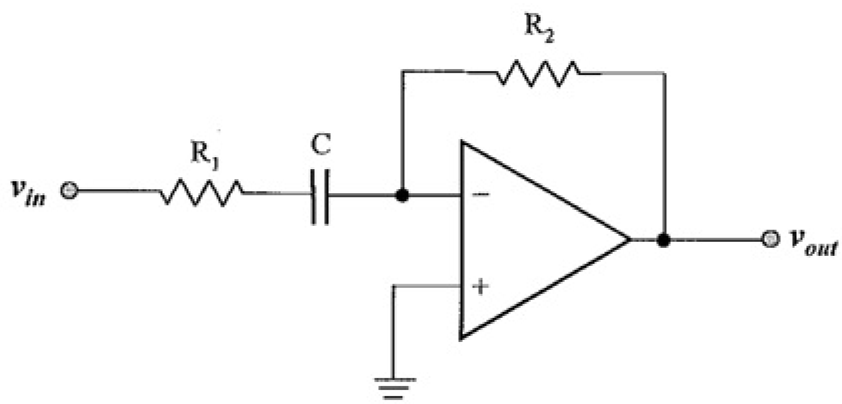
Physics 623
The Operational Amplifier

January 16, 2023

1 Prelab Worksheet

1) In the lecture we have shown how to construct an integrator using an op-amp. With an op-amp it is possible to construct many mathematical operations. Another example is differentiation.

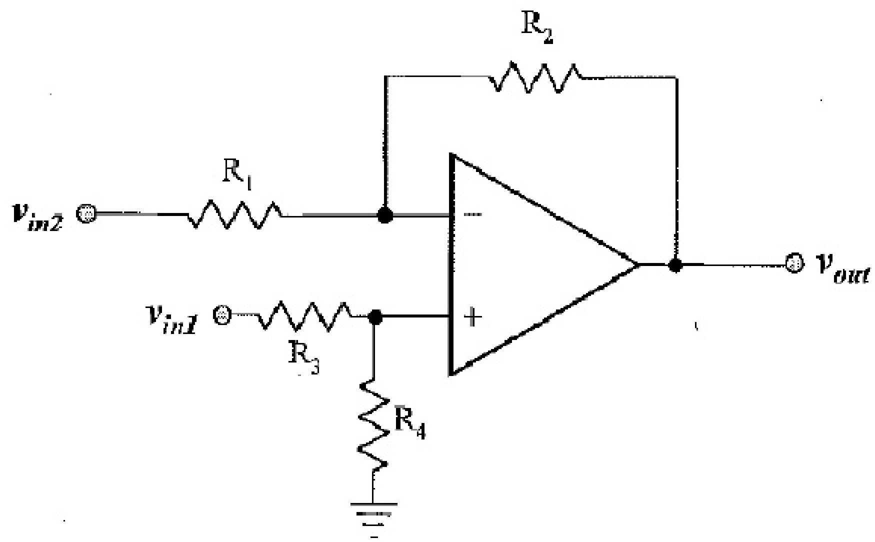
a) Find the relation between V_{in} and V_{out} for the circuit below:



b) Show that, when $R_1 \ll 1/\omega C$, ($\Rightarrow \omega \ll 1/R_1 C$), the circuit works as a differentiator. Find V_{out}. when $R_1 \gg 1/\omega C$, ($\Rightarrow \omega \gg 1/R_1 C$).

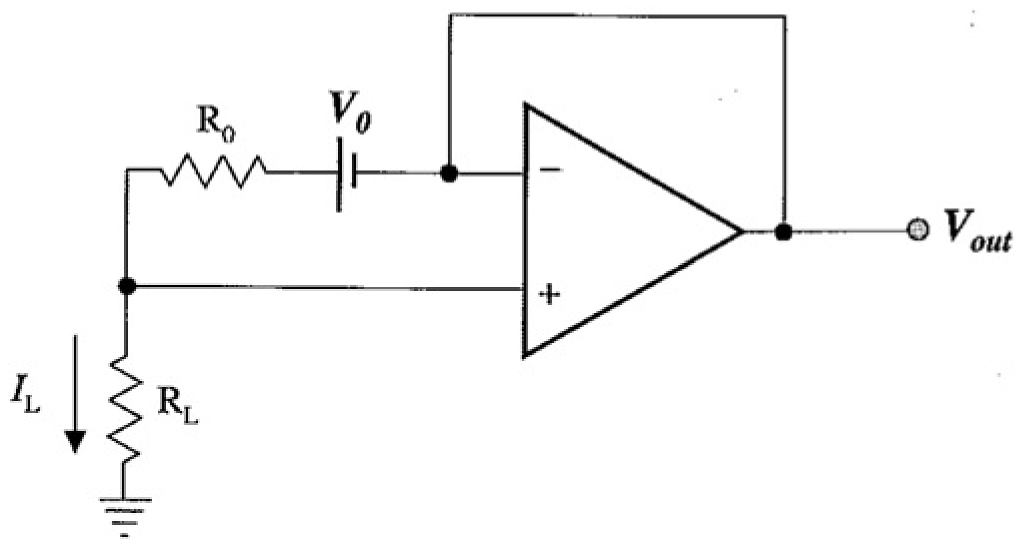
2) With an op-amp, one can also construct a difference amplifier.

a) How does the output voltage relate to the two input voltages in the circuit below:



b) Show that when $R_4/R_3 = R_2/R_1$, the circuit works as a difference amplifier. What is the voltage gain for a difference input? (Differential gain $V_{out}/(V_{in1} - V_{in2})$ What is the voltage gain for a common-mode input? (Common mode gain $V_{out}/[(V_{in1} - V_{in2})/2]$).

3) In the below circuit, show that the current flowing through the load resistor, I_L, is independent of the load, R_L. What is V_{out}? This circuit constitutes a constant current source with a grounded load.



2 Lab Instructions

2.1 Purpose

- To understand the basic concepts and characteristics of an ideal operational amplifier.
- To compare the characteristics of a high-performance low-cost I_C op amp with those of the ideal.
- To investigate the properties of the IC op amp in several circuits which demonstrate its great versatility and range of operation.
- Note that this is a two-week lab. You should be able to complete through part 4 or part 5 during the first week.

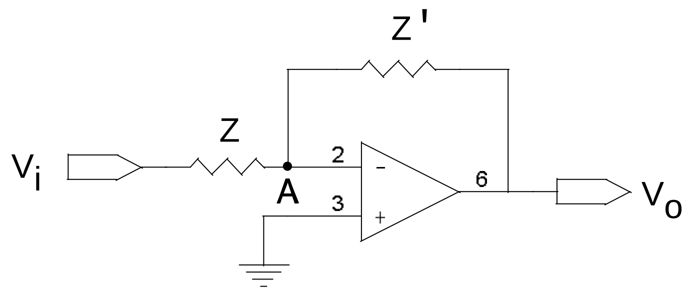
2.2 Discussion

Modern integrated circuit operational amplifiers (op amps) have characteristics so closely approaching the ideal op amp that they are components of almost all signal processing and instrumentation equipment. The properties of a commonly used 741 op amp are compared to the ideal values below:

Parameter	Ideal Value	$\mu A741$ Value	2006 best avail. value (not all in same device)
Input current	$I_{in} = 0$	~ 80 nA	0.01 pA
Voltage gain	$A_v = \infty$	$200,000$	2×10^6
Bandwidth	BW$= \infty$	1 MHz at $A_v = 1$	1000 MHz
Balance	$V_o = 0$ for $V_i = 0$	$V_o = 0$ at $V_i = 1 - 2$ mV	5 μV
Temperature dependence	none	$(dV/dT)_{offset}$ typically 15 $\mu V/°C$	$(dV/dT)_{offset}$ 0.1 $\mu V/C$

Op amps can be obtained commercially for $0.50 to $3.00 each. This and their versatility are the reasons for their great popularity. As you perform the suggested investigations, be alert to observe and note those cases in which the real op amp fails to match the ideal properties. Try to find the relevant properties in the "spec sheets", and take note of the "typical applications" section – this is a prime spot for getting circuit ideas or finding out how new devices might be used.

Almost all applications of op amps involve negative feedback as indicated in the diagram below:



Assume that point A is a virtual ground (*i.e.* $V_- = V_+$), and that $I_i = 0$, and prove the general result that

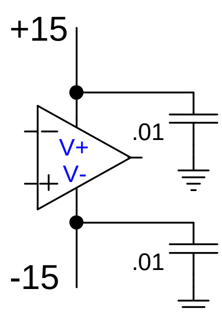
$$A_{vf} = \frac{V_o}{V_i} = -\frac{Z'}{Z}$$

.

3 Procedure

- For each circuit you will test, first draw a schematic diagram in your lab notebook, that includes IC pin numbers for the integrated circuit (obtainable from the specification sheets).

- Near the supply pins ($\pm 15\ V$), connect filter capacitors ($0.01\ \mu F$) to ground. As you can see from the circuits in this handout, the power supply connections and associated filter capacitors are not normally shown on the main circuit diagram. However, place a schematic in your lab notebook that shows the power supply connections, including the bypass capacitors as shown in the figure below.

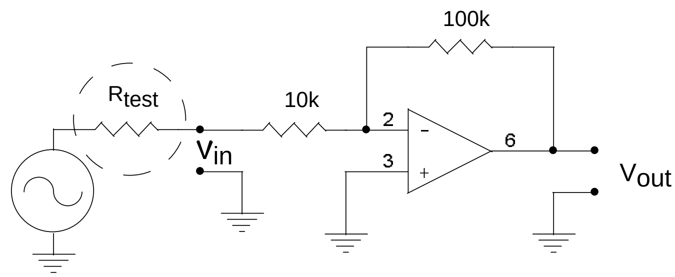


- Where appropriate in the exercises listed below, compare the measured gain A and frequency response to the values listed on the specification sheets.

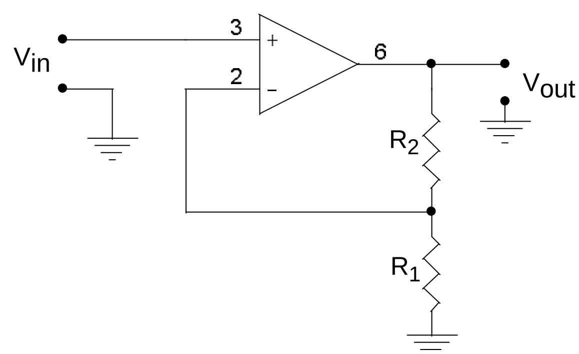
1. Connect the op amp as an **ordinary amplifier** as shown below.

    - Find the “output voltage swing” and the “slew rate” specifications on the data sheet and determine what they mean.

- Can you measure them?
- Check the magnitude and phase of the gain.
- Measure the bandwidth and the input impedance at the V_{in} terminals. (The insertion of the R_{test} resistor is useful in determining the input impedance.)



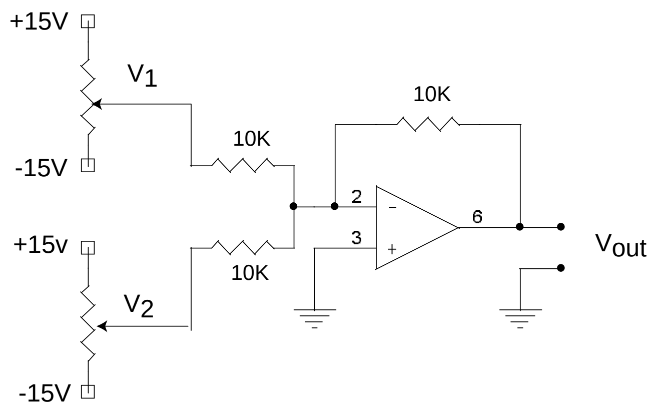
2. Connect the op amp as a **non-inverting amplifier**. $R_1 = 10\text{k}, R_2 = 100\text{k}$.
   - Confirm the magnitude and phase of the gain.
   - What is the input impedance in this configuration?



3. Construct an **adder**. Verify, using three or four pairs of input values, that:

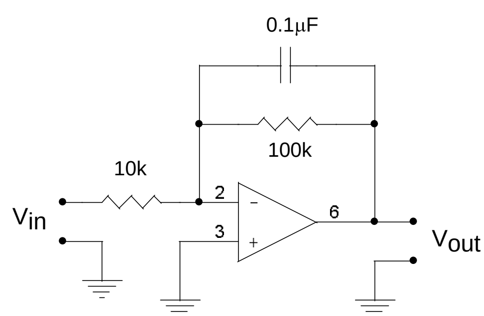
$$V_o = -(v_1 + v_2)$$

   It is most convenient to use the square 10k potentiometers with pins on the back side as adjustable voltage sources for v_1 and v_2.



4. As shown below, connect the op amp as an **integrator**. Use positive pulses 1 msec wide at a frequency of 40 Hz as the input.

   - Observe the input and output using scope inputs with DC coupling. Because of the 100k resistor, this is not a true integrator, but is referred to as a **leaky integrator**.
   - What is the effect of the resistor?

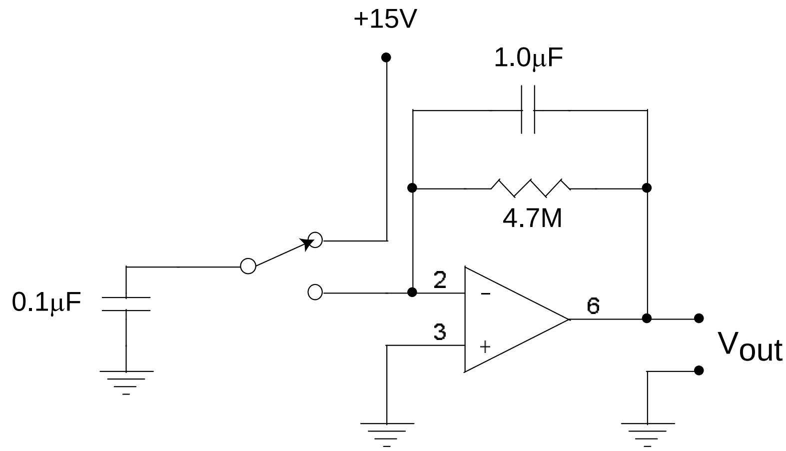


5. Now modify the integrator to be a **charge sensitive amplifier**. This is the electronic analog of a ballistic galvanometer.

   - Charge a 0.1 μ F capacitor on the +15 V supply.
   - Connect it to the inverting input.
   - Derive the equation:

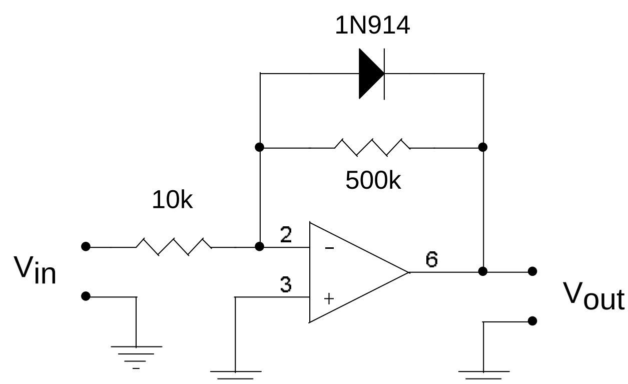
$$V_{\circ} = -\frac{1}{C_f}\int i_{in}dt = -\frac{Q_{in}}{C_f}$$

   - Experimentally confirm it with your measurement.
   - Try another value of input capacitance and note whether the peak value of V_{out} tracks the input charge.



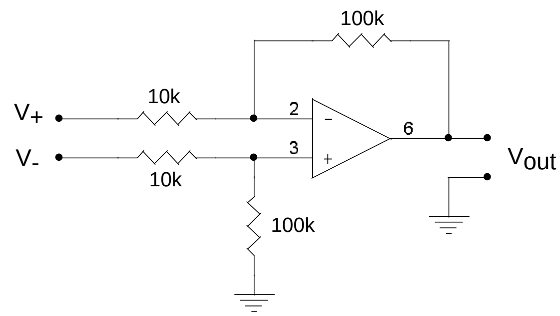
6. Construct a **logarithmic amplifier** as shown below.

   - Vary V_{in} and plot $V_o = A + B \ln V_i$ using a semi-log scale. Five or six values are sufficient – be sure they cover a wide range in V_0. (You can use the Log functions on your calculator and the ruled paper in your notebook for the plot.)
   - Does it make any sense to use an AC input voltage for this measurement?
   - What are your values of A and B?



7. Note that, while an Op-Amp has differential inputs, the gain stabilized amplifier circuits in parts 1 and 2 above do not.

   - To gain the advantages of a differential input with an accurate gain and good common mode rejection, construct the **Instrumentation Amplifier** as shown below.
   - Understand out how it works.
   - Try a few combinations of v_{in}^{+} and v_{in}^{-} to find the differential and common mode gains.



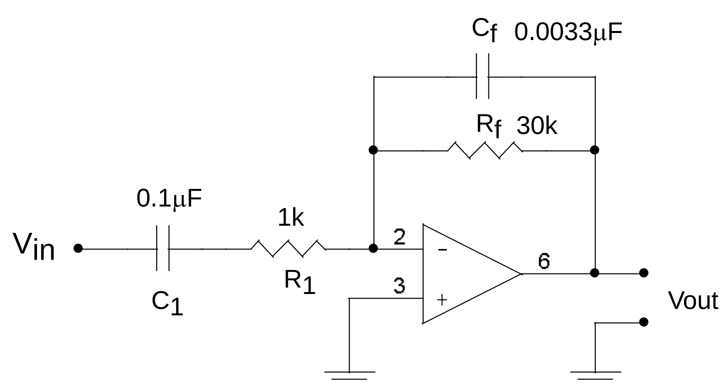
(This particular circuit has several drawbacks. Check Horowitz & Hill for a nifty "3 Op-Amp Instrumentation Amplifier" that has:

- a CMRR over 100,000
- an essentially infinite input impedance on both inputs
- gain that is adjustable over a wide range by changing one resistor.)

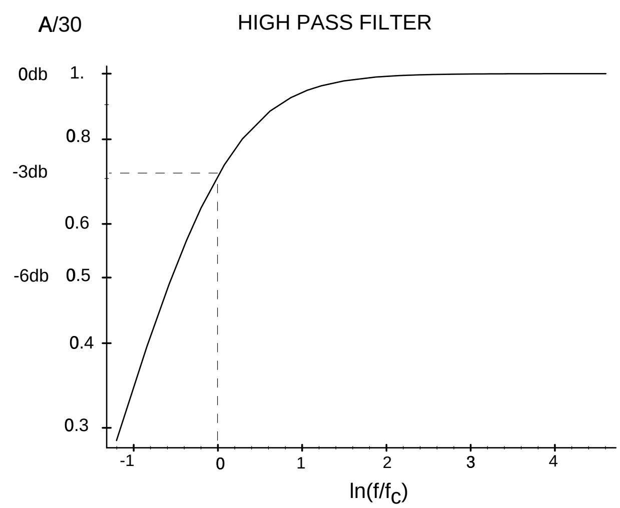
8. The following circuit will be used in the next lab, so build it on the circuit board that is marked with your name and save it. This is a high gain circuit and some care in the layout is needed; the instructor should have an example to show you before you start.

   The circuit consists of three identical stages, which should be arranged from left to right across the upper breadboard block, leaving about 1/3 of the block free on the left. Clip the component leads short and bend them with your pliers so that the component bodies lie flat against the breadboard – this minimizes stray capacitances. **Use a single bus on the socket for all the grounds – for example, the inner strip just below the op amps.** It is a good idea to put 0.1 μF ceramic capacitors from the ± 15 V supply pins to the ground bus as close as possible to each op-amp. The instructor will show you a sample layout before you start. Follow this layout very closely. A good layout is critical for the next two labs.

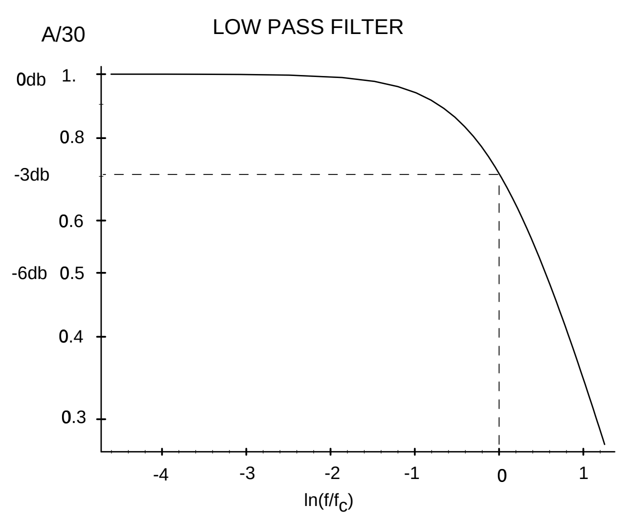
   The circuit for a single tuned amplifier stage is:



   Ignoring the capacitors for a moment, this is just an inverting amplifier with a gain of $R_f/R_1 = 30$. The addition of C_1 introduces a high-pass corner at $f_1 = 1/2\pi R_1 C_1$ that reduces the gain at **low** frequencies, ie $f \ll f_1$:

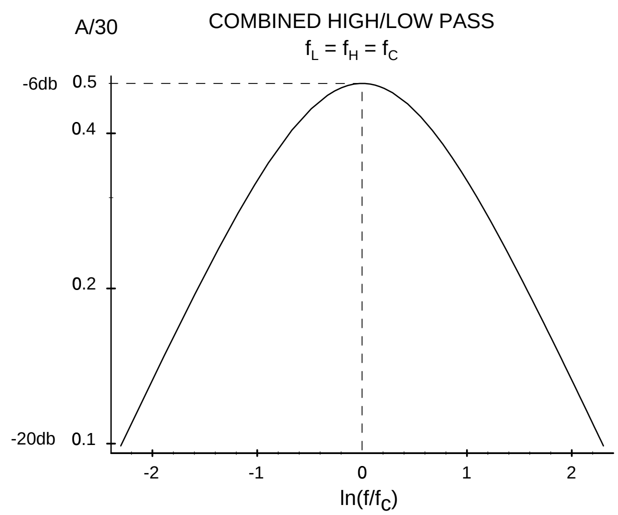


The addition of C_f reduces the gain at **high** frequencies, i.e. $f_2 = 1/2\pi R_f C_f$



With **both** capacitors, the gain is just the **product** of these two curves. Since $f_1 = f_2 \equiv f_0$, the result is :

$$A_v = -\left(\frac{R_f}{R_1}\right)\left(\frac{(f/f_0)}{1+(f/f_0)^2}\right)$$

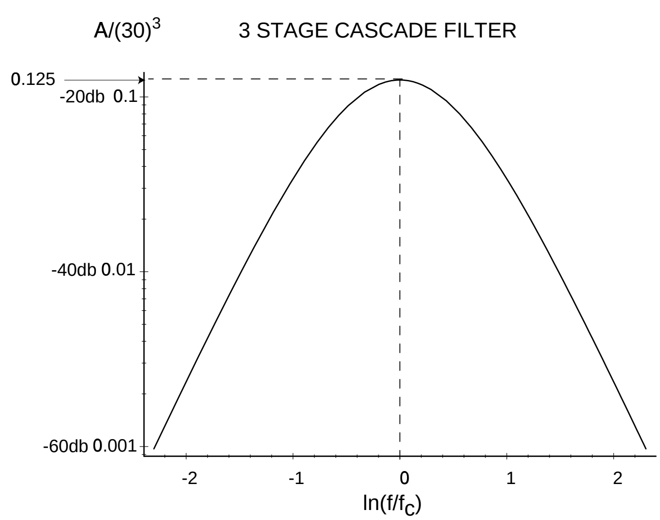


Therefore, the maximum gain of the stage is $1/2(R_f/R_1) = 15$ at f_0, and drops off $\propto f$ for $f \ll f_0$ and as $1/f$ for $f \gg f_0$ – both 6 *db per octave*. What is f_0 for the given component values?

To make a high gain amplifier with a fairly narrow bandwidth, we cascade **three** (3) identical stages. The gain is then:

$$A_v = (30)^3 \left(\frac{(f/f_0)}{1 + (f/f_0)^2} \right)^3$$

The peak gain is now $A_v = 30^3/8 = 3375$ at $f = f_0$ and drops off as $1/f^3$ for $f \gg f_0$, and as f^3 for $f \ll f_0$.



- Construct the three stage amplifier;
- measure the frequency at which the gain is maximum; and

- record the gain at this frequency.
- How does the frequency of peak gain compare to your calculated f_0? (For the input signal, use the 100× attenuator on the wave-form generator output). Measure the input and output voltage with a scope, not the DVM.
  You can use the DVM if *you are careful to take the noise into account. How do you do this?*
- Plot the frequency response ($\log A_v$ *vs.* $\log \omega$ from $\sim$ 50 Hz to 50 kHz with about 3 points per decade. (This implies about a factor of 2 between points to be about evenly spaced on the logarithmic scale.)
- Record the value at 60 Hz.