AWN-01 Analog Waterfall Node: BOM and Build Instructions

Rev A. Covers the schematic AWN-01 (cell A relay rungs, cell B transformer rungs), plus the modules it depends on: HV supply, 47 V ping bus, detector bank, ground system and logger. Values come from the design thread; items marked **VERIFY** are assumptions to confirm on the bench before you commit.

0. Read first: safety and assumptions

- **190 V DC is dangerous.** Build the HV section in a grounded metal enclosure, one hand at a time, with a bleeder on every HV capacitor. Discharge and measure before touching anything.
- **Mains isolation.** Every supply here is fed from an isolating transformer. Never bond BLK (earth return) to mains ground or neutral.
- **Ground rods.** Call 811 (or your local locate service) before driving rods. Keep the ping rods at least 10 m apart and well away from the house grounding electrode, utilities and where people or pets stand. Peak ping current is about 1 A for about 5 ms on rung S0.
- **Fuse every path.** 2 A slow-blow in the rod loop, 100 mA on the 47 V feed, 50 mA fast on the HV rail.
- **Unverified assumptions behind the numbers:**
    1. Tube fires at 130 V and extinguishes at 30 V (from your post 22). If the 0A4G extinguishes near 70 V, multiply every C_c by 1.415 and use transformers at 30:1 or more.
    2. Earth resistance R_g = 10 Ω (model value) and relay contact dwell about 5 ms.
    3. Λ_φ is taken as written (absolute), giving the rung weights in section 4.
    4. The 0A4G base, peak cathode current and holding current have not been checked against the datasheet.

1. Module map

Module	Ref prefix	Qty	What it does
Oscillator ladder	V5-k, R_ck, C_ck, divider	7 (k = 0 to 6)	Relaxation stages at 0.97875 × 2^k Hz
2:1 injection	C_inj, D_inj, R_inj	6 (S1 to S6)	Locks each stage to the one before it
Relay output	RY1 to RY3	3 (S0 to S2)	Ping the rods from the C_s bus
Transformer output	T3 to T6	4 (S3 to S6)	Tube cathode drives a step-down transformer into the rod loop
Ping bus and ground	C_s, rods	1	47 V reservoir, rods X1 and X2
HV supply	PS-HV	1	190 V DC rail
47 V supply	PS-47	1	Feeds C_s
Detector bank	D1 to D7	1	Receives soil signal, drives each starter
Logger	DAQ	1	Waterfall and lock measurements

2. Bill of materials

Ratings are minimums. Use film capacitors (polypropylene) for all timing and injection parts.

2.1 Oscillator ladder (per rung, seven rungs)

Ref	Qty	Part	Value	Rating	Notes
V5-0 to V5-6	7 (+2 spare)	Cold-cathode gas triode	0A4G		**VERIFY** base and ratings
XV-0 to XV-6	7	Tube socket	per datasheet		
R_c0 to R_c6	7	Resistor, metal film, 1%	470 kΩ	0.5 W, 350 V	Sets period with C_c

Ref	Qty	Part	Value	Rating	Notes
C_c0 to C_c6	7 sets	Film capacitor	see 2.2	400 V DC	Parallel sets, trim by measurement
R_up0 to R_up6	7	Resistor, metal film, 1%	2.2 MΩ	0.5 W, 350 V	Starter divider top
R_tr0 to R_tr6	7	Multi-turn trimmer	2 MΩ	0.5 W	Sets firing threshold
R_lo0 to R_lo6	7	Resistor, metal film, 1%	10 MΩ	0.5 W, 350 V	Starter divider bottom
D_fw0 to D_fw6	7	Diode	1N4007	1000 V	Flyback across coil or primary

2.2 Timing capacitors C_c (design values, 30 V extinguish case)

Rung	Target f (Hz)	Target C_c	Build as (parallel)	Sum	Error
S0	0.97875	2216 nF	2.2 µF + 15 nF selected	2215 nF	-0.1%
S1	1.9575	1108 nF	1 µF + 100 nF + 8.2 nF	1108.2 nF	0.0%
S2	3.915	554 nF	470 nF + 82 nF + 2.2 nF	554.2 nF	0.0%
S3	7.83	277 nF	270 nF + 6.8 nF	276.8 nF	-0.1%
S4	15.66	138.5 nF	100 nF + 39 nF	139.0 nF	+0.4%
S5	31.32	69.3 nF	68 nF + 1 nF	69.0 nF	-0.4%
S6	62.64	34.6 nF	33 nF + 1.5 nF	34.5 nF	-0.3%

Add a spare footprint on each rung for 1 nF, 2.2 nF and 4.7 nF trim pads. Final values are set by measuring the period (section 5, step 4), not by this table. If the extinguish voltage turns out near 70 V, the targets become 3136, 1568, 784, 392, 196, 98 and 49 nF.

2.3 Injection and coupling (S1 to S6)

Ref	Qty	Part	Value	Rating
C_inj1 to C_inj6	6	Film capacitor	2.2 nF	630 V
D_inj1 to D_inj6	6	Diode	1N4007	1000 V
R_inj1 to R_inj6	6	Resistor	100 kΩ	0.5 W, 350 V

S0 has no injection from a previous stage. It is the master and is entrained only by the soil detector. Each injection input connects to the previous stage's cathode node (see schematic).

2.4 Relay output rungs (S0 to S2)

Ref	Qty	Part	Value	Notes
RY1 to RY3	3	Relay, SPST-NO, 12 V coil	contacts ≥ 2 A / 60 V DC	Coil about 400 Ω class, operate time ≤ 10 ms. **VERIFY** pull-in from the C_c pulse
R_w0	1	Wirewound trimmer	100 Ω, 2 W	Nominal 36 Ω
R_w1	1	Wirewound trimmer	5 kΩ, 2 W	Nominal 2.14 kΩ
R_w2	1	Wirewound trimmer	500 Ω, 2 W	Nominal 172 Ω

2.5 Transformer output rungs (S3 to S6)

Ref	Qty	Part	Value	Notes
T3 to T6	4	Power transformer, 120 V primary	secondary 4 V to 5 V, ≥ 2 A	Ratio ≥ 24:1, 30:1 preferred. A 6.3 V (19:1) part is **too low** for S4
R_sh3	1	Wirewound trimmer	10 Ω, 2 W	Nominal 3.0 Ω
R_sh4	1	Wirewound trimmer	100 Ω, 2 W	Nominal 52 Ω
R_sh5	1	Wirewound trimmer	25 Ω, 2 W	Nominal 10.3 Ω
R_sh6	1	Wirewound trimmer	50 Ω, 2 W	Nominal 14.7 Ω

The 120 V winding is the primary (in the tube cathode circuit). The low-voltage winding goes in the rod loop. The pulses stay within a 60 Hz core's volt-second rating (0.16, 0.08, 0.04, 0.02 V·s for S3 to S6, against about 0.45 V·s usable).

2.6 Ping bus, rods and protection

Ref	Qty	Part	Value	Notes
C_s	1	Electrolytic, low ESR	1000 µF, 63 V	Shared reservoir for RY1 to RY3
R_ch	1	Resistor	100 Ω, 2 W	Charge limit from the 47 V supply
F1	1	Fuse, slow-blow, with holder	2 A	In the rod loop
F2	1	Fuse	100 mA	On the 47 V feed
X1, X2	2	Copper-clad ground rod	5/8 in x 8 ft	Spaced ≥ 10 m
	2	Rod clamps		
	1	Direct-burial wire	#10 AWG, length to suit	
X3, X4	2	Receive electrodes	non-polarizing Cu/CuSO4 recommended	Separate from ping rods. Steel rods polarize and add ELF noise

2.7 HV supply, 190 V DC (optional if you already have the post-16 B+ supply)

Ref	Qty	Part	Value
T_iso	1	Isolation transformer, 120:120	≥ 50 VA
D_a, D_b	2	Diode	1N4007
C_a	1	Capacitor	22 µF, 250 V
C_b	1	Capacitor	22 µF, 450 V
Q1	1	NPN pass transistor	MJE340 (300 V), heatsink
Z1, Z2	2	Zener	1N5387B (180 V, 5 W) + 1N4740A (10 V, 1 W) in series

Ref	Qty	Part	Value
R_bias	1	Resistor	15 kΩ, 3 W
C_out	1	Capacitor	10 µF, 250 V
R_bleed	1	Resistor	100 kΩ, 2 W
F_HV	1	Fuse, fast	50 mA

Half-wave doubler (D_a, D_b, C_a, C_b) gives about 330 V unloaded. Q1 as an emitter follower from the zener stack gives about 189 V. Expect about 3.5 W in Q1 at 25 mA.

2.8 47 V supply

Ref	Qty	Part	Value
T_47	1	Transformer	120 V to 36 V AC, 1 A
BR1	1	Bridge rectifier	3 A, 100 V
C_47	1	Capacitor	4700 µF, 63 V

No regulation is needed. About 45 to 48 V, and the R_w and R_sh trims absorb the difference.

2.9 Detector bank (new design, prototype on a breadboard first)

This is not from your posts. It replaces the earlier detector box so the coupling strength can be set per rung.

Ref	Qty	Part	Value	Notes
U_in	1	Instrumentation amp	INA128, gain resistor 49.9 Ω (G ≈ 1000)	AC-coupled input
Cin_a, Cin_b	2	Film capacitor	10 µF, 63 V	Input coupling
Rb_a, Rb_b	2	Resistor	10 MΩ	Input bias to analog ground

Ref	Qty	Part	Value	Notes
U_bpf0 to 6	4	Quad op-amp	TL074	7 band-pass + 7 rectifier sections use 14 of 16
BPF parts	7 sets	see 4.3		Q = 2, unity gain
Rect parts	7 sets	1N4148 x2, 10 kΩ x3		Half-wave precision rectifier
R_d	7	Resistor	100 kΩ	Detector averaging
C_d	7	Film capacitor	see 4.4	tau = T/5
U_cmp	4	Dual comparator	LM393	One section per rung
Thr	7	Trimmer	10 kΩ	Detection threshold
OC0 to OC6	7	Opto, V_CEO ≥ 300 V	TLP627-1 class	**VERIFY** part and rating
R_k0 to R_k6	7 sets	100 kΩ fixed + 2 MΩ multi-turn in series		Sets starter pulse (the coupling K)
PS-AN	1	±12 V analog supply	12-0-12 V transformer + 7812/7912	Tie analog ground to BLK at one point only

Each opto output transistor connects collector to +190 V and emitter through R_k to that rung's starter tap.

2.10 Logger and test tap

Ref	Qty	Part	Value
DAQ	1	24-bit ADC board, ≥ 8 channels	sample at 512 Hz or 2048 Hz
	1	Single-board computer or laptop for capture	battery or isolated supply
Tap R1, R2	7 each	Resistor	1 MΩ and 10 kΩ divider from each cathode node

Ref	Qty	Part	Value
Tap Z	7	Zener	5.1 V clamp at the ADC input
Rsense	1	Resistor	1 Ω, 1%, 2 W (in the rod loop for current checks)

2.11 Hardware and tools

Grounded aluminum chassis, HV-rated standoffs, HV wire (≥ 600 V), safety labels, 100:1 HV scope probe, oscilloscope, frequency counter, multimeter, resistor and capacitor substitution boxes, and a variable HV bench supply for tube characterization.

3. Rung weight tables

Ping charge rule: $Q_k = w_k \times I_u / f_k$, with $I_u = 5$ mA and $w = \Omega(f)$ as written.

Rung	f (Hz)	w_k	Q_k (µC)	Weight element	Nominal
S0	0.97875	0.942	4810	R_w0 series	36 Ω
S1	1.9575	0.043	110	R_w1 series	2.14 kΩ
S2	3.915	0.996	1270	R_w2 series	172 Ω
S3	7.83	0.239	153	R_sh3 shunt	3.0 Ω
S4	15.66	0.874	279	R_sh4 shunt	52 Ω
S5	31.32	0.529	84.5	R_sh5 shunt	10.3 Ω
S6	62.64	0.619	49.4	R_sh6 shunt	14.7 Ω

These assume $R_g = 10$ Ω and 5 ms contact dwell. Trim to the measured Q_k, not the nominal resistor value.

4. Detector bank values

4.1 Architecture

X3/X4 receive electrodes → AC coupling → INA128 → seven parallel channels, one per rung: band-pass, precision rectifier, averaging RC, comparator, opto, R_k, starter tap.

4.2 Why these choices

Band-pass Q = 2 suits octave-spaced rungs. The averaging time constant is T_k/5, which keeps the "0.2 s tail" ratio from your post-22 detector. The opto isolates the 190 V starter side from the op-amps.

4.3 Band-pass (multiple-feedback, C1 = C2 = C, unity gain, Q = 2)

Rung	f_k (Hz)	C	R1	R2	R3	Resulting f0
S0	0.979	2.2 µF	147 kΩ	21.0 kΩ	294 kΩ	0.984
S1	1.958	1.0 µF	162 kΩ	23.2 kΩ	324 kΩ	1.963
S2	3.915	470 nF	174 kΩ	24.9 kΩ	348 kΩ	3.889
S3	7.83	220 nF	187 kΩ	26.1 kΩ	374 kΩ	7.817
S4	15.66	100 nF	205 kΩ	28.7 kΩ	402 kΩ	15.82
S5	31.32	47 nF	215 kΩ	30.9 kΩ	432 kΩ	31.34
S6	62.64	22 nF	232 kΩ	33.2 kΩ	464 kΩ	62.32

Resistors are E96, 1%. Use film or C0G capacitors. If a center frequency lands off, adjust R3 first.

4.4 Averaging capacitors (R_d = 100 kΩ)

Rung	tau target	C_d
S0	204 ms	2.2 µF
S1	102 ms	1 µF
S2	51 ms	470 nF
S3	25.5 ms	220 nF
S4	12.8 ms	120 nF
S5	6.4 ms	68 nF
S6	3.2 ms	33 nF

5. Build instructions

Step 1. Bench power. Build the 47 V supply and the HV supply (or confirm your existing B+ gives 190 V at ≥ 25 mA). With a dummy load, confirm 190 V ± 5 V and 45 to 48 V. Check the bleeders drop HV below 30 V within a minute of power-off.

Step 2. Characterize the tubes. For each 0A4G, wire a test oscillator: 190 V → 470 kΩ → tube anode, 1 µF to BLK, cathode to BLK through 100 Ω, starter through your R_up/R_tr/R_lo divider. Measure with a 100:1 probe (a 10:1 probe loads a 470 kΩ node by about 4.5%). Record V_fire, V_extinguish (valley), period, and starter breakdown. Compute C_c for any target period with $C = T / (R_c \times \ln((HV - V_{low})/(HV - V_{fire})))$. Match tubes into rungs by similar V_fire. If V_extinguish is near 70 V, switch every value to the alternate set in 2.2 and use transformers ≥ 30:1.

Step 3. Build S0 alone. Wire R_c0, C_c0, V5-0, the starter divider, RY1 and D_fw0. Do not yet connect the rods. Set R_tr0 so the tube fires reliably. Measure the period over 50 cycles with the counter and adjust C_c0 trim pads until the frequency is 0.97875 Hz ± 0.2%.

Step 4. Build S1 to S6 free-running. For each rung, tune C_ck so the free-run period is 1% to 3% longer than half the previous rung's period (2:1 lock requires the driver pulse to arrive before the stage would fire on its own). Measure each over 50 cycles.

Step 5. Enable injection and verify lock. Connect C_inj, D_inj, R_inj from each previous cathode node. Check that each stage now runs at exactly twice the previous rung's rate. Fine-tune C_ck until the half-rate sideband on the stage's line is as small as it can be while the lock holds.

Step 6. Wire the outputs. Cell A: add RY1 to RY3, R_w trimmers and C_s with R_ch and F2. Cell B: add T3 to T6, R_sh trimmers and F1. Rods stay disconnected. Replace them with a 10 Ω, 5 W dummy load, and a 1 Ω sense resistor in series.

Step 7. Calibrate weights. For each rung, record the sense-resistor voltage on the scope, integrate current over one ping to get Q_k, and trim R_w or R_sh until Q_k matches section 3. Cell B secondaries sit in one series loop X1 → T3 → T4 → T5 → T6 → X2. The cell A relay branch connects across the rods, not in the loop.

Step 8. Build the detector bank. Build and test one channel on a breadboard first. Inject a known sine at each f_k through a 1000:1 attenuator and confirm the band-pass center, the averaging RC and the comparator threshold. Then build all seven. With the opto output

disconnected from the starter, set R_k fully out. Connect, then raise the pulse (lower R_k) until a detected input fires the stage, and finally back off so it just fails, then add about 20% margin.

Step 9. Dummy-soil test with two nodes. Build a second node. Replace the rods with 10 Ω each and a 100 kΩ coupling resistor between the two. Run ratio sweeps by changing node B's C_c0: 2.2 µF (ratio 1), 3.3 µF (1.5), 3.567 µF (1.618), 4.4 µF (2). Log at least 50 cycles per setting.

Step 10. Install the ground system. Drive X1 and X2 at least 10 m apart, and X3/X4 at least 10 m from them and from each other. Measure R_g with a ground tester and re-trim the weights to hit Q_k. Fit F1.

Step 11. Log the waterfall. Sample at 512 Hz (or 2048 Hz for comparability with earlier runs). Use a 128 s Hann window and an 8 s hop. Also log the S0 ping times for the phase waterfall (one row per cycle, one column per node). Lock criterion: coefficient of variation of the inter-node ping phase below 0.05 over at least 50 cycles.

6. Acceptance tests

Test	Pass condition
S0 period	0.97875 Hz ± 0.2%
Ladder ratios	Each rung exactly 2× the previous over 50 cycles
Ping charge	Measured Q_k within ±10% of section 3
Detector	Each channel fires its starter only at its own f_k
Two-node lock	Ratio 1.0 and 2.0 lock (CV < 0.05); log 1.5 and 1.618
Mains	No lock of S6 to 60 Hz hum with the antenna connected

7. Troubleshooting

Symptom	Likely cause	Fix
Tube latches on	R_c too small for the holding current	Raise R_c
Tube never fires	HV below breakdown, or starter bias too low	Check 190 V, lower R_tr
Stage won't divide-lock	Free-run period outside 1 to 3% window	Re-tune C_ck
Relay doesn't pull in	C_c pulse too weak for the coil	Raise C_c or use a more sensitive relay
S6 follows 60 Hz	Hum entering the detector	Shield, narrow the S6 band-pass, or move the electrodes
Transformer rung weak	Saturation or low ratio	Use ≥ 30:1, check volt-seconds

8. Known unknowns

The 0A4G fire and extinguish voltages and holding and peak current; the base pinout; relay pull-in from an impulse; the real earth resistance and contact dwell; the detector bank's sensitivity (new design, not bench-tested); and which Λ_φ convention best matches the measured lock ranges.