Application Note

Ratiometric Data Acquisition of Remote Sensors When Vref and Vsupply are Unequal

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ABSTRACT

The TPS7B4255-Q1 and TPS7B4256-Q1 are low drop-out, tracking, linear regulators designed for use in automotive applications to power a remote off-board sensor which has a ratiometric output. Sensors with ratiometric outputs have an output voltage which is proportional to the supply voltage, as well as the parameter being sensed. Traditionally it is assumed that the supply voltage to the sensor is 5V and the same 5V is also used as the voltage reference to the analog to digital converter (ADC). However, in modern data acquisition systems, the voltage reference specified by the ADC is more often either 3.3V, 2.5V or 1.8V. This means the 5V full-scale signal from the sensor must be scaled down before the ADC input. Likewise, the 5V sensor supply is derived from the voltage reference and must be scaled up to 5V. The scaling creates inaccuracy in the acquisition system. This application note shows a technique to enable engineers to restore the accuracy of the acquisition by using a matched resistor divider RES11A-Q1.

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1 Introduction

Ratiometric data acquisition of remote or offboard sensors is a technique that improves overall system accuracy in the presence of errors. Figure 1-1 shows a typical ratiometric system, where a sensor supply voltage, Vsupply, is created using a reference voltage, Vref, such that Equation 1 is true:

$$\mathrm{Vsupply} = \mathrm{Vref} \tag{1}$$

The sensor outputs a voltage (Vsensor) that is proportional to Vsupply by 0 ≤ K ≤ 1 (Equation 2):

$$\mathrm{Vsensor} = \mathrm{KVsupply} = \mathrm{KVref} \tag{2}$$

Vsensor is digitized by a single-ended unipolar-input analog-to-digital converter (ADC) having N bits and supplied with Vref (Equation 3):

$$\mathrm{ADCoutput} = \frac{\mathrm{Vsensor}}{\mathrm{Vref}}\left(2^{\mathrm{N}} - 1\right) \tag{3}$$

Because Vsupply = Vref, the resulting acquisition of K by the ADC is independent of Vsupply or Vref (Equation 4):

$$\mathrm{ADCoutput} = \mathrm{K}\frac{\mathrm{Vref}}{\mathrm{Vref}}\left(2^{\mathrm{N}} - 1\right) = \mathrm{K}\left(2^{\mathrm{N}} - 1\right) \tag{4}$$

While designers normally think that an acquisition system ADC's Vref must be very precise, in a ratiometric data-acquisition system it does not necessarily have to be, as the Vref terms cancel in Equation 4.

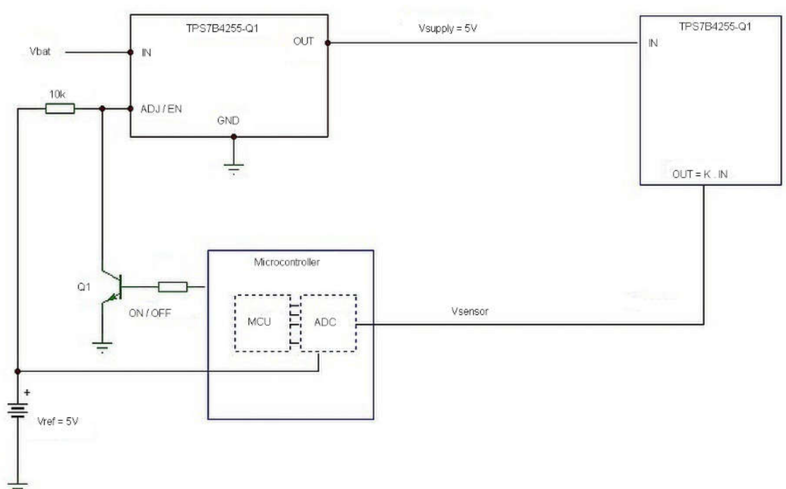

Figure 1-1. A Ratiometric Data-Acquisition System Where Vsupply = Vref

While this works well for systems where Vsupply = Vref, many systems are forced to use Vsupply ≠ Vref, introducing significant error into a ratiometric measurement system that is not cancelled. To remedy this, in this article I propose a modified system that maintains the ratiometric measurement with excellent tolerance.

2 Detailed Description

2.1 Tracker LDOs

Intrinsic to this ratiometric data-acquisition system is a tracker low-dropout linear regulator (LDO), which provides Vsupply. A tracker LDO differs from a standard LDO in that it does not have an internal Vref; instead, the tracker LDO output tracks an externally supplied Vref. The Vsupply to the sensor is often 5V, which then necessitates that the ADC Vref be also 5V, which is shown in Figure 1-1.

The TPS7B4255-Q1 tracker LDO [1] from Texas Instruments (TI) powers remote offboard sensors, and includes features to protect against faults such as short-circuit to ground or supply, blocking of reverse current, overtemperature, and reverse polarity of supply. The tracker LDO can also be disabled by pulling the ADJ/EN pin low using Q1 in Figure 1-1.

Tracker LDOs do have a tracking error, which is an offset voltage, Vos, between the ADJ pin and the FB node. This offset appears on the output and is 6mV maximum for the TPS7B4255-Q1. Even in ratiometric systems such as the one shown in Figure 1-1, Vos is not removed and remains as an error. This is because Vos changes Vsupply and therefore Vsensor, but it does not change Vref. In a 5V system, the 6mV error is a small 0.12% error.

2.2 Systems where Vsupply ≠ Vref

Offboard remote sensors often have a Vsupply requirement of 5V. In a ratiometric system, this necessitates also making Vref = 5V. Many modern ADCs cannot use a Vref = 5V, however, and instead require a Vref of a lower voltage, where Vref = 1.8V, 2.5V or 3.3V. Modern ADCs that can accept Vref = 5V are uncommon. If Vref and Vsupply are different voltages, then you must use resistor dividers (see Figure 2-1), where Vsupply = 5V and Vref = 1.8V. The TPS7B4256-Q1 tracker LDO [2] is used because it has a feedback pin and allows adjustment of the output voltage relative to its Vref.

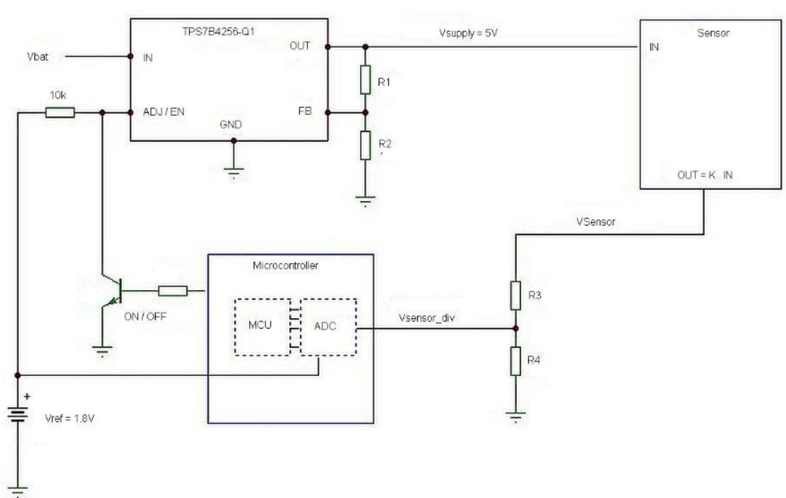

Figure 2-1. Schematic of a Data-Acquisition System Where Vsupply ≠ Vref

A resistor divider scales Vref up to Vsupply, expressed by Equation 5:

$$\text{Vsupply} = \text{Vref}\frac{\text{R1} + \text{R2}}{\text{R2}} = \text{Vref}\left(1 + \frac{\text{R1}}{\text{R2}}\right) \tag{5}$$

Another divider must scale Vsensor down to fit within the ADC's Vref range (Equation 6):

$$\text{Vsensor\_div} = \text{Vsensor}\frac{\text{R4}}{\text{R3} + \text{R4}} \tag{6}$$

The resistor dividers are not perfect, and have tolerances associated with the resistors used to make them. Resistors that possess 0.1% headline tolerance have other error terms associated with them that are not included in this headline initial tolerance, as listed in Table 2-1 [3]. The list in Table 2-1 is not exhaustive and is highly application-dependent, making the question, "What is the true accuracy of a 0.1% tolerance resistor?" surprisingly tricky to answer. Summing all terms in Table 2-1 for the absolute worst-case resistor tolerance, T, gives a T = ±0.65%.

Table 2-1. Some error terms of a 0.1% headline tolerance resistor

Error Term	Tolerance (±%)	Test Conditions
Initial tolerance	0.1	
Temperature drift	0.15	±15ppm/°C resistor over a 100°C span
Cold temperature	0.05	–55°C/2 hours
Endurance	0.1	70°C/1,000 hours of operation
Humidity	0.1	40°C/93% relative humidity/56 days
Temperature cycling	0.05	–10°C (30 minutes) to +85°C (30 minutes) × 5 cycles
Vibration	0.05	10Hz-2,000Hz/7.5 hours
Soldering	0.05	260°C/10 seconds

Greater precision resistors are available, but at greater cost, and can result in the system not being cost-effective.

The errors introduced into the system by the two resistor dividers are not cancelled and limit the accuracy of the measurement.

The Vos of the tracker LDO is multiplied by (R1 + R2)/R2 and appears on the output. For example, in a system where Vsupply = 5V and Vref = 1.8V, the output Vos max = 6mV × 5V/1.8V = 16.7mV. This error is divided back down again by R3 and R4 so that the Vos at the ADC is 6mV. However, the Vref is only 1.8V, and so the error from Vos at the ADC is 6mV/1.8V = 0.33%, which is larger compared to the case where Vref = 5V.

2.3 A Ratiometric Data Acquisition System With Vsupply ≠ Vref

To remedy this, Figure 2-2 shows the proposed ratiometric data-acquisition system where Vsupply ≠ Vref. In this example, Vsupply = 5V and Vref = 1.8V, although this approach will work if Vref is another common ADC reference voltage, such as 3.3V or 2.5V.

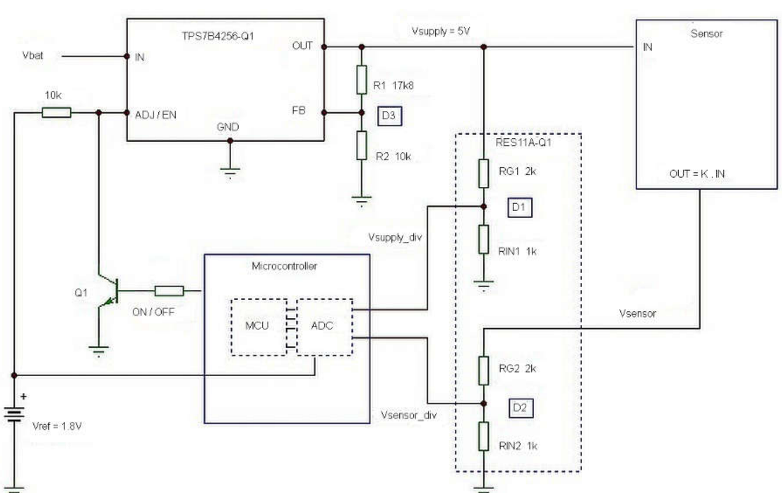

Figure 2-2. Schematic of Proposed Data-Acquisition System Where Vsupply ≠ Vref

Comparing Figure 2-2 to Figure 2-1, there is now a resistor divider, D1, which scales Vsupply down so that it can also be captured by the ADC. D1 and divider D2 scaling Vsensor are made using the RES11A-Q1 [4], which is a matched pair of dividers integrated inside the same package. There is also a non-automotive version, RES11A [5]. You can make the divider on the OUT-to-FB of the tracker LDO, D3, using standard 1% tolerance resistors, as you will see. Using the three dividers enables the ability to choose D3 to exactly scale the 1.8V Vref to be

5V for Vsupply. If you were to use one of the matched pair of dividers instead, then the ratios available does not allow for exact scaling of 1.8V to 5V. This is important because the sensor has a requirement for the accuracy of the Vsupply and you want Vsupply to sit right at the nominal supply voltage, 5V.

Figure 2-3 shows the TI RES11A (or the automotive version, RES11A-Q1), which consists of two independent resistor dividers. For each divider, RINx = 1kΩ always. There are different orderable versions of the RES11A with different RGx values, as detailed in the data sheet. Whilst the absolute tolerance of an individual resistor in the RES11A is quite loose (12% maximum), the fact the four resistors are monolithic, and are interdigitated with each other gives them excellent matching characteristics from resistor to resistor in each divider of ±0.05% maximum. The matching of the first divider to the second divider within the RES11A is also excellent, at ±0.1% maximum. Furthermore, other errors such as drift with temperature of the resistors in a divider are also matched, and result in very low divider temperature drift of $\Delta t_{Dx}/\Delta Ta$ = ±2ppm/°C drift mismatch maximum [6].

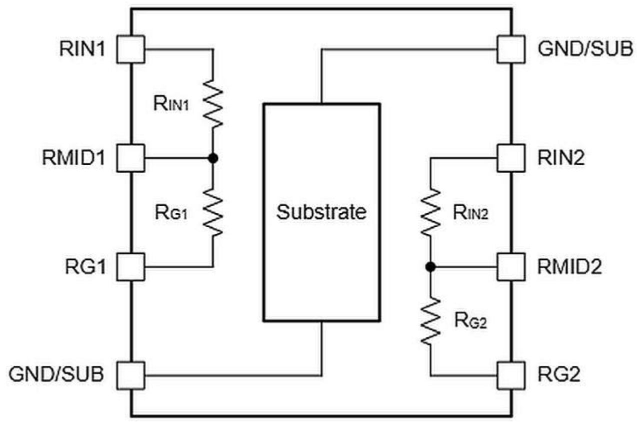

Figure 2-3. The RES11A or RES11A-Q1

Alternatively, the RES21A-Q1 [7] / RES21A [8] can be used, Table 2-2. This device is the same as the RES11A-Q1 but uses proportionally higher resistances, where RINx = 10kΩ always. Likewise, the RES31A-Q1 [9] / RES31A [10] implement RINx = 100kΩ always. These devices can withstand higher voltages than RES11A, for applications like a short-to-battery fault condition in a truck.

Table 2-2. The RES Family of Dual Resistor Dividers

Device	RINx (kΩ)	RGx / RINx Ratio
RES11A	1	1:1, 1:1.5, 1:1.667, 1:2, 1:2.5, 1:3, 1:4, 1:5, 1:9, 1:10
RES11A-Q1	1	
RES21A	10	
RES21A-Q1	10	
RES31A	100	
RES31A-Q1	100	

Depending on which Vref you need to use, Table 2-3 shows which orderable RES11A devices have a ratio that scales the 5V Vsupply and Vsensor voltages to fit within that Vref range. The RINx and RGx in a divider can connect either way around for scaling the voltage, like RIN/(RIN + RG) or like RG/(RIN + RG).

Table 2-3. Usage of the RES11A to give different ratios

Vref (V)	Device	Usage of RINx and RGx	Scales 5V to … (V)
1.8	RES11A20	RIN / (RIN + RG)	1.67
1.8	RES11A25	RIN / (RIN + RG)	1.43
2.5	RES11A10	RIN / (RIN + RG)	2.5
2.5	RES11A15	RIN / (RIN + RG)	2.0
3.3	RES11A15	RG / (RIN + RG)	3.0

Table 2-3. Usage of the RES11A to give different ratios (continued)

Vref (V)	Device	Usage of RINx and RGx	Scales 5V to … (V)
3.3	RES11A16	RG / (RIN + RG)	3.12

Let's analyze the effectiveness of the proposed measurement scheme shown in Figure 2-2.

Define the resistor-divider ratios, Dx (x = 1, 2, 3) in Equation 7, Equation 8 and Equation 9, where D1 and D2 are attenuators that scale down a voltage and D3 is a gain that scales up a voltage:

$$\mathrm{D1} = \frac{\mathrm{RIN1}}{(\mathrm{RG1} + \mathrm{RIN1})} \tag{7}$$

$$\mathrm{D2} = \frac{\mathrm{RIN2}}{(\mathrm{RG2} + \mathrm{RIN2})} \tag{8}$$

$$\mathrm{D3} = \frac{\mathrm{R1} + \mathrm{R2}}{\mathrm{R2}} = 1 + \frac{\mathrm{R1}}{\mathrm{R2}} \tag{9}$$

The output from the tracker LDO, including the Vos, is expressed by Equation 10:

$$\mathrm{Vsupply} = \mathrm{D3}(\mathrm{Vref} + \mathrm{Vos}) \tag{10}$$

Vsupply is measured by the ADC through RES11A divider D1 to give Vsupply_div according to Equation 11:

$$\mathrm{Vsupply\_div} = \mathrm{D1D3}(\mathrm{Vref} + \mathrm{Vos}) \tag{11}$$

The sensor has a gain of K (0 ≤ K ≤ 1) and the output is proportional to the supply voltage, Vsupply. The sensor output is measured by the ADC through divider D2 according to Equation 12:

$$\mathrm{Vsensor\_div} = \mathrm{KD2Vsupply} = \mathrm{KD2D3}(\mathrm{Vref} + \mathrm{Vos}) \tag{12}$$

The ADC has N bits and uses Vref. It is a single-ended, unipolar measurement with an output expressed by Equation 13:

$$\mathrm{ADCoutput} = \frac{\mathrm{Vinput}}{\mathrm{Vref}}\left(2^{\mathrm{N}} - 1\right) \tag{13}$$

where Vinput is the voltage input to the ADC.

Equation 14 and Equation 15 calculate the digitized Vsupply_div and Vsensor_div voltages as:

$$\mathrm{Vsupply\_div\_digitized} = \mathrm{D1D3}\frac{(\mathrm{Vref} + \mathrm{Vos})}{\mathrm{Vref}}\left(2^{\mathrm{N}} - 1\right) \tag{14}$$

$$\mathrm{Vsensor\_div\_digitized} = \mathrm{KD2D3}\frac{(\mathrm{Vref} + \mathrm{Vos})}{\mathrm{Vref}}\left(2^{\mathrm{N}} - 1\right) \tag{15}$$

The microcontroller takes the digitized ADC readings of Vsupply_div_digitized and Vsensor_div_digitized and computes the ratio (Equation 16):

$$\mathrm{Computedratio} = \frac{\mathrm{Vsensor\_div\_digitized}}{\mathrm{Vsupply\_div\_digitized}} = \mathrm{K}\frac{\mathrm{D2}}{\mathrm{D1}} \tag{16}$$

The computed ratio value is independent of Vref, Vsupply, Vos and D3.

That's why it's possible to make divider D3 using standard 1% tolerance resistors.

If the two resistor dividers in the RES11A (D1, D2) are perfectly matched, then D1 = D2 and ratio = K. The acquisition system is measuring only K, which is the output of the sensor from 0 to 100% of full scale. In practice, dividers D1 and D2 are not error-free; let's analyze that next.

2.4 Comparing the RES11A vs. Discrete 0.1% Tolerance Resistors

You could make dividers D1 and D2 from discrete 0.1% resistors instead of the RES11A. However, this would negatively impact the accuracy of the system, as the resistors are not matched, and the errors do not track each other.

When using discrete resistors in a single resistor divider, D, the overall tolerance of the divider ratio depends on the ratio of the divider being used [11]. In other words, the tolerance of each resistor in the divider does not simply add. Equation 17 gives the relative divider error as:

$$\frac{\Delta D}{D} = \pm 2T(1 - D) \tag{17}$$

where ΔD is the absolute error in D and T is the tolerance of each resistor in the divider.

At the limits, as D → 1, then ΔD/D → 0. Whereas as D → 0, then ΔD/D → ±2T, which is the worst-case error. In other words, the higher the attenuation of the divider, the larger the error from the resistor tolerances.

Applying this to the proposed system, which uses two resistor dividers, the computed ratio from the two ADC readings was proportional to D2/D1. Therefore, Equation 18 calculates the computed ratio including divider errors ΔD1 and ΔD2:

$$\text{Computedratioerror} = \frac{D2 + \Delta D2}{D1 + \Delta D1} \tag{18}$$

The unerrored resister-divider ratios are D1 = D2 = D; therefore, Equation 18 gives the error of the computed ratio as:

$$\text{Computedratioerror}(\%) = \pm\left[\frac{1 + 2T(1 - D)}{1 - 2T(1 - D)} - 1\right]100\% \tag{19}$$

At the limits, as D → 1, then the computed error ratio → 0. Whereas as D → 0, then the computed ratio error → ±4T, which is the worst case. Equation 19 applies when considering other errors in D2/D1, such as drift with temperature.

For the RES11A, the analysis is different. The data sheet puts limits on the accuracies of the devices that TI ships – these are the maximum values in the parametric tables. The matching tolerance, t_M, between the two dividers has a maximum value of ±1,000ppm, or ±0.1%. The temperature coefficient of each divider has a maximum value of $\Delta t_{Dx}/\Delta Ta$ = ±2ppm/°C drift mismatch. Thus, a very conservative value of the temperature drift of D2/D1 is ±4ppm/°C. The data sheet does specify the typical matching temperature coefficient of resistance between the two dividers $\Delta t_M/\Delta Ta$ = ±0.05ppm/°C, but this does not give the maximum value.

Table 2-4 compares the use of the RES11A for the D1 and D2 dividers compared to the use of discrete 0.1% tolerance resistors, like the one shown in Figure 2-1. The table compares the initial accuracies and temperature drift. The use case is for the RES11A20 to make D1 and D2; therefore D = 0.333.

Table 2-4. Comparison of Errors of D2/D1 When Using Discrete 0.1% Resistors vs. the RES11A

Parameter	RES11A Tolerance (±%)	Discrete 0.1% Resistor-Divider Tolerance (±%)
Initial tolerance	0.1	0.267
Drift with temperature	0.04	0.401

The total error from the RES11A is ±0.104% vs. ±0.668% for the discrete resistor design. As previously discussed, there are other error terms to consider for both cases. Expect that the matching of the dividers in the RES11A outperforms the discrete 0.1% resistor dividers.

2.5 TINA-TI™ Software Simulation

Figure 2-4 shows a behavioral model TINA-TI™ software simulation, running a DC analysis. The TPS7B4256-Q1 tracker LDO is modeled as a gain equal to D3. The RES11A20 is being used to scale 5V to 1.67V, where RINx = 1kΩ and RGx = 2kΩ. The output of the sensor is set to K = 0.15. To see how the system reacts in the presence of errors, D3 is increased by 3% to 2.86, Vos = –6mV, and Vref is increased by 1% to 1.818V. In Figure 2-4, the computed ratio remains at the ideal value of 0.15, which is K.

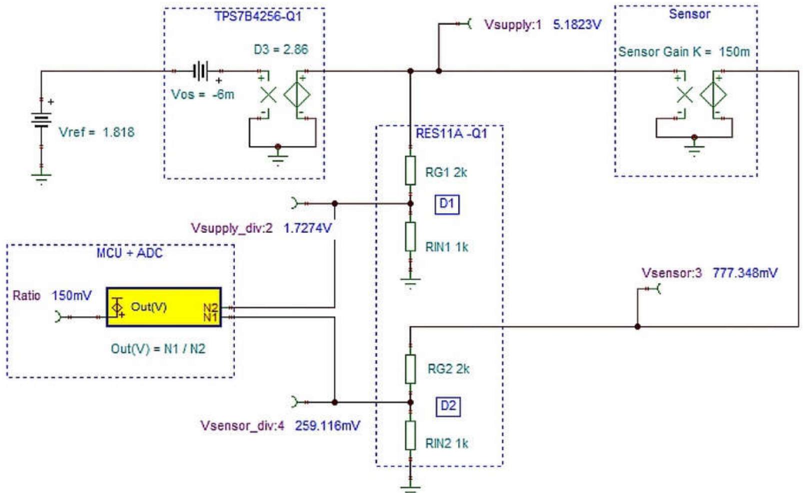

Figure 2-4. TINA-TI Software DC Analysis of a Ratiometric Data-Acquisition System Where Vsupply ≠ Vref

3 Summary

When a ratiometric data acquisition system uses a topology where Vref ≠ Vsupply, then additional errors are introduced which impact the accuracy. Using a matched pair of resistor dividers (RES11A) restores the accuracy of the acquisition system and is preferred (and lower cost) to using individual precision resistors. When comparing the error in the RES11A to the error when using 0.1% discrete resistors for D1 and D2 for initial tolerance and temperature drift, the RES11A is 6.4 times better.

4 References

1. Texas Instruments, *TPS7B4255-Q1*, product page.
2. Texas Instruments, *TPS7B4256-Q1*, product page.
3. Vishay, *MCS 0402, MCT 0603, MCU 0805, MCA 1206 - Precision*
4. Texas Instruments, *RES11A-Q1*, product page.
5. Texas Instruments, *RES11A*, product page.
6. Texas Instruments, *Navigating Precision Resistor Networks* , product overview.
7. Texas Instruments, *RES21A-Q1* , product page.
8. Texas Instruments, *RES21A*, product page.
9. Texas Instruments, *RES31A-Q1*, product page.
10. Texas Instruments, *RES31A*, product page.
11. Texas Instruments, *Effect of Resistor Tolerances on Power Supply Accuracy*, application note.

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