WaveLabX: A Python and web-based toolkit for wave statistics and incident–reflected decomposition

Sandesh Lamsal[a,*], Claudia Deveaux Garrido[a]
Brian K. Haus[b], Landolf Rhode-Barbarigos[a]

[a]Department of Civil and Architectural Engineering, University of Miami, Coral Gables, FL 33146, USA

[b]Department of Ocean Sciences, Rosenstiel School of Marine, Atmospheric, and Earth Science, University of Miami, Miami, FL, USA

[*]Corresponding author: sandeshlamsal@miami.edu

Abstract

WaveLabX is an open-source toolkit for processing laboratory wave-probe time series in coastal and hydraulic engineering. It provides a unified, reproducible workflow for zero-crossing wave statistics and frequency-domain incident–reflected decomposition using either the classical two-probe Goda–Suzuki method or a redundant three-probe array method. Both decomposition methods share a single spectral formulation and embed reliability diagnostics directly into the analysis: per-frequency probe-spacing checks, conditioning of the inversion, and a retained-energy fraction that flags results computed from too little of the measured spectrum. The software is distributed as a Python package and as a zero-install, client-side browser application. WaveLabX is validated against known-truth synthetic records generated from linear wave theory: for well-conditioned probe arrays both methods recover incident and reflected wave heights to within a few percent, and the diagnostics correctly flag geometries for which the estimates are unreliable.

Keywords: wave reflection, Goda–Suzuki method, wave flume, physical modeling, coastal engineering, signal processing.

1 Motivation and significance

Wave-probe measurements are central to the physical modeling of wave–structure interaction. Wave heights, spectra and reflection coefficients are required to assess coastal-protection systems, breakwaters and the quality of generated wave conditions in flumes and basins. Two analyses are almost universally needed: zero-crossing statistics of single-probe records, and the separation of a measured surface elevation into incident and reflected components.

The separation of incident and reflected waves from co-linear probe arrays is a long-established problem. The two-probe frequency-domain method of Goda and Suzuki [1] remains the most widely used approach, and least-squares multi-probe formulations [2, 3] improve robustness by adding redundancy. Although these methods are textbook material [4–6], their implementations are typically fragmented across laboratories as facility-specific scripts. This fragmentation limits reproducibility, cross-study comparability and the long-term preservation of experimental workflows.

A second, less widely appreciated issue motivates this work. Frequency-domain reflection analysis is sensitive to probe spacing and to the numerical conditioning of the inversion. The decomposition becomes singular when the probe spacing approaches an integer number of half wavelengths, and the classical guideline that the non-dimensional spacing satisfy $0.05 \leqslant \Delta x/L \leqslant 0.45$ only bounds, but does not eliminate, this sensitivity. Even within the recommended band, certain probe configurations yield ill-conditioned inversions and physically inconsistent

Nr.	Code metadata description	Value
C1	Current code version	v0.3.1
C2	Permanent link to code/repository used for this code version	https://github.com/sandslamsal/WaveLabX
C3	Permanent link to reproducible capsule	https://github.com/sandslamsal/WaveLabX (scripts/ directory)
C4	Legal code license	MIT License
C5	Code versioning system used	git
C6	Software code languages, tools, and services used	Python (NumPy, SciPy, pandas, Matplotlib); JavaScript (browser application)
C7	Compilation requirements, operating environments & dependencies	Python $\geqslant$ 3.9; Windows, macOS, Linux. Install with `pip install -e .`
C8	Link to developer documentation/manual	https://github.com/sandslamsal/WaveLabX (README and in-source docstrings)
C9	Support email for questions	sandeshlamsal@miami.edu

Table 1: Code metadata.

estimates. In typical implementations these conditions are silent: the code returns a number with no indication that it is unreliable.

WaveLabX addresses both issues. It provides a single, transparent reference implementation of zero-crossing statistics, the two-probe Goda–Suzuki method and a redundant three-probe array method, with the two decomposition methods built on one shared spectral formulation so that they are mutually consistent. Crucially, it embeds reliability diagnostics into the analysis itself: at every frequency it evaluates the spacing guideline and the condition number of the inversion, discards frequencies that fail either test, and reports the fraction of measured spectral energy retained after this filtering. The user therefore obtains not only incident and reflected wave quantities but also a quantitative basis for judging whether to trust them.

Existing open tools cover parts of this workflow; the MATLAB zero-crossing routines of Neumeier [7] are one example, and other laboratory-specific implementations exist. To the authors' knowledge, no openly licensed, documented and tested package currently unifies single-probe statistics with both two- and three-probe reflection analysis and exposes the underlying conditioning diagnostics in a single workflow. By gathering these analyses together, and by additionally providing a browser-based interface that requires no installation, WaveLabX lowers the barrier to reproducible and comparable reflection analysis across laboratories. WaveLabX does not introduce a new reflection-decomposition theory; its contribution is a reproducible, open-source implementation that combines established two- and three-probe methods with automated reliability diagnostics and a no-install browser workflow.

2 Software description

2.1 Software architecture

WaveLabX is organized as a small Python package, `wavelabx`, accompanied by a self-contained browser application in the `web/` directory. The package is deliberately modular:

- `core`: the linear dispersion relation, solved for the wavenumber by Newton–Raphson iteration started from the explicit Fenton–McKee approximation [8], which converges reliably from deep to shallow water;
- `stats`: zero-crossing wave statistics for single-probe records;
- `two_probe`: the two-probe Goda–Suzuki decomposition;
- `three_probe`: the redundant three-probe array decomposition;

- `analysis`: a high-level workflow that combines the above and selects a recommended method;
- `sensitivity`: known-truth synthetic-record generators and scan utilities used for validation.

The overall workflow is shown in Fig. 1. The two-probe and three-probe methods are *alternatives*, not a procedural sequence: WaveLabX evaluates the probe geometry and selects the method expected to be most reliable for the given array. Both methods are constrained by the same Goda spacing band and conditioning criteria, and both discard frequencies that fail those criteria; the three-probe method is preferred when it retains a sufficient fraction of the measured spectral energy, and a well-spaced two-probe pair is used otherwise.

WaveLabX is additionally distributed as a browser application that provides the three-probe method with no installation; it is described in Section 2.3.

2.2 Software functionalities

Zero-crossing statistics `zero_crossing` detects individual waves in a single-probe record and returns the significant wave height, mean wave height, mean of the highest one-tenth waves, maximum wave height, and mean and significant wave periods. Wavenumbers are obtained from the linear dispersion relation

$$\omega^2 = g\,k\,\tanh(kh), \tag{1}$$

where $\omega = 2\pi/T$ is the angular frequency, T the period, $k = 2\pi/L$ the wavenumber, L the wavelength, h the water depth and g gravitational acceleration.

Two-probe Goda–Suzuki decomposition `two_probe_goda` separates the incident and reflected components from a pair of co-linear probes. The free surface is modeled as a superposition of incident and reflected linear waves; at each frequency the cosine/sine Fourier coefficients of the two records are combined to solve for the incident and reflected coefficients. A frequency is retained only if the non-dimensional spacing satisfies the Goda guideline

$$0.05 \leqslant \Delta x/L \leqslant 0.45 \tag{2}$$

and the 2×2 inversion is acceptably conditioned. Incident and reflected spectra are integrated to spectral wave heights and the reflection coefficient,

$$H_{m0} = 4\sqrt{m_0}, \quad m_0 = \int S(f)\,df, \qquad K_r = \frac{H_{m0,r}}{H_{m0,i}}. \tag{3}$$

Three-probe redundant array decomposition `three_probe_array` uses three co-linear probes to form three independent probe pairs. The incident and reflected Fourier coefficients are computed for every pair using the same formulation as the two-probe method; at each frequency the solutions from all pairs that satisfy Eq. (2) and the conditioning test are averaged. This redundancy improves robustness when one pair is unfavorably spaced.

Reliability diagnostics Both decomposition routines compute the condition number of the 2×2 inversion at every frequency and discard frequencies above a configurable threshold. Both report a *retained-energy fraction*, defined as the fraction of measured spectral energy that survives the spacing and conditioning filters. The three-probe routine warns the user when this fraction falls below a threshold (default 0.8); this provides an explicit, quantitative criterion for when a decomposition should be treated as unreliable, and answers the practical question of how to interpret a result for which a large part of the spectrum has been rejected.

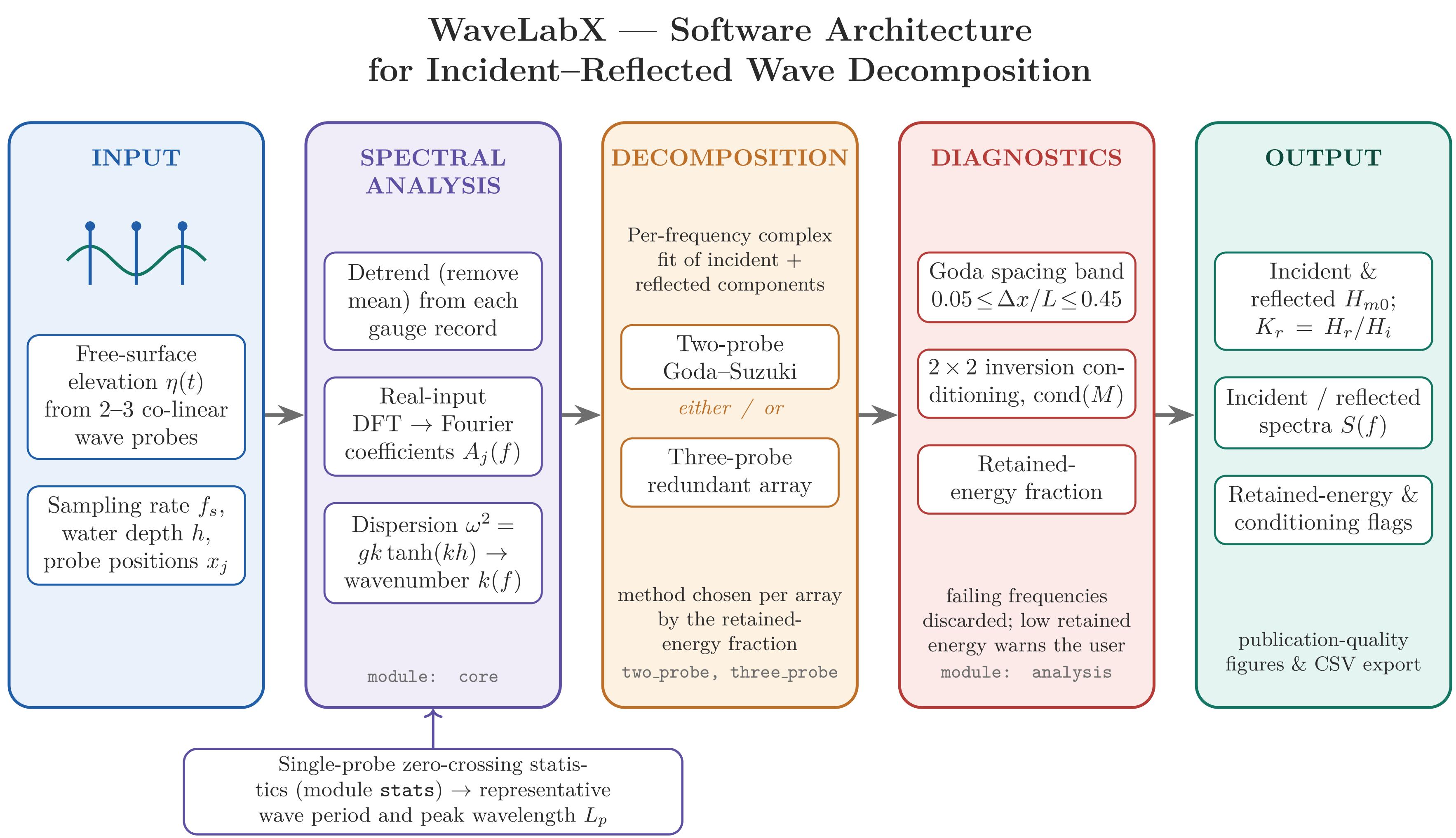

Figure 1: WaveLabX software architecture. The analysis pipeline runs from left to right; the two-probe and three-probe methods are a choice, not a sequence, selected per array from the probe geometry and the fraction of spectral energy the three-probe method retains. Both the Python package and the browser application implement this identical pipeline.

High-level workflow `reflection_analysis` runs the zero-crossing analysis to obtain a representative period, evaluates every available probe pair against Eq. (2) and the conditioning test, runs the three-probe method when three probes are available, and selects a recommended method based on the retained-energy fraction. A minimal example:

```
import numpy as np
from wavelabx import reflection_analysis

# eta: (N, 3) array of probe elevations [m]
eta = np.loadtxt("wavedata.csv", delimiter=",")

# fs in Hz, depth h in m, gpos in m
out = reflection_analysis(
    eta, fs=100.0, h=0.25, gpos=(0.0, 0.35, 0.70))

tp = out["three_probe"]
print(out["method_used"], tp["Kr"],
      tp["retained_energy_fraction"])
```

2.3 Browser application

In addition to the Python package, WaveLabX provides a browser application (Fig. 2) that makes the three-probe method available with no installation. It is a static, client-side web page: there is no build step and no server, and no data leaves the user's machine. The application is organised in two JavaScript modules. The numerical core, `spectral.js`, is a faithful port of the Python `three_probe_array` routine; it includes a Bluestein-algorithm [9] discrete Fourier transform that handles records of arbitrary length, the dispersion solver and the conditioning test. The interface layer, `app.js`, handles file input, the results table and an interactive visualization. An automated cross-check, run as part of the test suite, confirms that the port reproduces the results of the Python reference implementation.

The application accepts one or more wave-gauge CSV files by drag-and-drop and processes them as a batch. The data layout is detected automatically from the number of CSV columns: two columns are analyzed with the two-probe Goda–Suzuki routine; three columns with a single three-probe array; six columns as two co-linear three-probe arrays (channels 1–3 seaward and channels 4–6 shoreward). For *regular* waves the incident–reflected separation is performed at a single dominant frequency detected automatically from the spectrum; for *irregular* waves it is performed at every frequency bin and integrated to spectral wave heights, exactly as in the Python routine. The results table reports, for each file, the incident and reflected wave heights and the reflection coefficient of both arrays together with a transmission coefficient, and can be exported as CSV. When a three-gauge inversion is ill-conditioned the application falls back to the best-conditioned gauge pair and flags the affected files. An interactive panel visualizes the gauge time series and the energy and power spectra, with zoom, pan, per-point readout and spectral smoothing. The browser application follows the same reflection method as the package [1, 3] and is hosted at `https://wave-lab-x.vercel.app`.

The complete feature set of the browser application is the following:

- Drag-and-drop batch upload of wave-gauge CSV files; processing runs entirely client-side and no data is uploaded.
- Automatic detection of the data layout from the CSV column count: a two-column file is analyzed with the two-probe Goda–Suzuki routine (`twoProbeGoda`); a three-column file with a single three-probe array (`reflectionAnalysis`, with an automatic two-probe fallback if the three-probe retained energy is below 80%); a six-column file as two co-linear three-probe arrays (seaward channels 1–3, shoreward channels 4–6).
- Independently configurable gauge spacings X_{12}, X_{23} for the seaward array and X_{45}, X_{56} for

the shoreward array; gauge positions are derived from the spacings. Two-column files use only X_{12}.
- Global water depth applied to every file with optional per-file override, auto-read from the filename if it contains "`Depth=d`".
- Auto-detection of the dominant wave frequency f from the record spectrum, editable per row, within a user-configurable detection band $[f_{min}, f_{max}]$.
- Optional analysis window ("skip first N waves" and "analyse N waves") for trimming the record.
- *Analysis method* selector that lets the user override the default automatic selection: *three-probe only* (no fallback), *two-probe (best admissible pair)*, or a forced two-probe pair (gauges 1–2, 1–3 or 2–3). Intended for cross-checking a published result with a specific method.
- Results table reporting, per file, the incident and reflected spectral wave heights and reflection coefficient of each array plus the transmission coefficient $K_t = H_{i,2}/H_{i,1}$ for six-column files; each row carries a small badge per array ("3P" for the redundant three-probe routine, "2P" for two-probe Goda–Suzuki) and a layout tag for non-default column counts.
- CSV export (incl. the method-used columns), recompute and clear actions on the results table.
- Three interactive plot modes (time series, decomposed incident/reflected spectrum and raw per-probe spectrum) with per-probe checkboxes and, in the decomposed mode, incident/reflected/transmitted curve toggles.
- Plot navigation: box-zoom, pan, zoom in/out, reset; snap-to-nearest-point hover readout pinned on click; spectral smoothing slider; m / cm / mm unit selector.

3 Illustrative examples

3.1 Validation against a known reference

Because incident and reflected components cannot be measured independently in a physical flume, WaveLabX is validated against synthetic three-gauge records generated from linear wave theory with prescribed incident height, reflection coefficient and probe geometry (`wavelabx.sensitivity`). For a well-spaced array, both methods recover the incident and reflected spectral wave heights and the reflection coefficient to within a few percent of the prescribed truth (Fig. 3). The decomposition is therefore shown to be correct in a controlled setting before it is applied to laboratory data.

3.2 Probe-spacing sensitivity of the two-probe and three-probe methods

To quantify how probe spacing controls accuracy, both methods were applied to known-truth synthetic records under deliberately different geometric conditions (Fig. 4); the two panels are designed to highlight the distinct purpose of each method.

Panel (a) is a single-pair two-probe scan: at every $\Delta x/L$ the gauges sit at $(0, \Delta x, 2\Delta x)$ and only the first pair is used. The recovery stays within $\pm 5\%$ for approximately $0.07 \leqslant \Delta x/L \leqslant 0.36$, with one borderline point at $\Delta x/L \approx 0.14$ reaching $\approx 5\%$; outside this range the error degrades smoothly because the inversion approaches a singularity.

Panel (b) tests the redundancy of the three-probe routine on an *asymmetric* geometry: the first spacing is held fixed at $X_{12} = 0.10\,L$ (well inside the Goda band) while the second spacing X_{23} is varied across the same range as panel (a). The routine stays within $\pm 5\%$ across virtually the entire varied range, even where X_{23} is far outside the Goda band, because the per-frequency masking keeps the in-band pairs and discards the out-of-band one. No single-pair two-probe analysis can match this behaviour. This is the redundancy benefit the three-probe method was designed for.

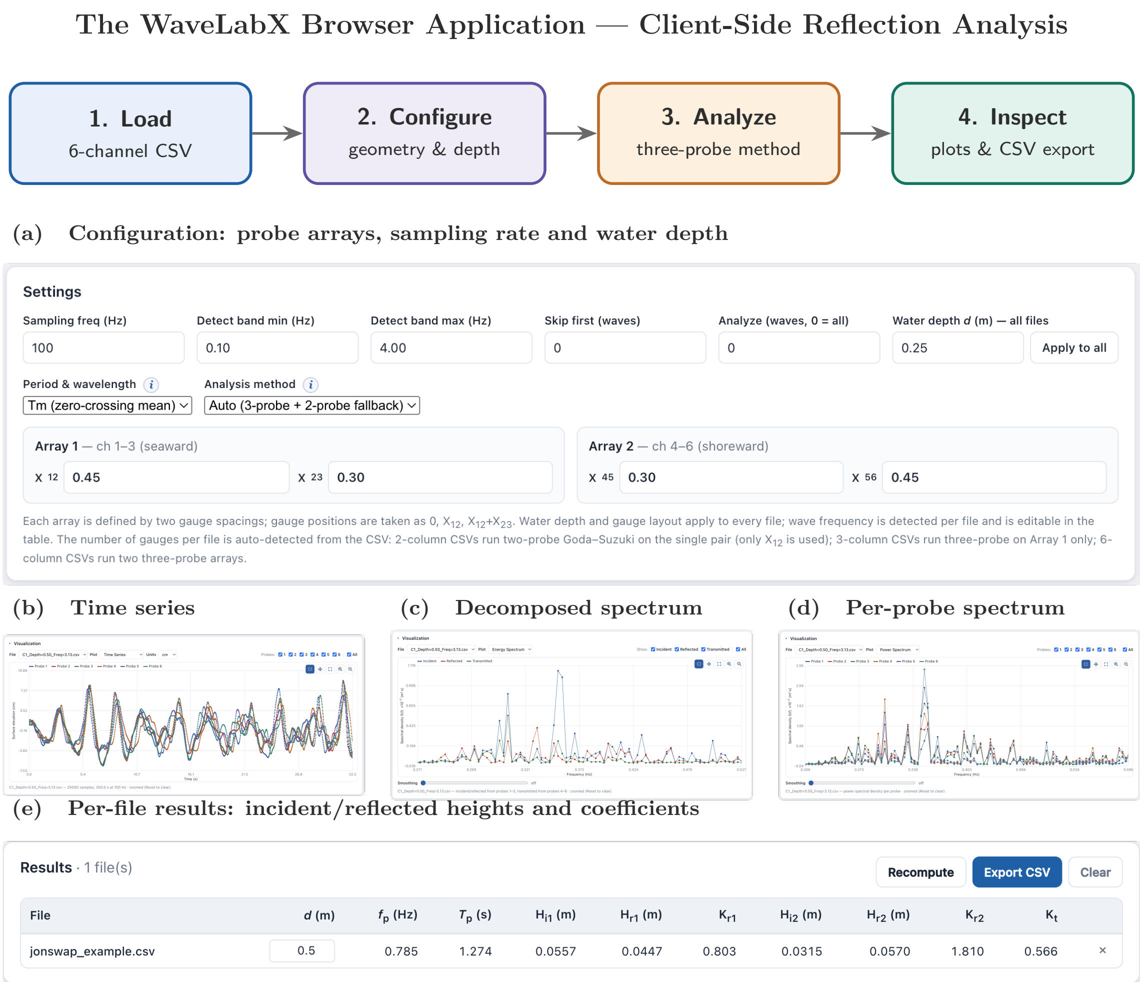

Figure 2: The WaveLabX browser application, applied to a six-gauge laboratory record. The tool follows a four-step workflow: load, configure, analyze, inspect. (a) The configuration panel sets the two probe arrays, the sampling rate and the water depth. (b–d) The interactive visualization offers time-series, decomposed incident/reflected and raw per-probe spectrum views, each with zoom, pan and per-point readout. (e) The results table reports the incident and reflected wave heights and the reflection coefficients of both arrays for every file, and exports them as CSV. The application runs entirely in the browser, with no installation and no server.

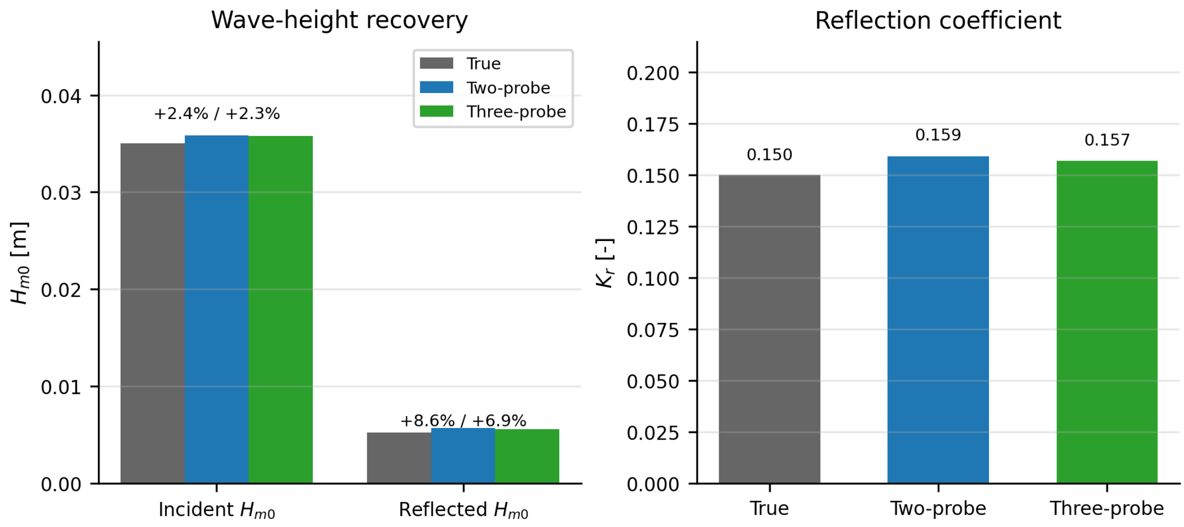

Figure 3: Recovery of incident/reflected wave heights and the reflection coefficient against a known synthetic truth, for a well-spaced array. Both methods agree with the prescribed values to within a few percent.

Both scans were repeated at three noise levels (3%, 10% and 30% of the incident height), covering typical flume signal-to-noise ratios and a deliberately extreme stress test. Inside the recommended spacing band the noisy two-probe curves are visually indistinguishable from the noise-free curve up to 10% noise; at 30% noise a small but visible spread appears. The three-probe panel shows almost no noise sensitivity at any level, because the in-band pair carries the estimate. The 0.8 default retained-energy threshold separates the in-band, ±5% regime from the regime in which the routine flags the case automatically.

3.3 Robustness of the three-probe method on non-uniform geometries

Beyond the varied asymmetric geometry of Fig. 4(b), three representative non-uniform geometries illustrate the redundancy benefit and the failure mode of the three-probe routine. A well-spaced array (0, 0.35, 0.70) keeps all three pairs inside the band and recovers the incident height to within 3.3%. An array of mixed spacing (0, 0.10, 0.60) keeps all pairs admissible and recovers the truth to within 3.1%. An array in which all probes are too closely spaced (0, 0.05, 0.10) leaves only one pair marginally admissible: the retained-energy fraction collapses to 0.58 and the incident height is in error by roughly 22%, which the routine flags through the retained-energy diagnostic. The 0.8 default threshold is therefore not arbitrary; it is the value below which the $\Delta x/L \in [0.07, 0.36]$ guarantee of Fig. 4 breaks down because no admissible pair remains.

3.4 Application to laboratory and synthetic datasets

To exercise WaveLabX across regular, irregular and known-truth scenarios, the three-probe method was applied to three contrasting cases (Table 2), all reproduced by the script `multi_example_test.py` in the `scripts/` directory:

1. *Synthetic regular wave with prescribed reflection.* A monochromatic incident–reflected superposition is generated from linear theory ($T_p = 1.25$ s, $h = 0.50$ m, $H_i = 0.113$ m, prescribed $K_r = 0.300$) and the three-probe routine is asked to recover the truth.
2. *Real regular wave ($f = 1.25$ Hz, H_3 target, $h = 0.35$ m).* Recorded in `regular_example.csv` under `data/` (six channels, 100 Hz). The seaward three-gauge array (channels 1–3) is analyzed with the exact gauge spacings shown in Fig. 5: $X_{12} = 0.60$ m, $X_{23} = 0.30$ m.

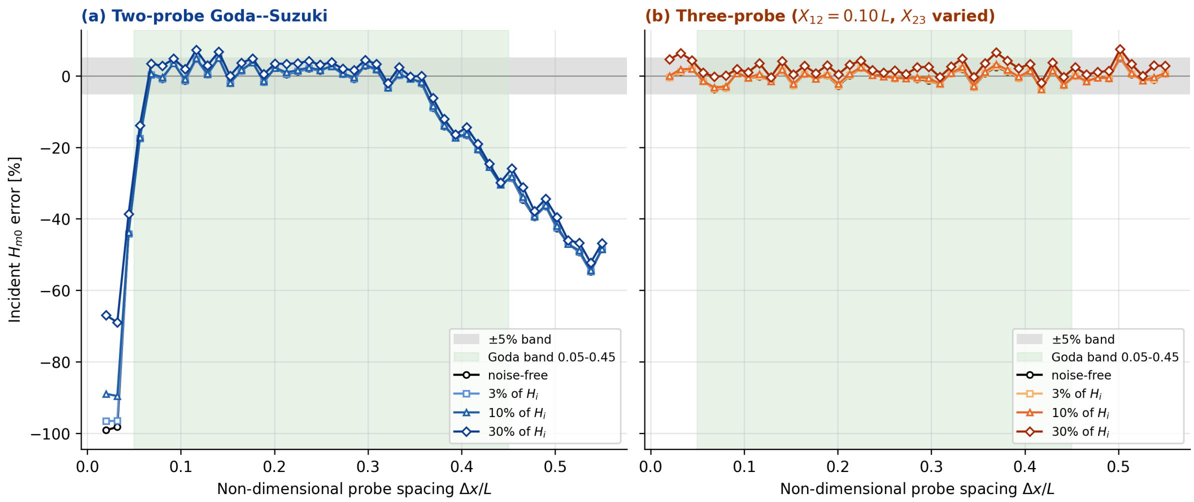

Figure 4: Probe-spacing sensitivity. Panel (a): two-probe scan with $X_{12} = \Delta x$. Panel (b): three-probe scan with the first spacing held fixed at $X_{12} = 0.10\,L$ (inside the Goda band) and the second spacing $X_{23} = \Delta x$ varied across the same range. Each panel is shown at four gauge-noise levels (noise-free, and 3%, 10% and 30% of the true incident wave height). The shaded grey band marks ±5% incident-height error; the green band marks the classical Goda spacing range $0.05 \leqslant \Delta x/L \leqslant 0.45$. The three-probe panel stays inside the ±5% band over the entire varied range, showing that the routine's per-frequency pair masking lets it recover the truth even when one pair is well out of the Goda band. Per-point errors and the three-probe retained-energy fraction are bundled with the release in `results/spacing_sweep.csv`.

3. *Real irregular wave (JONSWAP, $h = 0.50$ m).* Recorded in `jonswap_example.csv` under `data/` (six channels, 100 Hz). The seaward three-gauge array (channels 1–3) is analyzed with the WaveLabX browser-application default spacings $X_{12} = 0.45$ m, $X_{23} = 0.30$ m.

Fig. 5 shows the wave-flume layout used to acquire the two laboratory records: a 15 m flume with a piston wavemaker at the seaward end and an absorbing beach at the shoreward end, an instrumented submerged structure near mid-flume, and two co-linear three-gauge arrays (channels P1–P3 seaward and P4–P6 shoreward) placed between the wavemaker, the structure and the beach. The exact gauge spacings used for each case are listed in Table 2.

For the synthetic case (a controlled-truth check) the routine recovers the prescribed reflection coefficient to three decimal places ($K_r = 0.300$ recovered against $K_r = 0.300$ prescribed, an exact match), and the incident and reflected heights to within rounding. The real regular wave is recovered with a clean physical reflection coefficient ($K_r = 0.13$) and a high retained-energy fraction (0.94). For the JONSWAP record the seaward three-gauge array returns a physically admissible reflection coefficient ($K_r = 0.80$) and a healthy retained-energy fraction (0.95), and the conditioning diagnostic flags only a small number of frequencies. Fig. 6 shows the resulting incident, reflected and composite spectra. The same analysis runs without any installation through the browser application (`https://wave-lab-x.vercel.app`), which accepts wave-gauge CSV files directly; the browser implementation reproduces the Python results on identical inputs (verified by the JavaScript/Python cross-check in the test suite). A step-by-step walkthrough is provided in the Jupyter notebook `run_wavelabx_example.ipynb`.

The regular-wave case is an instructive corner case. With the SEAHIVE-flume spacings of Fig. 5 ($X_{12} = 0.60$ m, $X_{23} = 0.30$ m) and a dominant frequency $f = 1.25$ Hz at $h = 0.35$ m, the linear-wave wavelength is $L \approx 0.98$ m. The three probe pairs therefore sit at $\Delta x/L \approx 0.61$ (pair 1–2), 0.92 (pair 1–3) and 0.31 (pair 2–3); only pair 2–3 falls inside the Goda band $0.05 \leqslant \Delta x/L \leqslant 0.45$ at this frequency. The per-frequency masking inside `three_probe_array` reduces the calculation at the dominant frequency to a single-pair Goda–Suzuki estimate on the in-band pair 2–3, while the retained-energy fraction of 0.94 confirms that the great majority of the spectral energy lies

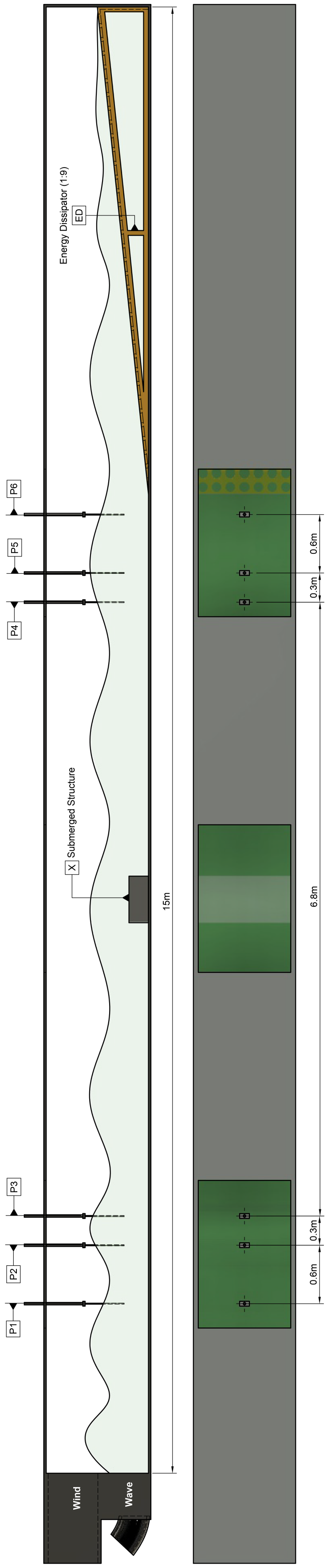

Figure 5: Wave-flume experimental setup that produced the laboratory records analyzed in Section 3.4. The campaign is described in [10]. Top: elevation view, showing the wavemaker (left), the two co-linear three-gauge probe arrays P1–P3 and P4–P6, an instrumented submerged structure near mid-flume, and the absorbing beach at the shoreward end. Bottom: plan view, showing the in-flume location of each three-gauge array and the submerged structure with measured spacings.

Case	Type	Data file	Spacings (m)	H_i (m)	H_r (m)	K_r	Retained
Synthetic regular	regular	`wavelabx.sensitivity`	0.60, 0.30	0.1131	0.0339	0.300	1.00
Regular wave (real)	regular	`regular_example.csv`	0.60, 0.30	0.1199	0.0151	0.126	0.94
JONSWAP (real)	irregular	`jonswap_example.csv`	0.45, 0.30	0.0557	0.0447	0.803	0.95

Table 2: Summary of the three illustrative cases analyzed in Section 3, the data file used and the seaward-array gauge spacings X_{12}, X_{23} of each. For the synthetic case a prescribed reflection coefficient $K_r = 0.300$ was imposed and recovered exactly. The regular-wave case uses the spacings shown in Fig. 5; the JONSWAP case uses the WaveLabX browser-application default spacings. Data files are located under `data/` in the repository; numbers are reproduced by `scripts/multi_example_test.py` and stored in `results/multi_example_results.csv`.

in bins where at least one pair is admissible. That the same routine recovers the prescribed synthetic-truth reflection coefficient exactly under identical conditions (Table 2, first row) shows the single-pair fallback to be self-consistent. The same diagnostic is surfaced by the per-pair Goda warnings emitted by the Python package and by the browser application, so this state is visible at a glance to a user who runs the example.

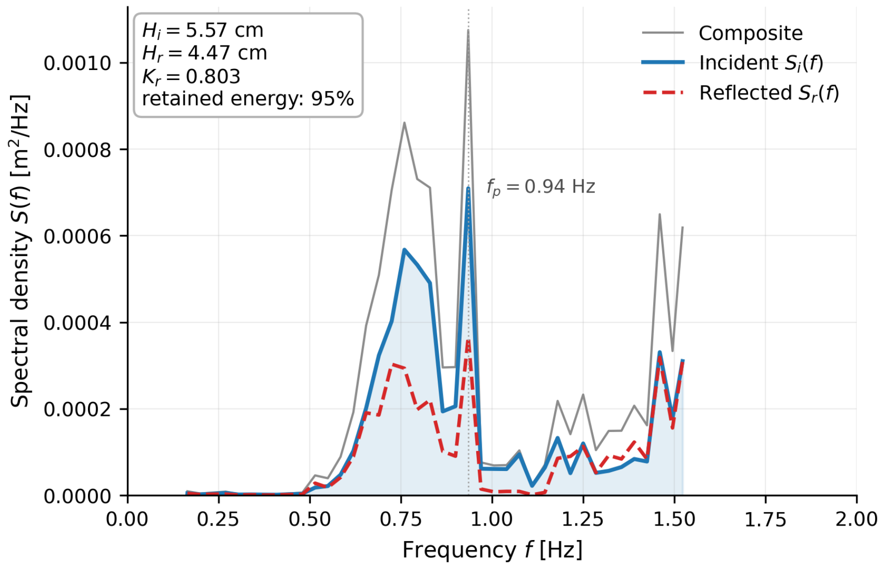

Figure 6: Incident, reflected and composite wave spectra from the real irregular-wave (JONSWAP) laboratory record `data/jonswap_example.csv`, computed for the seaward three-gauge array (channels 1–3).

4 Impact

WaveLabX is intended to make reflection analysis in physical wave modeling reproducible, comparable and transparent. Its impact arises from three features. First, it consolidates analyses that are usually re-implemented as facility-specific scripts into a single openly licensed, documented and tested package, so that results from different laboratories and studies are produced by an identical, citable workflow. Second, by embedding spacing, conditioning and retained-energy diagnostics into the analysis, it allows users to detect unreliable estimates that classical implementations report silently; reliability assessment becomes part of routine post-processing rather than an afterthought. Third, the browser application removes the installation barrier entirely, making the methods accessible to experimentalists who need a fast evaluation.

The software was developed alongside laboratory programs at the SUSTAIN Laboratory of the University of Miami, where it has supported a sustained body of experimental wave–

structure-interaction research. The three-probe method it implements was used to separate incident and reflected waves in a peer-reviewed study of wave transmission over submerged SEAHIVE breakwaters [10], in the doctoral dissertation on submerged breakwaters for coastal protection [11], and in experimental studies of perforated breakwater structures [12], hybrid coral-reef structures [13], wave dissipation by mangrove forests [14], hurricane-induced wind and wave loading [15], and a beach-erosion-control modeling and design project [16]; the toolkit itself is openly archived [17]. Typical applications include reflection-coefficient estimation, comparison of alternative probe layouts, and quality-controlled post-processing of experimental datasets. The probe-spacing sensitivity and retained-energy criteria documented here also give experimentalists a practical basis for designing probe arrays before a test campaign begins.

WaveLabX is intended for one-dimensional wave propagation with co-linear probe arrays and linear-wave behavior. Strongly nonlinear waves, breaking and multi-directional wave fields are outside its current scope. When the retained-energy fraction is low, the software reports the result together with an explicit warning, so that the limitation is visible to the user.

5 Conclusions

WaveLabX is an open-source toolkit that unifies zero-crossing wave statistics with two-probe and three-probe incident–reflected decomposition under a single, consistent spectral formulation. Its distinguishing feature is that reliability diagnostics (probe-spacing checks, conditioning of the inversion and a retained-energy fraction) are embedded directly in the analysis, so that estimates are accompanied by a quantitative measure of their trustworthiness. Validation against known-truth synthetic records shows that both methods recover incident and reflected wave heights to within a few percent for well-conditioned arrays, that the two-probe error grows predictably outside the spacing range $0.07 \leqslant \Delta x/L \leqslant 0.36$, and that the three-probe method automatically flags geometries for which its estimates are unreliable. Distributed as both a Python package and a zero-install browser application, WaveLabX supports reproducible and comparable reflection analysis across coastal and hydraulic laboratories. Future work includes extending the methods to oblique and multi-directional wave fields.

Data and code availability

The WaveLabX source code, example datasets, reproducible scripts and the browser application are openly available under the MIT License at `https://github.com/sandslamsal/WaveLabX`. The version that supports the figures, tables and analyses reported in this manuscript is archived on Zenodo as [17] (doi:10.5281/zenodo.20347447). The example records analyzed in Section 3 (`regular_example.csv` and `jonswap_example.csv` under the `data/` directory) are bundled with the release. Running `multi_example_test.py` under `scripts/` regenerates the numerical results in Table 2; running `real_data_example.py` regenerates the spectra in Fig. 6. The browser application is deployed at `https://wave-lab-x.vercel.app` and runs the same analysis routine as the Python package (Section 2.3).

Acknowledgements

The development of WaveLabX was motivated by experimental workflows used in the SUSTAIN Laboratory at the University of Miami. The authors thank colleagues and technical staff who supported the laboratory programs that informed the design of this software.

References

[1] Yoshimi Goda and Yoshio Suzuki. Estimation of incident and reflected waves in random wave experiments. In *Proceedings of the 15th International Conference on Coastal Engineering*, pages 828–845. American Society of Civil Engineers, 1976.

[2] Etienne P. D. Mansard and E. R. Funke. The measurement of incident and reflected spectra using a least squares method. In *Proceedings of the 17th International Conference on Coastal Engineering*, pages 154–172. American Society of Civil Engineers, 1980.

[3] Nobuhisa Kobayashi, Donald T. Cox, and Andi Wurjanto. Irregular wave reflection and run-up on rough impermeable slopes. *Journal of Waterway, Port, Coastal, and Ocean Engineering*, 116(6):708–726, 1990.

[4] Yoshimi Goda. *Random seas and design of maritime structures*. World Scientific, 3rd edition, 2010.

[5] Robert G. Dean and Robert A. Dalrymple. *Water wave mechanics for engineers and scientists*, volume 2. World Scientific, 1991.

[6] Leo H. Holthuijsen. *Waves in oceanic and coastal waters*. Cambridge University Press, 2007.

[7] Ulrich Neumeier. Wave analysis matlab functions, 2025. URL `http://neumeier.perso.ch/matlab/waves.html`. Accessed 2025.

[8] John D. Fenton and W. D. McKee. On calculating the lengths of water waves. *Coastal Engineering*, 14(6):499–513, 1990.

[9] Leo I. Bluestein. A linear filtering approach to the computation of discrete Fourier transform. *IEEE Transactions on Audio and Electroacoustics*, 18(4):451–455, 1970. doi:10.1109/TAU.1970.1162132.

[10] Sandesh Lamsal, Brian K. Haus, and Landolf Rhode-Barbarigos. An experimental study on wave transmission over submerged SEAHIVE® breakwaters. *Coastal Engineering Journal*, pages 1–13, 2026. doi:10.1080/21664250.2026.2661171. URL `https://doi.org/10.1080/21664250.2026.2661171`.

[11] Sandesh Lamsal. *Submerged breakwaters for coastal protection: A performance review from physical testing*. PhD thesis, University of Miami, 2025. URL `https://scholarship.miami.edu/esploro/outputs/doctoral/Submerged-Breakwaters-for-Coastal-Protection-A/991032728534702976`.

[12] Sandesh Lamsal, Gustavo Aguilar, Peisen Tan, Katie Simi, Gerald Clark, Brian K. Haus, and Landolf Rhode-Barbarigos. Quantifying wave energy dissipation in perforated breakwater structures: An experimental study with porous hexagonal seahive configurations. In *American Geophysical Union Ocean Sciences Meeting*, pages CP51B–02, 2024.

[13] Sandesh Lamsal, Gustavo Aguilar, Peisen Tan, Gerald Clark, Brian K. Haus, and Landolf Rhode-Barbarigos. A sustainable and efficient structural solution for hybrid coral reefs. In *Proceedings of the ASCE Earth & Space Conference*, pages 67–68. American Society of Civil Engineers, 2024.

[14] Gerald Clark, Sandesh Lamsal, Brian K. Haus, and Landolf Rhode-Barbarigos. Wave energy dissipation from adult red mangroves based on mangrove forest density. In *AGU Fall Meeting Abstracts*, 2024. Abstract OS53B-0787.

[15] Gustavo Aguilar, Sandesh Lamsal, Peisen Tan, Alba Uriarte, Brian K. Haus, and Landolf Rhode-Barbarigos. Investigating hurricane-induced wind and wave loads through scaled physical testing. In *Proceedings of the ASCE Earth & Space Conference*, pages 68–69. American Society of Civil Engineers, 2024.

[16] Mohammad Ghiasian, M. Barnett, J. Rakich, A. Cook, Brian K. Haus, Sandesh Lamsal, and Landolf Rhode-Barbarigos. Developing sustainable and innovative systems for beach erosion control through modeling and design. In *39th Annual National Conference on Beach Preservation Technology (FSBPA)*, 2026.

[17] Sandesh Lamsal, Claudia Deveaux Garrido, Brian K. Haus, and Landolf Rhode-Barbarigos. WaveLabX (v0.3.1) [software]. Zenodo, 2026. URL https://doi.org/10.5281/zenodo.20347447.