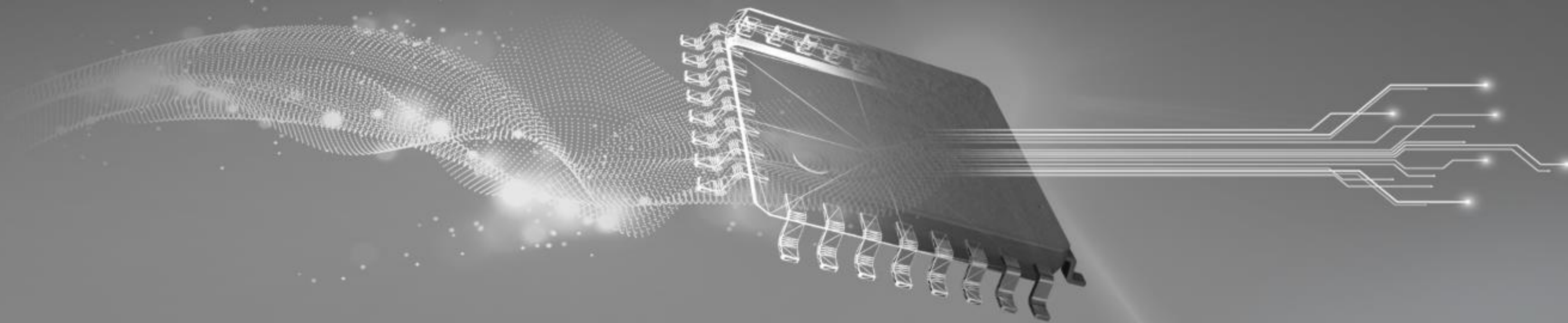
TI TECH DAYS



Improving accuracy in temperature & humidity measurements to optimize cost and performance

Daniel Mar & Gordon Varney

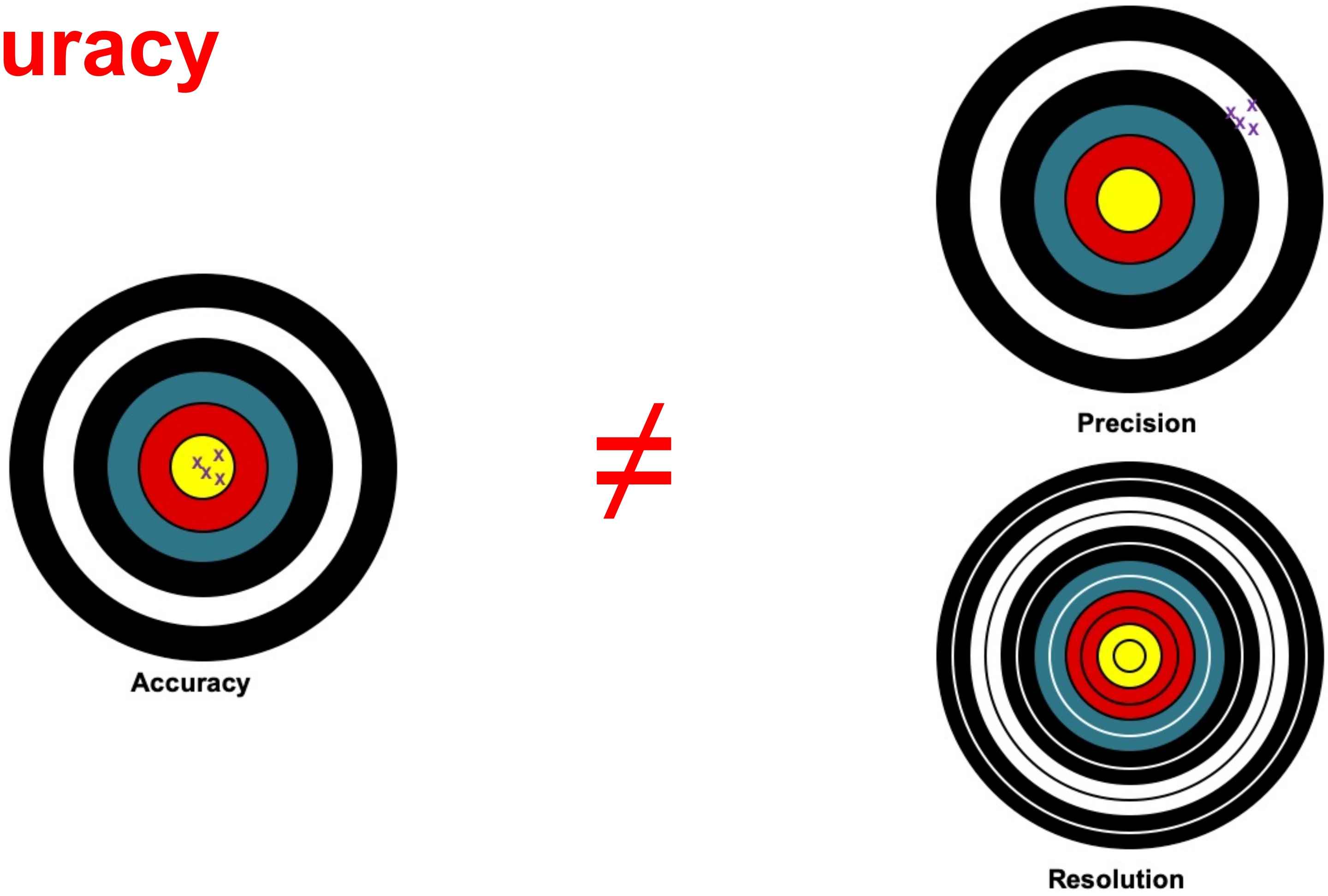
Temperature and Humidity

Agenda

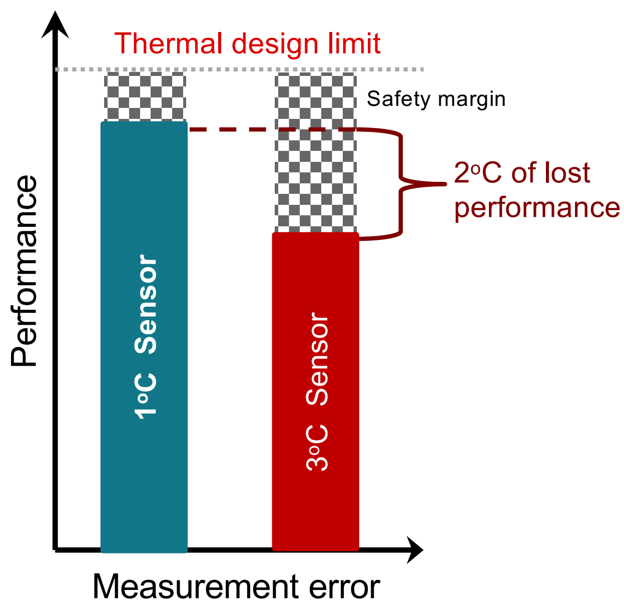
- Performance trade-offs vs. sensor accuracy
- Types of temperature sensors
- TI’s new linear thermistor family
- Direct monitoring of FPGA / Processor / ASIC Temperature
- Humidity
- Q&A

Temperature sensing accuracy

Accuracy



Accuracy performance impact

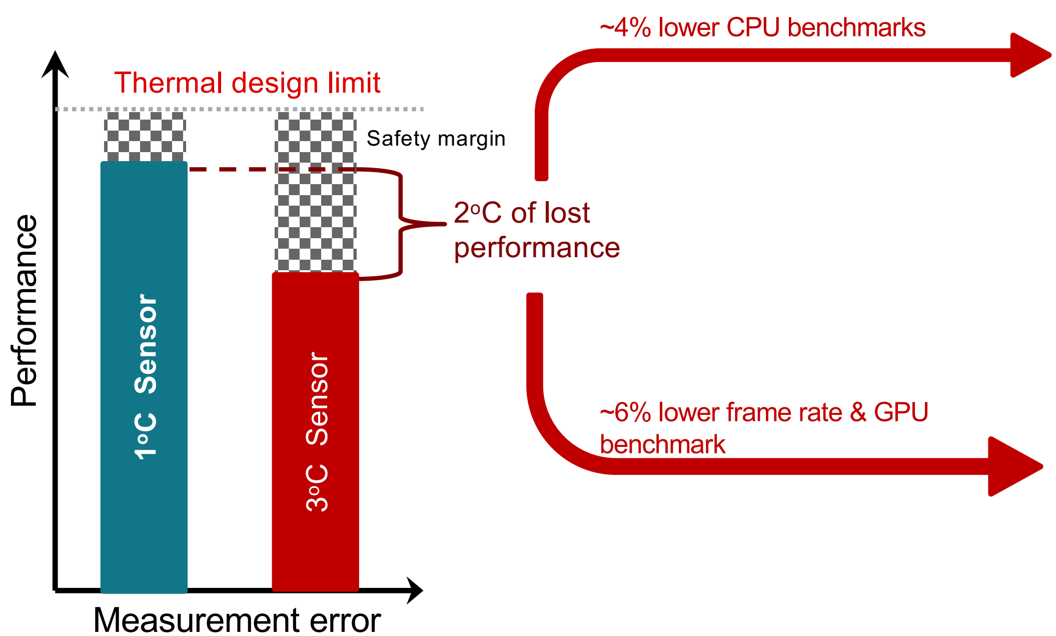


Measurement inaccuracy results in:

- Slower speeds
- Higher costs to over design
- Premature shutdown (greater downtime)

Accuracy vs processor/GPU performance

<u>Gaming PC:</u>
Clock speed modulated to measure gain in benchmark performance vs temperature



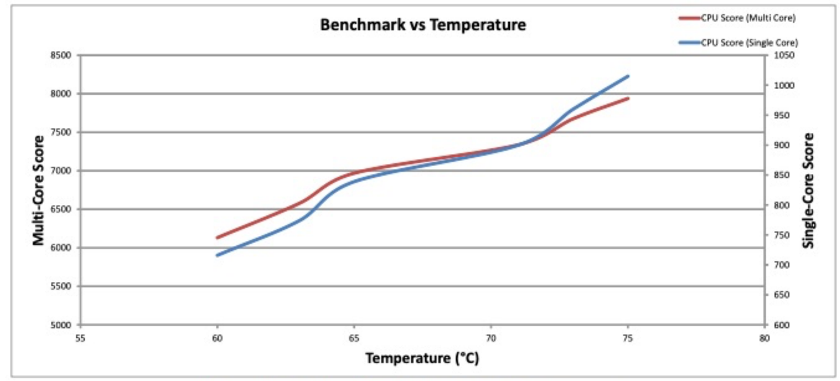


Figure 4-4. Gaming PC: CPU Benchmark vs Temperature

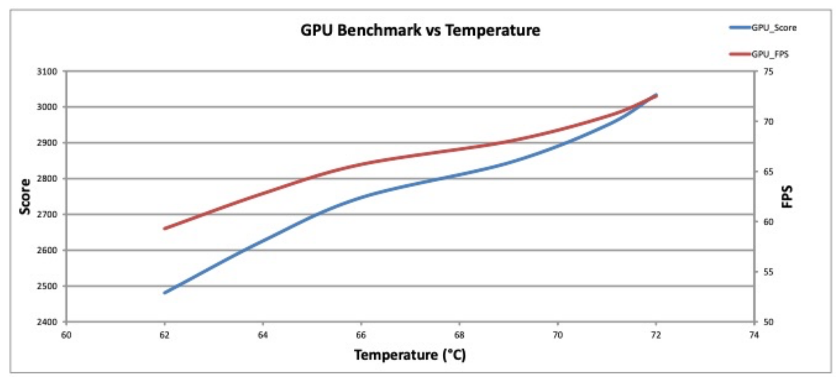


Figure 4-7. Gaming PC: GPU Benchmark Score vs Temperature

Accuracy vs motor power stage

Example:

- 48V 500W three-phase inverter (TIDA-01629)
- Safe Operating Area (SAO): -40°C to 85°C

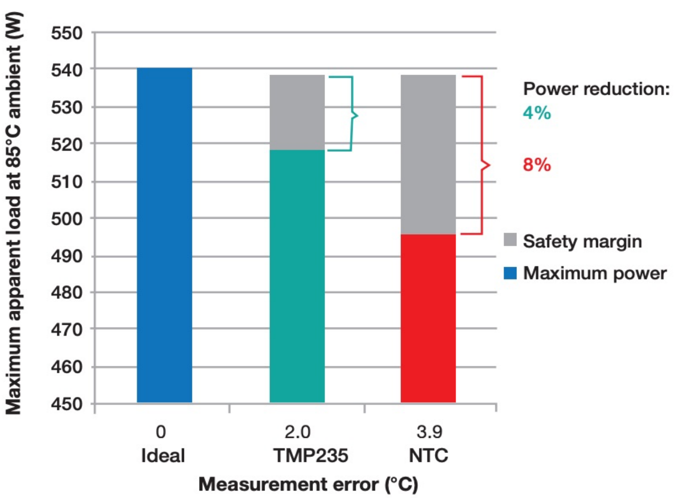


Figure 1: Useable apparent load at 85°C

4% reduction in power for every 2°C of error

Corrective Options:

1. Over design power stage to compensate for sensor inaccuracy (higher cost)
2. Derate SAO
3. Reduce measurement error

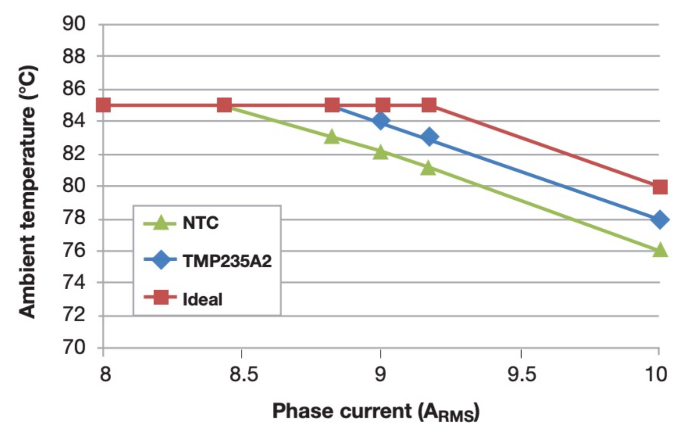


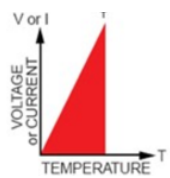
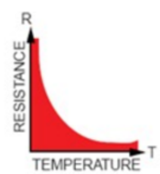
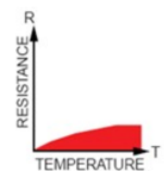
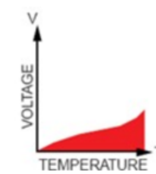
Figure 2: SOA difference cause by temp sensor error

Getting the most out of your power stage at the full temperature range
https://www.ti.com/lit/eb/ssiy006/ssiy006.pdf. (Chapter 2.2.9)

Texas Instruments

Types of temperature sensors

Commonly used temperature sensors

	Temp sense IC	NTC Thermistor	RTD	Thermocouple
				
Output function				
Temp range	-55°C to +175°C	-100°C to +500°C	-240°C to 600°C	-260°C to +2300°C
Accuracy	Best (0.1°C)	Depends on calibration **	Best (<0.1°C)**	Good (depends on calibration)**
Linearity	Best	Low	Best	Better
Drift	Low	High	Low	High
Circuitry & software complexity	Easy	Moderate	Complex	Complex
Topology	Point to point multi-drop Daisy Chain	Point to Point	Point to Point	Point to Point
Price	Low-Moderate	Low-Moderate	Expensive	Expensive

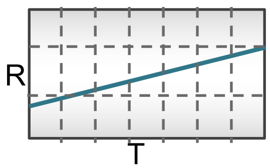
**Additional circuitry required which will contribute to total measurement error

TI Temperature sensor families

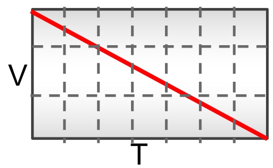
On-board temperature solutions

Local
Measures temp at device itself

Linear thermistor



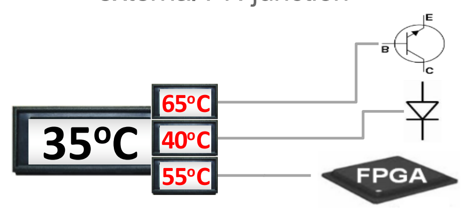
Analog



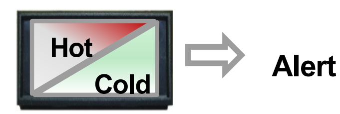
Digital

I2C
SPI
Pulse Count
UART

Remote
Multi-channel, measures temp at external PN junction

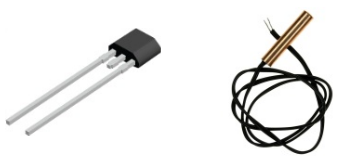


Switch/thermostat
Configurable & preprogrammed temperature comparators with Hysteresis

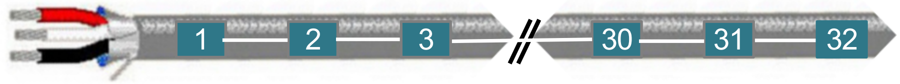


Off-board temperature solutions

2 pin digital
Simple pulse count interface can be integrated into probes up to 2 meters

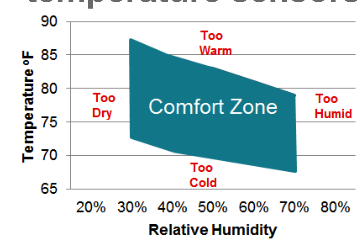


Daisy Chain
String multiple sensors in a single cable up to 300 meters using standard UART interface



Humidity

Integrated humidity & temperature sensors



Texas Instruments

NTC Vs Linear thermistors

Key advantages vs NTCs

Our thermistors ***improve reliability*** over NTCs

- Use less power above 25ºC, minimizes self-heating, and greatly reduces long-term sensor drift.

Achieves ***greater accuracy*** with less effort

- Down to ±0.3ºC with a simple 1-point room temp offset during your final programming, no need for a temperature chamber.
- 2/3 faster response time than NTCs (down to 0.6s).

Simplifies design in hardware and software

- Eliminates the need for additional linearization circuitry and multi-point calibration.
- Reduces memory requirements in look up table and speeds up temperature conversion through the use of a highly accurate linear regression formula.

"The benefits of new thermistor technology, at the same low cost and small size of traditional NTC thermistors"

TMP6x

Silicon-based linear thermistors for temperature sensing

Features

Resistance options at 25°C:

- **10kΩ**, **100kΩ**, **47kΩ**

Resistance tolerance from 0 to 70°C:

- **± 1%**

Max lifetime resistance sensor drift:

- **< 1%**: 2/3rd less than NTC thermistor competition

Thermal response time:

- **0.6 seconds** (DEC package): 66% faster than NTC thermistors

TCR : 6400ppm/°C **± 0.2%**

Operating temperatures:

Qualification	DEC (0402)	DYA (0603)	LPG (TO-92s)
Commercial	-40 to 125°C	-40 to 125°C	-40 to 150°C
Automotive AEC-Q100	-40 to 125°C	-40 to 150°C	-40 to 170°C

Applications

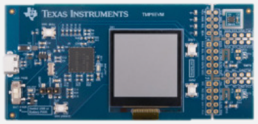
- Displays
- DC/DC
- Power modules
- Inverters
- GPUs
- Motor control
- Charging infrastructure
- Batteries
- HVAC
- Appliances
- Speakers

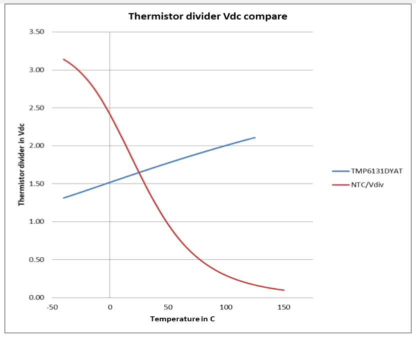
Benefits

- Smallest and most cost-effective linear thermistor in the market.
- Outperforms both NTCs and linear PTC thermistors.
- Enables ±0.3°C accuracy via a 1-point room temperature offset.
- Small size allows for closer proximity to thermal hotpots and quicker thermal response.
- Minimizes thermistor self-heating and reduces power consumption.
- Eliminates linearization circuitry and simplifies software.
- **Easy switch from NTCs and linear PTCs.**

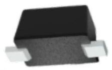
Tools

- Thermistor design tool
  - Includes voltage and current biasing
  - R-T tables, code examples, NTC comparison
- TMP6x EVM
  - Detachable sensor for remote prototyping

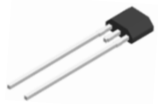




X1SON (DEC)
0402 footprint compatible



SOT-5X3 (DYA)
0603 footprint compatible



TO-92S (LPG)
Through-hole

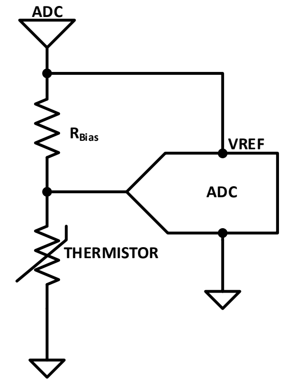
Thermistors

Not all thermistors are passive components.

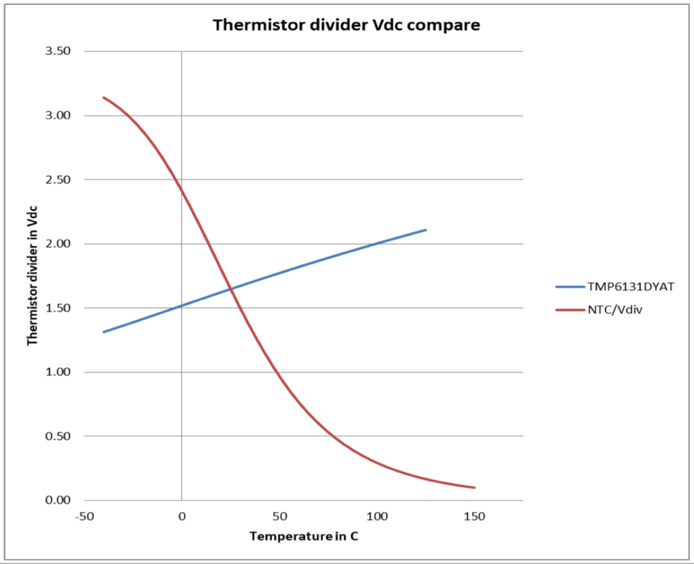
- NTCs will change resistance with temperature and are passive.
- The TMP6x thermistors are silicon and will change the conducted current with temperature. (The resistance provide is an apparent resistance value)
- Each thermistor will then output a Vsense voltage based on the temperature.
- Thermistors fall into two categories, NTC (negative temperature coefficient) and PTC (positive coefficient)

Pros:
- Relatively low cost
- Easy to source

Cons:
- Non-linearity (NTCs)
  - Software overhead: Memory or MIPS
- Long term reliability
  - Sensitivity to shock or humidity
- Difficult to determine actual system accuracy
- # of components



Typical implementation



VBias and IBias (constant current source)

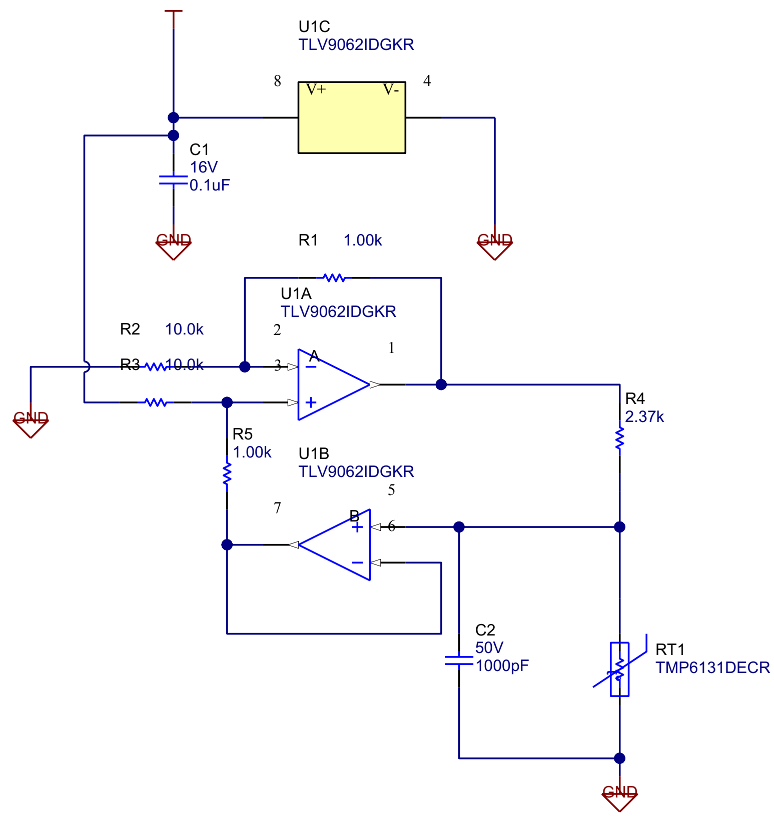
- Benefits of a constant current source:
  - (A) Wider dynamic range for the Vsense
  - (B) Increased accuracy
  - (C) Better stability across the entire temperature range

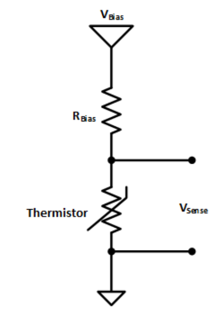
- This circuit is sensitive to VCC changes. It's recommended to operate the constant current source from the VREF being used for the ADC to operate in ratio-metric mode.

- If the VREF voltage is not available then a 0.5% or better, precision low noise LDO is recommended.

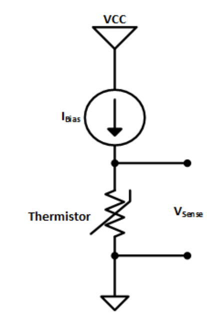
Constant current source circuit BOM

R2, R3	10k 0.5% 25ppm
R1, R5	1k 0.5% 25ppm
RS	2.37k 0.5% 25ppm
U1	TLV9062IDDFR dual op-amp
C1	MLCC 0.1uf 50V 10% X7R
C2	MLCC 1000pf 50V 10% NPO



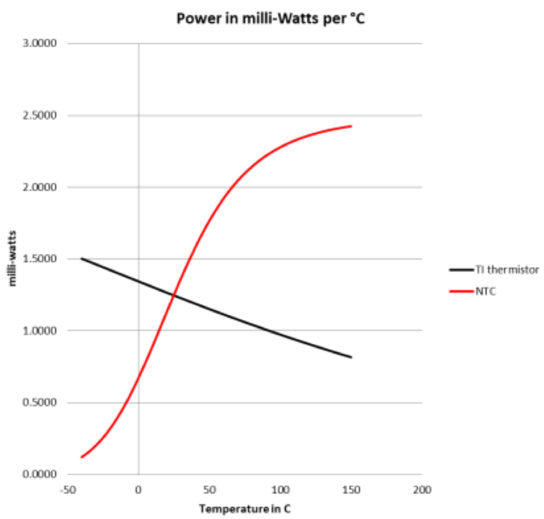


VBias circuit



IBias circuit

Reliability vs NTCs



TMP6x offers greater stability and long-term reliability

Less power consumption & self-heating

- NTCs increase power as temperature rises, which dissipates in the form of heat. This leads to self-heating which can affect the NTC's precision.

✓ TMP6x decreases power as temperature rises. Thanks to their silicon materials and small thermal mass, our thermistors have minimal self-heating.

Minimized long-term sensor drift

- NTCs are known to have a large sensor drift (> 3%) due to their material composition, self-heating, and large variance.

✓ TMP6x minimizes sensor drift over time even in harsh conditions, and has greater immunity to vibrations than NTCs.

Sensor drift vs NTCs

TMP6x minimizes sensor drift

Manufacturer	Part number	Max resistance drift at 25 °C	Test conditions
Texas Instruments	All TI thermistors	< 1 %	96 hours, RH = 85% TA = 130°C, VBias = 5.5V
	TMP6x (DEC)	< 1.8 %	600 Hours, TA = 150°C, VBias = 5.5V
	TMP6x (DYA)	< 1.2 %	600 hours, TA = 150°C, VBias = 5.5V
	TMP6x (LPG)	< 1.4 %	1000 Hours, TA = 150°C, VBias = 5.5V
TDK (Epcos)	B572xx	< 5 %	250 Hours, TA = -40°C to 150°C
Panasonic	ERTJ0xx	< 3 %	1000 Hours, TA = 150°C
QTI Solutions	M32192Dxx	< 25 %	1000 Hours, "High Temperature"
	M32192Axx	< 3 %	1000 Hours, "High Temperature"

Accuracy vs NTCs

TMP6x delivers better accuracy, especially at high temp

Smaller resistance tolerance

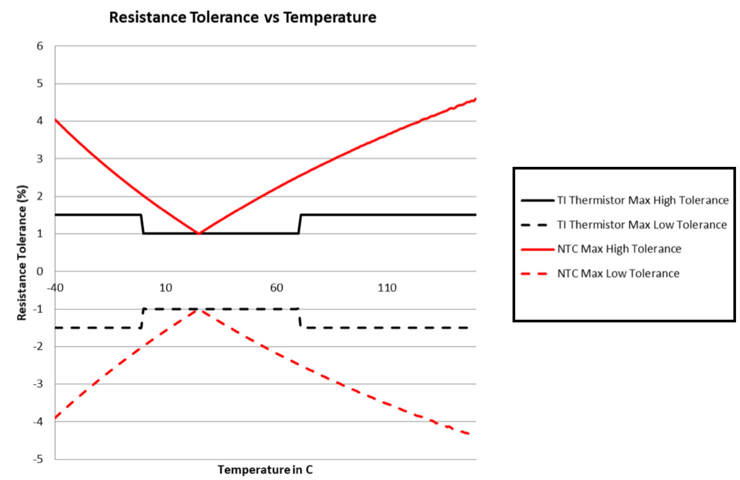
- The large increase of resistance tolerance in NTCs can lead to a large error if not calibrated out.

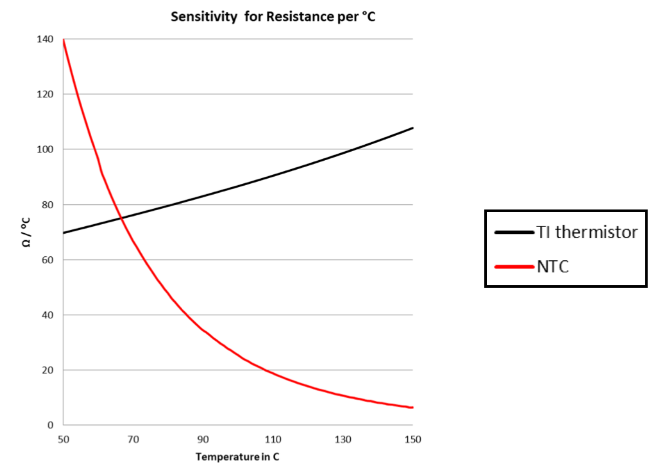
✓ TMP6x significantly outperforms NTCs across the full temperature range in systems requiring single-point calibration.

Stable sensitivity

- NTCs drastically decrease their change in resistance per degree C (sensitivity) as temperature rises, leading to unstable temperature readings.

✓ TI thermistors maintain a much more stable sensitivity across the whole temperature range, and surpass that of NTCs typically above 64°C.





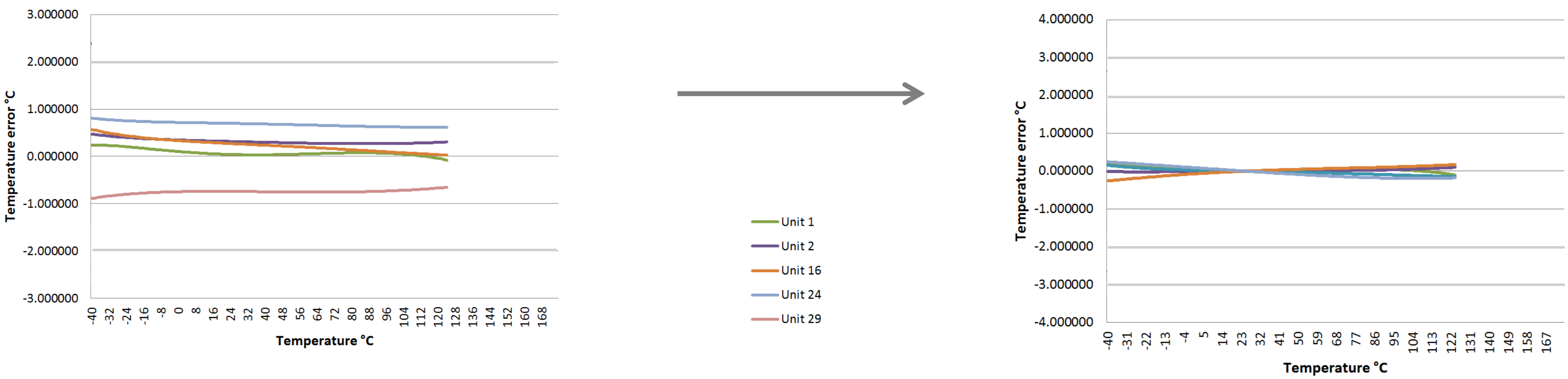
Calibration

TMP6x achieves ±0.3°C with a 1-point room temperature offset

- Consistency of silicon enables stable accuracy across the whole temperature range, regardless of calibration efforts. This enables greater accuracy at higher temperatures with no calibration vs NTCs.

- If ±0.3°C is desired, one simple offset adjustment done during your final programming can automatically correct the temperature measurement in milliseconds with no hands on, without the need for a temperature chamber.

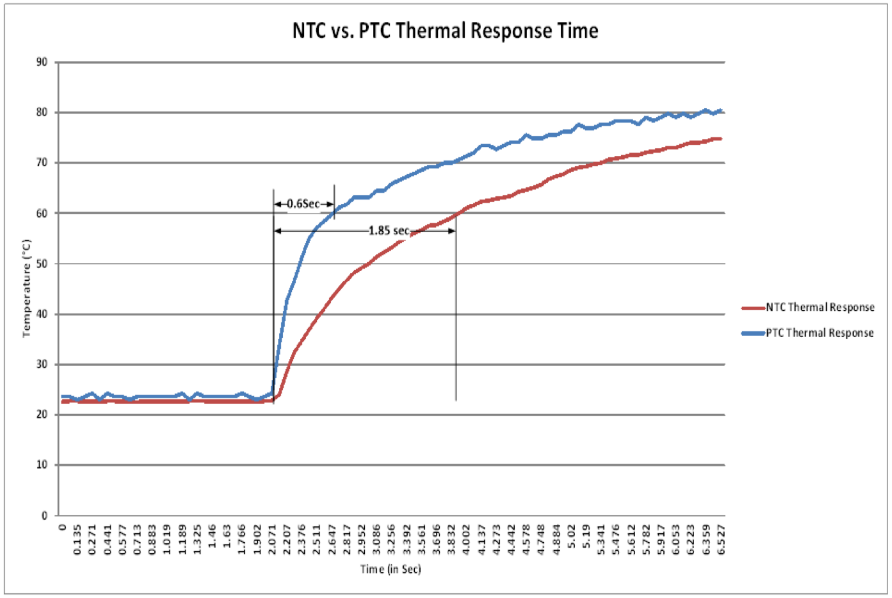
No offset calibration **1-point room temp offset**



Response time vs NTCs

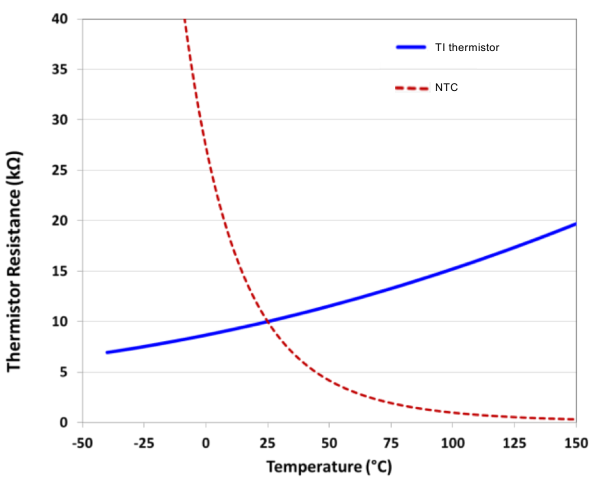
TMP6x is 1/3 faster than typical NTCs

- Faster response times help your MCU take action when needed most, and can prevent thermal failures in your system.



TEXAS INSTRUMENTS

Linearity vs NTCs



TMP6x reduces costs and simplifies system requirements.

Reduce BOM cost

- NTCs need a network of resistors to achieve a linear voltage drop across temperature.

✓ TMP6x already has this linear characteristic, saving you board space and money by not adding additional linearization circuitry.

Minimize calibration efforts

- NTCs need multiple calibration points for applications requiring accuracy across a wide temperature range due to a large tolerance of resistance and TCR.

✓ TMP6x is more stable than NTCs, allowing for a room temperature offset correction to achieve high accuracy across the whole temperature range.

Shrink memory requirements

- NTCs have a very non-linear R-T curve, and therefore need many resistance values in the lookup table.

✓ The linearity of the TMP6x enables the interpolation of a much smaller look up table than NTCs, taking up less memory in the MCU.

Free up CPU bandwidth

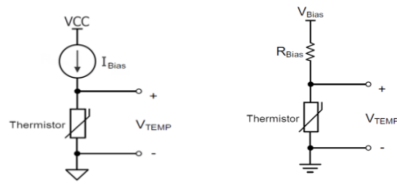
- NTCs typically use the Steinhart-Hart equation to convert temperature if not a lookup table, requiring the natural log and multiple calculations which add to the processing time.

✓ TMP6x can take advantage of a simple 4^{th} order regression that saves CPU cycles, and is more accurate than the Steinhart-Hart equation.

Easy to use: Thermistor design tool

Unique resistance tables

- Choose circuit, OPN, source value, and Rbias



Code & examples

- Kickstart design with conversion methods and C code provided

Temperature Conversion Methods

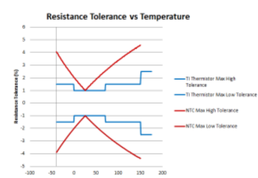
4th Order Polynomial Regression
Steinhart-Hart
Lookup table
Interpolation From Lookup Table
Threshold Detection

Helpful formula worksheets

Averaging
Basic Formulas
RBias TCR_PPM

Competitor analysis

- Input competitor resistance table to compare characteristics



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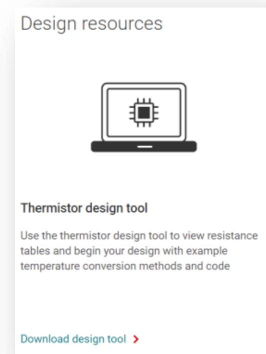
TI.com/thermistors



Key support links

Product Folders

- TMP61 (10 kΩ)
- TMP61-Q1 (10 kΩ)
- TMP63 (100 kΩ)
- TMP63-Q1 (100 kΩ)
- TMP64 (47 kΩ)
- TMP64-Q1 (47kΩ)

Datasheets

- TMP61
- TMP61-Q1
- TMP63
- TMP63-Q1
- TMP64
- TMP64-Q1

Key Technical Documentation

- Temperature Sensing with Thermistors
- Choosing the right thermistor
- Designing with linear thermistors
- Methods to calibrate temperature sensors
- Self-heating in NTC and PTC thermistors
- Using thermistors to optimize IGBT modules
- Error analysis between NTC and silicon-based PTC thermistors

Factory Applications Support

- E2E Customer Support FAQs

Design Tools

- Thermistor Design Tool
- TMP6x EVM
- TMP6x EVM User's Guide

Direct die temperature monitoring

Integrated temperature sensors

Process flows optimized for digital logic are not optimized for accurate temperature measurement

XILINX. Virtex-7 T and XT FPGAs Data Sheet: DC and AC Switching Characteristics

XADC Specifications

Table 84: **XADC Specifications**

On-Chip Sensors					
Temperature Sensor Error	T_j = –40°C to 100°C.	–	–	±4	°C
	T_j = –55°C to +125°C	–	–	±6	°C

Intel® Agilex™ Device Data Sheet

DS-1060 | 2020.06.30

Local Temperature Sensor Specifications

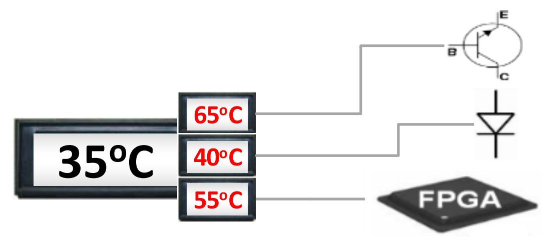
Table 26. Local Temperature Sensor Specifications for Intel Agilex Devices

For specification status, see the *Data Sheet Status* table

Description	Temperature Range		Accuracy		Sampling Rate	Conversion Time
Local Temperature Sensor	–40 to 125 °C[30]		±5 °C		1 KSPS	< 1 ms

Key Advantages of Remote Temperature Sensors

- Optimize performance
  - Direct die temperature
  - More accurate temperature than internal sensor
  - Faster response time vs external temp sensor
- Protection
  - Independent temperature monitor
  - Faster response time
- Integration
  - Central source for temperature status
  - Smaller footprint
  - Less complex
  - Options for fan control, digital power monitors



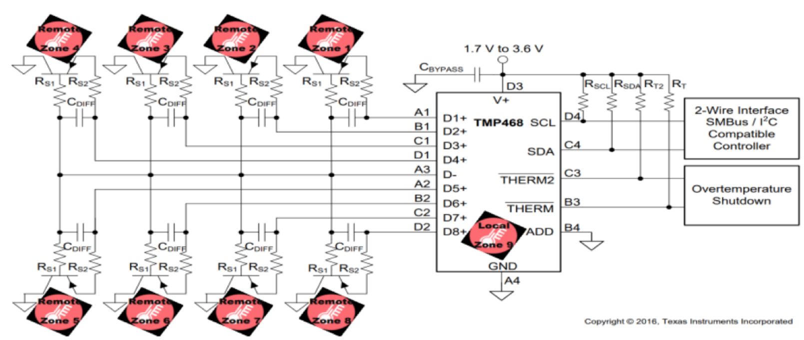
TMP461

www.ti.com SBOS722B – JUNE 2015 – REVISED AUGUST 2016

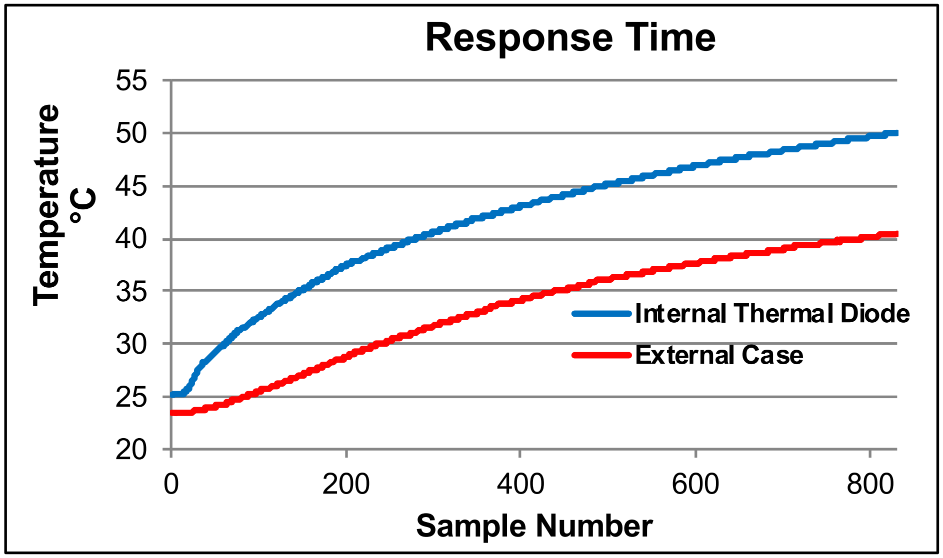
7.5 Electrical Characteristics

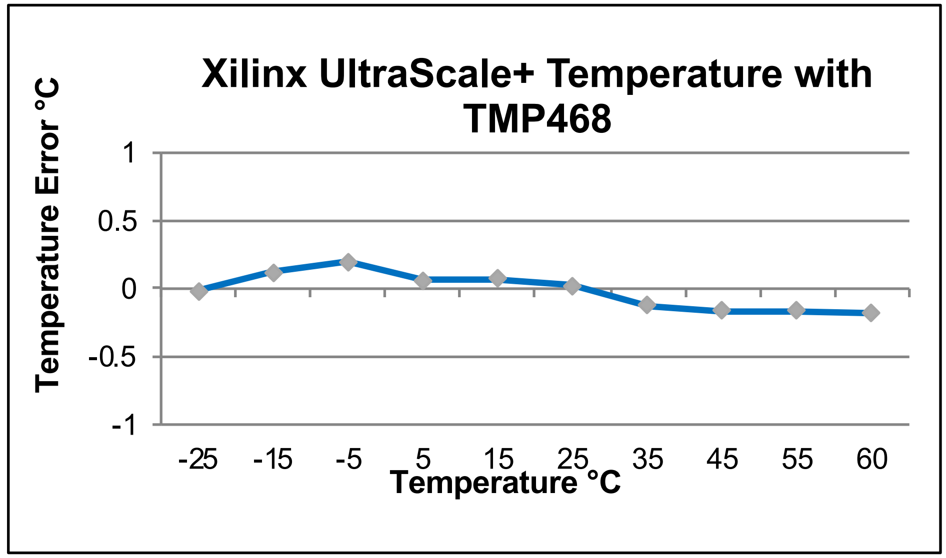
At T_A = –40°C to 125°C and V+ = 1.7 V to 3.6 V, unless otherwise noted.

PARAMETER		CONDITIONS	MIN	TYP	MAX	UNIT
TEMPERATURE MEASUREMENT						
TA_{LOCAL}	Local temperature sensor accuracy	T_A = –10°C to 100°C, V+ = 1.7 V to 3.6 V	-1	±0.125	+1	°C
		T_A = –40°C to 125°C, V+ = 1.7 V to 3.6 V	-1.25	±0.5	+1.25	
TA_{REMOTE}	Remote temperature sensor accuracy	T_A = 0°C to 100°C, T_D = –55°C to 150°C, V+ = 1.7 V to 3.6 V	-0.75	±0.125	+ 0.75	°C
		T_A = –40°C to 125°C, T_D = –55°C to 150°C, V+ = 1.7 V to 3.6 V	-1.5	±0.5	+1.5	

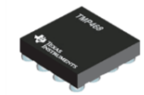


TMP468 monitoring Xilinx UltraScale+ RFSoC





Featured remote/multi-channel temperature sensors



Commercial, EP, and space grade options may be available

	TMP461	TMP422	TMP468	AMC6821
# of Remote Channels	1	2	8	1
Local accuracy (max)	**±1 °C** @ -10 °C to 100 °C (max) **±1.25 °C** @ -40 °C to 125 °C (max)	**±1.0C** @ 15 °C to 85 °C **±2.5° C** @ -55 °C to 125C	**±0.35C** @ 20 °C to 30 °C **±0.75C** @ -40 °C to 125 °C	**±2.0° C** @ 0 °C to 90 °C **±3.0C** @ -25 °C to 100 °C
Remote accuracy (max)	**±0.75 °C @** TA = 0°C to +100°C, TD = –55°C to +150°C, **± 1.25 °C @** TA = –40°C to +125°C, TD = –55°C to +125°C	**±1.0 °C @** TA = +15°C to +85°C, TD = –40°C to +150°C, **± 3.0 °C @** TA = –55°C to +125°C, TD = –55°C to +125°C	**±0.75 °C** TA = -10°C to +85°C, TD = –55°C to +150°C **±1.0 °C** TA = -40°C to +125°C, TD = –55°C to +150°C	**±2.0° C** @ 50 °C to 90 °C **±3.0C** @ -40 °C to 125 °C
Supply range	1.7 V to 3.6 V	2.7 V to 5.5 V	1.7 V to 3.6 V	2.7 V to 5.5 V
Series resistance cancellation	1kΩ	3kΩ	1kΩ	0.0025°C/Ω
N-Factor correction	Yes	Yes	Yes	No
ADC resolution	12-bit	12-bit	13-bit	11-bit
Package	10-WQFN (2 x 2mm)	SOT23-8 (3 x 3mm)	VQFN(3 x 3mm) DSBGA(1.6 x 1.6mm)	SSOP(6 x 5mm)
Interface	I2C/SMBus	I2C/SMBus	I2C/SMBus	I2C/SMBus
Integrated fan control	No	No	No	Yes

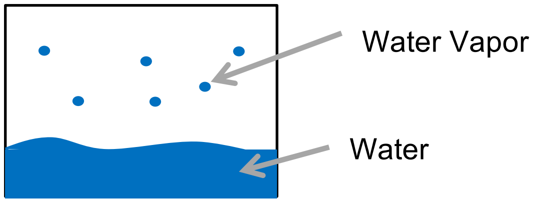
Humidity

Humidity

- What's Relative Humidity?
  - Ratio (at a given temperature) between *actual water vapor* and *saturation water vapor* expressed as percentage (saturation is the max water vapor)

$$\%RH = \frac{Actual\ Water\ Vapor}{Saturation\ Water\ Vapor}\ (given\ temperature)$$

Saturation → water vapor start to condense

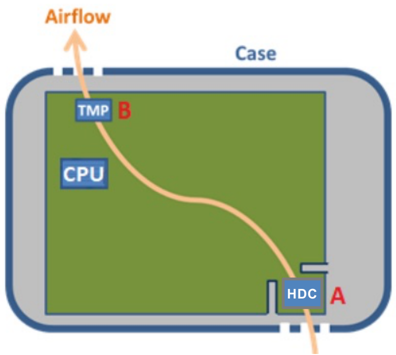


  - %RH varies significantly with the temperature
    - +1°C variation → -4%RH relative humidity

Humidity: Internal case vs. ambient

Precise temperature measurement is needed

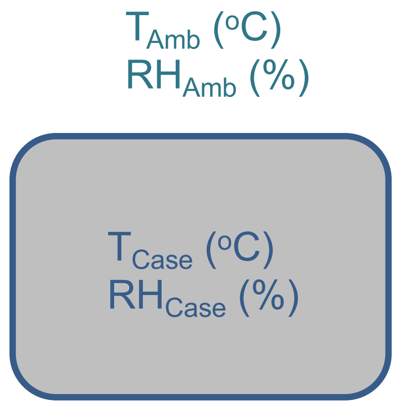
- Methods improve ambient accuracy
  - Airflow
  - PCB layout
  - Multiple sensors to measure differential (heat flux)
  - Power monitoring



TI Resources:

- Ambient Temperature Measurement Layout Considerations
- Temperature sensors: PCB guidelines for surface mount devices (Rev. A)
- 4.2 TI Precision Labs - Temperature Sensors: How to Monitor Ambient Temperature

Humidity: Internal case vs ambient



Calculating Ambient Humidity

Ambient RH% ≠ Case RH%

Ambient Absolute Humidity = Case Absolute Humidity

$$RH_{Amb} = \frac{P_{WScase}}{P_{WSamb}}\, x\, \frac{T_{Amb}}{T_{Case}}\, x\ RHCase$$

- T_C = Temperature inside the case in kelvin (as measured by the sensor)
- T_{amb} = Ambient temperature in kelvin
- RH_c = Relative humidity in the case
- Rh_{amb} = Ambient Relative humidity
- PWS_c is the saturation vapor pressure at T_C
- PWS_{amb} is the saturation vapor pressure at T_{amb}

$$P_{WS} = 6.1094\ x\ e^{\frac{17.625xT}{T+243.04}}$$

Application Note: Compensating Temperature and Humidity Sensors in HVAC Systems

Texas Instruments

Featured parts

Featured temperature sensors

	TMP117 Ultra-high accuracy	TMP1075 Next Gen LM75/TMP75	TMP103 Ultra-small	TMP235 Value analog	TMP390/392 Resistor programmable	TMP61 Precision thermistor
Interface	I2C w/ Alert	I2C w/ Alert	I2C	Analog	Dual Temp Switch	Linear Resistance
# of I2C Addresses	4	32	8 (fixed)	N/A	N/A	N/A
Supply range	1.9V to 3.6V	1.7V to 5.5V	1.4V to 3.6V	2.3V to 5.5V	1.62V to 5.5V	<5.5V
Accuracy (Typical)	±0.05ºC	±0.25ºC	±1.0ºC	±0.5ºC	±0.5ºC	
Accuracy (max)	TMP117: ±0.1°C (-20°C – 50°C) TMP117M: ±0.1°C (30°C – 45°C) TMP117N: ±0.2°C (-40°C – 100°C)	±1.0°C (-40°C to 110°C)	±2°C (-10C to 100°C)	±1°C (0ºC to 70°C)	±1.5°C (0ºC to 70°C)	±1% (0ºC to 70ºC)
Full temp range	-55ºC to 150ºC	-55ºC to 125ºC	-40ºC to 125ºC	-40ºC to 150ºC	-40ºC to 150ºC	-40ºC to 150ºC
Resolution	16-bit	12-Bit	8-Bit	N/A	2ºC	N/A
Quiescent current (max)	3uA	4uA	3uA	14.5uA	1uA	N/A
NIST traceable	Yes	Yes	-	-	-	-
Integrated EEPROM	Yes	-	-	-	-	-
Shutdown current	0.3uA	0.65uA	1uA	-	-	-
Package footprint	WCSP: 1.5 x 1mm WSON: 2 x 2 mm	WSON: 2 x 2mm VSSOP: 3 x 4.9mm SOIC: 4.9 x 6mm	WCSP: 0.8 x 0.8 mm	SC70: 2.0 x 125mm SOT-23: 2.9 x 1.3mm	SOT563: 1.6 x 1.6mm	0402 0603 TO-92S

SLYP718

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