Art Kay

*TI Precision Designs: Reference Design*

# *Single Supply Op Amp with True Drive to GND*

## TI Precision Designs

TI Precision Designs are analog solutions created by TI's analog experts. Reference Designs offer the theory, component selection, and simulation of useful circuits. Circuit modifications that help to meet alternate design goals are also discussed.

## Circuit Description

Single supply rail-to-rail amplifiers are commonly used in analog systems. In some cases it is important to have an amplifier output that drives very close to GND (i.e. a few microvolts). However, no amplifier can inherently drive this close to GND. This TI Precision Design shows a simple design modification that allows most standard single supply rail-to-rail amplifiers to drive very close to GND.

## Design Resources

| | |
|---|---|
| Design Archive | All Design files |
| TINA-TI™ | SPICE Simulator |
| OPA140 | Product Folder |
| OPA376 | Product Folder |

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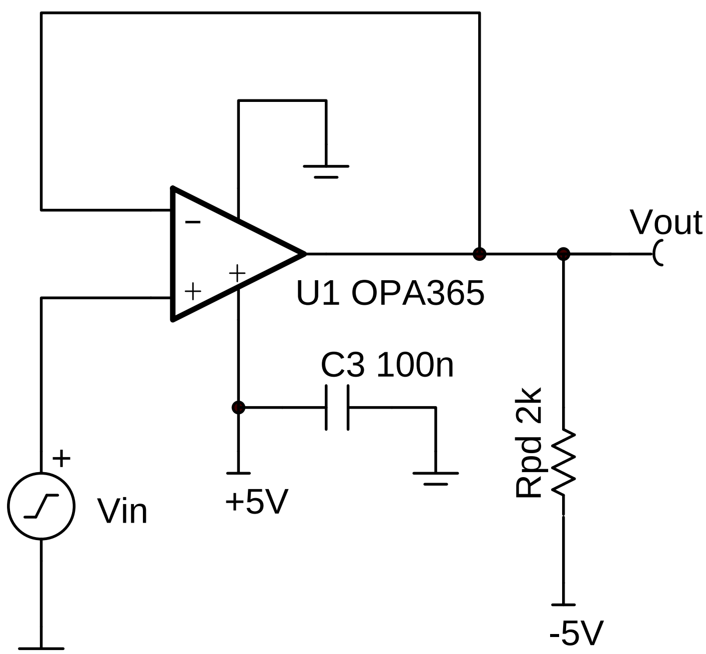


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## 1 Design Summary

The design requirements are as follows:

- Supply Voltage: +5V
- Input: 0V to 5V
- Output: 0V to 5V with accuracy at 0V

The design goals and performance are summarized in Table 1. Figure 1 depicts the difference in outputs between a traditional output connection and a pull-down to a negative supply. Note that the circuit with pull-down to negative supply can drive very close to GND (3.2µV).

**Table 1. Comparison of Design Goals, Calculations, and Simulated Performance**

| | Goal | Calculated | Simulated |
|---|---|---|---|
| **Zero Scale Error** | ±500µV | ±100µV (Typ)<br>±200µV (Max) | -3.1µV |
| **Zero Scale Error (without Pull-Down)** | -na- | 10mV (Typ)<br>20mV (Max) | 4.9mV |

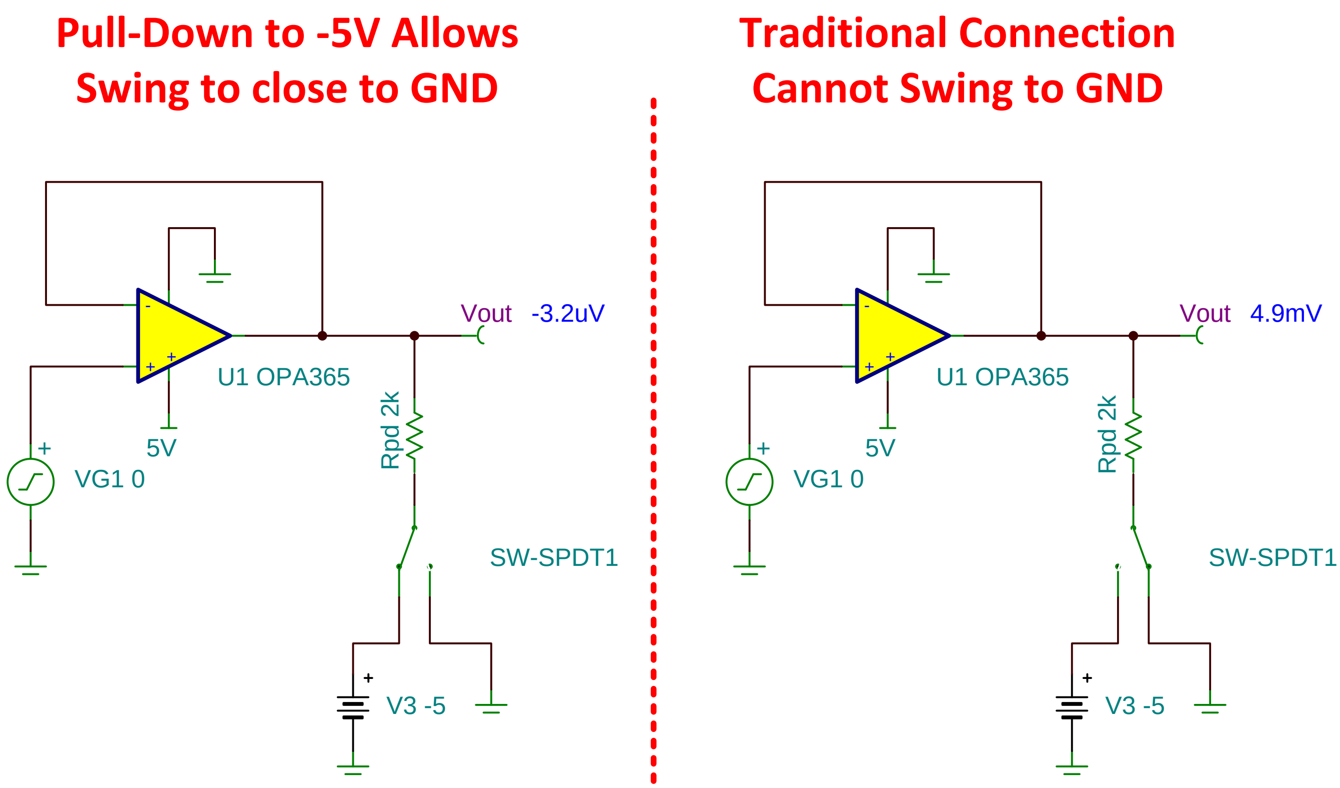


**Figure 1: Output results with pull-down to -5V and traditional output connection to GND**

# 2 Theory of Operation:

## 2.1 Normal Operation of Output Stage

Figure 2 shows the normal operation of a rail-to-rail CMOS amplifier. The quiescent current for the amplifier in this example is 760µA. One half of the quiescent current powers the input stage (see blue arrows). The other half of the quiescent current powers the output stage (see red arrows). The output is driven to the input voltage (2.5V) as expected for normal operation.

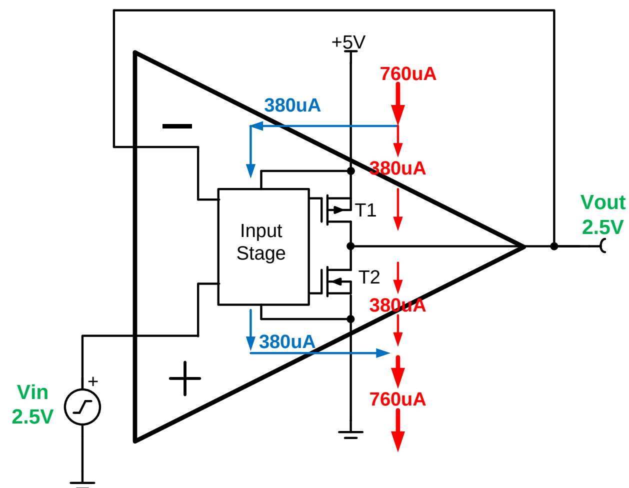


**Figure 2: Normal Operation of Output Stage**

Figure 3 shows the operation of a rail-to-rail CMOS amplifier with a zero volt input signal applied. In this example the ideal output is 0V (true GND). However, the output cannot drive to ground because the transistor T2 has a finite resistance (53Ω in this example). Remember that half of the quiescent current is biasing the output stage, so the voltage across T2 is about 20mV ($V_{T2}$ = (380µA x 53Ω = 20mV). All op amp output stages will have this limitation. The minimum output voltage will vary according to the sizing of the output stage transistors, but any practical output stage will have output swing limitations in the range of milivolts to hundreds of milivolts.

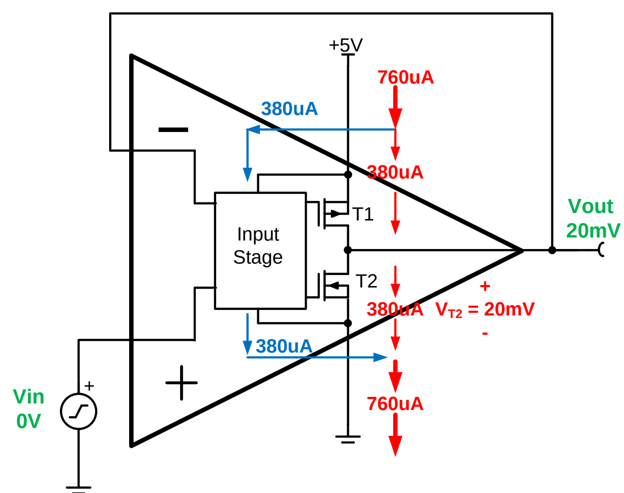


**Figure 3: Output Stage Cannot Drive to Ground**

Figure 4 shows the characteristics for the output stage transistor (T2) in this example. The figure is meant to emphasize the fact that the drain to source voltage across a transistor cannot be zero when current is flowing. In this example, the drain current is 380µA and the corresponding drain to source current is 20mV. The slope of the drain current curve determines its resistance (53Ω).

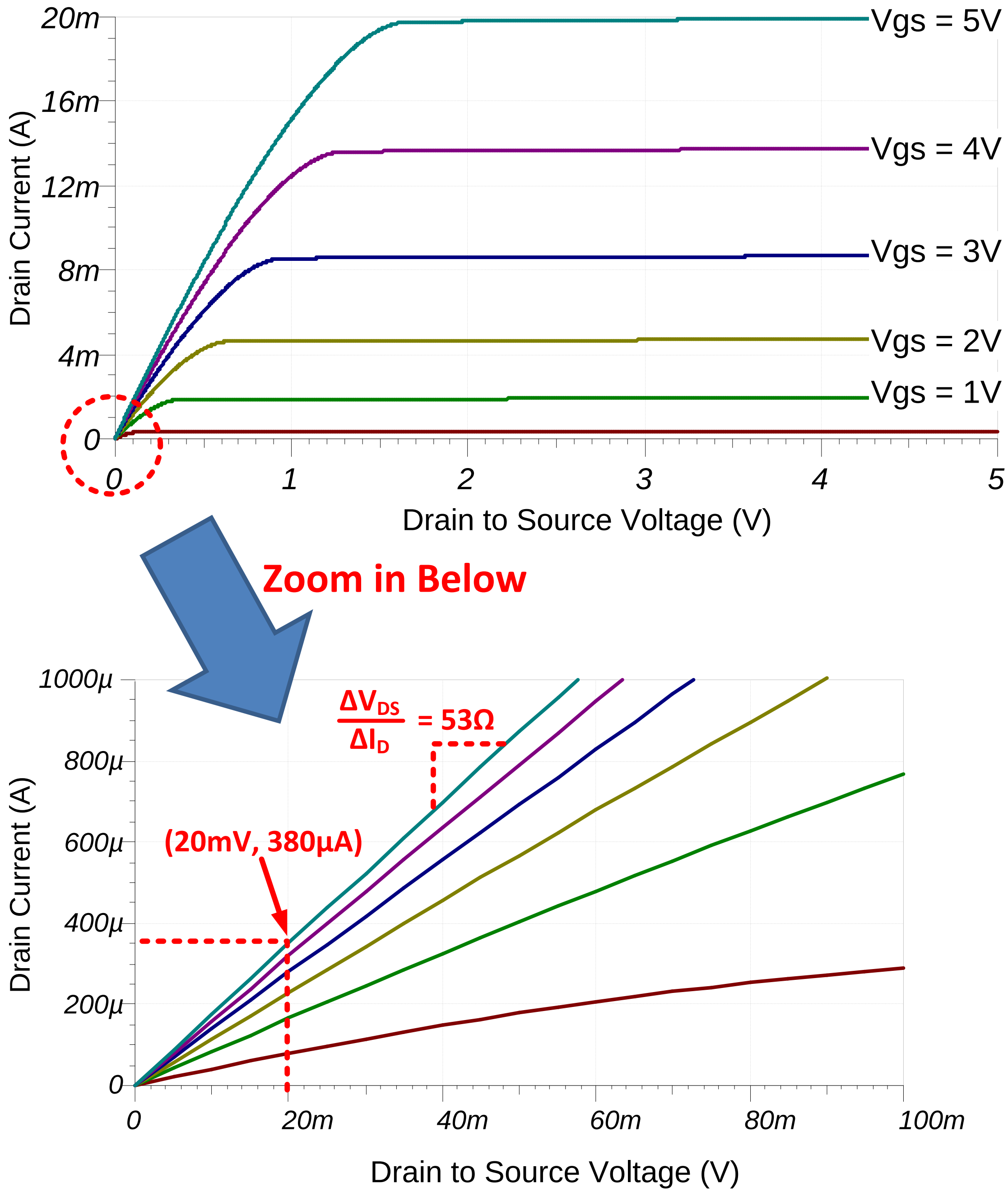


**Figure 4: Output Stage Transistor Drain to Source Voltage**

## 2.2 *Output Stage Operation with Pull-Down Resistor*

Figure 5 illustrates a simple solution that allows the output to drive down to 0V (ground). This design uses a pull-down resistor to the negative supply (RL). The pull-down resistor provides a path for the output stage current to a negative supply. When the output drives to ground, T2 will turn off allowing the output to drive to 0V. In any practical op amp configuration there will be some small error in the output voltage due to input offset voltage and other errors.

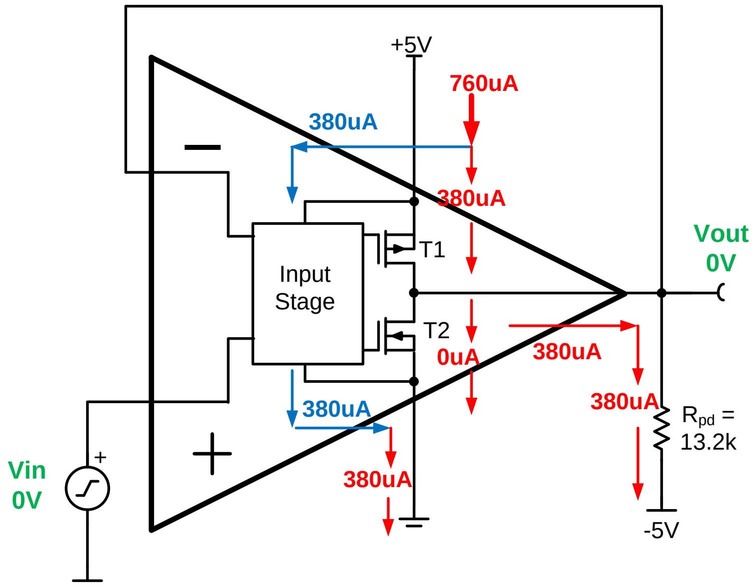


**Figure 5: Pull-Down Allows Output to Reach "True GND"**

# 3 Component Selection

## *3.1 Selecting the Pull-Down Resistor*

As a rule of thumb, the output stage consumes one half of the quiescent current of the op amp. To successfully swing to ground, the pull down resistor must sink all of the output stage current so that no current flows through the p-channel FET (T2). Table 1 is an excerpt from the OPA365 data sheet showing quiescent current, and Equation (1) shows the calculation for selecting the pull-down resistor. Table 3 provides a list of pull-down resistors that can be used for other single supply amplifiers. The pull-down resistors in Table 3 assume a -5V supply. Other negative supplies could be used (e.g. -15V); however, the value of the pull-down resistor would need to be recalculated.

**Table 2: Quiescent Current Specification from OPA365 Data Sheet**

| PARAMETERS | CONDITIONS | OPA365 | | | UNIT |
|---|---|---|---|---|---|
| | | MIN | TYP | MAX | |
| Quiescent Current Per Amplifier $I_Q$ | $I_O = 0A$ | | 4.6 | 5.0 | mA |

$$R_{pd} = \frac{-V_{pd}}{0.5I_Q} = \frac{-(-5.0V)}{0.5(4.6mA)} = 2.17k\Omega \quad (1)$$

Where
$R_{pd}$ = The pull-down resistor connected from output to negative supply.
$V_{pd}$= Pull-down supply voltage. Must be negative (current sink).
$I_Q$ = Device supply current with no load (quiescent current).

**Table 3: Pull-Down Resistor for Single Supply Amplifiers**

| Part # | Resistor Value for -5V Supply |
|---|---|
| OPA364 | 2 kΩ |
| OPA335 | 40 kΩ |
| OPA340 | 7.5 kΩ |
| OPA343 | 7.5 kΩ |
| OPA348 | 250 kΩ |
| OPA350 | 2 kΩ |
| OPA353 | 2 kΩ |
| OPA333 | 20 kΩ |

# 4 Simulation

The TINA-TI™ schematic shown in Figure 6 includes the circuit values obtained in the design process. It is important to understand that the simulation of the pull-down method will not work for all device models. Many models use behavioral blocks to match the device characters. Other models use a transistor design to model the device performance. This method can only be simulated on transistor based models. In general behavioral models are preferred because they generally converge faster with better accuracy. However, in this case a transistor based model is needed to demonstrate the interaction of the output stage and the pull-down resistor. The OPA365 is an example of a transistor based model.

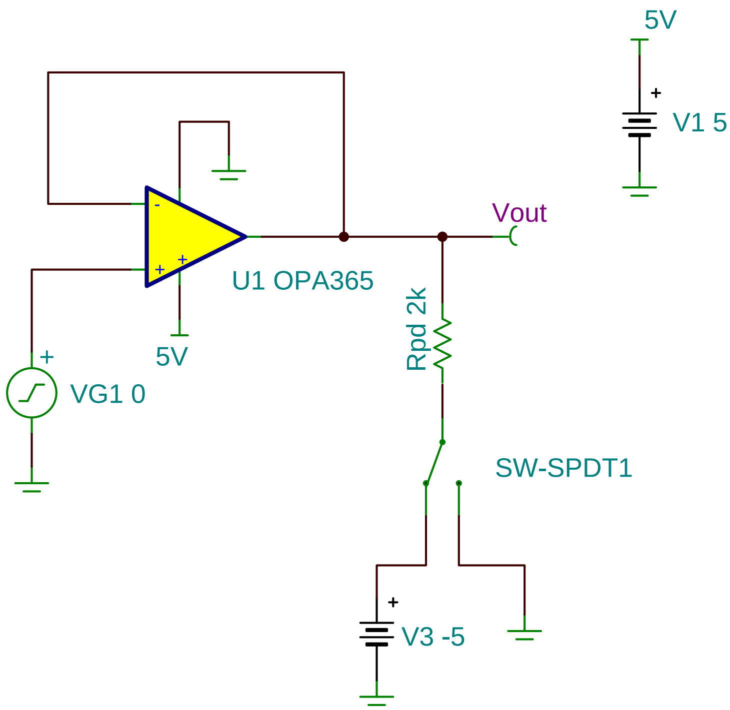


**Figure 6: TINA-TI™ Schematic**

### 4.1 Transfer Function

The result of the dc transfer function is shown in Figure 7. Of special interest is the region of the transfer function where the input is near zero volts.

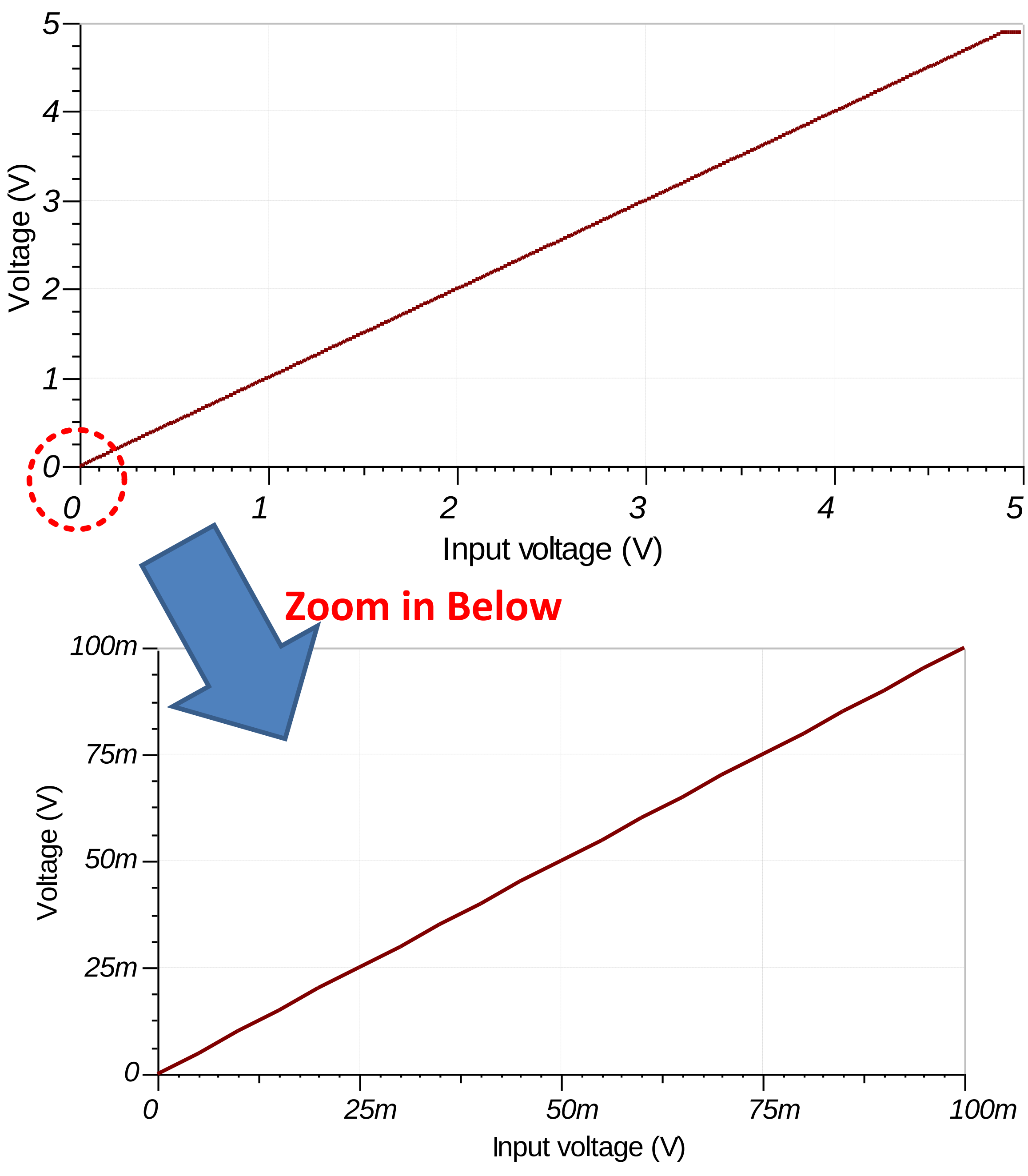


**Figure 7: Simulated Transfer Function**

### 4.2 Output with Vin = 0V

The goal of this circuit is to allow the output to drive to 0V (true GND). This simulation checks the drive to 0V for the circuit with the pull-down and the traditional circuit. The circuit with the pull-down drives very close to GND (Vout = -3.2µV). The traditional circuit swing to ground is significantly limited (Vout = 4.9mV). Figure 4 shows simulation of the output with a 0V input for both cases.

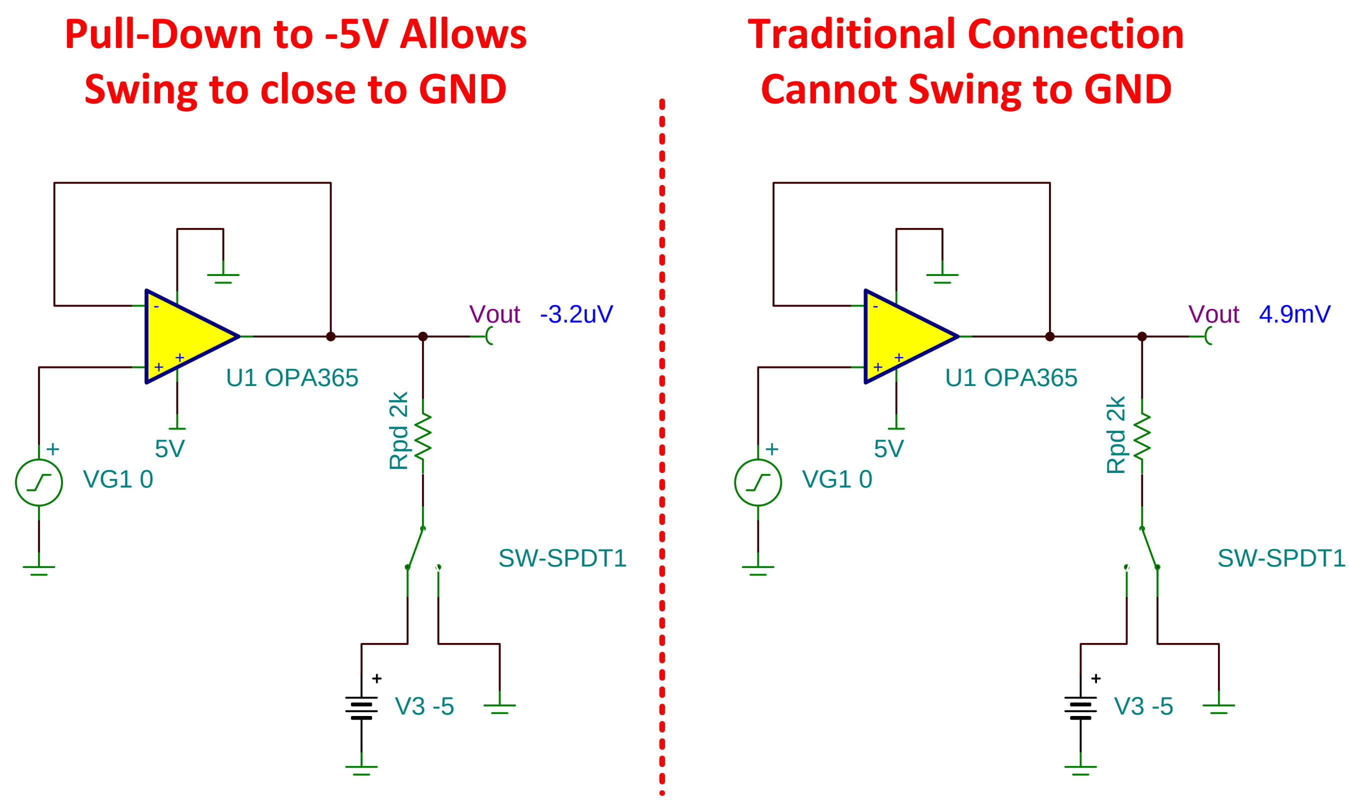


Table 4 summarizes the calculated and simulated performance of the design.

**Table 4. Comparison of Design Goals, Calculations, and Simulations**

| | Goal | Calculated | Simulated |
|---|---|---|---|
| **Zero Scale Error** | ±500µV | ±100µV (Typ)<br>±200µV (Max) | -3.1µV |
| **Zero Scale Error (without Pull-Down)** | -na- | 10mV (Typ)<br>20mV (Max) | 4.9mV |

# 5 Modifications

The method described Section 3.1 can be used with other single supply amplifiers. Table 5 provides examples of different amplifiers that can be used to achieve different design objectives.

**Table 5. Brief Comparison of 5V Single Supply Amplifiers**

| Output Amplifier | Design Objective | Vos uV | Vos Drift uV/degC | Iq uA | Voltage Noise nV/√Hz | BW MHz | SR V/uS | Approx. Price US$ / 1ku |
|---|---|---|---|---|---|---|---|---|
| OPA365 | Wide Band, Low Noise, DC Precision, No Crossover Distortion | 100 | 1 | 4600 | 4.5 | 50 | 25 | 0.65 |
| OPA313 | Low Noise, Low Iq | 500 | 2 | 50 | 25 | 1 | 0.5 | 0.3 |
| OPA333 | DC Precision, Low Iq | 2 | 0.02 | 17 | 50 | 350 | 0.16 | 0.95 |
| OPA350 | Wide Band, Low Noise, DC Precision | 150 | 4 | 5200 | 7 | 38 | 22 | 1.15 |

# 6 About the Author

Arthur Kay is an applications engineering manager at TI where he specializes in the support of amplifiers, references, and mixed signal devices. Arthur focuses a good deal on industrial applications such as bridge sensor signal conditioning. Arthur has published a book and an article series on amplifier noise. Arthur received his MSEE from Georgia Institute of Technology, and BSEE from Cleveland State University.

# 7 Acknowledgements & References

## *7.1 Acknowledgements*

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