KOREA–ITALY WORKSHOP ON MULTI-MESSENGER ASTROPHYSICS AND COSMOLOGY

Underground Microgravity Measurements at YeMiGO

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Earthquake Signals in a Gravity Record

Combined SG Record

A superconducting gravimeter (SG) records gravity changes and ground motion simultaneously.

Physical Drivers

Mass redistribution, seismic waves, gravity changes, and ground motion.

Analytical Workflow

Calibration: Instrument scale factor

Corrections: Environmental & tides

Comparisons: Seismic records

Current study: earthquake transients. Future question: pre-P-wave signal.

YeMiGO: A Deep Underground Observatory

~1 km

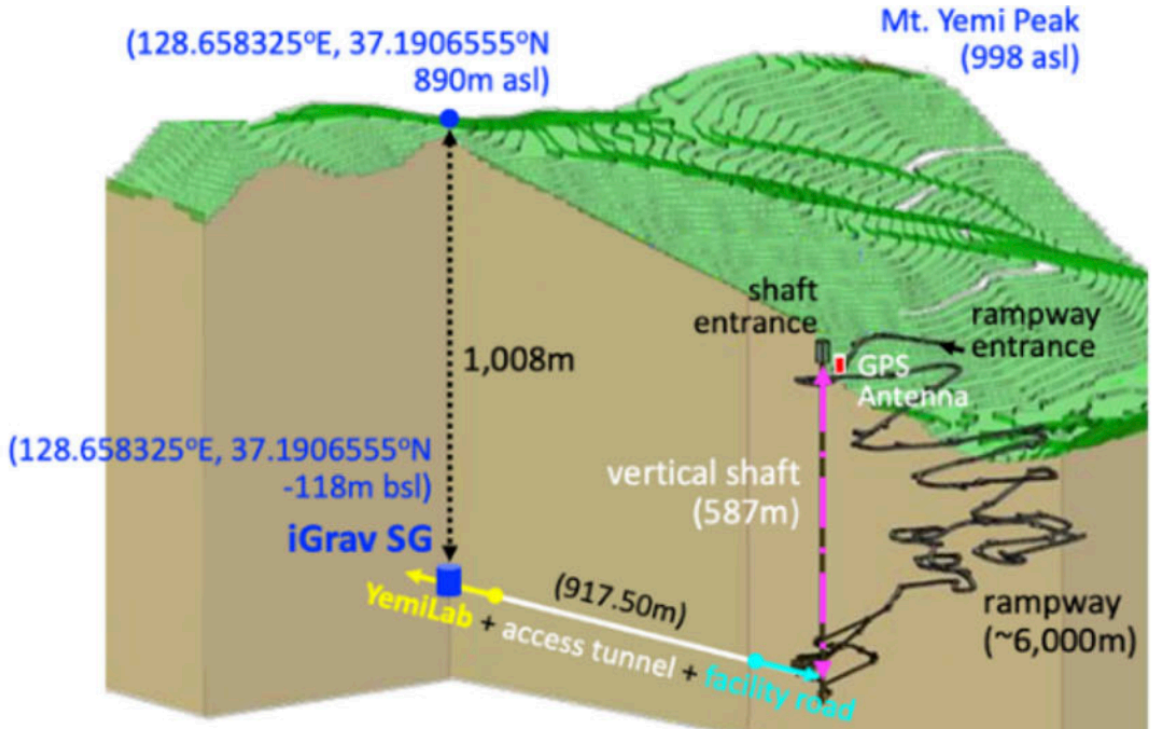
Below local surface in YemiLab, Jeongseon, South Korea

Depth Metric

118 meters below mean sea level.

Environmental Impact

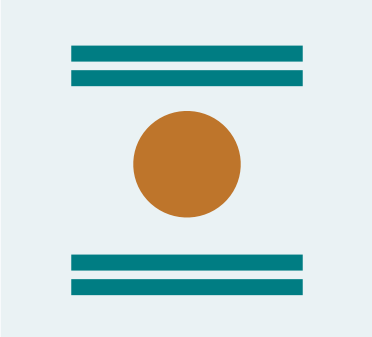
Deep setting alters environmental noise; rigorous performance measurement is required.



How the Superconducting Gravimeter Works

Levitated Sphere

Position sensing feedback holds the superconducting sphere in stable levitation.



Voltage Output

Relative gravity formula:

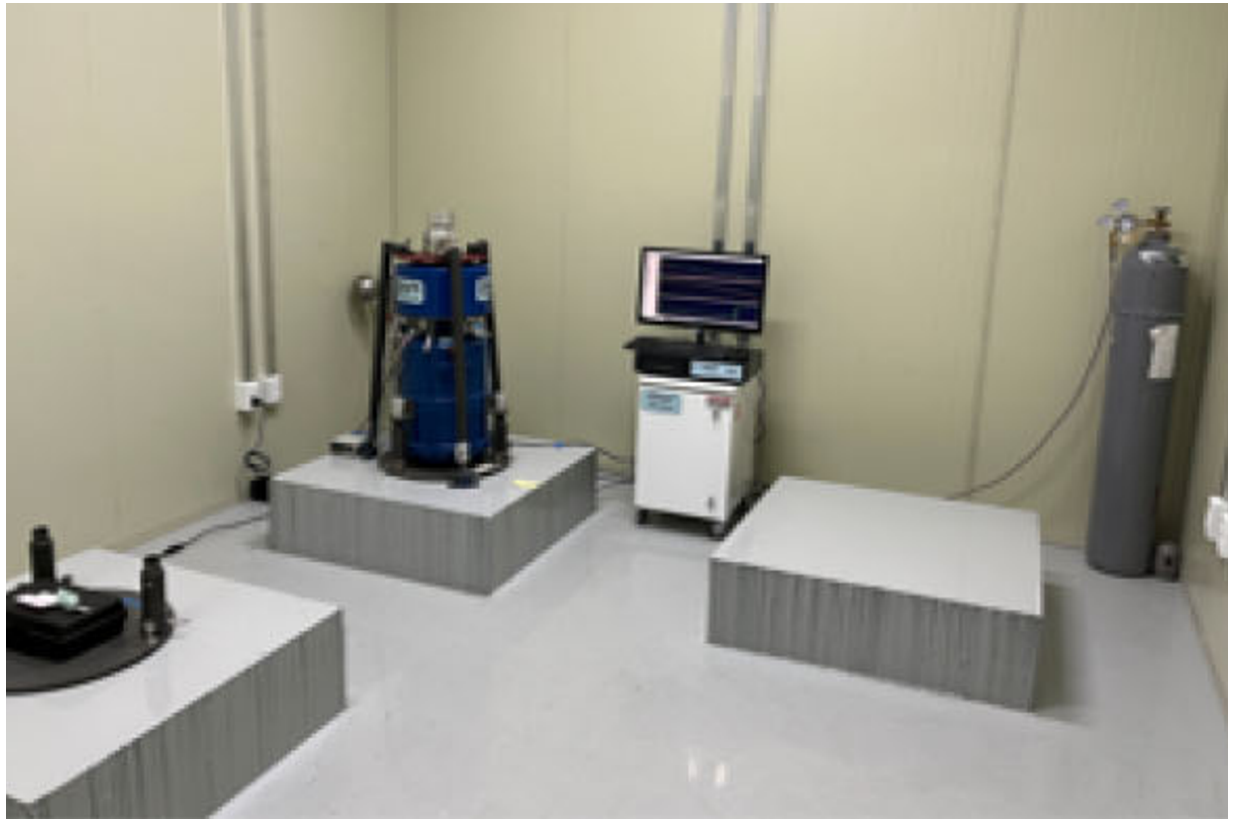
$$\Delta g = k\,\Delta V$$

Precision Unit

Calibration determines scale factor k.

$$1\ \mu\text{Gal} = 10^{-8}\ \text{m/s}^2$$

Stable support and synchronized timing



Bedrock-Anchored Platform

Installed in October 2022. The heavy platform connects directly to bedrock beneath the tunnel floor.

Synchronization & Timing

Surface GNSS provides absolute timing. Stable support limits seismic disturbance for arrival comparisons.

Observing Run 1 Performance & Timeline

Run 1 Duration

16 Nov 2022 – 25 Jun 2024. GNSS timing established; run ended when levitation was lost.

Data Availability

98.65%

579.14 days recorded out of 587.08 total days.

Data Gaps

Only ~7.95 days missing due to data acquisition software, computer, and power interruptions.

Commissioning

Oct–Nov 2022

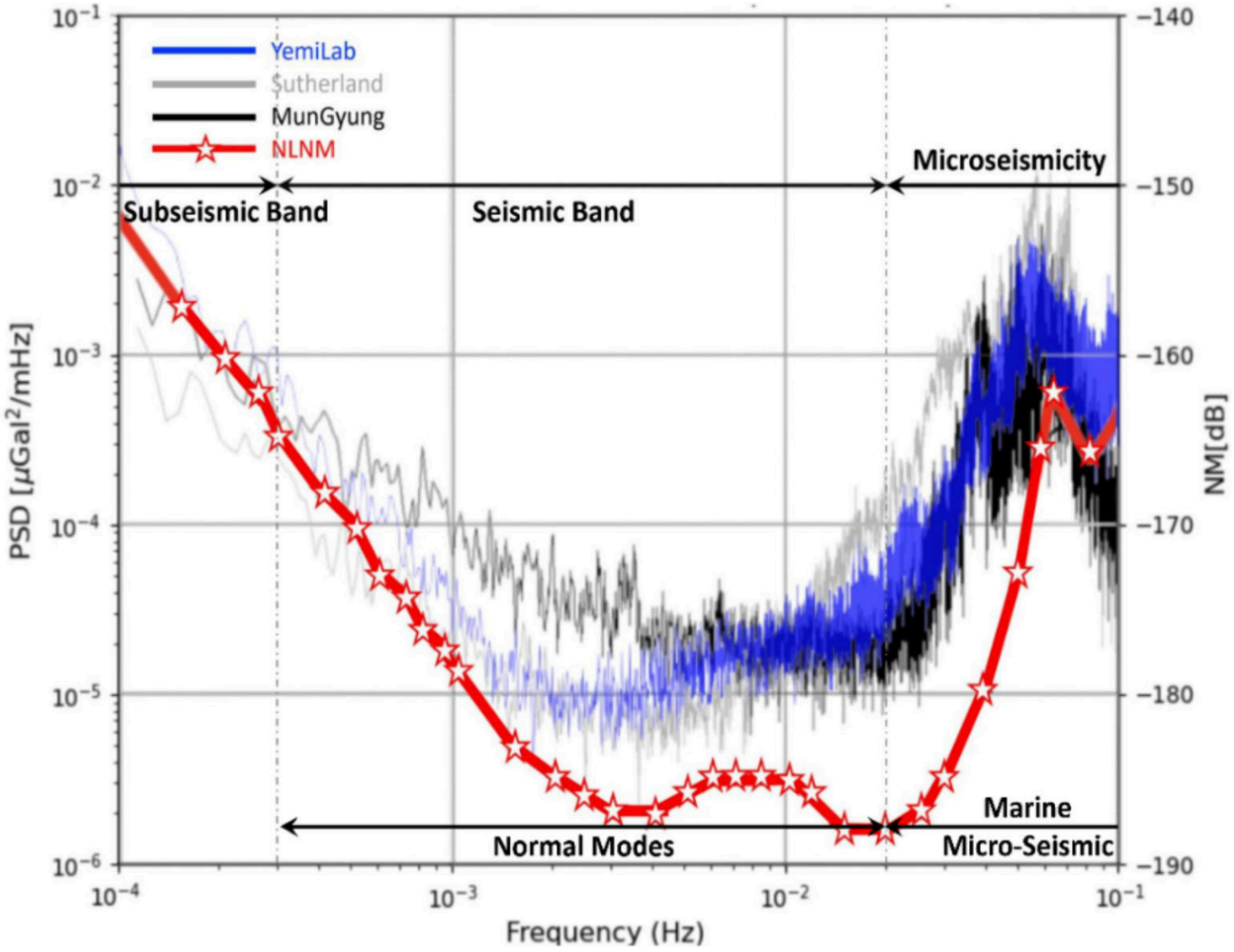
Observing Run 1

16 Nov 2022–25 Jun 2024

Reinstallation

Aug 2024

Published Noise Spectrum and the NLNM



YeMiGO Noise Model

Evaluated against New Low Noise Model (NLNM) standards.

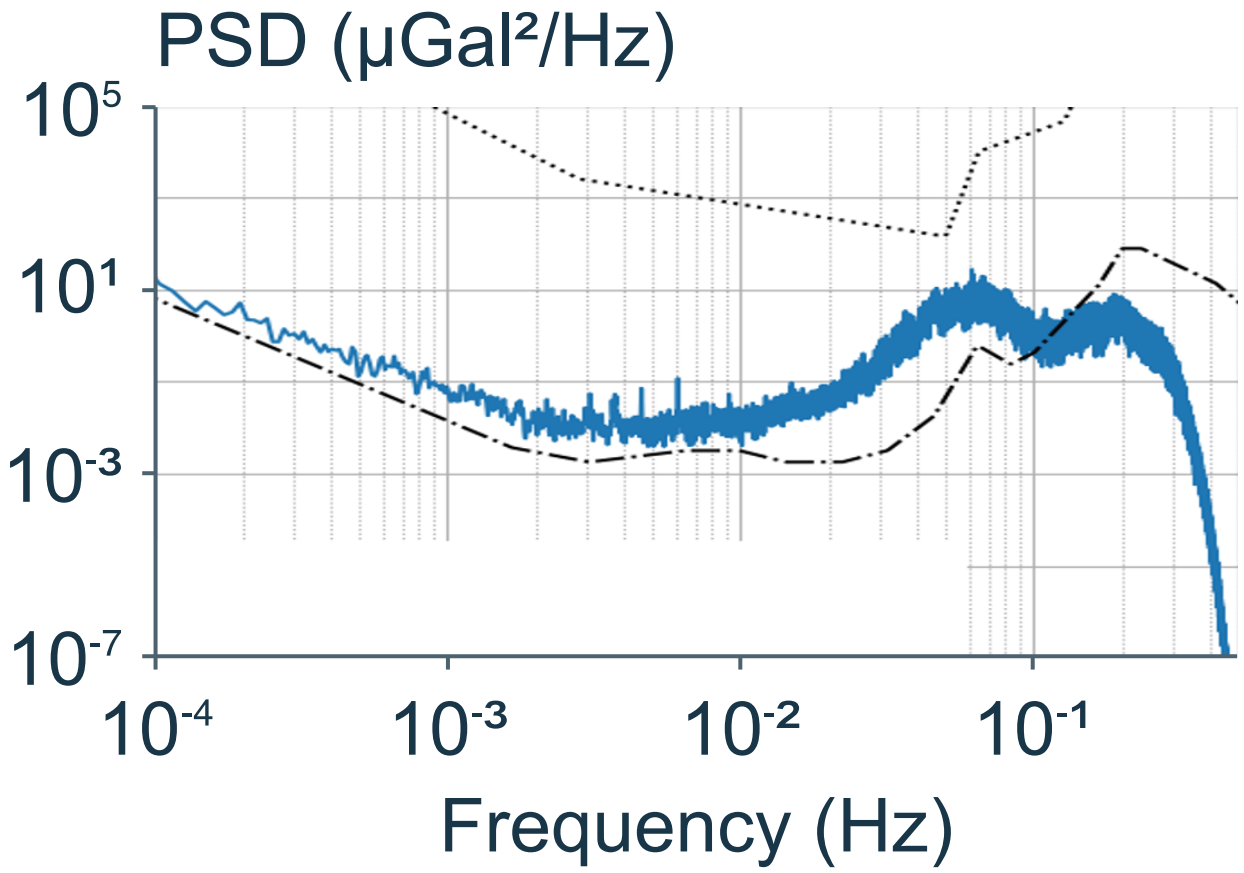
Microseismic Peak

30–100 mHz band highlights the marine microseismic peak.

FFT Parameters

Sep 2023 data · 1 s samples · 24 h Hann segments · no overlap.

Recent PSD



28 Sep – 4 Oct 2026 UTC

Absolute-Gravity Calibration

Parallel Observations

Dates: 9–14 November 2023

iGrav #001: Relative gravity output, voltage at 1 s sampling.

FG5 #231: Absolute gravity, 28,800 drops at 15 s values.

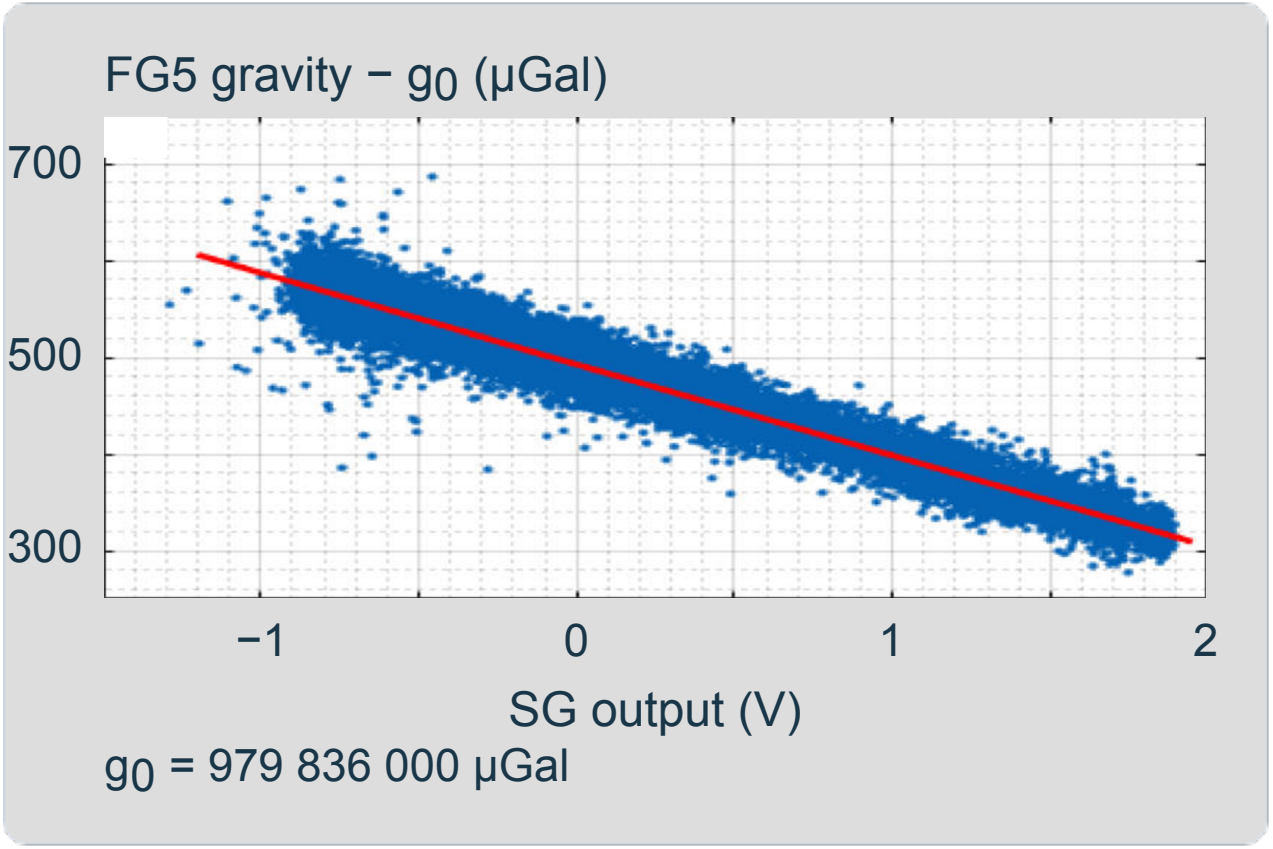
Calibration Methodology

Resample and synchronize time series.

Least-squares fit estimates the scale factor and nuisance polynomial trend.

Result: –94.38 ± 0.14 μGal/V

Calibration Results and Scale Factor



Scale Relation

Linear relation:

$$\Delta g = k\,\Delta V$$

Uncertainty & Baseline

Relative uncertainty ≈0.15%.

Dominant Tidal Constituents

Data Window

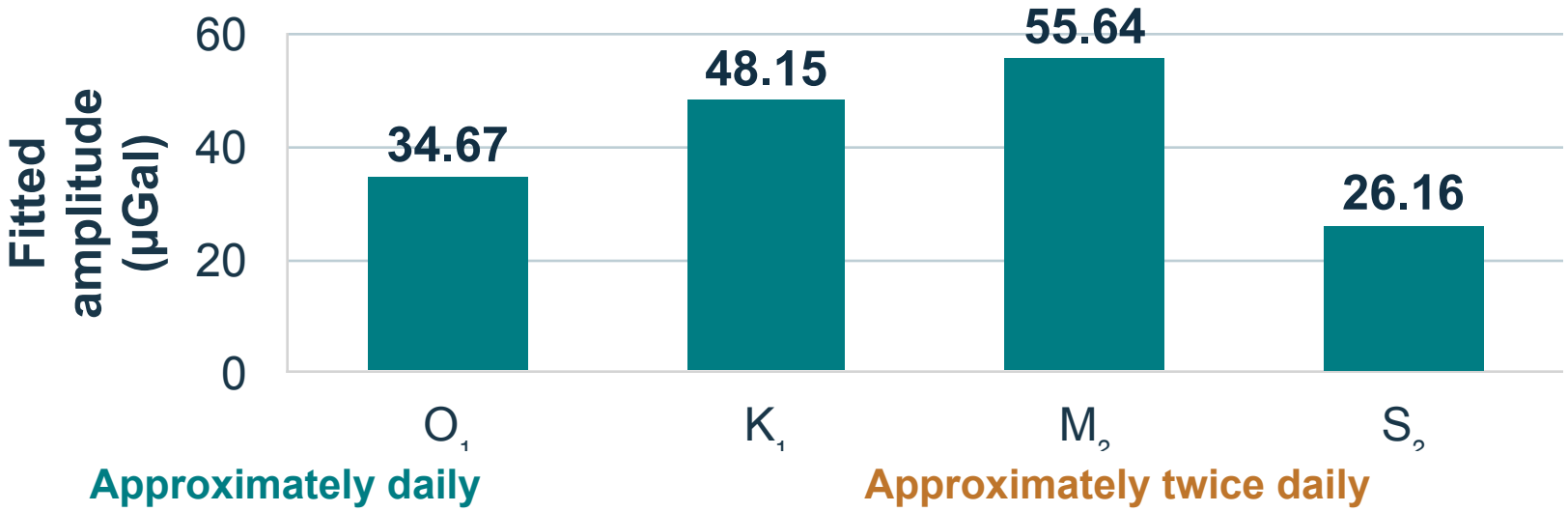
Dec 2022 – May 2024 hourly data analyzed via Eterna-x software.

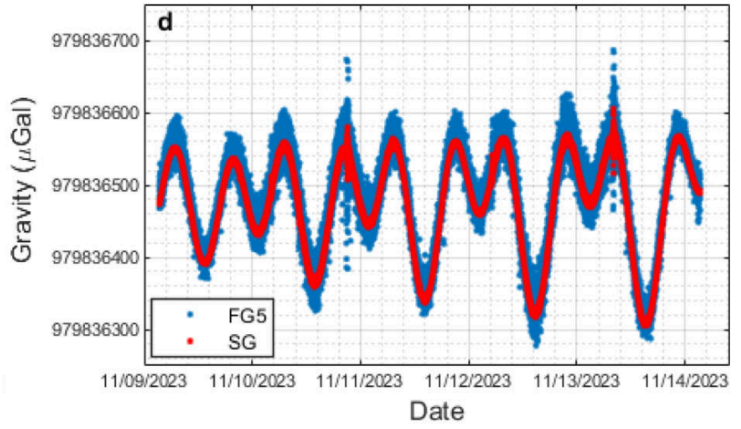
Frequency Bands

Approximately daily and twice-daily constituent families resolved.

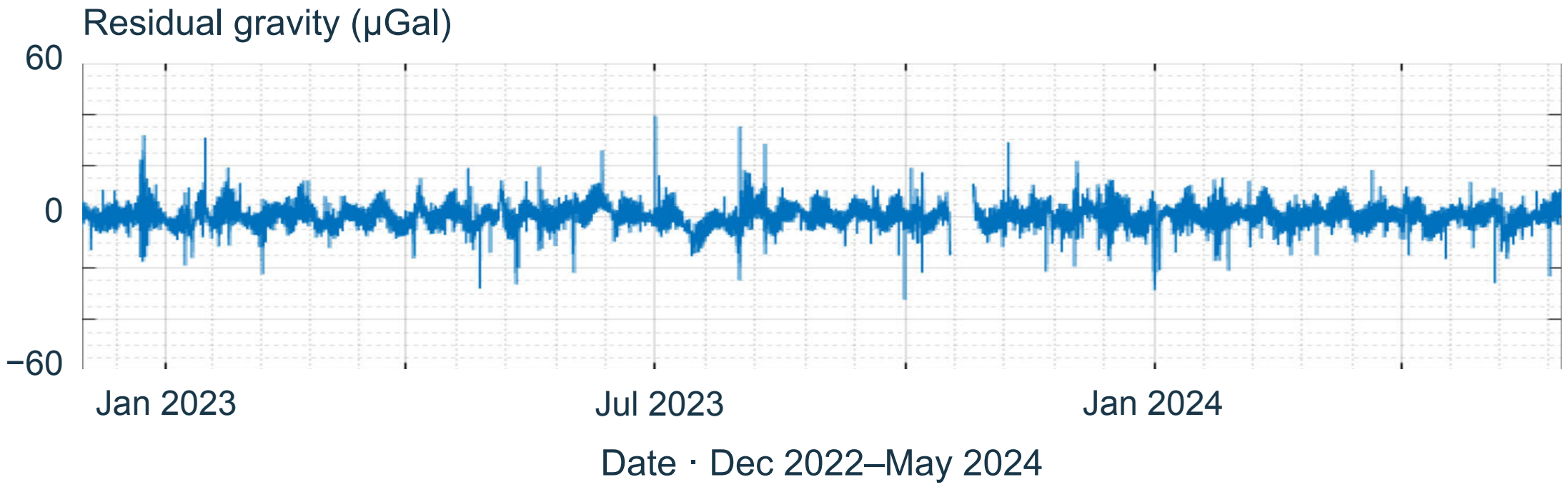
M_2 Amplitude

M_2 exhibits the largest fitted harmonic amplitude (representing signal, not noise).





Environmental Corrections and Residual



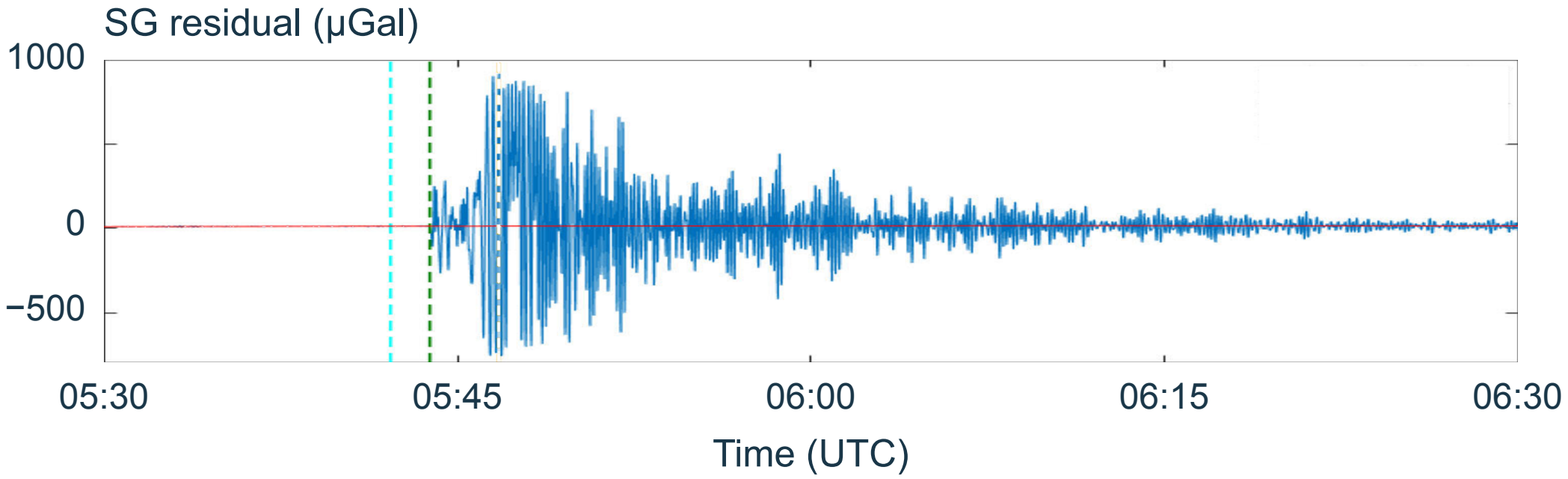
Model Subtractions

Earth tides, ocean loading, atmospheric pressure, and polar motion.

Residual Dynamics

Hydrology uncorrected. Residuals retain ground motion, unmodelled gravity, and instrument effects.

A Regional Mw 6.2 Earthquake Case Study



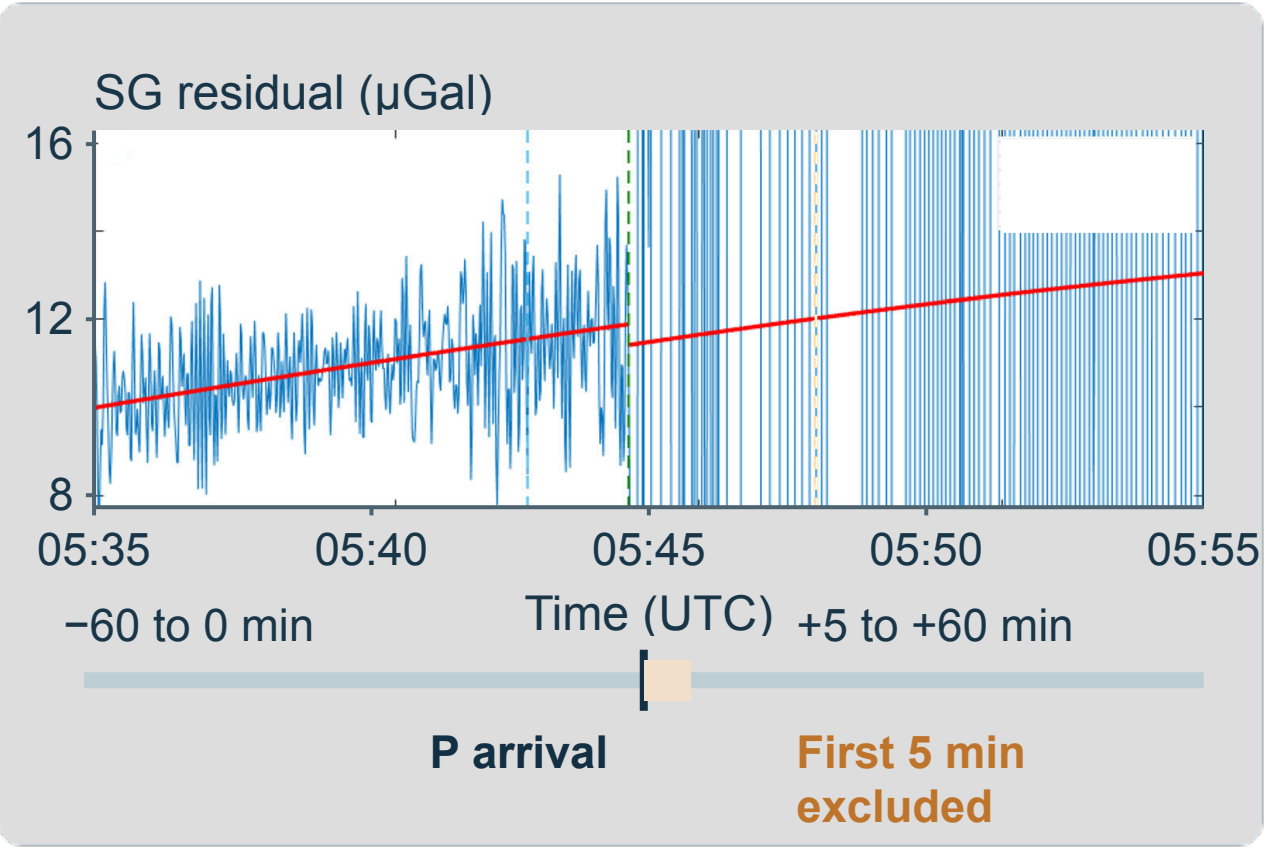
Event Details

5 May 2023 · 05:42:04 UTC · Near Anamizu, Japan.

Geometry

Depth: 10 km · Distance to YeMiGO: 765 km.

Earthquake Residual Response & Amplitude Fit



Quadratic Fit Analysis

Window: –60 to 0 min (pre-arrival) & +5 to +60 min (post-arrival).

First 5 min excluded. Separate quadratic fits evaluated at P arrival.

Uncertainty unquantified; permanent change unestablished.

Markers & Range

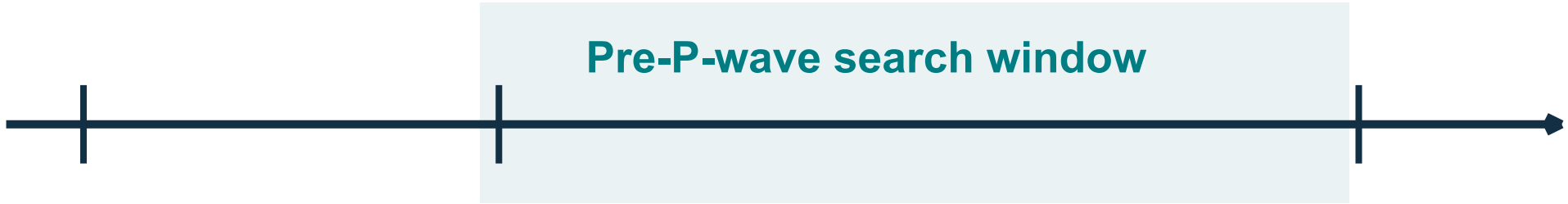
Cyan: origin. Green: first arrival. Signal remained fully within instrument range.

Fitted Difference

–0.561 *μ*Gal

Prompt Elastogravity Signals (PEGS)

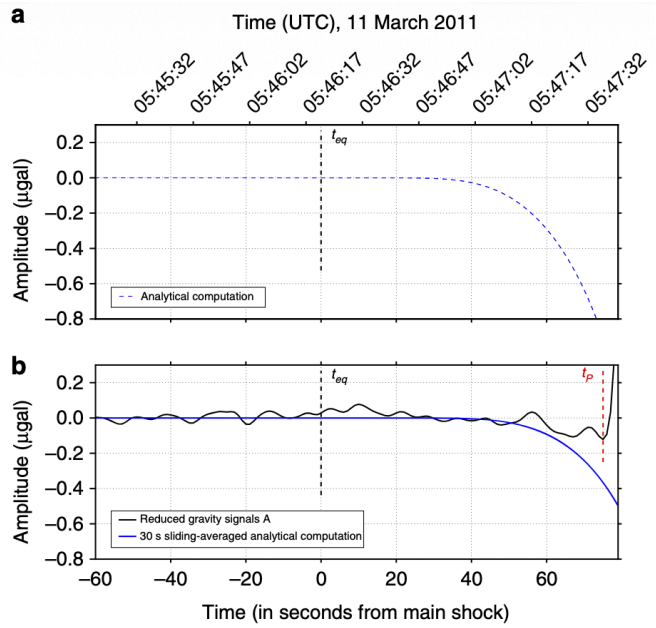
Gravity perturbation Schematic timing



Physical Mechanism

Earthquake-induced gravity changes and elastic response produce signals before seismic arrival.

Speed Comparison: Gravity travels at speed of light; seismic waves propagate through Earth.



YeMiGO Results

98.65%

Data Availability

Continuous observation from Nov 2022 to Jun 2024.

–94.38 μGal/V

Absolute Calibration

Rigorous FG5 absolute comparison (±0.14 μGal/V).

–0.561 μGal

Earthquake Fit

Model-dependent transient estimate.

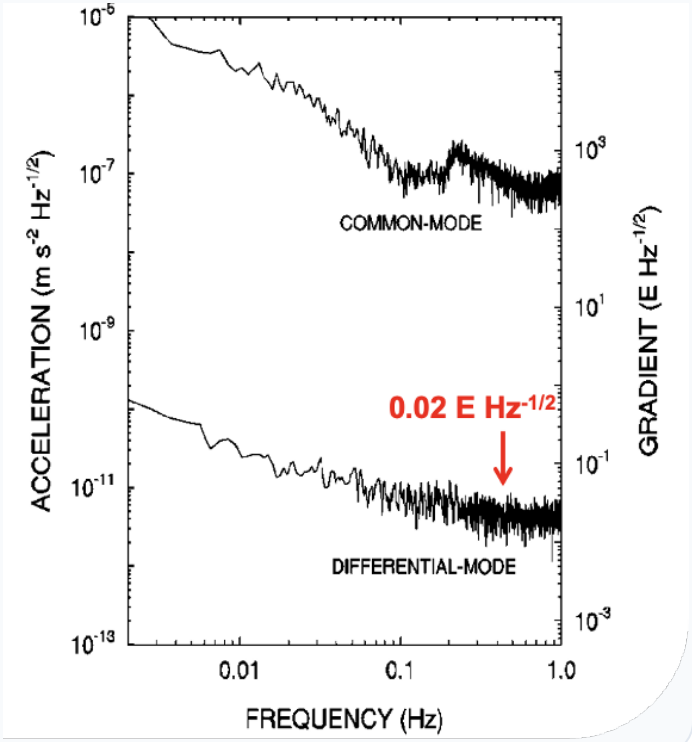
Gravity Changes Across Space: SGG Development Plan

Gravimeter vs Gradiometer

Gravimeter: Single location, changes over time.

Gravity Gradiometer:

Separated masses, changes across space.
- CM: gravimeter mode
- DM: gradiometer mode

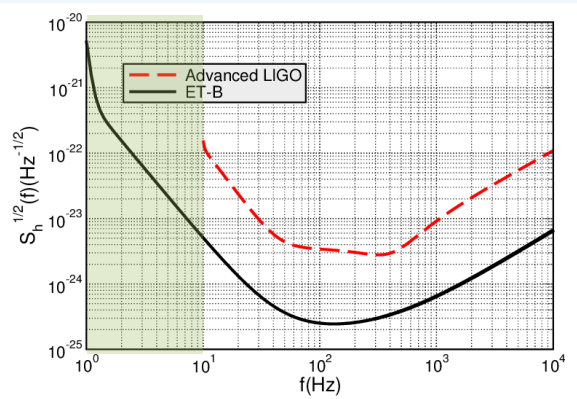


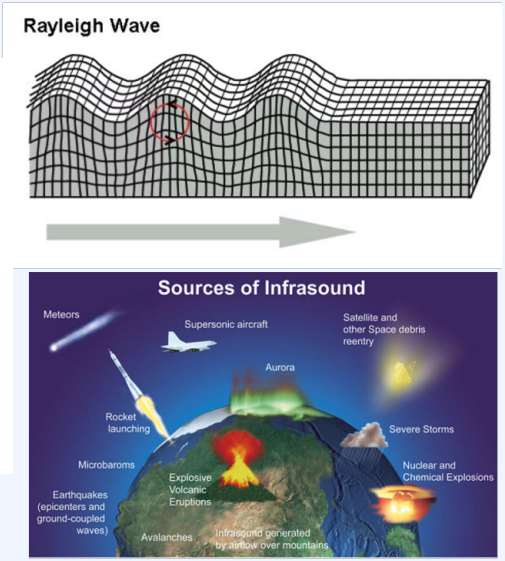
Paik et al. (2012)

Newtonian Noise

Gravitational disturbance caused by moving or changing surrounding mass.

Critical for next-generation gravitational wave detectors like Einstein Telescope.

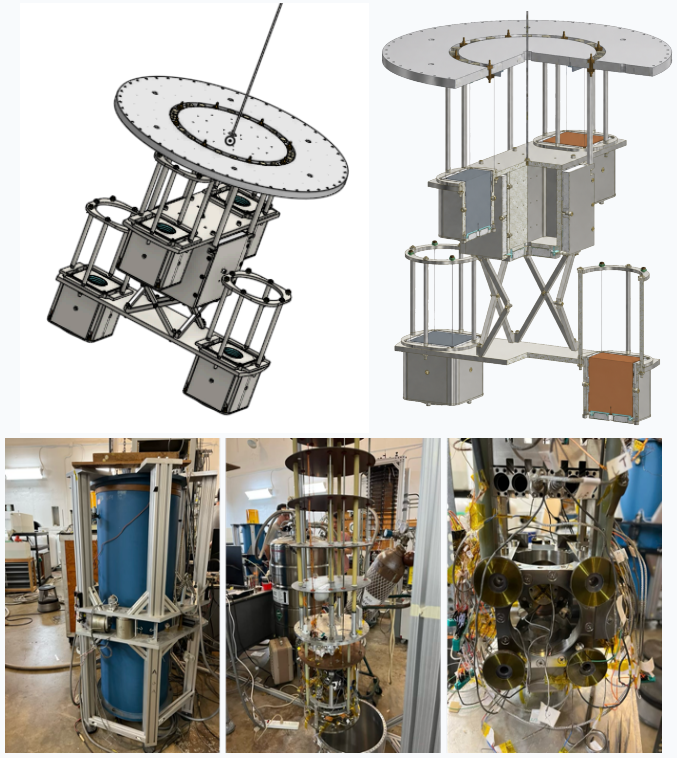




SGG Development Scope

1. Build Sensor

Tetrahedral suspended SGG
0.05–0.5 Hz prototype band



2. Underground Test

Rayleigh NN gradient detection
with seismic-array observations



3. ET Application

Theory and design for 1–10 Hz
ET application requirements

1) SGG prototype development and testing

2) Low-frequency NN detection and validation

3) ET sensitivity, baseline and sensor-layout design

ET installation and 1–10 Hz subtraction trials are out of scope.

Definition of a Gravity Gradient

Spatial Derivative

$$\Gamma_{zx} = \partial g_z / \partial x \approx \Delta g_z / \Delta x$$

Eötvös Unit

$$1\ \text{Eötvös (E)} = 10^{-9}\ \text{s}^{-2}$$

Tensor Foundation

Gradient approximately constant
across the test-mass separation.

$$\Delta g \approx \Gamma\, \Delta r$$

**Five independent components
in a source-free sensing region**

Suspension and Superconducting Readout

Test Masses

Four suspended test masses
Superconducting negative spring for stiffness tuning



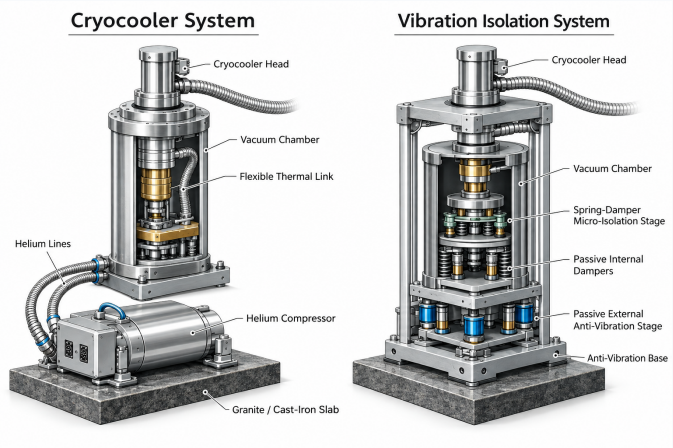
Readout System

Superconducting transducers
Magnicon two-stage DC SQUIDs



Cryogenic System

Low-vibration cryocooler
Vacuum and magnetic shielding
Thermal and magnetic stability



Prototype Development and NN Detection

0.05–0.5 Hz prototype development and underground Rayleigh NN detection

Development Area	Main Tasks	Verification
Prototype Fabrication	Four suspended test masses and platform Superconducting negative-spring tuning Thermal-noise and readout-noise budget	Mechanical response and stability Alignment and dynamic matching
Readout and Cryogenic Integration	Integrate transducers and Magnicon SQUIDs Build and test a low-vibration cryocooler Synchronize SGG and environmental channels	Multichannel response and crosstalk Cryogenic vibration and drift
Calibration, Modelling and NN Detection	Calibrate with controlled gravity sources Predict tensor CSD from seismic arrays Model cavity, depth and wavefield effects	Amplitude and directional consistency Separate gravity from mechanical leakage

ET contribution: sensor requirements and a design study for 1–10 Hz

Prototype Targets and Verification

Test Area	Proposed Target	Verification Conditions
Prototype and Tensor Recovery	**1 integrated prototype + 1 auxiliary unit** **5 independent tensor components**	Suspended tetrahedral configuration Calibrated multichannel reconstruction
Self-noise and Common Mode	**Noise target fixed after Year 1 budget** **CMRR: 10^7 (140 dB), goal 10^8 (160 dB)**	Measure noise and CMRR versus frequency Control tilt, rotation and platform modes
Gravity Calibration	**Response-matrix calibration error ≤10%** **Controlled gravity-source tests**	Define the error metric in Year 1 Calibrate amplitude and phase
NN Detection	**0.05–0.5 Hz target band** **Focus: 0.1–0.3 Hz microseisms**	Seismic-array prediction versus SGG data Verify gravity response and bound leakage
GW Preservation (simulation)	**Injected GW amplitude change ≤1%**	Define injected signals and filter response Check phase and directional dependence
Underground Operation	**≥90 days of observation** **NN detection or a quantified upper limit**	Set detection thresholds from noise budget and integration time

Proposed targets; sensitivity and test criteria fixed after the Year 1 noise budget.

Five-Year Experimental Roadmap

Prototype fabrication, underground NN detection and ET requirements

Phase and Period	Main Activities	Milestones
Year 1 **Design and** **Baseline Tests**	Fix band, sensitivity and CMRR targets Complete SGG and cryogenic designs Develop cavity NN model and array plan	Noise budget and detection criteria Designs and test infrastructure Initial ET requirements analysis
Years 2–3 **Fabrication and** **Integration**	Fabricate masses, suspension and transducers Integrate SQUIDs, cryocooler and acquisition Develop array-based CSD and leakage tests	1 integrated prototype 5-component response validation Calibration and analysis procedures
Years 4–5 **Validation and** **Underground Tests**	Verify sensitivity, CMRR and calibration Run joint underground observations ≥90 days Complete NN assessment and ET design study	NN detection or upper limit Leakage-separation report ET gradiometer requirements

Experimental Scope and ET Contribution

Validate Rayleigh NN gradients in the 0.05–0.5 Hz prototype band.
ET 1–10 Hz: requirements and design only. ET hardware and subtraction trials are outside this project.

Responsibilities and Deliverables

Participants	Proposed Responsibilities
NIMS Gravity Applications Research Group	Lead SGG design and readout integration Calibrate and verify sensor performance Develop NN analysis and ET requirements
Hana, SNU, University of Maryland, and specialist vendors	Fabricate sensor and cryogenic hardware Build and test the cryocooler system Support SGG integration
SGG/mSOGRO (UMD) and ET NN researchers (GSSI and partners)	Review readout, suspension and noise models Review cavity NN response and ET requirements
IBS Yemilab and environmental-sensor partners	Support underground installation and operation Co-observe with seismic arrays and tiltmeters Estimate wavefield direction and wavenumber

Equipment and Facilities

Expand NIMS–Hana fabrication and cryogenic test facilities.
Use Yemilab infrastructure with jointly operated seismic arrays and tiltmeters.

Planned Deliverables

1 integrated SGG + 1 auxiliary unit
Cryocooler, SQUID readout
and synchronized acquisition

Tensor calibration and leakage separation
Measured noise, CMRR and stability
NN analysis and observation data

NN detection assessment
ET gradiometer requirements
Designs and operating manuals

Conclusions and Discussion

Established Progress

Calibrated underground gravity record successfully supports ongoing earthquake and seismic studies.

Future Horizons

PEGS: Requires advanced source/sensor modelling.

SGG: Tensor reconstruction & underground Newtonian-noise reduction.

Thank You

Questions & Discussion

National Institute for Mathematical Sciences, Korea