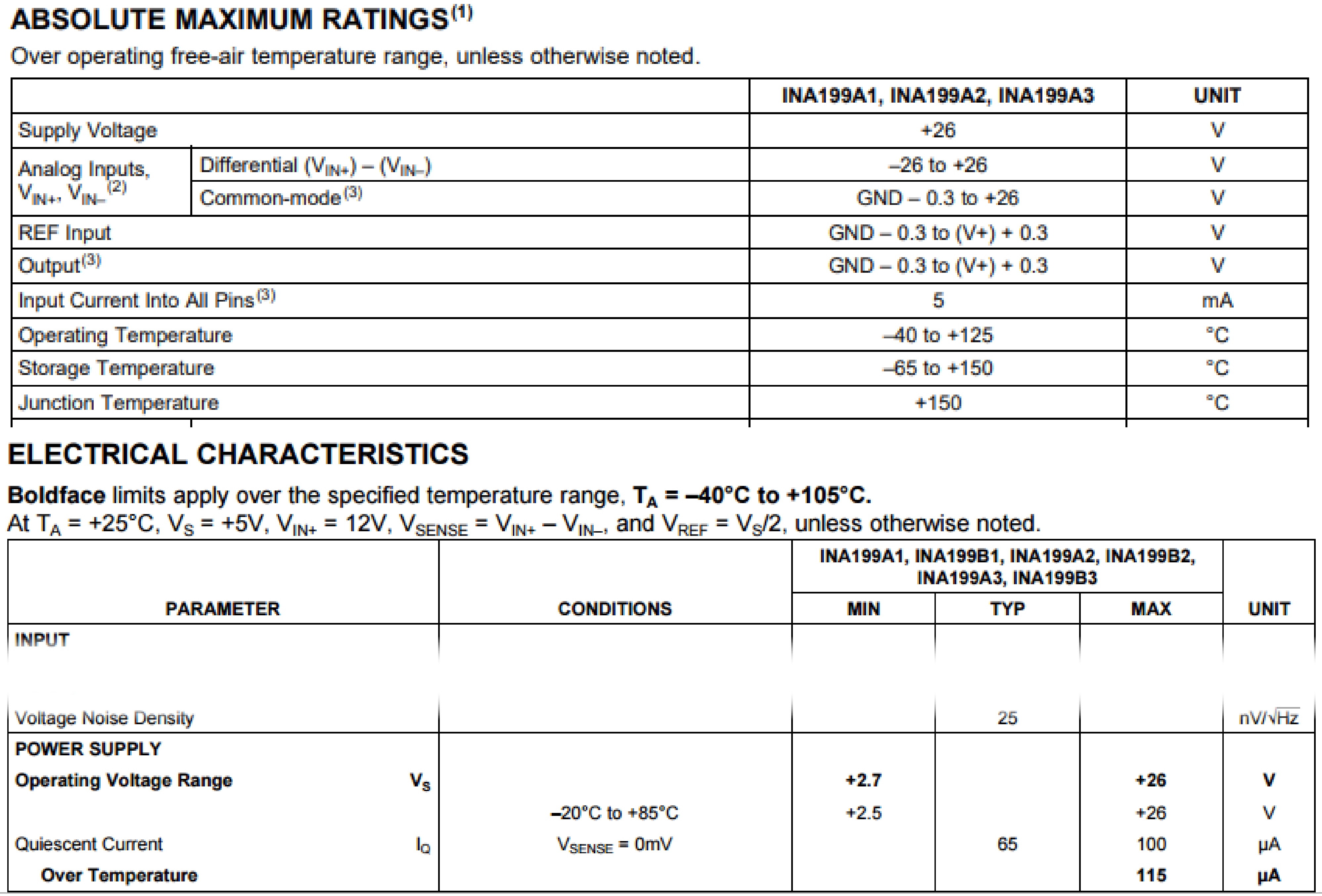
Temperature Error

TI Precision Labs – Current Sense Amplifiers

Presented and prepared by Patrick Simmons

Hello, and welcome to the TI precision labs series on current sense amplifiers. My name is Patrick Simmons, and I’m an Applications engineer in the Current Sensing & Position Sensing product line. In this video, we will focus on how temperature affects various error sources in a current shunt monitor measurement.

Temperature specifications in the datasheet



ABSOLUTE MAXIMUM RATINGS[1]

Over operating free-air temperature range, unless otherwise noted.

		INA199A1, INA199A2, INA199A3	UNIT
Supply Voltage		+26	V
Analog Inputs, V_{IN+}, V_{IN-}[2]	Differential (V_{IN+}) – (V_{IN-})	–26 to +26	V
	Common-mode[3]	GND – 0.3 to +26	V
REF Input		GND – 0.3 to (V+) + 0.3	V
Output[3]		GND – 0.3 to (V+) + 0.3	V
Input Current Into All Pins[3]		5	mA
Operating Temperature		–40 to +125	°C
Storage Temperature		–65 to +150	°C
Junction Temperature		+150	°C

ELECTRICAL CHARACTERISTICS

Boldface limits apply over the specified temperature range, **T_A = –40°C to +105°C.**
At T_A = +25°C, V_S = +5V, V_{IN+} = 12V, V_{SENSE} = V_{IN+} – V_{IN-}, and V_{REF} = V_S/2, unless otherwise noted.

PARAMETER		CONDITIONS	INA199A1, INA199B1, INA199A2, INA199B2, INA199A3, INA199B3			UNIT
			MIN	TYP	MAX	
INPUT						
Voltage Noise Density				25		nV/√Hz
POWER SUPPLY						
Operating Voltage Range	V_S		**+2.7**		**+26**	**V**
		–20°C to +85°C	+2.5		+26	V
Quiescent Current	I_Q	V_{SENSE} = 0mV		65	100	µA
Over Temperature					**115**	**µA**

If we look at any given datasheet, we can see information relating to temperature scattered throughout several tables in the datasheet. The first table it is typically presented in is the absolute maximum ratings table. There you can see what operating and storage temperatures it can survive before degrading or failing. The range you find in this table may be wider depending on whether you looking at a typical commercial device, automotive qualified, military grade, or space grade device.

Beyond the abs max table, you will see the electrical characteristics table. Above you should see a temperature or temperature range over which the majority of the table specification measurements were collected. For specifications collected over a different range, you will see some temperature range specified in the conditions column.

Error sources affected by temperature

Root-sum-square (RSS) total error – more realistic

$$\varsigma_{RSS}(\%) \approx \sqrt{e_{Vos}{}^2 + e_{CMRR}{}^2 + e_{PSRR}{}^2 + e_{Gain\_error}{}^2 + e_{Linearity}{}^2 + e_{Shunt\_tolerance}{}^2 + e_{Bias\_current}{}^2 + e_{Other}{}^2}$$

- Gain error
- Shunt tolerance
- Input offset voltage error

PPM definition

$$PPM = \frac{1}{1000000} \longrightarrow \%PPM = \frac{100\%}{1000000} = \frac{1}{10000}\%$$

In previous videos, we introduced the root-sum-of-squares, RSS, which is a total error equation for current sense amplifier circuits, as shown here. This video focuses on error related to temperature. A quick glance at the formula reveals that there is no specific term called e_temperature. So where is the temperature error contribution then?

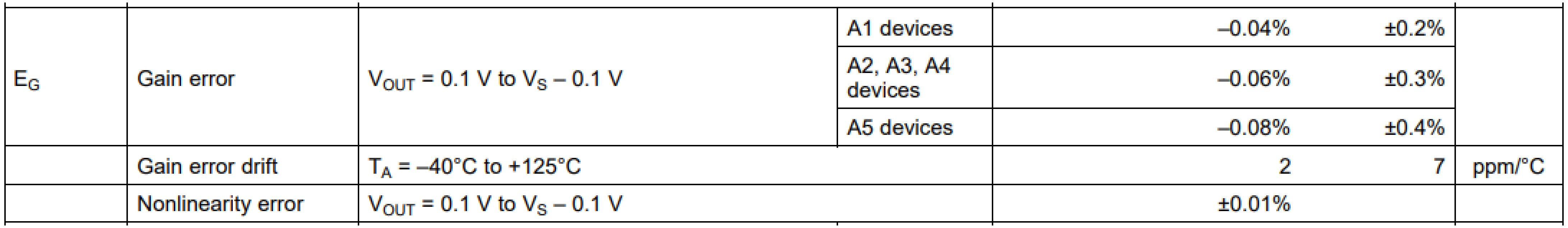
Turns out that the impact of temperature needs to be included in the calculation of multiple error terms founds in the RSS formula. The relevant error terms include gain error, shunt tolerance, and input offset voltage error.

When incorporating temperature in these error calculations, you often will need to use a unit called parts per million, ppm.

Ppm is an unit-less coefficient adopted by the scientific community for expressing a very small fraction, such as 5 ppm would equate to 5 units out of million units

As we often calculate percentages for our error sources, we simplify our equations involving a ppm coefficient to being multiplied by 1 over ten thousand as shown on the right.

Gain error over temperature



E_G	Gain error	V_{OUT} = 0.1 V to V_S – 0.1 V	A1 devices	–0.04%	±0.2%	
			A2, A3, A4 devices	–0.06%	±0.3%	
			A5 devices	–0.08%	±0.4%	
	Gain error drift	T_A = –40°C to +125°C		2	7	ppm/°C
	Nonlinearity error	V_{OUT} = 0.1 V to V_S – 0.1 V		±0.01%		

- $e_{Gain}\ (\%) \approx e_{Gain\_Error} + e_{Linearity} + e_{Shunt\_Tolerance}$
- Drift in linearity typically small and insignificant
- Shunt tolerance contribution calculated separately

Gain error (including drift)

$$e_{Gain\_Error} = Gain\ Error\% + \left(\frac{Gain\ Error\ drift\left(\frac{1}{°C}\right)}{10{,}000} \times \Delta T\right)\%$$

So within the RSS formula, it’s possible to generically lump all terms into two categories. One category is gain error and the other is voltage offset.

The gain subset includes specifications for gain error, nonlinearity, and shunt tolerance. Typically the non linearity error is quite small and the magnitude it drifts is even more negligible and therefore is not typically provided in the datasheet. As for the shunt tolerance, this specification is typically found on a separated datasheet as only a few current shunt monitors include and internal shunt.

For gain error at room temperature you would just need to pluck the max specification from the datasheet and plug into the RSS formula. However, if your temperature is not 25 degrees Celsius, you will need to incorporate the gain error drift coefficient as shown in the formula here. Delta T corresponds to how far the temperature is from 25C or the typical temperature stated right above the electrical characteristics table.

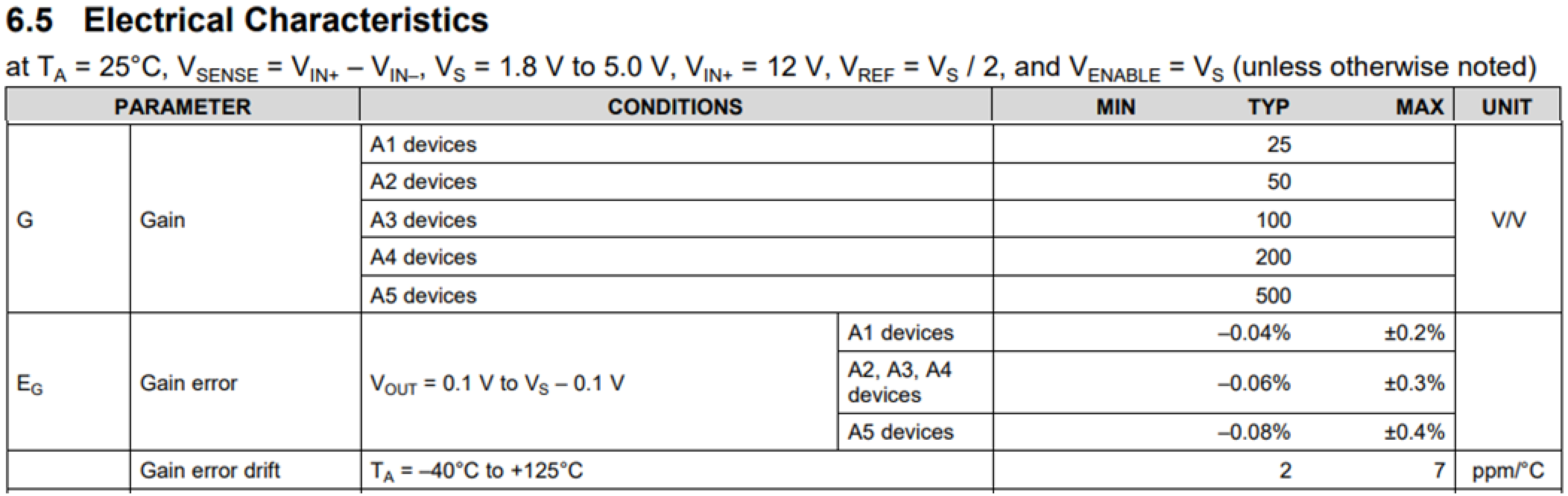
Gain error example

Conditions

$$G = 500\ \frac{V}{V}$$

$$E_G = \pm 0.4\%$$

$$E_G\ drift = 7\,\frac{ppm}{°C}$$



6.5 Electrical Characteristics

at $T_A = 25°C$, $V_{SENSE} = V_{IN+} - V_{IN-}$, $V_S = 1.8$ V to 5.0 V, $V_{IN+} = 12$ V, $V_{REF} = V_S / 2$, and $V_{ENABLE} = V_S$ (unless otherwise noted)

PARAMETER		CONDITIONS		MIN	TYP	MAX	UNIT
G	Gain	A1 devices			25		V/V
		A2 devices			50		
		A3 devices			100		
		A4 devices			200		
		A5 devices			500		
E_G	Gain error	$V_{OUT} = 0.1$ V to $V_S - 0.1$ V	A1 devices		–0.04%	±0.2%	
			A2, A3, A4 devices		–0.06%	±0.3%	
			A5 devices		–0.08%	±0.4%	
	Gain error drift	$T_A = -40°C$ to $+125°C$			2	7	ppm/°C

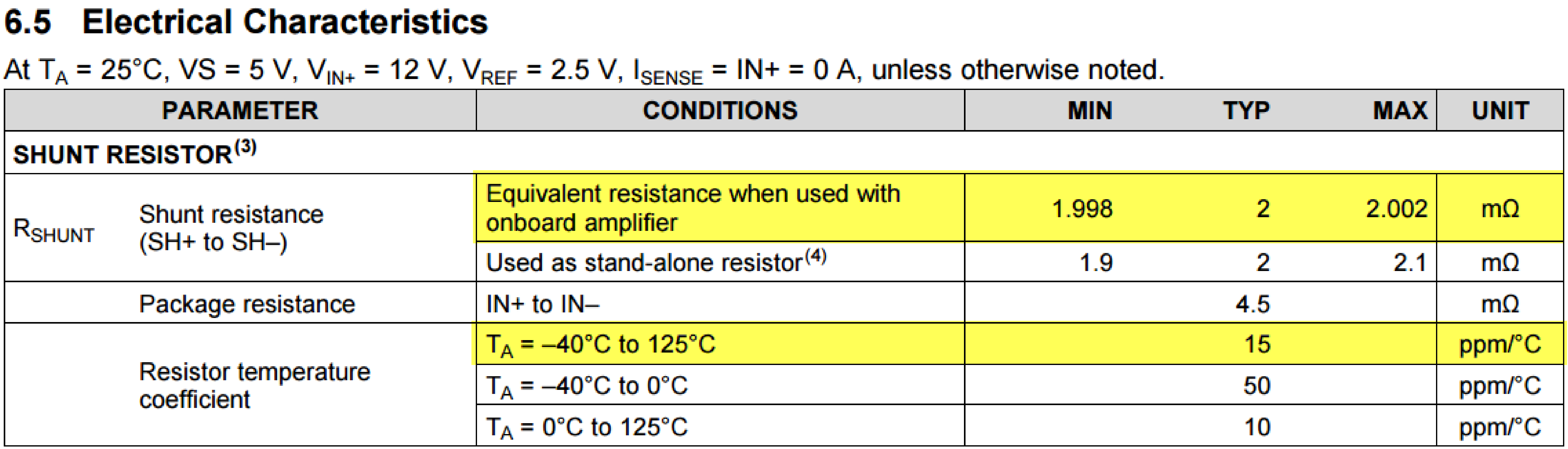
Calculations

$$e_{Gain\_Error} = Gain\ Error\% + \left(\frac{Gain\ Error\ drift\left(\frac{1}{°C}\right)}{10{,}000} \times \Delta T\right)\% = 0.4\% + \left(\frac{7}{10000} \times (105 - 25)°C\right)\% = 0.456\%$$

Lets work an example! We plan on our device operating in environment with a max of 105 degrees C and we need a 500V/V gain. So, we decided to use the following device. From the electrical characteristics table, we see that the gain error at 25C is +-0.4% and we see that the max gain error drift is 7 ppm/°C. If plug our operating conditions and the device specifications into the gain error equation we get 0.456%.

If this yields more error than you can stomach. You could consider heat sinks… or you could choose a different device. When choosing a different device you will often find that a better drift specification often accompanies a better gain error specification.

Shunt tolerance over temperature

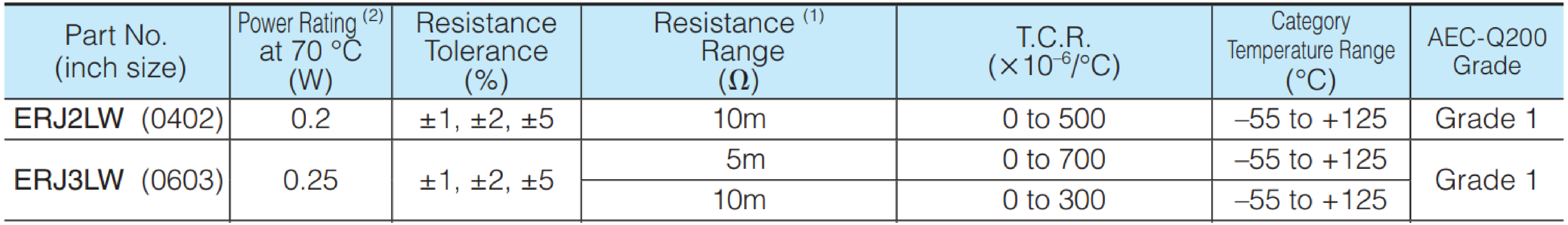


6.5 Electrical Characteristics

At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
SHUNT RESISTOR(3)						
R_{SHUNT}	Shunt resistance (SH+ to SH–)	Equivalent resistance when used with onboard amplifier	1.998	2	2.002	mΩ
		Used as stand-alone resistor(4)	1.9	2	2.1	mΩ
	Package resistance	IN+ to IN–		4.5		mΩ
	Resistor temperature coefficient	T_A = –40°C to 125°C		15		ppm/°C
		T_A = –40°C to 0°C		50		ppm/°C
		T_A = 0°C to 125°C		10		ppm/°C

$$e_{shunt\_tolerance} = \frac{\left|R_{shunt\ limit} - R_{shunt\ typ}\right|}{R_{shunt\ typ}} \times 100\% = \frac{|1.998m\Omega - 2m\Omega|}{2m\Omega} \times 100\% = 0.1\%$$



Part No. (inch size)	Power Rating (2) at 70 °C (W)	Resistance Tolerance (%)	Resistance (1) Range (Ω)	T.C.R. ($\times 10^{-6}$/°C)	Category Temperature Range (°C)	AEC-Q200 Grade
ERJ2LW (0402)	0.2	±1, ±2, ±5	10m	0 to 500	–55 to +125	Grade 1
ERJ3LW (0603)	0.25	±1, ±2, ±5	5m	0 to 700	–55 to +125	Grade 1
			10m	0 to 300	–55 to +125	

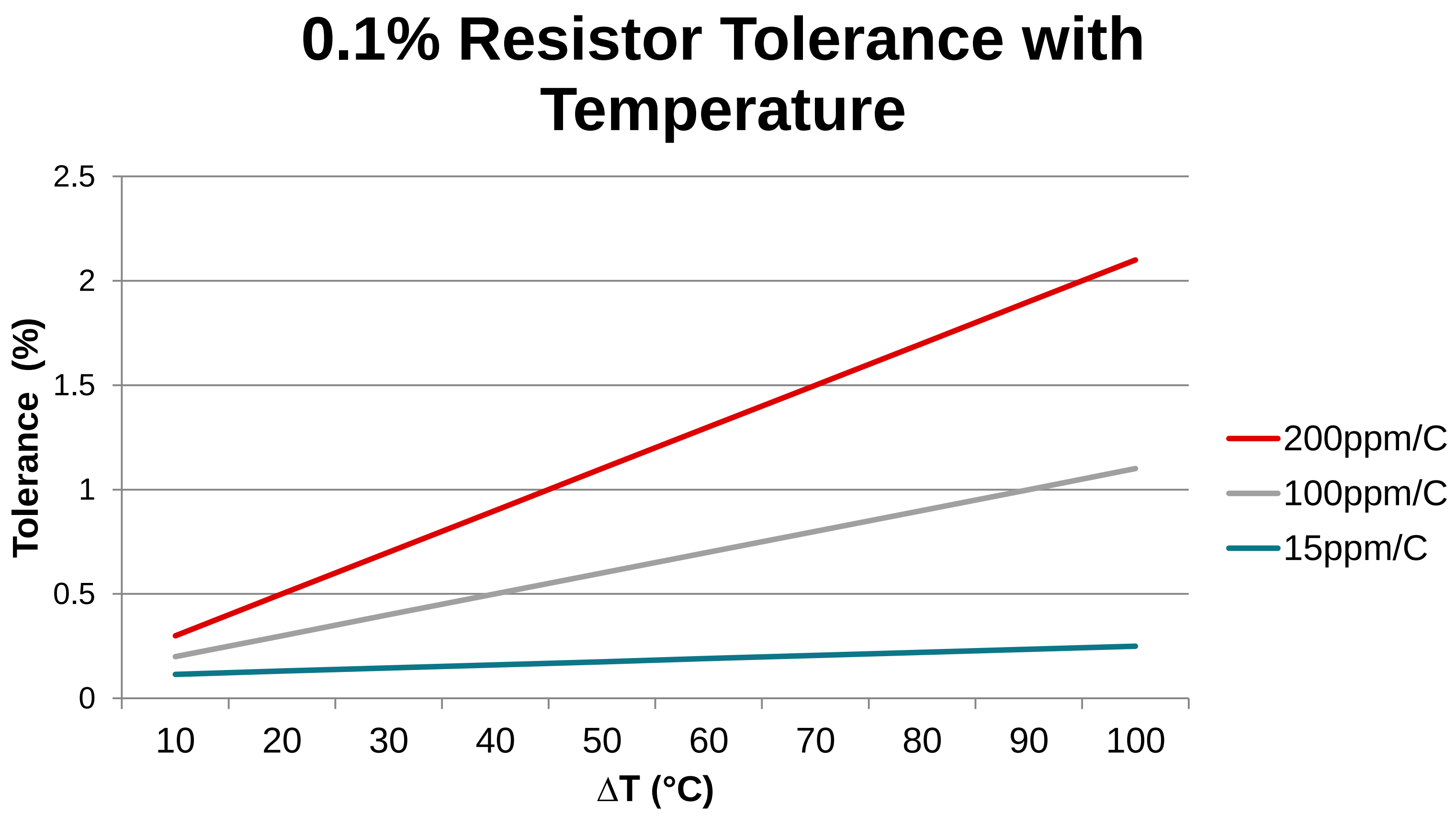
As we stated before. The shunt resistor tolerance will not typically be found in our current shunt monitor datasheets, as most current shunt monitors do not include an internal shunt. However, there are a few devices that do feature an internal shunt. One device in particular is the INA250, shown in the upper table. In this table we see that the INA250 internal shunt can range from 1.9998mohm to 2.002mohm. To get the shunt tolerance in percent form we would simply take the absolute value of the typical subtracted from either the min or max. We would then take quotient of that value divided by the typical. Lastly we would multiply by 100% to get the percent value.

In the second table is an example extracted from a datasheet of a resistor manufacturer, Panasonic. From their table we see a given shunt might come in a variety of tolerances with different drift performance. In their table, the temperature coefficient is under T.C.R and 10^-6 is substituted in for what we would normally have as ppm.

Shunt tolerance over temperature

Shunt tolerance with temperature calculation

$$e_{R_{SHUNT}} = Shunt_{\%\ at\ 25C} + Temp\ Co \times \Delta T \times 100\%$$



Shunt tolerance very simply is a linear adder – a 1% shunt resistor will contribute 1% error while a 0.1% shunt will only contribute 0.1% error. The trade-offs on shunt tolerance are the physical size of the shunt resistor and the cost.

That said, the real “gotcha” with most shunt resistors is the temperature coefficient! Shunts with 1% or even 0.5% tolerance are easily found and can be priced very reasonable. However, when you need to drive stability over temperature is where the shunt becomes expensive.

The additional error is very easy to calculate – just like the additional error seen with gain.

So to see the impact of different drift coefficients, lets look at an example with some coefficients you may run across in a part distributors website. Here we look at 0.1% at room temperature resistors. One has a drift coefficient of 15 ppm/C, another at 100ppm/C, and the last at 200 ppm/C. We expect the ambient temperature range to fluctuate by as much as 100 degrees Celsius.

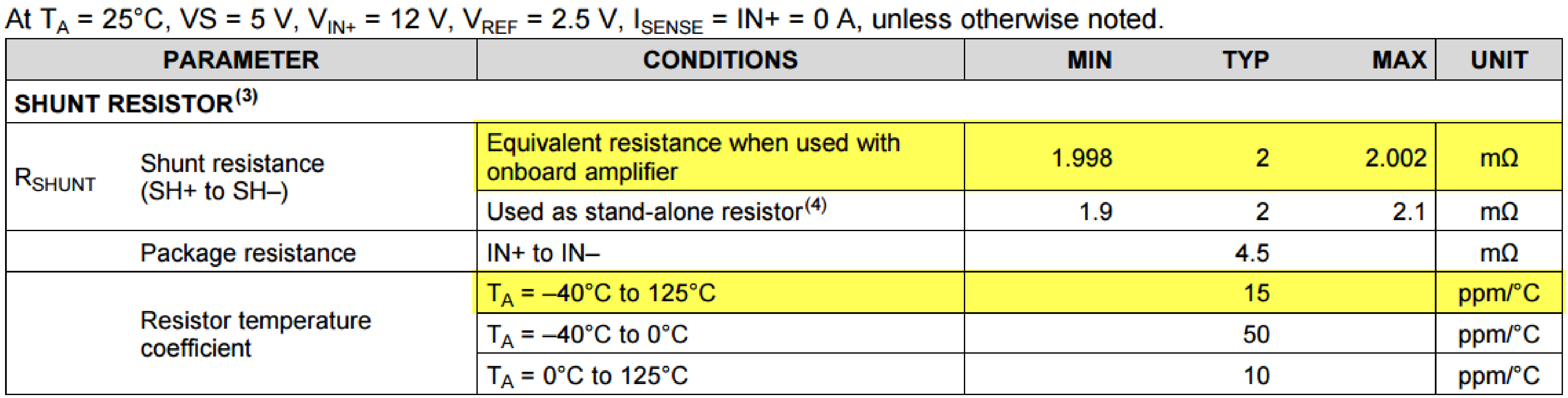
The max operating temperature for 200 PPM resistor will result in an nearly an additional 2% error while the 15PPM resistor adds 0.15% to the initial 0.1% error. What becomes evident is that for high accuracy shunts, the temperature coefficient can become the dominant error source.

Shunt tolerance example

Conditions:

$$T = 125°C$$

$$R_{Shunt}(typ) = 2\ \mathrm{m\Omega}$$



At T_A = 25°C, VS = 5 V, V_{IN+} = 12 V, V_{REF} = 2.5 V, I_{SENSE} = IN+ = 0 A, unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
SHUNT RESISTOR[3]						
R_{SHUNT}	Shunt resistance (SH+ to SH–)	Equivalent resistance when used with onboard amplifier	1.998	2	2.002	mΩ
		Used as stand-alone resistor[4]	1.9	2	2.1	mΩ
	Package resistance	IN+ to IN–		4.5		mΩ
	Resistor temperature coefficient	T_A = –40°C to 125°C		15		ppm/°C
		T_A = –40°C to 0°C		50		ppm/°C
		T_A = 0°C to 125°C		10		ppm/°C

Shunt tolerance at 25°C

$$e_{R_{Shunt}} = \frac{R_{Shunt\_max} - R_{Shunt\_typ}}{R_{Shunt\_typ}} \times 100\% = \frac{2.002m\Omega - 2m\Omega}{2m\Omega} \times 100\% = 0.1\%$$

Shunt tolerance at 125°C

$$e_{R_{Shunt}} = Shunt_{\%\ at\ 25C} + Temp\ Co \times \Delta T \times 100\% = 0.1\% + \left(\frac{15°C}{1000000} \times 100°C\right) \times 100\% = 0.35\%$$

As we do have some devices with an internal shunt, lets work an example. We will use the INA250 and we will assume that the device will be subjected to the max recommended operating temperature of 125C.

Using the shunt tolerance equation we had before, we know the shunt tolerance error at 25C is 0.1%. When we account for the drift from the temperature at 125C, we see that the error becomes 0.35%

When we recall from the last slide that external shunts can significantly increase the error as the temp coefficient increase, we can understand the value a device like the INA250 provides. The internal shunt provides good trace matching, reduced board space, and most importantly minimal drift across temperature.

Copper trace as a shunt

NOT RECOMMENDED for high precision applications

- Subject to board manufacturing tolerance
- Copper resistance highly sensitive to temperature
- Localized temperature influenced by load

$$R = R_{Ref} \times (1 + Temp\ Co \times (T_{MAX} - T_{REF}))$$

One shunt implementation that may be tempting to try is a copper board trace. For applications in which precision is paramount, we highly recommend against this approach. The primary reasons are as follows.

The board manufacturer does not have perfect manufacturing capabilities and therefore the sample of boards produced might have much looser tolerances than what can be accepted.

Second, copper is highly sensitive to temperature. Consequently, as the ambient temperature changes for your system, the trace shunt may see large changes in resistance.

Related to this, is the third reason. The very current you pass through the trace will produce heat in either the trace or in adjacent components which then leads to changes in your resistance.

Copper trace as a shunt example

Conditions:

$$T_{REF} = 20°C$$
$$T_{MAX} = 60°C$$
$$Temp\ Co_{Cu\ at\ 20°C} = 0.00393$$
$$R_{ref} = 0.001\Omega$$

Cu shunt resistance at 60°C

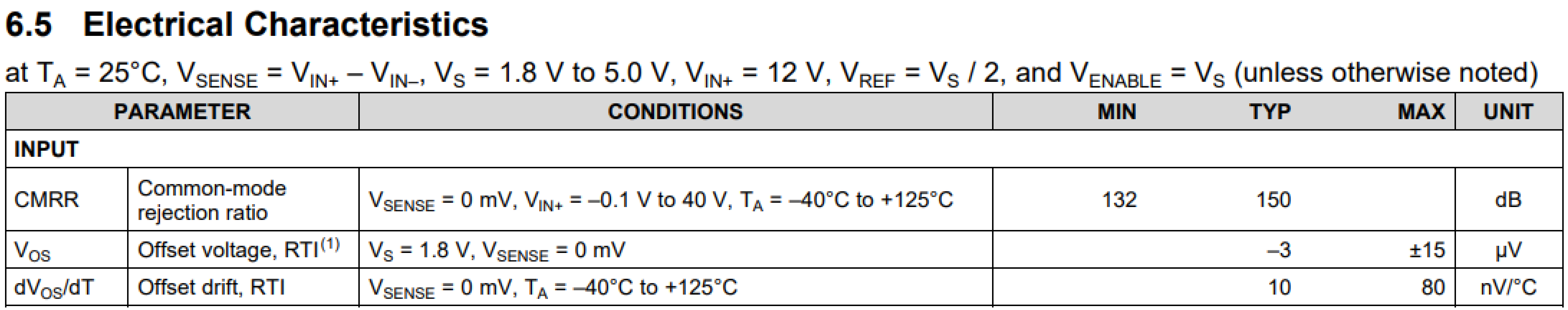
$$R = 0.001\Omega \times (1 + 0.00393 \times (60°C - 20°C)) = 0.001157$$

Cu shunt error at 60°C

$$e_{shunt} = \left(\frac{0.001157 - 0.001}{0.001}\right) = 15.72\%$$

As you might question how significant the impact of temperature on a copper trace is, lets work an example. Opposed to the example of the internal shunt before, I will use a relatively smaller temperature change of just 40C. The copper resistance equation uses 20C instead of 25C as the reference Temperature. Our expected max temperature is 60C. The typical copper coefficient for this equation is 0.00393. If our resistance is 1mohm at 20C, we can expect it to be 1.157mohm at 60C. This drift shifts the resistance such that it now has an error 15.72%. This does not even include the error introduced from manufacturing.

Offset error over temperature



6.5 Electrical Characteristics

at T_A = 25°C, $V_{SENSE} = V_{IN+} - V_{IN-}$, V_S = 1.8 V to 5.0 V, V_{IN+} = 12 V, $V_{REF} = V_S / 2$, and $V_{ENABLE} = V_S$ (unless otherwise noted)

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
INPUT						
CMRR	Common-mode rejection ratio	V_{SENSE} = 0 mV, V_{IN+} = –0.1 V to 40 V, T_A = –40°C to +125°C	132	150		dB
V_{OS}	Offset voltage, RTI(1)	V_S = 1.8 V, V_{SENSE} = 0 mV		–3	±15	μV
dV_{OS}/dT	Offset drift, RTI	V_{SENSE} = 0 mV, T_A = –40°C to +125°C		10	80	nV/°C

- Offset specified at room, $T_A = 25°C$
- Drift component specified separately

Offset voltage (including drift)

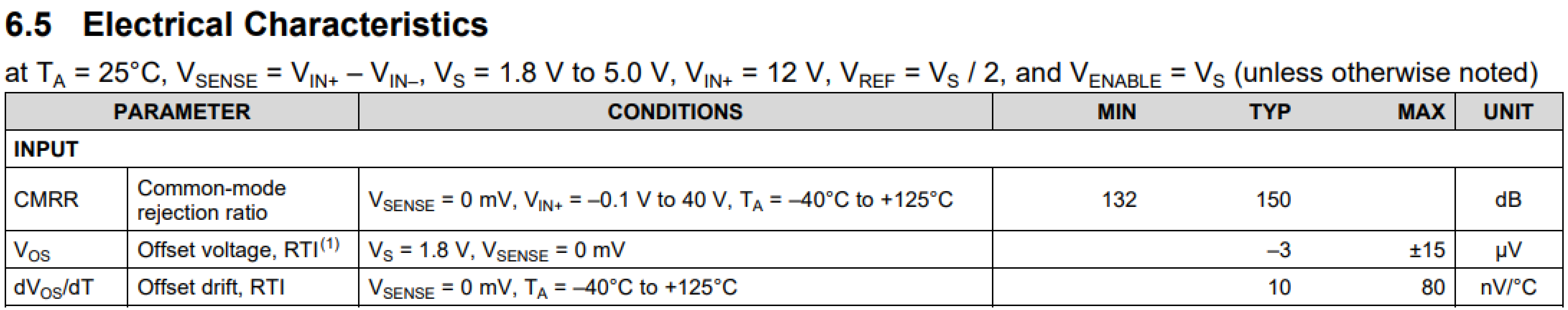
$$V_{OS(MAX)} = V_{OS(SPEC)} + \left(\frac{\Delta V_{OS}}{\Delta T} \times |T_{MAX} - T_{SPEC}|\right)$$

Now lets cover the last error source influenced by temperature that is typically specified in the datasheet, voltage offset error referred to the input. Unlike the specifications from before, you will notice that the offset drift is typically specified in nano Volts per degree C. This is because the entire change in offset over temperature needs to be compared to Vsense.

Offset error over temperature example

Conditions

$$T_{MAX} = 85°C$$
$$T_{SPEC} = 25°C$$
$$V_{Sense\ min} = 10mV$$
$$\frac{\Delta V_{OS}}{\Delta T} = 80nV/°C$$



6.5 Electrical Characteristics

at T_A = 25°C, V_{SENSE} = V_{IN+} – $V_{IN–}$, V_S = 1.8 V to 5.0 V, V_{IN+} = 12 V, V_{REF} = V_S / 2, and V_{ENABLE} = V_S (unless otherwise noted)

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
INPUT						
CMRR	Common-mode rejection ratio	V_{SENSE} = 0 mV, V_{IN+} = –0.1 V to 40 V, T_A = –40°C to +125°C	132	150		dB
V_{OS}	Offset voltage, RTI[1]	V_S = 1.8 V, V_{SENSE} = 0 mV		–3	±15	µV
dV_{OS}/dT	Offset drift, RTI	V_{SENSE} = 0 mV, T_A = –40°C to +125°C		10	80	nV/°C

Calculations

$$V_{OS(MAX)} = V_{OS(SPEC)} + \left(\frac{\Delta V_{OS}}{\Delta T} \times |T_{MAX} - T_{SPEC}|\right) = 15\mu V + \left(\frac{80nV}{°C} \times |85°C - 25°C|\right) = 19.8\mu V$$

$$e_{V_{OS}} = \frac{V_{OS}}{V_{Sense}} \times 100\% = \frac{19.8\mu V}{10mV} \times 100\% = 0.198\%$$

$$\frac{V_{OS(MAX)}}{V_{OS(SPEC)}} = \frac{19.8}{15} = 1.32$$

- Offset error increased by **1.32x**

Now lets work an offset drift example. Because of the low offset voltage specification we decide to work with the INA190, which has an offset drift of 80 nV per degree C. Our max operating temperature is expected to be 85C. Minimum voltage across the shunt is expected to be 10mV.

Plugging the conditions and specification we have into the voltage offset equation equals 19.8uV. If we take the ratio of the voltage offset to vsense and multiple by 100%, we get 0.198%. Well under 1% even after a the offset increased by 1.32x.

Temperature error summary

- Primary error sources influenced by temperature include:
  - Gain error
  - Shunt tolerance
  - Input offset voltage, RTI
- Drift is specified in PPM/°C, or in V /°C
- Do not use copper trace shunts for precision applications involving wide temperature ranges.

Let’s take a minute to summarize what we learned in this video.

Temperature affects gain error, shunt tolerance, and input offset voltage

Drift specifications often have either PPM or some unit of V per degree C.

Lastly avoid copper traces for precision measurements.

To find more current sense amplifier technical resources and search products, visit ti.com/currentsense

That concludes this video - thank you for watching! Please try the quiz to check your understanding of the content.

For more information and videos on current sense amplifiers please visit ti.com/currentsense.

Temperature Error

TI Precision Labs – Current Sense Amplifiers

Quiz

Temperature error – quiz

1. What are the three typical primary error sources to analyze for precision measurements over a broad operating temperature range?
   a) RTI voltage offset, input bias, and gain error
   b) CMRR, input bias, and gain error
   c) Linearity, shunt tolerance, and PSRR
   d) RTI voltage offset, shunt tolerance, and gain error

2. In the Electrical Characteristics, EC, table of the INA226, the shunt offset voltage RTI, is defined at what temperature?
   a) -40°C to 105°C
   b) -40°C to 125°C
   c) 25°C

Temperature error – quiz

3. If gain error increases by 2 on a scale of 5000 for every 5°C change in temperature, how would it be defined in the EC table?

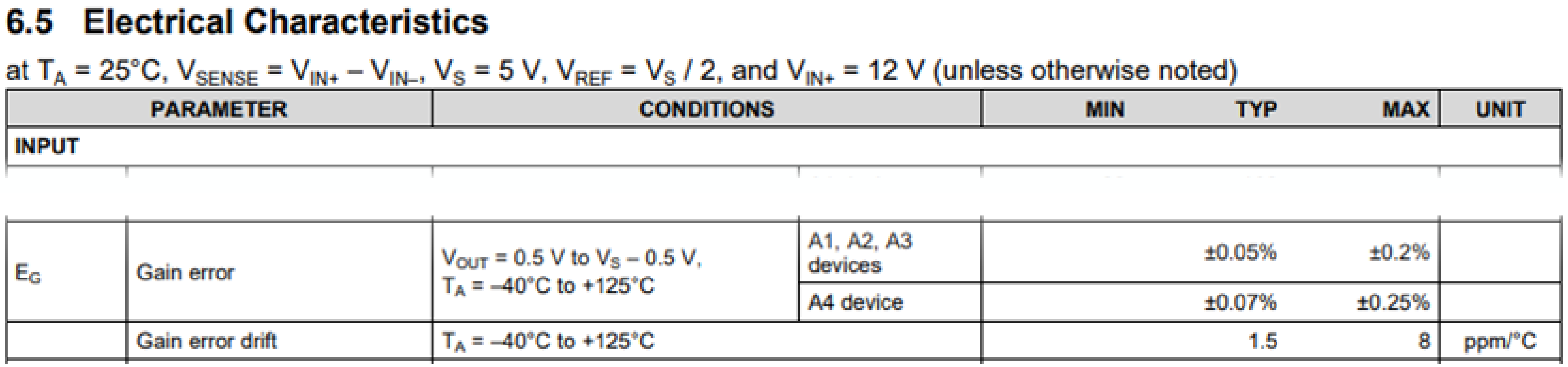
4. For the gain error drift calculated in question #3, what would be the % change for a 30°C change in temperature?

Temperature error – quiz

5. If you can only tolerate an error contribution ≤ 2% from your shunt, which of the following options will work for you? For your design you intend to use a 10mΩ shunt, with $25°C \le T_A \le 100°C$.
    a) 1% resistor @25C, 15ppm/C
    b) 0.1% resistor @25C, 300ppm/C
    c) 0.01% copper trace

Temperature error – quiz

6. What is the max possible gain error of the INA185 when it operates at 80°C?



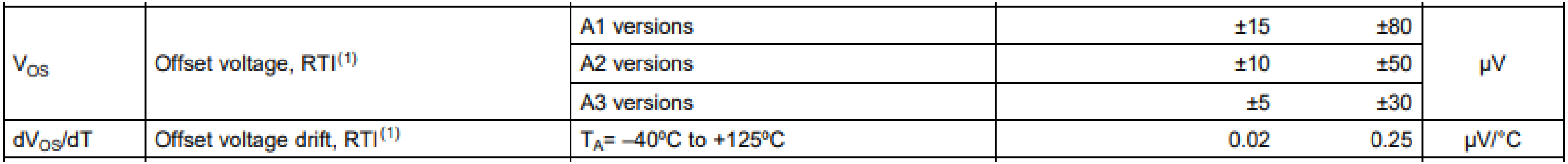
6.5 Electrical Characteristics

at T_A = 25°C, $V_{SENSE} = V_{IN+} – V_{IN–}$, V_S = 5 V, $V_{REF} = V_S / 2$, and V_{IN+} = 12 V (unless otherwise noted)

PARAMETER		CONDITIONS		MIN	TYP	MAX	UNIT
INPUT							
E_G	Gain error	V_{OUT} = 0.5 V to V_S – 0.5 V, T_A = –40°C to +125°C	A1, A2, A3 devices		±0.05%	±0.2%	
			A4 device		±0.07%	±0.25%	
	Gain error drift	T_A = –40°C to +125°C			1.5	8	ppm/°C

Temperature error – quiz

7. What is the max possible offset error of the INA302A2 when it operates at 65°C and is measuring 4A across a 10mΩ shunt?



V_{OS}	Offset voltage, RTI[1]	A1 versions	±15	±80	µV
		A2 versions	±10	±50	
		A3 versions	±5	±30	
dV_{OS}/dT	Offset voltage drift, RTI[1]	T_A= –40°C to +125°C	0.02	0.25	µV/°C

Answers

Temperature error – quiz

1. What are the three typical primary error sources to analyze for precision measurements over a broad operating temperature range?
    a) RTI voltage offset, input bias, and gain error
    b) CMRR, input bias, and gain error
    c) Linearity, shunt tolerance, and PSRR
    d) RTI voltage offset, shunt tolerance, and gain error

2. In the Electrical Characteristics, EC, table of the INA226, the shunt offset voltage RTI, is defined at what temperature?
    a) -40°C to 105°C
    b) -40°C to 125°C
    c) 25°C

Temperature error – quiz

3. If gain error increases by 2 on a scale of 5000 for every 5°C change in temperature, how would it be defined in the EC table?

$$\frac{2}{5000} \times \frac{1}{5℃} \times 10^6 = 80ppm/℃$$

4. For the gain error drift calculated in question #3, what would be the % change in gain for a 30°C change in temperature?

$$\left(\frac{80\left(\frac{1}{°C}\right)}{1000000} \times 30℃\right) \times 100\% = 0.24\%$$

Temperature error – quiz

5. If you can only tolerate an error contribution ≤ 2% from your shunt, which of the following options will work for you? For your design you intend to use a 10mΩ shunt, with 25°C ≤ T_A ≤ 100°C.
    a) 1% resistor @25C, 15ppm/C
    b) 0.1% resistor @25C, 300ppm/C
    c) 0.01% @ 20C copper trace

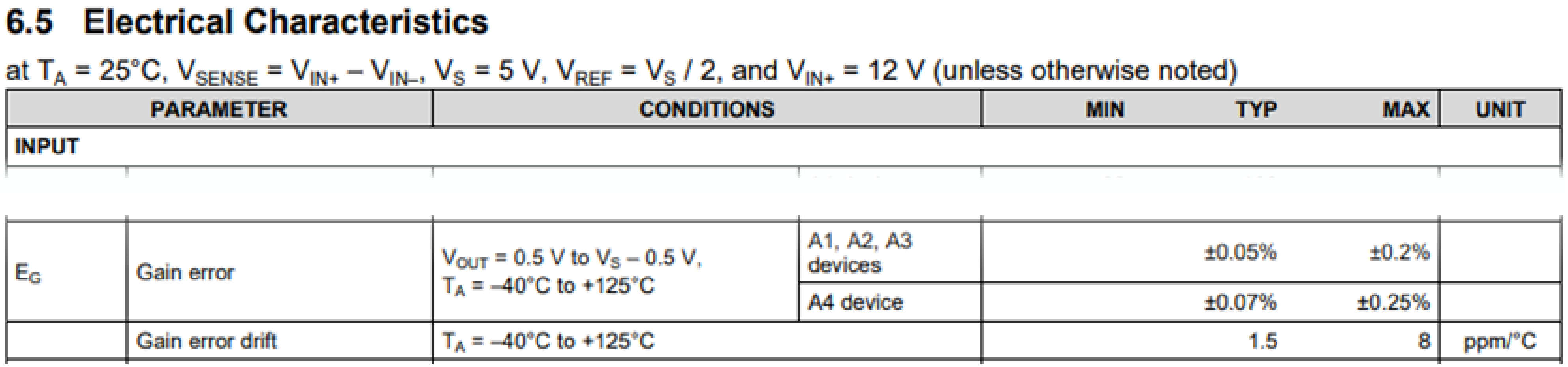
$$e_{shunt_{1\%}} = 1\% + \left(\frac{15\left({}^{1}/_{°C}\right)}{10000} \times 100°C\right) = 1.1125\%$$

$$e_{shunt_{0.1\%}} = 0.1\% + \left(\frac{300\left({}^{1}/_{°C}\right)}{10000} \times 100°C\right) = 2.35\%$$

$$e_{shunt_{0.01\%}} = 0.01\% + \left(\frac{0.01\Omega \times (1 + 0.00393 \times (100°C - 20°C)}{10m\Omega} \times 100°C\right) = 131.44\%$$

Temperature error – quiz

6. What is the max possible gain error of the INA185A1 when it operates at 80°C?



6.5 Electrical Characteristics

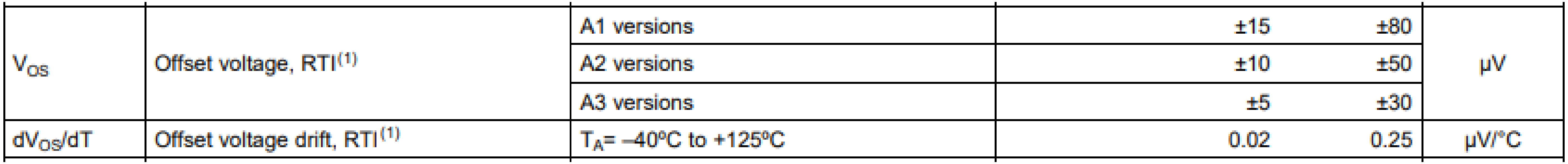
at $T_A = 25°C$, $V_{SENSE} = V_{IN+} – V_{IN–}$, $V_S = 5\ V$, $V_{REF} = V_S / 2$, and $V_{IN+} = 12\ V$ (unless otherwise noted)

PARAMETER		CONDITIONS		MIN	TYP	MAX	UNIT
INPUT							
E_G	Gain error	$V_{OUT} = 0.5\ V$ to $V_S – 0.5\ V$, $T_A = –40°C$ to $+125°C$	A1, A2, A3 devices		±0.05%	±0.2%	
			A4 device		±0.07%	±0.25%	
	Gain error drift	$T_A = –40°C$ to $+125°C$			1.5	8	ppm/°C

$$e_{Gain\_Error} = Gain\ Error\% + \left(\frac{Gain\ Error\ drift\left(\frac{1}{^\circ C}\right)}{10{,}000} \times \Delta T\right) = 0.2\% + \left(\frac{8}{10000} \times (80-25)^\circ\mathrm{C}\right) = 0.20044\%$$

Temperature error – quiz

7. What is the max possible offset error of the INA302A2 when it operates at 65°C and is measuring 4A across a 10mΩ shunt?



V_{OS}	Offset voltage, RTI[1]	A1 versions	±15	±80	μV
		A2 versions	±10	±50	
		A3 versions	±5	±30	
dV_{OS}/dT	Offset voltage drift, RTI[1]	T_A= –40°C to +125°C	0.02	0.25	μV/°C

$$V_{OS(MAX)} = V_{OS(SPEC)} + \left(\frac{\Delta V_{OS}}{\Delta T} \times |T_{MAX} - T_{SPEC}|\right) = 50\mu V + \left(\frac{250nV}{°C} \times |65°C - 25°C|\right) = 60\mu V$$

$$e_{V_{OS}} = \frac{Vos}{V_{Sense}} \times 100\% = \frac{60\mu V}{4A \times 10m\Omega} \times 100\% = 0.15\%$$