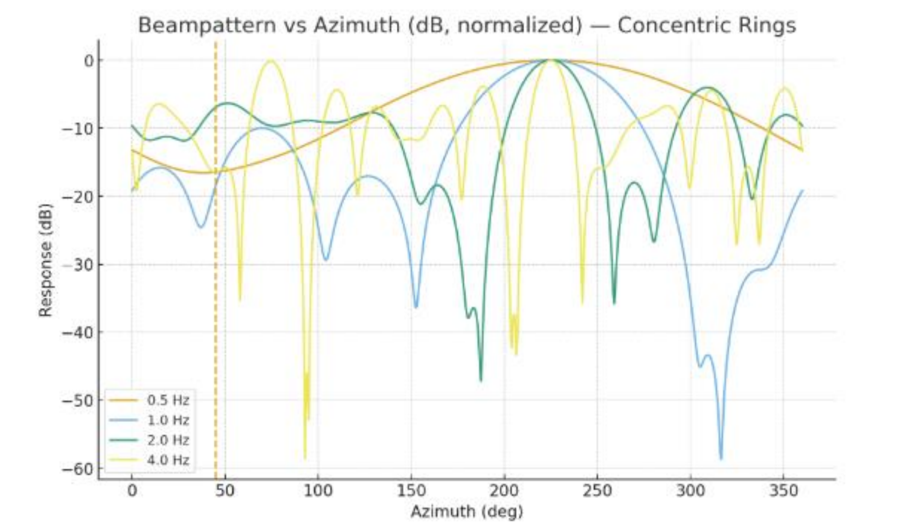
# Methodology: Array Processing for Infrasound Detection






- Geometry plots show sensor layouts:
- Equilateral triangle (side ≈ 200 m; 3 sensors).
- Concentric rings (inner radius 50 m with 3 sensors; outer radius 150 m with 6 sensors).
- Beampattern (normalized, in dB) vs azimuth for 0.5, 1, 2, 4 Hz, steered to 45°:
- The triangle gives broad mainlobes with 3-fold symmetry; good for simple, low-cost arrays.
- The concentric rings sharpen the mainlobe and push some sidelobes down, providing better directional discrimination across the band.

# Sensitivity Analysis for Optimal Infrasound Station Placement

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## Signal Detection Sensitivity

$$S_i = (A/d_i^2) * G_i - N_i$$

Where:
A = Seismicity/Eruption intensity
$d_i$ = distance from volcano
$G_i$ = array geometry factor
$N_i$ = ambient noise level

Example:

Comparing 2 candidate sites to Mt. Krakatau

Ujung Kulon (West Java):

- Distance: 40 km
- Geometry: Concentric ring (G=1.2)
- Noise: 0.3 (low)
- S = (A / 40²) * 1.2 - 0.3

South Sumatra:

- Distance: 150 km
- Geometry: Triangular (G=1.0)
- Noise: 0.6 (higher)
- S = (A / 150²) * 1.0 - 0.6

## Array-wide Optimization

$$S_{total} = \sum_{i=1}^{n} S_i$$

Where:
- Maximize $S_{total}$ by placing stations along volcanic arcs and in regions of tectonic plate boundaries and fault systems.
- Ensure overlapping coverage between Sumatra, Java, Bali, Lombok, NTT, Sulawesi, Maluku, and Papua.
- Avoid high-noise or urban zones to enable clearer detection.

| Station Location | Distance (km) | Geometry (G) | Noise (N) | S_i |
|---|---|---|---|---|
| Ujung Kulon | 60 | 1.5 | 0.8 | 0.042 |
| Lampung Coast | 100 | 1.4 | 1.0 | 0.04 |
| Anyer (Banten) | 80 | 1.6 | 0.9 | 0.05 |
| Pelabuhan Ratu | 150 | 1.3 | 1.1 | 0.028 |
| South Sumatra | 200 | 1.2 | 1.2 | 0.018 |

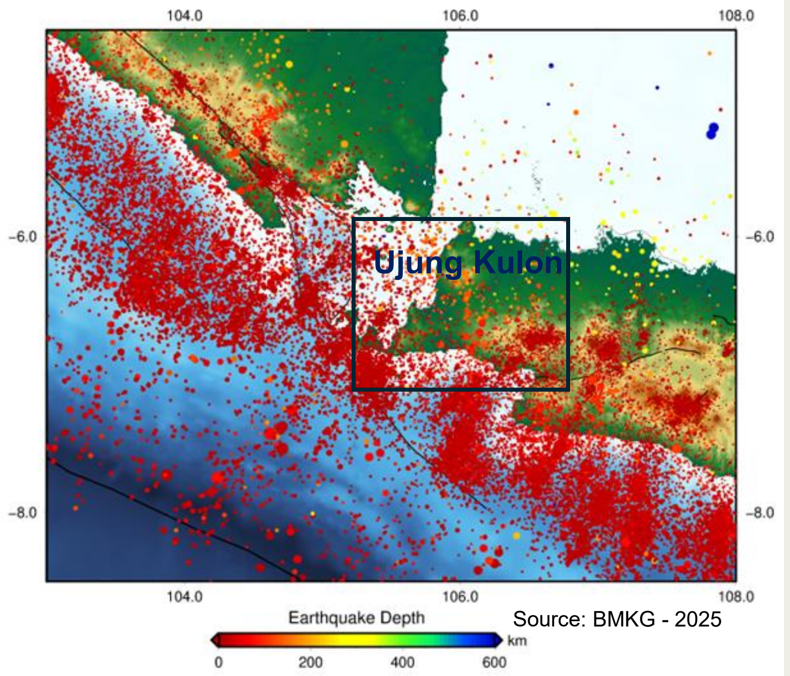


*Fig 3. Seismicity Around Sunda Strait 2009 – 2024 source BMKG and IMS data (2025)*

Ujung Kulon shows stronger sensitivity ($S_i$) due to shorter distance and low noise. While South Sumatra has weaker detection due to longer distance and higher noise. Conclusion: Ujung Kulon is optimal for monitoring Sunda strait area (Krakatau)

# Ujung Kulon: Site Rationale & Proposed Infrasound Array

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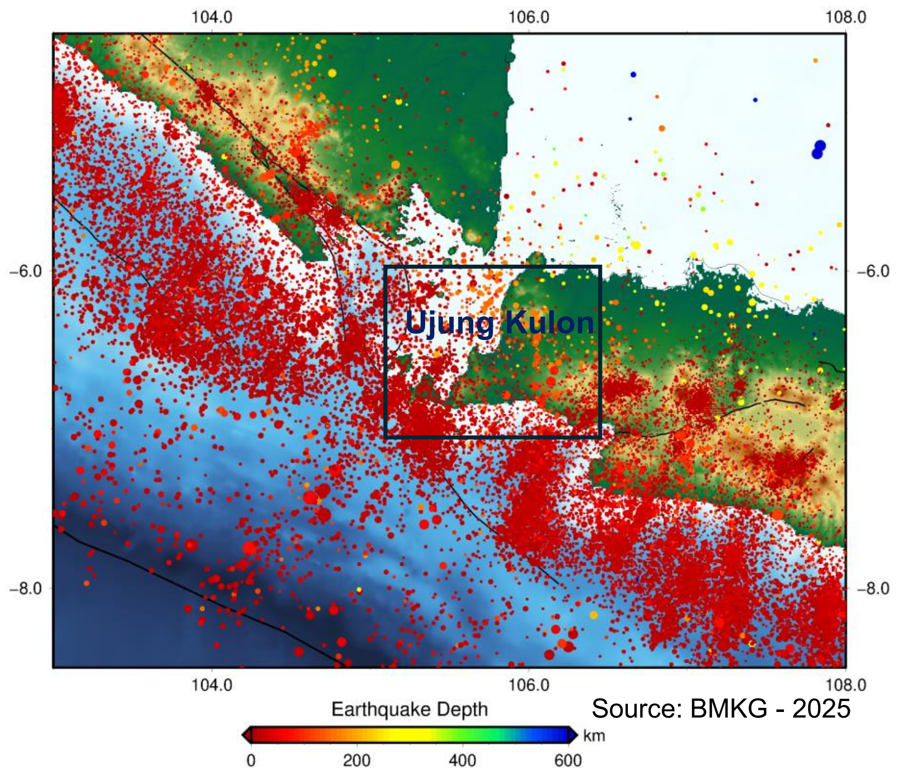


Source: BMKG - 2025

## Site Rationale:

- Optimal site from array modeling and Seismic activity clusters.
- Strategic location: downwind of Krakatau, along Sunda subduction front
- Concentric-ring arrays → best SNR & directional resolution under wind noise
- High source activity: frequent eruptions, quakes, tsunamigenic events
- Clear propagation: over-water paths reduce attenuation & blockage
- Low-noise setting: sparse population, wind-noise filters mitigate turbulence
- Accurate geometry fit improved azimuth estimates to Strait & outer arc
- Strong network synergy: co-located with seismic nodes for rapid confirmation

## Proposed Infrasound Array Model

- Geometry: Concentric rings — inner radius 50 m (3 sensors), outer radius 150 m (6 sensors).
- Elements: 9 microbarometers with rosette/pipe wind-noise filters and a met station (winds, temperature).
- Sampling: 20 Hz (or higher), GPS-disciplined timing.
- Processing: Delay-and-sum beamforming; adaptive noise whitening; daily beampattern QA.
- Expected gain: SNR improvement ≈ 10 log10(N) ≈ +9–10 dB for N=9 (independent noise), with improved azimuthal resolution vs. triangular/square layouts.

**References Summary**

- **Infrasound & Volcano Monitoring**
  Campus & Christie (2010); Fee & Matoza (2013)
- **Array Design & Sensitivity**
  Evers & Haak (2005); Christie & Campus (2010)
- **Seismic–Infrasound Integration**
  Le Pichon et al. (2009); Johnson & Ripepe (2011)
- **Indonesia Tectonic & Volcanic Context**
  Hamilton (1979); Smithsonian GVP; BMKG reports
- **Case Study: Sunda Strait / Ujung Kulon**
  Perttu et al. (2019); BMKG (2018–2022)

# Results and Strategic Recommendations for Infrasound Monitoring in Indonesia



| Result | Conclusion | Suggestion |
|---|---|---|
| • By integrating **infrasound array beamforming models** with seismic hazard data from the Indonesian seismic network, we identified the most suitable candidate sites for infrasound station deployment.<br>• Optimal coverage is achieved by co-locating stations with seismic nodes in **Sumatra, Java (including Ujung Kulon), Bali, and Sulawesi**.<br>• Additional arrays in **Banda/Maluku** and potentially **Papua** extend monitoring to eastern tectonic interactions and submarine volcanic activity.<br>• The analysis indicates Indonesia requires **at least 4–5 infrasound stations** for comprehensive coverage.<br>• **Array geometry testing** shows that concentric ring arrays are more effective in high-noise environments, while triangular arrays are efficient in remote or low-noise settings. | • Indonesia's tectonic setting, dominated by subduction zones and active volcanoes, demands a **dedicated infrasound monitoring network** to complement seismic and volcanic hazard systems.<br>• **Ujung Kulon (West Java)** emerges as a strong candidate due to its proximity to high seismic and volcanic activity zones.<br>• A **hybrid array strategy** (concentric rings in noisy regions and triangular arrays in remote areas) maximizes detection capabilities, azimuthal resolution, and adaptability. | • **Deploy 4–5 infrasound stations** strategically in Sumatra, Java (Ujung Kulon), Sulawesi, and Banda/Maluku, with an optional extension to Papua.<br>• **Conduct site-specific noise studies** to determine the most effective array geometry (ring vs triangular) at each location.<br>• **Integrate with the existing seismic network** to maximize detection efficiency and ensure cross-validation of geophysical events.<br>• **Prioritize phased deployment**, starting with high-risk subduction zones (Sumatra and Java), followed by eastern regions (Sulawesi, Maluku, Papua).<br>• **Continue simulation and beamforming modeling** to refine network design and enhance real-time monitoring capabilities. |

**Thank You for Your Attention and Feedback**