Ombrier Field 25 — Relay-Switched Precision Attenuator

Design, Implementation and Experimental Verification · Engineering Design Record · Revision 1.0 · 7 November 2026

Prepared by Oxy for Henk Mulder. Every figure in this document is taken from the project's own files — the schematic, the netlist, the bill of materials, the plotted fabrication set, the control firmware and the three measurement campaigns — and where the record is silent the document says so rather than filling the gap.

Design specification at a glance

The verified characteristics of the board as built and as measured on 7 November 2026. Everything below this page is the argument, the derivation and the evidence.

Function	Six-bit binary relay-switched analogue attenuator, constant-impedance L-pad cascade, plus a separate mute relay
Range	**0 to 63 dB** in **1 dB** steps; 64 states
Nominal impedance	**10 kΩ**, maintained in every state (the L-pads are constant-impedance by construction)
Topology	Six series L-pads, binary-weighted 1 · 2 · 4 · 8 · 16 · 32 dB, each bypassed or inserted by one changeover contact
Signal path	Metal-film resistors and reed-relay contacts only — no semiconductors, no capacitors, no power in the audio path
Relays	7 × **Standex-Meder DIP05-1C90-51D**, 5 V coil, 200 Ω, 1 Form C, internal coil diode
Drive	**74HC595** shift register (QA–QF stages, QG mute, QH unused) → **ULN2003AN** Darlington array → relay coils
Control interface	Three-wire serial: **DS, SHCP, STCP** on 3-pin header J3; 5 V logic
Control polarity	**Inverted**: a logical 1 (stage inserted) is written as a physical 0. Relay energised = stage **bypassed**
Change sequence	Current code + MUTE → 5 ms → new code + MUTE → 5 ms → new code + PLAY; all eight bits transfer at once on STCP
Unpowered state	**Muted** — the mute relay is released with the output taken to ground
Board	**55,0 × 90,0 mm**, 2 copper layers, 33 footprints (29 components + 4 mounting holes), 37 nets, 4 DRC violations (3 silkscreen, 1 starved thermal), 0 unconnected
Fabrication	`ATTENUATOR-v06-gerbers.zip`, 14 files, sha256 `d1b2a5fa2b677977…`; 140 plated holes, 4 × Ø3,20 mm mounting
Measured, 0–50 dB	Fitted **1.0022 / 0.9935 / 0.9853 dB per code** in the three regions; worst error **0.196 dB**
Measured, 51–63 dB	Resolution-limited by the oscilloscope; worst apparent error 1.359 dB at code 63, where 50 µV is one decibel
Landmark results	code 16 = **15.970 dB** · code 32 = **32.022 dB** · code 48 = **47.846 dB**
Not measured	Channel matching (one channel built), noise, distortion, long-term contact repeatability, absolute accuracy below 50 dB

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1. Introduction

1.1 What this document is

Field 25 is a 25 W class-A/B audio power amplifier built as a development machine, one module at a time. The attenuator is the module that sits between the input connector and the preamplifier, and it is the first of them to be designed, built, tested and — since 7 November 2026 — measured across its whole range.

This is an engineering design record, not a product brochure and not a maintenance manual. It exists to answer three questions: **why** the attenuator is built the way it is, **how** another engineer would build and drive it, and **what was learned** while getting it to work. The third of those is the part that a schematic alone cannot carry.

1.2 Design philosophy: why relays at all

A volume control has four candidate technologies, and the choice between them is not a matter of taste:

- **A potentiometer.** A contact slides along a resistive track. It wears, its law is a curve somebody chose, and its two channels never track each other exactly. Its great virtue is that it is cheap and needs no power.
- **A digital potentiometer or volume IC.** Cheap, small, remote-controllable, and in the signal path it brings an active device with its own distortion, noise and on-resistance — and, critically, a supply and a ground reference that the audio signal now shares.
- **A relay-switched resistor network.** The signal passes through metal-film resistors and the contacts of sealed reed relays. Nothing amplifies, nothing is biased, nothing needs power to keep a state, and the same code gives the same resistance tomorrow. The costs are real: seven relays per channel, a driver array, a control interface, board area, and — as this project discovered — a grounding discipline that has to be got right (see §12).
- **A CMOS switch matrix.** Silent, small, cheap — and its on-resistance sits in the series arms of the ladder, where it moves with signal level and becomes a distortion term.

The project closed that last door in September: **no FETs in the attenuation ladder, reed relays only**. What that buys is the property that matters in a machine meant to be measured rather than admired: at any setting the signal passes through passive parts whose values are known to 0.1 % and whose contacts are sealed in glass.

1.3 The board in one paragraph

Six binary-weighted constant-impedance L-pads, 1 dB to 32 dB, in series. Each is bypassed by moving its relay into the energised state and inserted by releasing it — one changeover contact per stage does both jobs. A seventh relay mutes the output by taking it to ground during a change and at power-up. A single 74HC595 holds all eight bits and transfers them together, so the six stages change in one instant; the ULN2003 provides the coil current. The control interface is three wires. The board is 55 × 90 mm, two layers, and everything that defines the attenuation is on the front copper, returning to a signal ground that is deliberately not the same conductor as the relay supply.

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2. Design requirements

The requirements are the ones the board was designed against; the column on the right says how each stands today. "Measured" means the 7 November sweep; "calculated" means the arithmetic in §4.

#	Requirement	Target	Standing
R1	Attenuation range	0–63 dB	**Met** — all 64 codes present and monotonic

#	Requirement	Target	Standing
R2	Step size	1 dB nominal	**Met** — fitted 1.0022 dB/code at the top, 0.9853 at 33–50
R3	Step accuracy, 0–50 dB	≤ 0.5 dB per step	**Met** — worst 0.196 dB against the ideal curve
R4	Impedance	10 kΩ constant	**By construction**; not measured directly
R5	Transparency	Passive components only in the signal path	**Met** — resistors and reed contacts
R6	Repeatability	Same code, same attenuation	**By construction**; contact repeatability not yet measured
R7	Channel matching	< 0.1 dB between channels	**Not measured** — one channel built
R8	Mute	Output silenced during change and at power-up	**Met** — fails safe to mute
R9	Control	Three-wire serial, 5 V, remote	**Met** — DS/SHCP/STCP
R10	Power	5 V only, relay coils from the same rail	**Met** — 7 coils at 200 Ω, ≈175 mA when all energised
R11	Size	Fits the Field 25 flat layout	**Met** — 55 × 90 mm
R12	Silence in the audio band	No active device in the path	**Met by design**; noise not measured

Two requirements were added during the work and are now part of the design: **R13, separate ground domains** for the audio reference and the relay logic (§5.5), and **R14, a defined output impedance during mute** (R13, 10 kΩ to ground, so the preamplifier never sees an open circuit).

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3. Architecture

3.1 Signal path

```
J1  audio in
 └─► stage 5 (32 dB) ─► stage 4 (16 dB) ─► stage 3 (8 dB) ─► stage 2 (4 dB) ─► stage 1 (2 dB) -
       └─► R14 10 kΩ termination ─► RL7 mute contact ─► J2 audio out
```

The stages are cascaded from the heaviest weight to the lightest so that the largest attenuation comes first and every later stage works on a smaller signal. Each stage is a two-resistor L-pad; the cascade is constant-impedance because each pad presents 10 kΩ at its input whatever state it is in (§4.3).

3.2 Control path

```
J3 (DS, SHCP, STCP) ─► 74HC595 U1 ─► QA…QG ─► ULN2003 U2 ─► coil low sides of RL1…RL7
                       │
                       └─ +5 V and 0 V from J4
```

The 595 has two registers: an **8-bit shift register** that takes the bits in serially, and an **8-bit storage register** that holds what the relays see. Bits are shifted while the storage register keeps its old contents; STCP then transfers all eight at once. That is the mechanism the design brief calls the *shadow bank*: the new code is built up off-stage and applied in a single edge, so no two stages ever change at measurably different times.

The mute relay is what covers the interval in which the mechanical contacts are actually moving. Its contact is on the output side, so the preamplifier sees ground (through 10 kΩ, R13) rather than an open circuit during a change.

3.3 Interfaces

Connector	Type	Pins	Function
J1	KK-254 1×02	2	Audio in, signal ground
J2	KK-254 1×02	2	Audio out, signal ground
J3	KK-254 1×03	3	DS, SHCP, STCP (control)
J4	Mini-Fit Jr 2×02	4 (3 used)	+5 V, 0 V, and a spare

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4. Attenuation theory

4.1 One L-pad

For a pad terminated in its own impedance Z and required to give a voltage ratio k = 10^(–dB/20):

```
R_series  = Z · (1 − k)
R_shunt   = Z · k / (1 − k)
```

Check the input impedance: `Z_in = R_series + (R_shunt ∥ Z) = Z(1−k) + kZ = Z`. The chain is unidirectional, so only the *input* impedance has to equal Z — an L-pad is enough, and neither a T nor a π section is needed.

4.2 Six pads, six weights

Bit	dB	k = 10^(–dB/20)	R_series exact	R_shunt exact	R_series E96	R_shunt E96	Board refs
0	1	0,89125	1,0875 kΩ	81,95 kΩ	**1,10 kΩ**	**82,5 kΩ**	R1 / R2
1	2	0,79433	2,0567 kΩ	38,62 kΩ	**2,05 kΩ**	**38,3 kΩ**	R3 / R4
2	4	0,63096	3,6904 kΩ	17,10 kΩ	**3,74 kΩ**	**16,9 kΩ**	R5 / R6
3	8	0,39811	6,0189 kΩ	6,614 kΩ	**6,04 kΩ**	**6,65 kΩ**	R7 / R8
4	16	0,15849	8,4151 kΩ	1,883 kΩ	**8,45 kΩ**	**1,87 kΩ**	R9 / R10
5	32	0,02512	9,7488 kΩ	257,7 Ω	**9,76 kΩ**	**255 Ω**	R11 / R12

These twelve values are the board's own parts list. Because each pad is constant-impedance, the contributions add exactly: an n-bit word N gives N dB, 0–63 dB in 1 dB steps, with no correction table.

4.3 Why the property survives the cascade

Each pad presents Z at its input *only if* its output is terminated in Z. The cascade is therefore built from the right: the last stage is terminated by R14 (10 kΩ), so its input is 10 kΩ in either state; the next stage's load is that input, so it too sees 10 kΩ; and so on back to the first stage. Every pad sees what it was designed for, whatever the word, which is why the dB values add cleanly instead of interacting.

4.4 The topology that does not work

A chain of series resistors each shorted by a switch, with a single shunt at the far end, *looks* like a binary attenuator and is not one. Resistances add linearly, not logarithmically: 1 dB + 2 dB comes out near 2,8 dB, and all six together near 33 dB instead of 63. The constant-impedance pad is what makes the weights independent; without it there is no binary scale to switch.

4.5 Termination, and the two 10 kΩ resistors

R14 is the ladder's own termination: 10 kΩ fitted where 10,1 kΩ is the exact value for a 1 MΩ preamplifier (R_term = Z·R_in/(R_in − Z)). The 1 % shortfall moves the ladder's last stage by a few hundredths of a decibel and is recorded rather than corrected.

R13 is not a termination in the ladder. It gives the preamplifier 10 kΩ to ground *while the mute relay is released*, and it is out of circuit entirely during playback.

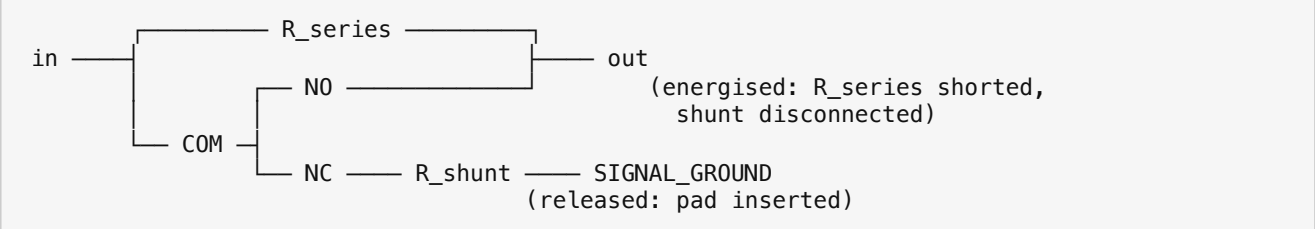
4.6 Resistor tolerance, calculated

With independent ±1 % parts the stage error budget is ±0,011 dB at 1 dB rising to ±0,167 dB at 32 dB; worst case with all six accumulating is 0,45–0,5 dB. The 0,1 % parts fitted to the retest boards cut that by ten, to about 0,05 dB worst case. Neither figure explains the error the first prototype showed — see §12, where the cause turned out to be a ground, not a resistor.

5. Circuit implementation

5.1 The stage, as built

Each of the six stages is two resistors and one changeover contact:



The relay contact's **common** sits at the junction between the series resistor and the shunt. Its **normally closed** contact goes to the shunt, which returns to `SIGNAL_GROUND`; its **normally open** contact goes back to the stage's input node. One Form C contact therefore does both jobs that bypassing requires:

- **released** — the junction is connected to the shunt, the series resistor is in circuit: **the pad is inserted**;
- **energised** — the junction is shorted to the input node, the series resistor is bypassed *and* the shunt is left with one end open: **the pad is out**.

This is why a single-pole changeover relay per stage is sufficient even though bypassing needs two simultaneous actions: they are the two throws of the same contact, and they cannot disagree.

The stage order matters for headroom, not for the arithmetic. The cascade runs **32 dB first**, then 16, 8, 4, 2 and 1 dB, so that the largest attenuation happens while the signal is largest. Nothing downstream sees a smaller signal than the arithmetic requires.

5.2 Drive

`U1`, a **74HC595**, takes three signals from `J3` — `DS` (pin 14), `SHCP` (pin 11), `STCP` (pin 12) — and presents eight outputs. `QA`–`QF` are the six stage bits in ascending weight; `QG` is the mute relay; `QH` is unused and both of its pins are left unconnected.

The 595 cannot drive a relay coil, so `U2`, a **ULN2003AN**, sits between: each 595 output drives one Darlington input, and each Darlington sinks the low side of one coil. `U2` pin 9 (COM) is returned to **+5 V**, which is the flyback path for the internal diodes — the relay coils have their own diodes (the `-51D` suffix), so this is a second line of defence rather than the only one.

Coils are 200 Ω at 5 V: **≈25 mA each**, so ≈150 mA with five energised and ≈175 mA with all seven. That current is the reason the board has two grounds (§5.5): it is the one significant current on an otherwise passive board, and it must not travel in the conductor that defines the attenuation.

5.3 Supply and decoupling

`J4` brings **+5 V and 0 V** to the board. `C1` (47 µF, Panasonic FR) is the bulk reservoir for the coil pulses; `C2` (100 nF, WIMA MKS2) decouples the 595 at its own pins. There is no analogue supply on this board, because there is nothing analogue on it that needs one.

5.4 Control connector

`J3` is a 3-way KK-254 header carrying **DS, SHCP, STCP** — a plain shift-register interface with no clock recovery, no address, and no protocol. Holding the clock low leaves the output register untouched. A controller that has nothing to say says nothing.

5.5 The two grounds

The board carries two distinct nets, and the distinction is the most important thing on it:

net	what returns on it
`/SIGNAL_GROUND`	**every resistor that defines the attenuation**: `R2.2, R4.2, R6.2, R8.2, R10.2, R12.2, R13.2, R14.2`, plus `J1.2` and `J2.2` — ten connections
`/GND`	the logic and coil returns: `C1.2, C2.2, J4.2, U1.8, U1.13, U2.8` — six connections

The two meet at the system star, once, and nowhere on this board. The first revision did not do this — the shunts returned on the coil ground — and the consequence is documented in §12 because it was the defect that dominated the project's first month of measurement.

Both nets are poured as `GND` zones (F.Cu and B.Cu, 0,25 mm minimum thickness) but they are separate zones on separate nets; the pour is not a single ground.

5.6 What is deliberately absent

- **No buffer, no amplifier, no switch.** The signal enters on `J1` and leaves on `J2` through resistors and contacts.
- **No DC-blocking capacitor.** There is nothing to block; the ladder is resistive.
- **No on-board regulator.** 5 V arrives from the auxiliary supply.
- **No address decoding or protocol logic.** The 595 is the whole interface.

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6. Component selection

Ref	Part	Why this one
RL1–RL7	**Standex-Meder DIP05-1C90-51D** — 5 V, 200 Ω, 1 Form C, internal coil diode, DIP package	Sealed reed contact: no wear surface in the signal path, stable contact resistance, and a DIP footprint that is easy to replace. The `-51D` variant adds the coil diode *inside* the relay — and pin 2 is its positive end, which is how the board wires it. The no-diode `-51L` was at zero stock when the order was placed; the diode variant was decided on 17 September
U1	**CD74HC595E**, DIP-16	The canonical serial-in/parallel-out latch. The SOIC version does not fit the DIP footprint on this board
U2	**ULN2003AN**, DIP-16	Seven Darlington sinks with internal freewheel diodes — exactly one per relay, no spare logic

Ref	Part	Why this one
R1–R14	**YAGEO MFR-25** (R7: MFR50S), 1 % metal film, 0,25 W	Bulk metal-film: low excess noise, ±50 or ±100 ppm/°C depending on packaging code, and cheap enough that the 0,1 % upgrade for the retest boards cost cents rather than pounds
C1	**Panasonic EEU-FR1E470B**, 47 µF 25 V	Enough reservoir for seven coil pulses; the same series as the driver board
C2	**WIMA MKS2C031001A00KSSD**, 100 nF 63 V	Close to the 595's own pins
J1–J3	**Molex KK-254**	Matches the harness family used everywhere else in Field 25
J4	**Molex Mini-Fit Jr 2×02** (3 pins used)	Power connector, keyed, with a positive latch

A note on the relays, because it is easy to be misled here. A description of this design that mentions *Omron G6K* is describing a different relay: the G6K is a signal relay in a smaller package, and it is not what is on this board. The built part is the Standex-Meder DIP05 reed relay, chosen for its sealed contact and its DIP footprint. The bill of materials, the netlist and the fabrication data all name the same part, and it is that part that the measurements in §11 were made on.

Resistor tolerance, and the upgrade that was tried. The first prototype was built with 1 % parts. Two further boards were built with 0,1 % parts specifically to test whether tolerance explained a 4,8 dB error at the 32 dB stage. It did not: the error reproduced to within a few millivolts on both 0,1 % boards, which sent the investigation to the ground (§12).

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7. PCB and mechanical design

7.1 The board

Outline	**55,01 × 90,01 mm**, rectangular, four Ø3,20 mm mounting holes
Layers	**2**, 1,6 mm, 1 oz copper (fabrication options as ordered)
Footprints	**33** on the board (29 components + 4 mounting holes)
Nets	**37**
Copper	**292 track segments**, **11 vias**, two `/GND` pours (F.Cu and B.Cu, 0,25 mm minimum)
Drill	**140 plated holes**: 0,30 / 0,70 / 0,80 / 1,19 mm; **4 unplated** Ø3,20 mm
DRC	**4 violations**: 1 error (starved thermal, `J4` pad 2 to the F.Cu zone), 3 warnings (2 silk-to-edge, 1 silk overlap). **0 unconnected pads**

7.2 Layout intentions

- **The ladder runs along the length of the board**, 32 dB stage first, and the shunt returns are taken to the `SIGNAL_GROUND` trunk rather than to the nearest copper. On the revised layout the right-hand tails are 0,8–2,0 mm stubs onto a trunk at x = 129,09 mm; the left-hand runs are 13–25 mm. Lengths differ, but every one of them terminates on the same conductor and carries no coil current.
- **The control and coil currents stay at the other end** of the board, with `U1`/`U2` and the supply connectors sharing `J4`'s end of the layout.
- **Silkscreen carries the three ground names** (`+`, `−`, `GND`) where the harness lands, so a wire cannot be put on the wrong terminal without the label disagreeing with it.

7.3 Dimensions that changed, and why

Three layout revisions were plotted in October. The one that matters here is **v05 → v06**, a single change: `J1` moved **1,42025 mm to the right** (x 115,360 → 116,78025), which took its clearance to `C2` from 0,590 mm to **2,010 mm** and to the mounting hole `MH2` from 3,431 mm to **2,010 mm**. Everything else on the board is byte-identical: no other component moved, no hole was added or removed, and the outline is unchanged. The copper, mask and silkscreen around `J1` were redrawn with it, and both pours refilled.

7.4 Fabrication data

The released set is **`ATTENUATOR-v06-gerbers.zip`** — 14 files (7 gerbers, PTH and NPTH drill plus their maps, position file, DRC report, `.gbrjob`), 115 871 B, sha256 `d1b2a5fa2b677977…`. It was submitted to JLCPCB on 25 October 2026 as `ATTENUATOR-v06-gerbers_Y10`, alongside the preamp, power distribution and riser panel, in order `W2026102605379238`. Earlier sets (v04, v05) are kept beside it; v05 differs from v06 only in the position of `J1`.

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8. Firmware and control

8.1 Bit mapping

The 74HC595's outputs, as the control software must think of them:

Output	Bit	Function
QA	0	1 dB stage
QB	1	2 dB stage
QC	2	4 dB stage
QD	3	8 dB stage
QE	4	16 dB stage
QF	5	32 dB stage
QG	6	**mute relay**
QH	7	unused

8.2 The inverted control word

This is the detail that cost the project the most measurement time, and it belongs in the record in plain words:

- **relay energised (output high) = stage bypassed**
- **relay released (output low) = stage inserted**

So the six physical bits are the **inverse** of the logical attenuation code. A logical `000000` (0 dB, nothing inserted) is written as `111111`; a logical `111111` (63 dB, everything inserted) is written as `000000`.

The mute relay has its own polarity, and it is the safe one: `QG = 0` releases the mute relay and takes the output to ground; `QG = 1` energises it and connects the output to the attenuator. **A board with no power is muted**, which is the behaviour a power amplifier wants.

The control firmware composes the byte as:

```
byte = (~code & 0x3F) | (playing ? 0x40 : 0x00)
```

8.3 Change sequence

Every code change follows the same five steps, and the mute relay is what makes them safe:

1. write the **current** code **with mute asserted**;
2. wait **5 ms** (mute settles);
3. write the **new** code, **still muted**;
4. wait **5 ms** (contacts settle);
5. write the new code **with mute released**.

Because all eight bits transfer together on the STCP edge, the six stages change in the same instant; the mute relay covers the interval in which the reed contacts are physically moving, so the preamplifier never hears a partial code. A full sweep in the test harness steps every 100 ms, well inside the relays' mechanical settling time.

8.4 Interfaces in the record

Two pieces of firmware exist:

- **`measure/sweep/sweep.ino`** — the Arduino Nano harness that drove the 64-state sweep. Pins: `SER` = 4 (DS, 595 pin 14), `SRCLK` = 3 (SHCP, pin 11), `RCLK` = 2 (STCP, pin 12). It contains the bit map, the inversion, the mute sequencing and the timing constants above, and it is the code that produced the measurements in §11.
- **`measure/fastg_change_test/fastg_change_test.ino`** — the companion harness for contact behaviour during rapid changes.

And one gap, stated rather than papered over: the Field 25 controller firmware (`firmware/src/controller-rtc/Ombrier_Field25_Controller_RTC.ino`) holds a volume value **0–63** in FRAM, exposes `GET VOLUME` / `SET VOLUME n` over its serial command interface, and persists the setting — but it contains **no shift-register drive** for the 595. The attenuator has been driven by the Nano harness, not by the controller. Wiring the controller's volume state to `DS/SHCP/STCP` is therefore **integration work still to be done**, not a finished part of this record.

9. Integration with Field 25

9.1 Where it sits

The attenuator is the first block after the input connector and the last before the preamplifier. In the machine it occupies 55 × 90 mm of the flat layout, on the same plate as the preamp, and its audio ground is one of the star's spokes — not the plate, and not the relay ground.

9.2 What connects to what

From	To	Conductors
Input connector	`J1`	signal + its return
`J2`	preamplifier input	signal + its return
Controller	`J3`	`DS`, `SHCP`, `STCP` + 0 V
Auxiliary 5 V supply	`J4`	+5 V, 0 V

9.3 The control side, as it stands

The Field 25 controller is a Raspberry Pi Pico 2 W with an OLED, an FRAM, an RTC and a rotary encoder. Its firmware already carries a **volume value 0–63**, restores it from FRAM at boot, and accepts `GET VOLUME` / `SET VOLUME n`. What it does not yet contain is the three-wire output to the 595 (§8.4). Until that is written, the

attenuator is driven by the Nano test harness and the controller's volume number is a stored preference rather than a physical setting.

That is the one integration gap between the modules, and it is small: three GPIO pins, the bit mapping in §8.1, the inversion in §8.2 and the five-step sequence in §8.3 are all that the controller needs to acquire.

9.4 What the machine expects of the attenuator

- **Fail-safe muting.** No power means muted, which is what the amplifier wants during power-up.
- **No ground current.** The relay return must not reach the audio reference inside this board, and it does not.
- **No supply in the signal path.** There is none, so the preamplifier sees only the ladder's impedance.

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10. Test methodology

10.1 Stimulus and reference

The 7 November sweep used a **DC battery stimulus** (≈4,5 V) rather than an audio generator: the property under test is a ratio, and DC removes every question about source impedance and level drift. The oscilloscope's ch1 reading at 0 dB — **459 mV** — is the reference for all ratios; the probe's absolute calibration was not independently established, which does not affect dB ratios but does mean the voltages quoted here are scope volts, not battery volts.

10.2 Capture and stitching

Capture	Vertical scale	Sample interval	Quantization	Codes used
`fswp1.csv`	50 mV/div	1 ms	2 mV	0–19
`fswp2.csv`	5 mV/div	0,5 ms	0,2 mV	20–32
`fswp3.csv`	1 mV/div	0,5 ms	0,04 mV	33–63

One scale cannot cover 63 dB with useful resolution, so three were used and stitched on **overlapping plateaux**: a code present in two captures is evidence that the time-to-code alignment is right. Code 33, for example, reads ≈10,2 mV in `fswp2` and 10,08 mV in `fswp3`. Each plateau's value is the **median** of its stable portion, with about 20 ms either side of every relay transition excluded; the mute pulses are 135 ms apart and were used as timing markers. Every code from 0 to 63 is measured — none is interpolated or modelled.

10.3 What the method cannot see

- Plateaus shorter than the settling window would be smeared; at 100 ms per step there is no such case here.
- At the deepest codes the wanted signal is a fraction of a millivolt and the scope's own noise, baseline drift and probe ground pickup are of the same order. The report marks those codes **resolution-limited** rather than pretending otherwise.
- Only **one channel** was measured. Channel matching, which the design intends to be within a few hundredths of a decibel, has not been measured at all.

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11. Measured performance

11.1 The headline

All 64 states are present, monotonic, and inside 0,2 dB of the ideal curve to 50 dB. The three plateaux that carry the argument:

Code	Programmed	Measured	Error
16	16,000 dB	**15,970 dB**	−0,030 dB
32	32,000 dB	**32,022 dB**	+0,022 dB
48	48,000 dB	**47,846 dB**	−0,154 dB

The same code 32 measured **27,31 dB** on the 1 % prototype in October (§12.3). The difference between those two numbers is the whole of the development story: not a resistor, but a ground.

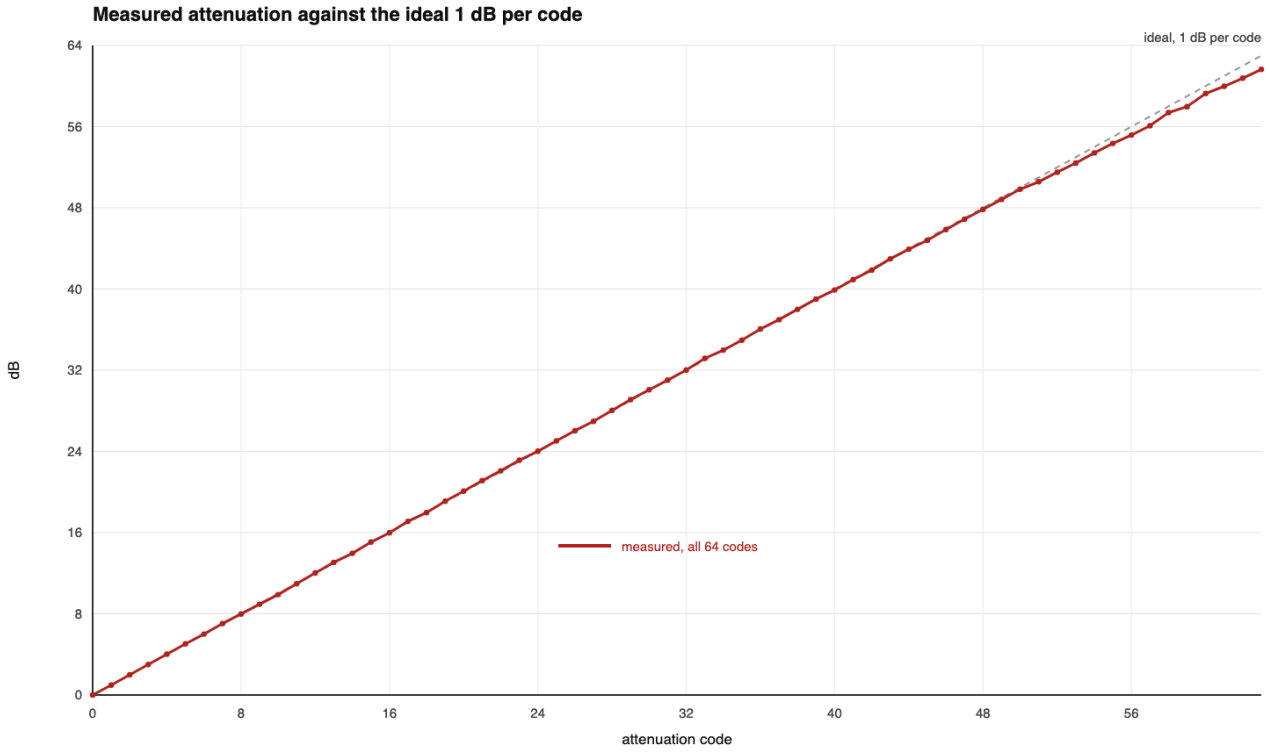


Figure 1 — Measured attenuation for all 64 codes against the ideal 1 dB per code. The two lines are indistinguishable to about 50 dB, where the measurement floor begins to dominate.

11.2 Accuracy by region

Codes	Fitted dB per code	RMS about the fit	Worst error vs ideal	Interpretation
0–19	**1,0022**	0,050 dB	0,113 dB	limited by the 2 mV quantization of the coarse capture
20–32	**0,9935**	0,041 dB	0,133 dB	the best-resolved region; agreement to a tenth of a decibel
33–50	**0,9853**	0,049 dB	0,196 dB	still inside 0,2 dB at 40 µV quantization
51–63	0,9343	0,125 dB	1,359 dB	**resolution-limited**, not a demonstrated circuit error

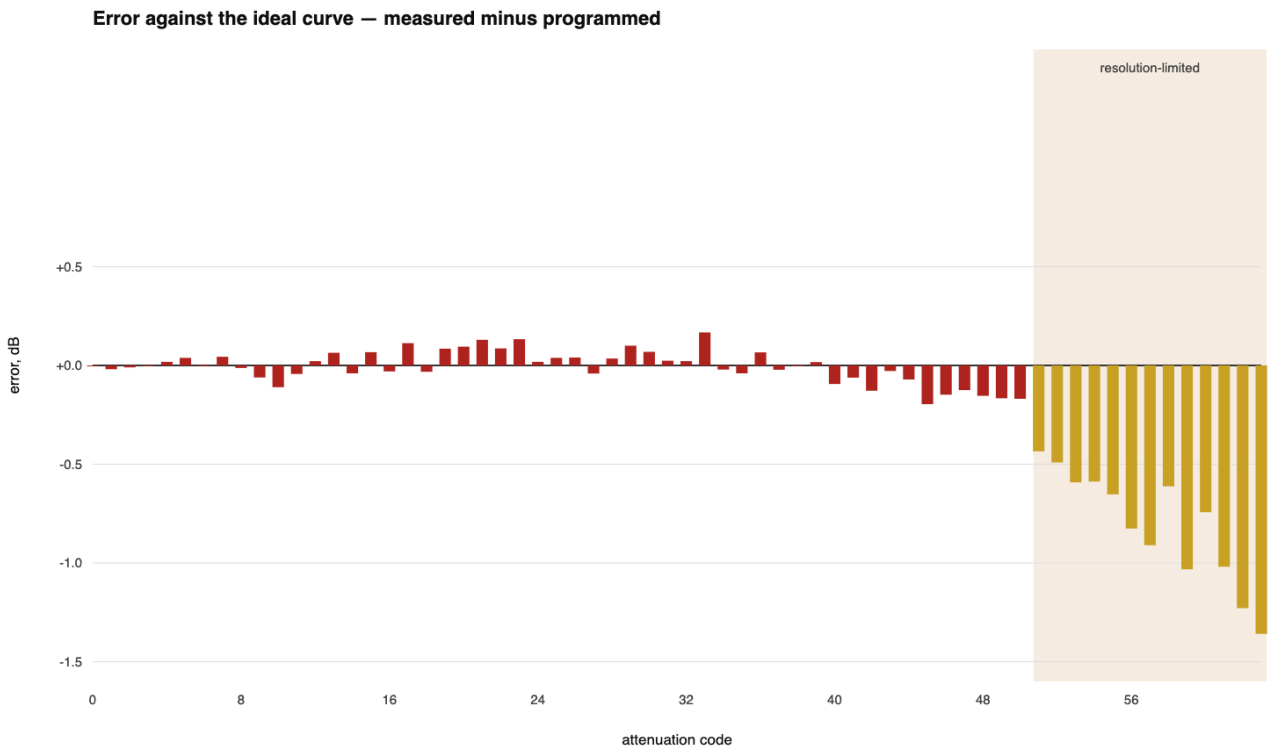


Figure 2 — Error per code, measured minus programmed. Everything to the left of the shaded band is inside 0,2 dB; inside the band the oscilloscope, not the attenuator, is the limit.

11.3 Every code

The complete table, as measured — no interpolation, no model, and the dagger marks the codes the report itself flags as resolution-limited.

Code	Bits QF…QA	Programmed dB	Measured dB	Error dB	Confidence
00	000000	0,000	0,000	+0,000	measured
01	000001	1,000	0,981	−0,019	measured
02	000010	2,000	1,990	−0,010	measured
03	000011	3,000	2,999	−0,001	measured
04	000100	4,000	4,018	+0,018	measured
05	000101	5,000	5,038	+0,038	measured
06	000110	6,000	6,002	+0,002	measured
07	000111	7,000	6,997	−0,003	measured
08	001000	8,000	7,983	−0,017	measured
09	001001	9,000	8,931	−0,069	measured
10	001010	10,000	9,995	−0,005	measured
11	001011	11,000	10,982	−0,018	measured
12	001100	12,000	12,048	+0,048	measured
13	001101	13,000	12,990	−0,010	measured
14	001110	14,000	13,983	−0,017	measured
15	001111	15,000	14,993	−0,007	measured
16	010000	16,000	15,970	−0,030	measured
17	010001	17,000	16,972	−0,028	measured

Code	Bits QF…QA	Programmed dB	Measured dB	Error dB	Confidence
18	010010	18,000	18,039	+0,039	measured
19	010011	19,000	18,991	−0,009	measured
20	010100	20,000	20,050	+0,050	measured
21	010101	21,000	21,074	+0,074	measured
22	010110	22,000	22,041	+0,041	measured
23	010111	23,000	23,045	+0,045	measured
24	011000	24,000	23,941	−0,059	measured
25	011001	25,000	24,960	−0,040	measured
26	011010	26,000	25,966	−0,034	measured
27	011011	27,000	26,959	−0,041	measured
28	011100	28,000	27,969	−0,031	measured
29	011101	29,000	28,943	−0,057	measured
30	011110	30,000	30,069	+0,069	measured
31	011111	31,000	31,024	+0,024	measured
32	100000	32,000	32,022	+0,022	measured
33	100001	33,000	33,167	+0,167	measured
34	100010	34,000	33,979	−0,021	measured
35	100011	35,000	34,960	−0,040	measured
36	100100	36,000	36,066	+0,066	measured
37	100101	37,000	36,978	−0,022	measured
38	100110	38,000	37,998	−0,002	measured
39	100111	39,000	39,017	+0,017	measured
40	101000	40,000	39,906	−0,094	measured
41	101001	41,000	40,938	−0,062	measured
42	101010	42,000	41,872	−0,128	measured
43	101011	43,000	42,972	−0,028	measured
44	101100	44,000	43,929	−0,071	measured
45	101101	45,000	44,804	−0,196	measured
46	101110	46,000	45,852	−0,148	measured
47	101111	47,000	46,875	−0,125	measured
48	110000	48,000	47,846	−0,154	measured
49	110001	49,000	48,834	−0,166	measured
50	110010	50,000	49,831	−0,169	measured
51	110011	51,000	50,565	−0,435	resolution-limited
52	110100	52,000	51,509	−0,491	resolution-limited
53	110101	53,000	52,408	−0,592	resolution-limited
54	110110	54,000	53,412	−0,588	resolution-limited
55	110111	55,000	54,347	−0,653	resolution-limited
56	111000	56,000	55,174	−0,826	resolution-limited
57	111001	57,000	56,090	−0,910	resolution-limited
58	111010	58,000	57,388	−0,612	resolution-limited

Code	Bits QF…QA	Programmed dB	Measured dB	Error dB	Confidence
59	111011	59,000	57,968	−1,032	resolution-limited
60	111100	60,000	59,257	−0,743	resolution-limited
61	111101	61,000	59,981	−1,019	resolution-limited
62	111110	62,000	60,771	−1,229	resolution-limited
63	111111	63,000	61,641	−1,359	resolution-limited

11.4 What is still unverified, in one place

Claim	Status
Attenuation 0–50 dB, 1 dB steps	**Measured**, inside 0,2 dB
Attenuation 51–63 dB	**Resolution-limited**; not established to better than about a decibel
Monotonic over all 64 codes	**Measured**
Channel matching	**Not measured** — one channel built
Noise and distortion	**Not measured**
Contact repeatability over cycles	**Not measured**
Impedance constancy	**By construction**, not measured
Absolute accuracy at any code	Requires a DMM and a documented zero-input offset; **not yet done**

---

12. Development history, and what it taught

12.1 Where the design came from

The first schematic was an EasyEDA export. It had the right twelve resistor values and the wrong topology: series resistors with a single end shunt, which cannot form a binary dB scale (§4.4). The sheet was rebuilt in KiCad, the ladder became a cascade of constant-impedance pads, and the board was laid out from that sheet. The rebuild also settled the interfaces: four connectors, three control wires, one supply.

12.2 The first prototype (September–October)

Built with 1 % resistors and measured on 5 October across all 64 codes. The first four stages tracked the ideal closely; 16 dB read 15,16 dB and **32 dB read 27,31 dB**. The report for that measurement said plainly that ±1 % tolerance could not produce a 4,8 dB error and named the candidates rather than choosing one.

12.3 Two 0,1 % boards, and the shape of the error (21 October)

Two new boards were built with 0,1 % resistors specifically to test the tolerance hypothesis. They reproduced the same staircase — 32 dB read 0,22 V on both, to the last digit. That ruled out tolerance, relays, joints and assembly faults in one step.

What the numbers did show was that the error was not a ratio error at all. It was an **offset**: the measured output was well fitted by `0,975 × ideal + 0,118 V`. At 4 V the offset is invisible; at the 32 dB output of 114 mV it is as large as the signal.

12.4 The cause

The bottoms of all six shunt resistors were on `/GND`, the auxiliary ground — the same net the ULN2003 and the relay coils return on. The attenuation ratio was therefore referenced to a node carrying relay current. Five coils

at ≈25 mA give ≈150 mA; to displace the reference by 110 mV needs only **0,73 Ω** of shared return, which is easily accumulated through traces, connectors and bench wiring.

The prediction and the measurement then agreed across all six stages: one displacement of 110 mV reproduces every measured output from 1 dB to 32 dB. That agreement, not the hypothesis, is what made the diagnosis credible.

12.5 The correction, and the decision to prove it before ordering

The sheet and the board were changed on 25 October: every shunt return and the ladder termination moved to `/SIGNAL_GROUND`; the coils, the driver and the logic stayed on `/GND`; the two nets meet only at the star. The board was re-routed and re-plotted (v05, then v06 after `J1` was moved clear of `C2`), and the whole set went to fabrication on 25 October with the preamp, distribution board and riser panel.

The method worth recording: **the correction was proven on an existing board before another PCB was ordered.** Lifting eight shunt ends and wiring a signal ground is half an hour's work and turns a hypothesis into a measurement. It is also the argument for the next section.

12.6 Two lessons that belong to every future board

1. **The first board of a design is an instrument, not a product.** This one would have been much easier to diagnose with a link between the two grounds that can be cut, a test point on each reference, and a way to isolate a net without lifting a pad. Those cost almost nothing on a development board.
2. **The control word is not the circuit.** The inverted relay polarity (§8.2) is a property of the contact topology — energise to bypass — and it silently inverts every code the firmware sends. An afternoon of measurements was spent on "wrong" attenuation steps that were, in fact, correct behaviour of an incorrectly driven word.

12.7 What the correction bought

The 7 November sweep, on the new board with the two grounds separated: **code 32 = 32,022 dB**. The additive floor is gone, the fitted slope through the first 51 codes is 0,9853–1,0022 dB per code, and the remaining spread at the bottom of the range is a property of the oscilloscope rather than of the board.

---

13. Final specification

13.1 Verified

Parameter	Value	Basis
Range	0–63 dB, 64 states	measured
Steps	1 dB nominal	measured slope 1,0022 / 0,9935 / 0,9853 dB per code
Accuracy, 0–50 dB	≤ 0,196 dB worst case	measured
Monotonicity	monotonic across all 64 codes	measured
Muting	fails safe to mute, output to ground through 10 kΩ	measured behaviour and firmware
Control	3-wire serial, 5 V, latch on STCP	design, exercised by the test harness

13.2 Operating limits

Supply	5 V (coils 7 × 200 Ω; ≈175 mA all energised)
Logic	5 V CMOS at the 595 inputs

Minimum mute settle	5 ms (firmware constant)
Minimum attenuation settle	5 ms (firmware constant)
Audio level	limited by the resistors and contacts, not by any device on the board

13.3 Revision identifiers

Item	Identifier
Schematic	`Attenuator_GridNet_v02_KIcad-symbols.kicad_sch-1.kicad_sch` — sha256 `ae4f21023e12…`
Board	`Attenuator_GridNet_v02_KIcad-symbols.kicad_sch-1.kicad_pcb` — sha256 `c1c7f512f81d5247…`, DRC 4/0
Fabrication	`ATTENUATOR-v06-gerbers.zip` — 14 files, sha256 `d1b2a5fa2b677977…`
Bill of materials	`bom.csv` (29 components) + `bom-connectors.csv`
Netlist	`reports/2026-10-25-netlist-from-schematic.xml`, 37 nets
Test data	`test/2026-11-07-attenuator-per-code-0-63.csv` and the report it came from

Appendix A — Schematic

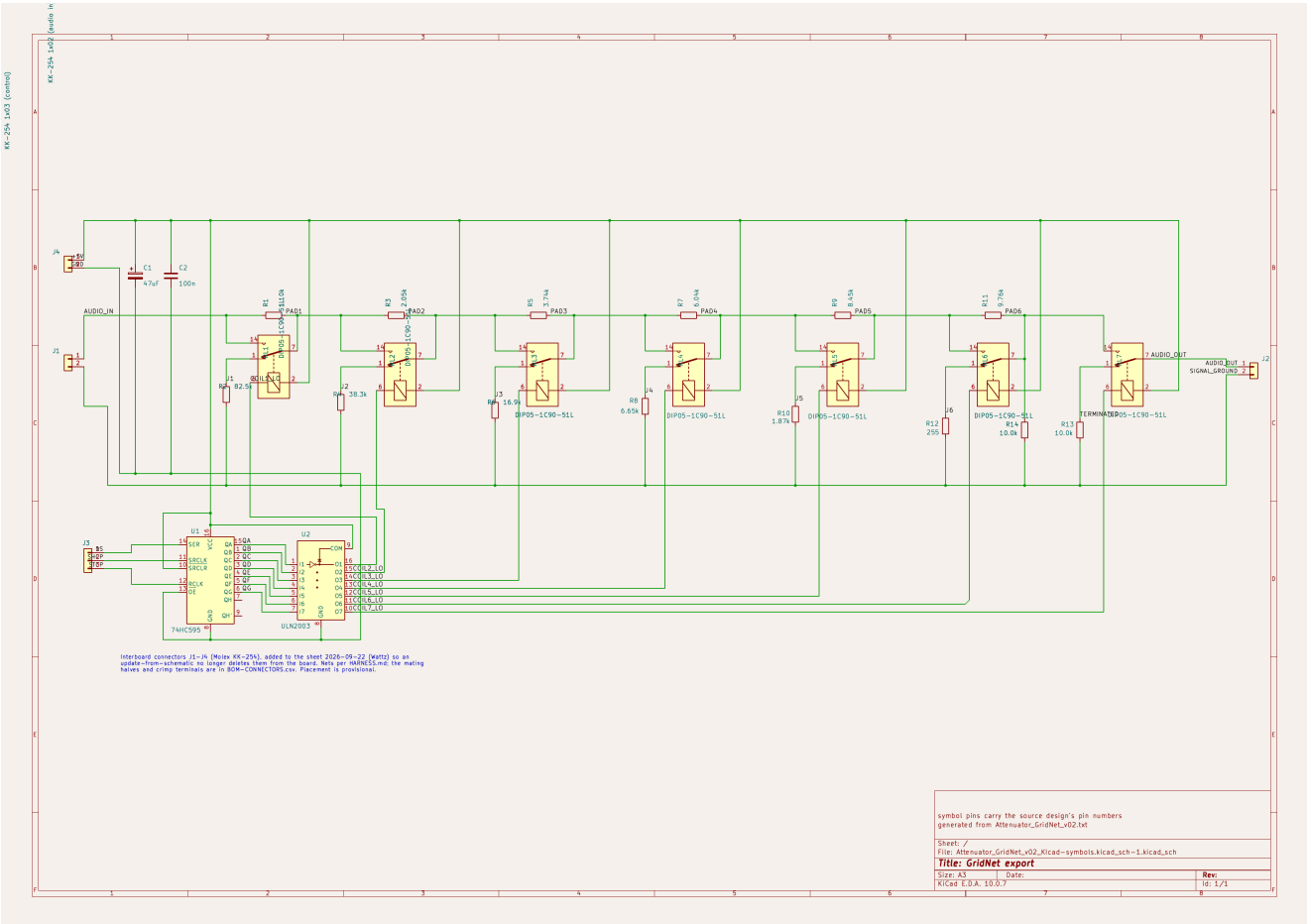


Figure A1 — the complete sheet, one A3 page: `Attenuator_GridNet_v02_KIcad-symbols.kicad_sch-1.kicad_sch`. The eight shunt returns run on the lower rail to `SIGNAL_GROUND`; the logic and coil returns are the upper rail, `GND`. The two rails are separate conductors and meet only at the system star.

The sheet is also supplied as `reports/ATTENUATOR-schematic-2026-11-06.pdf`, and the machine-readable netlist as `reports/2026-10-25-netlist-from-schematic.xml`.

Appendix B — PCB drawings

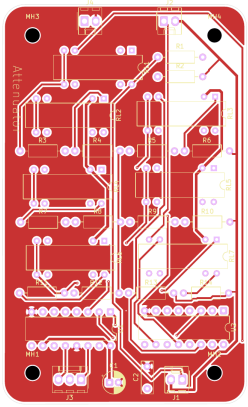


Figure B1 — front copper, silkscreen and mask openings.

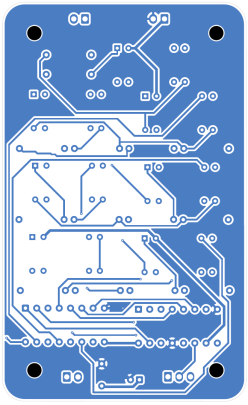


Figure B2 — back copper and silkscreen, viewed from the back.

Fabrication detail	Value
Outline	55,01 × 90,01 mm
Layers	2
Plated holes	140 across four tools: 0,30 / 0,70 / 0,80 / 1,19 mm
Unplated holes	4 × Ø3,20 mm (mounting)
Copper	292 track segments, 11 vias, `/GND` pours on F.Cu and B.Cu at 0,25 mm minimum
DRC	1 error (starved thermal at `J4` pad 2), 3 warnings (2 silk-to-edge, 1 silk overlap), 0 unconnected
Release	`ATTENUATOR-v06-gerbers.zip`, 14 files, sha256 `d1b2a5fa2b677977…`

Appendix C — Bill of materials

Designator	Value	Rating / note	Manufacturer part	Mouser no.	Qty
C1	47 µF	16 V min, Ø5 mm case, 2.0 mm lead pitch	EEU-FR1E470B	667-EEU-FR1E470B	1
C2	100 n	63 V, film, RM 5 mm	MKS2C031001A00KSSD	505-MKS2.1/63/10	1
R1	1.10 k	0.25 W, 1% metal film	MFR-25FTE52-1K1	603-MFR-25FTE52-1K1	1
R10	1.87 k	0.25 W, 1% metal film	MFR-25FTE52-1K87	603-MFR-25FTE52-1K87	1
R11	9.76 k	0.25 W, 1% metal film	MFR-25FTE52-9K76	603-MFR-25FTE52-9K76	1

Designator	Value	Rating / note	Manufacturer part	Mouser no.	Qty
R12	255 R	0.25 W, 1% metal film	MFR-25FTE52-255R	603-MFR-25FTE52-255R	1
R13	10.0 k	0.25 W, 1% metal film	MFR-25FRF52-10K	603-MFR-25FRF5210K	1
R14	10.0 k	0.25 W, 1% metal film	MFR-25FRF52-10K	603-MFR-25FRF5210K	1
R2	82.5 k	0.25 W, 1% metal film	MFR-25FRF52-82K5	603-MFR-25FRF52-82K5	1
R3	2.05 k	0.25 W, 1% metal film	MFR-25FTE52-2K05	603-MFR-25FTE52-2K05	1
R4	38.3 k	0.25 W, 1% metal film	MFR-25FTE52-38K3	603-MFR-25FTE52-38K3	1
R5	3.74 k	0.25 W, 1% metal film	MFR-25FTE52-3K74	603-MFR-25FTE52-3K74	1
R6	16.9 k	0.25 W, 1% metal film	MFR-25FRF52-16K9	603-MFR-25FRF52-16K9	1
R7	6.04 k	0.25 W, 1% metal film	MFR50SFTE52-6K04	603-MFR50SFTE52-6K04	1
R8	6.65 k	0.25 W, 1% metal film	MFR-25FTE52-6K65	603-MFR-25FTE52-6K65	1
R9	8.45 k	0.25 W, 1% metal film	MFR-25FTE52-8K45	603-MFR-25FTE52-8K45	1
RL1, RL2, RL3, RL4, RL5, RL6, RL7	DIP05 1 form C	5 V coil, 200 Ω, 125 mW, changeover	DIP05-1C90-51D	876-DIP05-1C90-51D	7
U1	74HC595	DIP-16	CD74HC595E	595-CD74HC595E	1
U2	ULN2003	DIP-16	ULN2003AN	595-ULN2003AN	1

Prices and stock as read on 17 September 2026 and noted per row in `bom.csv`; the relays were 8,44 € each and the resistors 0,086–0,189 €, so the board's component cost is dominated by the seven relays.

Appendix D — Netlist

The sheet defines **37 nets**. Every connection, by net:

Net	Connections
`/+5V`	C1.1, C2.1, J4.1, RL1.2, RL2.2, RL3.2, RL4.2, RL5.2, RL6.2, RL7.2, U1.10, U1.16, U2.9
`/AUDIO_IN`	J1.1, R1.1, RL1.14
`/AUDIO_OUT`	J2.1, RL7.7, RL7.8
`/COIL1_LO`	RL1.6, U2.16
`/COIL2_LO`	RL2.6, U2.15
`/COIL3_LO`	RL3.6, U2.14
`/COIL4_LO`	RL4.6, U2.13
`/COIL5_LO`	RL5.6, U2.12
`/COIL6_LO`	RL6.6, U2.11
`/COIL7_LO`	RL7.6, U2.10
`/DS`	J3.1, U1.14

Net	Connections
`/GND`	C1.2, C2.2, J4.2, U1.8, U1.13, U2.8
`/J1`	R2.1, RL1.1
`/J2`	R4.1, RL2.1
`/J3`	R6.1, RL3.1
`/J4`	R8.1, RL4.1
`/J5`	R10.1, RL5.1
`/J6`	R12.1, RL6.1
`/PAD1`	R1.2, R3.1, RL1.7, RL1.8, RL2.14
`/PAD2`	R3.2, R5.1, RL2.7, RL2.8, RL3.14
`/PAD3`	R5.2, R7.1, RL3.7, RL3.8, RL4.14
`/PAD4`	R7.2, R9.1, RL4.7, RL4.8, RL5.14
`/PAD5`	R11.1, R9.2, RL5.7, RL5.8, RL6.14
`/PAD6`	R11.2, R14.1, RL6.7, RL6.8, RL7.14
`/QA`	U1.15, U2.1
`/QB`	U1.1, U2.2
`/QC`	U1.2, U2.3
`/QD`	U1.3, U2.4
`/QE`	U1.4, U2.5
`/QF`	U1.5, U2.6
`/QG`	U1.6, U2.7
`/SHCP`	J3.2, U1.11
`/SIGNAL_GROUND`	J1.2, J2.2, R10.2, R12.2, R13.2, R14.2, R2.2, R4.2, R6.2, R8.2
`/STCP`	J3.3, U1.12
`/TERMINATED`	R13.1, RL7.1
`unconnected-(U1-QH'-Pad9)`	U1.9
`unconnected-(U1-QH-Pad7)`	U1.7

Machine-readable form: `reports/2026-10-25-netlist-from-schematic.xml`.

Appendix E — Control firmware

The harness that drove the measurements is `measure/sweep/sweep.ino` (Arduino Nano). Three functions contain everything the design requires, and they are reproduced verbatim below; the serial diagnostics around them are omitted only for space.

E.1 Composing the byte

```
```

E.2 Writing it to the shift register

```
static void load595(uint8_t value)
{
  /*
    Shift register contents change during shiftOut(),
    but QA..QH remain unchanged until RCLK rises.
  */

  digitalWrite(PIN_RCLK, LOW);

  shiftOut(
    PIN_SER,
    PIN_SRCLK,
    MSBFIRST,
    value
  );

  // Latch complete byte to QA..QH
  digitalWrite(PIN_RCLK, HIGH);

  // Leave latch clock LOW between transfers
  digitalWrite(PIN_RCLK, LOW);
}
```

Bits are shifted while STCP is low, so `QA…QH` hold their old state throughout; the rising edge of STCP transfers all eight at once. That single edge is what makes the six stages change simultaneously.

E.3 The change sequence

```
static void changeCode(uint8_t code)
{
  code &= MASK_ATTENUATOR;


  const uint8_t mutedBefore =
    compose(currentCode, false);

  const uint8_t mutedAfter =
    compose(code, false);

  const uint8_t playing =
    compose(code, true);




  // ============================================================
  // 1. MUTE
  //
  // Keep current attenuation.
  // QG goes LOW.
  // Output is pulled to ground by mute relay.
  // ============================================================

  load595(mutedBefore);

  delay(MUTE_SETTLE_MS);


  // ============================================================
  // 2. CHANGE ATTENUATION WHILE MUTED
  // ============================================================

  load595(mutedAfter);

  delay(ATT_SETTLE_MS);


  // ============================================================
  // 3. UNMUTE
  //
  // QG goes HIGH.
  // New attenuation is already stable.
  // ============================================================

  load595(playing);


  currentCode = code;


}
```

E.4 Timing constants

Constant	Value	Meaning
`MUTE_SETTLE_MS`	5 ms	time allowed between muting and changing the ladder
`ATT_SETTLE_MS`	5 ms	time allowed for the reed contacts before unmuting
`STEP_MS`	100 ms	sweep step interval in the harness
`END_PAUSE_MS`	1000 ms	pause at 63 dB and at 0 dB

The sweep runs **up to 63 dB and back down again**, pausing a second at each end, so a repeatability check between directions is available in the same capture.

Appendix F — Test data, reproduction and manifest

F.1 The three campaigns

Campaign	Board	Result	Where
5 October 2026	first prototype, 1 % resistors	32 dB measured **27,31 dB**; report stated tolerance could not explain it	`test/2026-10-05-attenuator-original-1pct.md`
21 October 2026	two 0,1 % boards	same staircase on both; error fitted as an **offset** of ≈0,1 V; cause traced to the shared ground	`test/2026-10-21-attenuator-retest-0p1pct.md`
7 November 2026	**new board, grounds separated**	64 codes monotonic; **32 dB = 32,022 dB**; inside 0,2 dB to 50 dB	`test/2026-11-07-attenuator-full-range.md`

F.2 Data files

File	What it is
`test/2026-11-07-attenuator-per-code-0-63.csv`	all 64 codes: bits, median and ideal volts, programmed/measured/error dB, step, capture, confidence
`test/2026-11-07-attenuator-full-range-report.html`	the report as delivered, 620 366 B, sha256 `99a3168c801c50d4…`
`fswp1.csv`, `fswp2.csv`, `fswp3.csv`	the raw oscilloscope captures — **on the bench Mac, not in the repository**. The report's numbers derive from them; anyone re-analysing from raw data needs those three files

F.3 Reproducing this board

1. **Fabricate** from `fabrication/ATTENUATOR-v06-gerbers.zip` (14 files, sha256 `d1b2a5fa2b677977…`): 2 layers, 1,6 mm, 55,01 × 90,01 mm, 140 plated holes and 4 × Ø3,20 mm unplated.
2. **Fit** the parts in Appendix C. The only parts that are not generic are the seven `DIP05-1C90-51D` relays — the `-51D` variant's pin 2 is the coil's positive end, and the internal diode assumes it.
3. **Wire** `J4` to +5 V and 0 V, `J1`/`J2` to the audio path, and `J3` to `DS`, `SHCP`, `STCP`.
4. **Program** a Nano with `measure/sweep/sweep.ino`, or implement Appendix E's three functions on any controller. The inverted word is not optional: a board driven with the logical code un-inverted will appear to work while attenuating by the complement of the requested value.
5. **Verify** at two codes before trusting a sweep: 0 dB and 63 dB, measured at `J2`. If 63 dB does not read about 0,113 V from a 4,55 V input, stop and check the ground domains before measuring anything else.
6. **Measure** with the technique of §10: three vertical scales, overlapping plateaux, medians, transitions excluded.

F.4 Revision manifest

Item	Path	Size	sha256 (first 16)
Schematic	`electronics/attenuator/kicad/Attenuator_GridNet_v02_KIcad-symbols.kicad_sch-1.kicad_sch`	125,886 B	`ae4f21023e124fda…`
Board	`electronics/attenuator/kicad/Attenuator_GridNet_v02_KIcad-symbols.kicad_sch-1.kicad_pcb`	539,299 B	`c1c7f512f81d5247…`

Item	Path	Size	sha256 (first 16)
Fabrication zip	`electronics/attenuator/fabrication/ATTENUATOR-v06-gerbers.zip`	115,871 B	`d1b2a5fa2b677977…`
Schematic PDF	`electronics/attenuator/reports/ATTENUATOR-schematic-2026-11-06.pdf`	151,161 B	`e0c8fc81df8d74d3…`
Bill of materials	`electronics/attenuator/bom.csv`	7,751 B	`2ecf9eb08826e5a9…`
Connectors BOM	`electronics/attenuator/bom-connectors.csv`	2,174 B	`60e43daad7298bf9…`
Control firmware	`electronics/attenuator/measure/sweep/sweep.ino`	9,692 B	`de10cd4480c1b316…`
Test data (derived)	`test/2026-11-07-attenuator-per-code-0-63.csv`	4,374 B	`e17383e75ec5e164…`

F.5 Colophon

Compiled on 7 November 2026 from the project's own files by Oxy. Figures were plotted from the 64-code table in §11.3; the schematic and PCB views were exported from the released KiCad files at the hashes above. Where this record is silent — channel matching, noise, distortion, absolute deep-attenuation accuracy, and the raw oscilloscope captures — it says so rather than estimating.