Chapter I: Op Amp Voltage-Range Issues

1. Op amp voltage ranges: input and output, clearing some confusion

System designers often have questions about the power supply input and output voltage-range capabilities of operational amplifiers (op amps). It can be confusing, so here is my attempt to sort it out.

First, common op amps do not have ground terminals. A standard op amp does not "know" where ground is, so it cannot know whether it is operating from a dual supply (±) or a single power supply. As long as the power-supply input and output voltages are within their operating ranges, all is well.

Here are three critical voltage ranges to consider:

1. The total supply-voltage range. This is the total voltage between the two supply terminals. For example, ±15 V is a total of 30 V. The operating voltage range for an op amp might be 6 V to 36 V, for example. At the low-voltage extreme, this could be ±3 V or +6 V. At maximum, it could be ±18 V or +36 V or even –6 V/+30 V. Yes, unbalanced supplies are OK, but only if you heed the second and third bullet points below.
2. The input common-mode voltage range (C-M range) is generally specified relative to the positive and negative supply voltages, shown in **Figure 1**. In some equation-like form, the C-M range of this hypothetical op amp would be described as 2 V above the negative rail to 2.5 V below the positive rail. Something like this: (V–)+2 V to (V+)–2.5 V.
3. The output-voltage range (or output-swing capability) is, again, commonly specified relative to the rail voltages. In this case, (V–)+1 V to (V+)–1.5 V.

Figures 1, 2 and **3** show a G = 1 buffer configuration. A key point here: The output capability of the example in **Figure 1** will be limited to 2 V from the negative rail and 2.5 V from the positive rail, which is due to the limited-input C-M range. You would need to configure this op amp in a higher gain to deliver its full output-voltage range.

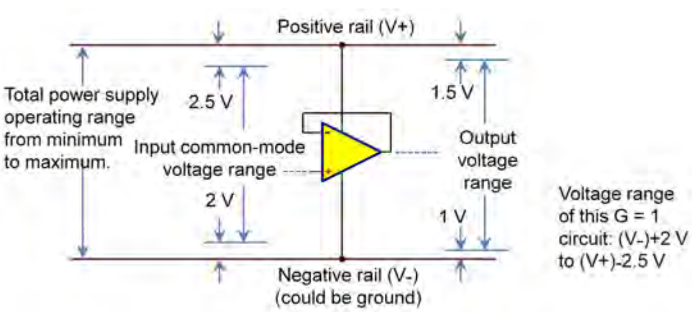


Figure 1: Input and output voltage ranges of a typical op amp used on dual supplies (±).

The example in **Figure 1** is typical of an op amp generally used on dual supplies. It would not be called a "single-supply" type, but it could operate as a single supply by staying within those ranges.

Figure 2 shows a so-called single-supply op amp. It has a C-M range that extends to, and often slightly below, the negative rail. That range allows its use in a wider range of circuits that operate close to ground. So an op amp that is not called "single supply" is actually usable in some single-supply circuits, but a true single-supply type is more versatile.

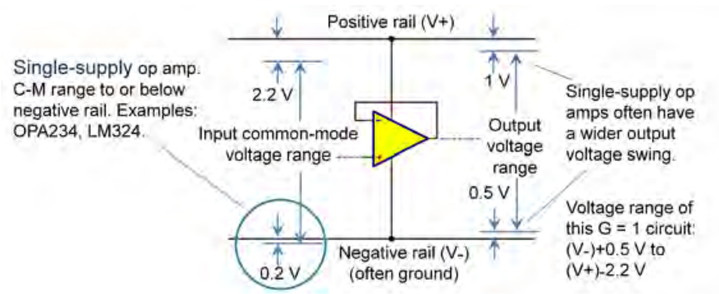


Figure 2: Input and output voltage ranges of a typical single-supply op amp.

In a G = 1 buffer circuit, this op amp could produce an output swing of 0.5 V from the V– rail (limited by the output capability) and 2.2 V from the V+ rail (limited by the input C-M range).

Figure 3 shows a "rail-to-rail" op amp. It can operate with an input voltage equal to or even slightly beyond both supply-voltage rails, as shown in **Figure 3**. A rail-to-rail output means that the output voltage can swing very close to the rails, often within a 10- to 100-mV range from the supply rails. Some op amps claim only a rail-to-rail output, lacking the input characteristics shown in **Figure 3**. Rail-to-rail op amps are very commonly used on single 5-V supplies and lower because they maximize the signal-voltage capability on their limited supply range.

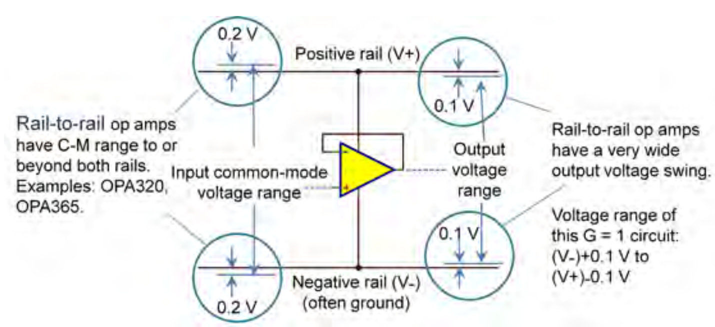


Figure 3: Input and output voltage ranges of a typical rail-to-rail op amp.

Rail-to-rail op amps are appealing because they ease signal-voltage constraints, but they are not always the best choice. Like other life choices, there are often trade-offs with other performance attributes. But that is why you are an analog designer. Your life is full of complex issues and trade-offs, and you love it!

To see this original post with comments, click here.

2. Rail-to-rail inputs: what you should know!

Rail-to-rail operational amplifiers (op amps) are extremely popular and especially useful with low supply voltages. You should know how to accomplish rail-to-rail inputs and understand some trade-offs.

Figure 4 shows a typical dual-input, rail-to-rail stage comprising both N-channel and P-channel transistor pairs. P-channel field-effect transistors (FETs) handle the signal through the lower portion of the common-mode voltage range to slightly below the negative rail (or single-supply ground).

The N-channel FETs operate with a common-mode voltage near and slightly above the positive rail. Additional circuitry (not shown) directs traffic, determining which input-stage signal the next stage will process. Most TI dual-input-stage op amps are designed so that the transition occurs approximately 1.3 V from the positive rail. Above this voltage, there is insufficient gate voltage for the P-channel stage, so the signal path is redirected to the N-channel stage.

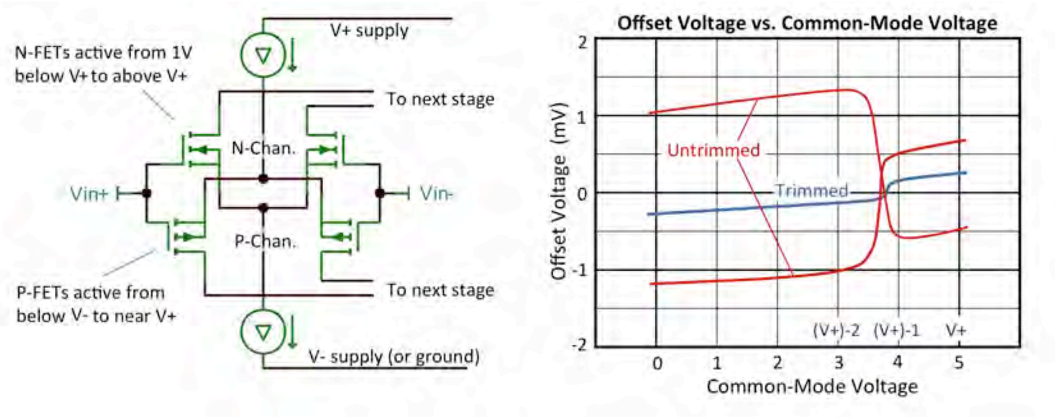


Figure 4: A typical dual-input rail-to-rail stage using both N- and P-channel transistor pairs.

The P and N input stages will have somewhat different offset voltages. If the common-mode voltage moves through this transition (as it does with rail-to-rail G = 1 operation), it creates a change in the offset. Some op amps are factory-trimmed by laser or electronic trimming, adjusted to reduce the offset of the input stages. This trimming reduces the change through the transition but still leaves a residual bobble. Circuitry controlling the transition from the P to N input stage is referenced to the positive supply voltage, not to ground. On a 3.3-V supply, the transition moves to an awkward point – midsupply.

While unnoticed in most applications, this change in offset voltage may be an issue if you require high accuracy. It can also cause distortion in alternating current (AC) applications. But again, distortion will only occur if the common-mode input voltage crosses the transition between stages.

Figure 5 shows a second type of rail-to-rail input stage. An internal charge pump boosts the voltage powering a single P-channel input stage to approximately 2 V above the positive supply rail. This voltage boost allows a single-input stage to perform seamlessly over the full rail-to-rail input-voltage range – below the bottom rail to above the top rail – with no transition glitch.

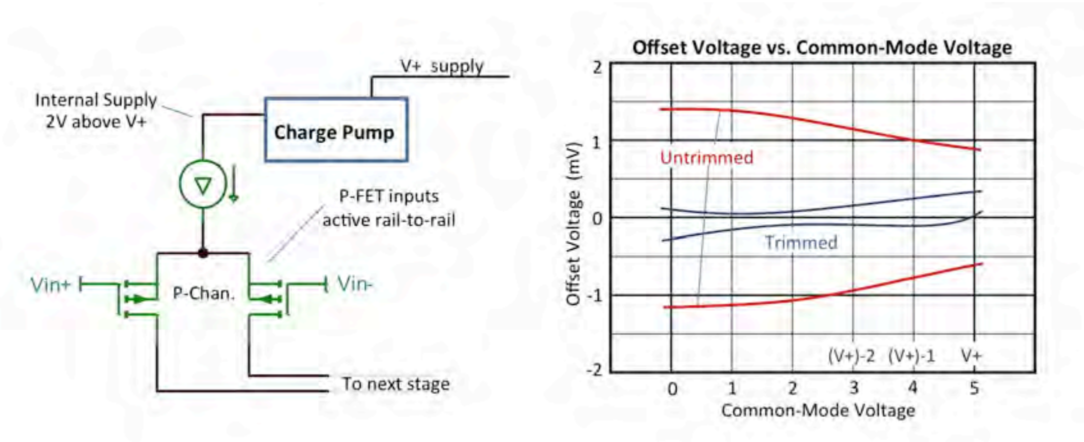


Figure 5: A rail-to-rail input stage with an internal charge pump to boost the voltage, powering a single P-channel FET.

"Charge pump" ... it sounds spooky to some designers. They are noisy, right? But TI's most recent ones are remarkably quiet. Charge pumps require very little current because they only power the input stage. There are no extra pins or capacitors – it is all internal. Charge-pump noise is below the broadband noise level; rarely can you see it in the time domain. Applications that analyze the spectral response below the broadband noise level, however, may see some artifacts.

Not all applications need an op amp with rail-to-rail input. Inverting op amp circuits or amplifiers in gain greater than unity, for example, often do not require rail-to-rail input, yet still have rail-to-rail output. Do you really need a rail-to-rail input amplifier? Many engineers prefer to use them so that they do not need to worry about exceeding the common-mode range. They use the same op amp in various points in their systems: some need rail-to-rail input; others not. Whatever your choice, with knowledge of rail-to-rail types and trade-offs, you can select more wisely. If in doubt, you are welcome to ask the engineers on the TI E2E™ Community Precision Amplifiers forum.

Here are a few example op amps:

- OPA340 dual-input stage, trimmed offset, 5.5-MHz, rail-to-rail CMOS.
- OPA343 dual-input stage, untrimmed offset, 5.5-MHz, rail-to-rail CMOS.
- OPA320 charge-pumped input stage, 20 MHz, rail-to-rail CMOS.
- OPA322 charge-pumped input stage, untrimmed offset, 20 MHz, rail-to-rail CMOS.

To see this original post with comments, click here.

3. Swinging close to ground: single-supply operation

Rail-to-rail amplifiers can produce output voltages very close to ground – but how close? I am talking about complementary metal-oxide semiconductor (CMOS) operational amplifiers (op amps) that often are used in low-voltage designs when you are trying to maximize output-voltage swing. TI's specifications for these devices generally look something like Table 1.

Parameter	Conditions	Min	Typ	Max	Unit
Output					
Voltage output swing from both rails	RL = 10 kΩ		15	25	mV
	RL = 2 kΩ		35	50	mV

Table 1: Output specifications for rail-to-rail amplifiers.

Table 1 makes it appear that the output will never swing much closer than 15 mV from ground, and that last 15 mV can be critical for accurate zero-based measurements. But wait: You really need to carefully interpret all of the conditions of this specification, because the assumption is that the load is connected halfway between the power-supply terminals.

You will often find conditions cited at the top of the specifications table, where you will see a statement like this: R_L connected to $V_S/2$.

In this specified condition, the amplifier must sink current through the load resistor as the output approaches ground. This reflects the way the amplifier is tested, assuring that it can properly source and sink current. It is a sensible and conservative way to test and specify the amplifier, but what if it is not the way your load is connected? Suppose your load is connected to ground as in Figure 6. The load resistor actually helps pull the output to ground, and the amplifier is not required to sink current.

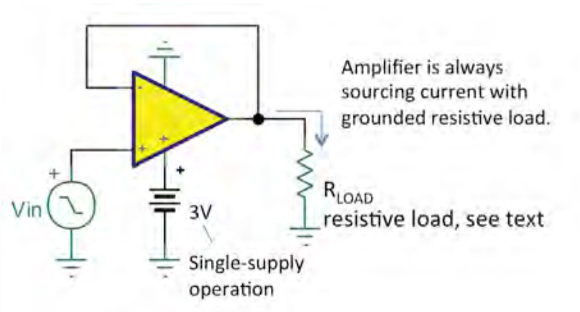
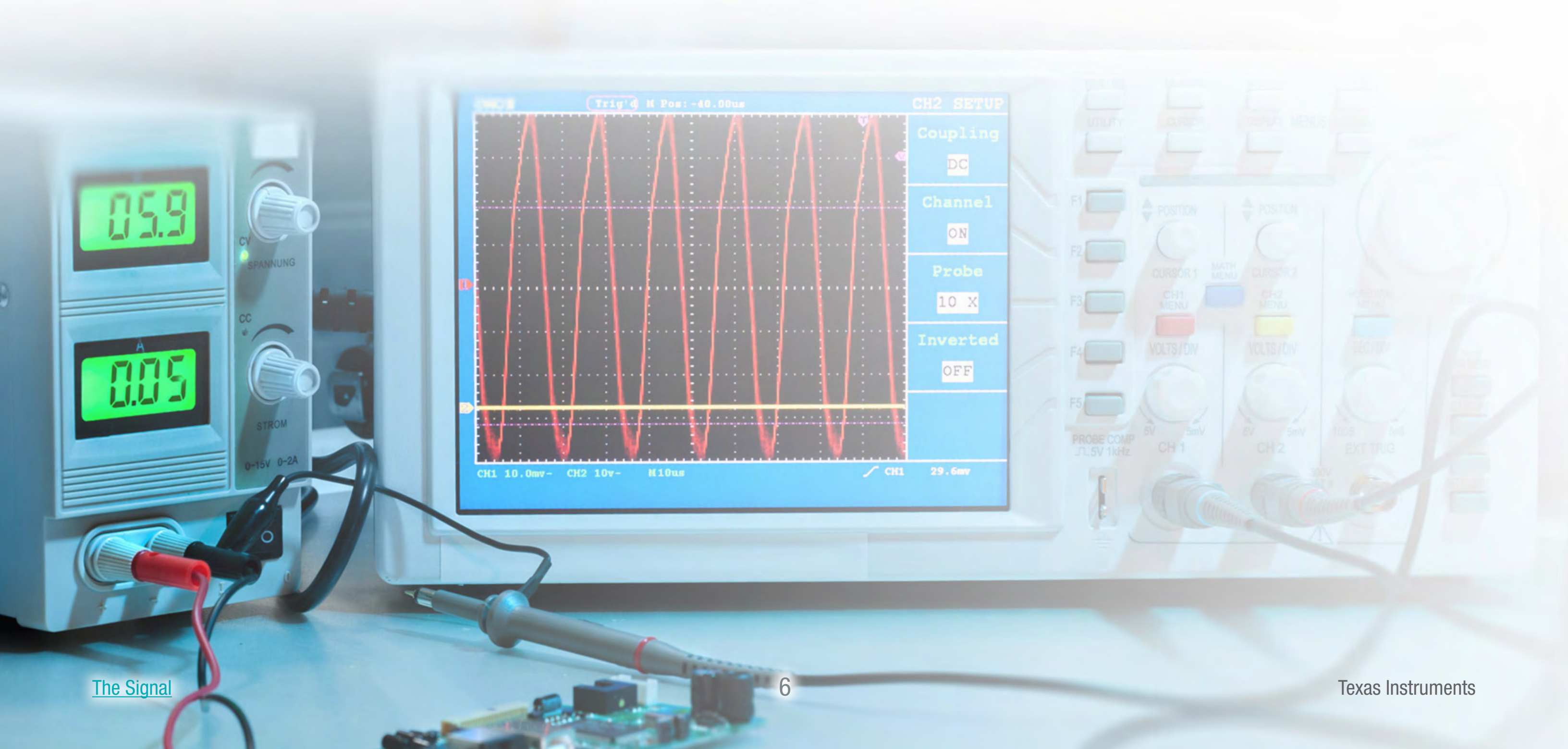


Figure 6: Example of an amplifier load connected to ground.



In this condition, most CMOS op amps can swing very close to ground – within a millivolt or two. The specifications may not highlight this capability, but it is hinted at in **Figure 7**, showing output-voltage swing as a function of output current. The graph could perhaps benefit from more resolution, but you can see that the output voltage converging on the specified voltage rails for this test is ±2.75 V. For single-supply operation, the V– supply is equal to 0 V.

Now I need to add a few provisions. Notice that in **Figure 8**, the feedback network is referenced to ground. You need to consider all sources of load on the amplifier, not just RL. In this case, R1 + R2 are effectively additional ground-referenced loads in parallel to RL. But if R1 is referenced to a positive voltage, the amplifier would have to sink current coming through the feedback network as the output neared 0 V. The output would not be able to swing quite so close to ground.

In this same circuit, if the gain is high, the input offset voltage may affect your apparent output swing. For example, in G = 20, if the input offset voltage of the op amp is +1 mV, zero input will produce a 20-mV output. That is not due to an output-swing limitation – it is an offset-voltage issue. Of course, a small, negative input voltage will bring the output very near 0 V, but your circuit may never have a negative input voltage.

Alternating current (AC) signals with reactive loads may be an exception. Load current and voltage are not in phase with a reactive load, so the amplifier may have to sink current as the output voltage approaches ground.

(Referring to CMOS op amps, bipolar op amps cannot swing so close to ground.)

Low-voltage battery-operated circuits are challenging, and it seems that we are always struggling to maximize voltage swings. With a good understanding of op amp capabilities, you may be able to squeak out additional output swing close to ground. If you have questions about a specific amplifier or circuit configuration, submit your question to the Precision Amplifiers forum on TI's E2E Community.

To see this original post with comments, click here.

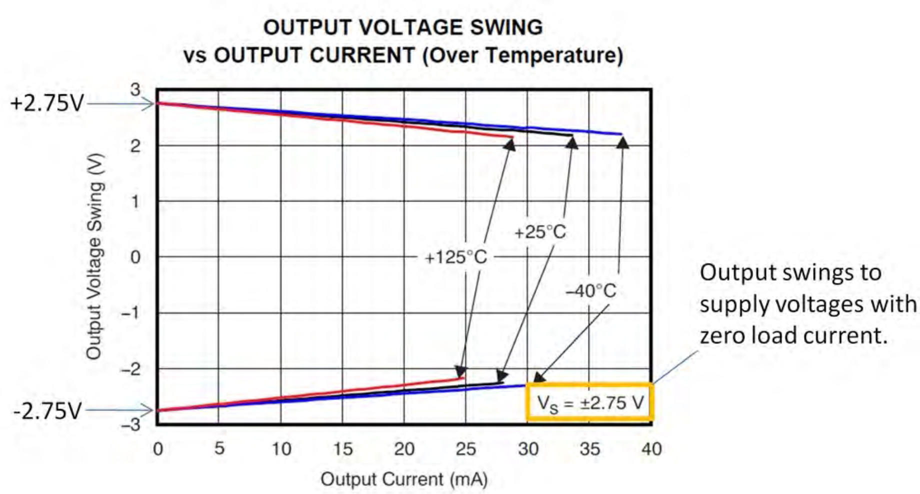


Figure 7: Output-voltage swing shown as a function of output current.

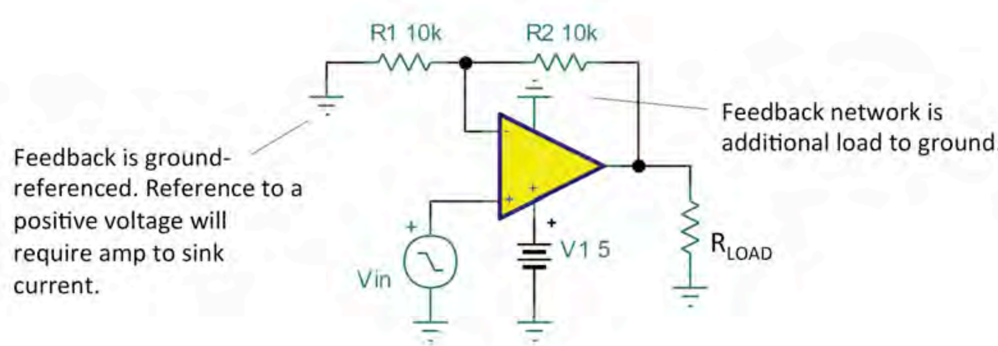


Figure 8: Single-supply op amp configuration with the feedback network referenced to ground.