Signal Conditioning and Linearization of RTD Sensors

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Texas Instruments

HPA Precision Linear Applications

9/24/11

Introduction

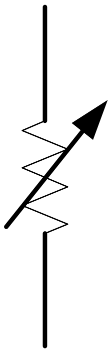
- Primary Support
  - 4-20mA Loop Drivers (XTRXXX)
  - Gamma Buffers (BUFXXXXX)
- Other Support
  - Temperature Sensors (TMP)
  - IR Temperature Sensors (TMP006)
  - OPA Stability
  - Instrument Amplifiers
- Applications (Other)
  - Industrial – Programmable Logic Controllers (PLC)
  - RTD
  - Reference Designs

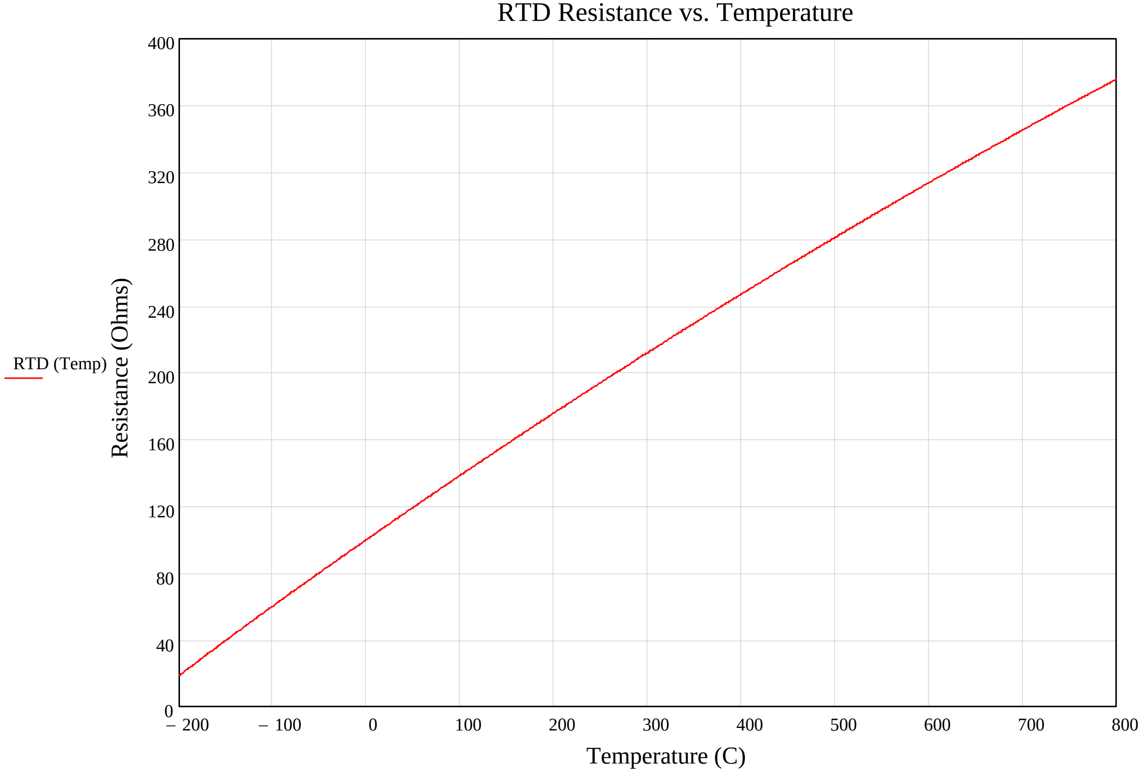
Contents

What is an RTD?

- Resistive Temperature Detector
- Sensor with a predictable resistance vs. temperature
- Measure the resistance and calculate temperature based on the Resistance vs. Temperature characteristics of the RTD material

R_{RTD}





PT100

α = 0.00385

How does an RTD work?

$$\text{Resistance} = R = \frac{\rho \cdot L}{A}$$

$$\text{Resistivity} = p = \frac{1}{e \cdot n \cdot \mu}$$

- L = Wire Length
- A = Wire Area
- e = Electron Charge (1.6e-19 Coulombs)
- n = Electron Density
- u = Electron Mobility

- The product n*u decreases over temperature, therefore resistance increases over temperature (PTC)

- Linear Model of Conductor Resistivity Change vs. Temperature

$$\rho(t) = \rho_0\left(1 + \alpha\left(t - t_0\right)\right)$$

What is an RTD made of?

- Platinum (pt)
- Nickel (Ni)
- Copper (Cu)

•Have relatively linear change in resistance over temp
•Have high resistivity allowing for smaller dimensions
•Either Thin-Film or Wire-Wound

Metal	Resistivity (Ohm/CMF)
Gold (Au)	13
Silver (Ag)	8.8
Copper (Cu)	9.26
Platinum (Pt)	59
Tungsten (W)	30
Nickel (Ni)	36

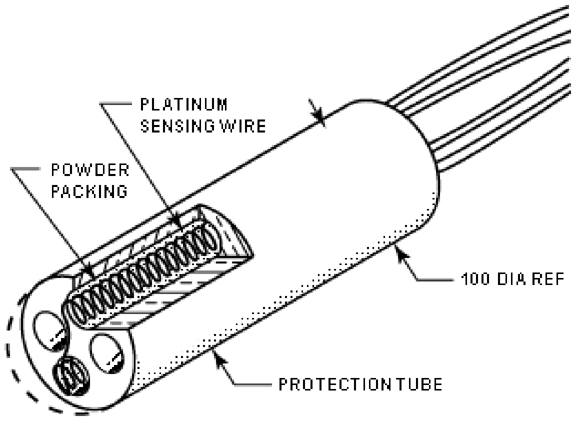


Figure 1. The coiled element sensor, made by inserting the helical sensing wires into a packed powder-filled insulating mandrel, provides a strain-free sensing element.

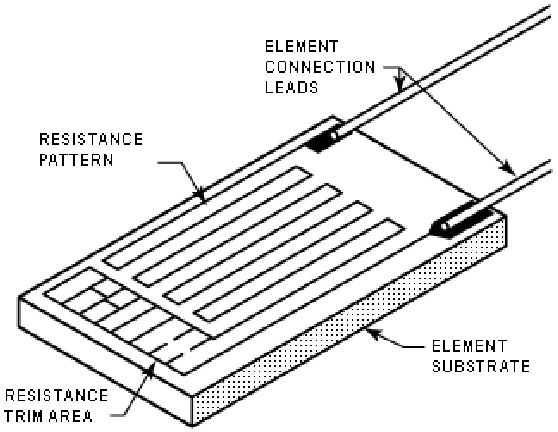


Figure 2. The thin film sensing element is made by depositing a thin layer of platinum in a resistance pattern on a ceramic substrate. A glassy layer is applied for seal and protection.

***Images from RDF Corp**

How Accurate is an RTD?

- Absolute accuracy is “Class” dependant - defined by DIN-IEC 60751. Allows for easy interchangeability of field sensors

Tolerance Class (DIN-IEC 60751)	**Temperature Range of Validity		Tolerance Values (C)	Resistance at 0C (Ohms)	Error at 100C (C)	Error over Wire-Wound Range (C)
	Wire-Wound	Thin-Film				
*AAA (1/10 DIN)	0 - +100	0 - +100	+/-(0.03 + 0.0005*t)	100 +/- 0.012	0.08	0.08
AA (1/3DIN)	-50 - +250	0 - +150	+/-(0.1 + 0.0017*t)	100 +/- 0.04	0.27	0.525
A	-100 - +450	-30 - +300	+/-(0.15 + 0.002*t)	100 +/- 0.06	0.35	1.05
B	-196 - +600	-50 - +500	+/-(0.3 + 0.005*t)	100 +/- 0.12	0.8	3.3
C	-196 - +600	-50 - +600	+/-(0.6 + 0.01*t)	100 +/- 0.24	1.6	6.6

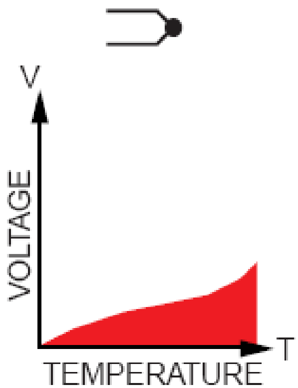
*AAA (1/10DIN) is not included in the DIN-IEC-60751 spec but is an industry accepted tolerance class for high-performance measurements

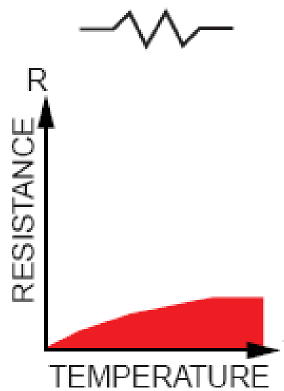
**Manufacturers may choose to guarantee operation over a wider temperature range than the DIN-IEC60751 provides

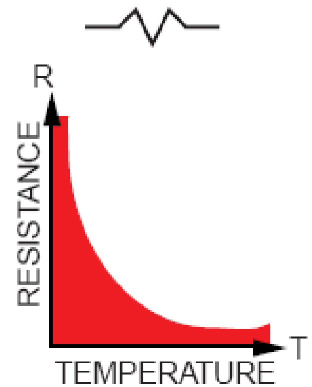
- Repeatability usually very good, allows for individual sensor calibration
- Long-Term Drift usually <0.1C/year, can get as low as 0.0025C/year

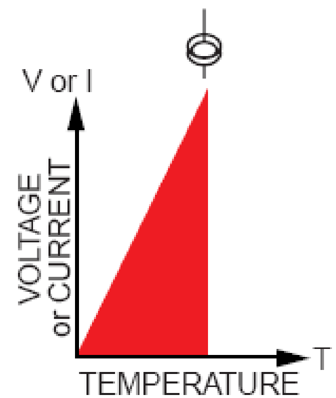
Why use an RTD?

Table Comparing Advantages and Disadvantages of Temp Sensors







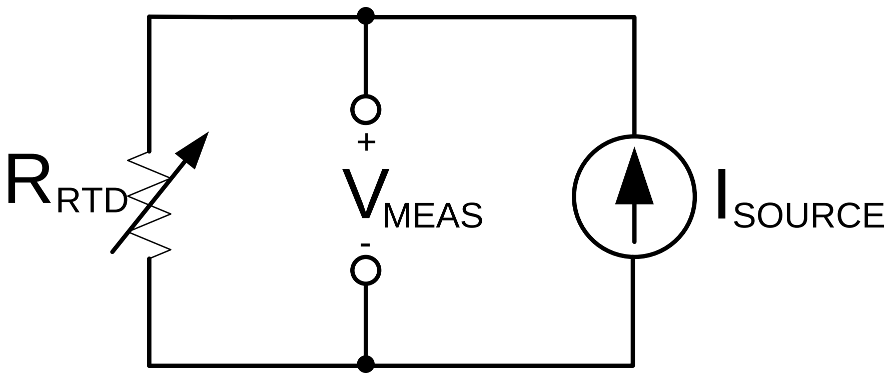


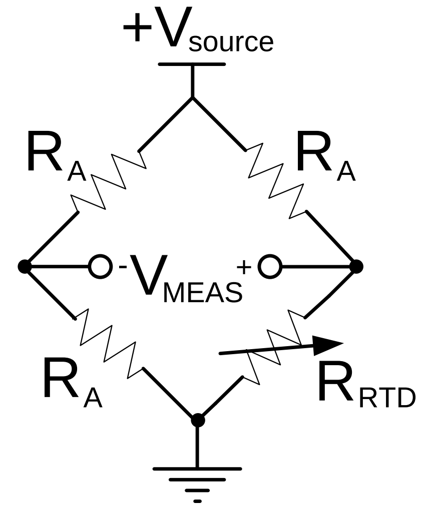
	Thermocouple	RTD	Thermistor	I. C. Sensor
Advantages	☐ Self-powered ☐ Simple ☐ Rugged ☐ Inexpensive ☐ Wide variety ☐ Wide temperature range	☐ Most stable ☐ Most accurate ☐ More linear than thermocouple	☐ High output ☐ Fast ☐ Two-wire ohms measurement	☐ Most linear ☐ Highest output ☐ Inexpensive
Disadvantages	☐ Non-linear ☐ Low voltage ☐ Reference required ☐ Least stable ☐ Least sensitive	☐ Expensive ☐ Current source re-quired ☐ Small Δ R ☐ Low absolute resistance ☐ Self-heating	☐ Non-linear ☐ Limited temperature range ☐ Fragile ☐ Current source re-quired ☐ Self-heating	☐ T<200°C ☐ Power supply re-quired ☐ Slow ☐ Self-heating ☐ Limited configurations

How to Measure an RTD Resistance?

- Use a…….

Current Source **or** **Wheatstone Bridge**





$$V_{meas} = I_{source} \cdot R_{RTD}$$

$$V_{meas} = V_{source} \cdot \left[\left(\frac{R_{RTD}}{R_A + R_{RTD}} \right) - \frac{1}{2} \right]$$

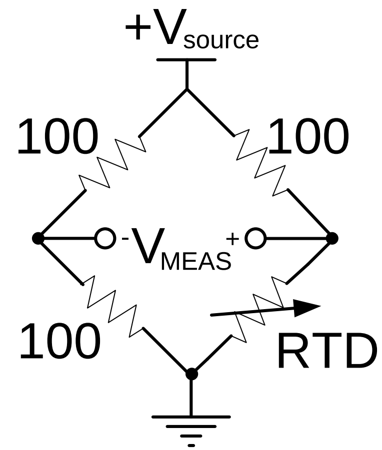
$$R_{RTD} = \frac{V_{meas}}{I_{source}}$$

$$R_{RTD} = \frac{2 \cdot R_A \cdot V_{meas} + R_A \cdot V_{source}}{V_{source} - 2 \cdot V_{meas}}$$

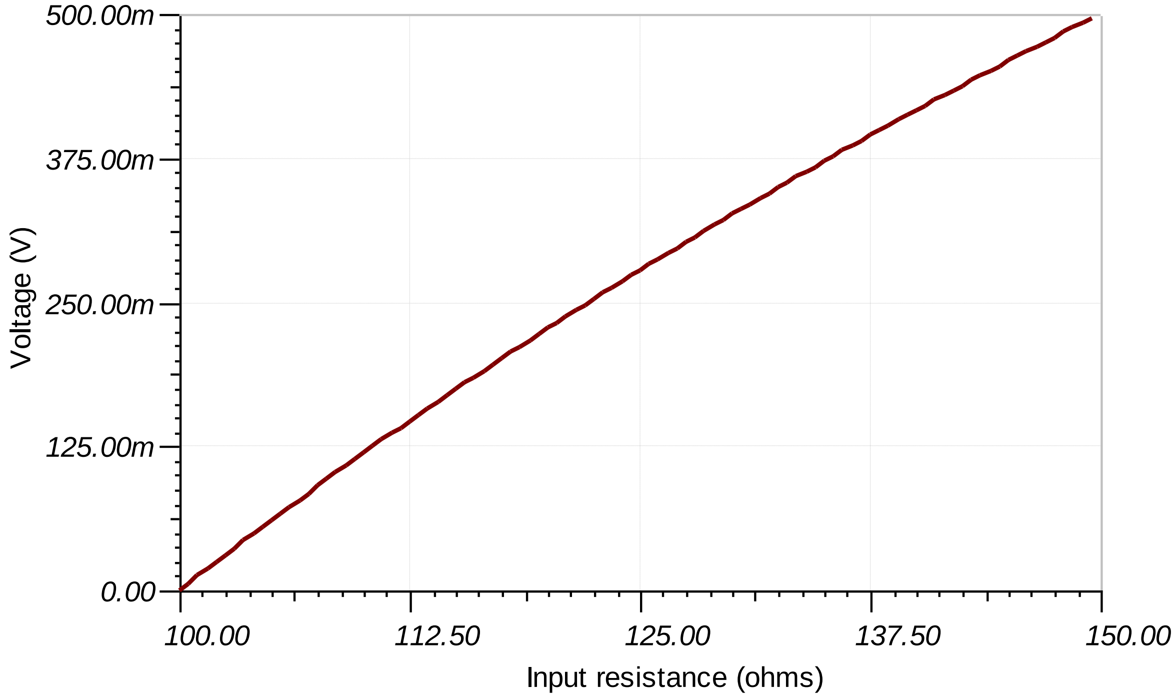
Note on Non-Linear Output of Bridge

$$V_{meas} = V_{source} \cdot \left[\left(\frac{R_{RTD}}{R_A + R_{RTD}} \right) - \frac{1}{2} \right]$$

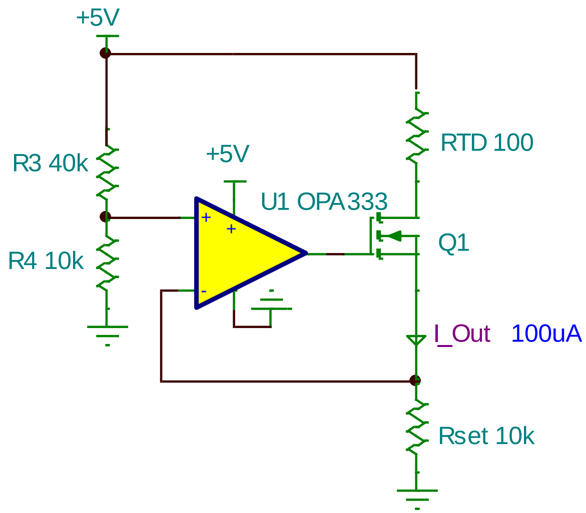
Denominator causes a non-linear output even for a linear sensor

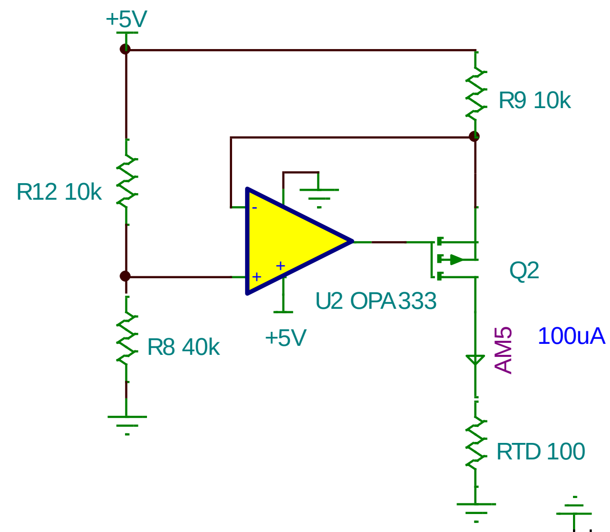


ΔRTD = 50Ohms

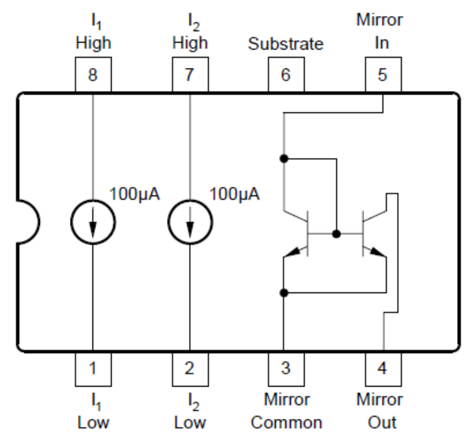


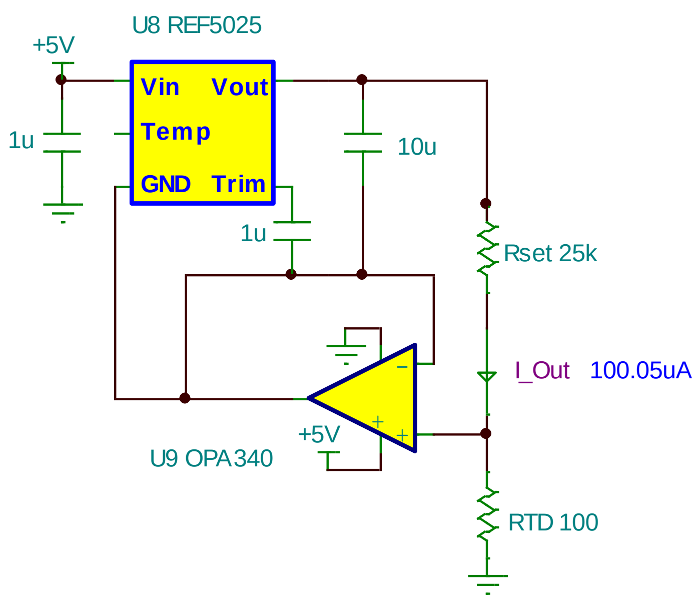
Simple Current Source / Sink Circuits

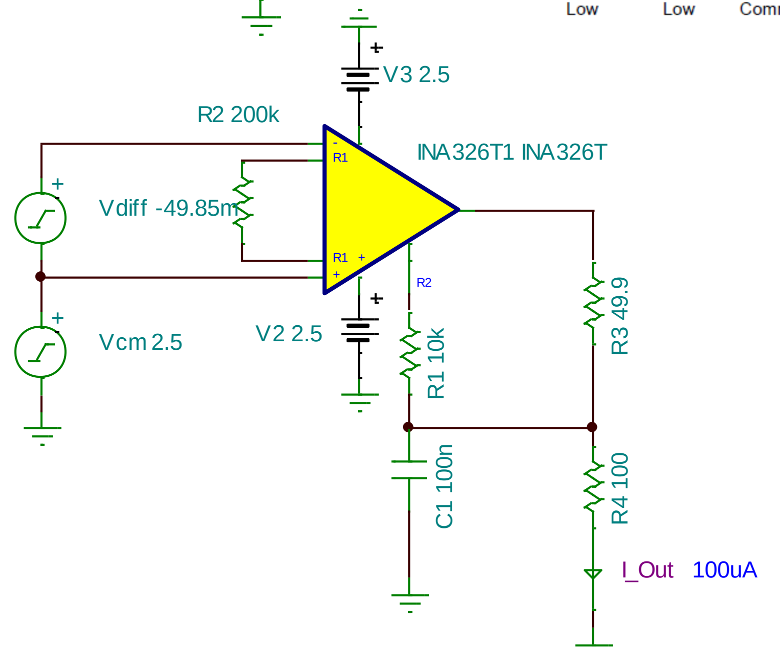




REF200

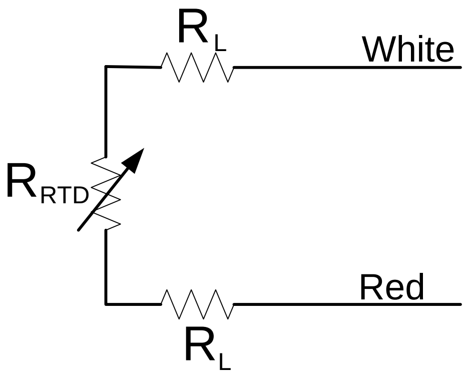




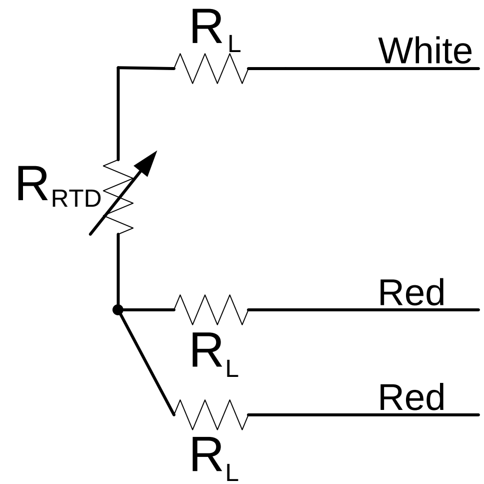


RTD Types and Their Parasitic Lead Resistances

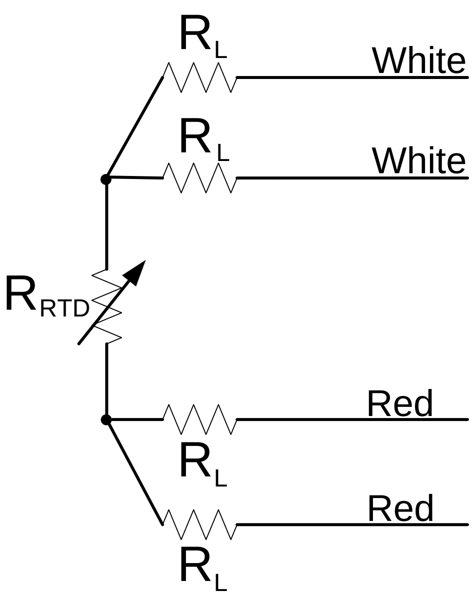
2-Wire



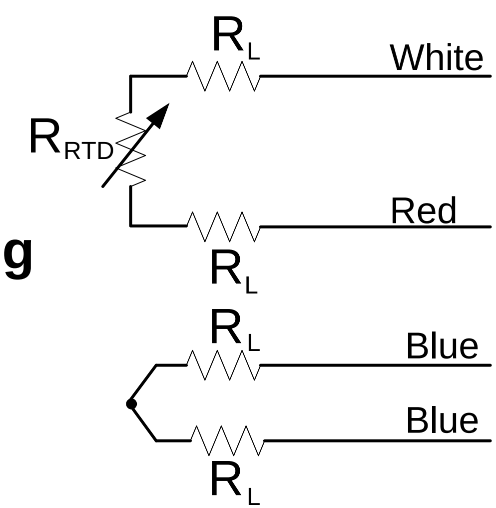
3-Wire



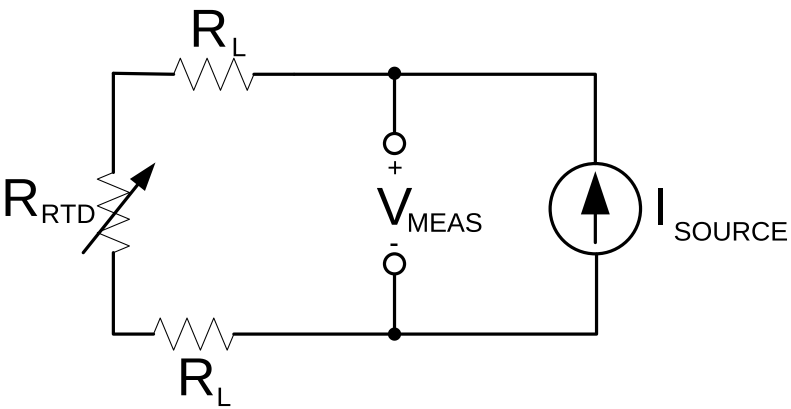
4-Wire



2-Wire with Compensating Loop

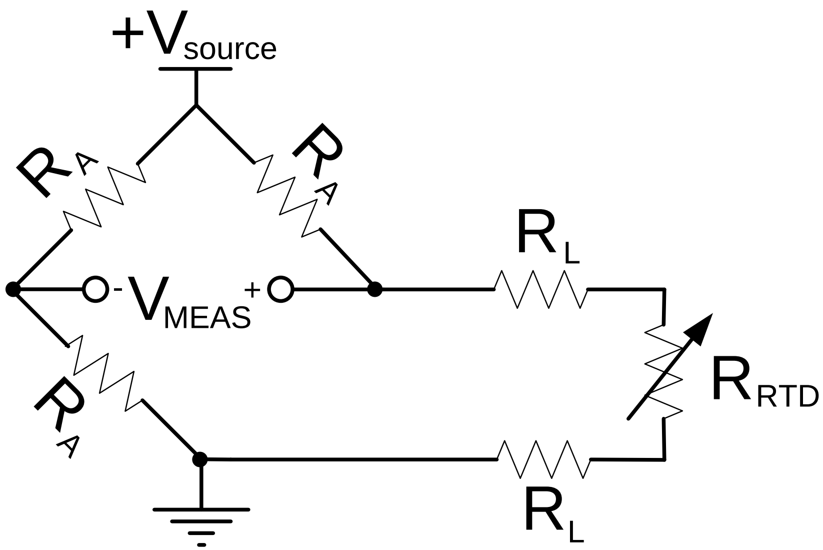


2-Wire Measurements



$$V_{meas} = I_{source} \cdot R_{RTD} + I_{source} \cdot 2 \cdot R_L$$

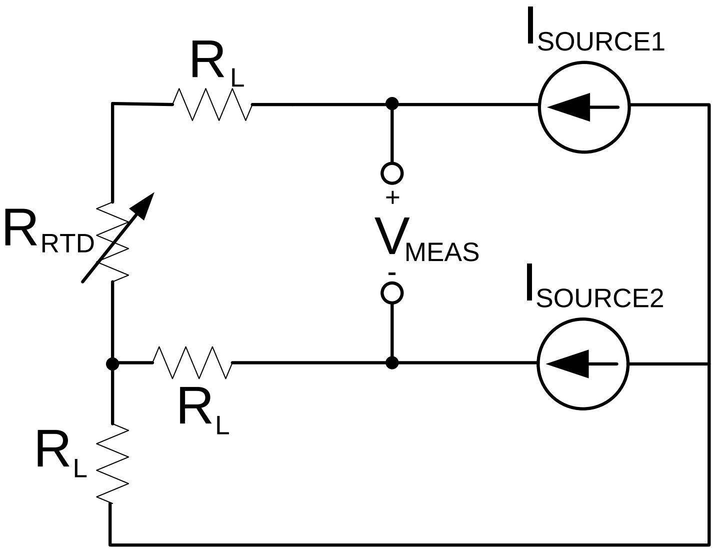
$$Error = I_{source} \cdot 2R_L$$

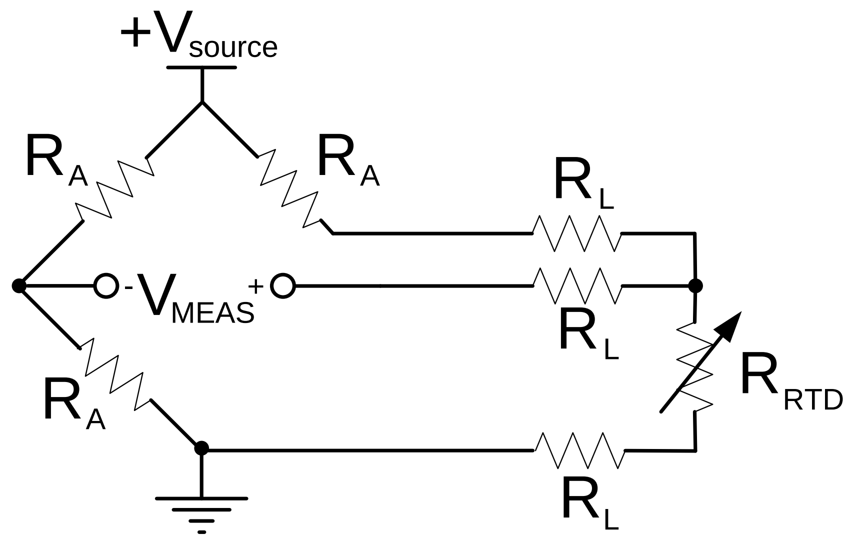


$$V_{meas} = V_{source} \cdot \left[\left(\frac{R_{RTD} + 2R_L}{R_A + R_{RTD} + 2.R_L} \right) - \frac{1}{2} \right]$$

$$Error = V_{source} \left[\frac{2 \cdot R_A \cdot R_L}{(R_A + R_{RTD}) \cdot (R_A + 2 \cdot R_L + R_{RTD})} \right]$$

3-Wire Measurements





$$I_{source1} = I_{source2} = I$$

$$V_{meas_+} = I \cdot R_L + I \cdot R_{RTD} + (2 \cdot I) \cdot R_L = I \cdot R_{RTD} + 3 \cdot I \cdot R_L$$

$$V_{meas_-} = I \cdot R_L + (2 \cdot I) \cdot R_L = 3 \cdot I \cdot R_L$$

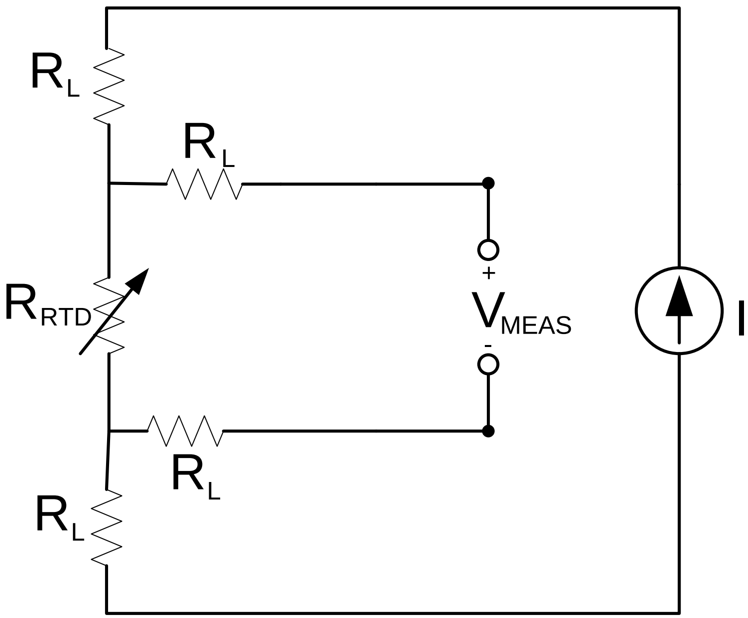
$$V_{meas_+} - V_{meas_-} = \left(I \cdot R_{RTD} + 3 \cdot I \cdot R_L\right) - \left(3 \cdot I \cdot R_L\right) = I \cdot R_{RTD}$$

Error = 0 as long as Isource1 = Isource2 and RL are equal

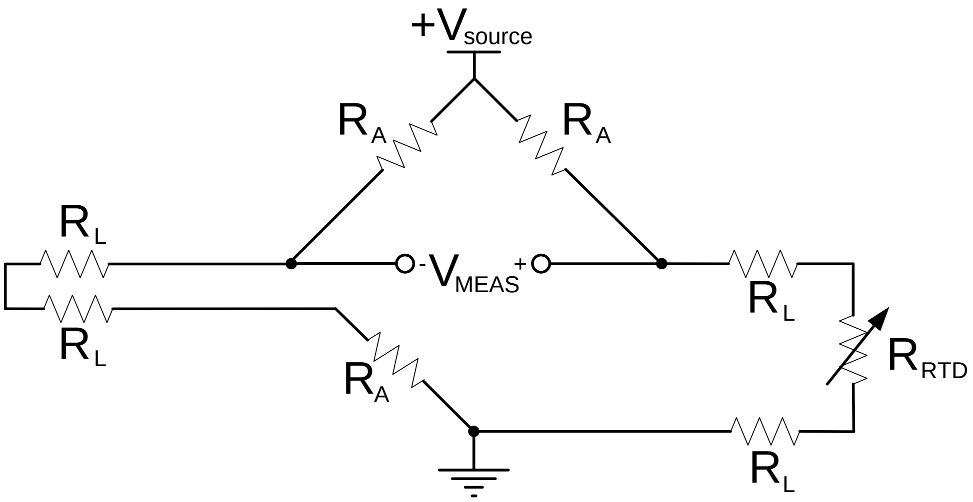
$$V_{meas} = V_{source} \left[\left(\frac{R_{RTD} + R_L}{R_A + R_{RTD} + 2 \cdot R_L} \right) - \frac{1}{2} \right]$$

$$Error = V_{source} \cdot \left[\frac{R_L \cdot \left(R_A - R_{RTD}\right)}{\left(R_A + R_{RTD}\right) \cdot \left(R_A + 2 \cdot R_L + R_{RTD}\right)} \right]$$

4-Wire Measurements



$$V_{meas} = I_{source} \cdot R_{RTD}$$



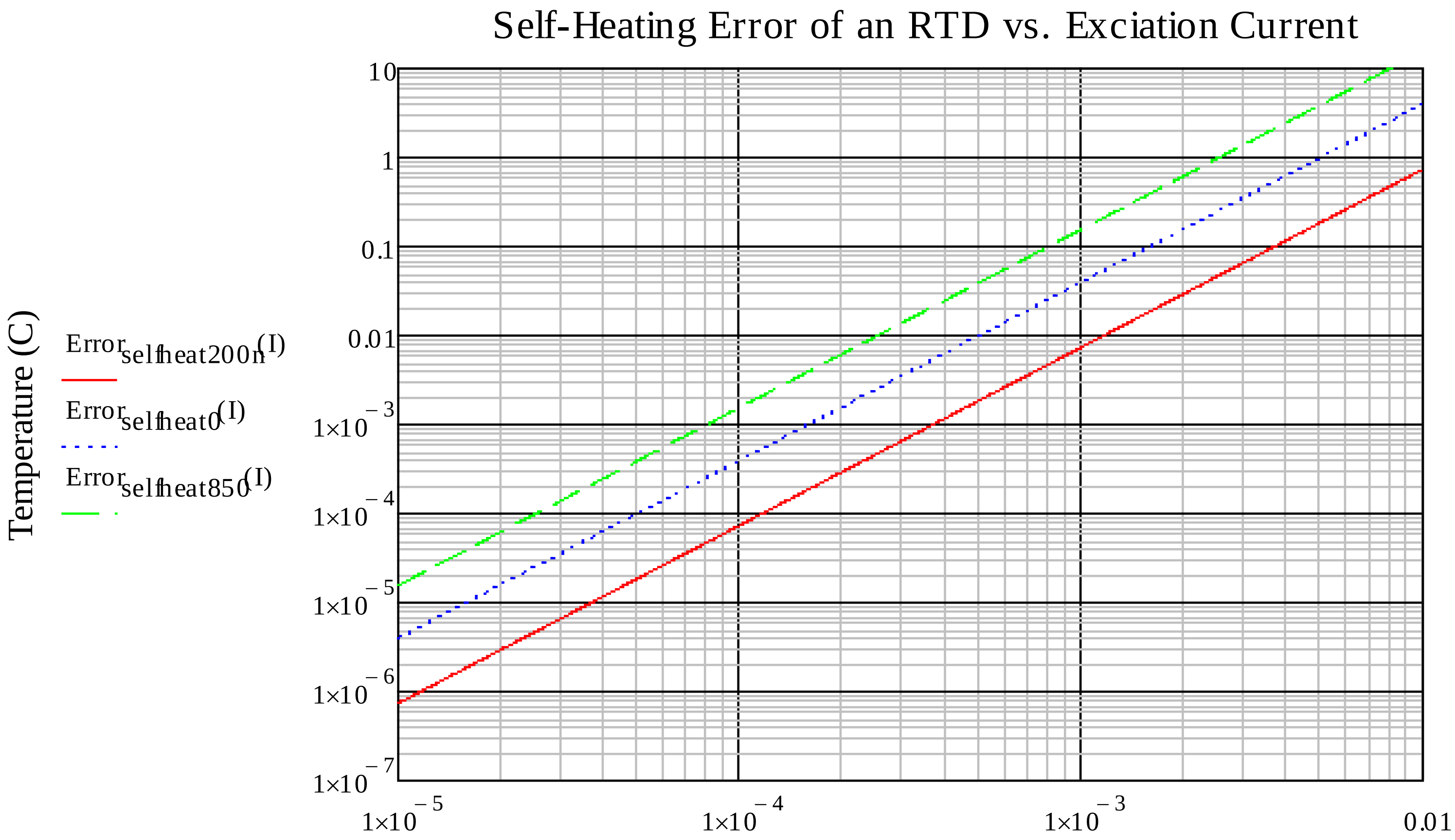
$$Vmeas = -\frac{R_A \cdot V_{source} \cdot (R_A - R_{RTD})}{2 \cdot R_A^2 + 6 \cdot R_A \cdot R_L + 2 \cdot R_{RTD} \cdot R_A + 4 \cdot R_L^2 + 2 \cdot R_{RTD} \cdot R_L}$$

System Errors reduced to measurement circuit accuracy

$$Error = V_{source} \left[\frac{R_L \cdot (2.0 \cdot R_A - 2.0 \cdot R_{RTD})}{(R_A + R_{RTD}) \cdot (R_A + 4.0 \cdot R_L + R_{RTD})} \right]$$

Self-Heating Errors of RTD

- Typically 2.5mW/C – 60mW/C
- Set excitation level so self-heating error is <10% of the total error budget

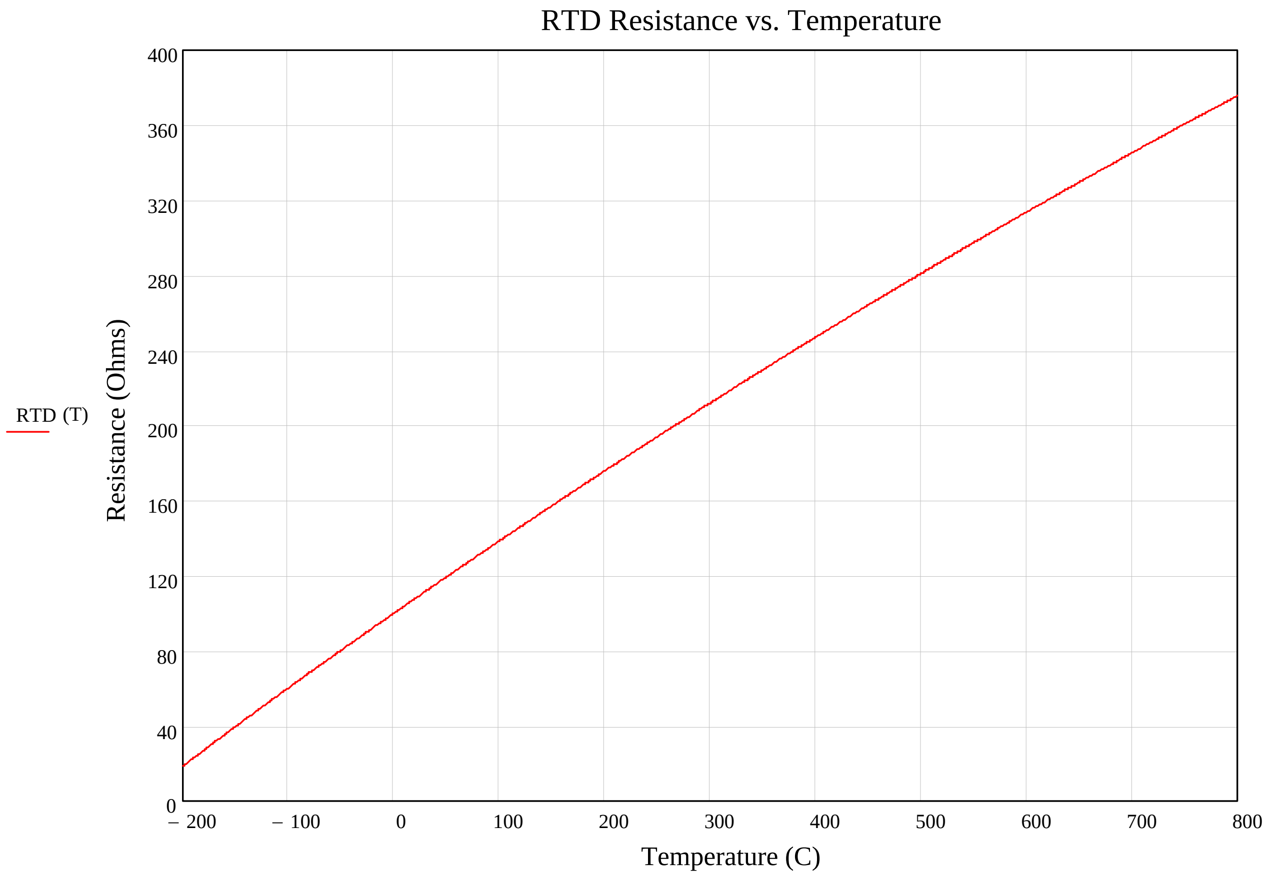


RTD Resistance vs Temperature

Callendar-Van Dusen Equations

For (T > 0) : $RTD(T) := R_0 \cdot \left[1 + A \cdot T + B \cdot \left(T^2\right)\right]$

For (T < 0) : $RTD(T) := R_0 \cdot \left[1 + A \cdot T + B \cdot \left(T^2\right) + C \cdot \left(T^3\right) \cdot (T - 100)\right]$



Equation Constants for IEC 60751 PT-100 RTD (α = 0.00385)

$R_0 := 100$

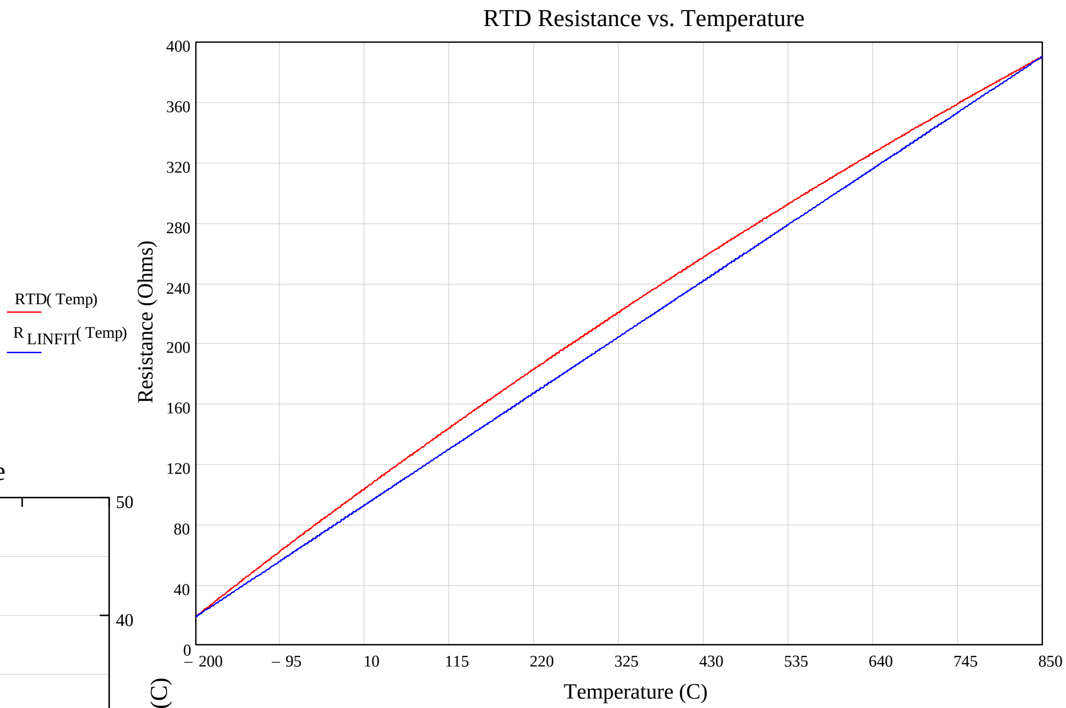
$A := 3.9083 \cdot 10^{-3}$

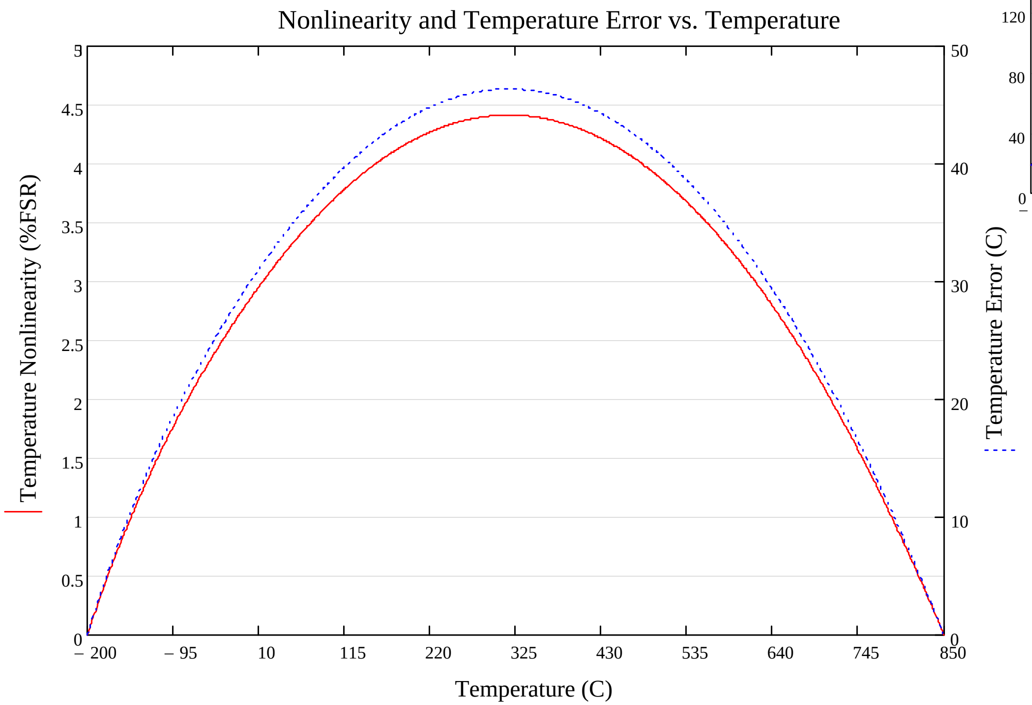
$B := -5.775 \cdot 10^{-7}$

$C := -4.183 \cdot 10^{-12}$

RTD Nonlinearity

Linear fit between the two end-points shows the Full-Scale nonlinearity





Nonlinearity = 4.5%

Temperature Error > 45C

RTD Nonlinearity

For (T > 0) : $RTD(T) := R_0 \cdot \left[1 + A \cdot T + B \cdot \left(T^2\right)\right]$

For (T < 0) : $RTD(T) := R_0 \cdot \left[1 + A \cdot T + B \cdot \left(T^2\right) + C \cdot \left(T^3\right) \cdot (T - 100)\right]$

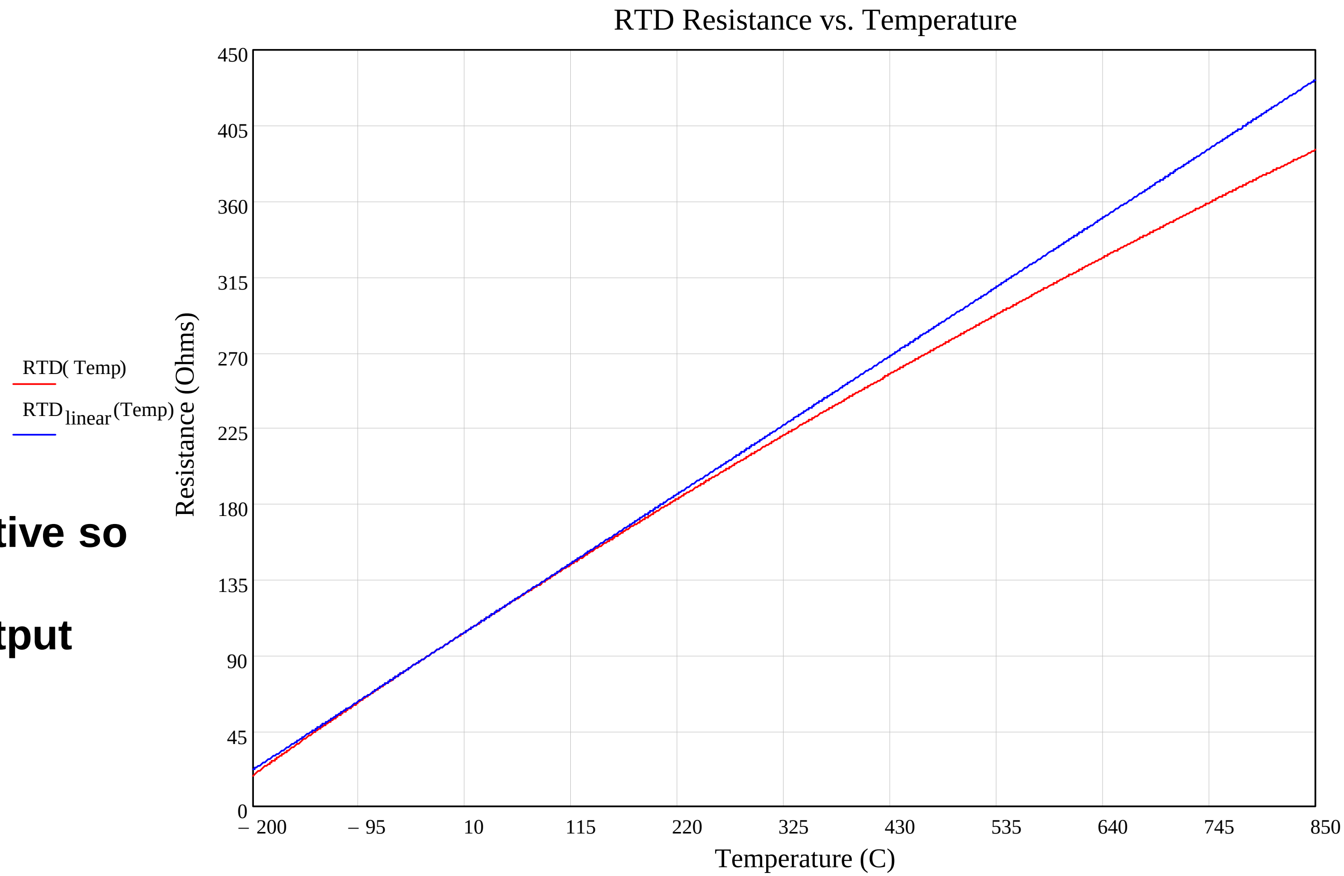
$RTD_{linear}(T) := R_0 \cdot (1 + A \cdot T)$

$R_0 := 100$

$A := 3.9083 \cdot 10^{-3}$

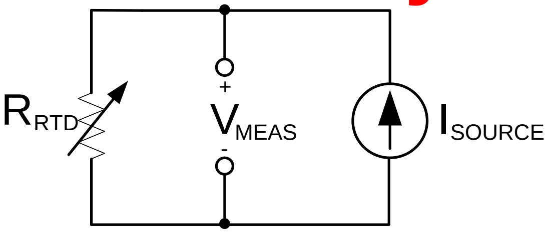
$B := -5.775 \cdot 10^{-7}$

$C := -4.183 \cdot 10^{-12}$

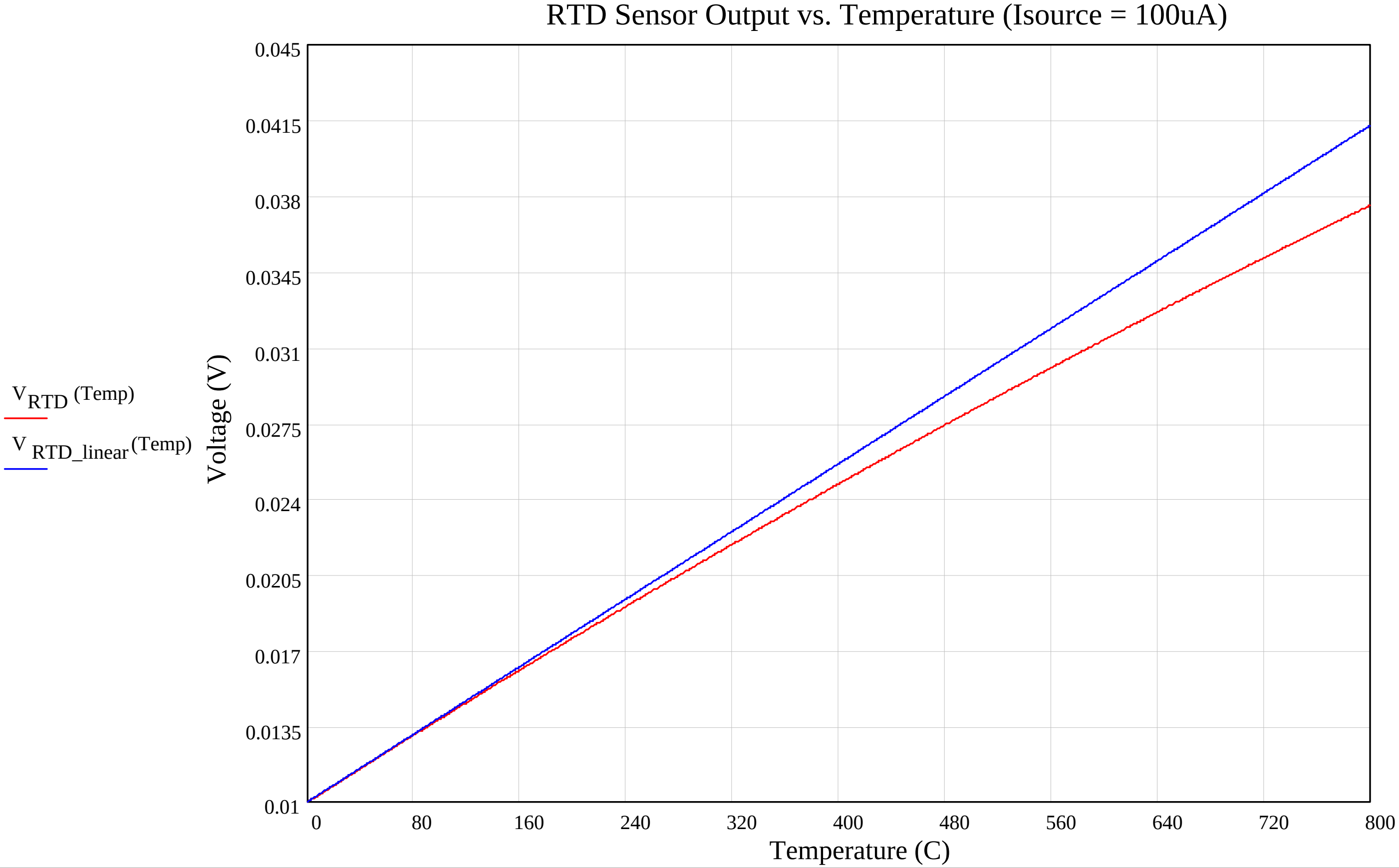


B and C terms are negative so 2nd and 3rd order effects decrease the sensor output over the sensor span.

Measurement Nonlinearity

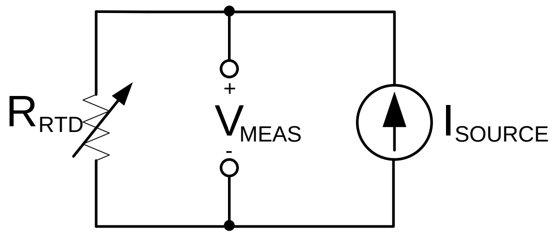


$$V_{meas} = I_{source} \cdot R_{RTD}$$

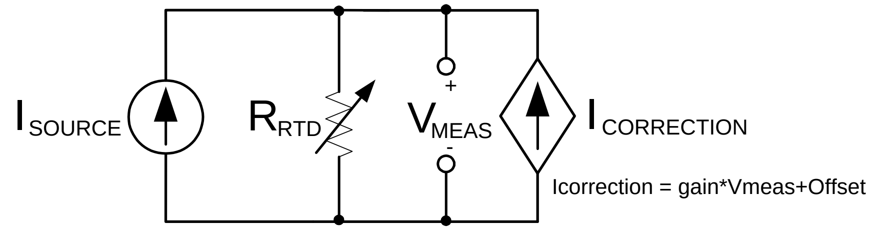


Correcting for Non-Linearity

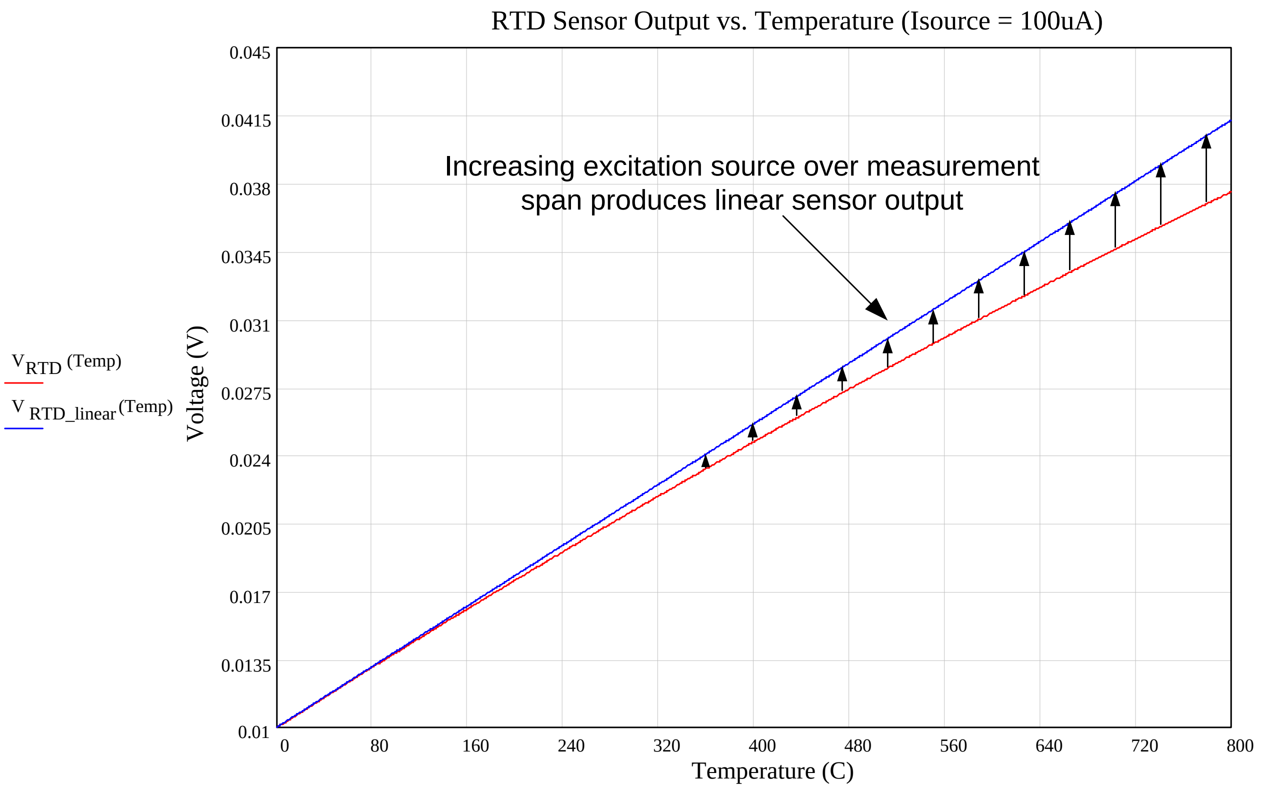
Sensor output decreases over span? Compensate by increasing excitation over span!



$$V_{meas} = I_{source} \cdot R_{RTD}$$



$$V_{meas} = (I_{source} + I_{correction}) \cdot R_{RTD}$$



Correcting for Non-linearity

$$I_{source} := 0.0005$$

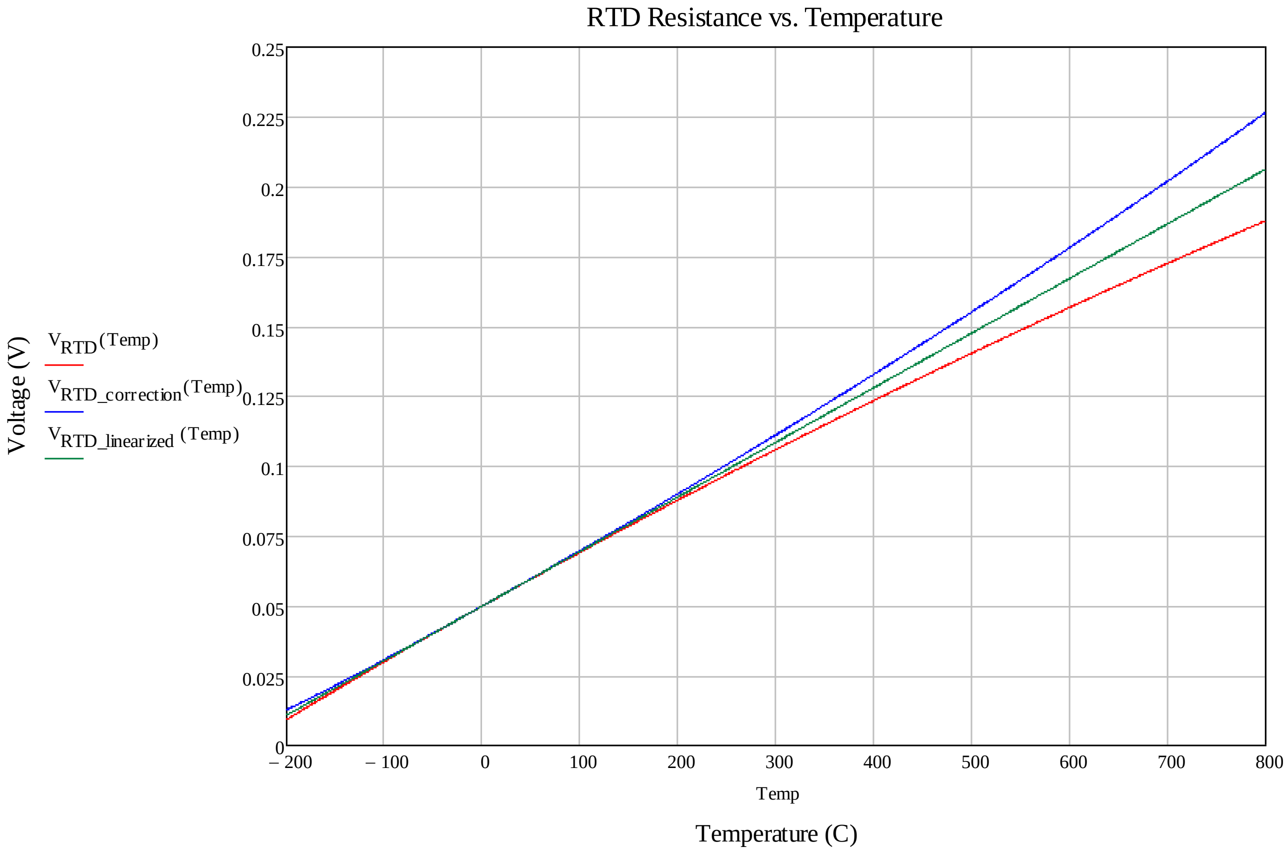
$$V_{RTD}(T) := RTD(T) \cdot I_{source}$$

$$V_{RTD\_linear}(T) := RTD_{linear}(T) \cdot I_{source}$$

$$I_{source\_correction}(T) := I_{source} + \frac{\left(V_{RTD\_linear}(T) - V_{RTD}(T)\right)}{RTD(T)}$$

$$V_{RTD\_correction}(T) := RTD_{linear}(T) \cdot I_{source\_correction}(T)$$

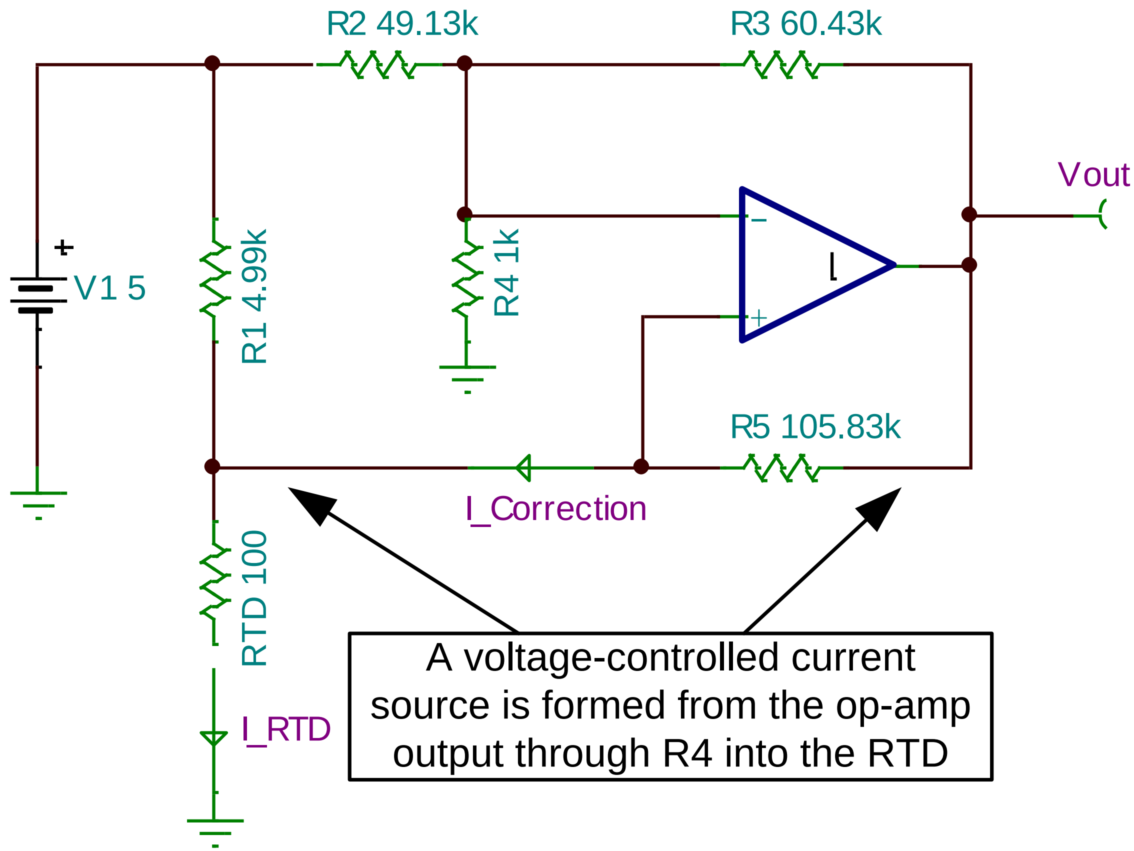
$$V_{RTD\_linearized}(T) := I_{source\_correction}(T) \cdot RTD(T)$$



Analog Linearization Circuits

Analog Linearization Circuits

Two-Wire Single Op-Amp



Example Amplifiers:

Low-Voltage:

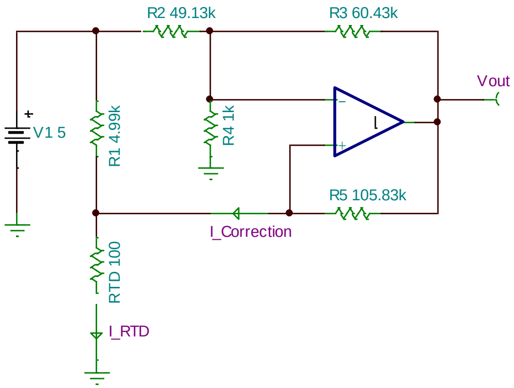
OPA333
OPA376

High Voltage:
OPA188
OPA277

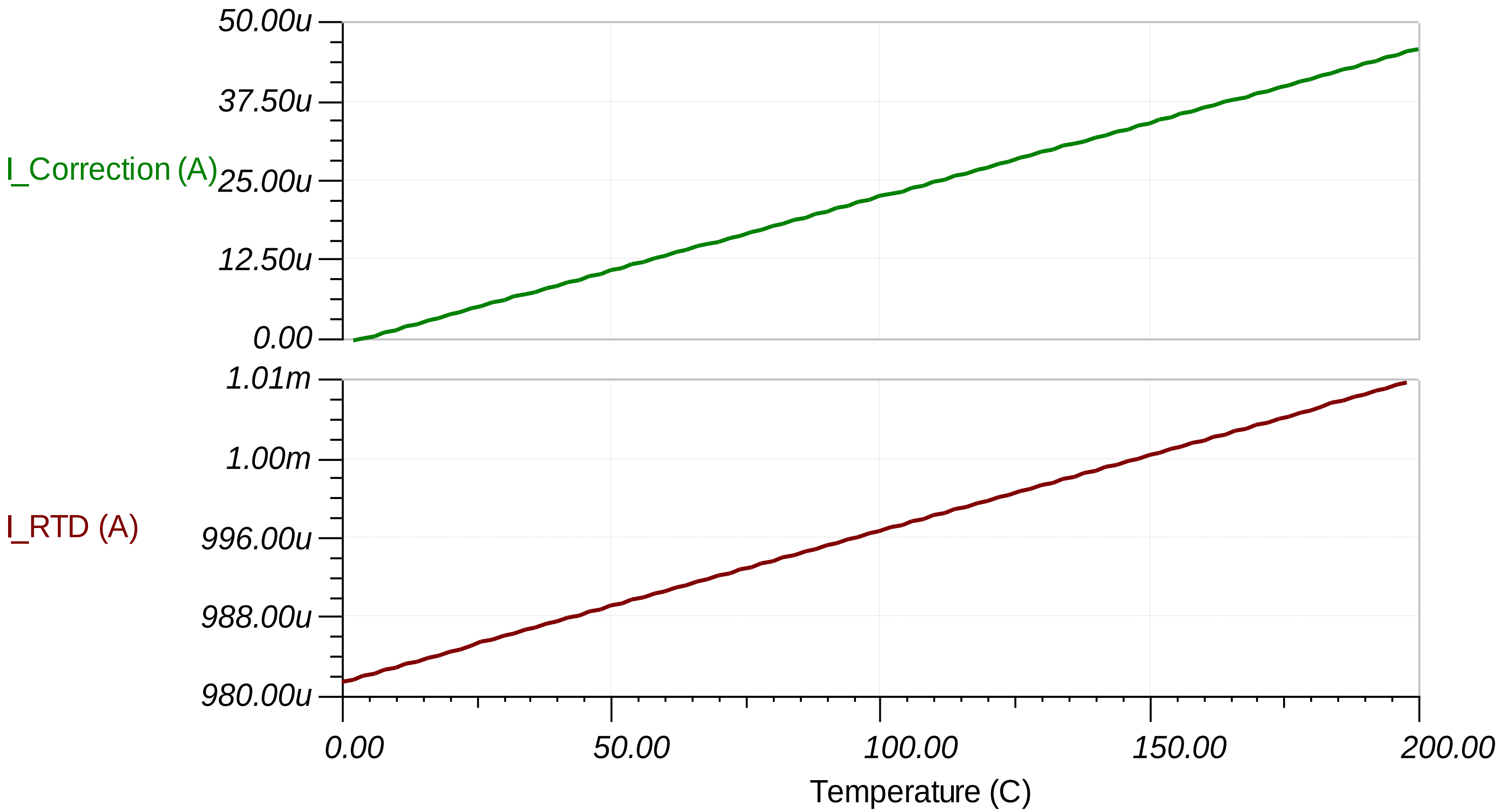
This circuit is designed for a 0-5V output for a 0-200C temperature span. Components R2, R3, R4, and R5 are adjusted to change the desired measurement temperature span and output.

Analog Linearization Circuits

Two-Wire Single Op-Amp



Non-linear increase in excitation current over temperature span will help correct non-linearity of RTD measurement



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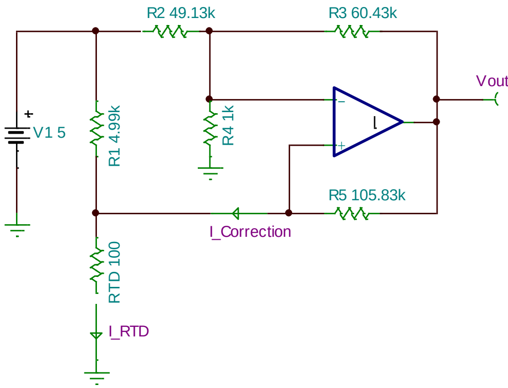
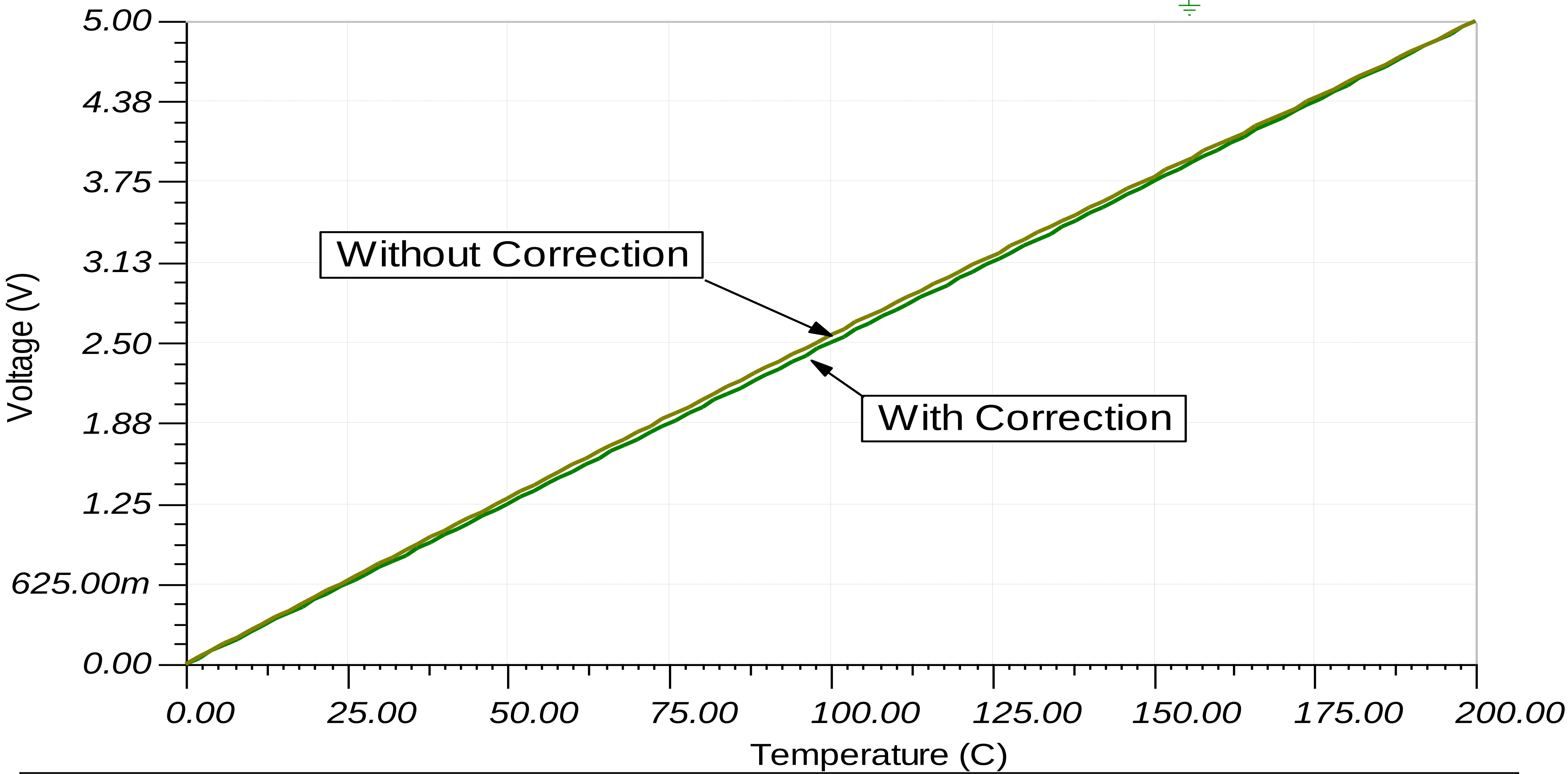
Analog Linearization Circuits

Two-Wire Single Op-Amp

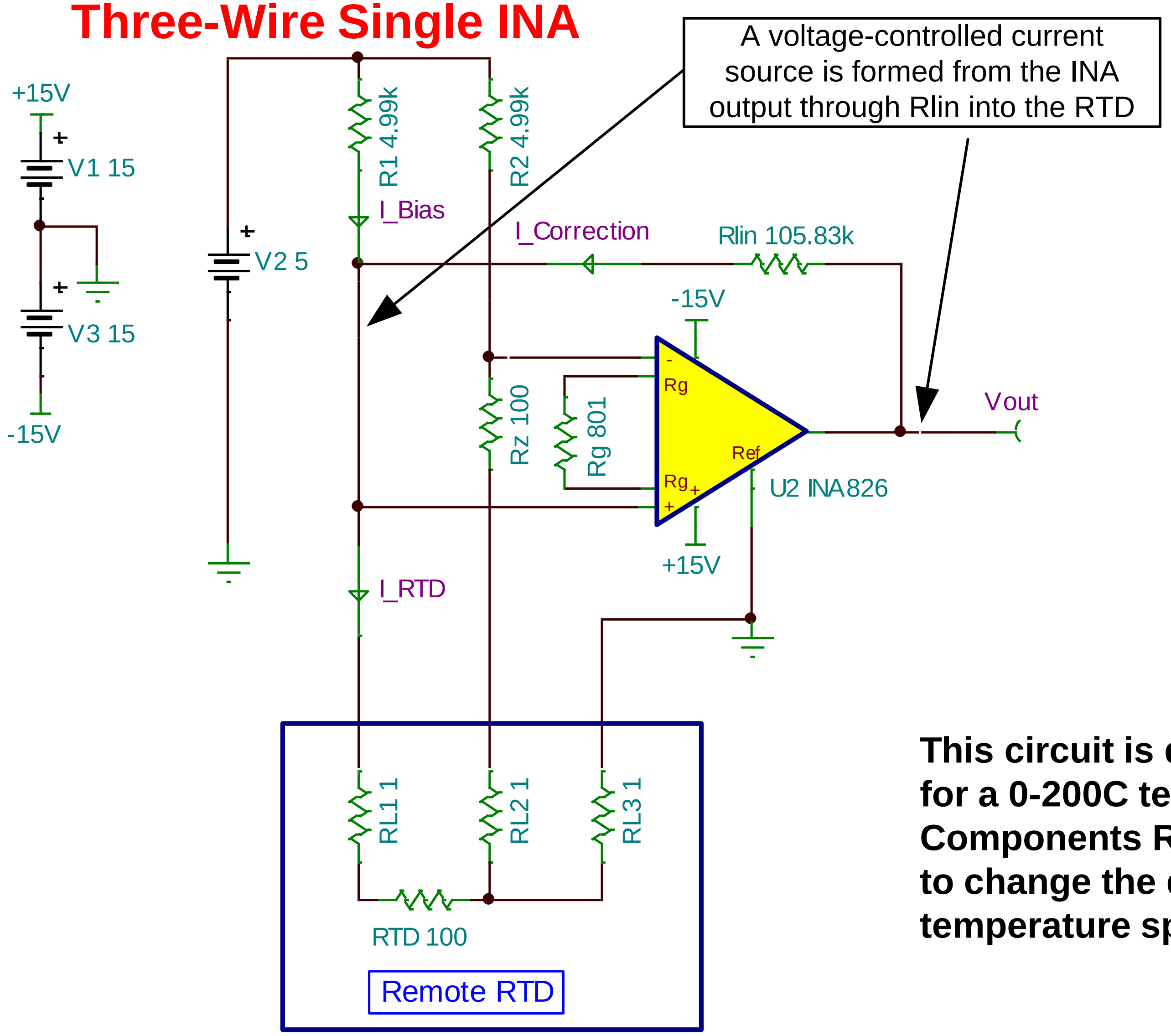


This type of linearization typically provides a 20X - 40X improvement in linearity



Analog Linearization Circuits

Three-Wire Single INA



Example Amplifiers:

Low-Voltage:

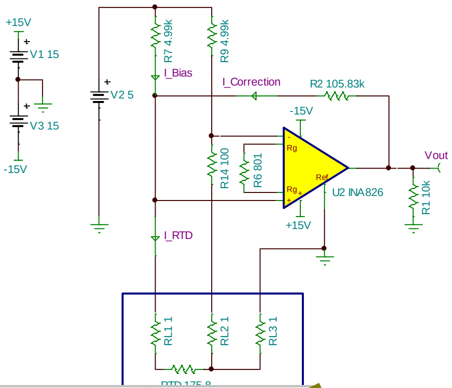
INA333
INA114

High Voltage
INA826
INA114

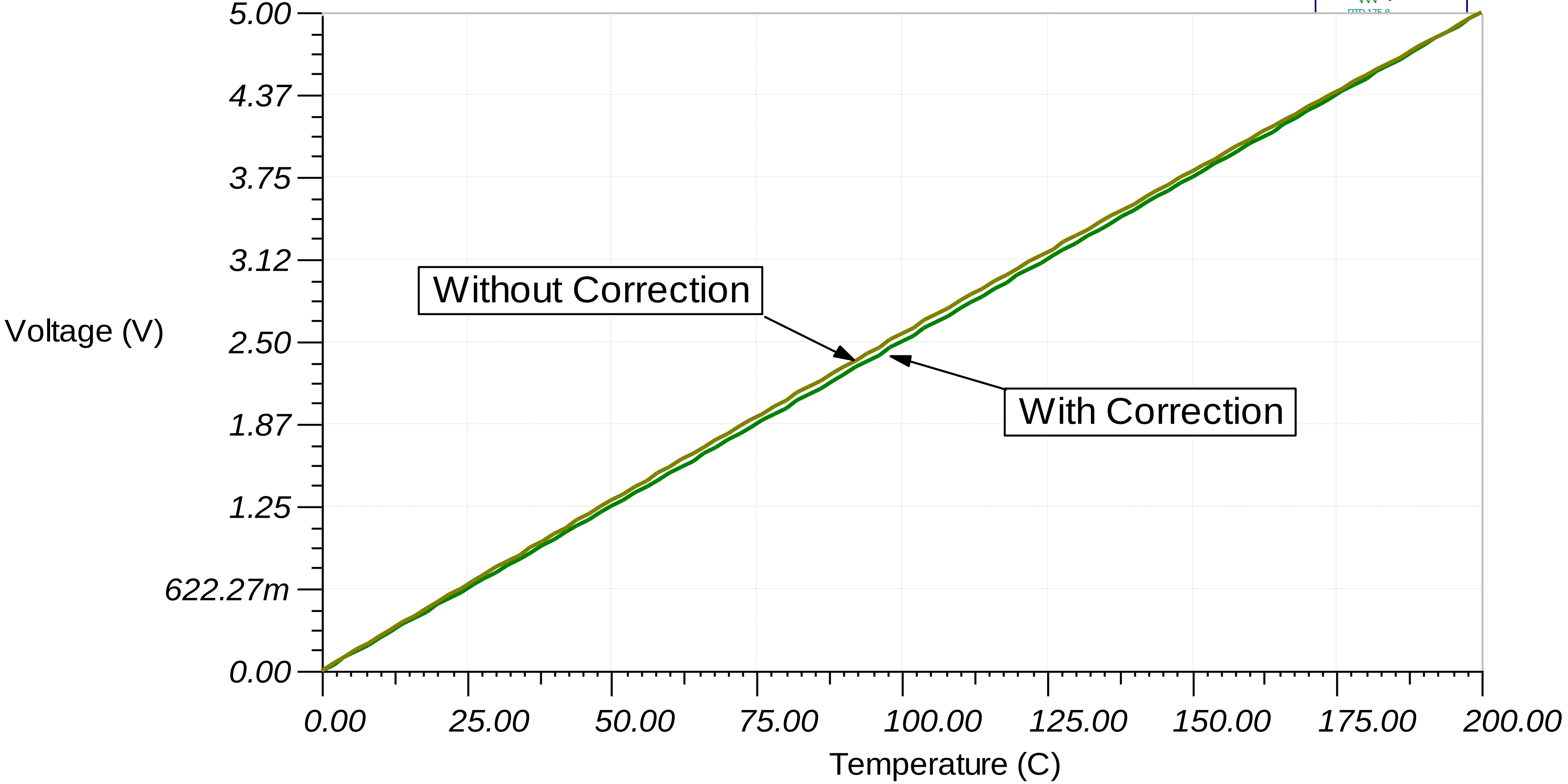
This circuit is designed for a 0-5V output for a 0-200C temperature span. Components Rz, Rg, and Rlin are adjusted to change the desired measurement temperature span and output.

Analog Linearization Circuits

Three-Wire Single INA

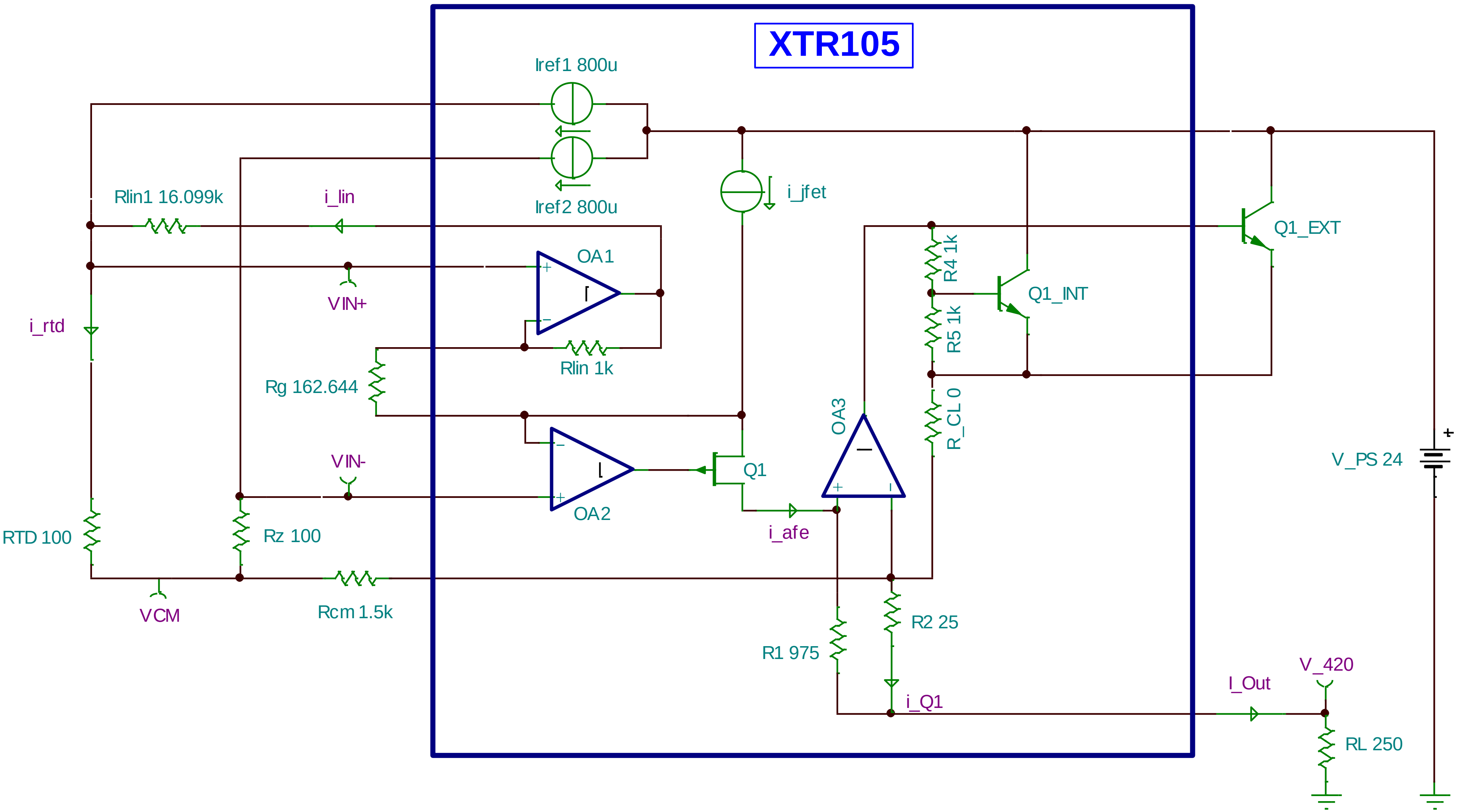


This type of linearization typically provides a 20X - 40X improvement in linearity and some lead resistance cancellation



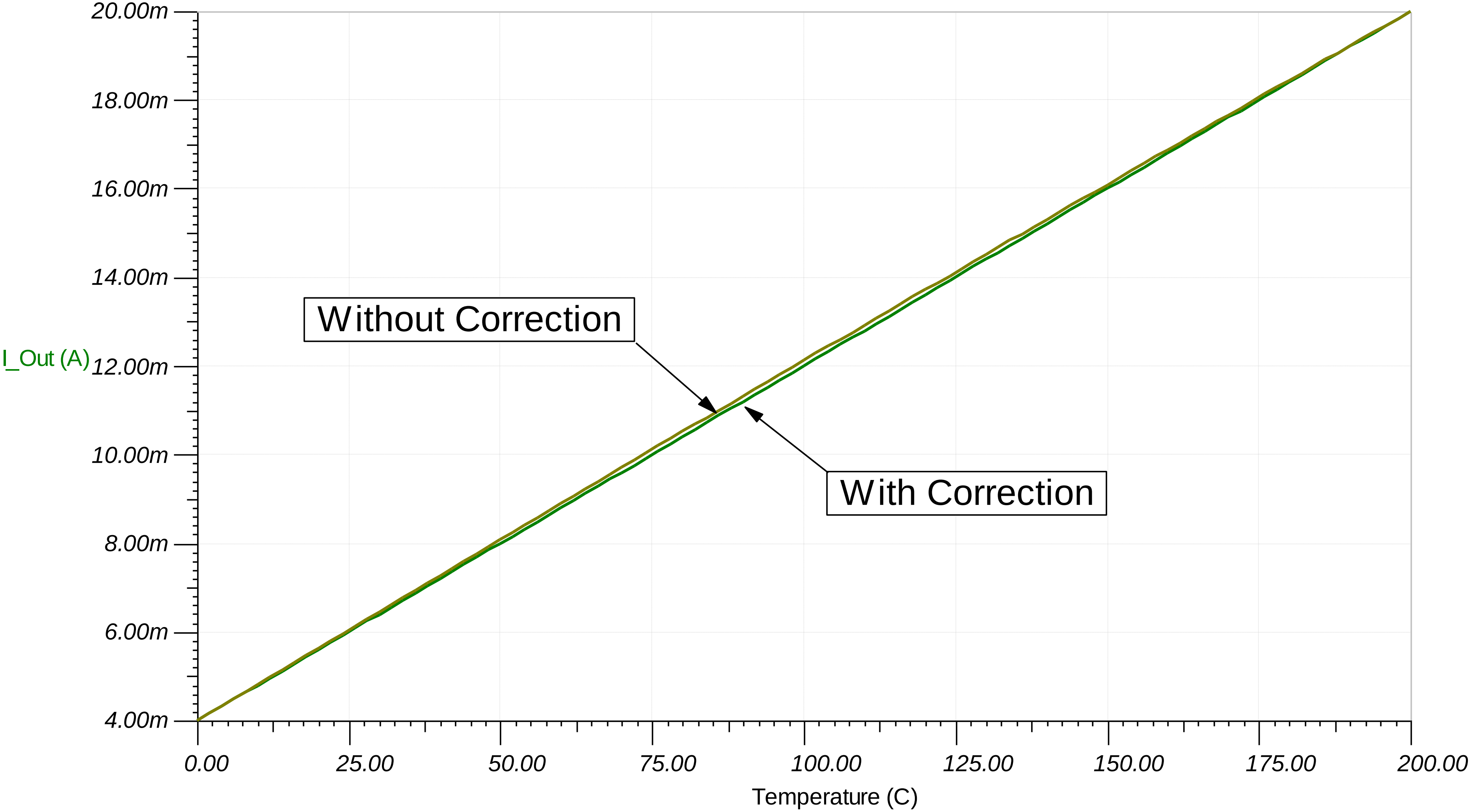
Analog Linearization Circuits

XTR105 4-20mA Current Loop Output



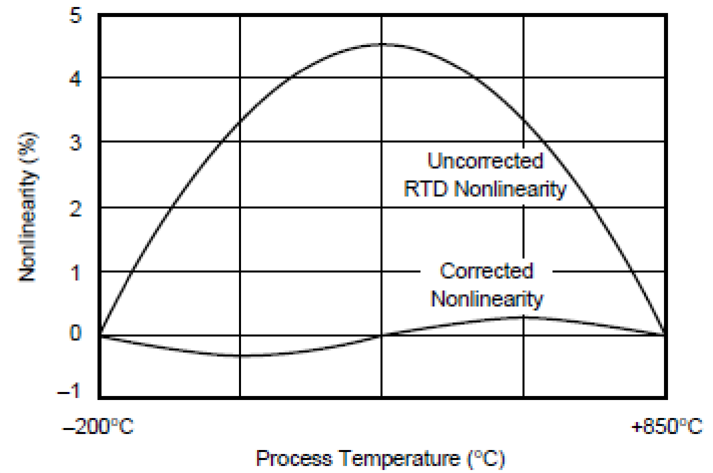
Analog Linearization Circuits

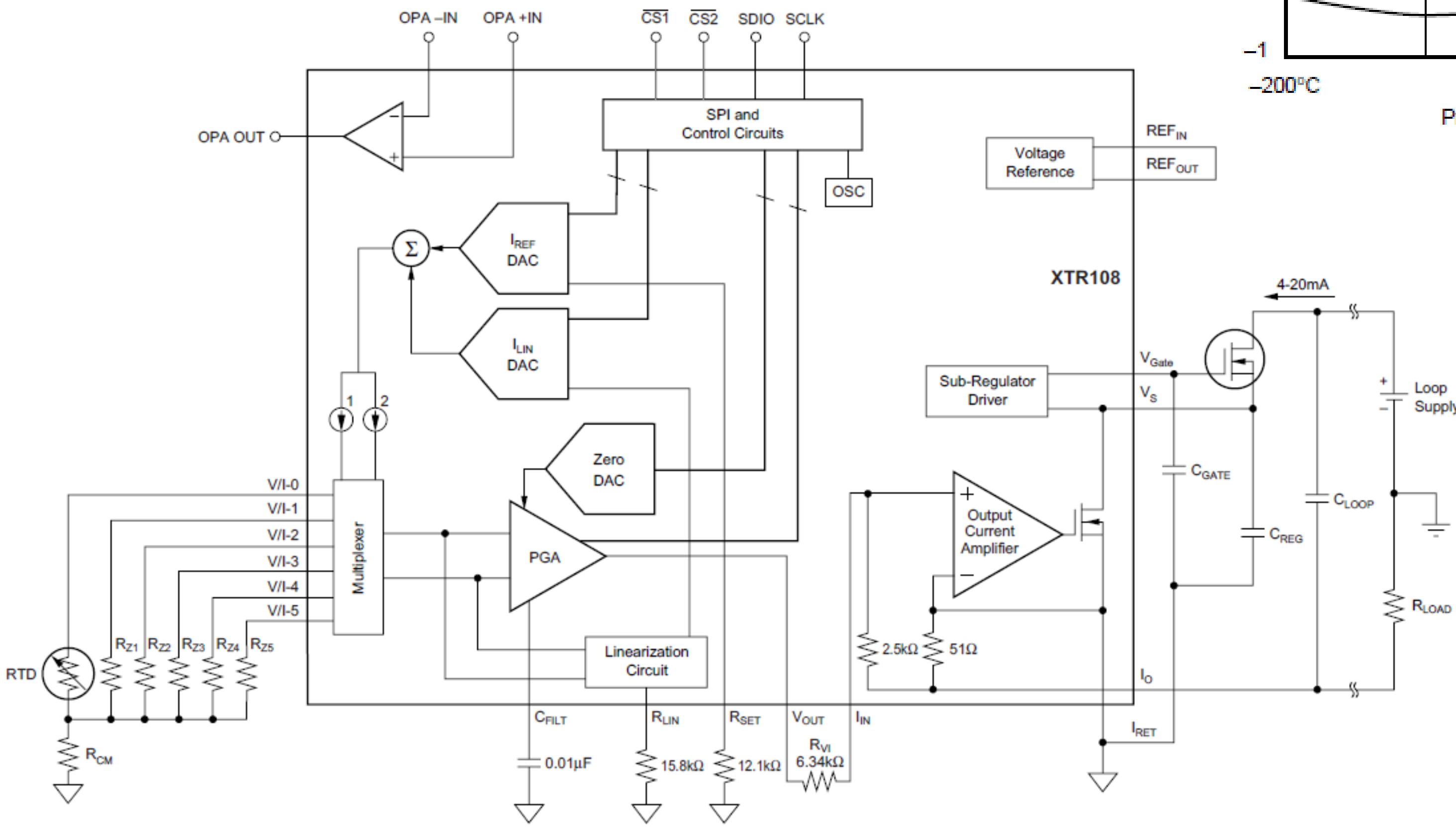
XTR105 4-20mA Current Loop Output



Analog + Digital Linearization Circuits

XTR108 4-20mA Current Loop Output

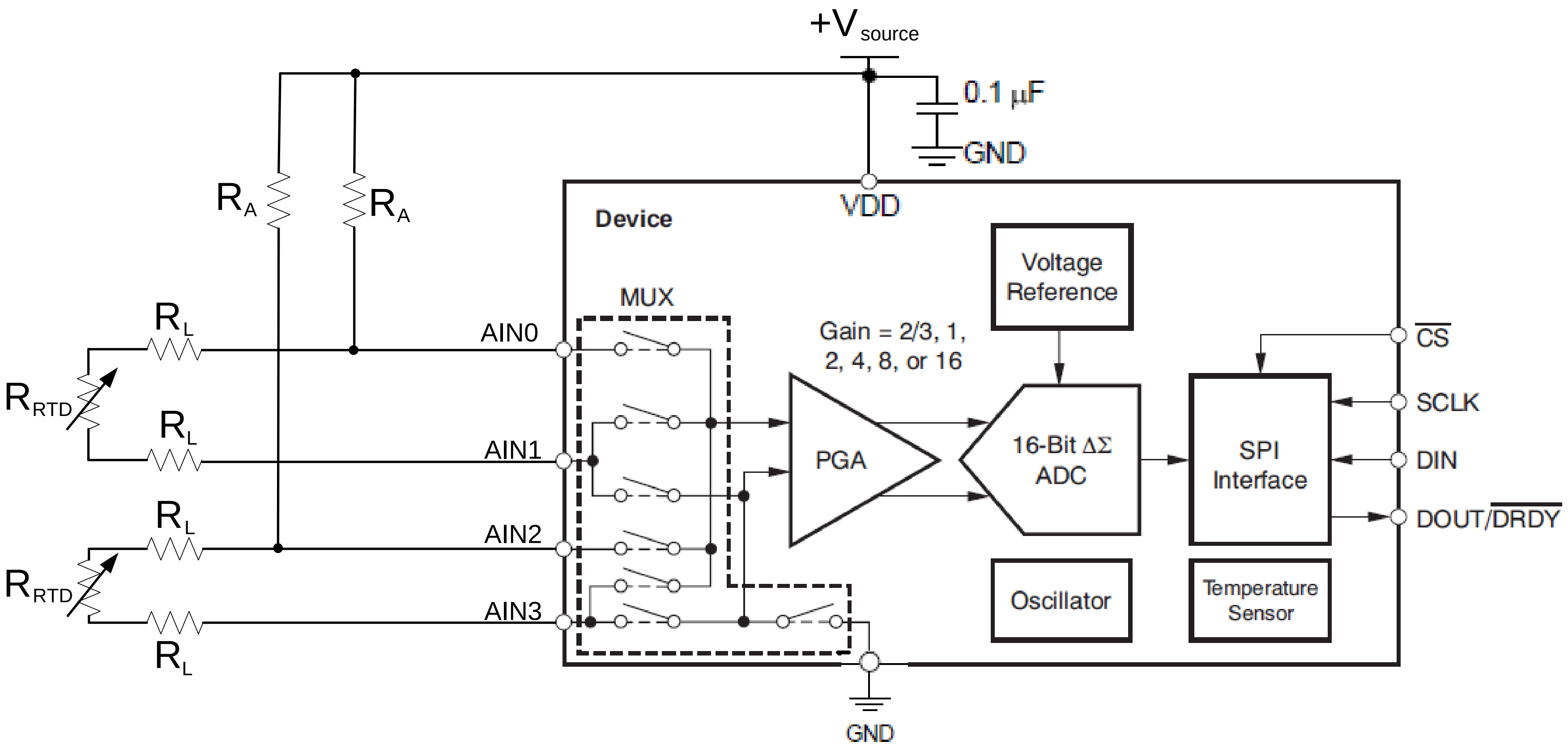




Digital Acquisition Circuits and Linearization Methods

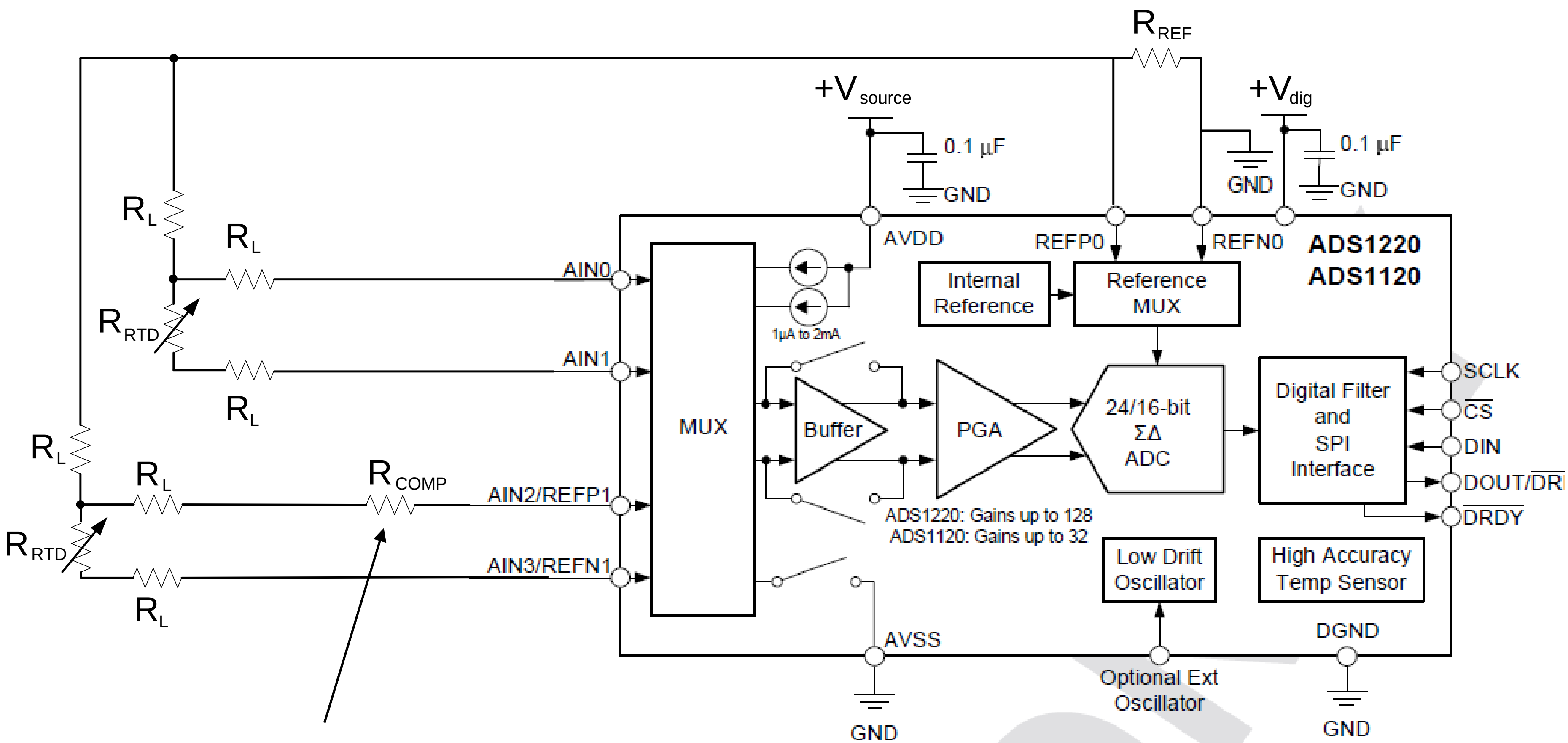
Digital Acquisition Circuits

ADS1118 16-bit Delta-Sigma 2-Wire Measurement with Half-Bridge



Digital Acquisition Circuits

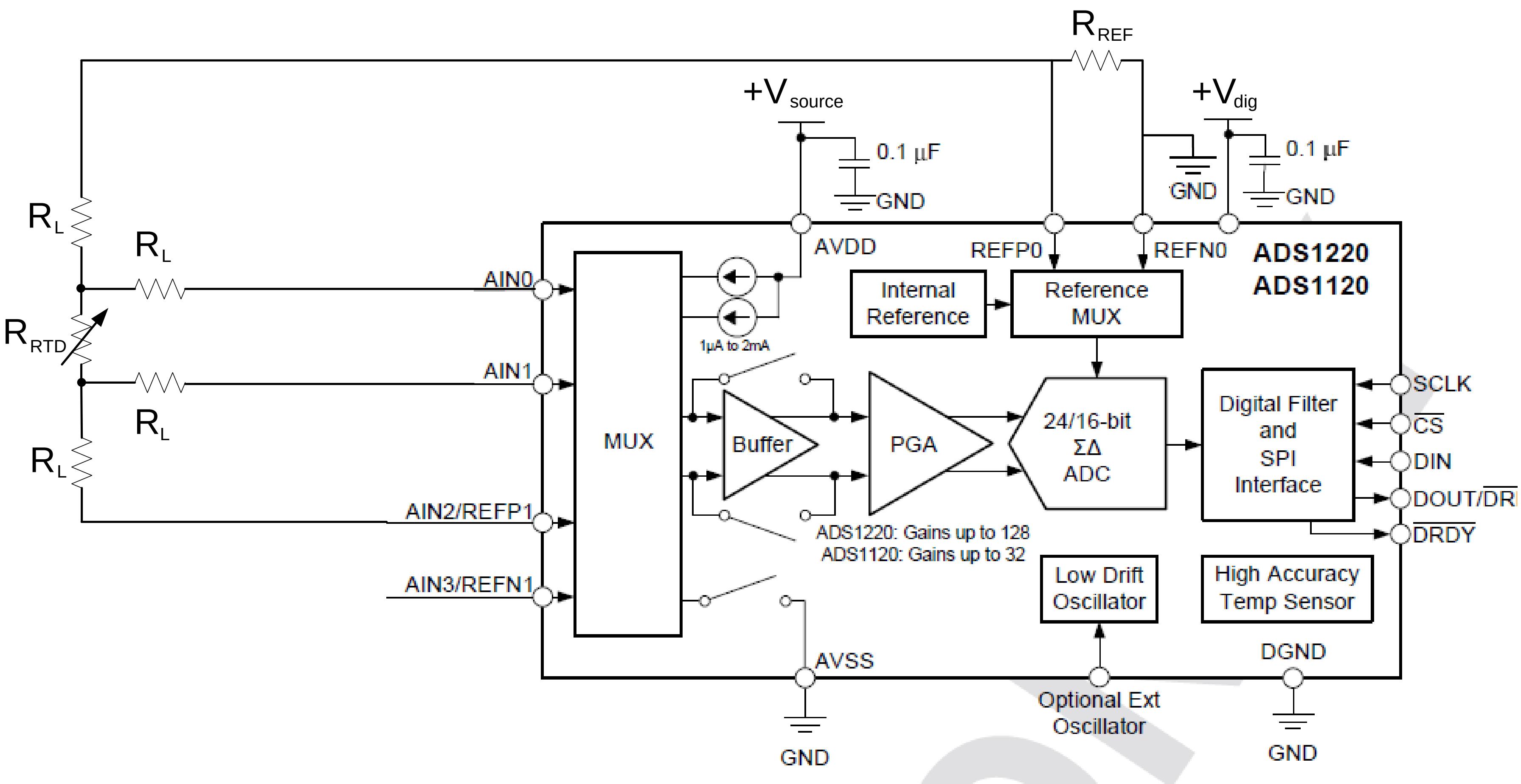
ADS1220 24-bit Delta-Sigma Two 3-wire RTDs



3-wire + Rcomp shown for AIN2/AIN3

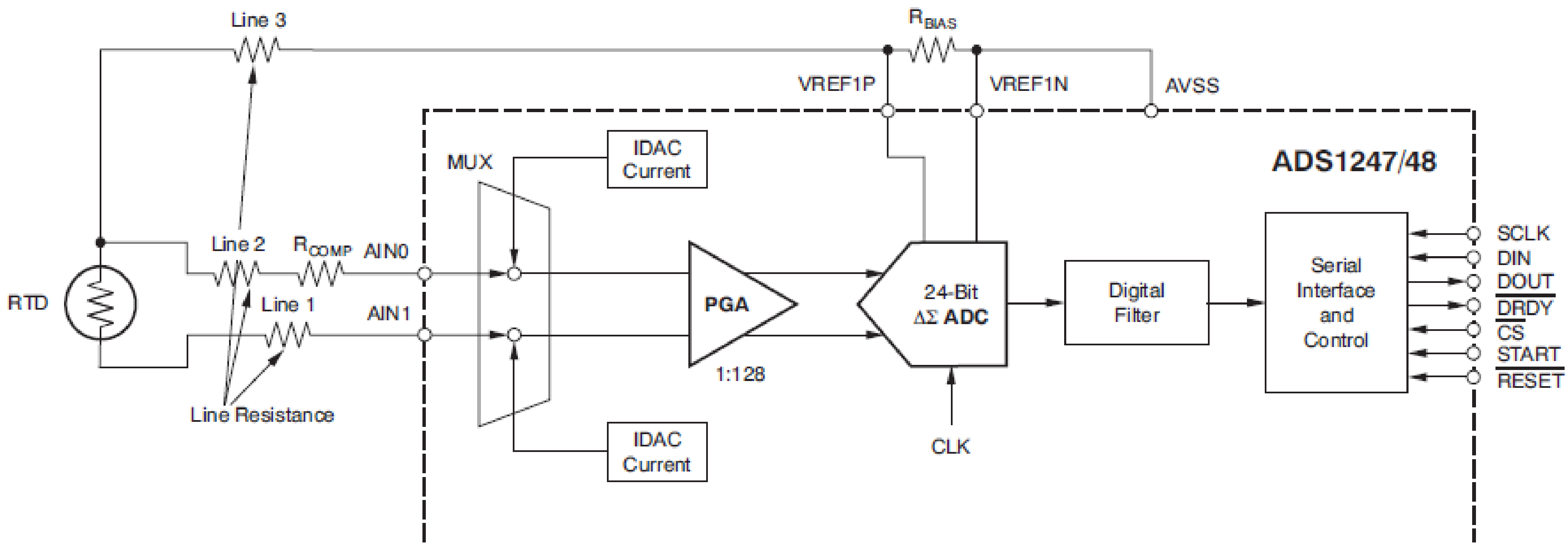
Digital Acquisition Circuits

ADS1220 24-bit Delta-Sigma One 4-Wire RTD



Digital Acquisition Circuits

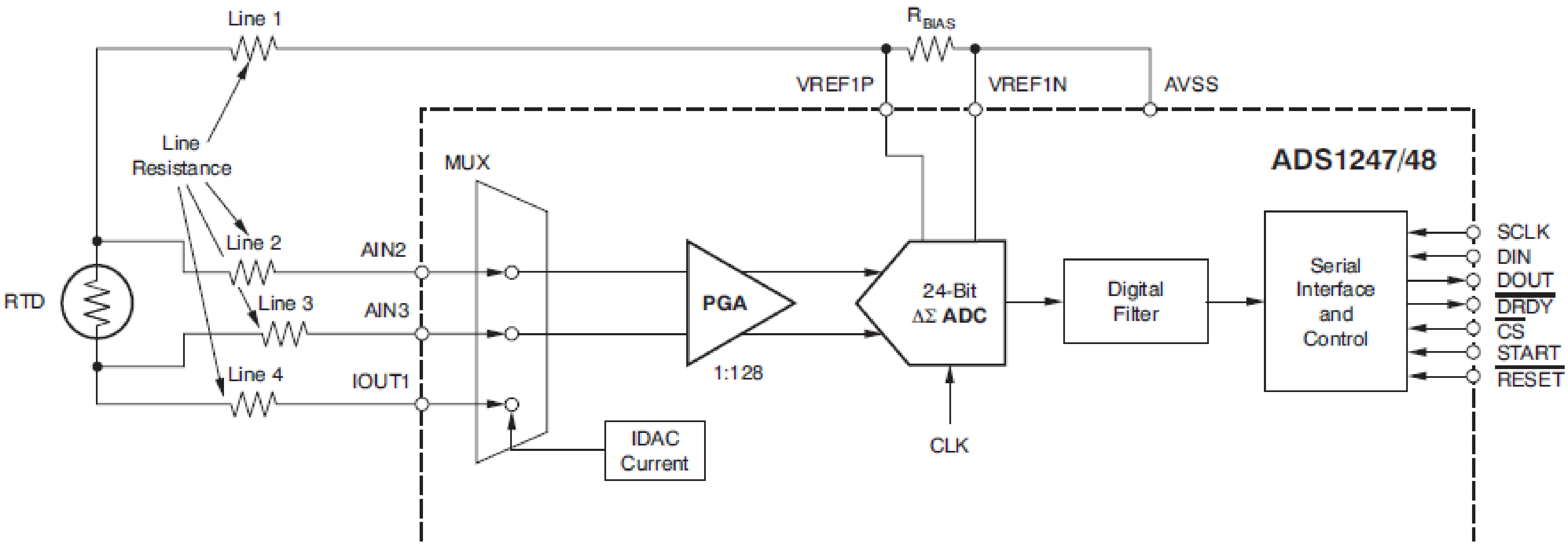
ADS1247 24-bit Delta-Sigma Three-Wire + Rcomp



Note: R_{BIAS} and R_{COMP} should be as close to the ADC as possible.

Digital Acquisition Circuits

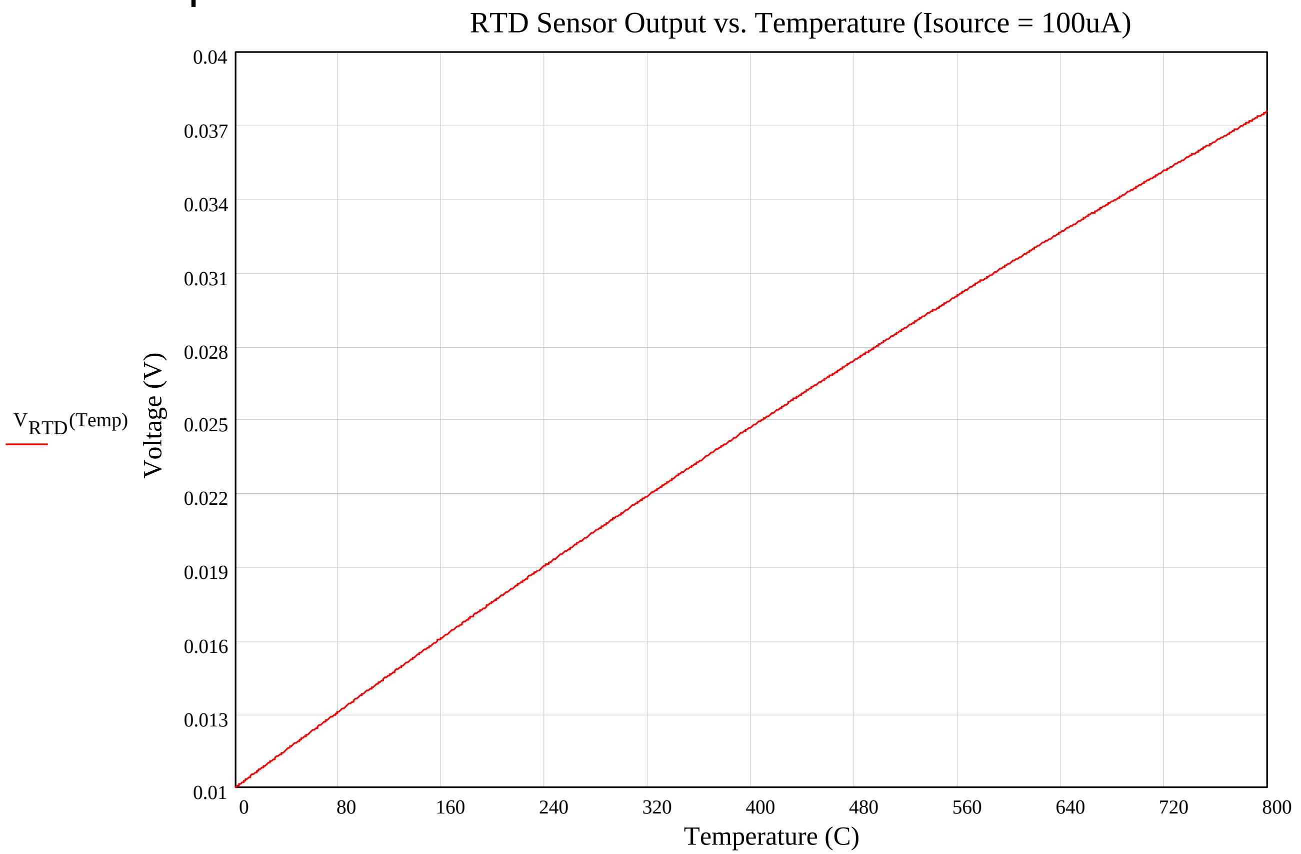
ADS1247 24-bit Delta-Sigma Four-Wire



Note: R_{BIAS} should be as close to the ADC as possible.

Digital Linearization Methods

- Three main options
  - Linear-Fit
  - Piece-wise Linear Approximations
  - Direct Computations



Digital Linearization Methods

Linear Fit

Pro's:

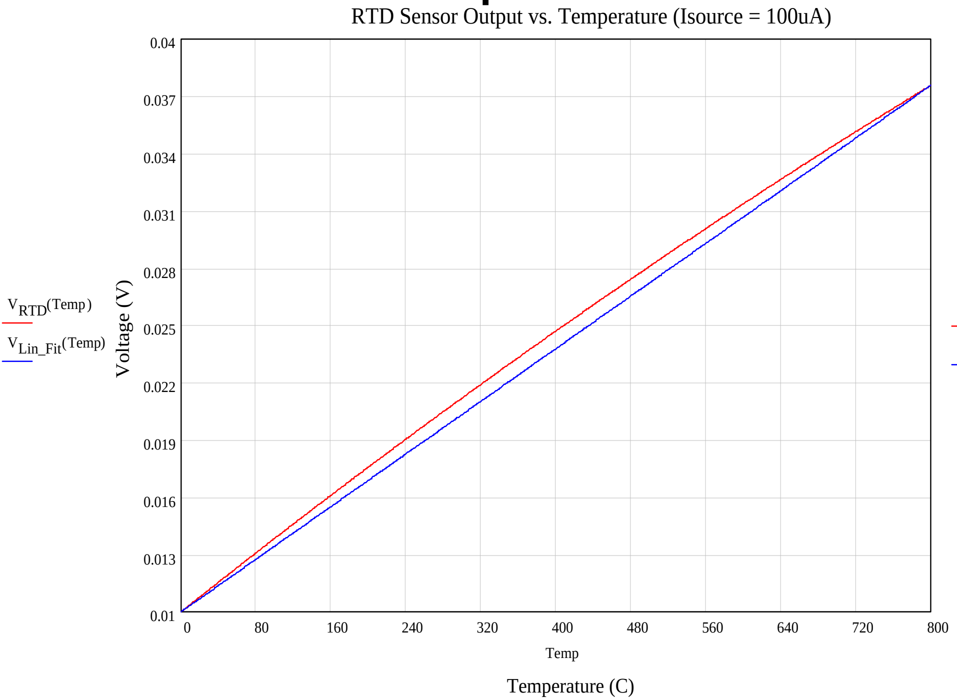
- **Easiest to implement**
- **Very Fast Processing Time**
- **Fairly accurate over small temp span**

Con's:

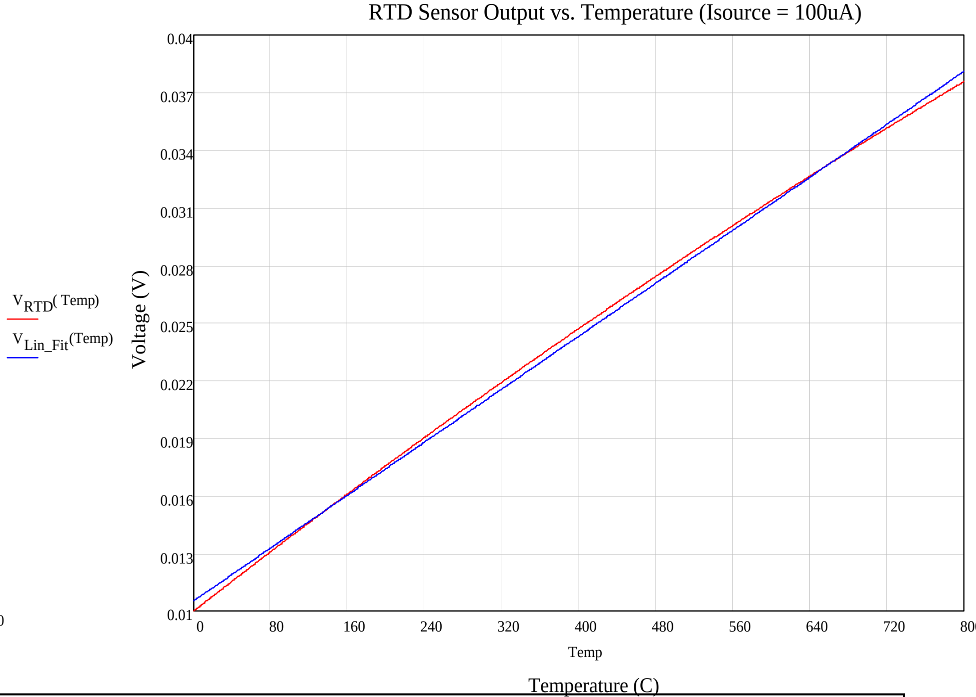
Least Accurate

$$T_{Linear}(t) = A \cdot RTD(t) + B$$

End-point Fit



Best-Fit



Digital Linearization Methods

Piece-wise Linear Fit

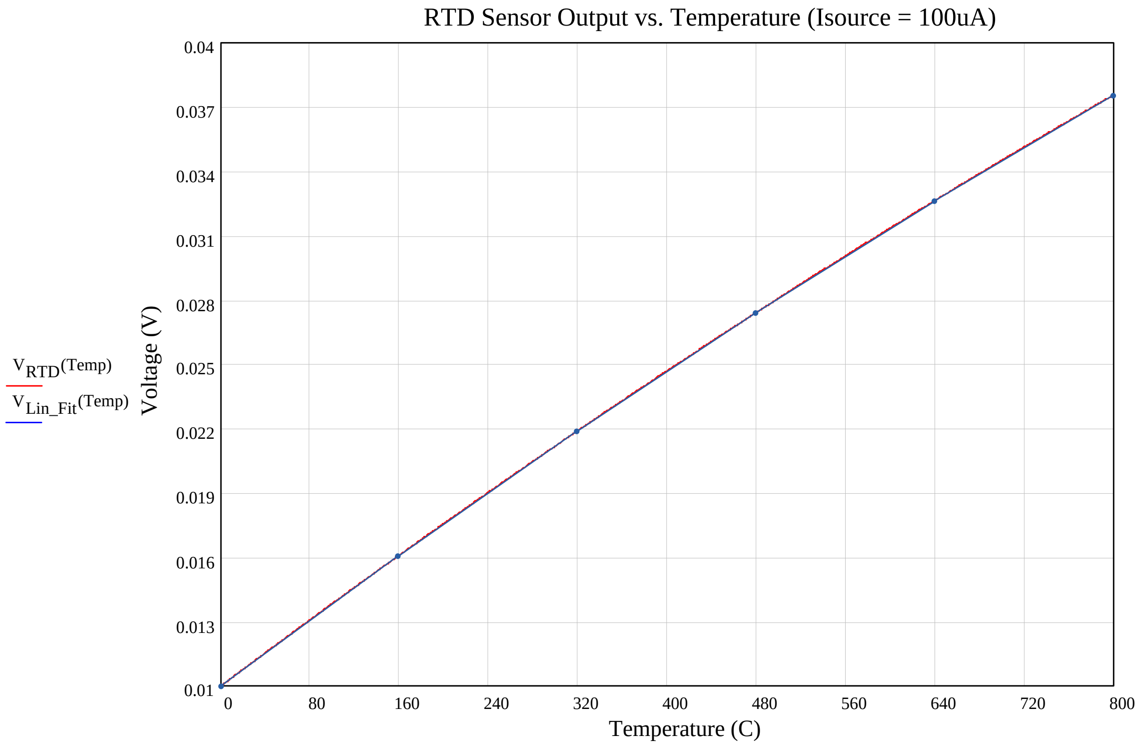
Pro's:

- **Easy to implement**
- **Fast Processing Time**
- **Programmable accuracy**

Con's:

- **Code size required for coefficients**

$$T_{Peicewise} = T(n-1) + (T(n) - T(n-1))\left(\frac{RTD - RTD(n-1)}{RTD(n) - RTD(n-1)}\right)$$



Digital Linearization Methods

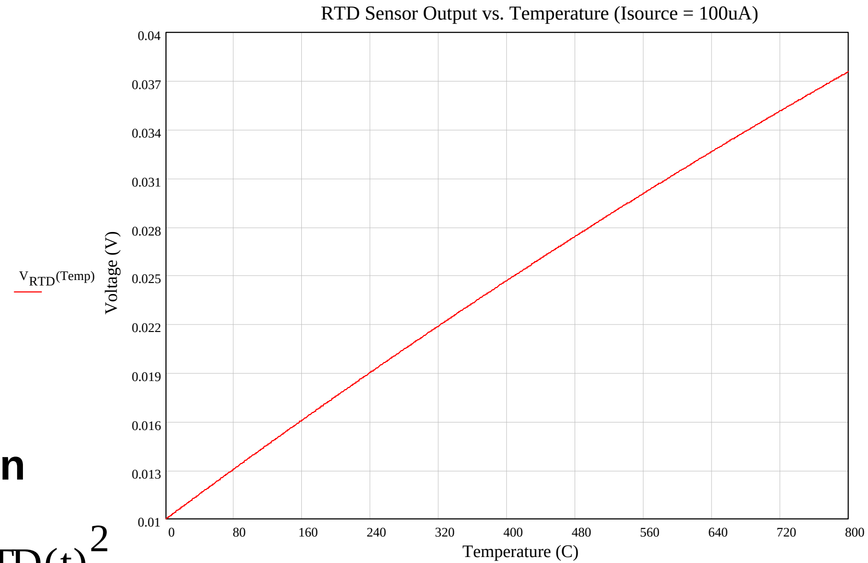
Direct Computation

Pro's:

- **Almost Exact Answer, Least Error**
- **With 32-Bit Math Accuracy to +/-0.0001C**

Con's:

- **Processor intensive**
- **Requires Math Libraries**
- **Negative Calculation Requires simplification or bi-sectional solving**



Positive Temperature Direct Calculation

$$T_{Direct_+}(t) = \frac{-A + \sqrt{A^2 - 4B\cdot\left(1 - \frac{RTD(t)}{R_0}\right)}}{2B}$$

Negative Temperature Simplified Approximation

$$T_{Direct_-}(t) = -241.96 + 2.2163\,RTD(t) + 2.8541\cdot 10^{-3}\cdot RTD(t)^2 - 9.9121\cdot 10^{-6}\cdot RTD(t)^3 - 1.7052\cdot 10^{-8}\cdot RTD(t)^4$$

Digital Linearization Methods

Direct Computation

Bi-Section Method for Negative Temperatures

$RTDError := 100 \quad Res := 60.256 \quad Tlow := -250 \quad Thigh := 50$

$$
T_{Bisection\_} := \left|
\begin{array}{l}
RTDTemp \leftarrow 0 \\
\text{while } (|RTDError| > 0.0001) \\
\quad \left|
\begin{array}{l}
Tmid \leftarrow \dfrac{(Tlow + Thigh)}{2} \\
Rcal \leftarrow 100\cdot\left[1 + A\cdot Tmid + B\cdot Tmid^2 + (Tmid - 100)\cdot C\cdot Tmid^3\right] \text{ if } Tmid < 0 \\
Rcal \leftarrow 100\cdot\left(1 + A\cdot Tmid + B\cdot Tmid^2\right) \text{ if } Tmid > 0 \\
Rcal \leftarrow 0 \text{ if } Rcal < 0 \\
RTDError \leftarrow Res - Rcal \\
Tlow \leftarrow Tmid \text{ if } RTDError > 0 \\
Thigh \leftarrow Tmid \text{ if } RTDError < 0
\end{array}
\right. \\
RTDTemp \leftarrow Tmid \\
\text{return } RTDTemp
\end{array}
\right. = -99.999
$$

$T_{Bisection\_} = -99.999$

Questions/Comments?

Thank you!!

Special Thanks to:
Art Kay

Bruce Trump

PA Apps Team

Mike Beckman

Omega Sensors

RDF Corp

IMPORTANT NOTICE FOR TI REFERENCE DESIGNS

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