SJSU ECG signal amplifier

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This Electrocardiogram (ECG) amplifier consists of 6 parts: (1) Power Supply, (2) Instrumentation Amplifier, (3) DC offset nulling circuit, (4) Gain/low-pass filter, (5) 60Hz notch filter, and (6) monostable circuit. The theory of operation of each part is explained below.

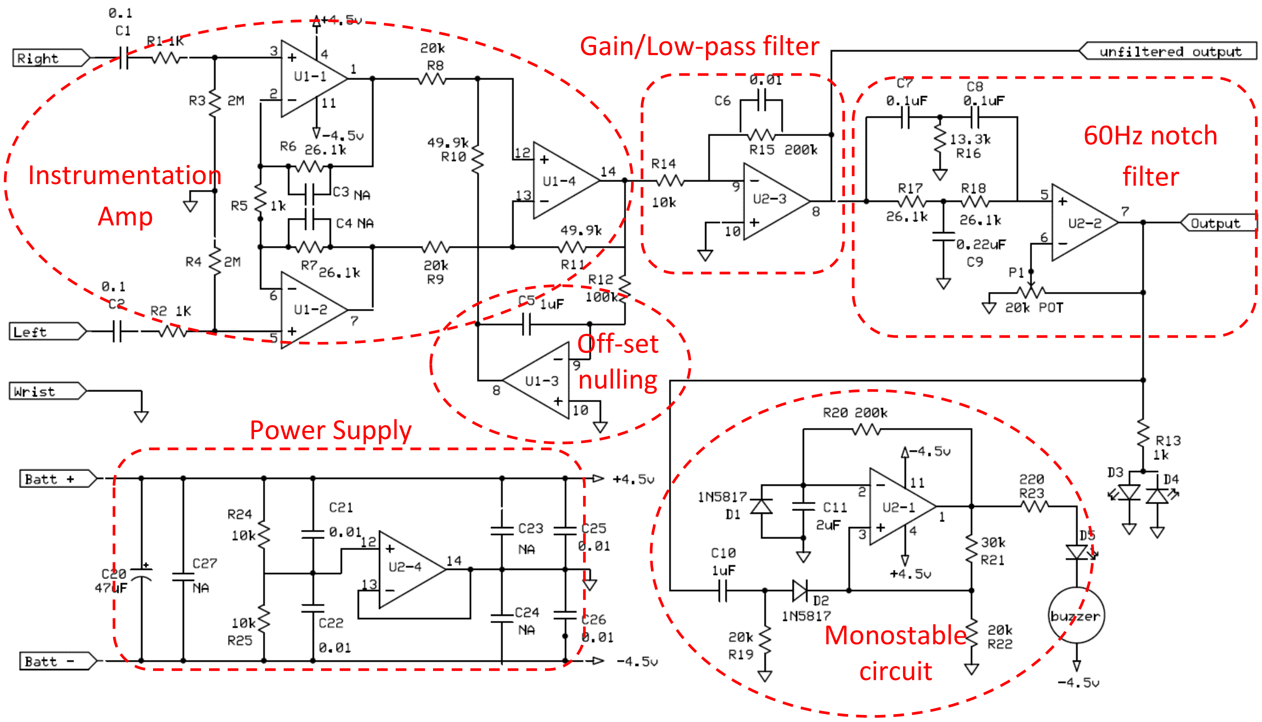


Figure 1

Power Supply. This ECG amplifier circuit requires three power supply lines: +4.5v, -4.5v, and 0v. These three lines establish two voltage levels: (1) +4.5v to 0v and 0v to -4.5v. Such a power supply is called 'dual power supply'. We can obtain these two voltage levels from a single 9v battery by using an op amp circuit. This circuit creates a 'mid-level' voltage between the '+' line and the '-' line from the battery. This 'mid-level' point is then designated as the ground node (the 0v connection). With respect to this ground node, the '+' line from the battery is +4.5v and the '-' line from the battery is -4.5v. In this circuit, two 10k resistors (R24 and R25) form a voltage divider circuit across the 9v supply. These two resistors create a 'mid-level' voltage. This mid-level voltage, however, cannot be directly used as the ground node because any other circuit connection to this node can affect its voltage. To maintain a constant mid-level voltage, a voltage follower op amp circuit (U2-4) is used. Note that the voltage of the output of this op amp is kept at the mid-level regardless of any other circuit connection to this output node. This output node is designated as the ground node for this circuit. Capacitors C21 and C22 filter out any high-frequency noise on three power supply lines.

Instrumentation amplifier. The 0.1uF capacitors (C1 and C2) at the input block any input DC offset. The 1k resistors R1 and R2 provide some isolation between the input pins of the op amps and the electrodes. Since the input impedance of the op amp is high, the attenuation of the input signal due to these 1k resistors is negligible. The 2MΩ resistors (R3 and R4) keep the op amps' DC offset at 0v. The 0.001uF capacitors (C3 and C4) make this amplifier a low-pass filter. These two capacitors are not necessary for this project. Consider the following instrumentation amplifier circuit, where v_x is assumed to be zero. In other words, the v_x node is assumed to be connected to ground.

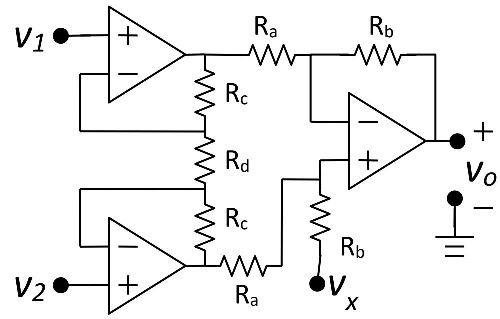


Figure 2

The following formula gives the voltage gain of this circuit. Note that the output depends on the difference between two input signals.

$$v_o = \underbrace{\frac{R_b}{R_a}\left(1+\frac{2R_c}{R_d}\right)}_{\text{gain}}(v_2 - v_1)$$

The voltage gain of the circuit is:

$$v_o = \frac{49.9k}{20k}\left(1+\frac{2\times 26.1k}{1k}\right)(v_2 - v_1) = 132.7(v_2 - v_1)$$

The ECG signal is typically about 1mV. This instrumentation amplifier boosts the ECG signal to about 0.13v.

DC offset nulling. The circuit in Figure 3 is an inverting integrator circuit.

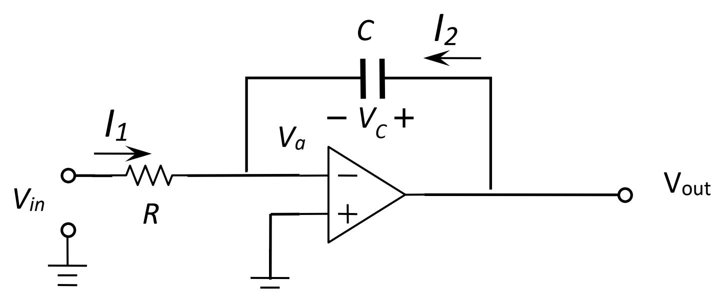


Figure 3

I_1 in the circuit is $I_1 = \frac{V_{in}}{R}$ since V_a is zero. Since the input current to the input of an Op Amp is zero, $I_2 = -I_1$.

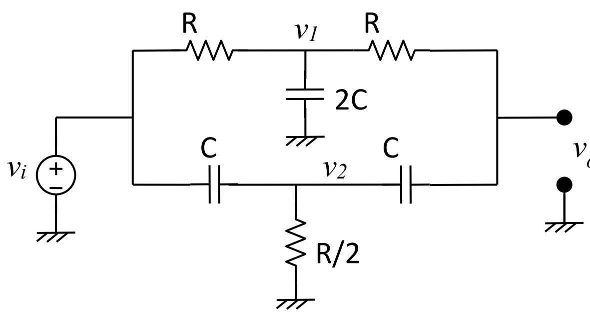
The voltage across the capacitor is $V_C = \frac{1}{C}\int I_2 dt = \frac{1}{C}\int\left(\frac{-V_{in}}{R}\right)dt = \frac{-1}{RC}\int(V_{in})\,dt$. Note that V_{out} is Vc.

$$V_{out} = \frac{-1}{RC}\int(V_{in})\,dt$$

The input to this inverting integrator is the output of the instrumentation amplifier. If this output contains any DC offset, it is integrated by the integrator. The output of the integrator is then fed back to the difference amplifier through the v_x node (see Figure 2). This feedback loop drives the DC offset at the instrumentation amplifier output to zero. Since the integration of a relatively fast-changing AC signal (such as the ECG signal) does not produce significant output; this feedback loop has a minimum effect on the ECG signal amplification.

Gain/low-pass filter. This circuit is an inverting low-pass filter with a DC gain of -R15/R14=-200k/10k=-20. This further boosts the ECG signal amplitude to 0.13v×20=2.6v. The bandwidth of this filter is set to much higher than the ECG signal so that any high-frequency component in the signal is attenuated by the filter. Determining the frequency characteristic of this filter is left as an exercise.

60Hz notch filter. High-gain circuits are prone to electromagnetic interference (EMI). When operating indoors, the most noticeable EMI is from the 60Hz power line. The RC network, consisting of C7, C8, C9, R16, R17, and R18, form a notch filter, blocking this 60Hz noise. The transfer function of the RC network can be determined by using nodal analysis as follows. Consider the following circuit.



There are three nodes v_1, v_2, and v_o in this circuit. The nodal equation of the circuit is shown below.

$$v_1 \text{ node: } \frac{v_1}{\frac{1}{s2C}} + \frac{v_1 - v_i}{R} + \frac{v_1 - v_0}{R} = 0$$

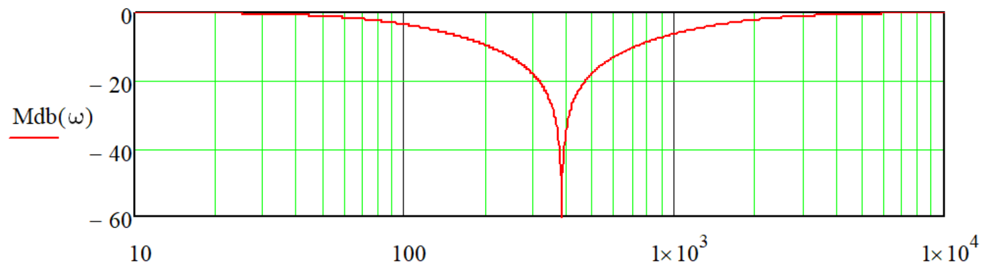
$$v_o \text{ node: } \frac{v_o - v_2}{\frac{1}{sC}} + \frac{v_o - v_1}{R} = 0$$

$$v_2 \text{ node: } \frac{v_2}{\frac{R}{2}} + \frac{v_2 - v_i}{\frac{1}{sC}} + \frac{v_1 - v_0}{\frac{1}{sC}} = 0$$

From this set of equations, we can derive the transfer function from the input voltage v_i to the output voltage v_o.

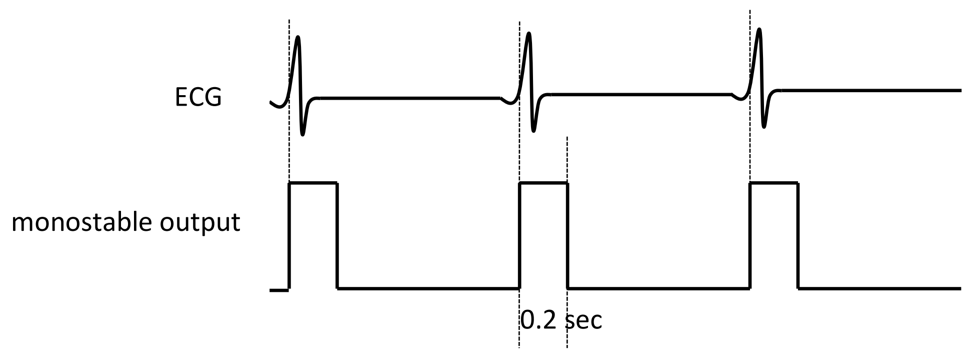
$$v_o = \frac{C^2R^2s^2 + 1}{C^2R^2s^2 + 4RCs + 1} v_i = H(s)v_i$$

If R=26.1k and C=0.1uF, the transfer function has a double-zero at 383 (rad/sec) or 61Hz which is the 'notch' frequency of this filter. The following is the magnitude Bode plot of this transfer function.



For this RC notch filter to function correctly, its output node (the common node of C8 and R18) should be left open or connected to a high input-impedance amplifier. In this circuit, U2-2 serves this purpose. U2-2 is a non-inverting amplifier with an adjustable gain. The gain is adjusted by turning POT P1. P1 should be preset to about the mid-point of the adjustable range. This sets the gain of the circuit to 2.

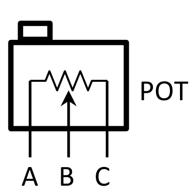
Monostable circuit. The width of each heartbeat pulse in the ECG signal is only about 0.05 seconds. This narrow pulse is too short to drive the LED and the buzzer directly. To solve this problem, a monostable circuit is used to produce a fixed-width pulse whenever a heartbeat pulse is detected. In this circuit, the fixed-width is about 0.2 seconds. The triggering sensitivity can be increased by reducing the value of the 20k resistor, R22. The duration of the on-period can be increased by increasing the 200k resistor, R20. Interested students can find the theory of operation of this circuit on the following web page. https://www.electronics-tutorials.ws/opamp/op-amp-monostable.html



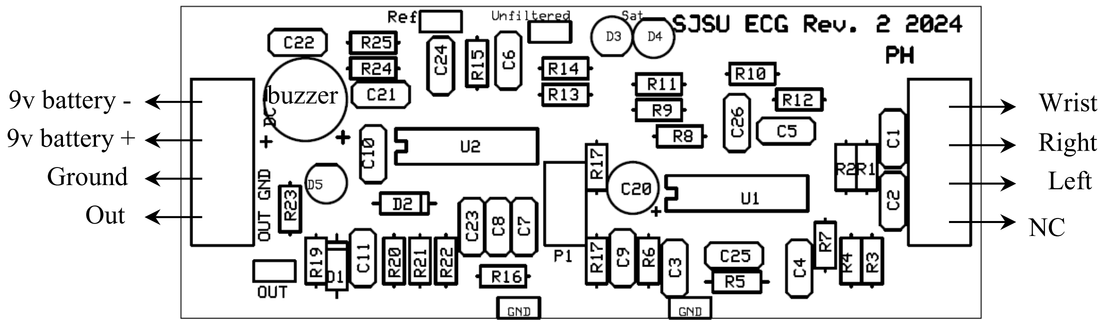
Circuit Construction and testing

You must know how to solder before attempting to assemble the circuit board. Soldering a component onto a PCB is easy, but removing one is difficult. For that, you should be absolutely sure of the placement of the components before soldering them. You should keep the following things in mind:

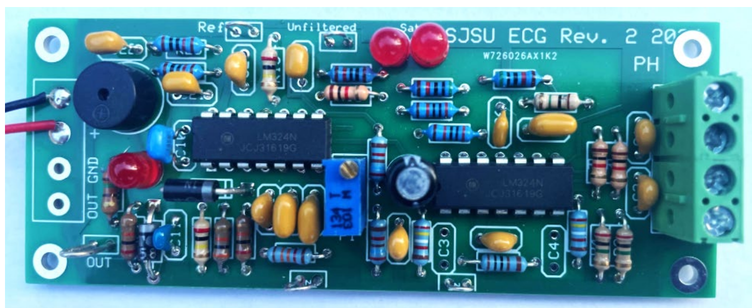
- All diodes, LEDs, and the capacitor C20 are polarized and should be installed according to the circuit diagram or the PCB layout figure below.
- The P1 20k POT should be preset to about the mid-point of the adjustable range. In other words, the resistance between A-B or B-C should be about 10k.



- There are two R17 labeled on the PCB by mistake. One of it should be R18. Fortunately, both R17 and R18 are 26.1k resistors.
- Use a piece of one-inch long bare wire to make a loop and solder it to the hole pads marked GND, Ref, OUT, and ‘unfiltered’ along the edge of the board. These are for the convenience of connecting probes to the board.
- C3 and C4 are not used.
- Fix the PCB errors as explained in the section 'Errata' on the last page of this document.

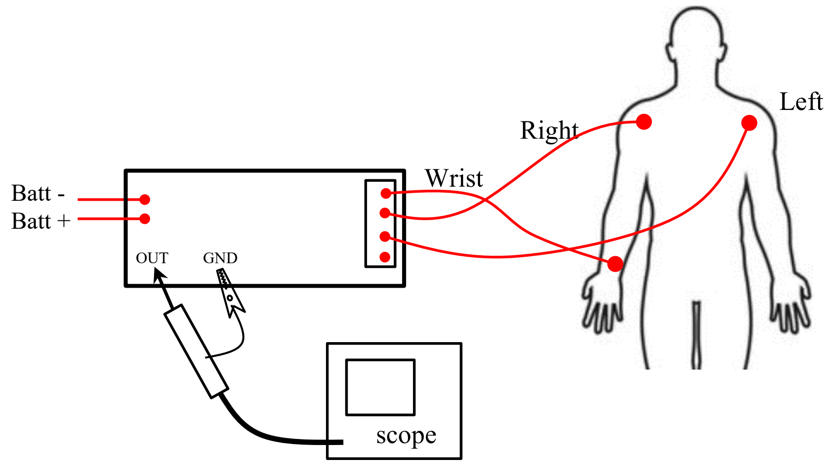


9v battery clip

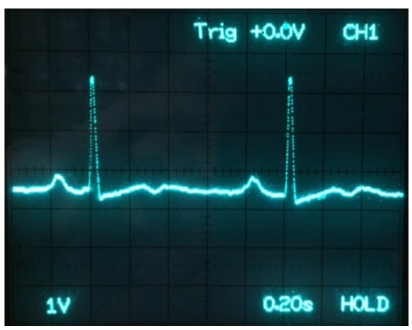


After the PCB is completely assembled, the first step is to give it a careful visual inspection. Place your board next to a known working board (or the picture above) and check any missing components. For the back side (the solder side), any bad solder joints or solder bridges.

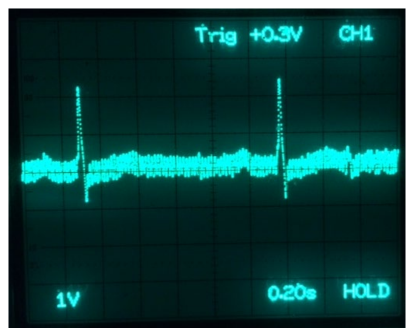
After the visual inspection, connect the circuit to a 9v battery. If the LEDs are turning on and off erratically when you touch the Right/Left input pins, there is a good chance that the circuit is working correctly. If that is the case, you can place sticky electrode pads on your chest/shoulder/wrist and use alligator clip cables to connect the pads to the board as shown below. It is possible to operate this circuit without using the specialized sticky electrode pads. You can tape wires with about 1-inch-long exposed copper directly to your skin. This, however, may not function properly due to the unreliable contacts.



You should relax and be calm during this test. If the circuit is working, after resting for a few seconds, you should hear a steady beep sound at about once every second. The LED should flash in sync with the beeps. You can observe the output signal with an oscilloscope. The waveform should be similar to the one below on the left side. Any slight movement will cause the ECG signal to deviate from its normal pattern. The ECG waveform shape is different for different people.



ECG signal after the 60Hz notch filter



ECG signal before the 60Hz notch filter

The figure on the right shows the ECG signal before the 60Hz notch filter. As shown, the signal contains a strong 60Hz noise component. This noise component is removed by the notch filter.

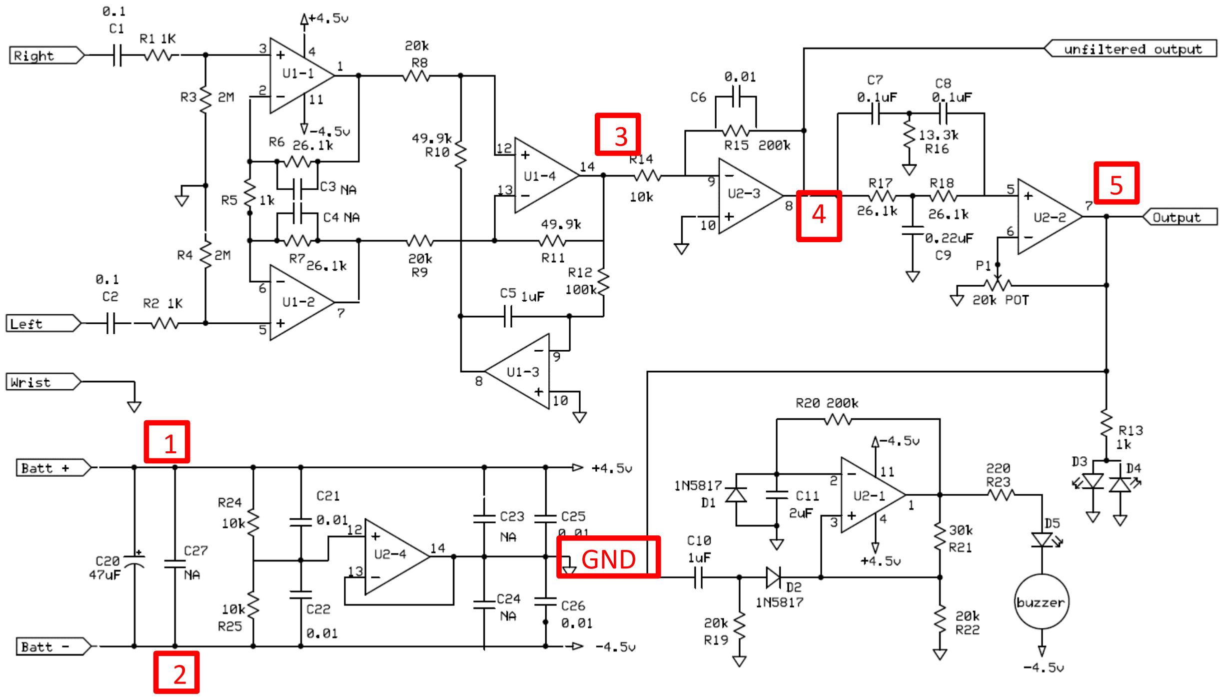
<u>Gain Adjustment</u>

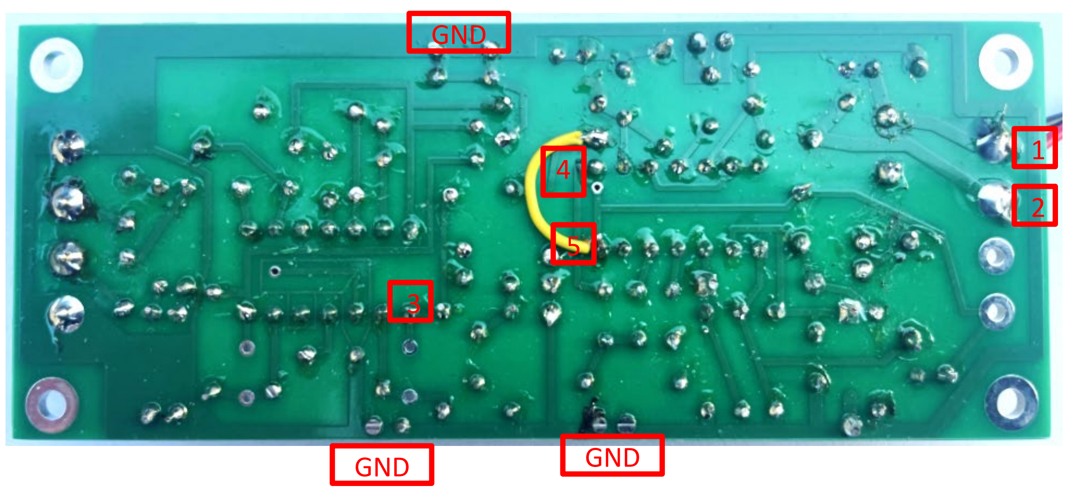
The ECG signal amplitude from the notch filter should be at least 1.5v peak in order to trigger the monostable circuit. If the amplitude is too low, the LED and the buzzer will not work. In this case, you can increase the circuit gain by adjusting the P1 POT. The gain of this non-inverting amplifier should be anywhere from 1 to 3, depending on the strength of the input ECG signal.

<u>Trigger sensitivity Adjustment (not required normally)</u>

After adjusting the gain of the circuit, if the flashing LED and the buzzer seem to work erratically (too sensitive) or not at all (not sensitive enough), you can adjust the ratio between R21 and R22 to set the trigger level of the 'pulse-stretching' circuit. The higher the ratio R21/R22 is, the higher the triggering sensitivity.

Key Voltages





Node (red probe)	Ref node (black probe)	voltage reading	
1	2	8v~9v	Battery voltage
1	GND	4.5v	+v supply voltage
2	GND	-4.5v	-v supply voltage
3	GND	0v	Instrumentation amp output
4	GND	0v	low-pass filter output
5	GND	0v	circuit output

Parts List

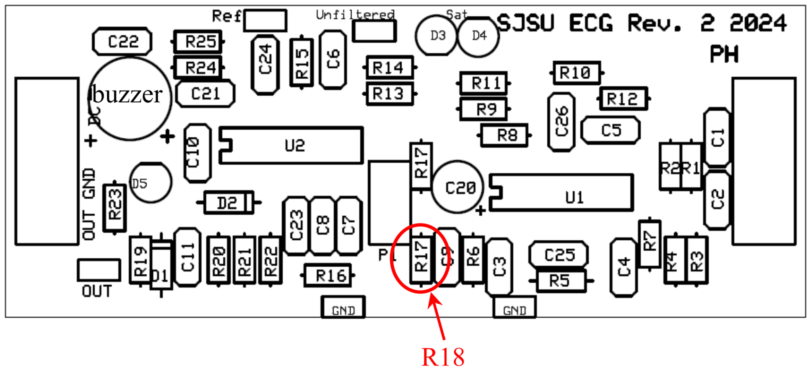
No.	Value (Ω)	Remark (all ¼W and 5% if not specified)
R1	1k	
R2	1k	
R3	2M	
R4	2M	
R5	1k	1%
R6	26.1k	1%
R7	26.1k	1%
R8	20k	1%
R9	20k	1%
R10	49.9k	1%
R11	49.9k	1%
R12	100k	
R13	1K	
R14	10k	
R15	200k	
R16	13.3k	1%
R17	26.1k	1%
R18	26.1k	1%
R19	20k	
R20	200k	
R21	30k	
R22	20k	
R23	220	
R24	10k	1%
R25	10k	1%
P1	200K POT	multi-turn potentiometer

No.	Value (μF)	Remark
C1	0.1	5%
C2	0.1	5%
C3	0.001	Not required
C4	0.001	Not required
C5	1	
C6	0.01	
C7	0.1	5%
C8	0.1	5%
C9	0.22	5%
C10	1	
C11	2	
C20	47	polarized
C21	0.1	
C22	0.1	
C23	0.1	Not required
C24	0.1	Not required
C25	0.1	
C26	0.1	
U1	LM324	Quad Op Amp
U2	LM324	Quad Op Amp
D1	1N5817	
D2	1N5817	
D3	LED	Sat. indicator
D4	LED	Sat. indicator
D5	LED	Beat indicator

PCB Errata

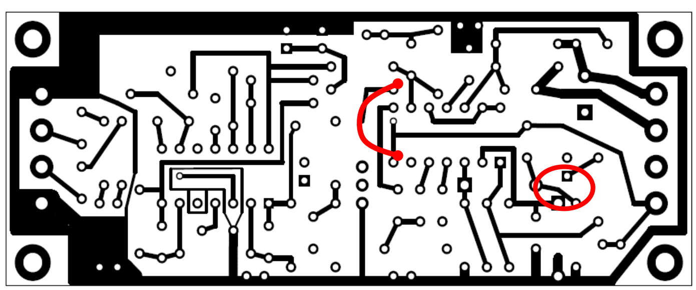
This version of the PC board has three errors:

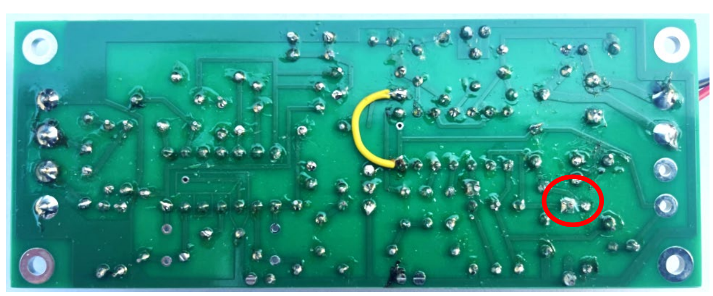
(1) There are two R17 labeled on the board. The lower one should be R18. Note that R17 and R18 have the same resistance 26.1k.



(2) The upper right corner of a square pad is shorted to a trace as <u>circled in red</u> in the figure below. This error can be fixed by scoring the board where the square pad touches the trace with a sharp knife to separate the square pad corner and the trace.

(3) A connection is missing. The missing connection is marked in red. This error can be fixed by soldering a jumper wire as shown.





4/16/2025 P. Hsu