METERBUILDER™ MB-1 PROGRAMMABLE METER FOR ANALOG SENSORS – USER'S MANUAL

Version 1.01

Patent and Copyright Notices

Patent Applied For

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1 Introduction

MB-1 is not restricted to Amateur Radio applications. The calibration routines that were originally designed to improve RF power measurements were expanded allowing MB-1 to provide generalized measurement capabilities for a wide range of other applications using analog sensors and transducers. When combined with MB-1's other features such as its programmable display devices, a programmable averaging window, and its alarm trip functions, we believe that MB-1 will be useful for a variety of different applications.

The MeterBuilder website provides an overview on using analog sensors with MB-1. You should also read the Quick Start section of the MB-1 User's Manual to gain a basic understanding of the meter's operation. Features like programming the display devices, the alarm trip functions, the averaging filter, and most of MB-1's other Amateur Radio features are equally applicable for use with analog sensors.

The overall steps for programming all Generic Applications are basically the same. Since the User's Manual provides the step by step procedure for calibrating a simple Generic Meter Application (i.e., a simple DC voltmeter), those detailed steps are not repeated here.

The examples below are not intended to show you how to create a $10 digital thermometer using MB-1. Instead, the intent is to illustrate how MB-1 can interface to a variety of analog sensors with different characteristics using different techniques. If you have an analog sensor that you would like to use for a particular application, it is likely that you will be able to interface it to MB-1 using one or more of the approaches shown in the examples below.

2 Overview

Assume you have an application that either generates a DC voltage or you have an application from which a DC voltage can be derived. The transfer function that relates the parameter of interest to the DC voltage generated by the sensor can be a complex non-linear function. But if there are no discontinuities in the transfer function, and if you can identify discrete calibration points for the parameter of interest, you should be able to calibrate MB-1 to measure the parameter.

The different approaches for integrating analog sensors with MB-1 can be categorized into four general categories:

Case 1: ***The function to be measured is linear and passes through the origin*** (the generated DC voltage is 0 when parameter is 0) and you know the transfer function.

Case 2: ***The function to be measured is linear, does not pass through the origin,*** and you know the transfer function.

Case 3: ***The function to be measured is nonlinear*** and you know the transfer function.

Case 4: ***The function to be measured is nonlinear, and you do not know the transfer function***, but you know that the voltage increases as the parameter increases, and you know that the DC voltage from the sensor is within the dynamic range of the MB-1's input circuitry.

Sample graphs of transfer functions for the first three cases are shown below. In Figure 1, the transfer function is linear and passes through the origin. In this case, MB-1 needs to determine only the slope of the transfer function. This can be accomplished by performing the calibration at any point along the line. For example, if we use the end point, MB-1 would be calibrated at 1000 "units" when 4 volts is applied to the coupler input. Once calibrated, MB-1 will be able to calculate the parameter value for any input voltage from the sensor.

In Figure 2, we have two cases. Case A is linear but does not pass through the origin. Case B is linear, and would pass through the origin if extended, but the transfer function indicates that the sensor is valid only for parameter values greater than 200 and less than 800. In both these cases, the two end points of the transfer function should be used for calibration. In case A, MB-1 uses the two calibration points to determine the slope and the intercept. The same is true is case B, but in addition, since the lower calibration point is not defined when the parameter is less than 200, this tells MB-1 what the valid lower range of the sensor is.

Figure 3In Figure 3, we also have two cases. Both sensors are nonlinear and require multiple calibration points to characterize the sensor. When MB-1 reads a voltage between any two calibration points, its uses piecewise linear interpolation to calculate the parameter value. Therefore, sensors with highly nonlinear transfer functions will require a larger number of calibration points for accurate tracking.

Figure 1 – Sensor with Linear Transfer Function passing through the origin

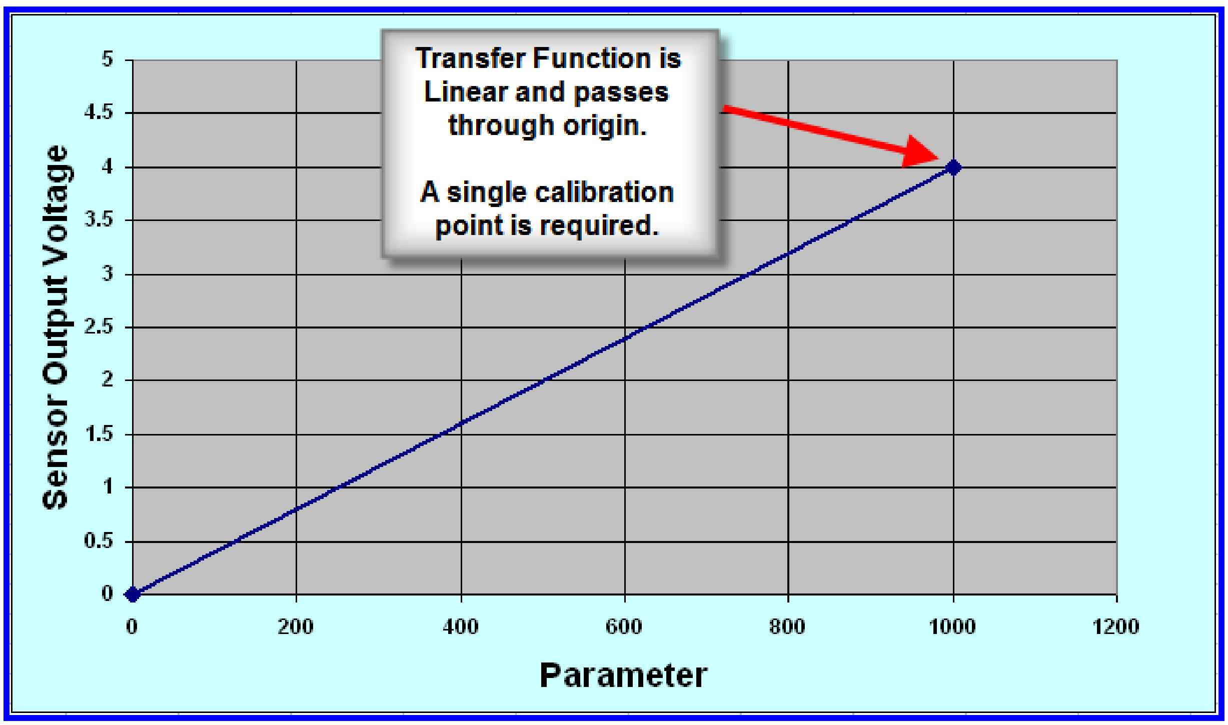


Figure 2 –Sensors with Linear Transfer Functions NOT passing through the origin

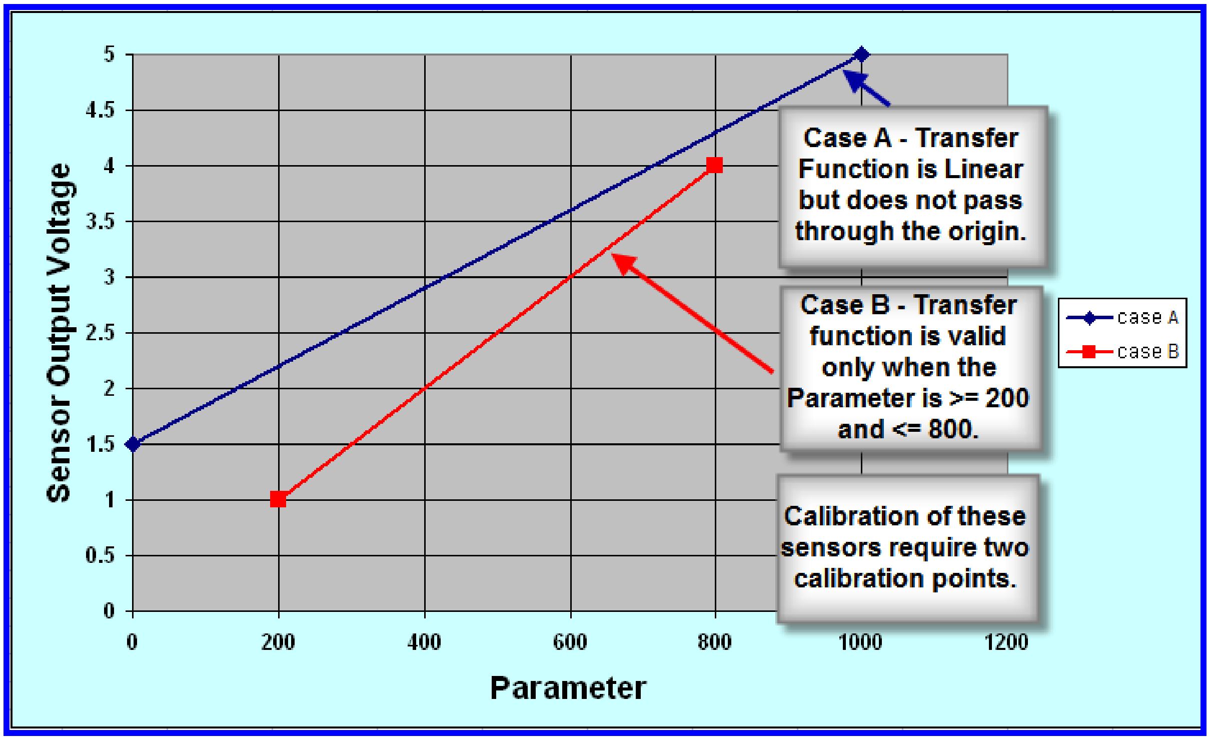
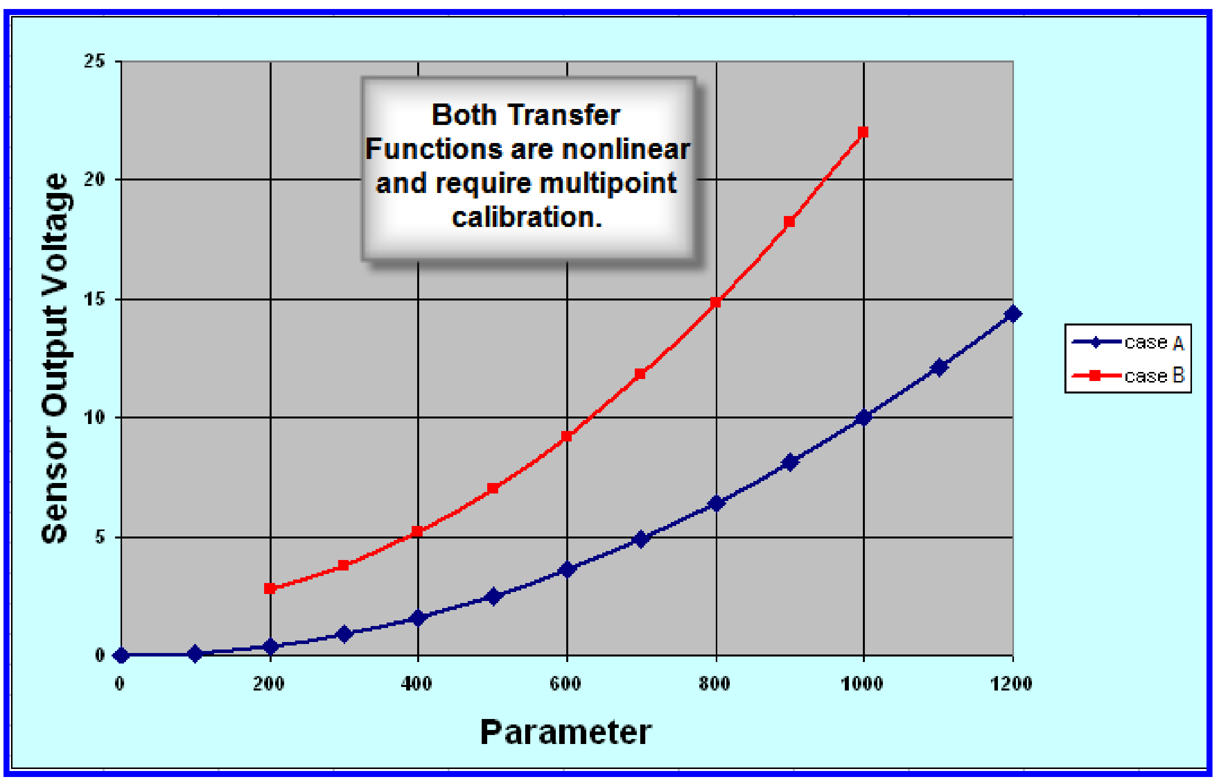


Figure 3 – Sensors with Nonlinear Transfer Functions



2.1 Examples of the Four Calibration Approaches

This section expands on the above overview by providing some examples.

Case 1: The temperature sensor in section 4.1 application generates 10 mV per degree, and has a linear transfer function that passes through the origin. Therefore, we know from the specs that at 100 degrees, the device will generate an output of 1.0 volt.

To calibrate this device, all we have to do is apply 1.0 volt to the coupler port while setting the calibration point to 100 (100 degrees). This can be done easily using a potentiometer connected to the 5 volt auxiliary power output on the MB-1 rear panel RCA jacks and then adjusting the pot until the pot's wiper voltage is 1.0 volt.

Figure 4 and Figure 5 below show a circuit that can accomplish this. A low resistance potentiometer should be used so that the input resistance of the coupler ports (300 K) can be ignored. A pair of clip leads connected to the output of the potentiometer lets you monitor the applied voltage with an external Digital Multimeter while performing the calibration.

Figure 4 - Using a Voltage Source and Potentiometer for Calibration

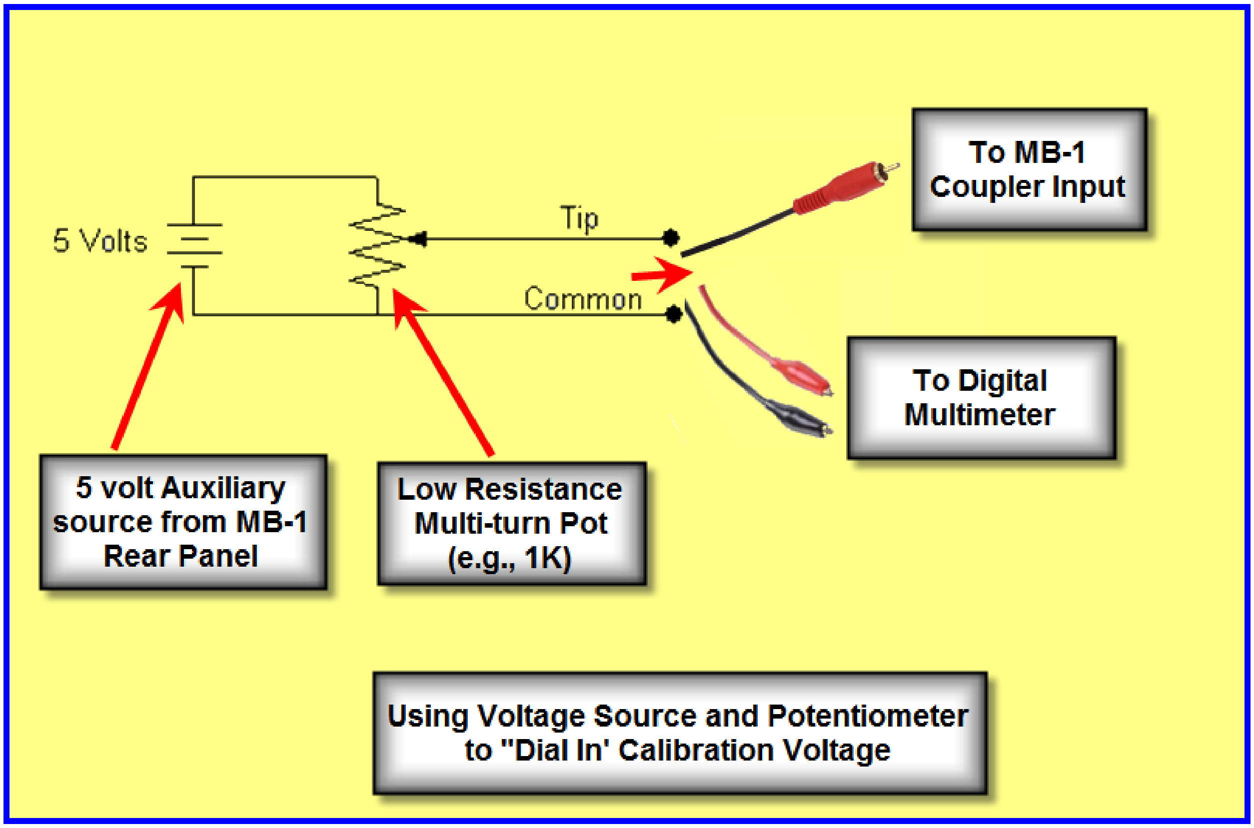
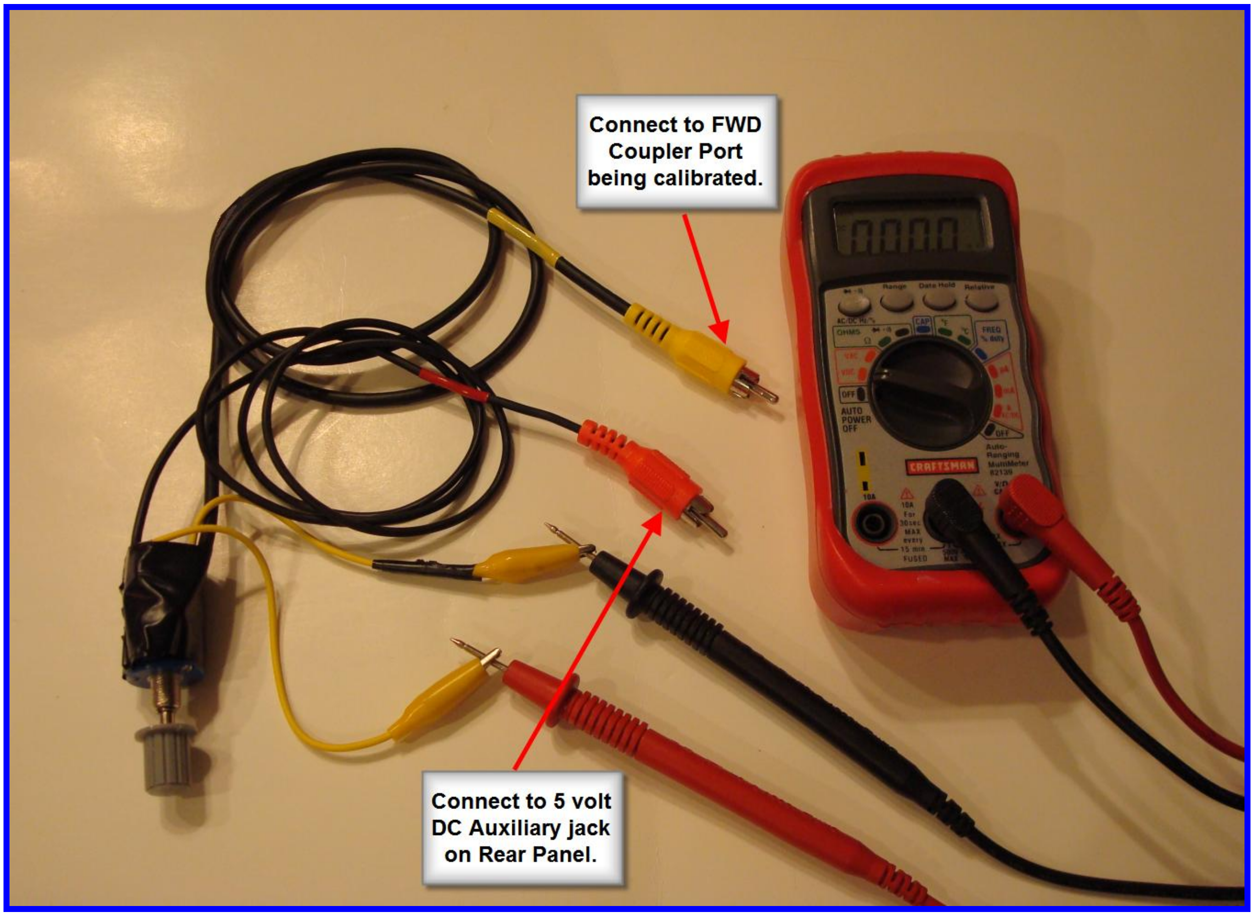


Figure 5 – Potentiometer, Multimeter, and RCA Cables



Case 2: The current sensor in section 4.4 isolates the lead whose current is being measured from the sensor output leads, which feed the MB-1 coupler port. The current sensor output is linear but does not pass through the origin. The sensor in this example generates an output voltage of approximately 133 millivolts per amp, but the idle current output voltage (when the current being measured = 0) is 500 millivolts. Its data sheet can be found here

Since this transfer function does not pass through the origin, we need two calibration points: one at the low end of the scale, and one at the high end of the scale. As with the example discussed in case 1 above, since we know the transfer function, we can "dial in" the corresponding voltages at each of the two calibration points.

Case 3: For nonlinear sensors, if you can characterize the parameter/voltage relationship mathematically, or if it is given in a spec sheet, you can create a simple a grouping of parameter/voltage points that line up with MB-1's available calibration points (see the nonlinear temperature sensor example in section 4.7). Using the potentiometer procedure in Figure 4, you can calibrate this series of points by setting the appropriate voltage at each calibration point.

To calculate measurements when the sensor voltage is at an intermediate voltage point with respect to the discrete calibration points, the MB-1 software uses linear interpolation.

Case 4: This approach can be used if we have a sensor that can not be easily characterized mathematically or where there is a large sample-to-sample variation. In this case, you can connect the sensor to the coupler port, and during calibration, you can “walk” the parameter through its range of values, saving the calibration data at discrete points. However, this approach requires the use of an independent “reference” during calibration. The example below will clarify this.

Assume that we have distance measuring application where the transfer function is nonlinear and not easily characterized. Also assume that there is a large sample-to-sample variation across sensors. We can connect the DC output from the distance sensor to a coupler port. Using a simple yard stick (or meter stick), we then move an object various distances from the senor (e.g., 1 inch, two inches, 5 inches, 20 inches, 50 inches, and 100 inches), saving the calibration data at each point. This empirical approach is fast and simple, at least in this example, since it requires only a simple reference such as a yard stick. And since the calibration was performed with the actual sensor, this approach also takes care of cases where a wide sample-to-sample variation exists.

3 Restrictions

If an application you have in mind is best addressed by the empirical approach (case 4 above), and if you have a good independent reference against which to measure the parameter of interest, you can quickly calibrate the application and evaluate its performance without going through a lot of analysis.

However, before expending a lot of the effort on a more complex application, spend some time reading the example in section 4.7, which addresses the issue of how a big a dynamic range can reasonably be handled taking into account the nonlinearity of the parameter. This will give you some insight into whether MB-1 is s a good match for your application.

For a sensor to be a candidate for interfacing with MB-1, it must meet the following criteria:

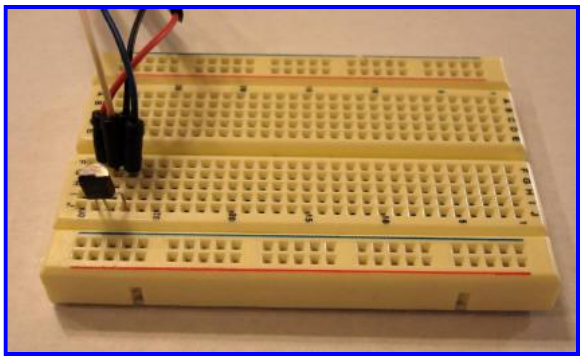
- The sensor must generate a DC voltage, or you must be able to derive a DC voltage from the sensor. The relationship between the parameter being measured and the DC voltage can be linear or nonlinear.
- The sensor must share a common ground with MB-1.
- The voltage must have a positive polarity.
- The DC voltage must increase monotonically as a function of the parameter being measured
- The quantity being measured must be >= 0 (since all of MB-1’s calibration points are >= 0). However, there are simple work-arounds for this, especially if you will be designing a custom analog scale for the application).
- The voltage must be compatible with the dynamic range of the coupler ports. This issue is discussed in more detail in section 7.

4 Examples using Analog Sensors

4.1 Temperature Measurements – Using a Linear Device

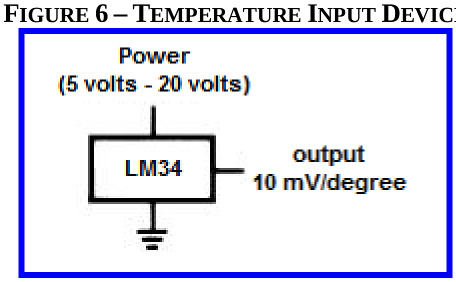
4.1.1 Overview

We use the output from a National Semiconductor LM34 Precision Fahrenheit Temperature Sensor and feed the signal to a coupler port that is calibrated using MB-1's Generic Meter calibration mode. Once calibrated, the temperature can be read directly from any of MB-1's display devices (LCD, analog meter, 7-Segment Displays, and Bar Graph).



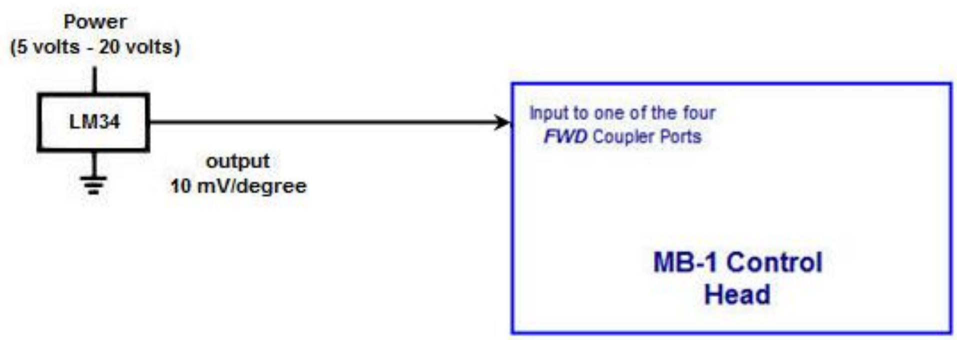
The data sheet for the LM34 can be found here. The device generates a DC output voltage that is proportional to the temperature in Fahrenheit (10 millivolts per degree). We use the LM34D, which has a range of 32° to 212°, which corresponds to an output voltage range of 320 millivolts to 2.120 volts.

FIGURE 6 – TEMPERATURE INPUT DEVICE



To program MB-1 to measure temperature, connect the LM34D to the FWD port of one of MB-1's four coupler ports as shown below.

FIGURE 7 – LM34 FEEDING MB-1



4.1.2 Calibration Procedure

The Generic Meter example in the MB-1 User's Manual provides a detailed list of steps. This application uses the same procedure with the following changes:

1. Since we are measuring degrees in Fahrenheit, set the Units character to be displayed on the LCD to "F" for Fahrenheit.

2. For the voltages involved in this application, you should adjust the side panel coupler trim pot to its maximum sensitivity – at least 15 turns CW. Since the MB-1 input does not saturate until approximately 6.14 volts when the pot is set to its maximum sensitivity, and since this application will never generate a DC voltage that comes close to this saturation point, setting the trim pot to its maximum sensitivity will provide the best resolution and accuracy).

3. Apply a source of 1.00 volt to the FWD port of the coupler being calibrated. This is most easily done by "dialing in" the calibration voltage using a stable voltage source and potentiometer as shown in Figure 4.

4. Using the Coupler setup screens, calibrate the meter ***at a single point*** at a calibration temperature of 100°. (This corresponds to the 1.00 volt being applied from step 2.)

   Since the LM34D input device has a linear transfer characteristic that passes through the origin, calibration is required at this single point only.

4.2 DC Current Measurements using a Meter Shunt

4.2.1 Overview

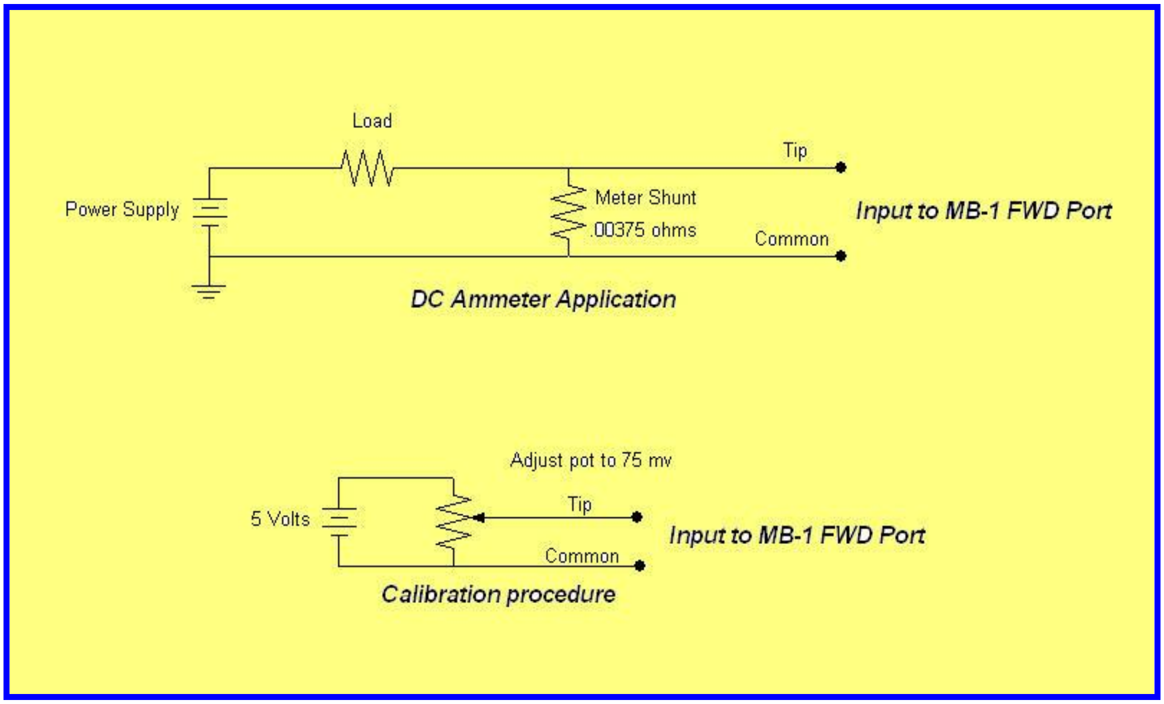
We can use a meter shunt in series with the current we want to measure, and feed the generated voltage across the shunt into one of the coupler ports to measure DC current.

This example makes use of a 20 amp shunt. Shunts in this current range typically generate 75 millivolts at the full scale current. Like the example above, the transfer function is linear, and passes through the origin, so this application also requires a single calibration point.

FIGURE 8 – METER SHUNT

The circuit diagram and suggested calibration procedure is shown in the figure below.

Figure 9 - DC Ammeter Application



4.2.2 Calibration Procedure

The detailed Generic Meter example in the main User's Manual provides a detailed list of steps. This application uses the same procedure with the following changes:

1. Since we are measuring current in amps, set the Units character to “A” for amps.

2. For a 20 amp full scale shunt, select a somewhat larger Full Scale value when doing the coupler setup – 30 amps for example.

3. For the low voltages involved in this application (75 mV full scale), you should adjust the side panel coupler trim pot to its maximum sensitivity (at least 15 turns CW).

4. During calibration, apply a source of 75 millivolts to the coupler input port being calibrated. This is most easily done by “dialing in” the calibration voltage using a stable voltage source and potentiometer as shown in Figure 4.

5. Using the Coupler setup screens, calibrate the meter ***at a single point*** - 20 amps. (This corresponds to the 75 mV that is being applied from step 4.)

4.3 Notes

The 75 millivolt full scale voltage generated by the sensor is close to minimum full scale voltage where MB-1 can still provide reasonable resolution (see section 7). To improve resolution for this application, an amplifier could be used, but a simpler approach is to place two shunts in series. The voltage drop, as seen by the load in minimally affected, and the full scale voltage available to MB-1 is doubled to 150 millivolts. If you use this approach, use a low resistance device, such as a copper or brass strip, to connect the two shunts in series.

A more flexible and less expensive approach for measuring DC current using MB-1 is given in the next example using an isolated current sensor.

4.4 DC Current Measurements using an Isolated Sensor

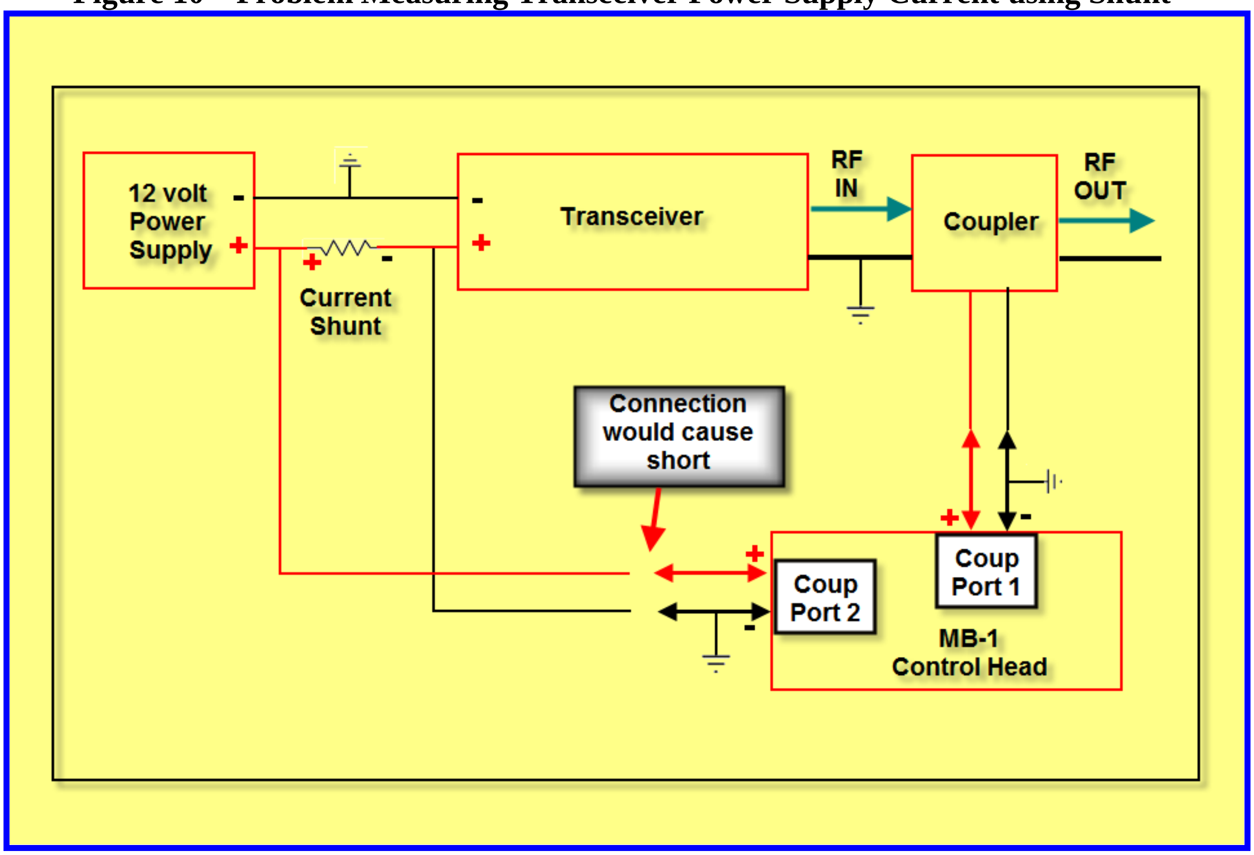
4.4.1 Overview

This example uses an isolated current sensor that allows isolation of the sensor leads from the MB-1 ground.

For Generic Meter applications, the negative lead of the sensor output must be connected to the MB-1 ground. For example, in the meter shunt example above, the meter shunt common lead must be connected to the MB-1 common (ground).

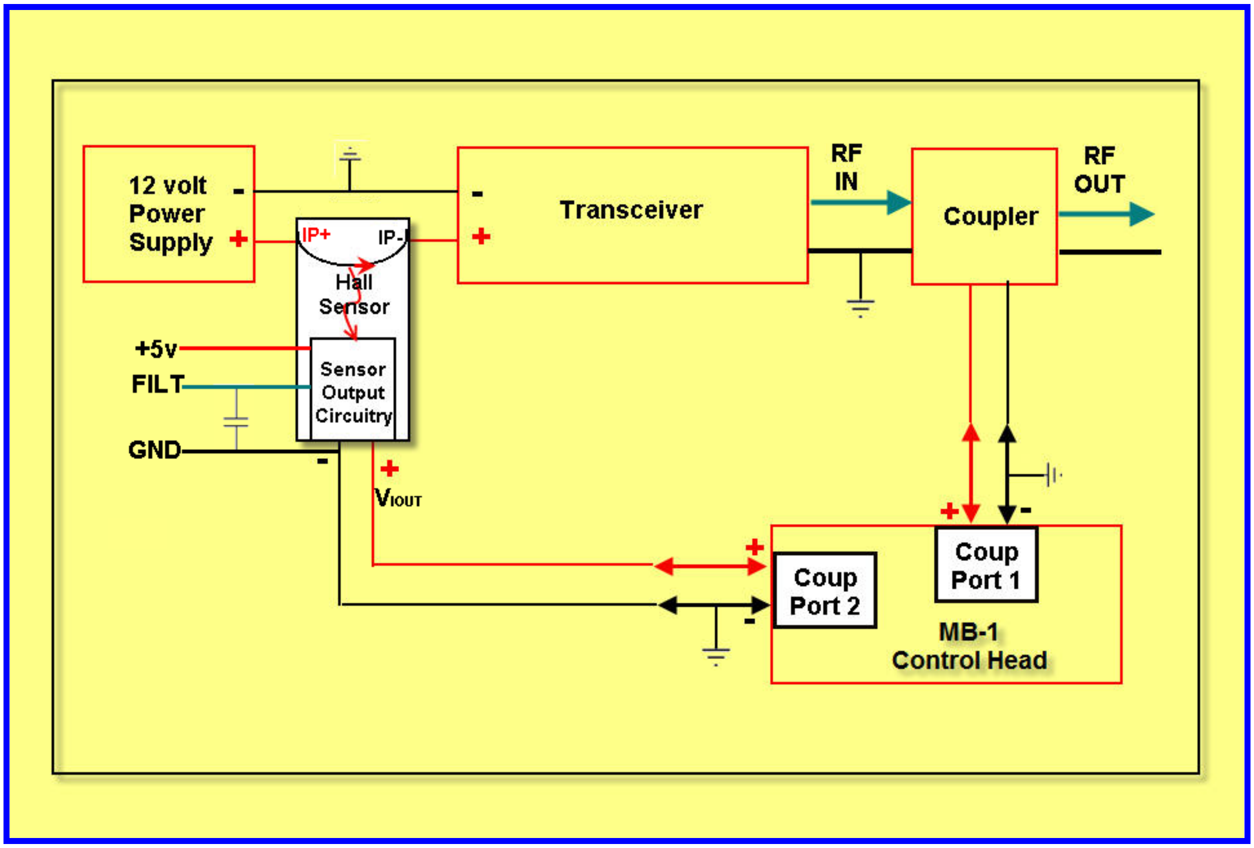
There are some applications where this restriction may prevent you from measuring a parameter with a particular sensor when other grounds and common leads are also connected to MB-1's ground. For example, in the figure below, assume you want to measure your transceiver's power supply current with MB-1 using a Current Shunt as discussed in the previous example. As can be seen in the figure below, the transceiver's ground is already connected to MB-1's ground via the coupler. Therefore, the series shunt can not be used to measure the power supply current when a coupler is also connected to the transceiver and to MB-1 since this would effectively short out the power supply. Likewise, ground loop problems would result if we placed the shunt in the negative leg of the power supply.

Figure 10 – Problem Measuring Transceiver Power Supply Current using Shunt



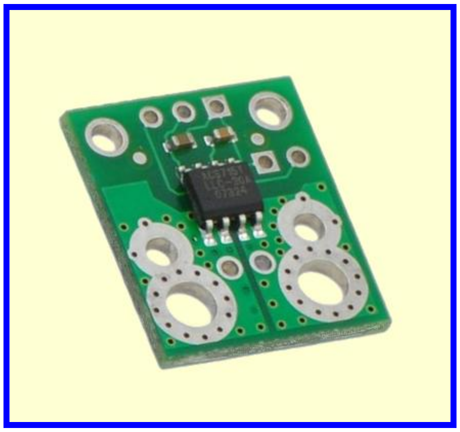
To measure current in such applications, we can use a sensor that provides isolation between the leads carrying the parameter to be measured and the sensor output leads that feed the MB-1 coupler port. For the power supply current measurement example, discussed above, a Hall Effect current sensor provides the necessary isolation as shown below.

Figure 11 - Measuring Transceiver Power Supply Current using an Isolated Current Sensor



An example of such a sensor is shown below. Its data sheet can be found here. This sensor is capable of measuring up to 30 amps DC, which provides a good match for the typical transmit mode current draw of 100 watt transceivers powered from 12 volt supplies. And surprisingly, this sensor is less expensive than most 20 amp and 30 amp meter shunts.

FIGURE 12 – HALL EFFECT CURRENT SENSOR



4.4.2 Calibration Procedure

The sensor outputs is a DC voltage that varies linearly with respect to the input current. The sensor has a DC offset of approximately 500 millivolts when the current = 0. The output increases at a rate of approximately 133 millivolts/Amp. Therefore, the transfer function is:

$$\mathbf{V_{IOUT} = V_{ZERO} + .133 * I}$$

where V_{ZERO} is idle voltage from sensor when the current is 0 (nominally 2.5 volts when Vcc = 5 volts).

Therefore, a typical sensor will have the following transfer function:

$$\mathbf{V_{IOUT} = .5 + .133 * I}$$

where I is the current being measured.

Since the transfer function for this sensor does not pass through the origin (0 sensor voltage when current = 0), we need to do calibration at two points, namely the two end points. If we set the full scale current to 30 amps, the two calibration points will then be 0 amps (MB-1's lowest calibration point), and 30 amps (the full scale value).

For maximum accuracy, $\mathbf{V_{ZERO}}$ should be measured for the actual sensor being used and substituted in the equation as shown in the table below:

Table 1 – Hall Current Sensor Calibration

Calibration Point	Sensor Voltage
I = 0	$\mathbf{V_{IOUT} = V_{ZERO}}$ **(typical 0.5 volts)**
I = 30a	$\mathbf{V_{ZERO} + 3.99}$ **(typical 4.49 volts)**

During calibration, these values can be "dialed in" with a potentiometer and the 5 volt auxiliary voltage source as previously discussed. Adjust the coupler trim pot for maximum sensitivity since there is no chance of overdriving the MB-1 input in this application.

4.4.3 Related Sensors

Other sensors capable of measuring DC current can be found here.

4.5 AC Current Measurements using an Isolated Sensor

4.5.1 Overview

This example is similar to the previous example, but makes use of a self powered AC current sensor that can measure up to 100 amps AC. The sensor produces 5 volts DC at the full scale rating of 100 amps with a linear transfer function. This sensor is electrically isolated from the AC wire whose current is being measured. The wire is simply passed through the sensor and inductive coupling is used to generate the DC output voltage that gets fed to MB-1.

Phidgets has a family of these sensors ranging from 10 amps AC to 100 amps AC. They all work the same way, producing 5 volts DC at the full scale rating.

4.5.2 Calibration Procedure

Below is a picture of the sensor. The specifications can be found here:

Calibration is straightforward with this coupler. Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application. During calibration, set the full scale value to 100 (or the full scale value corresponding to your sensor).

Because the transfer function of this sensor is linear, and passes through 0, 0, this application requires calibration at a single point, namely the full scale value. During calibration, select the full scale value calibration point. Then apply 5 volts DC to the coupler input, saving the calibration data. That is all that is required.

4.5.3 Related Sensors

Other sensors that can measure AC current can be found here.

4.6 DC Power Measurements

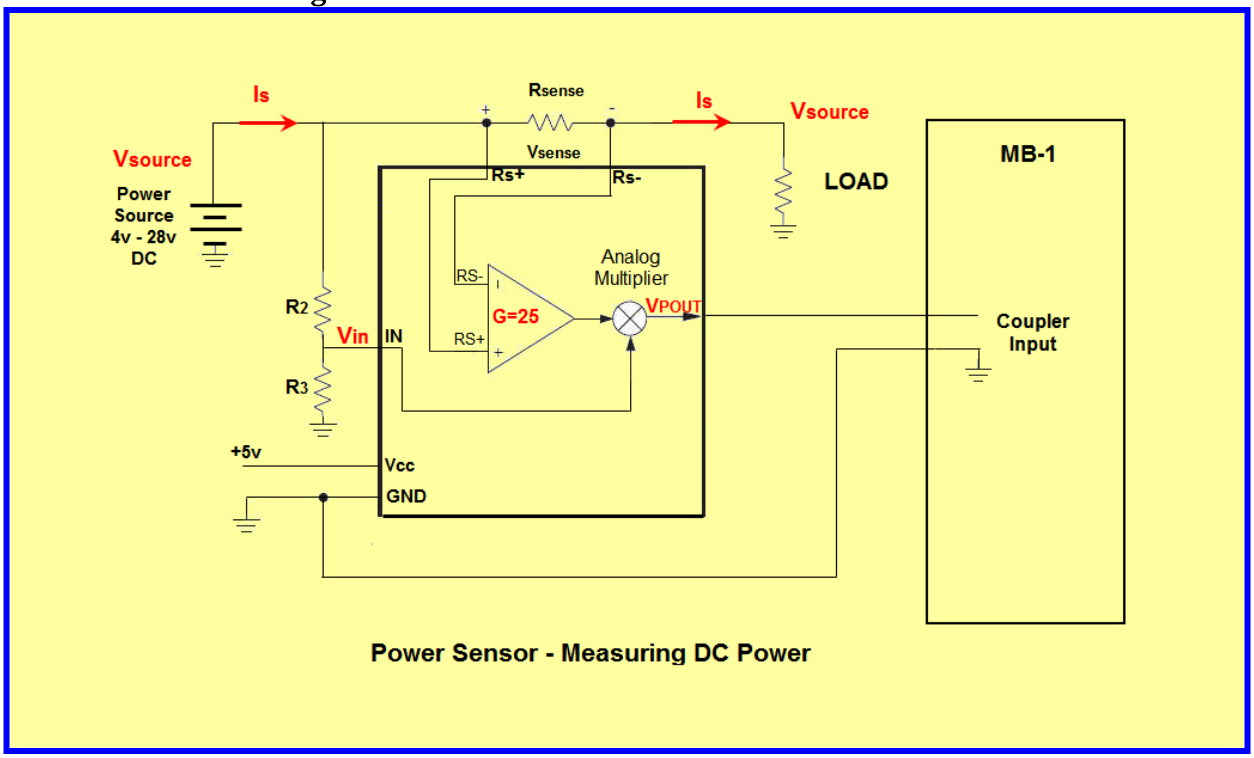
4.6.1 Overview

There are some applications, for instance, battery powered equipment or solar cell powered systems, where the delivered or consumed power measurement is more useful than either the voltage or current measurement. This example uses the Maxim MAX4210E real time power monitoring sensor to measure DC power directly. This chip uses a current-sense amplifier and an analog multiplier to perform a real time multiplication of the current and voltage. The sensor outputs a DC voltage that is proportional to the power being monitored. MB-1 can be easily calibrated to read the sensor output voltage and can display the power measurement or process the sensor output using the MB-1 averaging, Min/Max, and alarm functions.

The complete data sheet for this sensor can be found here.

Application notes, which are a little easier to follow, are found here.

Figure 13 – Maxim MAX4210E DC Power Sensor



In the figure above, the quantity we want to measure, namely delivered power, is:

$$\mathbf{P_{DELIVERED} = V_{SOURCE} * I_S}$$

$\mathbf{R_{SENSE}}$ is a low resistance shunt that generates a voltage based on the load current:

$$\mathbf{V_{SENSE} = R_{SENSE} * I_S}$$

For the 4210E device, the sense voltage is multiplied by the amplifier gain **G**, which has a value of 25, and the amplifier output is fed to one input of the multiplier.

The second input to the multiplier is a portion of the supply voltage as determined by voltage divider $\mathbf{R_2}$ and $\mathbf{R_3}$:

$$V_{IN} = V_{SOURCE} * R3 / (R2 + R3)$$

Finally, the output of the multiplier is given by:

$$V_{POUT} = V_{SENSE} * G * V_{IN}$$

$$V_{POUT} = (R_{SENSE} * I_S) * G * [\ V_{SOURCE} * R3 / (R2 + R3)\ ]$$

The maximum permissible $\mathbf{V_{SENSE}}$ value is 150 millivolts. For a given load current, this determines the maximum resistance of the shunt resistor, $\mathbf{R_{SENSE}}$. Assume that the maximum current in this application is 10 amps. This gives us an $\mathbf{R_{SENSE}}$ = .150/10 = **.015 ohms.**

Another constraint is that the sensor output voltage¸ $\mathbf{V_{POUT}}$**,** that represents the power, must not exceed $\mathbf{V_{CC}}$ **- .5v** or **4.5v.**

Assume that the source voltage powering the load has a maximum value of 15 volts. We can now calculate the voltage divider ratio **R3 / (R2 + R3**) so that $\mathbf{V_{POUT}}$ never exceeds 4.5 volts.

$$R3 / (R2 + R3) \ <= V_{POUT}\ / [\ G * V_{SOURCE} * \ (R_{SENSE} * I_S)\ ]$$

Plugging in the numbers from above,

$$R3 / (R2 + R3) \ <= 4.5\ / [\ 25 * 15 * \ .150)\ ] = .080$$

If we set **R2** = 120K and **R3** = 10K, we get a ratio of **.0769**, which meets the criteria.

We now have all of the values to determine the transfer function of $\mathbf{V_{POUT}}$ **vs.** $\mathbf{P_{DELIVERED}}$

$$V_{POUT} = (R_{SENSE} * I_S) * G * [\ V_{SOURCE} * R3 / (R2 + R3)\ ]$$

$$V_{POUT} = (.015 * I_S) * 25 * [V_{SOURCE} * .0769)\ ]$$

$$V_{POUT} = .0288 * I_S * V_{SOURCE}$$

Transfer Function: $\mathbf{V_{POUT} = .0288 * P_{DELIVERED}}$

As a sanity check, at the maximum voltage level (15 volts) and current level (10 amps), $\mathbf{V_{POUT}}$ should be less than 4.5 volts. Plugging the numbers in, we get a $\mathbf{V_{POUT}}$ of 4.32 volts, which checks out.

The above discussion can be used to determine component values for other voltage and current combinations as well.

4.6.2 Calibration Procedure

Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application.

Since the above transfer function is linear and passes through the origin, we need to perform the calibration at a single point. We can do the calibration at the power corresponding to the maximum voltage and current points, namely a power level of 150 watts. At that power,

$$\mathbf{V_{POUT} = .0288 * 15 = 4.320\ volts}$$

Calibration at the 150 watt point is most easily done by “dialing in” the desired voltage at the input to the coupler using a stable voltage source and potentiometer as shown in Figure 4.

4.7 Temperature Measurements – Using a Nonlinear Device

4.7.1 Overview

If you have an interest in measuring parameters with MB-1 that have nonlinear input/output relationships, this topic may be of interest to you.

The temperature application described above used a device that generated a DC voltage in a linear relationship with respect to the temperature in Fahrenheit. In this application, we use a nonlinear temperature device, namely a thermistor, to map DC voltage into temperature in degrees Celsius.

If we wanted to measure temperature, and a linear device like the LM34 satisfies the desired range, using such a device simplifies things considerably, since the calibration needs to be performed at a single point. However, we use a thermistor in this sample application since it provides a good example of how MB-1 can be used to measure a parameter that has a ***nonlinear function***. The device we use is a Vishay *BC1482 thermistor.* The data sheet for a nearly identical device can be found here.

The resistance vs. temperature transfer function is fairly complex. It is given by the following formula:

Equation 1:

T_{kelvin} = 1.0 / (A + B * ln (Rtherm/10.0)
+ C * ln (Rtherm/10.0) ^2
+ D * ln (Rtherm/10.0) ^3)

where **ln** is the natural logarithm function and A – D are constants for a specific device:

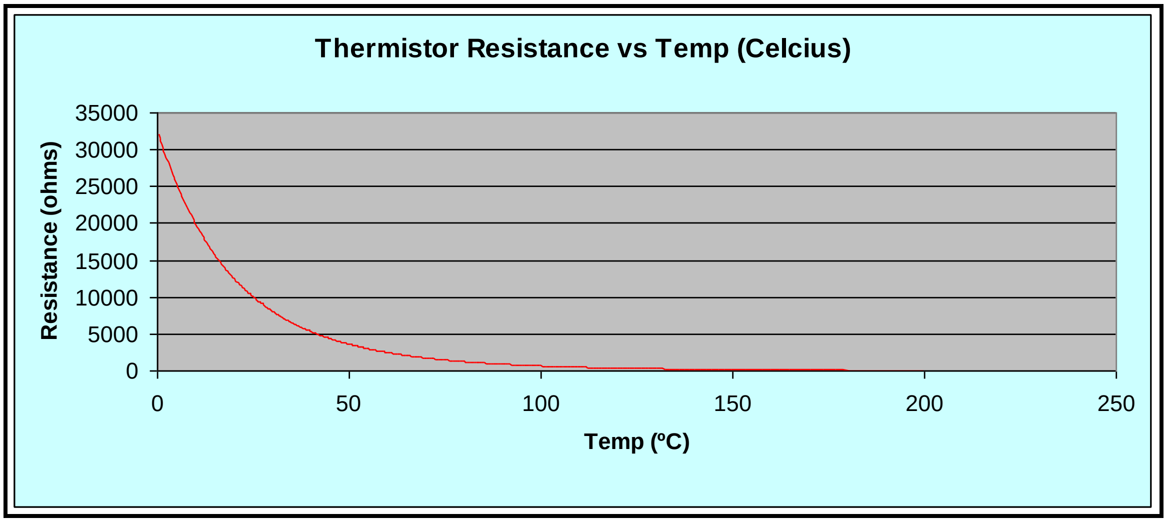
```
A = 3.354016e-3
B = 2.569107e-4
C = 2.626311e-6
D = 0.675278e-7
```

To convert to Celsius, we use the following formula:

$$\mathbf{T_{Celsius} = T_{kelvin} - 273.15}$$

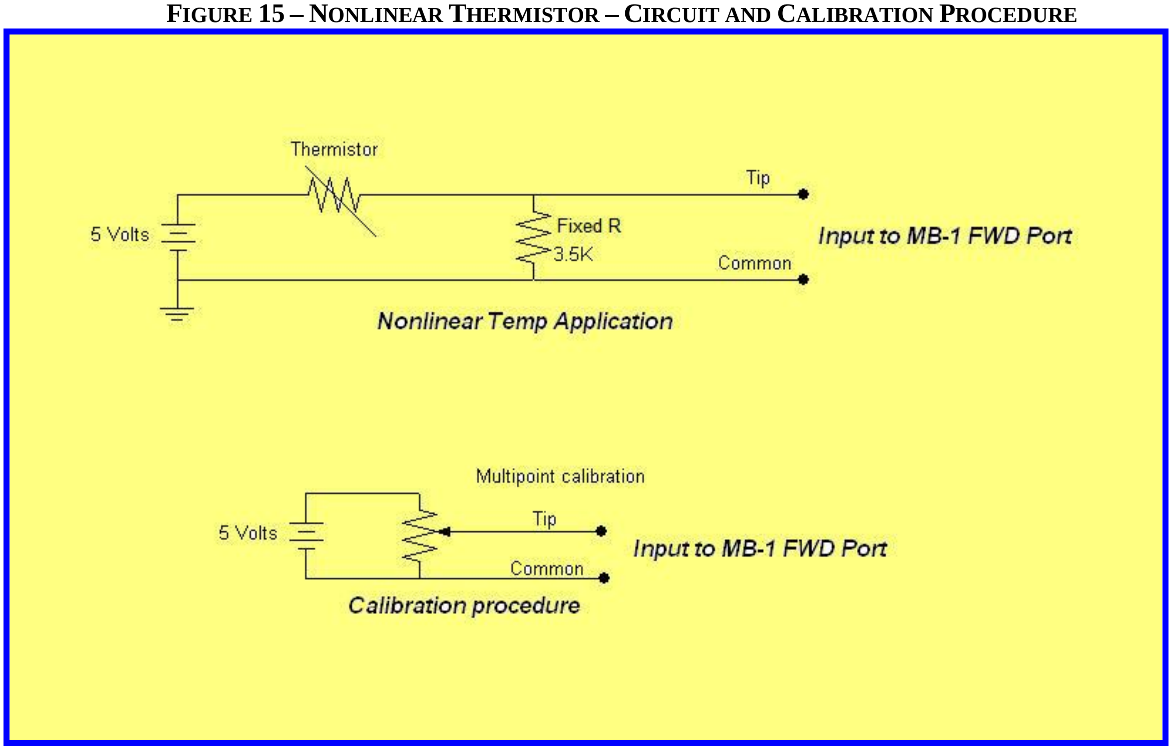
A plot of Resistance vs. Temperature for the thermistor is shown below. As expected, the function is nonlinear.

FIGURE 14 - THERMISTOR RESISTANCE



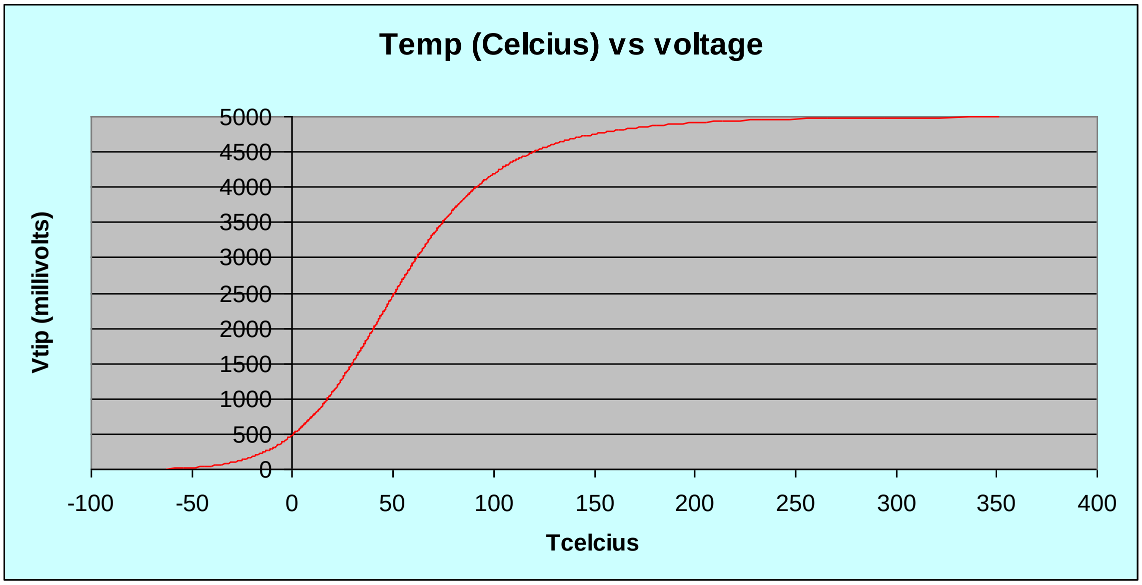
To measure temperature with MB-1, the top circuit in the figure below can be used. Since the thermistor resistance decreases with increasing temperature, this will cause the voltage into MB-1 to increase for increasing temperature, which is what we want (a monotonically increasing input function).

FIGURE 15 – NONLINEAR THERMISTOR – CIRCUIT AND CALIBRATION PROCEDURE



Using an Excel spreadsheet, we can calculate the voltage at the Tip of the top circuit as a function of temperature. A graph of the function is shown below.

FIGURE 16 – VOLTAGE INPUT INTO MB-1 VS. TEMPERATURE



If you are considering using MB-1 for a nonlinear application like this, you should have an idea of what your input/output function looks like because you want to make sure you have a reasonable resolution over the range you wish to measure. We see that the above graph starts to saturate noticeably above 150º. While the voltage still increases as the temperature ranges from 300º to 350º, the voltage change per degree gets smaller and would result in reduced resolution in this range. However, in the range 0º to 100º C, the slope is fairly large, and we could expect reasonable resolution and accuracy within this range.

4.7.2 Calibration Procedure

The calibration procedure is fairly straightforward. Using an Excel spreadsheet, we have calculated values for the input voltage vs. temperature. Let's assume that we want to run a calibration in the range 1º to 125º Celsius. When we set up the Generic meter calibration, we can set the Full Scale value to 125. We can then perform the calibration at temperatures of 0º, 10º, 20º, ... 100º, and 125º. For each of these calibration points, we simply need to dial in the corresponding voltage that the top circuit in **Figure 15** would generate using the circuit shown on the bottom of **Figure 15**.

To calibrate this application, we need a series of calibration points (in Celsius) and the corresponding voltage that the circuit in **Figure 15** will generate for each of the calibration points. Available MB-1 calibration points that make sense for this application are: 0º, 10º, 20º, 30º, ... 100º. To generate the table, we have to know the resistance of the thermistor for each of the calibration points. Since the thermistor forms a simple voltage divider with the 3.5K resistor, if we could determine the thermistor resistance for each calibration point (0º, 10º, 20º, ...), we can then determine the corresponding voltage that the coupler input would see. But solving for R, the Thermistor resistance, in terms of the temperature in Equation 1 is difficult. Instead, we can use Excel to determine the corresponding voltage values by creating a table with fine granularity and then interpolating.

A portion of the table is shown below, where we calculate TCELSIUS in terms of the voltage at the voltage divider tap. The two rows in red are rows that span the T= 10º calibration point. We can see that

10º will correspond to a voltage somewhere between 7.40 volts and 7.50 volts, which are the corresponding entries in the first column.

Excel has **FORECAST** function that simplifies doing the linear interpolation for these two rows. It is used in the rightmost column, and determines that the voltage corresponding to 10º is .7487 volts.

This approach is repeated for each of the 11 calibration points, and yields the values in Table 3 below.

Table 2 – Portion of the Resistance vs. Voltage Calculations for Thermistor

V_{DC}	R_{THERM}	T_{Kelvin}	$T_{CELCIUS}$	Exact Calibration Point	Exact Voltage
0.690	21862.319	281.1670	8.0170		
0.700	21500.000	281.5123	8.3623		
0.710	21147.887	281.8543	8.7043		
0.720	20805.556	282.1930	9.0430		
0.730	20472.603	282.5285	9.3785		
0.740	**20148.649**	**282.8608**	**9.7108**	**10**	**0.748781**
0.750	**19833.333**	**283.1902**	**10.0402**		
0.760	19526.316	283.5165	10.3665		
0.770	19227.273	283.8400	10.6900		
0.780	18935.897	284.1607	11.0107		
0.790	18651.899	284.4787	11.3287		

Table 3 – Voltage/Temperature Calibration Points for Thermistor

$T_{CELCIUS}$	V_{DC}
0	.4854
10	.7487
20	1.0945
30	1.5139
40	1.981
50	2.4631
60	2.9219
70	3.3318
80	3.6796
90	3.9639
100	4.1898

Using the above table, we simply need to dial in the corresponding voltage, $V_{DC,}$ at the various $\mathbf{T_{CELCIUS}}$ calibration points, and use the calibration setup screens to record these points.

We have left out some detail, such as accounting for the variability from the ideal curve among thermistor samples, but hopefully, the general concept is clear.

Application-specific programs can always be written for any measurement application. In fact, many examples are shown on Professor Anderson's Embedded Processor website (http://www.phanderson.com/), including several applications for measuring temperature. However, the novel concept of the Generic Application feature of MB-1 is that measurements can be performed on parameters that have complex parameter vs. voltage relationships *without the need to write an application-specific program.* The calibration can be achieved either through use of calculated voltages at various calibration points, as we did here, or with the use of a reference measuring device (in this example a thermometer would be used).

This generalized measurement approach will not likely do better than a custom application designed explicitly to measure a single type of parameter, but the tradeoff is obviously one of complexity and speed of implementation.

4.7.3 Related Sensors

There are a whole series of sensors that can measure temperature using linear and nonlinear sensors. Some of these can be found here.

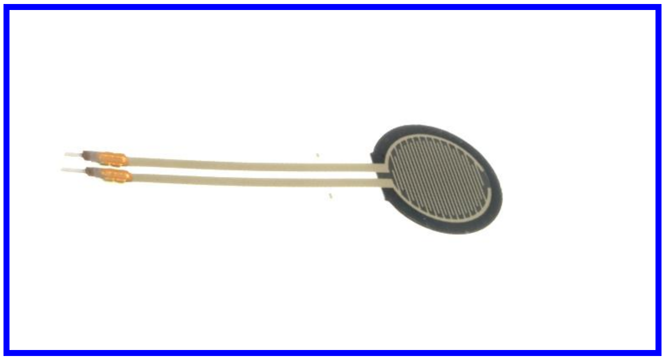
4.8 Pressure/Force Sensor – Using a Nonlinear Device

4.8.1 Overview

In the previous temperature application, we did a bit of analysis to generate a temperature vs. voltage chart that was needed for the calibration. The pressure sensor in this example is highly nonlinear as well. The specification for this sensor is detailed enough so that we could generate a force vs. voltage curve. However, in this example, we will use the empirical approach by applying a series of known forces to the sensor during calibration.

4.8.2 Calibration Procedure

Below is a picture of an Interlink 402 sensor:



It's resistance vs. force curve is given below:

Figure 17 – Force Sensor Curve

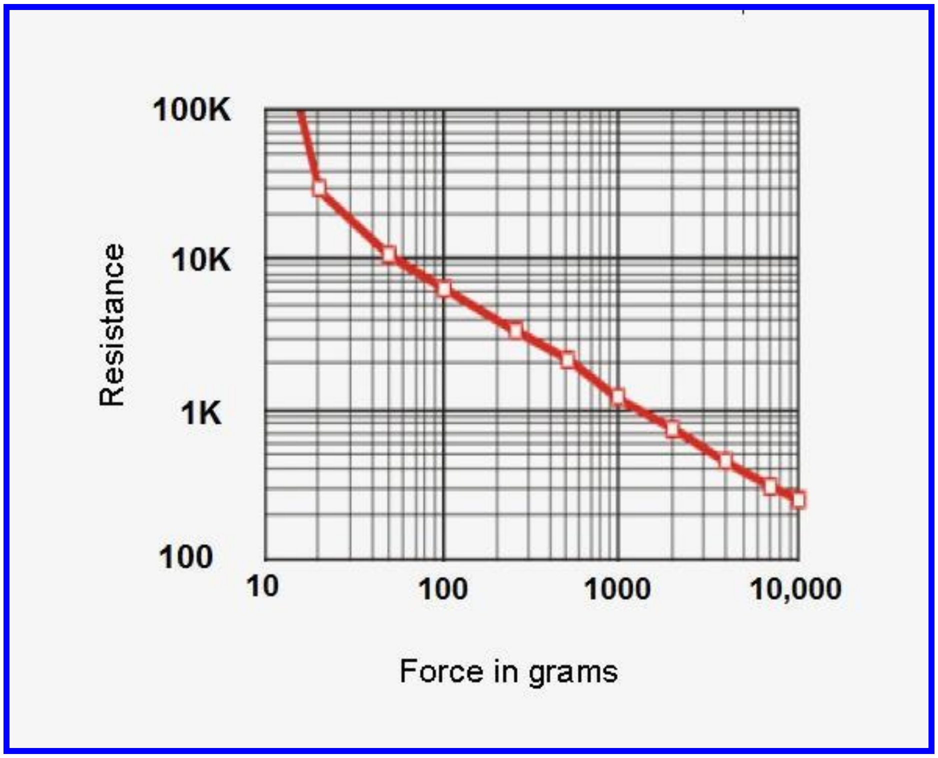
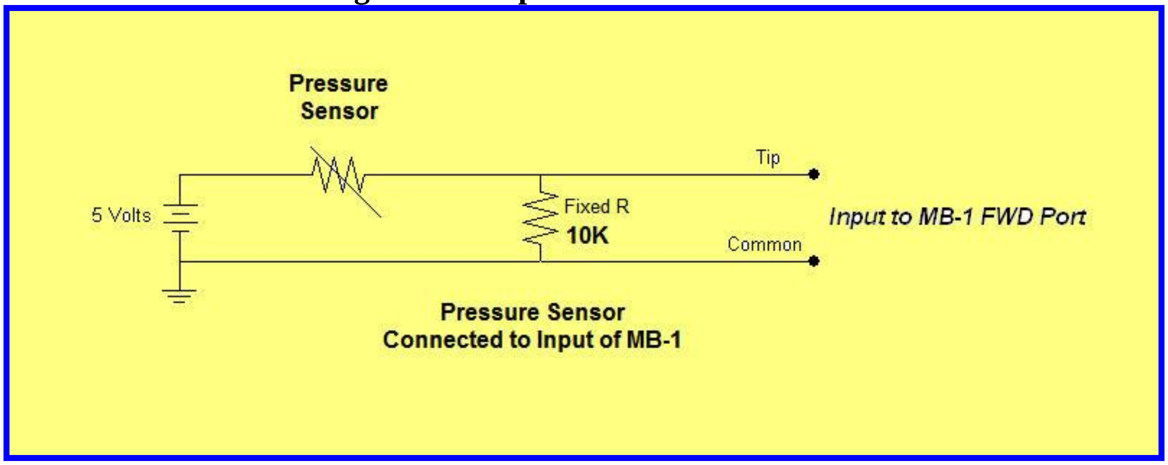


Figure 18 – Input Circuit to Measure Force



To measure the pressure with MB-1 using this sensor, the circuit in the figure above can be used. Since the sensor resistance decreases with increasing pressure, this will cause the voltage into MB-1 to increase for increasing pressure – again what we want – an output whose voltage increases as a function of the parameter being measured.

If we wanted to calculate the voltages corresponding to various pressures, that would be straightforward. For example, when the pressure is 20 grams, the resistance is 30K.

The voltage at the tap of the sensor and the 10 k resistor would be:

5 Volts * 30K/ (30K + 10K) = 3.75 volts

We could repeat the calculations at a number of points corresponding to MB-1 calibration points, for example, 20 grams, 30 grams, ... 10,000 grams. We could then calibrate MB-1 as we did for the non-linear temperature sensor above, namely selecting each calibration point, dialing in the corresponding voltage with a potentiometer, and saving the calibration data potentiometer as shown in Figure 4.

But this is a case where the empirical approach is easier (assuming we have some way to apply a series of accurate forces during calibration). The advantage of the empirical approach is that it automatically compensates for any variation in the sensor as well as the accuracy of the 5 volt supply and fixed 10K resistor.

It turns out that the Lincoln Memorial Reverse penny (mid 1982 to present) weighs 2.5 grams. Therefore various combinations of 4 to 40 pennies will give us a reasonable calibration source from 10 grams to 100 grams.

One liter of water weighs 1000 grams (1 kilogram). (You get the point – depending upon what you are measuring, actual calibration using a known “input” can yield the quickest and most accurate results).

4.8.3 Related Sensors

There are a whole series of sensors that can measure force and stress. Some of these can be found here.

4.9 Reflectance Sensor

4.9.1 Overview

This example makes use of a QTR-1A reflectance senor. This is another example where the sensor characteristics are a little vague, so it is difficult to come up with an exact transfer function. We therefore use the empirical approach in this example to calibrate the sensor.

Below is a picture of the Reflectance Sensor. Information on the sensor can be found here.

Figure 19 – Reflectance Sensor

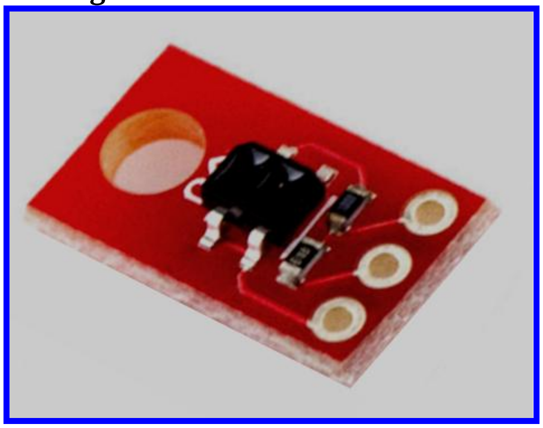
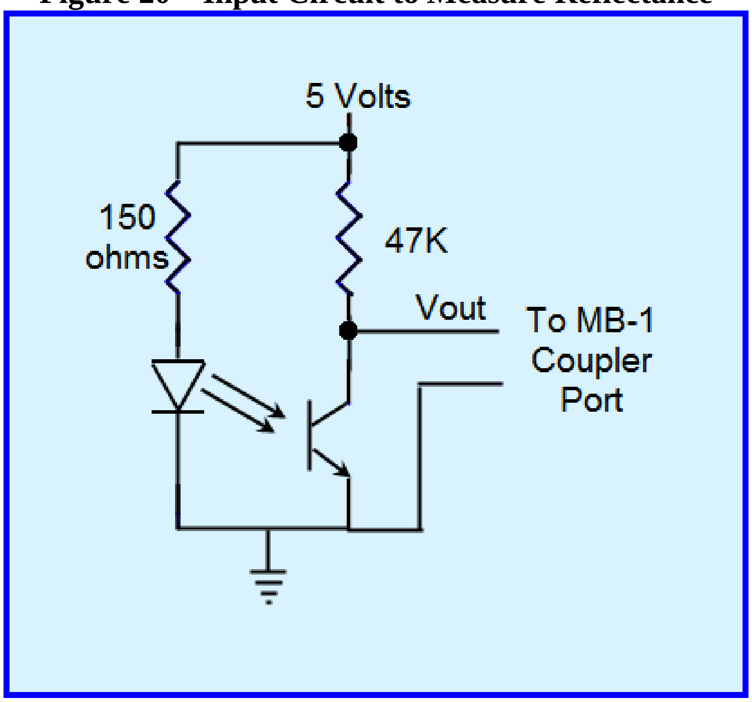


Figure 20 – Input Circuit to Measure Reflectance

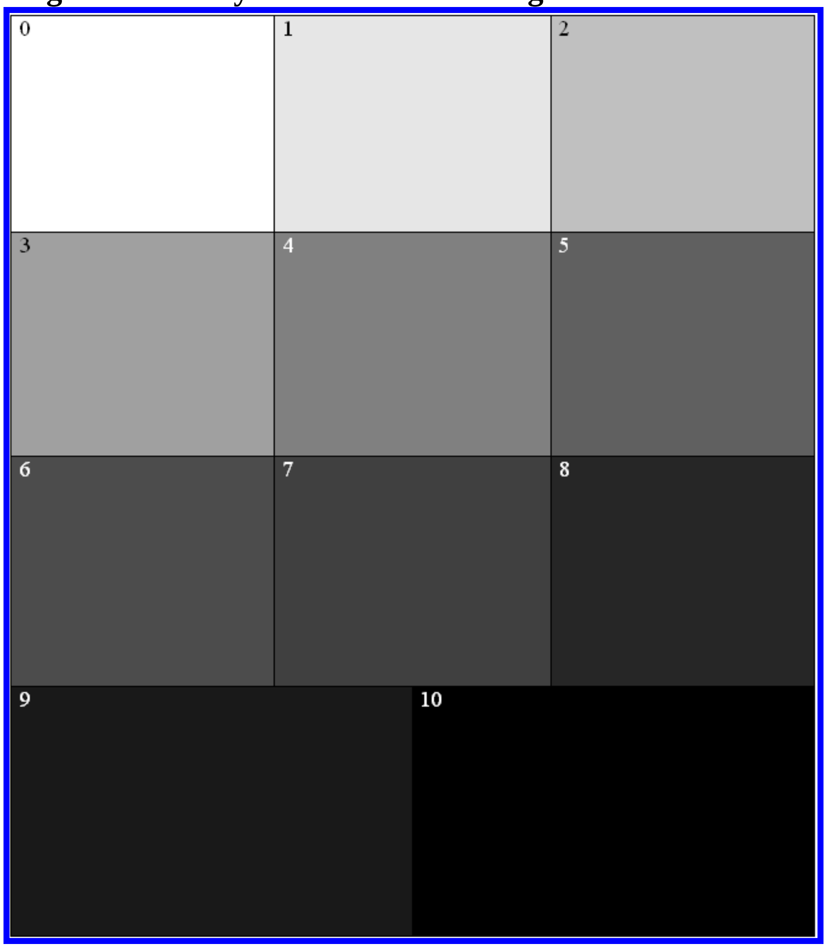


The sensor connections to MB-1 are shown above. As the reflectance increases, the current flow in the transistor increase, which decreases $\mathbf{V_{OUT}}$. Since the MB-1 measurements must track the direction of $\mathbf{V_{OUT}}$ with respect to the up/down sense of the parameter, we will define ***low measurements to have high reflectance*** (toward white), ***and high measurements to have low reflectance*** (toward black). An inverting Op Am could be inserted if desired to change the sense of the direction.

4.9.2 Coupler Calibration Procedure

Below is a simple grey scale created with Microsoft Word. A full size copy is available on the Downloads page.

Figure 21 – Grey Scale for Calibrating Reflectance Sensor



To calibrate the sensor, we set a full scale value of 10 during the coupler setup routine, and then save calibration data points at integer values ranging from 0 – 10. The calibration is done at each calibration point with the sensor viewing the corresponding grey scale value in the above chart at a fixed distance.

Analog Meter Calibration:

A Linear scale with a full scale value of 10 can be used for this application. Legends for "Low Reflectance" and "High Reflectance" are included on each end of the scale to clarify the meaning of low and high readings. A sample scale is shown here.

4.10 Measuring Distance – Using a Linear and Nonlinear Device

4.10.1 Overview

In the examples above, we have dealt with linear sensors and nonlinear sensors, and examined different approaches for performing the calibration. This example shows distance measurement applications. Both linear and nonlinear sensors are available for measuring distance. We briefly discuss the linear device but concentrate on the nonlinear device, because it brings in a new wrinkle – namely the fact that the output voltage, while well within MB-1's input range, is ***decreasing as a function of distance***, and MB-1 requires that the input voltage that it reads increases as the parameter being measured increases. We have not had to deal with this issue so far.

Using a Linear Distance Sensor - Maxbotix Ultrasonic Rangefinder - LV-EZ1 - EZ-1

The data sheet can be found here.

This sensor, shown in Figure 22, is an ultrasonic device that produces a linear output voltage per unit distance.

The output is given by:

$$V_{OUT} = V_{CC} /512$$

where V_{CC} is the supply voltage.

For a 5 volt supply, this corresponds to 9.8 millivolts per inch.

There is nothing new we can learn from calibrating this device compared with the above examples. We can either program a single point (for example 980 mV corresponding to a calibration point of 100 inches), or we can use the empirical method, (although you might need to take into account the beam width issues as the distance increases if using the empirical method).

Figure 22 Ultrasonic Distance Sensor

Using a Nonlinear Distance Sensor - Sharp IR distance sensor

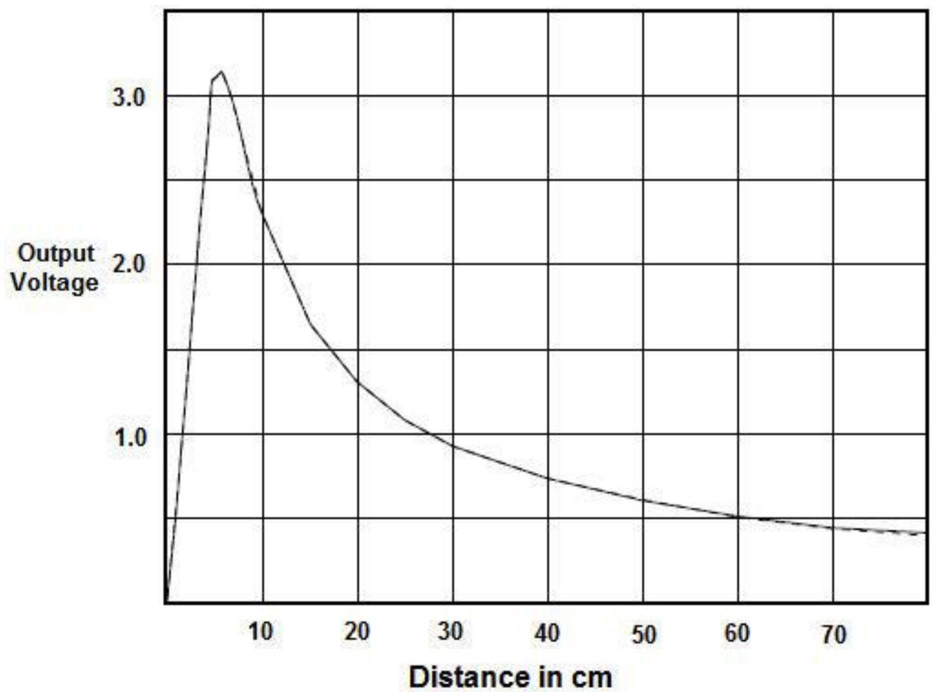
This sensor, shown in Figure 23, is an IR sensor with a highly nonlinear transfer function.

The data sheet for the device can be found here.

The input/output curve for this device is shown in Figure 24. As you can see, for the useful part of the curve (where distance is > 6 cm), ***the output voltage decreases as distance increases***. (Measurements can not be made below this point because the sensor output voltage must be unique for each parameter value, and that is not the case for the transfer function if the region where the distance is less than 6 cm. is included.)

Figure 23 – IR Distance Sensor

Figure 24 – Voltage vs. Distance for IR Sensor



4.10.2 Calibration Procedure

There are two ways to deal with the "upside down direction" of the transfer function.

4.10.2.1 Calibrate and display the reciprocal of the parameter

The reciprocal of the curve in Figure 24 – Voltage vs. Distance for IR Sensor, above 10 cm, is a monotonically increasing function. If we calibrated the meter to measure the reciprocal of the distance, this would require us to calculate the reciprocal of the measured value to get the actual distance parameter – not elegant. However, you could make a custom analog meter face with two scales. The first scale would be the actual parameter being measured (the reciprocal of distance). The second scale would be the corresponding distances, ***which could be read directly from the second analog scale*** (which would read from high to low).

4.10.2.2 Invert the output and Bias it so that the voltage seen by MB-1 is always positive

This can be done with op amps, but the approach we show below accomplishes the same thing, and is quick and easy to implement. If we reverse the normal polarity of the two sensor output leads, and place a 5 volt DC source in series with the sensor output leads so that the voltage will always be positive and monotonically increasing, this solves the problem. (The voltage sources must float with respect to MB-1's ground).

A simplified diagram is shown below, where BAT1 and BAT2 could easily be implemented with wall warts and 7805 voltage regulators. The resultant voltage vs. distance curve is shown in Figure 26.

Figure 25 – Sensor Reversed and Biased to get increasing voltage vs. parameter

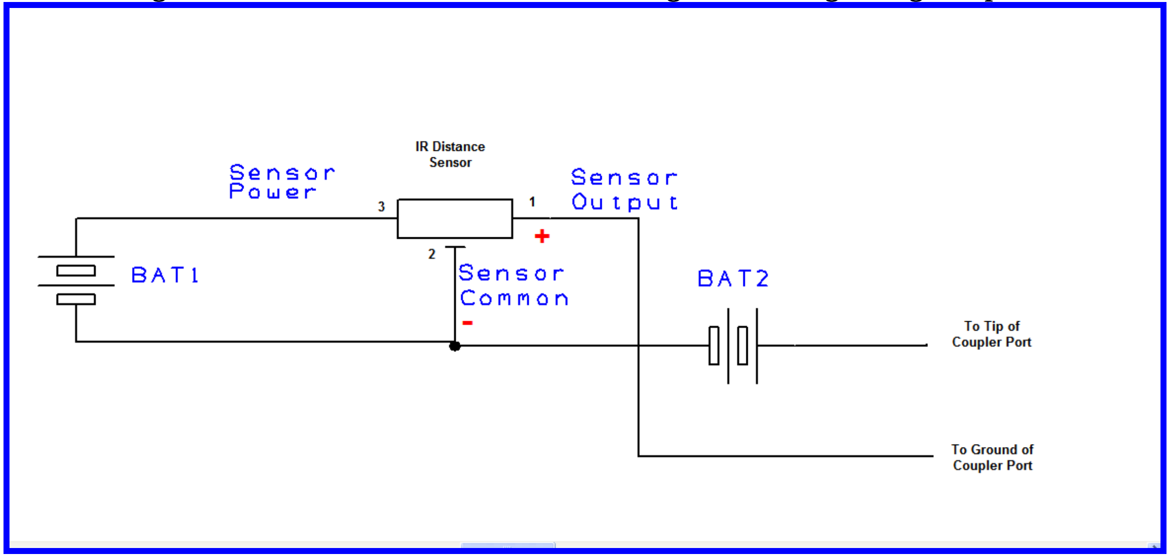
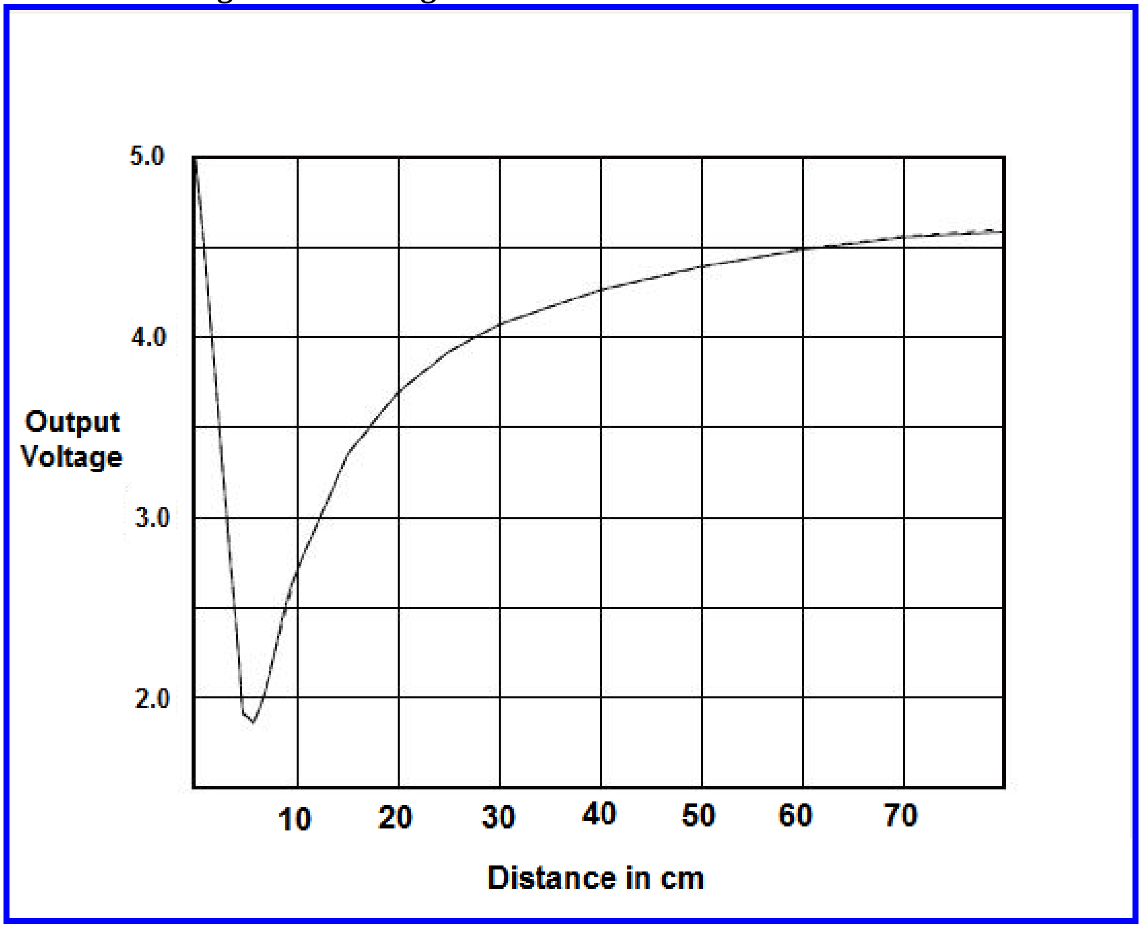


Figure 26 - Voltage vs. Distance for IR Sensor – Inverted Curve



4.10.3 Related Sensors

There are a whole series of sensors that can measure distance using infrared and ultrasonic techniques. Some of these can be found here.

4.11 Liquid Level Sensor

4.11.1 Overview

This application uses a PN-6573P-8 ***eTtape*** liquid level sensor that has a useful operating range from approximately 1 inch to 8.5 inches. The resistance of the sensor decreases as the height of the fluid column increases. The sensor resistance is approximately 385 ohms when the fluid level is 0 and approximately 60 ohms when the fluid level is at its maximum value of 8.5 inches with a resistance gradient of 40 ohms per inch.

However, the resistance specs are rated at ±10%, and a plot of the actual resistance vs. level is not perfectly linear. Therefore, this is a good application for the empirical approach, which is simple to do accurately with this application.

4.11.2 Calibration Procedure

Below is a picture of the sensor. The data sheet can be found here:

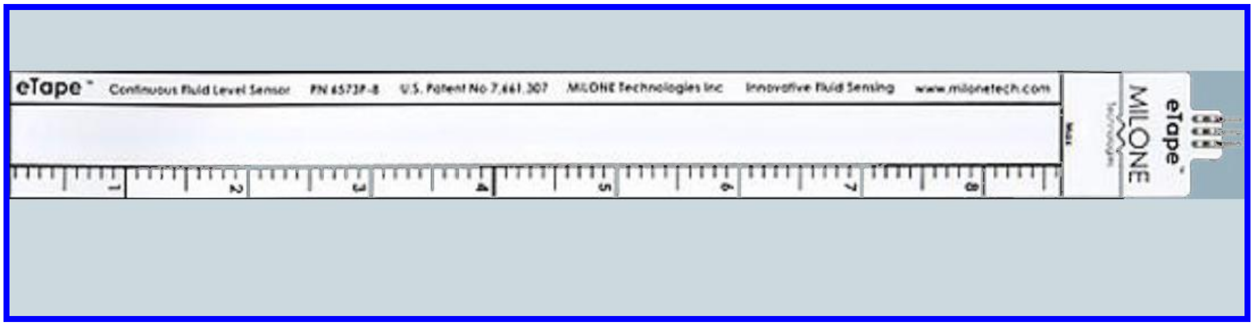
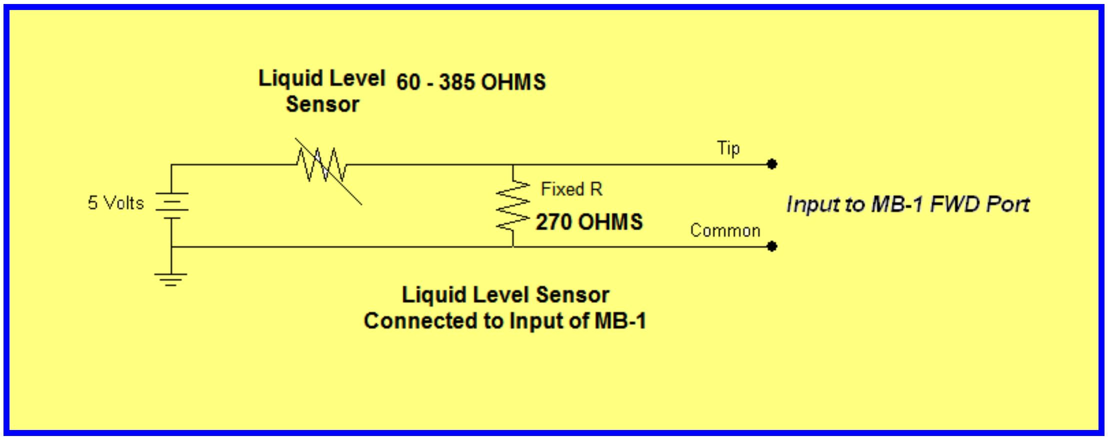


Figure 27- Input Circuit to Measure Liquid Level



To measure the level of a liquid with MB-1 using this sensor, the circuit in the figure above can be used. Since the sensor resistance decreases as the level of the liquid increases, this will cause the voltage into MB-1 to increase for increasing pressure – which is what we want. By picking the fixed resistor value approximately half way between the upper and lower resistance range of the sensor, we maximize the voltage swing seen at the input of the coupler port, which gives us good resolution.

To perform the calibration, first set the corresponding coupler trim pot to maximum sensitivity (max CW travel). Since the input stage of MB-1 can not saturate with an input voltage of less than 6.14 volts, and since we are using a 5 volts supply, setting the trim pot sensitivity to its maximum value will result in maximum accuracy and resolution without the possibility of saturating MB-1's input circuitry. Go into the coupler Setup screen, define the coupler type as GENERIC, and set the full scale value to 8 units.

Place the sensor in a container of adequate height. Add water at each one inch increment from 1 to 8, and save the calibration data at each of these points.

If you would like to obtain the full range of the sensor (8.5 inches), you can set the full scale value to 9 during the setup. However, since the sensor is not capable of measuring a liquid above 8.5 inches, you will have to calculate what the voltage would have been at 9 inches. This can be done by extending the data curve in the data sheet until it reaches 9 and extrapolating what the sensor resistance would have been at 9 inches. Knowing that value and the value of the fixed resistor above, you can calculate the input voltage at the coupler input for this point, and dial in the last calibration point using a pot and 5 the volt auxiliary source. If you want to extend the range above 8, for best accuracy, you should calculate the output resistance curve for your sensor and use it rather than the nominal curve.

If you add the calibration point for 9 inches, you have used a hybrid approach to calibration for this sensor - the empirical method for the first 8 points, and a calculated value for the last point (9 inches).

4.11.3 Using the Liquid Level Sensor with Alarm Functions

The MB-1 alarm functions can be used to detect a low or high liquid level condition by setting the alarm's high low or high trip points to the appropriate values.

4.12 *Light Level Sensor*

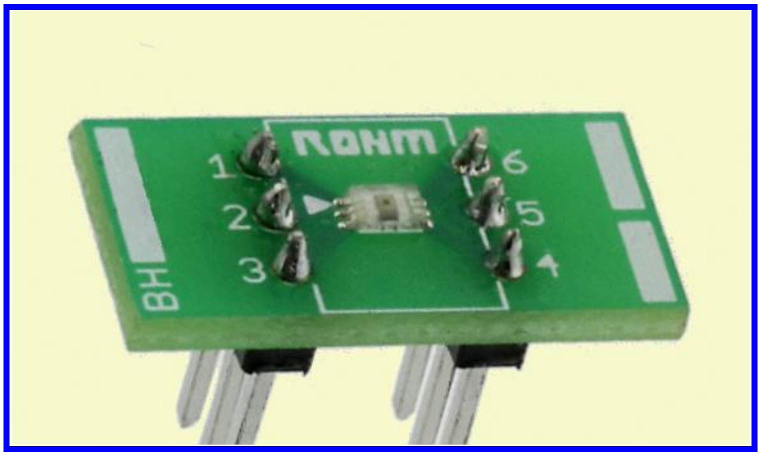
4.12.1 Overview

The sensor used in this example is a ROHM BH1620FVC integrated circuit. It generates a DC current proportional to the light intensity level, and has a range of more than 5 decades (1 lumen to > 100,000 lumens). In this example, we show how to take a sensor with a very wide range and display measurements that fall into each of the five decades with good resolution on an analog meter.

This example also shows how we can measure quantities larger than the maximum full scale value that MB-1 accommodates (30,000).

http://media.digikey.com/Photos/Rohm%20Photos/EVAL.BH1620FVC.jpg

Below is a picture of the light sensor. The data sheet can be found here:

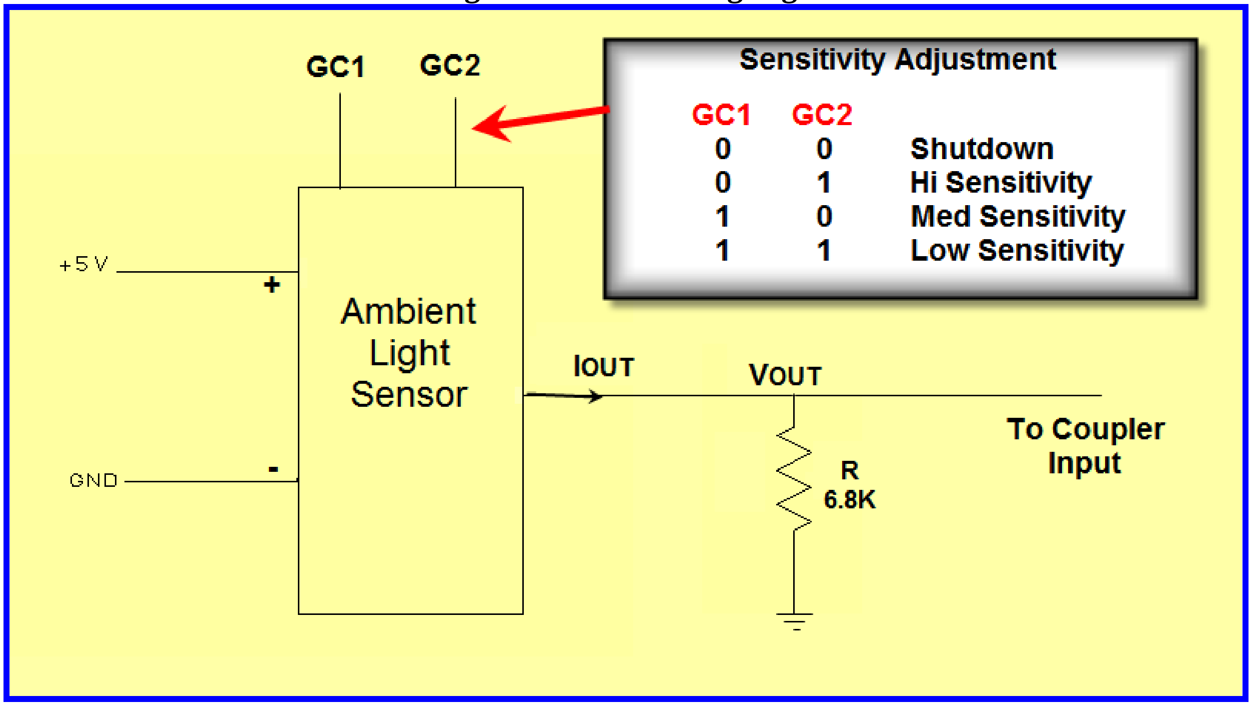


The sensor has a power and ground lead, two digital inputs to control the sensitivity, and a current output lead that gets connected to an appropriately sized resistor to generate a voltage proportional to the light intensity. The generated voltage is fed to an MB-1 coupler input for calibration and measurement.

4.12.2 Interface Circuit

The sensor connection to MB-1 is shown below.

Figure 28 –Interfacing Light Sensor to MB-1



The appropriate logic signals are applied to leads GC1 and GC2 to provide three different sensitivity settings. The output voltage is a function of the sensitivity setting according to the following equation:

$$\mathbf{Vout = S * E_V * R}$$

where **S** is the Sensitivity Constant and $\mathbf{E_V}$ is the Illumination Level.

The Sensitivity Constants are:

Sensitivity	S (Sensitivity Constant)
Low	$.0057 * 10^{-6}$
Medium	$.057 * 10^{-6}$
High	$.57 * 10^{-6}$

We will use the lowest sensitivity setting when measuring the highest light intensity (100,000 lumens). To calculate the resistance value, we want **Vout to** be less than 5 volts when the Illumination is 100,000. This limitation is required for the sensor current source to function properly when being powered with 5 volts.

$$\mathbf{Vout = .0057 * 10^{-6} * 100,000 * R}$$

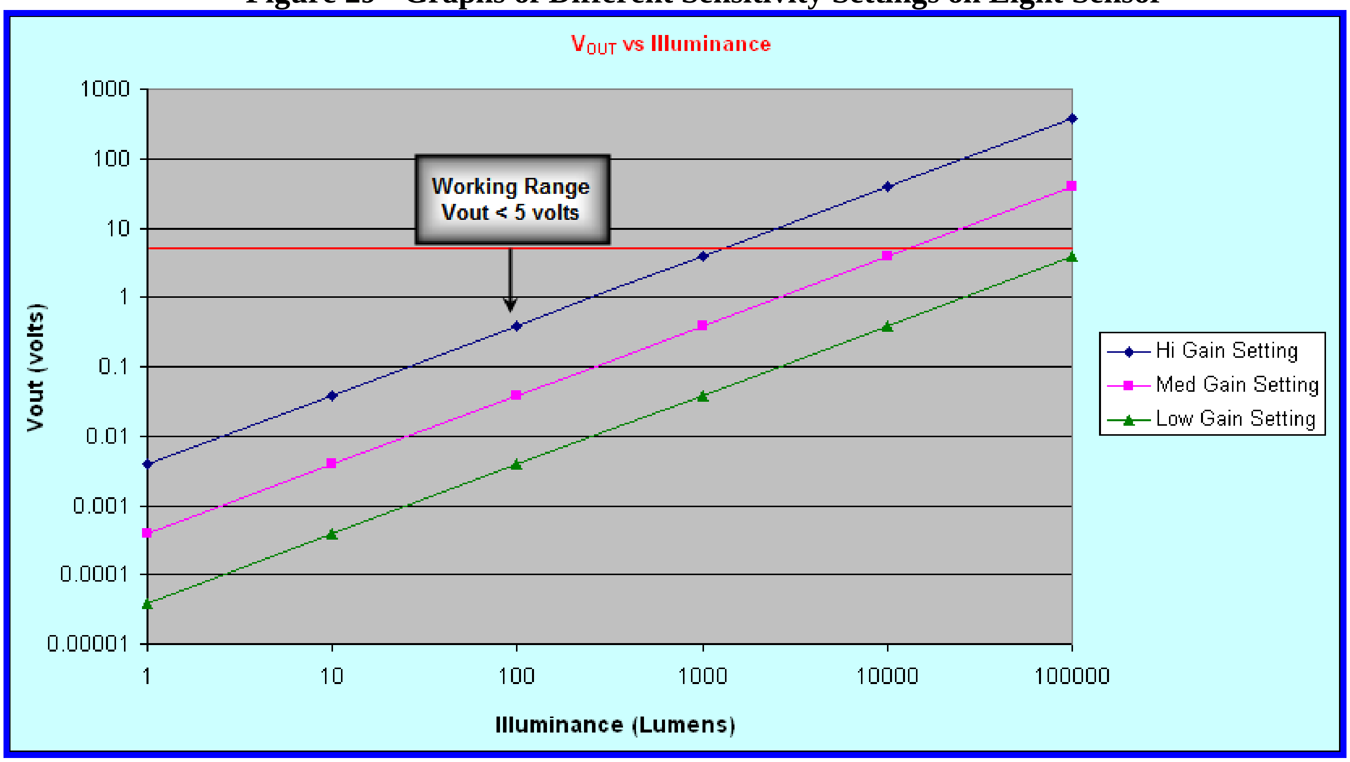
For Vout to be less than 5 volts when the full scale light intensity is present, R must be less than 8.8K. We will therefore use a standard value of 6.8K.

Taking into account MB-1s' input sensitivity and dynamic range, the table below shows the usable range for each sensitivity setting in yellow. For example, for the high sensitivity setting (which is used to measure low light levels), we will be able to measure from 1 lumen to 1000 lumens, which will generate a $\mathbf{V_{OUT}}$ from 3.876 millivolts to 3.3876 volts.

E_V	V_{OUT} (Hi Sensitivity)	V_{OUT} (Med Sensitivity)	V_{OUT} (Low Sensitivity)
1	0.003876	0.0003876	0.00003876
10	0.03876	0.003876	0.0003876
100	0.3876	0.03876	0.003876
1000	3.876	0.3876	0.03876
10000	38.76	3.876	0.3876
100000	387.6	38.76	3.876
Apply following corrections to MB-1 Digital Readings			
	Multiply by 10	No Correction	Divide by 10

Graphs for each of the sensitivity settings are plotted on log scales in the chart below. Since the sensor is powered from 5 volts, the portion of the graphs where the output exceeds 5 volts is not applicable.

Figure 29 - Graphs of Different Sensitivity Settings on Light Sensor



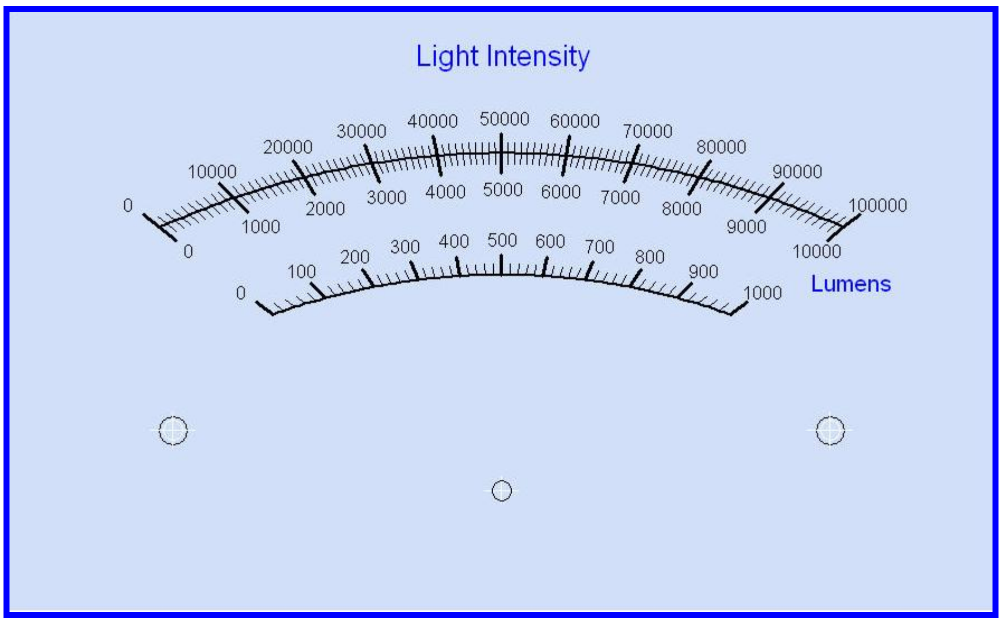
Coupler Port Calibration:

Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application.

Since we want to measure up to 100.000 units in this application, and since the maximum full scale value that MB-1 supports is 30,000, for the highest range, we will set the full scale value to 10,000 and interpret all digital readings as the measurement value divided by 10. This will be used with the sensor's lowest sensitivity setting (i.e., highest light intensity). For reading intermediate light levels, we use the medium sensitivity setting and will read the numerical values from MB-1directly with no correction. Finally, for the lowest light readings, we use the sensor's highest sensitivity setting. This requires us to multiply the digital readings displayed on MB-1 by 10 to determine the actual light intensity.

We can see from the transfer function equation that the equation is linear and passes through the origin. Therefore, we need to calibrate this application at a single point, namely the full scale value of 10,000. This is most easily done by "dialing in" the calibration voltage of 3.876 volts using a stable voltage source and potentiometer as shown in Figure 4.

Analog Meter Calibration:
Since we have the option of creating a custom meter face for an analog meter for use with this application, we can create 3 different scales that can be read directly based on whether the sensor is set to the low, medium or high sensitivity setting. The figure below shows such a scale. A full size copy can be found here.



Even though this meter face has three scales, during the Panel Meter calibration, you should specify only one linear scale, not three. The Panel Meter full scale value should be set to 10,000. When reading the analog meter, you should use the top scale, middle scale or bottom scale when the sensor sensitivity setting is set to low, medium, or high respectively. We use this approach since we have calibrated our "coupler" above to generate a full scale digital value of 10,000 for all three sensitivity settings.

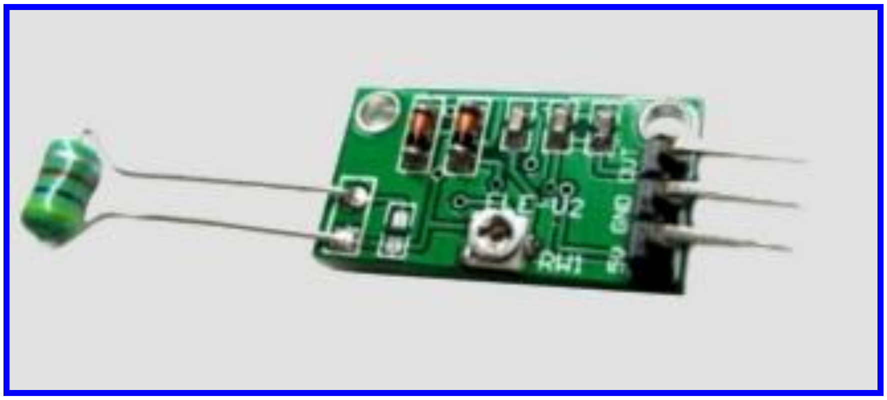
To summarize the approach we have used, when reading numerical values from MB-1 (LEDs or LCD), a multiplier factor of .1, 1, or 10 needs to be applied to the reading based on the sensitivity setting of the sensor. When reading the analog meter, the reading can be read directly from the appropriate scale without correction.

4.13 Field Strength Meter using Electromagnetic Signal Sensor

4.13.1 Overview

Any circuit that generates a DC voltage in the presence of an RF field can be used in this example. Many circuits can be found with a Google search. This example makes use of an Electromagnetic Field sensor specifically designed for this purpose.

Below is a picture of the RF sensor. Specifications for this sensor can be found here:



The sensor has only three leads: power, ground, and V_{OUT}. Since the specifications for this device simply indicate that VOUT increases as the RF field increases, the best we can do is make a relative field strength meter. The device specs state that the range of operation is from 50 Hz to 100 MHz. The sensor also has a built in sensitivity pot, and comes with its own "antenna", but that can be replaced with your own antenna to provide increased sensitivity.

Coupler Port Calibration:

Since we are using this as a relative strength indicator and since V_{OUT} from this sensor can never exceed 5 volts, this is an easy sensor to calibrate.

Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application. The full scale value we select is arbitrary. We will select a full scale value of 1000, which provides good resolution.

We need to perform the calibration for this sensor at a single point, namely the full scale value. Apply a calibration voltage of 5 volts to the coupler port and save the calibration data. Alternatively, you may set the calibration voltage to a lower value if you want to increase the sensitivity of the sensor/antenna combination. Calibration is most easily done by "dialing in" the desired voltage using a stable voltage source and potentiometer as shown in Figure 4.

Analog Meter Calibration:
Any linear scale analog meter with a full scale rating of 1 mA or less will work fine in this application. A sample Field Strength Intensity scale is shown here with three scales: 0- 10, 0- 100, 0 – 1000. Since we have built in a large amount of resolution during the coupler calibration step, we provide three ranges to make use of that resolution.

Notes: A homebrew unit that can be used with MB-1 that has provisions for amplification can be found on N9ZIA's web site.

4.14 RF Ammeter

4.14.1 Overview

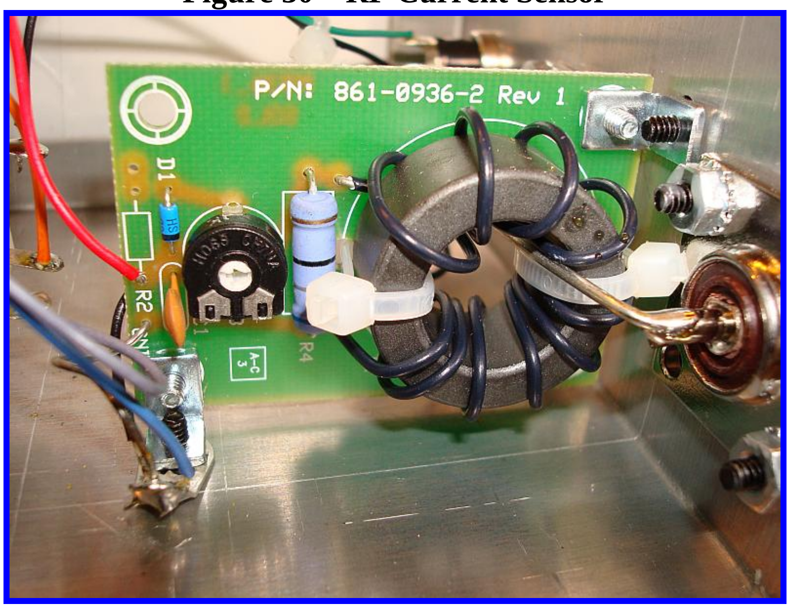
Like an RF power coupler and the other sensors discussed above, an RF Current Sensor is really just another form of an analog sensor. When you bring up the Coupler Setup screen however, you will see that there is a separate choice for the RF Ammeter setup (**AMPS**) as shown in the setup screen below.

PWR AMPS GENERIC –

This has to do with the way MB-1 processes analog voltages that are either below or above the voltages corresponding to the lowest and highest calibration points respectively. This is discussed in detail in 9.3. Suffice it to say here that for multipoint calibrations for both RF Power couplers and RF Ammeter couplers, ***MB-1 will compute power and current measurements respectively for all encountered voltage levels***, including voltages lower or higher than the voltages corresponding to the smallest and largest calibration points. That is not the case for multipoint calibrations identified as GENERIC in the setup screen.

Below is a picture of the RF Current sensor used in an MFJ RF current meter. You will also find circuits for several RF current sensors on the Internet. They are relatively easy to build.

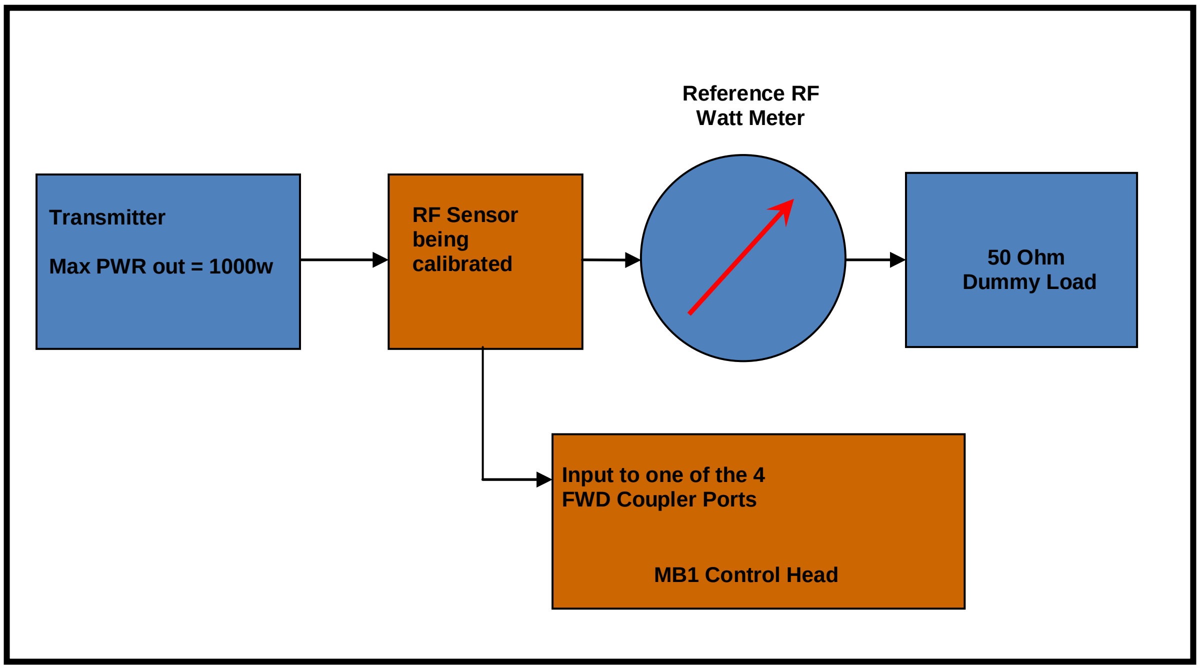
Figure 30 – RF Current Sensor



Even though an ideal current sensor has a linear transfer function that passes through the origin, and could therefore be calibrated at a single point, there is some advantage in terms of accuracy to calibrating the coupler at multiple points for the same reason we calibrate an RF Power coupler at multiple points: namely real world couplers are not ideal devices.

RF Sensor Calibration:

The following figure and table are taken from the MB-1 User's Manual. The figure shows one method of calibrating this application using a reference RF power meter in tandem with the RF current sensor. When driving a 50 ohm resistive load, the RF current can be calculated knowing the power level as read from the reference Power Meter. Multiple values are selected in the table below to ensure that we characterize the coupler over its low, medium, and high operating range.



RF Current Calibration Point (Amps)	Corresponding Power
0.1	0.5 watts
0.5	12.5 watts
1	50 watts
2	200 watts
3	450 watts
4	800 watts

As mentioned above, RF currents less than the lowest calibration point of .1 amps and higher than the largest calibration point of 4 amps (in the above example) will still be measured and displayed by MB-1. In these cases, MB-1 uses the transfer function characteristics at the lowest and highest calibration points respectively to compute the values.

Note – when performing the coupler setup, be sure to follow the procedure for setting the coupler trim pot to ensure that you do not drive the MB-1 Amplifier/Mux into saturation. This procedure is described in detail in the MB-1 User's Manual.

Analog Meter Calibration:

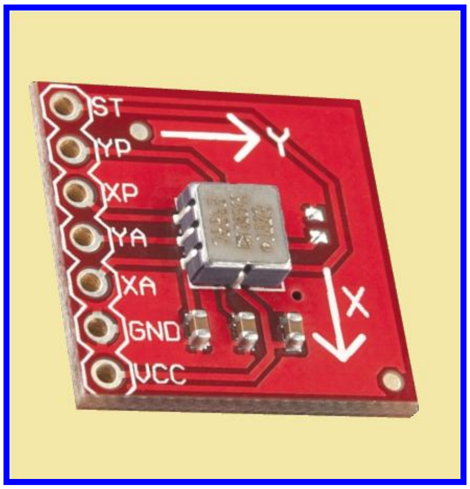
Analog Meter calibration is straight forward, and makes use of one or more linear scales depending upon the number of ranges desired. A sample RF Ammeter scale is shown here.

4.15 Measuring Tilt using an Accelerometer Sensor

4.15.1 Overview

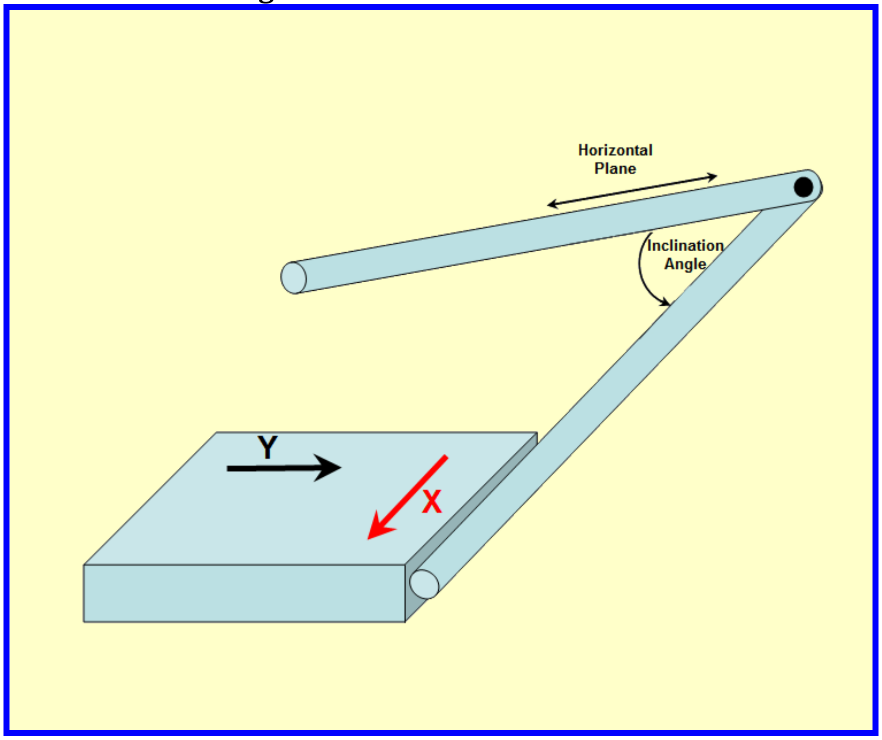
This example will measure tilt from 0 degrees to 90 degrees. The sensor used is a dual axis sensor, but we will use only a single channel. A good discussion of how tilt can be measured using an accelerometer is given here, but the main point is that the displacement that accelerometer would undergo on a given axis if the acceleration was 1g is identical to the displacement that the accelerometer undergoes when the board is oriented 90 degrees. At that point, the sensor is undergoing 1g due to gravity even though the sensor is not moving.

Below is a picture of the accelerometer sensor. The data sheet can be found here:



The figure below shows how the sensor would be mounted. When the inclination angle is 90º (X arrow pointing straight down), the X axis acceleration is 1g.

Figure 31 – Sensor Orientation



Hookup is straightforward:

Lead	Description
ST	Self Test (see data sheet)
YP	Not used
XP	Not Used
YA	Y Axis acceleration – not used
XA	Y Axis acceleration – connect to coupler input
GND	5 volt common from MB-1 Aux Power
VCC	+5 volts from MB-1 Aux Power

A .1 uF capacitor should be connected between XA and ground to reduce noise.
With no acceleration (or tilt) the idle output voltage is $V_{CC}/2$. When powered with 5 volts, this sensor generates 1000 millivolts per g. Therefore, the transfer function is:

$$\mathbf{XA = 2.5 + 1.0 * a}$$

$$\mathbf{a = XA - 2.5}$$

where **XA** is the analog output voltage in volts and **a** is the acceleration in g units.

This is a linear function, but the above equation applies for acceleration, not tilt. From the above equation, we know that the output voltage at 0 degrees (no tilt) will be the idle output voltage of 2.5 volts ($V_{CC}/2$). At 90 degrees, the sensor sees an acceleration of 1g. Therefore, the analog output voltage will be 2.5v + 1000 mv/g * 1g = 3.5 volts. But between the two end points, the output voltage varies as the arcsine of the acceleration (see Application notes for details). Therefore

$$\theta = \text{arcsine } a = \text{arcsine } (XA - 2.5)$$

Using the approach we have used in other examples, we want to determine the corresponding voltage that corresponds to a particular calibration point. Assume that we will calibrate this sensor at 10 degree points: 0º, 10º, 20º, 30º, ... 90º. We need to determine the corresponding voltage, XA, corresponding to these points. Therefore, we need to solve for **XA** in the above equation.

$$XA = \sin(\theta) + 2.5$$

The calibration points and the corresponding sensor output voltages are shown below:

Angle (degrees)	XA (analog voltage)
0	2.50000
10	2.67365
20	2.84202
30	3.00000
40	3.14279
50	3.26604
60	3.36603
70	3.43969
80	3.48481
90	3.50000

4.15.2 Error Analysis

We can take a look at how well the linear interpolation will do between the above calibration points. Because MB-1 uses linear interpolation between calibration points, MB-1 will declare the measurement value to be half way between the corresponding calibration points in the left column above when the voltage is exactly half way between the corresponding voltage levels

The error analysis is summarized in the table below. The numbers in red from the first two columns in the table below are copied from the table above, which are the calibration points.

The next column, **Midpoint Angle** is the midpoint between the two angles in the row below and above the entry in column 1. This is the measurement value that MB-1 will declare when the voltage from the sensor is exactly half way between the **XA** calibration points in column 2. These voltages are shown in the **Midpoint Voltage** column.

The next column subtracts the idle voltage of 2.5 volts. We then take the arcsine of that value to determine the actual angle that corresponds to the midpoint voltage. This is shown in **the Interpolated**

Measurement Angle column. The last column shows the error due to interpolation, which is the difference between the **Midpoint Column** entry and the **Interpolated Measurement Angle** column. The worst case error occurs at the higher angles and is slightly more than 2 degrees.

Table 4 - Error Analysis for Tilt Sensor

Angle	XA (Vout actual)	Midpoint Angle	Midpoint Voltage	Midpoint Voltage - 2.5	MB-1 Interpolated Measurement Angle for Midpoint values	Error (in degrees)	% Error
0.0	2.50000						
		5	2.5868	0.0868	4.9809	0.0191	0.381494
10	2.67365						
		15	2.7578	0.2578	14.9416	0.0584	0.389416
20	2.84202						
		25	2.9210	0.4210	24.8984	0.1016	0.406504
30	3.00000						
		35	3.0714	0.5714	34.8475	0.1525	0.435779
40	3.14279						
		45	3.2044	0.7044	44.7824	0.2176	0.483589
50	3.26604						
		55	3.3160	0.8160	54.6898	0.3102	0.563961
60	3.36603						
		65	3.4029	0.9029	64.5365	0.4635	0.713147
70	3.43969						
		75	3.4623	0.9623	74.2068	0.7932	1.057632
80	3.48481						
		85	3.4924	0.9924	82.9334	2.0666	2.431264
90	3.50000						

Coupler Port Calibration:

Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application.

To calibrate this application, set the full scale value to 90 “units”. Then perform calibration at the calibration points shown in the above table in columns 1 and 2. This is most easily done by “dialing in” the calibration voltage for each of the ten calibration points using a stable voltage source and potentiometer as shown in Figure 4.

Analog Meter Calibration:

A sample Tilt scale is shown here with three scales with a full scale reading of 90. This is a linear scale, and requires that calibration be done at a single calibration point, namely the full scale value of 90.

4.15.3 Related Sensors

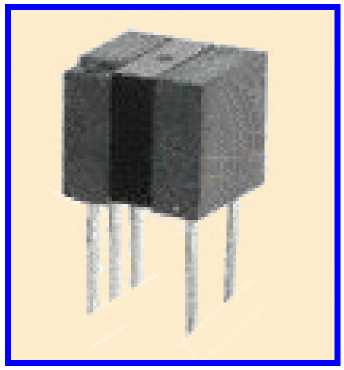
There are a whole series of sensors that can measure acceleration. Some of these can be found here.

This data sheet has the specifications for and Inductive Angle Sensor that generates an analog voltage that varies linearly with respect to the angular displacement, and can therefore be used with MB-1.

4.16 Measuring Tilt using a Discrete Tilt Sensor

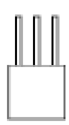
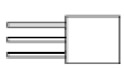
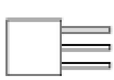
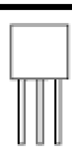
4.16.1 Overview

Some sensors have logic outputs that represent the state of the parameter being measured. An example of such a sensor is the SHARP GP1S036HEZ, which provides 4 output states using two logic outputs. Below is a picture of the discrete tilt sensor. The data sheet can be found here



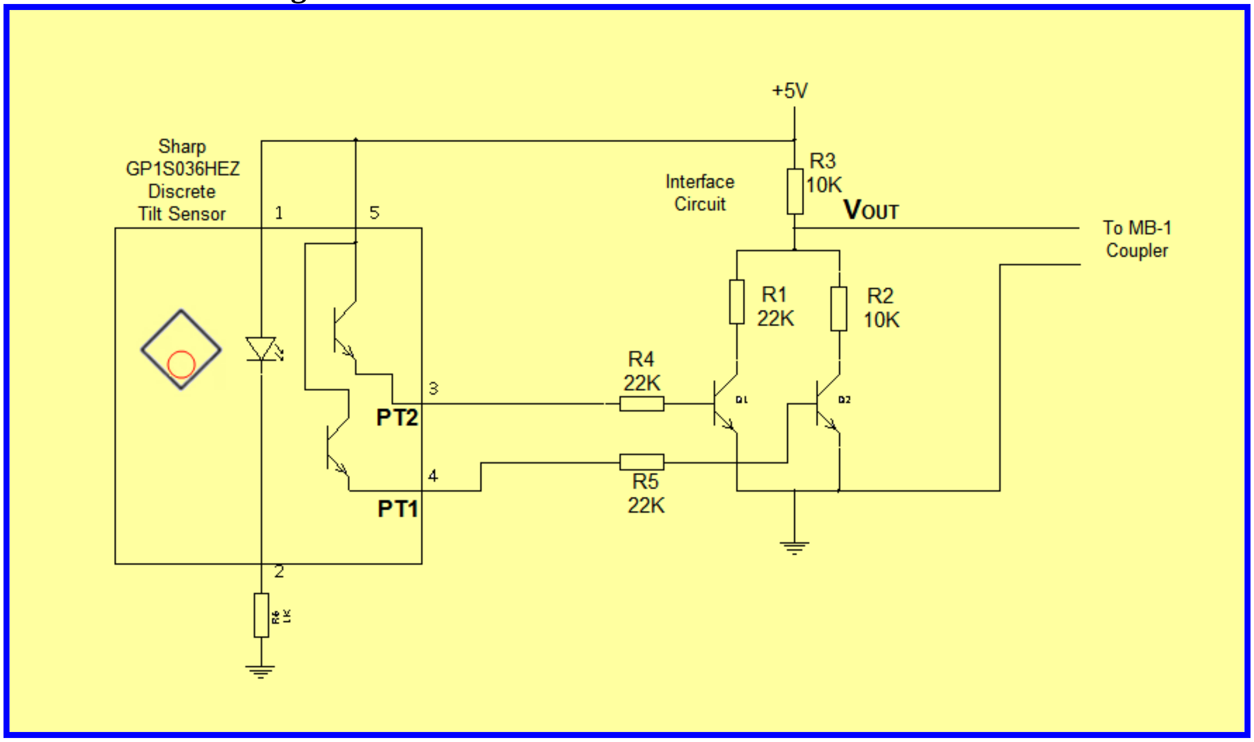
The logic outputs, **PT1** and **PT2**, indicate the sensor's orientation as either an upright, right, down or left as shown in the table below:

Table 5 – Logic Signals and Corresponding Analog Voltage for Discrete Tilt Sensor

Orientation	**PT1**	**PT2**	**V_{OUT} (Volts)** (ordered in increasing value)	**MB-1 Reading**
	1	1	2.037	0
	0	1	2.5	1
	1	0	3.437	2
	0	0	5.0	3

The circuit diagram below shows how we can derive 4 discrete analog voltages from this sensor for the four discrete orientations. We can then use the derived analog voltages to interface to MB-1.

Figure 32 – Interface Circuit for Discrete Tilt Sensor



The two transistors, Q1 and Q2 in the interface circuit, are turned on or off by the **PT1** and **PT2** sensor outputs.

By picking appropriate values of R1, R2, and R3, we can generate 4 different DC voltages at $\mathbf{V_{OUT}}$ corresponding to the sensor's four orientations. (This assumes a 0 volt drop across Q1 and Q2 when turned on. In practice, you would want to measure $\mathbf{V_{OUT}}$ for the four states to determine the actual calibration values to account for the $\mathbf{V_{CE}}$ drops and resistor tolerances).

Coupler Port Calibration:
Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application.

To calibrate this application, set the full scale value to 3 "units". Then perform calibration at the calibration points shown in the table below. These are the two rightmost columns from the table above. Digital readings of 0, 1, 2, and 3 correspond to orientations of down, right, left and up respectively.

Table 6 – Calibration Points for Discrete Tilt Sensor

Orientation in Numeric Form	V_{out} (volts)
0	2.037
1	2.5
2	3.437
3	5.0

Analog Meter Calibration:

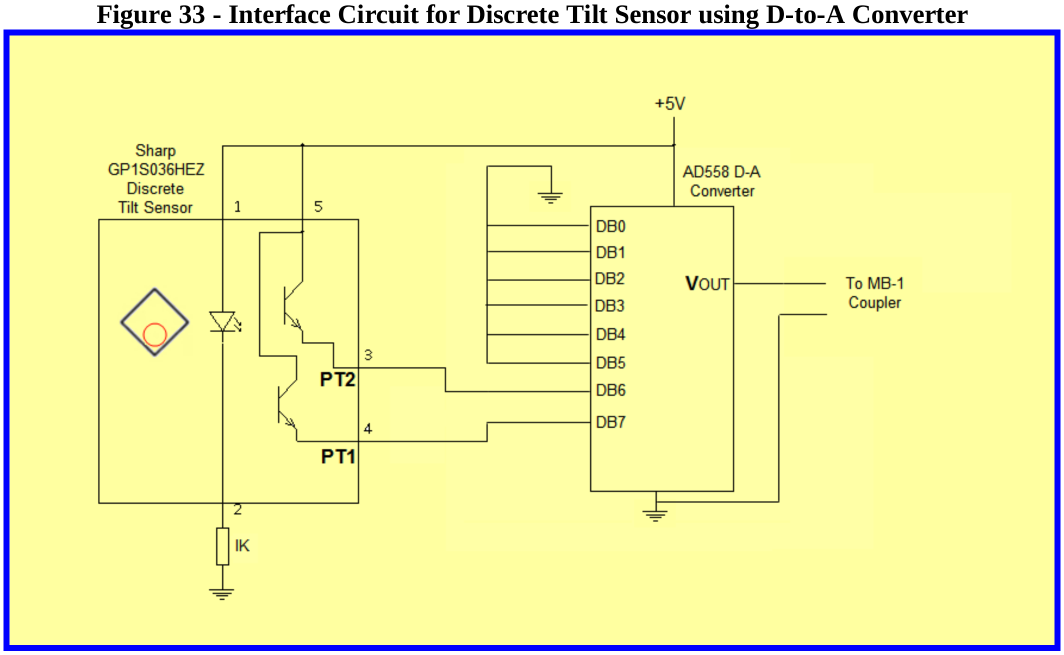
A sample scale for this application is shown here. This is a linear scale, and requires that calibration be done at a single calibration point, namely the full scale value of 3. In labeling the scale, we substitute the text "Down", "Right", "Left" and "Up" for the four numeric values.

Admittedly, driving LEDs in place of R1 and R2 is a much simpler way to use this particular sensor. But if you encounter a sensor with multiple logic outputs that represent the parameter being measured, if you want to display the parameter in numeric form or on an analog scale, an approach similar to this one could be used.

Notes:

In effect, the above interface circuit is a simple D-to-A converter. We could have used an 8 bit D-to-A converter such as the Analog Devices AD558 instead. When operated at 5 volts, this device generates a full scale voltage of 2.56 volts. A simplified schematic, using this device for the discrete tilt sensor is shown below. We use only the 2 most significant bits. Therefore, the four generated output voltages will be approximately 0, 2.56v/4, 2.56v/2, and 2.56v. If the AD558 was used to interface to this application, these would represent the voltages for the four calibration points.

Figure 33 - Interface Circuit for Discrete Tilt Sensor using D-to-A Converter



For the connections shown in the above diagram, these four voltages in increasing order would represent positions of UP, RIGHT, LEFT, and DOWN respectively. Using the D-to-A solution for interfacing to

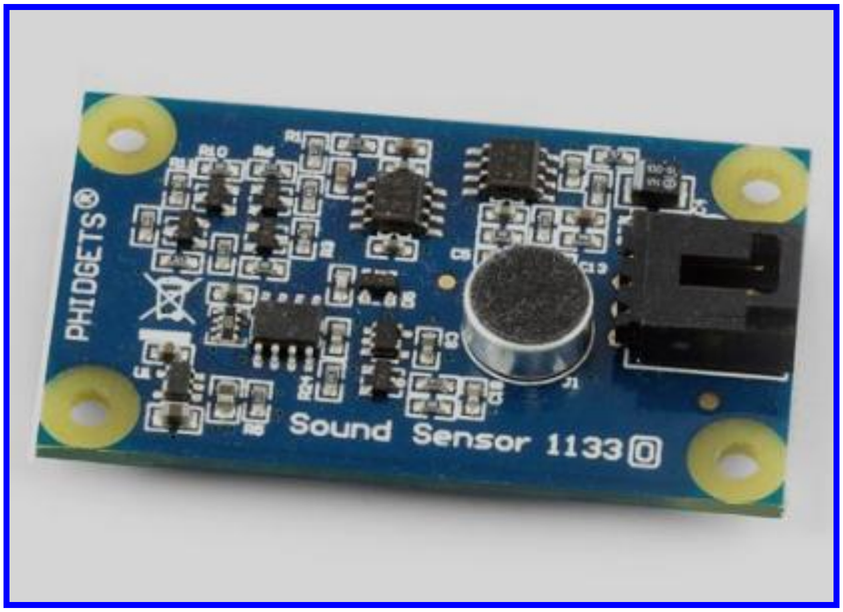
MB-1 starts to make more sense as the number of logic outputs representing the parameter being measured increases above two.

4.17 Logarithmic Sound Pressure Level Sensor

4.17.1 Overview

This example uses a Phidgets1133 Sound Sensor, which produces a DC output voltage that is a nonlinear function of the sound level. The sensor is rated at sound pressure levels of 50 dB to 100 dB with a frequency range from 100 Hz to 8 kHz. But as stated on the Phidgets website, these sensors are not industrial grade sensors and should not be expected to perform as such. This example will use this sensor to display sound pressure directly in logarithmic units (dB).

Below is a picture of the sound sensor. The data sheet can be found here:



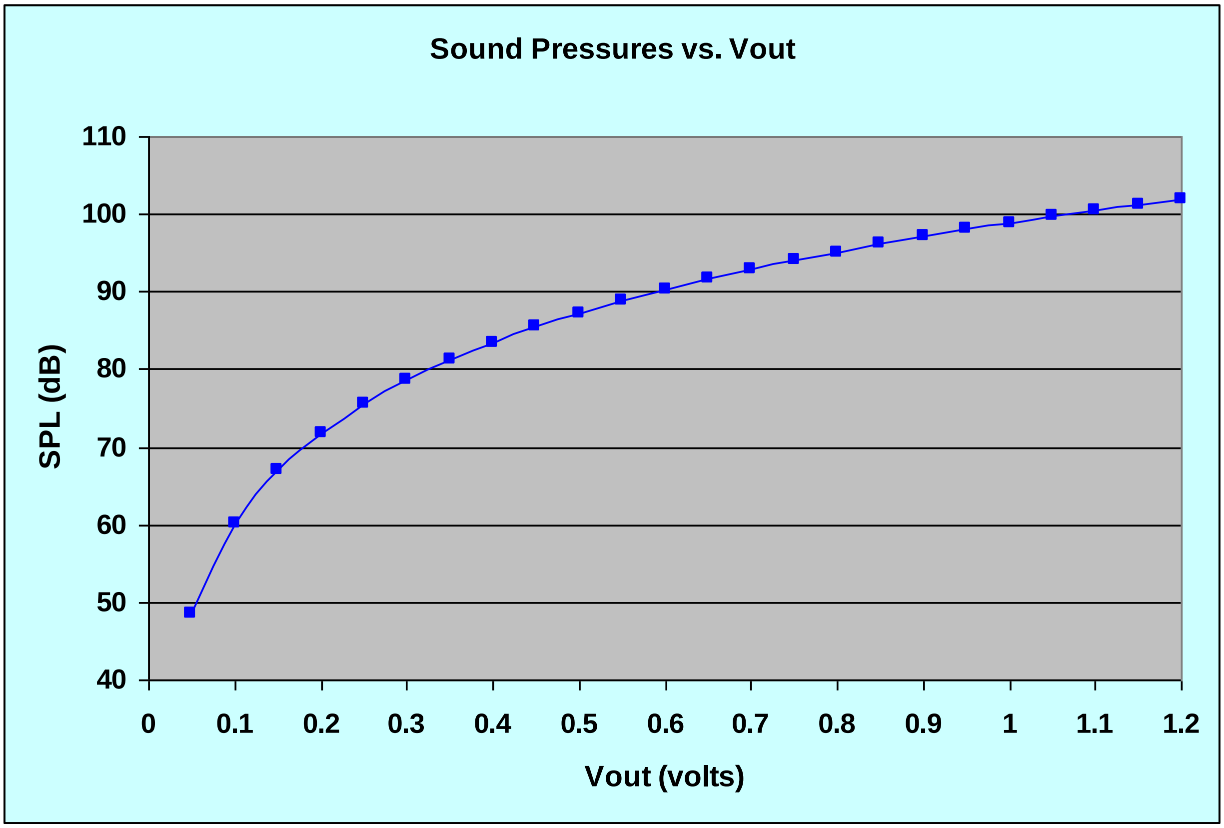
From the data sheet, the equation of the Sound Pressure Level with respect to output voltage, V_{OUT}, is shown below.

$$\mathbf{SPL = 16.801 * \ln(200 * V_{OUT}) + 9.872}$$

where ln is the natural log function.

The graph for this transfer function is shown below:

Figure 34 - Output voltage vs. Sound Pressure



For calibration, we need to know the voltages that correspond to the SPL values from 50 dB to 100 dB. Solving for **Vout** in the above equation:

$$\textbf{Vout} = \exp\left[(SPL - 9.872) / 16.801 \right] / 200$$

A chart of the voltages for these points is shown below.

SPL (in dB)	Vout	SPL (in dB)	Vout
50	0.054482	76	0.256055
51	0.057823	77	0.271759
52	0.061369	78	0.288425
53	0.065133	79	0.306113
54	0.069127	80	0.324886
55	0.073367	81	0.344811
56	0.077866	82	0.365957
57	0.082641	83	0.3884
58	0.087709	84	0.41222
59	0.093088	85	0.4375
60	0.098797	86	0.464331
61	0.104856	87	0.492807
62	0.111287	88	0.523029
63	0.118112	89	0.555105
64	0.125355	90	0.589148
65	0.133043	91	0.625279
66	0.141202	92	0.663626
67	0.149862	93	0.704324
68	0.159052	94	0.747518
69	0.168806	95	0.793362
70	0.179159	96	0.842016
71	0.190146	97	0.893655
72	0.201807	98	0.94846
73	0.214184	99	1.006627
74	0.227319	100	1.06836
75	0.24126		

The entries in red in the above table correspond to available MB-1 calibration points. At these points, the calibration should be exact. However, the entries in black will undergo linear interpolation. Since the transfer function is nonlinear, we know there will be some error at these points. For an application of this type, it is worth evaluating the magnitude of the errors at the intermediate points so that you can determine if the accuracy across the usable range will meet your needs.

4.17.2 Error Analysis

We can take a look at how well the linear interpolation is doing between calibration points. We know that the calibration will be exact for the red entries above, which are at multiples of 10. Look at the V_{OUT} values for 50 dB and 60 dB. If we look at each integral value in that range, we have ten data points. Because MB-1 uses linear interpolation between calibration points, MB-1 will declare the measurement value to be 51 dB when V_{OUT} is exactly at 1/10th of the voltage between the 50 dB and 60 dB voltage points. Likewise, MB-1 will declare the measurement value to be 52 dB when V_{OUT} is exactly 2/10^{ths} of the voltage between the 50 dB and 60 dB voltage points, and so forth.

The first two columns in the table below are copied from the table above, and represent the exact SPL and VOUT values calculated using the data sheet formula. The next column (Delta) is the difference between VOUT for the next 10 dB step and the current SPL value. For example, the Delta entry for the SPL=50 row is V_{OUT} (@ 60dB) - V_{OUT} (@ 50dB). The next column is simply 1/10th of that value.

Since MB-1 uses linear interpolation, adding the 1/10th step to V_{OUT} at 50 dB represents the V_{OUT} value at which MB-1 will declare the measurement to be 51 dB. Adding a 2/10^{ths} step to VOUT at 50 dB represents the voltage at which MB-1 will declare the measurement to be 52 dB, etc. These are the entries shown in the blue column below.

You can see, for example, that the exact VOUT that corresponds to SPL=51 is 0.057823047. But with linear interpolation, MB-1 will declare a measurement of 51 dB at the voltage in the corresponding blue column. You can see that the values are somewhat different.

The blue column therefore represents the voltages at which MB-1 will declare the measurement value to be an integral value in the 50 dB to 100 dB range. For the voltage entries in this column, we then calculate the exact SPL values corresponding to those voltages using the data sheet formula. With the exception of the entries in red (at each 10 dB point), the Nominal SPL value in column 1 and Actual SPL value in the green column will differ due to the interpolation. The difference is the error introduced by the interpolation at that point. The error values are shown in the last column.

This approach is repeated for each integer value in the active range (50 dB to 100 dB). As can be seen from the last column, none of the errors is greater than .73 dB.

Table 7 – Error Analysis for Sound Sensor

Nominal SPL	Vout (Exact)		Delta for this 10 dB range	1/10th Delta for this 10 dB Range	Interpolated Vout for which MB-1 will declare the Nominal SPL value in column 1	Actual SPL Value	Error (dB)
50	**0.0544818**		**0.04432**	**0.00443**	**0.05448**	**50**	**0**
51	0.057823047				0.058913	51.3138528	0.313853
52	0.061369177				0.063345	52.5323713	0.532371
53	0.065132781				0.067776	53.6684596	0.66846
54	0.069127197				0.072208	54.7325669	0.732567
55	0.073366579				0.07664	55.7332736	0.733274
56	0.077865951				0.081071	56.6777117	0.677712
57	0.082641257				0.085503	57.5718736	0.571874
58	0.08770942				0.089934	58.4208425	0.420843
59	0.093088399				0.094366	59.2289679	0.228968
60	**0.0987973**		**0.08036**	**0.00804**	**0.0988**	**60**	**0**
61	0.104856223				0.106833	61.3138528	0.313853
62	0.111286769				0.11487	62.5323713	0.532371
63	0.118111683				0.122906	63.6684596	0.66846
64	0.12535515				0.130942	64.7325669	0.732567
65	0.133042839				0.138978	65.7332736	0.733274
66	0.141201993				0.147014	66.6777117	0.677712
67	0.149861526				0.15505	67.5718736	0.571874

68	0.159052124				0.163086	68.4208425	0.420843
69	0.168806357				0.171123	69.2289679	0.228968
70	**0.1791588**		**0.14573**	**0.01457**	**0.17916**	**70**	**0**
71	0.190146109				0.193732	71.3138528	0.313853
72	0.201807251				0.208304	72.5323713	0.532371
73	0.214183539				0.222877	73.6684596	0.66846
74	0.227318831				0.23745	74.7325669	0.732567
75	0.241259674				0.252023	75.7332736	0.733274
76	0.256055471				0.266595	76.6777117	0.677712
77	0.271758654				0.281168	77.5718736	0.571874
78	0.288424871				0.295741	78.4208425	0.420843
79	0.306113181				0.310314	79.2289679	0.228968
80	**0.3248863**		**0.26426**	**0.02643**	**0.32489**	**80**	**0**
81	0.344810654				0.351312	81.3138528	0.313853
82	0.365956951				0.377739	82.5323713	0.532371
83	0.388400092				0.404165	83.6684596	0.66846
84	0.412219609				0.430591	84.7325669	0.732567
85	0.437499912				0.457017	85.7332736	0.733274
86	0.464330588				0.483443	86.6777117	0.677712
87	0.492806715				0.50987	87.5718736	0.571874
88	0.523029206				0.536296	88.4208425	0.420843
89	0.555105159				0.562722	89.2289679	0.228968
90	**0.5891482**		**0.47921**	**0.04792**	**0.58915**	**90**	**0**
91	0.625279097				0.637069	91.3138528	0.313853
92	0.663625757				0.684991	92.5323713	0.532371
93	0.704324113				0.732912	93.6684596	0.66846
94	0.747518389				0.780833	94.7325669	0.732567
95	0.793361651				0.828754	95.7332736	0.733274
96	0.842016355				0.876676	96.6777117	0.677712
97	0.89365492				0.924597	97.5718736	0.571874
98	0.948460337				0.972518	98.4208425	0.420843
99	1.00662682				1.020439	99.2289679	0.228968
100	**1.0683605**				**1.06836**	**100**	**0**

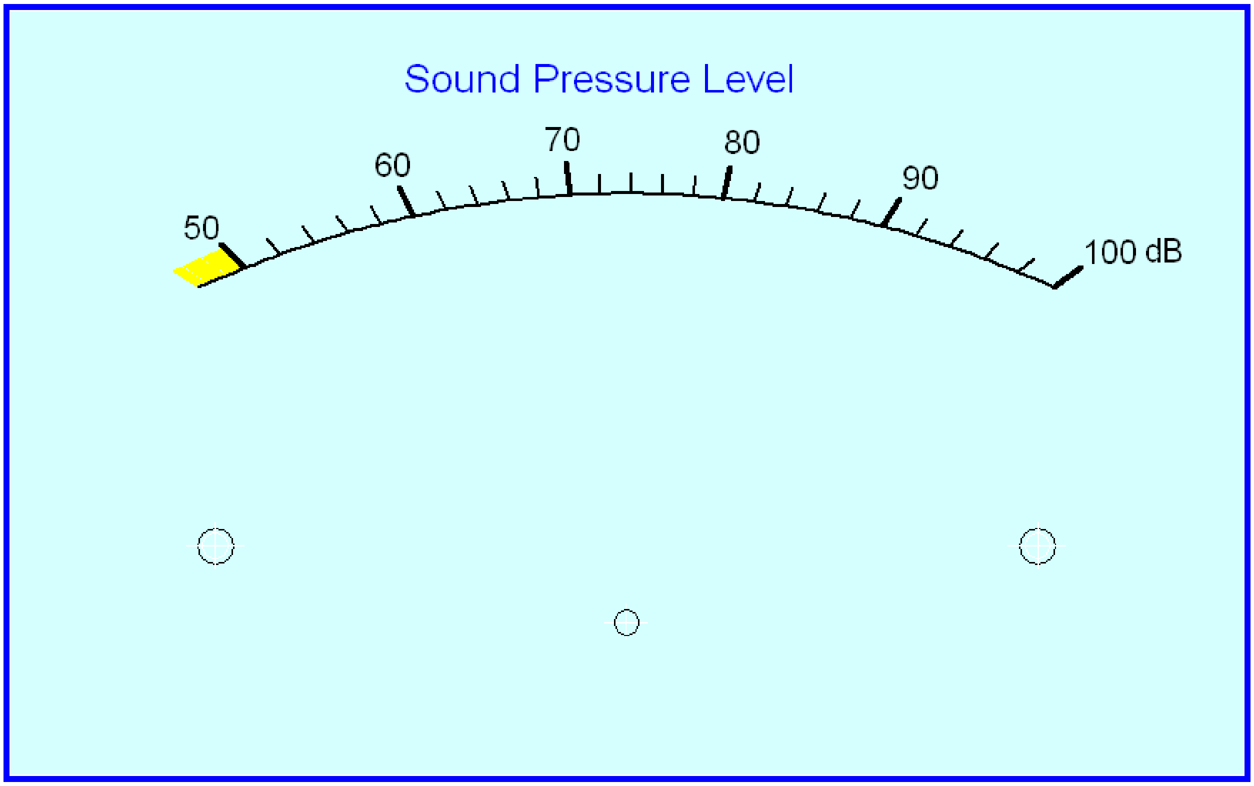
Coupler Port Calibration:

Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application.

To calibrate this application, set the full scale value to 100 “units”. Then perform calibration at the following points: 50, 60, 70, 80, 90, and 100 using the corresponding voltage levels shown in red (V_{OUT} Exact) in the table above. This is most easily done by “dialing in” the calibration voltage for each of the six calibration points using a stable voltage source and potentiometer as shown in Figure 4.

Analog Meter Calibration:

A Linear scale with a full scale value of 100 could be used for this application. However, Panel Meters can use the linear scale setup procedure only if the starting value on the scale is 0. If you used a scale with a range from 0 – 100, this would give you a dead zone from 0 – 50 since the sensor calibration just covers the range of 50 – 100 dB, which is the usable range of the sensor. If you use an existing meter face, this is the most straightforward approach. But if you decide to design your own meter face, you can essentially create a linear scale from 50 – 100, and calibrate the analog meter as a ***nonlinear meter scale*** during the Panel Meter calibration setup procedure. The nonlinear scale option must be used since the scale's starting value is not 0.



Above, we show a custom meter scale for this application. The majority of the scale covers the usable range: 50 – 100. A small portion of the scale, the section highlighted in yellow, is allocated for "don't care" calibration points that are required as part of the nonlinear scale calibration when the scale does not start at 0. This will become more apparent below.

To calibrate this scale for use with MB-1 using the Panel Meter calibration routine, set the full scale value to 100, and set the number of calibration points to 10. During Panel Meter calibration, you will be prompted to calibrate the meter scale at 10 points: 10, 20, 30, ... 100.

For calibration points 10 – 40, you must advance the needle beyond its 0 resting point. Furthermore, you must advance the needle forward slightly after calibrating each of these "phantom points" since the software integrity checks require the ADC value to be monotonically increasing for all of the calibration points (including these "don't care" points). As long as each of the four calibration points, 10 - 40, are in the yellow region, and each calibration point has a larger deflection than the preceding calibration point, you will be OK.

Once you reach the calibration points for 50 dB and above, calibrate the meter in the normal fashion by simply “dialing the needle” to each calibration point on the scale and pressing the SELECT menu button to save the calibration point. After calibration, any value from 50 - 100 will read correctly. Any value less than 50 will read in the yellow portion of the scale, effectively indicating an underrange (which is a valid indication for this application).

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4.18 *Color Sensor Module*

4.18.1 Overview

This application uses a TCS230 color sensor that produces an output voltage that varies linearly with respect to the color intensity of one of three colors (red, green, blue). The color to be monitored is selected by applying logic 0 or logic 1 signals to terminals S_0 and S_1 as shown in the data sheet.

4.18.2 Calibration Procedure

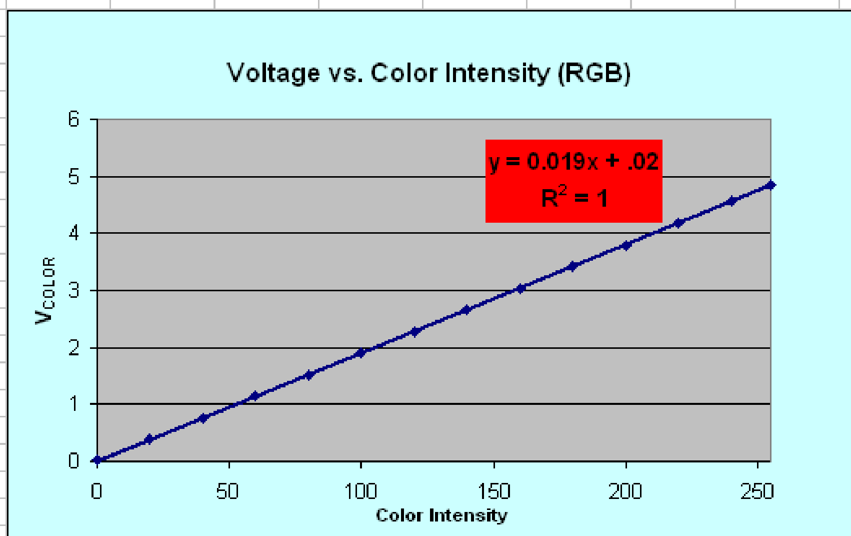
Below is a picture of the TCS230 sensor. The data sheet can be found here.

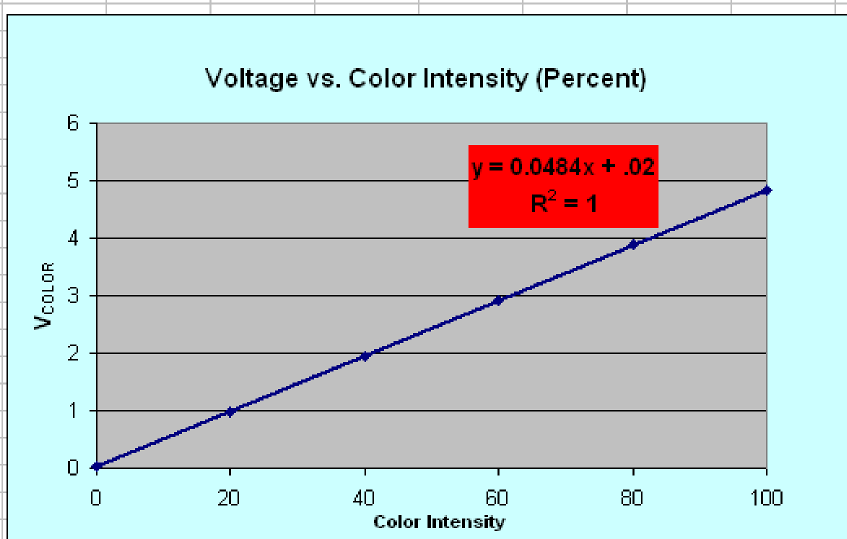
The analog output voltage (V_{COLOR}) vs. color density is shown below for two different scale arrangements. These graphs are applicable when the reference voltage is set to 4.95 volts. If you want to set the reference voltage exactly to this value, you can use the MB-1 5 volt auxiliary power with an appropriate voltage divider, but this value is close enough to 5 volts so that the 5 volt auxiliary power source can be used directly without much impact.

Figure 35 - Figure 36 – Color Sensor Curves for RGB Scale and % Scale

Color Intensity (RGB 0 - 255)	V_{COLOR}
0	0.02
20	0.38
40	0.76
60	1.14
80	1.52
100	1.91
120	2.28
140	2.66
160	3.04
180	3.42
200	3.79
220	4.18
240	4.56
255	4.84

Color Intensity (Precent)	V_{COLOR}
0	0.02
20	0.9762
40	1.9452
60	2.9142
80	3.8832
100	4.84





We can represent the color intensity using one of two scale arrangements:

1. The color intensity can be represented as an 8 bit value of the R, G, or B intensity. In this case, the scale would range from 0 – 255.

2. The color intensity can be represented as a percent in the range 0% to 100%. 100% would indicate that color being monitored is at its maximum intensity. In this case, the scale would range from 0 – 100.

We have used Excel's Trend Line feature in the above graphs with a linear fit. The $R^2 = 1$ value tells us that the linear fit is an exact fit (i.e., the data points in the spec sheet lie on a straight line). We will use the trend line equation on the top graph to display the color intensity as an 8 bit value. We will use the trend line equation on the bottom graph to display color intensity as a percent.

Since the equation does not pass through the origin for either scale arrangement, we need to do multipoint calibration. Since the equation is linear, only two points are required. For example, to cover the full range of the RGB transfer function (which ranges from 0 – 250), we can perform the calibration at the two closest available MB-1calibration points, namely 0 and 300.

The two approaches are show below.

RGB – 8 bit value (Displayed Measurement value 0 – 255) - The closest MB-1 calibration point to 0 (x axis) is 0. The closest MB-1 calibration point that encompasses the entire range on the high end is 300 (x axis).

Using the formula from the top graph, the voltages corresponding to these two points are as follows:

ColorIntenity = 0, V_{COLOR} = 7.2 mV

ColorIntenity = 300, V_{COLOR} = 5.7072 Volts

Percentage value (Displayed Measurement value 0 – 100%) - The closest MB-1 calibration point to 0 (x axis) is 0. The closest MB-1 calibration point that encompasses the entire range on the high end is 100 (x axis).

Using the formula from the bottom graph, the voltages corresponding to these two points are as follows:

ColorIntenity = 0%, V_{COLOR} = 7.2 mV

ColorIntenity = 100%, V_{COLOR} = 4.860 Volts

Regardless of which scale we use (R, G, B, or percent), the two calibration points can be dialed in with a stable voltage source and potentiometer as shown in Figure 4. You will not be able to achieve the 5.7072 volt setting in the RBG scale using just the potentiometer connected to MB-1's 5 volt auxiliary power output. You can either use a larger voltage source to power the pot during calibration or you can temporarily connect any 1.5 volt battery in series with the pot wiper during calibration. This will give your pot/battery arrangement a range of approximately 1.5 volts to 6.5 volts.

If you use the percentage scale, both calibration voltages can be achieved directly using just the auxiliary 5 volt source from MB-1.

4.18.3 Using the Color Sensor with Alarm Functions

The MB-1 alarm functions can be used to detect the presence or absence of a color by setting the alarm's high trip point to an appropriate threshold to detect the presence of a color, or by setting the alarm's low trip point to an appropriate threshold to detect the absence of a color. The alarm trip delay can be set to an appropriate value to accommodate varying conditions of the item(s) being monitored.

4.19 Measuring Blood Alcohol Level - Using a Nonlinear Device

4.19.1 Overview

The MQ-3 Alcohol Sensor samples the concentration of alcohol in an air sample and changes its resistance as a function of the alcohol concentration. A picture is shown below.

The data sheet can be found here.

While this example measures the ***alcohol concentration in air***, the conversion to Blood Alcohol Content (BAC) should be fairly straightforward if I understand the Wikipedia article on the topic.

The applicable conversion factor is:

.1 mg/L of exhaled breath alcohol = .02% BAC

This spec sheet is somewhat different than the ones used in previous examples. Instead of graphing resistance vs. alcohol concentration, the device specs show a resistance ratio vs. alcohol concentration. The ratio is:

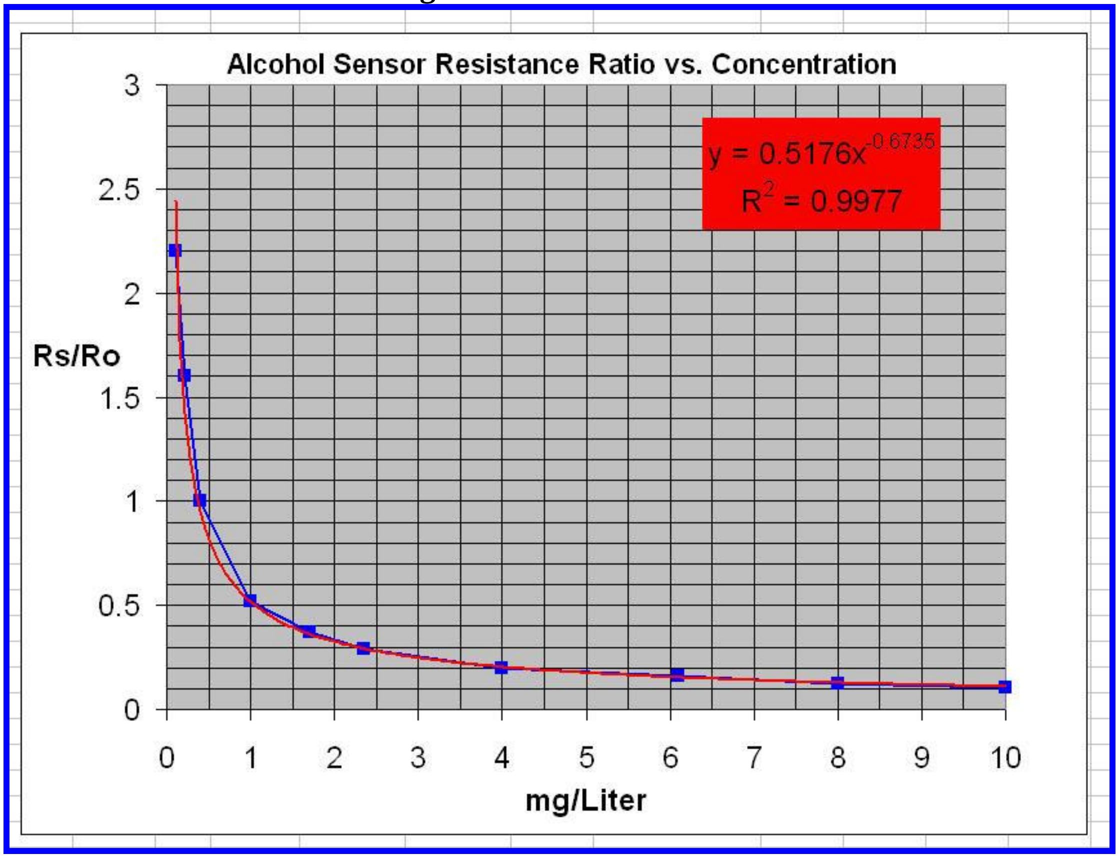
$$\mathbf{R_S/R_O}$$

where $\mathbf{R_S}$ is the sensing resistance for a given alcohol concentration, ***and Ro is the sensor resistance when the alcohol concentration is at a know reference value (.4 mg/Liter).*** I believe that the reason this was done is because there is a large variation in the sensor resistance reference points among samples. For example, at the reference level of .4 mg/Liter, the sensor resistance can vary anywhere from 1 Meg to 8 Meg depending on the sample. So to use this sensor, you have to be able to determine its resistance for the reference concentration of .4 mg/Liter.

What is guaranteed in the spec however, is the Rs/Ro ratio. So again, this sensor presents some new issues that we did not have to handle in the earlier examples.

The spec sheet is shown below. The manufacturer spec sheet graphs the data on log scales. We plotted the data on linear scales for this example.

Figure 37 – Alcohol Sensor Curve



The blue data series is the piecewise graph of the actual points from the manufacturer's spec. Since this was almost a straight line on a log graph scale, it is worth a little effort to determine if we can characterize the data with an equation. ***Excel's trend line feature is useful for this***. This Excel feature is usually used to predict trends – future data points, from the derived equation. But if you can get one of Excel's trend types to give a very close match to the data points, you can then get access to the actual trend line equation generated by Excel and use that equation to aid in calibration.

The generated trend line is shown in red in the above figure. Excel also computes what is called an R^2 value. The closer that value is to 1.0, the better the fit of the trend line. The data in the red box shows both the equation of the trend line and the R^2 value, which is in fact very close to 1. Therefore, we can assume that we have an accurate formula that characterizes our sensor, and we will use that instead of a few discrete data points.

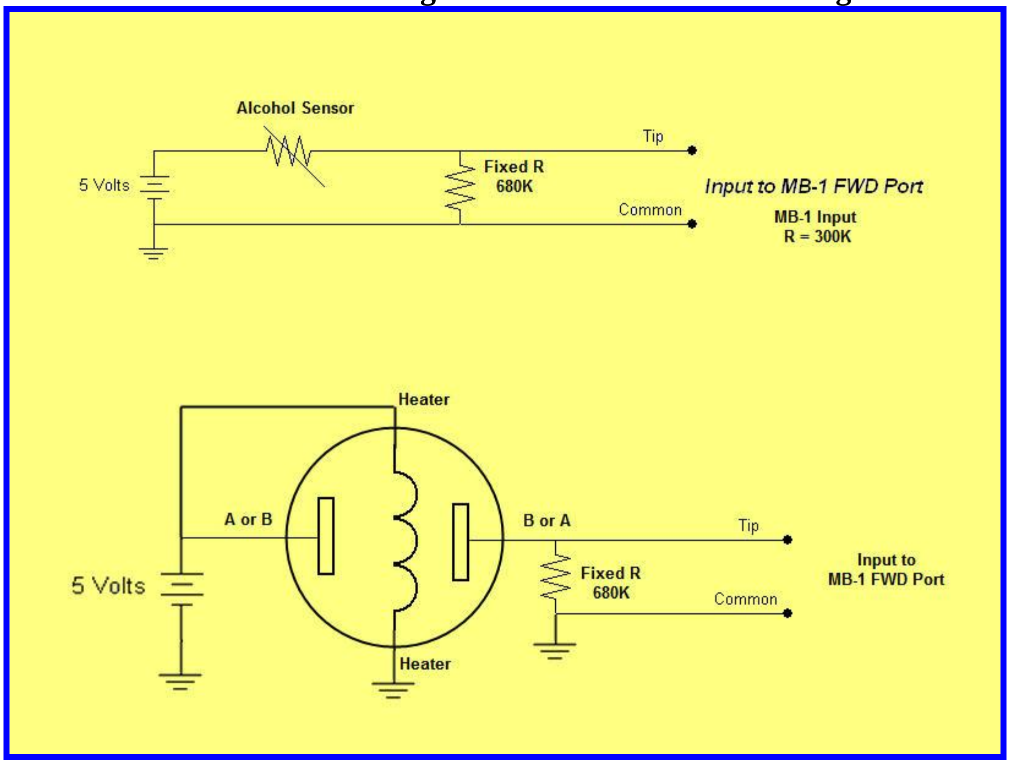
We used the Excel ***Power trend type*** to fit these data points. Unless you're a Math major, try all of the Excel trend types, one at a time using trial and error to see which, if any, gives the best R^2 value. That is the approach we used.

4.19.2 Wiring

The wiring for the alcohol sensor is shown below. Since the resistance of the sensor decreases as the alcohol concentration increases, we wire the alcohol sensor to the voltage source, which will cause the voltage fed to the MB-1 coupler port to increase as the alcohol concentration increases.

The spec applies when the ***Fixed R*** resistance is 200K. The input resistance of an MB-1 port is approximately 300K, so placing a 680K resistor in parallel gives a 209K, which is probably close enough to satisfy the spec sheet requirement for a 200K load.

Figure 38- Alcohol Sensor Wiring



The heater on the sensor can draw up to 750 milliwatts. If you decide to use the 5 volt auxiliary outputs on MB-1 to power the sensor, turn off the external Bar Graph display if on so as not to overload the Auxiliary power bus. (Any external 7-segment displays can be left on, since the current draw on those is not as high as the external Bar Graph).

4.19.3 Calibration Procedure

We have an equation for the graph in Figure 37:

$$Rs/Ro = 0.5176x^{-0.6735}$$

From that, we can determine the actual sensor resistance as a function of Ro.

$$Rs = Ro * 0.5176x^{-0.6735}$$

Remember that Ro is the sensor resistance when the alcohol concentration is a know reference value (.4 mg/Liter), and can vary from 1 Meg to 8 Meg sample-to-sample.

For this example, assume that we have a sensor with a known Ro value of 2 Meg. We can now determine the voltage seen by the MB-1 coupler port as a function of alcohol concentration. (Remember that x in the equation above is the alcohol concentration (the X axis)).

$$V_{in} = 5 * R_L (R_{in} + R_L)$$

where R_L is the load resistance in series with the sensor (209K).

If we plug the numbers into Excel, it provides us with the expected voltages for all of the calibration points within the sensor advertised range of 0.05mg/L-10mg/L.

Table 8 – Alcohol Sensor Calibration points

Calibration Point (mg/Liter)	Trend-Line Expression	Ro (ohms)	Vout (volts)
0.05	3.892584	7,785,168	0.130720
0.1	2.440587	4,881,174	0.205298
0.2	1.530208	3,060,417	0.319629
0.3	1.164536	2,329,073	0.411730
0.4	0.959416	1,918,832	0.491110
0.5	0.825540	1,651,079	0.561804
0.6	0.730145	1,460,291	0.626014
0.7	0.658144	1,316,287	0.685117
0.8	0.601538	1,203,076	0.740045
0.9	0.555664	1,111,327	0.791470
1	0.517600	1,035,200	0.839897
2	0.324527	649,054	1.217873
3	0.246975	493,950	1.486592
4	0.203473	406,946	1.696577
5	0.175081	350,161	1.868871
6	0.154849	309,699	2.014657
7	0.139579	279,158	2.140699
8	0.127574	255,149	2.251434
9	0.117845	235,690	2.349949
10	0.109773	219,545	2.438482

At this point, we can use the approach of connecting a stable voltage source to the end points of a pot, and feeding the wiper output of the pot into MB-1 as we did in some of the earlier examples. The calibration data would be saved for each point in the above table.

4.19.4 Error Analysis

We can take a brief look at how well the linear interpolation is doing between calibration points. For example, we know that if the voltage measured by MB-1 is exactly half way between two calibration points, the software will linearly interpolate and calculate a measurement value exactly half way between the two calibration points.

The data below shows the midpoint voltage at which the software interpolates the intermediate values between calibration points, and the actual voltages for the calibration mid points using the trend formula.

Table 9 – Error at Midpoints

Calibration Midpoints	Interpolated Midpoint Values	Exact Voltage at Midpoint Value	%Err
0.075	0.168008907	0.170368682	1.39
0.15	0.262463197	0.266328476	1.45
0.25	0.365679285	0.367651109	0.54
0.35	0.451419992	0.452695225	0.28
0.45	0.526457131	0.52737891	0.17
0.55	0.59390913	0.59462019	0.12
0.65	0.655565533	0.656137997	0.09
0.75	0.712580895	0.713055937	0.07
0.85	0.765757756	0.766160951	0.05
0.95	0.815683809	0.816032056	0.04
1.5	1.028884881	1.048334086	1.86
2.5	1.352232299	1.361589777	0.69
3.5	1.59158453	1.597272518	0.36
4.5	1.782723993	1.786595004	0.22
5.5	1.941763954	1.944583821	0.15
6.5	2.077677763	2.079828504	0.10
7.5	2.196066362	2.197762402	0.08
8.5	2.300691824	2.302063769	0.06
9.5	2.39421554	2.395347886	0.05

Surprisingly, the error at the midpoints is very small – less than 2%. Given the complexity of the trend line equation and the series resistance term that the voltage divider introduces, it is very surprising that the error is so small. This is probably not typical of what you would see for an “arbitrary nonlinear sensor” when used with MB-1. But the point here was to go through some error analysis – something you will want to do if you are thinking of using the MB-1 Generic Meter function for a serious application.

4.19.5 Details

You may have noticed that we never addressed how to determine the calibration of the alcohol sensor itself – in other words, what is its Ro value of a given sample since it can range from 1 Meg to 8 Meg. Good point. This appears to be a harder problem than it sounds like.

If one were serious about performing this calibration, I suppose you could get some liquor of a known proof and an enclosed container of known volumes such that when all of the liquor evaporates, the concentration would be .4 mg/ Liter. This is an approximation at best, but hopefully this example provided some additional insight on using MB-1 with the family of gas sensors listed above.

4.19.6 Related Sensors

There are a whole series of sensors that can measure force and stress. Some of these are listed below.

- Flammable Gas and Smoke Sensor (MQ-2) Data Sheet
- Methane Gas Sensor (MQ-4) Data Sheet
- LPG and Natural Gas Sensor (MQ-5) Data Sheet
- LPG / Isobutane / Propane Gas Sensor (MQ-6) Data Sheet
- Carbon Monoxide Gas Sensor (MQ-7) Data Sheet
- Hydrogen Sensor (MQ-8) Data Sheet
- Carbon Monoxide and Flammable Gas Sensor (MQ-9) Data Sheet
- Ozone Gas Sensor (MQ-131) Data Sheet
- Air Quality Gas Sensor (MQ-135) Data Sheet
- Carbon Dioxide (MG-811) Data Sheet

Other Gas or Air Sensors:

Advanced Micro Instruments 0 – 25% Oxygen Sensor Data Sheet

General Monitors Toxic Gas Detector   Data Sheet

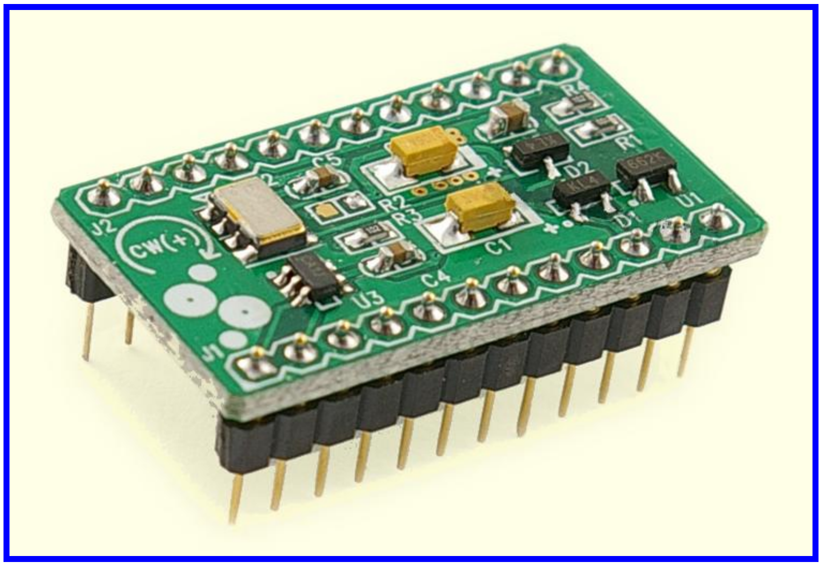
General Monitors H_2S Gas Detector   Data Sheet

Safety Systems Technology Infrared CO2 Sensor   Data Sheet

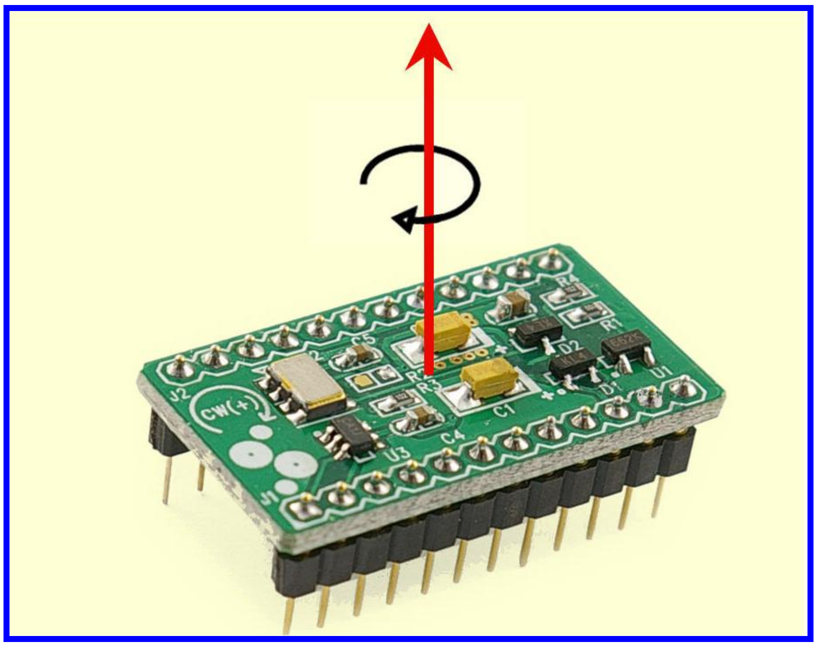
4.20 *Angular Rate Sensor (Gyroscope)*

4.20.1 Overview

This example makes use of an Angular Rate Sensor. These sensors generate an output signal that varies linearly with respect to the angular velocity around some axis. Below is a picture of the sensor. The data sheet can be found here:



This angular rate sensor will measure the angular velocity in degrees per second around the Z axis as shown in the figure below. The sensor's maximum and minimum range is range is 100° per second clockwise and 100° per second counter clockwise.



When the device is stationary, the device outputs a reference voltage of approximately 1.35 volts. As the device is rotated CCW, the output voltage decreases from the idle reference voltage by .65 millivolts per degree per second. As the device is rotated CW, the output voltage increases from the idle reference voltage by .65 millivolts per degree per second. This corresponds to a voltage range from (1.35 - .065 = 1.285 volts) to (1.35 + .065 = 1.415 volts) corresponding to an angular velocity of -100° per second to +100° per second respectively. Therefore, the range in the analog output voltage is only 130 millivolts.

MB-1 can read to millivolt resolution at the low end when the input voltage to MB-1 is small. This is the region where MB-1 applies the maximum gain of 32 from the Amplifier/Mux that processes the coupler input voltage. But since the working voltage range from the output of this sensor is in the vicinity of 1.35 volts, MB-1's resolution will be in the multi millivolt range, which is not good enough to give resolution of 1° per second. Therefore, to provide the improved resolution, we will insert an interface circuit between the sensor and the MB-1 coupler input to amplify the signal excursion.

4.20.2 Interface Circuit

The blue line in the graph below shows the sensor output voltage for the full range of angular velocities. The green line in the graph below shows the sensor output after it has been processed by the Amplifier circuit in Figure 39. The circuit has a gain of 19 (1 + (180K/10K)). A gain of 19 was chosen since it maximizes the + and – excursion around the idle voltage (1.35 v) without bottoming out at 0. The amplification is provided by op amp2 (right).

Op amp 1 (left) simply provides a low impedance source of approximately 1.35 volts (a virtual ground) so that the op amp 2 can amplify the delta between the sensor's idle voltage and the sensor's output when an angular velocity is being measured. Since the idle voltage from the sensor is not exactly 1.35 volts, adjustable resistor R1 is included so that the virtual ground output of op amp1 can be adjusted to match the actual idle voltage of the sensor during calibration.

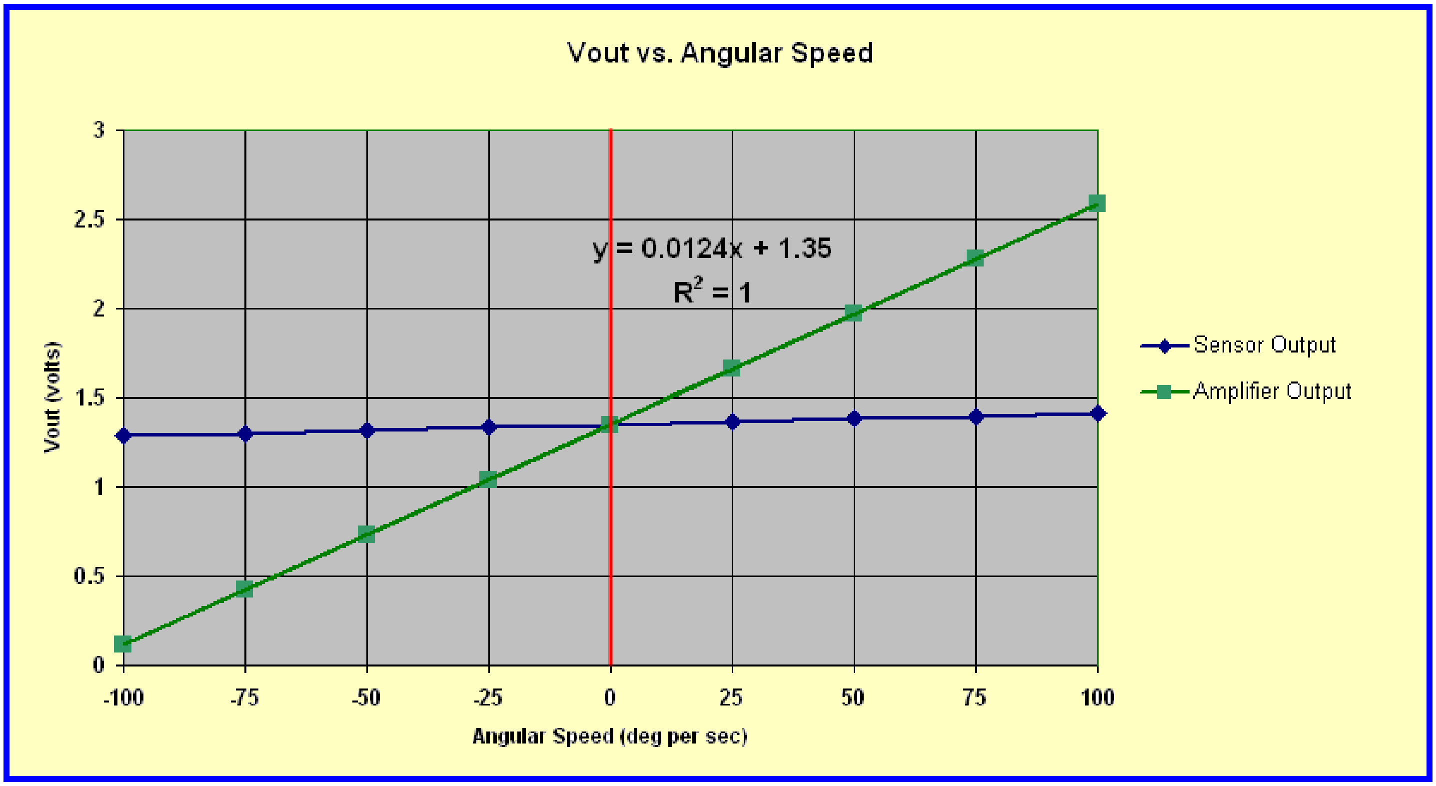
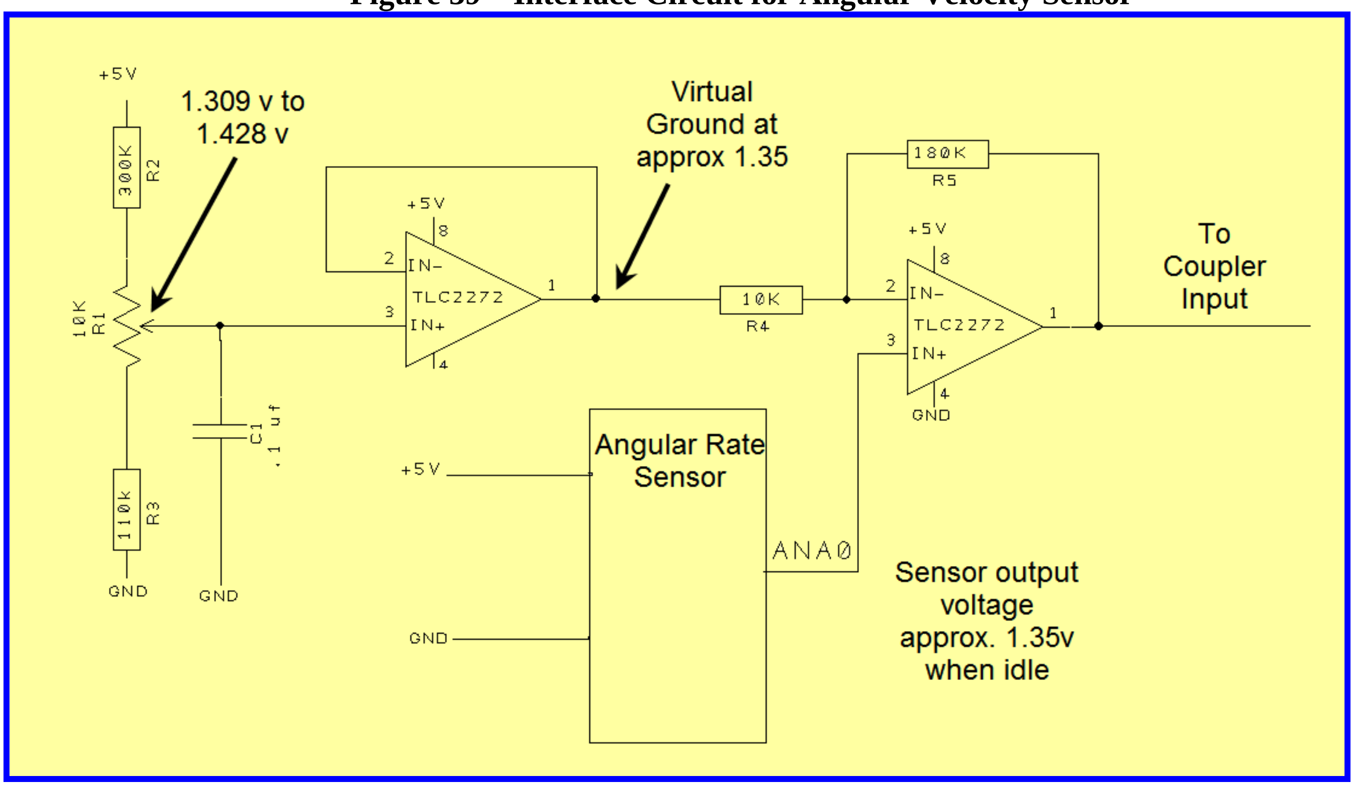


Figure 39 – Interface Circuit for Angular Velocity Sensor



4.20.3 Calibration Procedure

Coupler Port Calibration:
First, we must adjust R_1 to match the actual reference voltage of the sensor. With the sensor in a stationary position, measure the output voltage of op amp 2 with a multimeter. Adjust R1 until this voltage is 0. Read the actual reference voltage by measuring the output voltage at op amp1. It will probably be somewhat different from the nominal value of 1.35 volts. If that is the case, change the equations below and substitute the actual reference voltage for 1.35. The remainder of this example is done using the nominal reference voltage value of 1.35.

Since MB-1 is 0-based, we must start the low end of the range at 0. If we set up the calibration with a full scale value of 200, our digital readings on MB-1 will vary from 0 – 200. ***To read the actual angular velocity using the digital displays, subtract 100 from MB-1's digital reading.***

If you are adding an analog meter to MB-1 for this application, the scale can be created with the actual sensor limits (100 deg/sec CCW to 100 deg/sec CW) allowing the analog meter to be read directly.

If we add a trend line to the amplified signal and display its formula, we get:

Vout = .0124 v + 1.35

where v is the angular velocity. Since the curve is a straight line, we need to calibrate at only two points. (We need two points instead of one since the equation does not pass through the origin (0, 0)).

With the 100 deg/sec offset discussed above, the equation becomes:

Vout = .0124 (v - 100) + 1.35 = .0124 v + 0.11

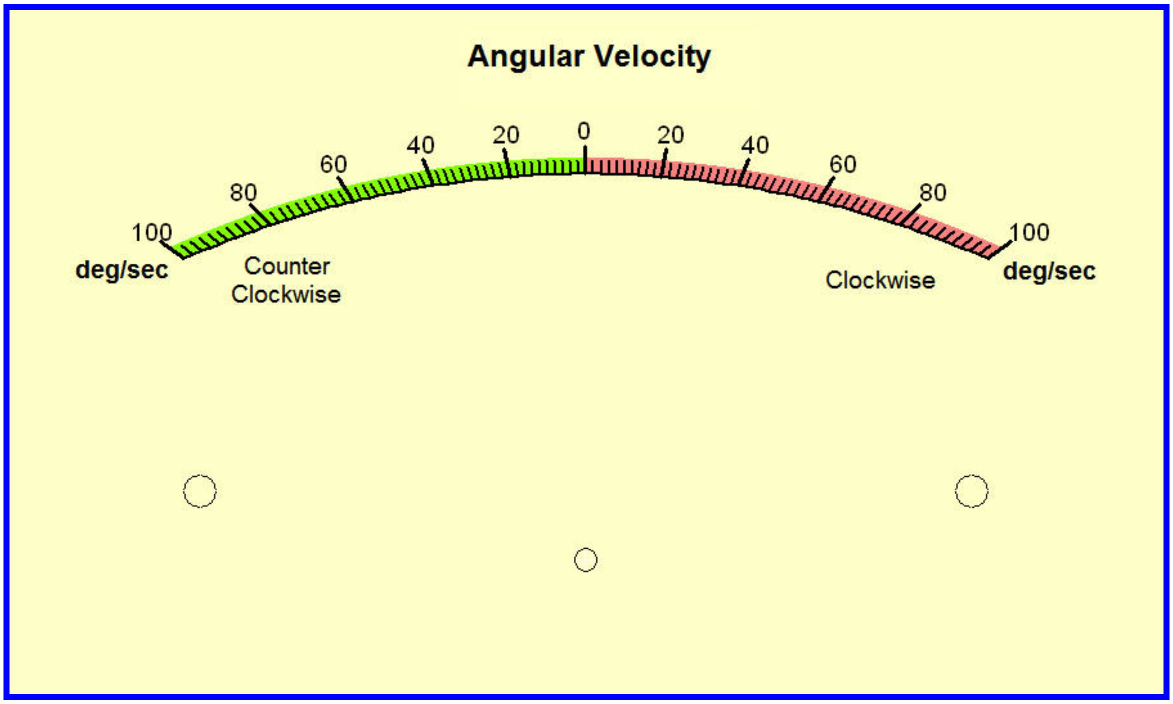
If we plug in the two closest available MB-1 calibration points (0 and 200), this gives the following calibration point input/output values:

v (Angular Velocity)	V_{out}
0.0	0.11 volts
200	2.59 volts

During calibration, these values can be "dialed in" with a potentiometer powered from the 5 volt auxiliary voltage source as previously discussed.

Analog Meter Calibration:
If we design an analog meter scale face, the range must be 200 units, but when creating the analog scale, we can set the tic marks to any value we choose. Instead of creating a scale with a starting value of 0, and a full scale value of 200, we can set the starting value to 100° **CCW** and the full scale value to 100° **CW**. We then calibrate the panel meter as a linear scale panel meter with a full scale value of 200. With this arrangement, the angular velocity can be read directly from the analog meter.

The figure below shows such a scale. A full size copy can be found here.

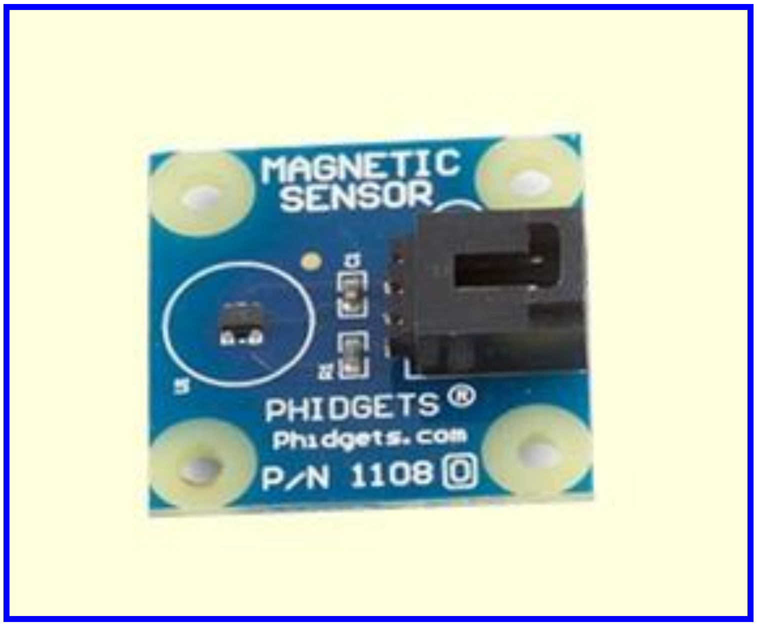


4.21 *Hall Effect Magnetic Sensor*

4.21.1 Overview

This example uses a Hall Effect Magnetic Sensor whose DC output voltage varies linearly with respect to the magnetic field. Below is a picture of the sensor. The data sheet can be found here.

If you are looking for a good reference on Hall Effect Sensors, check this documentation from the Honeywell Corporation.



The transfer unction for the magnetic field is:

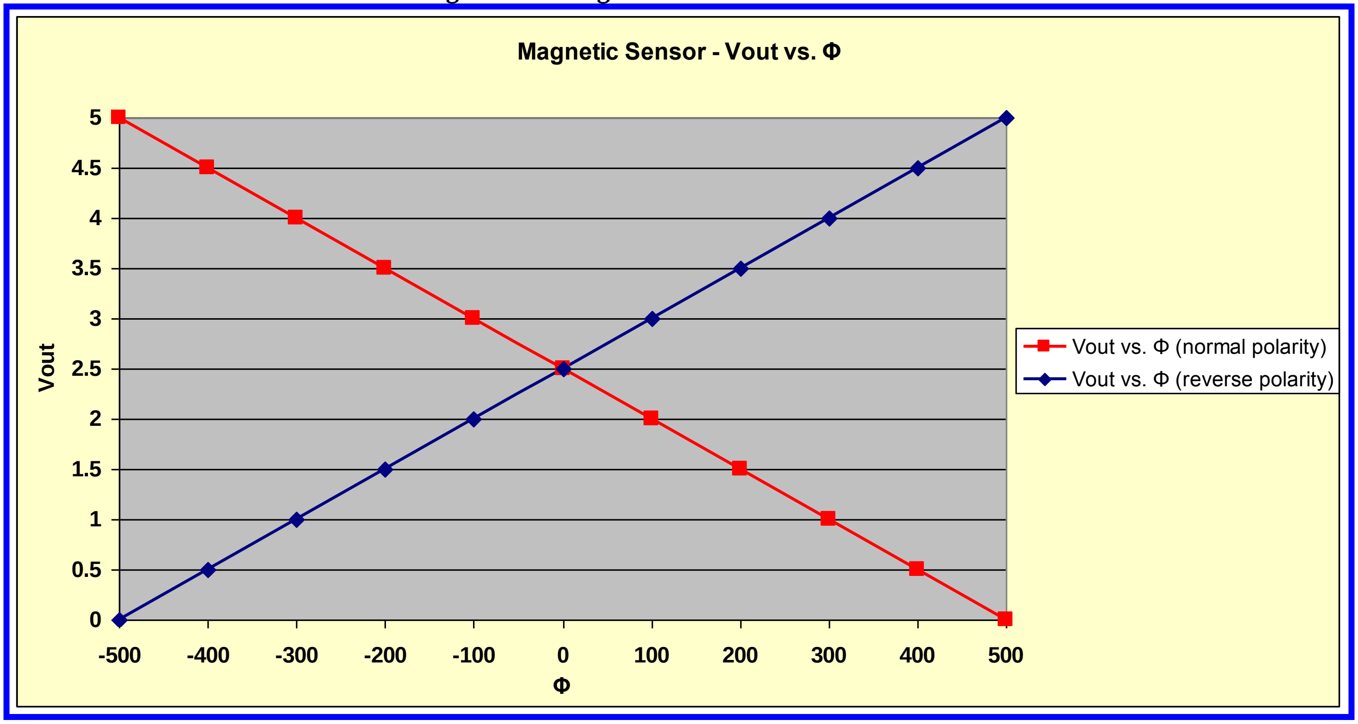
$$V_{OUT} = (500 - \Phi) / 200$$

where **Φ** is the magnetic field in gauss.

This sensor is designed to read both polarities of a magnetic field from approximately -500 gauss to +500 gauss. The sensor comes with two Neodymium magnets that are capable of generating a magnetic field of at least 500 gauss with both polarities when moved close to the sensor.

The transfer function is shown on the red data series in the chart below. The red curve does not satisfy the MB-1 requirement that the sensor voltage increase monotonically as the parameter value increases. But the definition of the magnetic polarities is arbitrary with respect to the sensor. If we reverse the sense of the polarity, we get the transfer function shown in the blue data series in the chart below. The transfer function in blue can therefore be used by MB-1 for calibration. All that this reversal means is that we now define the direction of the magnetic field that causes the sensor voltage to increase from its idle (0 gauss) value of 2.5 volts as positive, and vice versa.

Figure 40 – Magnetic Sensor Transfer Function



4.21.2 Coupler Port Calibration

The above curves are idealized. The sensor sheet indicates that the actual range of the output sensor is .2 volts to 4.7 volts.

We therefore have 3 well defined calibration points:

- Minimum sensor voltage (approximately .2 volts) at maximum detectable magnetic field with negative polarity.
- Idle voltage (approximately 2.5 volts) with no magnetic field applied.
- Maximum sensor voltage (approximately 4.7 volts) at maximum detectable magnetic field with positive polarity.

Since MB-1 calibration points are all positive, we define the calibration points as follows:

Φ	MB-1 Calibration Point
-500	0
0	500
500	1000

Therefore, when reading the MB-1 numeric displays, 500 must be subtracted from the MB-1 reading to determine the value of **Φ** as shown below:

Φ (in Gauss) = MB-1 Reading -500

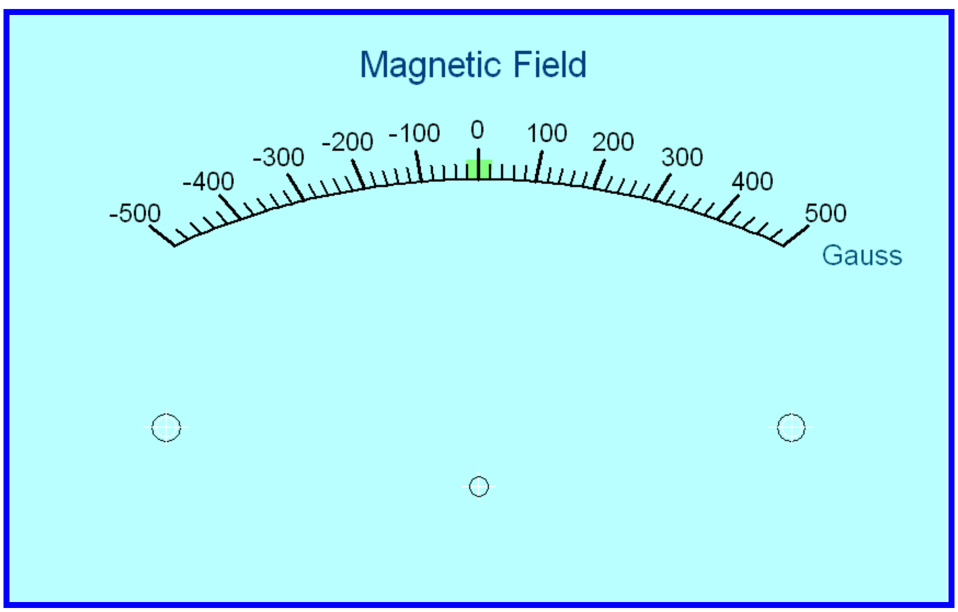
We use the empirical method for calibration as shown in the table below:

Table 10 – Calibration Method for Magnetic Sensor

MB-1 Calibration Point	Vout	Condition
0	Approximately .2 volts	Apply Magnet with orientation that ***reduces*** sensor voltage as magnet is brought closer to sensor. Continue to reduce distance between magnet and sensor until minimum voltage is just reached (avoid saturation).
500	Approximately 2.5 volts	No(external) magnetic field applied.
1000	Approximately 4.7 volts	Apply Magnet with orientation that ***increases*** sensor voltage as magnet is brought closer to sensor. Continue to reduce distance between magnet and sensor until maximum voltage is just reached (avoid saturation).

4.21.3 Panel Meter Calibration

The maximum signal excursion for this application is 1000 units. If we make a custom analog scale, we can label the scale to read the magnetic field directly without requiring the subtraction of 500 as was required when using the MB-1 numeric display values. All that is required is a single linear scale of 1000 units full scale with the lower end of the scale is labeled -500, and the upper end of the scale is labeled +500. A sample scale is shown below.



4.21.4 Related Sensors

There are a whole series of sensors that can measure magnetic fields. Some of these can be found here.

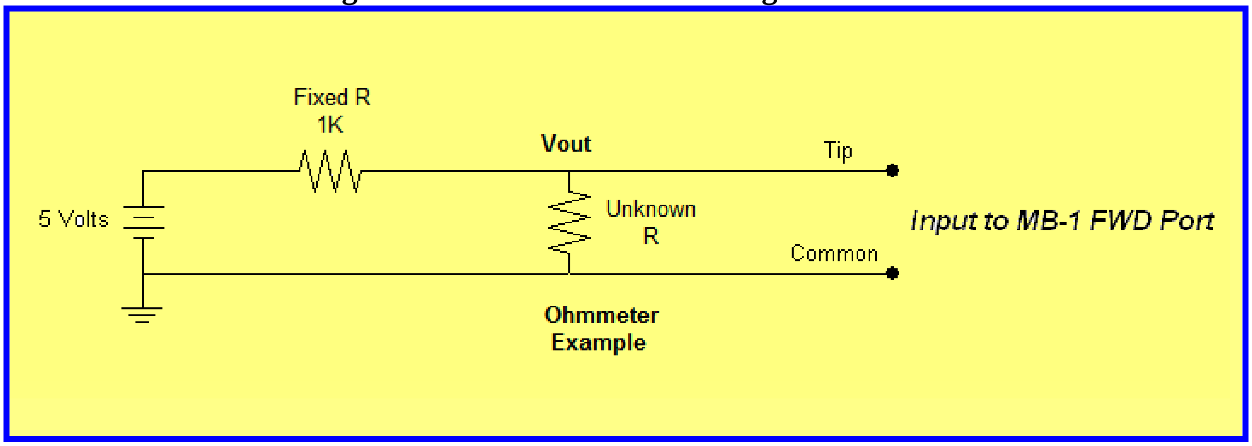
Another magnetic sensor, the Analog Devices AD22151, has more advanced capabilities than most of the sensors listed above. The Analog Devices sensor allows you to control the sensitivity of the sensor. It can also be configured for unipolar or bipolar operation.

4.22 Ohmmeter Example

4.22.1 Overview

This example uses the simple circuit shown below to measure an unknown resistance. **V_{OUT}**, the voltage at the tap of the voltage divider, increases as the unknown resistance increases.

Figure 41 – Circuit for Measuring Resistance



We can calculate the voltage for several resistance values corresponding to available MB-1 calibration points. These are shown in the table below.

Table 11 – Calibration points and Corresponding Voltages for Ohmmeter Application

R (ohms)	V_{OUT}	R (ohms)	V_{OUT}	R (ohms)	V_{OUT}	R (ohms)	V_{OUT}
1	0.004995	50	0.238095	600	1.875	1900	3.275862
2	0.00998	60	0.283019	700	2.058824	2000	3.333333
3	0.014955	70	0.327103	800	2.222222	3000	3.75
4	0.01992	80	0.37037	900	2.368421	4000	4
5	0.024876	90	0.412844	1000	2.5	5000	4.166667
6	0.029821	100	0.454545	1100	2.619048	6000	4.285714
7	0.034757	125	0.555556	1200	2.727273	7000	4.375
8	0.039683	150	0.652174	1300	2.826087	8000	4.444444
9	0.044599	175	0.744681	1400	2.916667	9000	4.5
10	0.049505	200	0.833333	1500	3	10000	4.545455
20	0.098039	300	1.153846	1600	3.076923	15000	4.6875
30	0.145631	400	1.428571	1700	3.148148	20000	4.761905
40	0.192308	500	1.666667	1800	3.214286	30000	4.83871

4.22.2 Calibration Procedure

To calibrate this application, we simply dial in the corresponding voltages for the various calibration points in the above table using a stable voltage source and potentiometer as shown in Figure 4.

4.22.3 Error Analysis

We can take a look at how well the linear interpolation will at the midpoint of the above calibration points. The **R** and $\mathbf{V_{OUT}}$ columns from the above table are repeated in the table below in the first two columns. Because MB-1 uses linear interpolation between calibration points, MB-1 will declare the measurement value to be half way between the corresponding calibration points in the left column when the voltage is exactly half way between the corresponding voltage levels in the $\mathbf{V_{OUT}}$ column.

Each entry in the $\mathbf{V_{MID}}$ column is the midpoint voltage for the current row and the following row. For example, the first $\mathbf{V_{MID}}$ entry is the voltage half way between the voltage calibration points for 1 and 2 ohms.

$\mathbf{R_{DECL}}$ is the resistance value that MB-1 will declare when the voltage equals the corresponding $\mathbf{V_{MID}}$ entry. For example, a resistance of 1.5 ohms, which is the midpoint of the first two resistance entries, will be declared when the measured voltage is .007488 volts.

$\mathbf{R_{ACT}}$ ***is the actual resistance*** that would result in at the corresponding $\mathbf{V_{MID}}$ voltage. This is calculated simply using the voltage divider formula.

ERR is the error in ohms between the actual resistance $\mathbf{R_{ACT}}$, and the declared resistance, $\mathbf{R_{DECL}}$, for each midpoint. Finally, the last column represents the error as a percentage of the nominal R value. The result is reasonable tracking between the MB-1 measurement value and the actual resistance value with a maximum error of 3.84%. For the majority of entries, the error is less than 1%.

Table 12 – Error Analysis for Ohmmeter Example

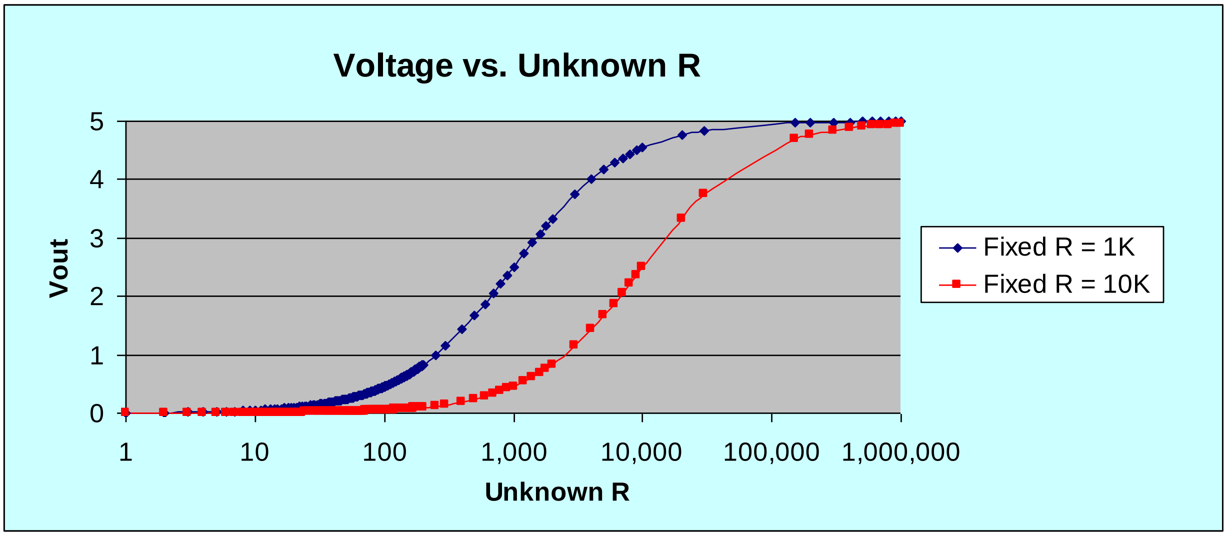
R(ohms)	V_{OUT}	V_{MID}	R_{DECL}	R_{ACT}	ERR (ohms)	%ERR
1	0.004995	0.007488	1.5	1.49975	0.000249626	0.016644
2	0.00998	0.012468	2.5	2.499751	0.000249377	0.009976
3	0.014955	0.017438	3.5	3.499751	0.000249128	0.007118
4	0.01992	0.022398	4.5	4.499751	0.00024888	0.005531
5	0.024876	0.027348	5.5	5.499751	0.000248633	0.004521
6	0.029821	0.032289	6.5	6.499752	0.000248385	0.003821
7	0.034757	0.03722	7.5	7.499752	0.000248139	0.003309
8	0.039683	0.042141	8.5	8.499752	0.000247893	0.002916
9	0.044599	0.047052	9.5	9.499752	0.000247647	0.002607
10	0.049505	0.073772	15	14.97537	0.024630542	0.164474
20	0.098039	0.121835	25	24.97561	0.024390244	0.097656
30	0.145631	0.168969	35	34.97585	0.024154589	0.069061
40	0.192308	0.215201	45	44.97608	0.023923445	0.053191
50	0.238095	0.260557	55	54.9763	0.023696682	0.043103
60	0.283019	0.305061	65	64.97653	0.023474178	0.036127
70	0.327103	0.348737	75	74.97674	0.023255814	0.031017
80	0.37037	0.391607	85	84.97696	0.023041475	0.027115
90	0.412844	0.433695	95	94.97717	0.02283105	0.024038

100	0.454545	0.505051	112.5	112.3596	0.140449438	0.125
125	0.555556	0.603865	137.5	137.3626	0.137362637	0.1
150	0.652174	0.698427	162.5	162.3656	0.134408602	0.082781
175	0.744681	0.789007	187.5	187.3684	0.131578947	0.070225
200	0.833333	0.99359	250	248	2	0.806452
300	1.153846	1.291209	350	348.1481	1.851851852	0.531915
400	1.428571	1.547619	450	448.2759	1.724137931	0.384615
500	1.666667	1.770833	550	548.3871	1.612903226	0.294118
600	1.875	1.966912	650	648.4848	1.515151515	0.233645
700	2.058824	2.140523	750	748.5714	1.428571429	0.19084
800	2.222222	2.295322	850	848.6486	1.351351351	0.159236
900	2.368421	2.434211	950	948.7179	1.282051282	0.135135
1000	2.5	2.559524	1050	1048.78	1.219512195	0.116279
1100	2.619048	2.67316	1150	1148.837	1.162790698	0.101215
1200	2.727273	2.77668	1250	1248.889	1.111111111	0.088968
1300	2.826087	2.871377	1350	1348.936	1.063829787	0.078864
1400	2.916667	2.958333	1450	1448.98	1.020408163	0.070423
1500	3	3.038462	1550	1549.02	0.980392157	0.063291
1600	3.076923	3.112536	1650	1649.057	0.943396226	0.057208
1700	3.148148	3.181217	1750	1749.091	0.909090909	0.051975
1800	3.214286	3.245074	1850	1849.123	0.877192982	0.047438
1900	3.275862	3.304598	1950	1949.153	0.847457627	0.043478
2000	3.333333	3.541667	2500	2428.571	71.42857143	2.941176
3000	3.75	3.875	3500	3444.444	55.55555556	1.612903
4000	4	4.083333	4500	4454.545	45.45454545	1.020408
5000	4.166667	4.22619	5500	5461.538	38.46153846	0.704225
6000	4.285714	4.330357	6500	6466.667	33.33333333	0.515464
7000	4.375	4.409722	7500	7470.588	29.41176471	0.393701
8000	4.444444	4.472222	8500	8473.684	26.31578947	0.310559
9000	4.5	4.522727	9500	9476.19	23.80952381	0.251256
10000	4.545455	4.616477	12500	12037.04	462.962963	3.846154
15000	4.6875	4.724702	17500	17162.16	337.8378378	1.968504
20000	4.761905	4.800307	25000	24038.46	961.5384615	4
30000	4.83871					

4.22.4 Increasing the Range

The highest resistance we can measure with the above configuration is 30K. To increase the range, the fixed resistor in Figure 41 can be increased. Figure 42 below shows the transfer function for two different values of the fixed resistor. The curve in blue shows the transfer function when R = 1K, which was the case covered in the above example. The curve in red shows the transfer function when the fixed R = 10K. With the 10K resistor, we can get an upper usable range close to 1 Megohm. The tradeoff is that the resolution at the lower end (e.g., 1 – 100 ohms) suffers somewhat.

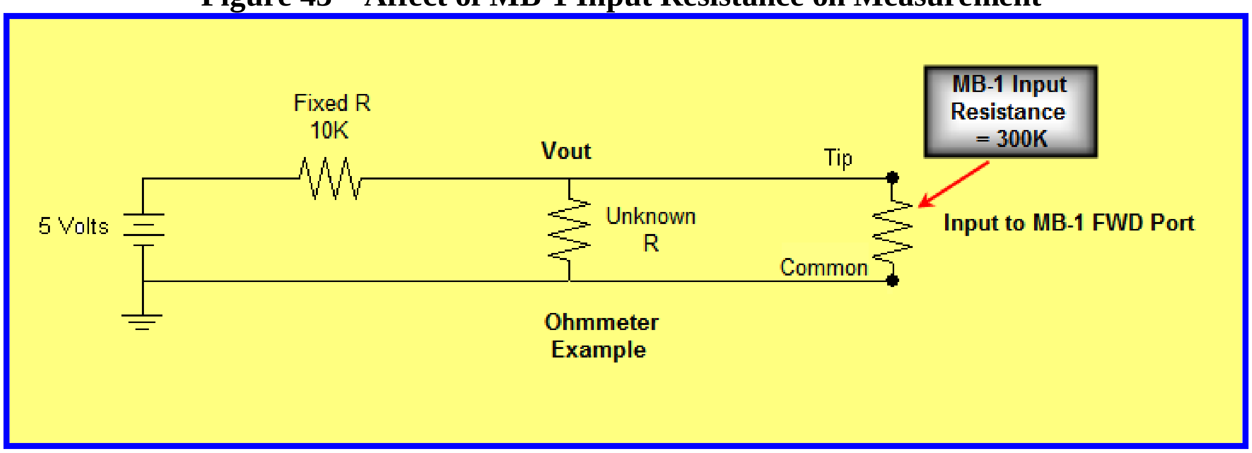
Figure 42 – Increasing Ohmmeter Range



To implement the higher range, since the maximum available MB-1 calibration point is 30,000, scaling would be required during the initial calibration. For example, we could define the actual measured value as the calibration value * 10. This means that we would perform the 300K calibration at the MB-1 calibration point of 30,000 (the highest available MB-1 calibration point). Then, all numeric readings on MB-1 would have to be multiplied by 10 by the user to determine the actual resistance value being measured. This would likewise apply to all other calibration points.

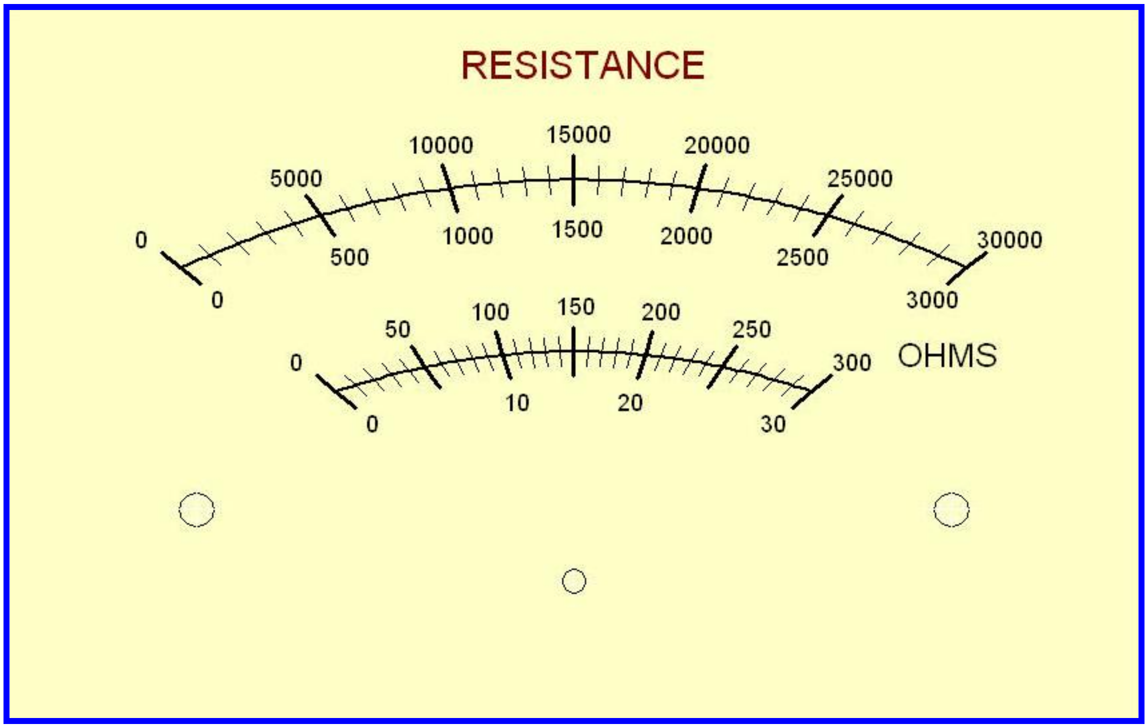
In the figure below, it can be seen that at the higher resistance values, the 300K input resistance of the MB-1 coupler port becomes significant. This resistance can be accounted for by calculating the transfer function taking into account the *Unknown R in parallel with the MB-1 input resistance*. This will give reasonable results for resistances up to 1 Meg. Above that value, the 300K resistance of the MB-1 input starts to dominate.

Figure 43 – Affect of MB-1 Input Resistance on Measurement



4.22.5 Analog Meter Calibration

Most analog ohmmeter scales have a nonlinear scale to account for the nonlinear transfer function of measuring the current directly with an analog meter movement. Since the MB-1 measurement and display functions are independent, there is no reason why the analog scale can not be linear. The figure below shows a linear scale that can be used in the above example. A full size copy can be found here.

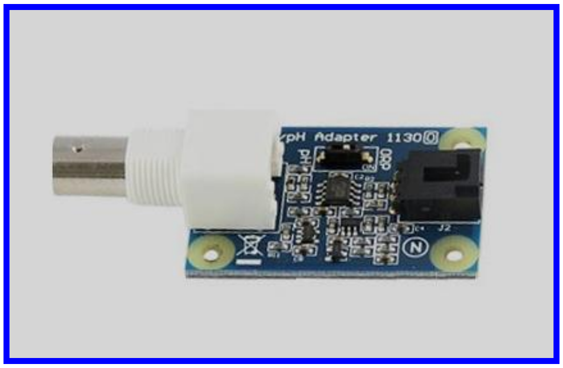


4.23 Measuring Temperature Compensated pH and Oxidation-Reduction Potential

4.23.1 Overview

This sensor interfaces with either a PH probe or an Oxidation-Reduction Potential (ORP) probe and generates a DC voltage that varies linearly with respect to the either the PH or ORP value respectively. This example covers the PH case because it is the more complex of the two cases. PH measurements require that the temperature be taken into account to arrive at the correct pH value. The ORP sensor does not have the temperature issue.

A picture of the sensor is below. The data sheet can be found here.



There are a couple of new issues encountered in this example. The first issue is that the highest PH, 14, is not an available MB-1 calibration point. The other issue, as mentioned above, is that the voltage produced by the PH sensor is affected significantly by temperature. Therefore, it is desirable to provide a method that generates temperature corrected pH measurements.

Calibration Procedure

We handle the first issue by picking a maximum calibration point of 20, which is the first available MB-1 calibration point above 14. We will see that the transfer function for this sensor is linear. Therefore, if we calibrate at two points, namely pH values of 0 and 20, the maximum allowable PH value of 14 will simply be a PH value that lies on the straight line transfer function. Note that during actual operation, the PH sensor will never produce a voltage that represents a PH greater than 14.

Temperature Dependence:

The temperatures that will be handled by this example are 0º, 25º, 50º, 75º, and 100º. Other temperatures could have been chosen as well. We will set up the coupler calibration for the highest temperature, 100º, since this is the case that produces the largest voltage excursion from the sensor across the full pH range (more on that below). This approach ensures that that the voltage excursions for the other temperatures will be within the100º calibration range, and therefore represent measurements that can be processed by MB-1 without bottoming out or topping out.

We will handle the temperature issue by creating an analog face that has scales for the 100º case as well as the other temperatures listed above. To read the temperature corrected pH value, all that is required is to read the scale corresponding most closely to the temperature of the sample being measured.

4.23.2 Coupler Port Calibration

The transfer function for the pH sensor, taking both the pH and temperature into account is:

$$\mathbf{V_{OUT} = (pH - 7) * (0.257179 + 0.000941468 * T) + 2.5}$$

where T is the temperature in centigrade.

Since the equation is linear but does not pass through the origin, we need to calibrate the sensor at two points. As discussed above, the two points that will be used are 0 and 20. The calibration points are shown below.

Table 13 – pH Calibration Points for T=100º C

pH	**V_{OUT}** (volts)
0	0.0407194
20	7.0672354

Note that the largest voltage in the table above is 7.067 volts, which is above the maximum voltage that can be applied to an MB-1 coupler port without saturating it ***when the coupler trim pots is set to maxim sensitivity*** (see **Table 22**). To ensure that the MB-1 Amp/Mux does not saturate during calibration or operation, use the Coupler Setup feature that allows you to view the output of the A-to-D chain while adjusting the trim pot. Set the output of the Amp/Mux chain to approximately 30,000 with a voltage of 7.067 volts applied.

The actual calibration is most easily done by "dialing in" the calibration voltage at the above two calibration points using a stable voltage source and potentiometer as shown in Figure 4. Note that the MB-1 5 volt auxiliary power output cannot be used in this case since we need a voltage level greater than 5 volts. A 9 volt battery or other stable higher voltage source can be used instead.

4.23.3 Analog Meter Calibration

Below is a table that shows the sensor output voltage as a function of pH and temperature. As mentioned above, it can be seen that the 100º case has the largest $\mathbf{V_{OUT}}$ excursion across the complete pH range. The items below in red correspond to our two calibration points.

Table 14 – Sensor Output Voltage as a function of pH and Temperature

pH	V_{OUT} (T=100)	V_{OUT} (T=75)	V_{OUT} (T=50)	V_{OUT} (T=25)	V_{OUT} (T=0)
0	0.0407194	0.2054763	0.3702332	0.5349901	0.699747
1	0.3920452	0.5332654	0.6744856	0.8157058	0.956926
2	0.743371	0.8610545	0.978738	1.0964215	1.214105
3	1.0946968	1.1888436	1.2829904	1.3771372	1.471284
4	1.4460226	1.5166327	1.5872428	1.6578529	1.728463
5	1.7973484	1.8444218	1.8914952	1.9385686	1.985642
6	2.1486742	2.1722109	2.1957476	2.2192843	2.242821
7	2.5	2.5	2.5	2.5	2.5
8	2.8513258	2.8277891	2.8042524	2.7807157	2.757179
9	3.2026516	3.1555782	3.1085048	3.0614314	3.014358
10	3.5539774	3.4833673	3.4127572	3.3421471	3.271537
11	3.9053032	3.8111564	3.7170096	3.6228628	3.528716
12	4.256629	4.1389455	4.021262	3.9035785	3.785895
13	4.6079548	4.4667346	4.3255144	4.1842942	4.043074
14	4.9592806	4.7945237	4.6297668	4.4650099	4.300253
20	7.0672354				

Remember that we calibrated the coupler port for the T=100º case. Therefore, the digital display readings on the MB-1 are valid only for the T=100º case. However, if we create an analog scale for this application using the T=100º case, and use the full meter movement range for that case, the analog scales for all other temperatures can be temperature corrected by determining what fraction of the analog needle displacement each scale occupies with respect to the T=100º case. Below, we show how to determine the temperature corrected scales.

We can use the sensor equation to determine what the pH value is for the temperatures other than T=100º that correspond to $\mathbf{V_{OUT}}$ @ T=100º for each integral pH value (column 2 in the table above).

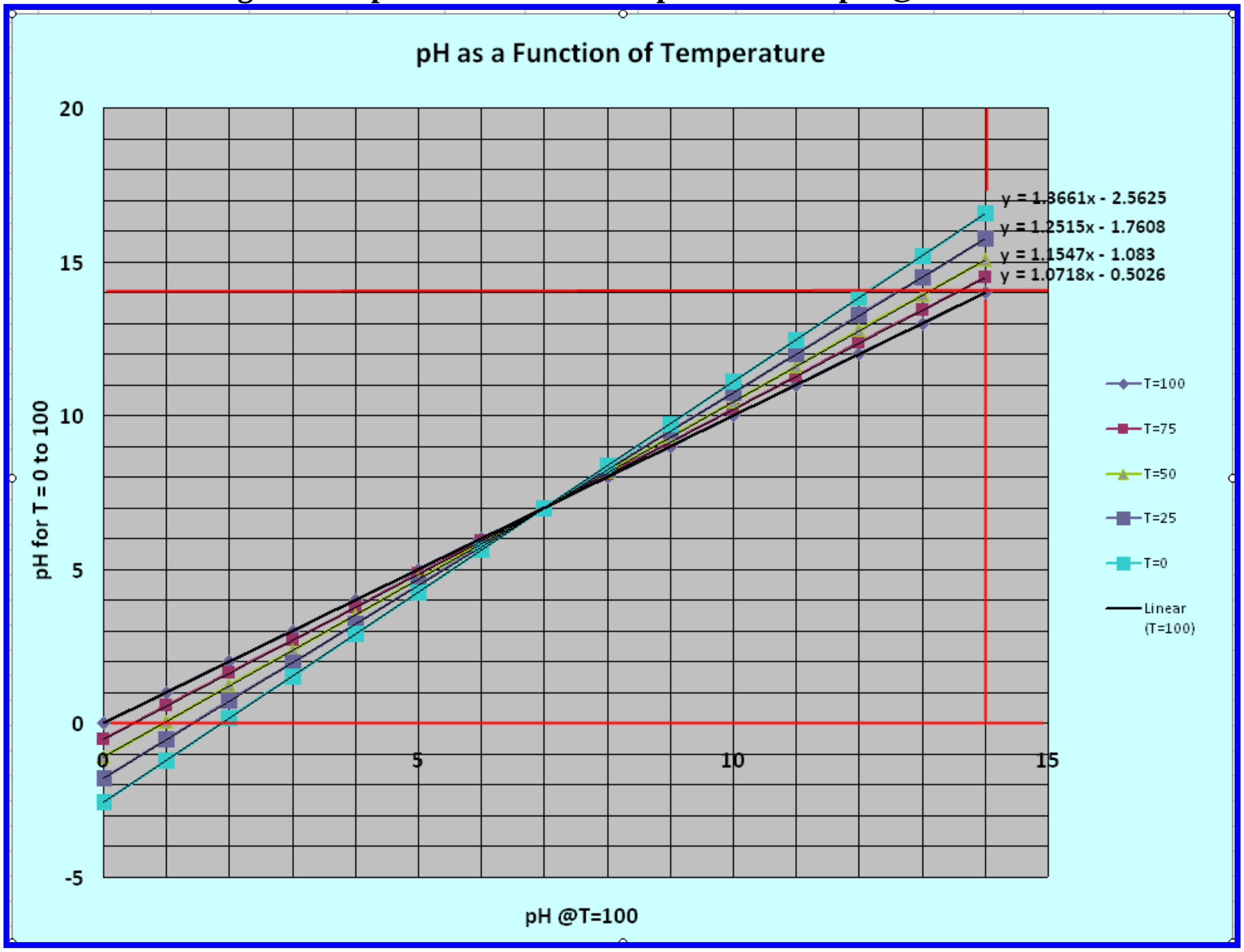
These pH values are shown in the table below for the four temperatures for which we will be creating additional analog scales.

Table 15 – pH Values for Different Temps corresponding to V_{OUT} at T=100^o Case

pH(T=100)	pH(T=75)	pH(T=50)	pH(T=25)	pH(T=0)
0	-0.50263	-1.08303	-1.76075	-2.56252
1	0.569174	0.07169	-0.50922	-1.19645
2	1.640978	1.226409	0.74232	0.169625
3	2.712782	2.381127	1.993856	1.5357
4	3.784587	3.535845	3.245392	2.901775
5	4.856391	4.690563	4.496928	4.26785
6	5.928196	5.845282	5.748464	5.633925
7	7	7	7	7
8	8.071804	8.154718	8.251536	8.366075
9	9.143609	9.309437	9.503072	9.73215
10	10.21541	10.46415	10.75461	11.09822
11	11.28722	11.61887	12.00614	12.4643
12	12.35902	12.77359	13.25768	13.83037
13	13.43083	13.92831	14.50922	15.19645
14	14.50263	15.08303	15.76075	16.56252

The data from the above table is charted below along with the trend line equations that show pH for T= 0º, T=25º, T=50º, and T=75º (Y axis) vs. the pH at 100º (X axis).

Figure 44 – pH for different Temperatures vs. pH @ T=100º



The top scale in the analog meter face shown below uses the T=100º case as the reference, and spans the entire range of the meter movement. Therefore each pH unit for the T=100º is 1/14th the scale deflection as shown below.

Table 16 – Analog Needle Deflection for T=100º Case

pH(T=100)	Deflection
0	0
1	0.071428571
2	0.142857143
3	0.214285714
4	0.285714286
5	0.357142857
6	0.428571429
7	0.5
8	0.571428571

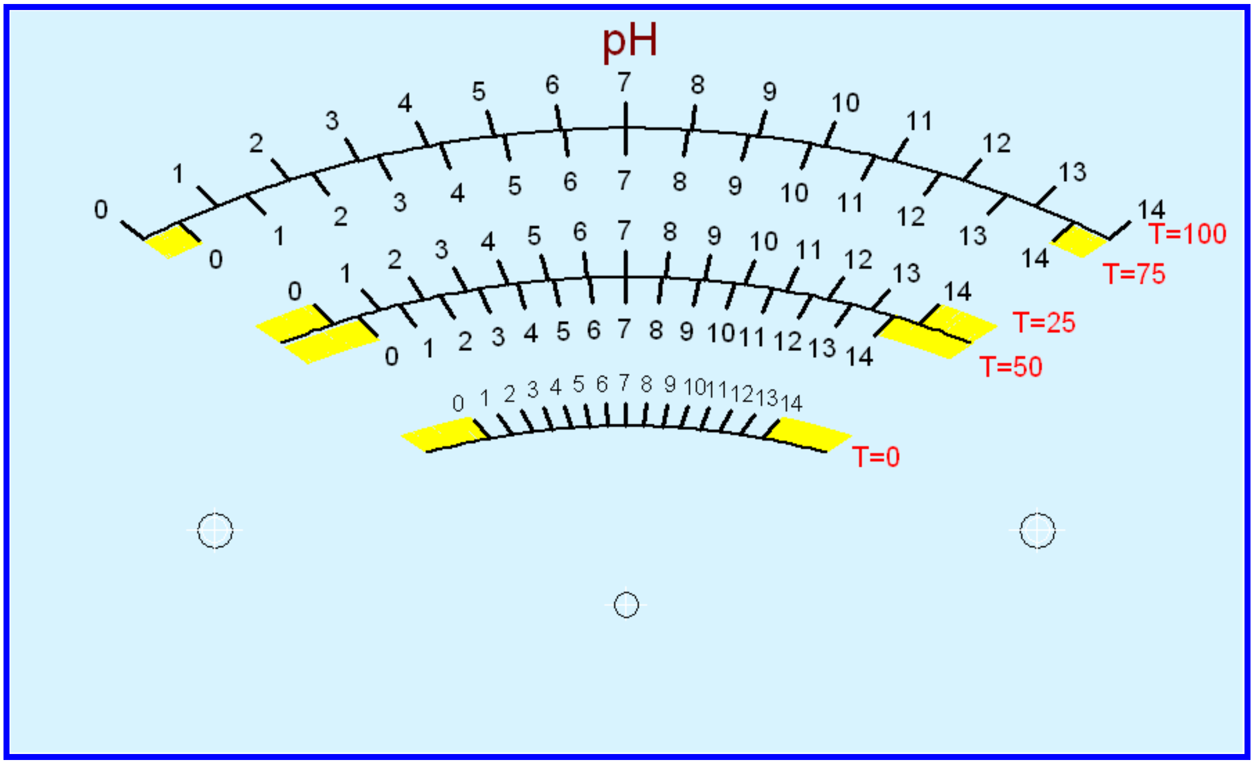
9	0.642857143
10	0.714285714
11	0.785714286
12	0.857142857
13	0.928571429
14	1

From the chart above (Figure 44), we know the relationship for the pH at a given temperature with respect to the pH at 100º. These are just the Trend Line equations. We use the Trend Line equation for the T = 75º case below. This table shows the corresponding values for integral pH values at 75º and the corresponding pH at 100º. For example, take the pH = 0 case at 75º. This corresponds to a pH value of .4689 at 100º (using the $\mathbf{V_{OUT}}$ from the sensor as the reference). Since we know the full analog meter deflection equation for the T=100º case, we can determine the % deflection for the pH = 0 case at 75º. It is .0334. This is done for the other pH values at 75º, and for the other temperatures.

Table 17 – Analog Needle Deflection for T=75º Case

pH(T=75)	pH(T=100)	Deflection
0	0.46893077	0.033495
1	1.40194066	0.100139
2	2.33495055	0.166782
3	3.26796044	0.233426
4	4.20097033	0.300069
5	5.13398022	0.366713
6	6.06699011	0.433356
7	7	0.5
8	7.93300989	0.566644
9	8.86601978	0.633287
10	9.79902967	0.699931
11	10.7320396	0.766574
12	11.6650494	0.833218
13	12.5980593	0.899861
14	13.5310692	0.966505

This gives us the temperature corrected pH meter face below.

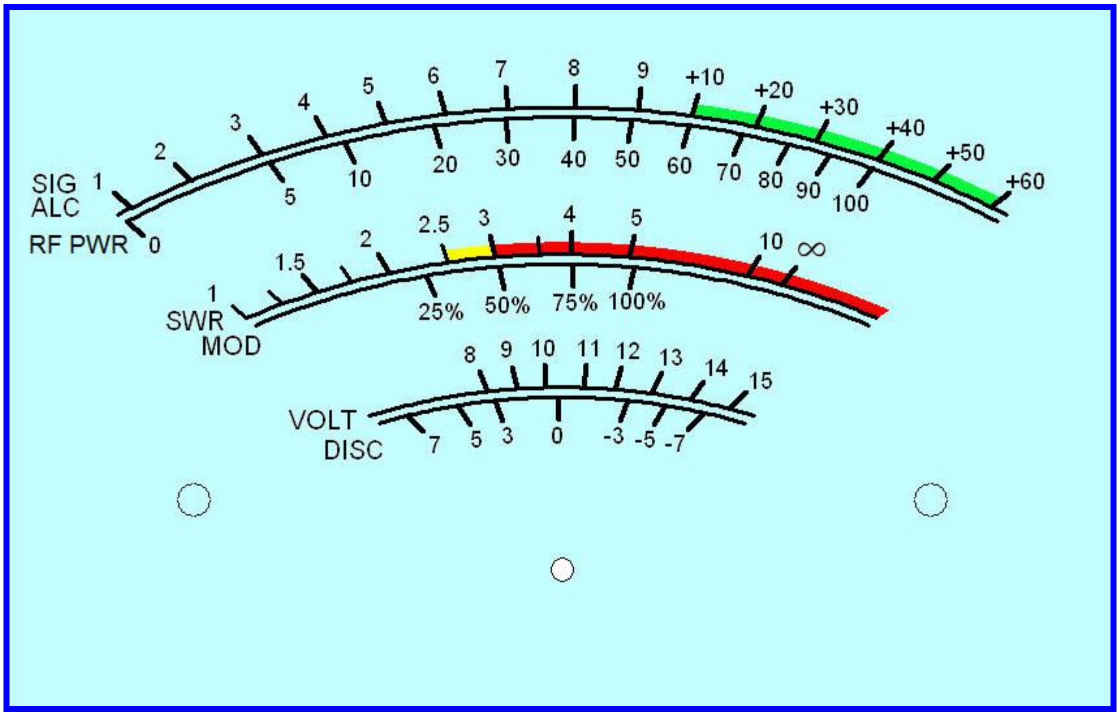


A full size copy can be found here

4.24 *Yaesu FT857/ 897 External Analog Meter*

4.24.1 Overview

These two Yaesu radios have an external jack that is intended to drive an external analog meter. A full size meter scale of the one shown below can be found here.



This meter face can affixed to an analog meter with a full scale current rating of 1 mA or less. The meter can then be connected directly to the Yaesu output in a conventional manner. In this case, you should insert an appropriate size potentiometer in series with the meter movement. This will allow you to set the meter movement for full scale deflection using the Yaesu calibration feature, which outputs a signal corresponding to the maximum drive signal.

If you want to make use of the MB-1 alarm functions or Min/Max functions to do some additional processing of the Yaesu parameters, you could instead connect the Yaesu analog output to an MB-1 coupler input and calibrate that input as a generic meter function. The analog meter with the Yaesu scales would then be driven by MB-1. Why would you want to do this?

Let's assume you got a radio back from repair due to an infrequent but annoying momentary loss in sensitivity. If the MB-1 was monitoring the analog meter output, you could set up the Yaesu to display the S meter function in receive mode on the analog output. You could then activate a low power signal source (e.g., the calibrator from an older vintage radio) to provide a stable readable signal for the Yaesu to receive, and monitor the signal level as reported by the Yaesu with MB-1's Min/Max function. In such a set up, you would expect little if any variation in the signal level. If, after an overnight test, the Max function reads 80 (e.g., 80% full scale) and the Min function reads 15 (e.g., 15% of full scale) your radio still has the problem.

Similar tests could be done to detect other intermittent conditions, such as an RF Power dropout during a long data transmission.

Admittedly this is a somewhat contrived example, but it may spark some ideas on using the Generic Meter function for applications that might not be initially obvious.

Here is how we would configure MB-1 to interface to the Yaesu and analog meter.

First, it is important to recognize that the Yaesu will generate the same full scale signal to drive an external meter to full scale regardless of which of the 7 parameters are being measured. Therefore, the easiest approach to take is to view the Yaesu output as a relative signal with a value ranging between 0 (no meter deflection) and 100 (full scale meter deflection). In this case, we simply have to calibrate the Generic (coupler input) for a full scale value of 100, and likewise, calibrate the external panel meter as a single ***linear scale analog meter*** with a full scale value of 100. In effect, this makes MB-1 transparent – i.e., the analog meter should respond as if it was connected directly to Yaesu output signal. We can use the linear scale Panel Meter calibration in this example since we are relying on the meter scale calibrations to give us the correct reading.

The following describes the steps in detail:

Coupler Calibration

1. Connect the Yaesu along meter output to the FWD port of one of the 4 coupler ports.
2. Adjust the coupler trim pot for maximum sensitivity. There is no chance of overdriving the MB-1 input in this application.
3. Bring up the coupler calibration menu for the coupler port being used.
4. Specify the coupler type as a GENERIC meter application.
5. Set the full scale value to 100 units.
6. Configure the Yaesu to apply a full scale signal on its analog meter output port.
7. Select a single calibration point of 100 and save the calibration data for the full scale signal being applied by the Yaesu.
8. Save the coupler calibration settings to EEProm.

Panel Meter Calibration

1. Connect the panel meter with the Yaesu scales to an unused panel meter port.
2. Enter the Panel Meter Setup screen and choose the appropriate panel meter port.
3. Set the calibration type to Linear.
4. Adjust the panel meter trim pot slightly beyond full scale deflection.
5. Select the number of Power Scales to 1.
6. Set the full scale value to 100.
7. Set the number of SWR scales to 0.
8. Proceed with calibration. Calibration is done at a single point, namely the full scale value (100). Simply dial the front panel pot until the meter needle reads full scale and save the calibration point.
9. Save the Panel Meter calibration data in EEProm.

This completes the calibration. When you select the coupler port connected to the Yaesu output and the analog meter with the Yaesu, MB-1 will drive the analog meter. The Yaesu menus determine the actual transmit mode and receive mode parameters whose values are being output from the Yaesu external jack.

This is transparent to MB-1 since the full scale values of all of the parameters on the analog scale correspond to the full scale meter deflection.

Since MB-1 is simply measuring the input signal and linearly driving the analog meter, if you wanted to use the Min/Max function, the Min/Max values would represent percent of full scale deflection. If you did a long term test as in the above example to monitor for an intermittent sensitivity problem, you would have to approximate the value on the appropriate scale to translate the Min/Max readings into actual values, but in this example, since we are looking for a signal dropout, interpreting the Min/Max readings as percentage full scale values is adequate to determine if a problem was detected.

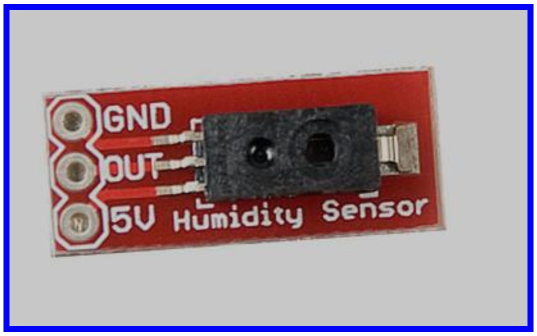
4.25 *Some other Sensors*

4.25.1 Overview

This section lists some miscellaneous sensors we have come across. The approaches discussed in the examples above will work for these sensors as well.

We will update this section periodically.

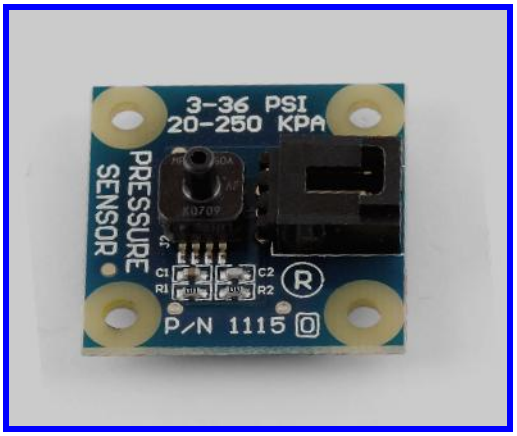
4.25.2 Humidity Sensor



This sensor generates a DC output voltage that varies linearly with respect to humidity.

Details on the humidity sensor can be found here.
The data sheet can be found here.

4.25.3 Pressure Sensor – (Barometer)



This sensor measures absolute pressure, and has a range of 20 to 250 kilopascals. Barometric pressure is approximately 100 kilopascals with limited variation around that value. Because of the broad measurement range, the resolution is approximately 1 kilopascal per 10 millivolts. If you set you lower and upper ranges to 80 kilopascals and 125 kilopascals during calibration, you should be able to get reasonable resolution.

The analog meter scale for the Barometer must be calibrated as a nonlinear scale since the starting value is not 0. See the discussion for the Panel Meter calibration in the Logarithmic Sound Pressure Level Sensor example above.

Details on the pressure sensor can be found here.
The data sheet can be found here.

4.25.4 Wind Direction Sensor

This sensor measures wind direction by outputting a DC voltage that ranges from 5% to 95% of power supply voltage. This corresponds to 250 millivolts to 4.75 volts for 5 volt power. When facing North, the sensors outputs its minimum voltage. The voltage increases linearly as the direction changes to East, South, West, etc.

Details on the sensor can be found here.

5 Some Industrial Sensors

The following sensors are used primarily in industrial applications. Detailed descriptions are provided for those sensors that cover some new interfacing topics.

5.1 Eleven Decade Vacuum Sensor

5.1.1 Overview

This example uses an 11 decade Inficon vacuum sensor that can measure pressure from approximately 10^{-8} to 10^{3} millibars. This corresponds to a ratio of 10^{11}, a range that can only be handled reasonably if we use a logarithmic scale.

A picture of the sensor is shown below.

The data sheet can be found here. The operating instructions, which contain additional specifications, can be found here.

The operating instructions provide the transfer functions for a variety of pressure units. The example below uses the **millibar** equation. The implementation for the **torr** and **Pascal** units are similar.

The sensor transfer function for millibars is:

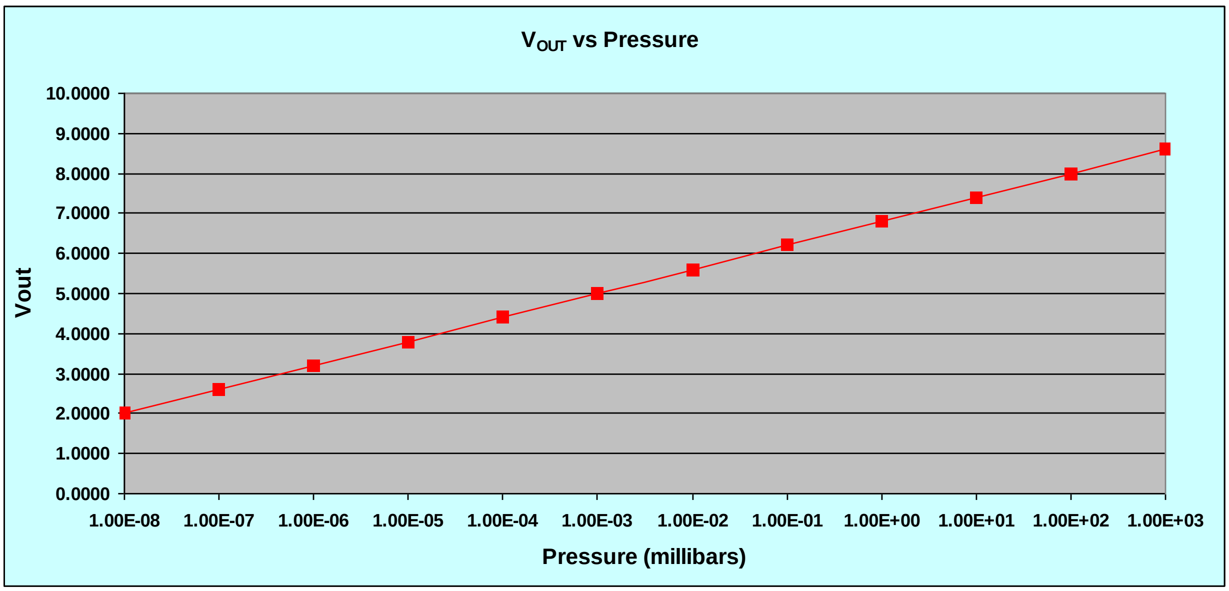
$$\mathbf{V_{OUT} = 6.8 + .6 * \log_{10} (P)}$$

where P is the pressure in millibars.

The data points and graph for the 11 decade range transfer function are shown below:

Table 18 – Transfer Function for 10^N Pressure Values for Vacuum Sensor

Pressure (millibars)	V_{OUT} (volts)
1.00E-08	2.0000
1.00E-07	2.6000
1.00E-06	3.2000
1.00E-05	3.8000
1.00E-04	4.4000
1.00E-03	5.0000
1.00E-02	5.6000
1.00E-01	6.2000
1.00E+00	6.8000
1.00E+01	7.4000
1.00E+02	8.0000
1.00E+03	8.6000



As can be seen from the above table, the sensor output voltage increases at a rate of 600 millivolts per decade.

5.1.2 Coupler Port Calibration

Since the sensor's range of pressure measurements using the actual pressure values is beyond the display range of MB-1, we must provide the measurement values in log form, which is a reasonable approach since this sensor's transfer function is also logarithmic.

It would be nice to display numerical values from MB-1 ranging from -8 to +3 corresponding to pressures of $\mathbf{10^{-8}}$ to $\mathbf{10^{3}}$ respectively. But since MB-1 does not display negative values, we will use the following translation:

Table 19- MB-1 Readings and Corresponding Pressures for Integral MB-1 Readings

Pressure (millibars)	MB-1 Numerical Reading
1.00E-08	0
1.00E-07	1
1.00E-06	2
1.00E-05	3
1.00E-04	4
1.00E-03	5
1.00E-02	6
1.00E-01	7
1.00E+00	8
1.00E+01	9
1.00E+02	10
1.00E+03	11

To convert an MB-1 numerical reading to a pressure, one would take the numerical reading

$$\mathbf{P = 10^{\text{(MB-1 Reading -8)}}}$$

But this equation is correct only for the integral values displayed on MB-1 as shown in the above table. We have to use the actual transfer function to determine the pressure value between integer MB-1 values.

The equation for pressure in terms of $\mathbf{V_{OUT}}$ is:

$$\mathbf{P = 10^{(1.667 \times Vout - 11.33)}}$$

Since each decade increase of pressure increases $\mathbf{V_{OUT}}$ by 600 millivolts, we can create a lookup table to interpolate non integral MB-1 readings for all 11 decades. If we break each decade into 20 segments, we can calculate an exact pressure/voltage relationship for those 20 points. The voltage step for each of these 20 segments is 600 millivolts / 20, or 30 millivolts, which is the value used in the second column in the table below. The third column shows the calculated pressure for the voltages in the second column using the above formula.

The following table summarizes the MB-1 readings, the sensor output voltage $\mathbf{V_{OUT}}$, and the calculated pressure for 20 segments equally spaced between P = $\mathbf{10^{-8}}$ and P = $\mathbf{10^{-7}}$.

Table 20 – Lookup Table for Interpolating non-integral MB-1 Measurements

MB-1 Reading	VOUT	Calculated Pressure
0	2	**1.01** E-08
0.05	2.03	**1.13** E-08
0.1	2.06	**1.27** E-08
0.15	2.09	**1.43** E-08
0.2	2.12	**1.60** E-08
0.25	2.15	**1.79** E-08
0.3	2.18	**2.01** E-08
0.35	2.21	**2.26** E-08
0.4	2.24	**2.54** E-08
0.45	2.27	**2.85** E-08
0.5	2.3	**3.19** E-08
0.55	2.33	**3.58** E-08
0.6	2.36	**4.02** E-08
0.65	2.39	**4.51** E-08
0.7	2.42	**5.06** E-08
0.75	2.45	**5.68** E-08
0.8	2.48	**6.37** E-08
0.85	2.51	**7.15** E-08
0.9	2.54	**8.02** E-08
0.95	2.57	**9.00** E-08
1	2.6	**1.01** E-07

To use this table, simply take the decimal portion of the MB-1 reading, and determine the coefficient in the third column. (***This coefficient will be the same for each of the 11 pressure decades.***) For example, assume that MB-1 reads 3.65. We know that the pressure is between $\mathbf{10^{-5}}$ and $\mathbf{10^{-4}}$ millibars. If we look up the fractional part in the above table (.65), we see that an MB-1 digital reading of 3.65 corresponds approximately to a coefficient of **4.51.** Therefore, an MB-1 reading of 3.65 corresponds to a pressure of $\mathbf{4.51 \times 10^{-5}}$ millibars. This lookup approach is workable but somewhat cumbersome. We come up with a better approach that will allow a direct reading of the pressure when using an analog meter calibrated for this application. This is discussed below.

Calibration Point:

Since the transfer function equation is linear but does not pass through the origin, we need to calibrate the sensor at two points. The two end points in the MB-1 column in the table above are 0 and 11. Since 11 is not an available MB-1 calibration point, we will use the next higher available calibration point of 20. Since the transfer function is linear, if we use calibration points of 0 and 20, the maximum allowable Pressure value of $\mathbf{10^{3}}$ millibars (corresponding to an MB-1 reading of 11) will simply be a value that lies on the straight line transfer function. Note that during actual operation, the vacuum sensor will never produce a voltage that represents a pressure greater than $\mathbf{10^3}$.

Table 21 – Vacuum Sensor Calibration Points

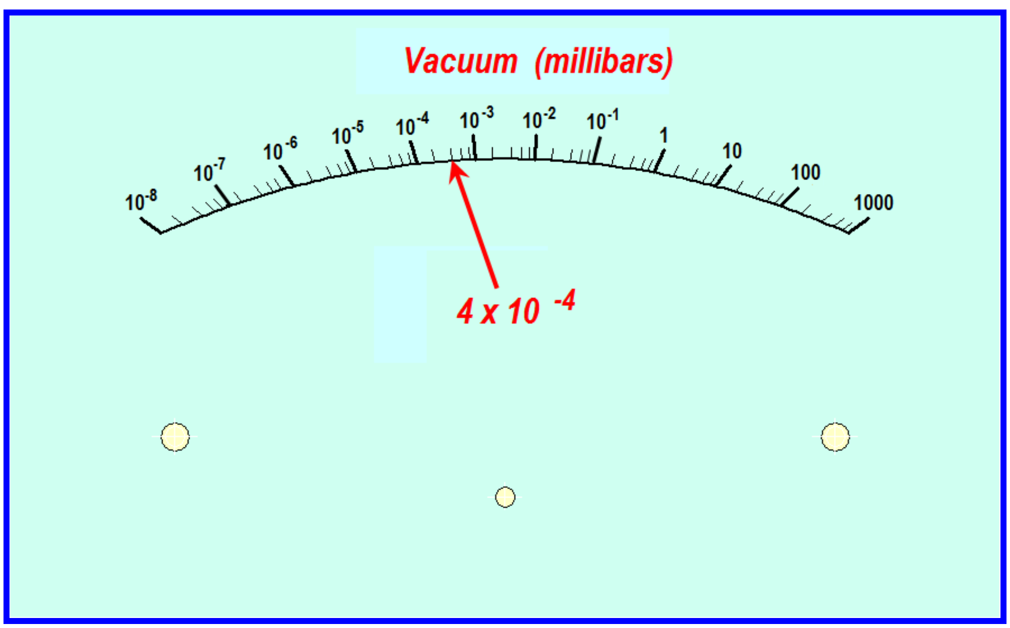
Pressure (millibars)	MB-1 Calibration Point	V_{OUT} (volts)	Comments
10^{-8}	0	2.000	
10^{-12}	20	14.000	Used only for calibration

Note that the largest voltage in the table above is 14.00 volts, which is above the maximum voltage that can be applied to an MB-1 coupler port without saturating it ***when the coupler trim pots is set to maxim sensitivity*** (see **Table 22**). To ensure that the MB-1 Amp/Mux does not saturate during calibration or operation, use the Coupler Setup feature that allows you to view the output of the A-to-D chain while adjusting the coupler trim pot. Set the output of the Amp/Mux chain to approximately 30,000 with a voltage of 14.00 volts applied.

The actual calibration is most easily done by "dialing in" the calibration voltage at the above two calibration points using a stable voltage source and potentiometer as shown in Figure 4. Note that the MB-1 5 volt auxiliary power output cannot be used to drive a pot for calibration since a voltage level greater than 5 volts is required. Two 9 volt batteries in series or other stable higher voltage source feeding a potentiometer can be used instead.

5.1.3 Panel Meter Calibration

If we design our own analog meter scale, we have the ability to label the scales so that the pressure can be read directly without the translations that had to be done when reading the MB-1 digital displays. This requires not only labeling the major tic marks from $\mathbf{10^{-8}}$ to **1000**, but also spacing the intermediate tic marks between decades with a logarithmic spacing. A sample scale is shown below with comments.



Each decade, or major tic mark, simply occupies 1/11th of the full scale range. Between each decade, we include 4 minor tic marks. For example, the four tic marks to the right of $\mathbf{10^{-8}}$ are $\mathbf{2\ x10^{-8}}$, $\mathbf{4\ x10^{-8}}$, $\mathbf{6\ x10^{-8}}$, and $\mathbf{8\ x10^{-8}}$. To account for the logarithmic behavior of the sensor, the minor tic marks must be positioned according to the log of the tic mark value. For example, for a linear scale, the $\mathbf{2\ x10}^{N}$ tic mark would be placed at 20% of the displacement between the major tic marks. But for this logarithmic sensor, it must be placed at log (2) = .301 or 30.1% of the distance between the major tic marks. Likewise, minor tic mark $\mathbf{4\ x10^{N}}$ must be placed at log (4) = .602 or 60.2% of the distance between the tic marks, and so forth.

Since the coupler has been calibrated for a full scale value of 11, when calibrating the Panel Meter, the scale type should be set to linear with a full scale value of 11.

5.2 Rotary Shaft Encoder

The Advanced Micro Controls AMCI DC25 encoder is an Absolute Single Turn sensor that generates a DC voltage proportional to the angular displacement.

The data sheet can be found here.

5.3 Linear Position Sensor

The Unimeasure family of Linear Position Sensors measure linear distance by measuring the amount a cable is extended from the sensor. These units measure distances from as small as 2 inches to as large as 2000 inches. These units are basically high resolution multi-turn potentiometers.

The data sheet on this family of sensors can be found here.

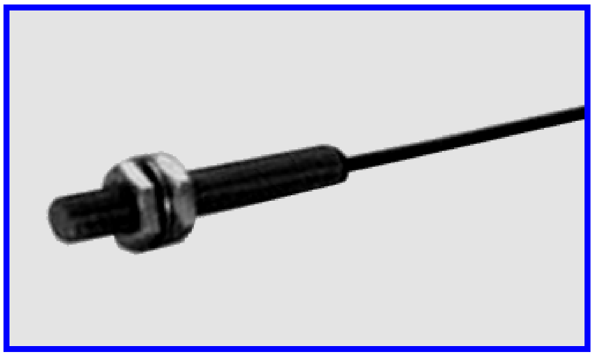
5.4 *Non-Contact Infrared Temperature Sensor*

The Omega OS136 sensor measures the temperature of a surface within in the optical field of view, which is 6:1 for this sensor. The sensor is internally calibrated for a fixed emissivity of .95.

This sensor can be ordered in different temperature ranges (either 0° – 400°F, or 300°F – 1000°F), and different output formats. The output formats that will work with MB-1 are: **V1** (0- 5 volts DC), **V2** (0 – 10 volts DC), **MVC**: 10 mV/°C, and **MVF:** 10 mV/° F.

Details on the sensor can be found here.

5.5 *High Precision Low Displacement Inductive Linear Sensor*



The Balluff M8 Linear Sensor provides accurate measurements for small linear displacements in the millimeter range, with repeatability in the micrometer range. These sensors are used primarily in industrial applications. The sensor shown above generates an analog output from 0 – 10 volts corresponding to displacements of .5mm to 1.5 mm.

Details on the sensor can be found here.

5.6 *Time of Flight Laser Distance Sensor*

The Banner Series of Analog Sensors have a large variety of uses in process control. One such sensor, referred to as a "Time of Flight" distance sensor, is shown above. The data sheet can be found here.

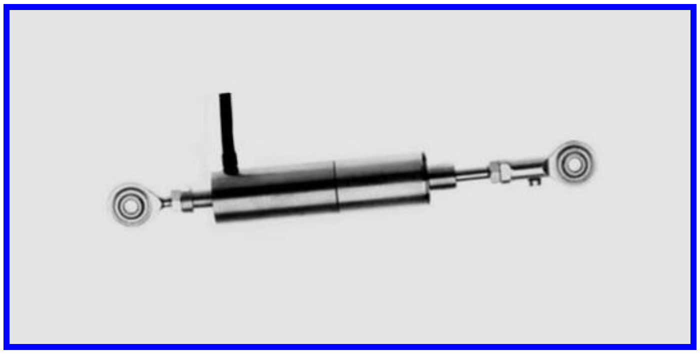
This sensor determines the distance by emitting light from a laser diode, which bounces off the target, and is detected by a sensor collocated with the laser. Using the speed of light and the round trip time, the distance can be measured very accurately. The sensor generates a 0 – 10 volt DC output that varies linearly with respect to the calculated distance, and easily processed by MB-1.

5.7 *Salt Water Conductivity Sensor*

The A4120 Alliance for Costal Technologies Conductivity Sensor is a high precision conductivity sensor for making measurements in salt water. The sensor produces a linear output of 0 – 5 volts DC corresponding to a conductivity of 0 – 75 millimhos/cm.

The data sheet can be found here.

5.8 Linear Variable Displacement Transformers



The P3 America LVDTs work by driving a transformer primary with AC voltage and measuring the voltage induced in two secondary transformers. The induced voltage is proportional to the displacement. The displacement (or stroke lengths) for these sensors is 2mm to 50mm.

Some LVDTs contain interface circuitry to convert the secondary AC voltages into DC voltages that are more easily processed. These AP3 sensors provide such an interface.

The data sheet for these devices can be found here.

5.9 Volumetric Flow Sensor

The Omega FPR Flow Sensor measure flow and comes in two models:

- .5 GPM to 15 GPM
- 1.5 GPM to 50 GPM

Both models have a 4-20 mA analog output that is proportional to the flow rate.

The specifications for these sensors can be found here. The manual can be found here.

5.10 Rotary Torque Transducer

The Interface Rotary Torque Transducer, rated at ± 200 Newton Meters, generates a DC voltage proportional to the torque. The analog output is 0 to -5 volt output for CCW torque, and a 0 to +5 volt output for CW torque. To measure torque in both directions, an isolated and regulated 5 volt DC-to-DC converter, or equivalent, needs to be inserted in series with the transducer output since MB-1 requires that the coupler input voltages to be positive. To measure torque in one direction only, the transducer output can be connected directly to MB-1.

The data sheet for this device can be found here.

5.11 *RPM Sensor using an Industry Standard 4 – 20 mA Current Output*

5.11.1 Overview

Many industrial sensors use an industry standard current loop interface of 4-20 mA to encode the magnitude of the parameter being measured. One such sensor is the ST420 DI from Electro Sensors. A picture of the sensor and its pulser disc are shown below. The pulser disc contains magnets that are sensed by the magnetic pulse detector in the sensor. In addition to the pulse detector, the sensor contains the signal processing circuitry to convert the magnetic pulse counts into a smooth 4 – 20 mA output.

The data sheet for this sensor is found here. The User's Manual for this sensor provides some additional information that specifies the relationship between RMP and the output current.

This sensor is available in two standard offerings:

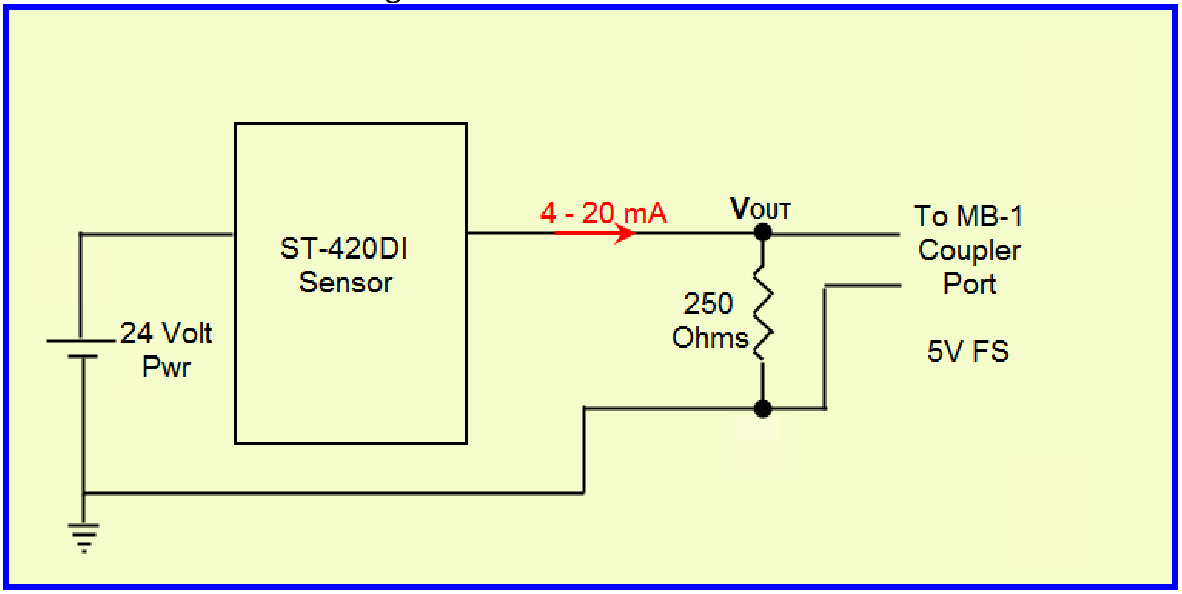
- ST420-DI-L – 2 RPM to 200 RPM
- ST420-DI-H - – 2 RPM to 2000 RPM

This example makes use of the lower speed sensor.

5.11.2 Interface Circuit

The connection of the sensor to MB-1 is shown in Figure 45 below. The current range of 4 mA to 20 mA will produce a voltage input to MB-1 of 1 volt and 5 volts respectively when a 250 ohm resistor is used. 1 volt corresponds to the lowest detectable RPM value of 2 RPM. 5 volts corresponds to the largest detectable RPM value of 200 RPM.

Figure 45 – RPM Sensor Interface



5.11.3 Calibration Procedure

Even though the $\mathbf{V_{OUT}}$ vs. RPM transfer function is linear, it does not pass through the origin. Therefore, we must perform the calibration at two calibration points. The lower RPM value of 2 and the higher RPM value of 200 are both available MB-1 calibration points, and can therefore be used directly as shown in the table below.

Calibration Point	V_{OUT}
2	1 volt
200	5 volts

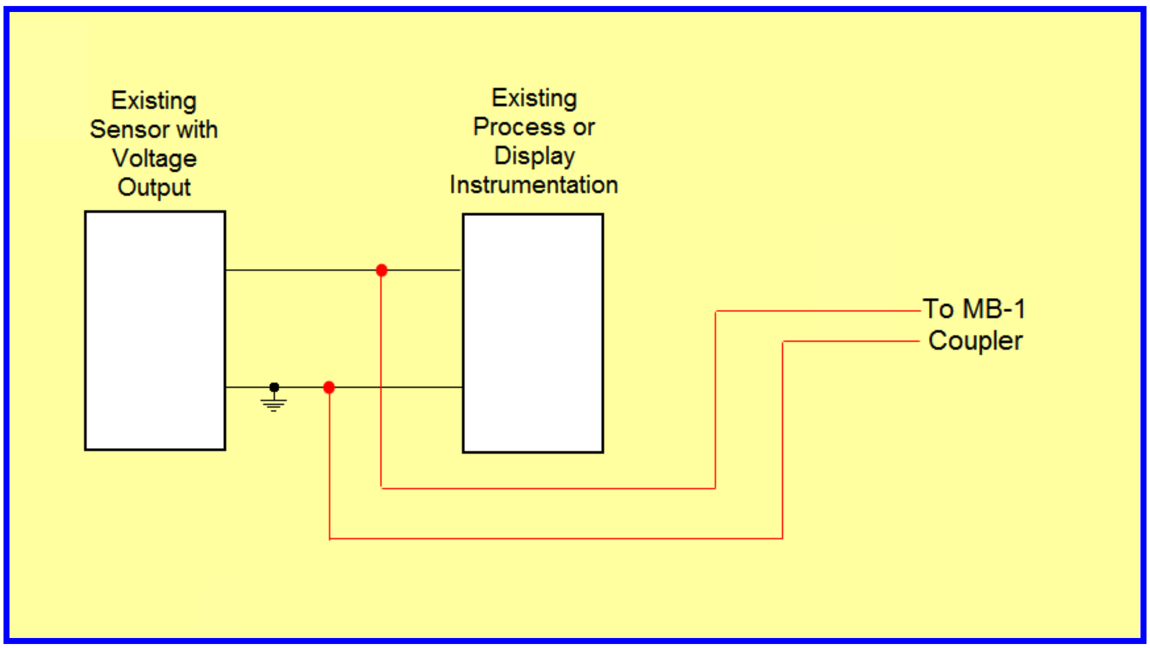
Calibration is most easily done by “dialing in” the calibration voltages at the corresponding calibration points as shown in Figure 4.

6 Adding MB-1 to Existing Measurement Systems

In some cases, you may wish to add MB-1 to an existing system that already includes a sensor and display instrumentation. You might want to do this to display the measurement on one of MB-1's display devices to complement the display on the existing instrumentation. You may also want to use one or more of MB-1's processing functions such as Min/Max, Averaging, and Alarm functions that might not be provided by the existing instrumentation.

If the existing sensor is generating an output voltage, MB-1 can be placed in parallel with the existing instrumentation as shown in Figure 46 as long as the 300K input resistance of the MB-1 input circuitry does not adversely impact the existing instrumentation.

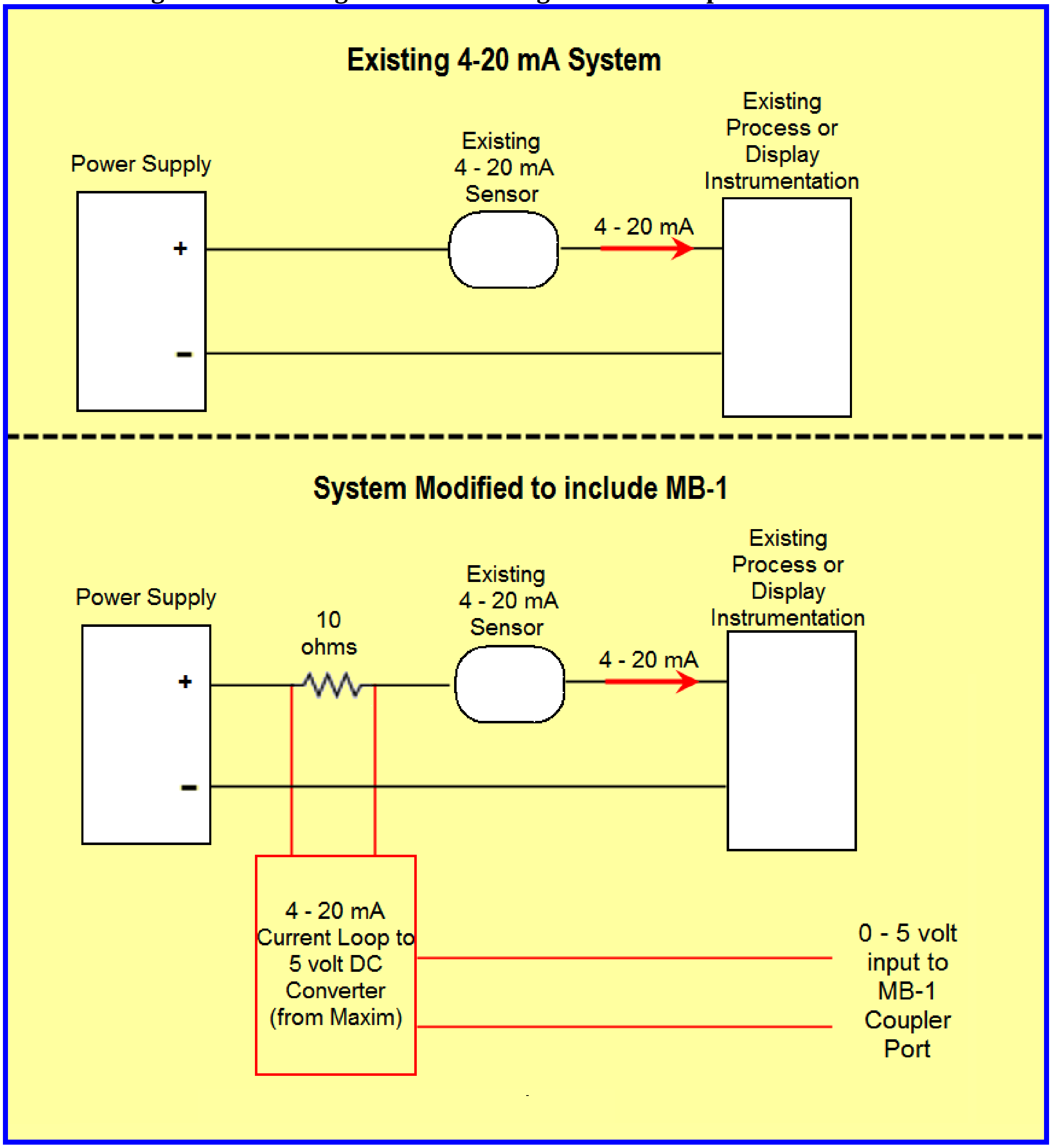
Figure 46 – Adding MB-1 to Existing Instrumentation using a Voltage Sensor



However, if you are using a 4 – 20 mA loop sensor, incorporating MB-1 into the system will take a bit more effort.

The top circuit in Figure 47 shows an existing 4-20 mA loop-based measurement system, including the power source, the loop sensor, and the instrumentation. In the bottom circuit, a 10 ohm resistor, which will have minimal impact on the operation of the existing measurement system, has been added in series with the loop, and the sensed voltage is processed by the circuit shown in this Maxim application note. The circuit, consisting of two ICs, converts the 4-20 mA sensed current through the 10 ohm resistor to 0 to 5 volts DC respectively, which is a suitable input to drive MB-1.

Figure 47 – Adding MB-1 to Existing 4-20 mA Loop Instrumentation



7 Input Sensitivity and Dynamic Range

If the DC voltage derived from the parameter you are trying to measure is approximately 6.14 volts or more full scale, you can derive the full 15 bit resolution from MB-1 (15 bits applies to the values on the low end of the range of MB-1's Amp/Mux). Depending upon the accuracy you want to achieve, as long as the derived DC voltage is at least 2 volts full scale, you will still get a minimum low range resolution of 10 bits. If you only need to resolve your measurements to 1 part in 10 or one part in 20, even a much lower maximum voltage from your sensor can be tolerated. Of course, if the maximum DC voltage generated from your application is very low, you can always add an Operational Amplifier to generate a suitable signal for MB-1's input circuitry. Some references are given in the web site.

8 Interpolation

When you set up a Generic Meter Application, all voltages that are at intermediate voltage levels with respect to the calibration points are linearly interpolated to calculate the parameter being measured.

The power meter functions associated with RF couplers use a square law interpolation (calculated value is the square of the input voltage). With power measurements, all voltages that are at intermediate voltage levels with respect to the calibration points are interpolated using a square law interpolation. If you have a Generic Application whose derived voltage is approximately the square root of the parameter being measured, you will gain additional accuracy at intermediate calibration points by calibrating your application as a conventional power meter instead of as a Generic Meter Application.

If you decide to use this approach, you will have to remember that the meter still thinks it is an RF power meter in this mode, so you will have to ignore parameters that have no meaning for your Generic Application, such as SWR (or better yet, program the display devices so that these values are not displayed). Ignore the w suffix (for watts), on the LCD, and you should be OK using the RF power mode for a "square law" Generic application.

TABLE 22 - MB-1 SPECIFICATIONS OF SPECIAL INTEREST WHEN USING MB-1 WITH ANALOG SENSORS

General	
Input Sensitivity – DC voltage required to drive the Multiplexer/Programmable Gain Amplifier to its maximum output of 32,736.	Approximately 6.14 volts
Coupler Port Input resistance	Approximately 300K
Supported Measurements	Instantaneous Value Average Value Peak-Value Min/Max Functions
Input Signal Processing Rate	> 500 per second
Maximum Number of Calibration Points Coupler points	60 – Same values as power points for power calibration with the addition of a calibration point for 0. (0 – 30,000) see **Table 22**
Interpolation	Linear or Square Law
Digital Filters	Separate Filters for Instantaneous and Average
Alarm Trip Point - Low Value	1 - 27,500
Alarm Trip Point - High Value	1 - 30,000 (High must be > Low)
Programmable Demo Mode (Integrated Simulator) – One Virtual Port (Coupler 8) for simulating Generic Measurements	6 Simulation Modes
Adjustable Peak Hold Time	.1 sec - 9.9 secs in steps of .1 sec
Min/Max Functions	Select the parameter to be processed (e.g., Instantaneous Value), and the Min/Max feature will capture the Min and Max values for display on any of the available display devices.
All Other Features	See MB-1 User's Manual

Table 23- Available MB-1 Calibration Points

0.0	3	40	200	1200	4000
0.05	4	50	300	1300	5000
0.1	5	60	400	1400	6000
0.2	6	70	500	1500	7000
0.3	7	80	600	1600	8000
0.5	8	90	700	1700	9000
0.6	9	100	800	1800	10000
0.8	10	125	900	1900	15000
1.0	20	150	1000	2000	20000
2.0	30	175	1100	3000	30000

The table above shows the values that a Generic Application can be calibrated at. Not surprisingly, these values correspond to the power calibration points used for RF power couplers with one exception discussed below. If your application falls outside of this range, simply apply a scaling factor when interpreting the output (e.g., x .001, x1000, etc).

9 Special Considerations when using MB-1 with Analog Sensors

9.1 An additional Calibration Point of 0 for use with Analog Sensors

For Generic Meter Applications only, we also include a calibration point of 0 during the calibration setup routine since this case will be encountered in many world examples. (For RF Ammeters and Power couplers, the minimum calibration point is .05 amps or .05 watts respectively).

9.2 Allowing a Voltage of 0 during Calibration with Analog Sensors

Another difference you will see is that when calibrating a Generic Meter Application, it is valid for the very first calibration point to have DC voltage of 0 associated with. This applies to the very fist calibration point used in the Setup routine, and is not limited to calibration point 0. (As contrasted to the RF Ammeters and Power couplers, whose lowest calibration point is .05, the calibration setup routines will declare any calibration point with a calibration voltage of 0 as invalid ***since an RF Power or RF Ammeter coupler should always produce a nonzero DC output voltage for all calibration points***).

9.3 Processing Measurements Outside of the Calibration Range

9.3.1 Single Point Calibration Cases

It is only valid to calibrate MB-1 at a single point if the sensor is linear and passes through the origin (0, 0). In this case, MB-1 can calculate any voltage from the sensor, and will calculate the measurement value for any voltage above or below the single calibration point as long as the dynamic range, discussed above, is not exceeded.

9.3.2 Multipoint Calibration Cases

This case applies when measurements, if the calibration table has two or more points.

If the sensor voltage is lower than the lowest calibration voltage or higher than the highest calibration voltage, MB-1 will bottom out or top out as the voltage is reduced or increased respectively. Unlike the single point case described above, MB-1 does not have enough information to reliably estimate the parameter undergoing measurement when the sensor voltage is outside of the calibration range.

For example, take the Tilt Sensor application described above. The table is repeated below. When the sensor voltage is lower than 2.500 volts, the measurement will bottom out at 0 degrees. If the voltage is greater than 3.500 volts, the measurement will top out at 90 degrees.

Angle (degrees)	XA (analog voltage)
0	2.50000
10	2.67365
20	2.84202
30	3.00000
40	3.14279
50	3.26604
60	3.36603
70	3.43969
80	3.48481
90	3.50000

9.3.3 Dialing In actual Parameter Value during Calibration

If you look at the detailed calibration steps in the MB-1 User's Manual, you will see that line 4 of the LCD displays the actual value being applied during calibration. In some cases, it is difficult to perform calibration at the exact calibration point, and this feature allows you to dial in the actual parameter value with the front panel pot. (It is assumed that this value is close to the nominal calibration point). By accounting for the actual value of the parameter being calibrated, MB-1 can then create a more accurate calibration table.

This can be done for Power couplers and RF Ammeters since either a square law (power couplers) or linear law (RF Ammeters) can be assumed and use to reliably correct the calibration point. When used with analog sensors, MB-1 can not make any assumptions, and thus this correction capability does not apply to Generic Meter Applications.