

# Absolute and Relative Gas Concentration: Understanding Oxygen in Air

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The amount of oxygen (O<sub>2</sub>) in air is described in two ways and it is essential to be able to convert between them. The conversion comes from the ideal gas law,  $PV = nRT$  (P is pressure, V is volume, n is absolute gas concentration, T is temperature, and R is the ideal gas constant), which most people were first exposed to in Chemistry 101. The simplest and most common way to report the amount of O<sub>2</sub> in air is to express it **relative** to the other compounds in the air as a fraction or percentage. The atmospheric concentration of O<sub>2</sub> has remained constant for several hundred years at 20.95%. This means that exactly 20.95% of the molecules in the atmosphere are O<sub>2</sub> molecules. The percentage is the same on the beach in Florida and in the mountains of Logan, Utah. However, the **absolute** O<sub>2</sub> concentration, or the amount of O<sub>2</sub> molecules per unit volume, does not remain constant. An O<sub>2</sub> tank is required to climb Mount Everest, even though the relative O<sub>2</sub> concentration is still 20.95%. The absolute O<sub>2</sub> concentration determines the rate of most biological and chemical processes, but the relative O<sub>2</sub> concentration is typically reported. This is similar to discussing relative humidity when absolute humidity is what determines evaporation rates.

Absolute and relative measurements are expressed using several different units. The following table shows the units used to describe both measurements.

<b>Absolute amount of gas</b>	<b>Relative amount of gas</b>
<b>moles of O<sub>2</sub> per unit volume</b> (e.g. moles per Liter)	<b>% O<sub>2</sub> in air</b> (e.g. 20.95% in ambient air)
<b>mass of O<sub>2</sub> per unit volume</b> (e.g. grams per Liter) (O <sub>2</sub> has a mass of 32 g per mole)	<b>mole fraction</b> (e.g. moles of O <sub>2</sub> per mole of air) (0.2095 mol O <sub>2</sub> per mole of ambient air) (this can also be expressed as 0.2095 kPa O <sub>2</sub> per kPa Air)
<b>partial pressure</b> (e.g. kilopascals (kPa))	

The absolute O<sub>2</sub> concentration changes a few percent from day to day with changes in barometric pressure and temperature. As barometric pressure decreases, or as temperature increases, air expands and the number of O<sub>2</sub> molecules per unit volume decreases. The opposite occurs as barometric pressure increases or as temperature decreases. Like most gas sensors, the Apogee O<sub>2</sub> sensor responds to the absolute concentration of O<sub>2</sub> in air. Thus changes in pressure and temperature change the output of the sensor even though the relative concentration of O<sub>2</sub> has not changed. Fortunately, the sensor responses to pressure and temperature (P and T) are repeatable, thus it is possible to measure P and T and correct for them in software.

## Effect of Barometric Pressure on the Output of the Apogee Oxygen Sensor

The ideal gas law shows that absolute gas concentration increases by 0.99% (1 kPa / 101.3 kPa) at sea level for every 1 kPa increase in pressure. Because air contains 20.95% O<sub>2</sub>, a 1 kPa pressure increase results in an increase of **0.21% O<sub>2</sub> per kPa** (0.99% \* 0.2095) increase in barometric pressure at sea level. Due to lower barometric pressure at higher elevations, the

percentage increase in absolute gas concentration per kPa increases with elevation. For example, the absolute gas concentration increases by 1.16% at 1400 m elevation for every 1 kPa increase in pressure. This results in an increase of **0.24% O<sub>2</sub> per kPa** (1.16% \* 0.2095) increase in barometric pressure. For the most precise measurements, this correction should be applied to all O<sub>2</sub> sensors. For example, the average barometric pressure in Logan, Utah, is 86 kPa (1400 m elevation). If an O<sub>2</sub> sensor were calibrated to read 20.95% O<sub>2</sub> at 86 kPa then the sensor would read 21.19% O<sub>2</sub> at 87 kPa [20.95 + 0.24\*(87-86)] and 20.71% O<sub>2</sub> at 85 kPa [20.95 + 0.24\*(85-86)]. The equation to correct O<sub>2</sub> measurements for barometric pressure at any elevation is:

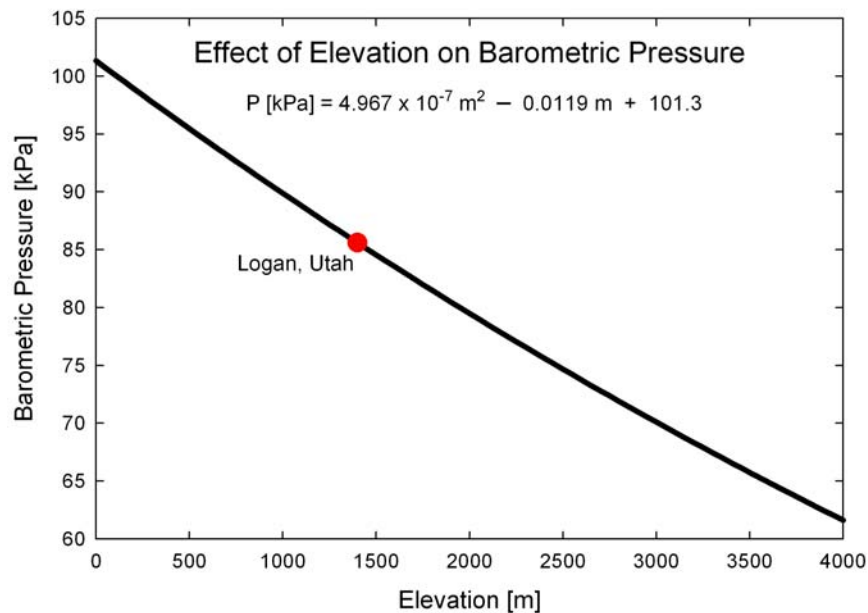
$$\% \text{ O}_2 = \text{measured } \% \text{ O}_2 - [(100 / P) * 0.2095] \% \text{ O}_2 / \text{kPa} * (\text{measured kPa} - \text{calibrated kPa}),$$

where P is the barometric pressure [kPa] at the given elevation and is calculated from:

$$P = 101.325 \text{ kPa} - 101.325 \text{ kPa} * \{1 - [1 - (E / 44307.69231)]^{5.25328}\},$$

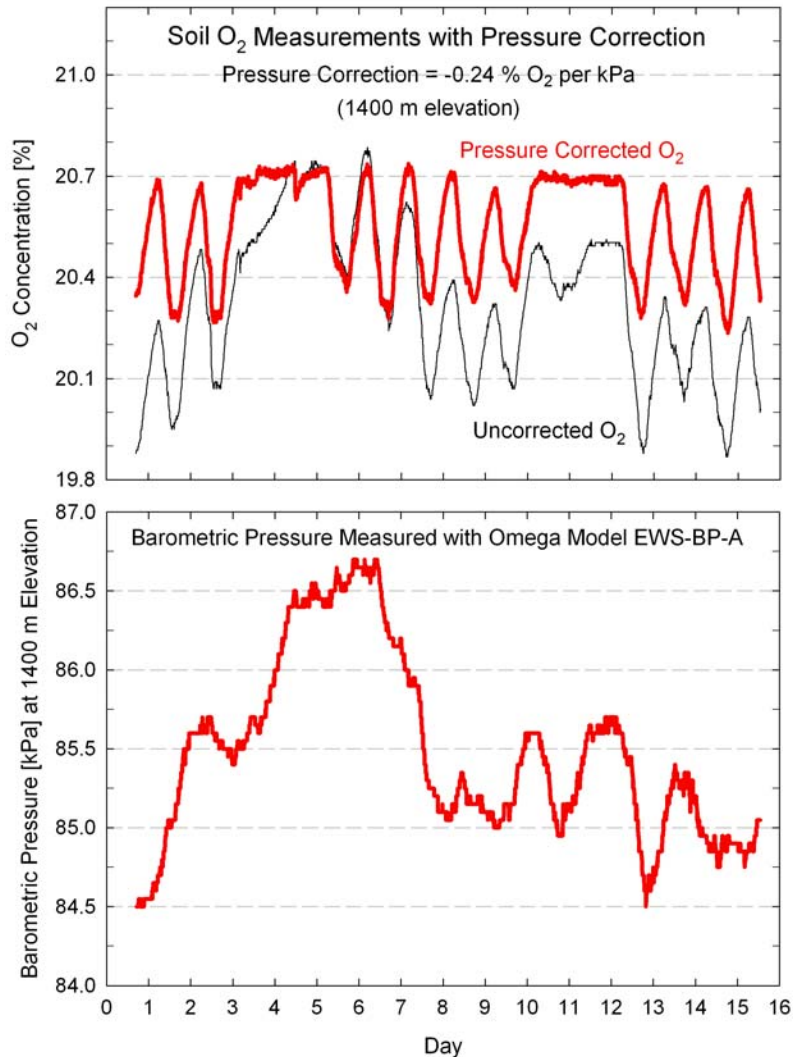
where E is elevation in meters. The correction factor in the first equation, [(100 / P) \* 0.2095] % O<sub>2</sub> / kPa, is tabulated below for several elevations and the corresponding barometric pressures, calculated from the second equation. A figure showing the barometric pressure decrease with increasing elevation (calculated from the second equation) is also shown, along with a second order polynomial fit to the data.

<b>Elevation [m]</b>	<b>Pressure [kPa]</b>	<b>Correction Factor [% O<sub>2</sub> / kPa]</b>
0	101.325	0.207
500	95.461	0.219
1000	89.874	0.233
1500	84.555	0.248
2000	79.494	0.264



## Example of Pressure Correction

The Figure below shows the uncorrected O<sub>2</sub> concentration in soil, the barometric pressure, and the O<sub>2</sub> concentration with the pressure correction applied. The data show the improvement in the measurement as a result of the pressure correction. The pressure-corrected O<sub>2</sub> measurements no longer slope up with increasing pressure and slope down with decreasing pressure. However, there is still a diurnal oscillation due to temperature, which is discussed in the next section.



Pressure can be simultaneously measured with O<sub>2</sub> measurements to correct for the pressure effect. Many electronic pressure sensors are available. If the pressure sensor is indoors, we have found that the Omega model EWS-BP-A Pressure Transmitter ([www.omega.com](http://www.omega.com)) is accurate and inexpensive (\$145). For comparisons among barometric pressure sensors see "*Electronic Measurement of Barometric Pressure: A Comparison of Omega Model EWS-BP-A, Setra Model 276, Setra Model 278, and Vaisala Model PTB101B*" published online by the Utah State University Crop Physiology Laboratory ([www.usu.edu/cpl/research\\_sensors.htm](http://www.usu.edu/cpl/research_sensors.htm)). Wiring instructions for the Omega EWS-BP-A are shown below.

## Effect of Temperature and Humidity on the Output of the Apogee Oxygen Sensor

### Sensor in Air

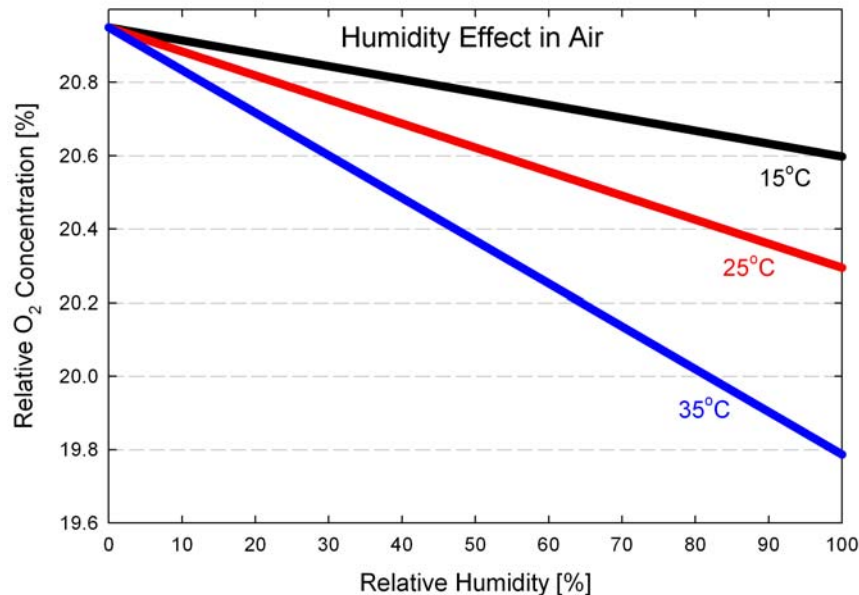
#### *Effect of temperature*

The ideal gas law shows that gas concentration decreases by 0.34% (1 K / 293 K) for every 1 °C increase in temperature. Because air contains 20.95% O<sub>2</sub>, a 1 °C temperature increase results in a decrease of **0.07% O<sub>2</sub> per °C** (0.34% \* 0.2095) increase in temperature. However, there is also an effect of temperature on the electronics in the sensor, which causes the output to increase by approximately **0.10% O<sub>2</sub> per °C** temperature increase. Because this is an effect on the sensor electronics, it varies slightly from sensor to sensor. The net effect of the ideal gas law (-0.07%) and the sensor electronics (+0.10%) is an increase in the output of the sensor by **0.03% per °C** increase in temperature in dry air. For example, if an O<sub>2</sub> sensor were calibrated to read 20.95% O<sub>2</sub> at 25 °C then the sensor would read 21.10% O<sub>2</sub> at 30 °C [20.95 + 0.03\*(30-25)] and 20.80% O<sub>2</sub> at 20 °C [20.95 + 0.03\*(20-25)]. The equation to correct O<sub>2</sub> measurements in air for temperature is:

$$\% \text{ O}_2 = \text{measured } \% \text{ O}_2 - 0.03 \% \text{ O}_2 / ^\circ\text{C} * (\text{measured } ^\circ\text{C} - \text{calibrated } ^\circ\text{C})$$

#### *Effect of humidity*

As the humidity in air increases, water vapor molecules displace O<sub>2</sub> molecules causing the output of the sensor to decrease. The effect of humidity is larger at warmer temperatures because there is more water vapor in the air. The figure below shows the humidity effect on relative O<sub>2</sub> concentration at three different temperatures. The correction factors for each temperature, 15, 25, and 35 °C, are 0.004, 0.007, and 0.011 % O<sub>2</sub> per 1 % increase in relative humidity, respectively.



## Sensor in Soil

The humidity correction is more important when the sensor is used to measure O<sub>2</sub> in soil gas, because the air is always at 100% relative humidity. Between 20 and 25 °C the water vapor displacement causes the output of the sensor to decrease by **0.04% per °C** increase in temperature. This exact effect can be calculated from psychometric equations and is slightly larger at higher temperatures and slightly smaller at cooler temperatures.

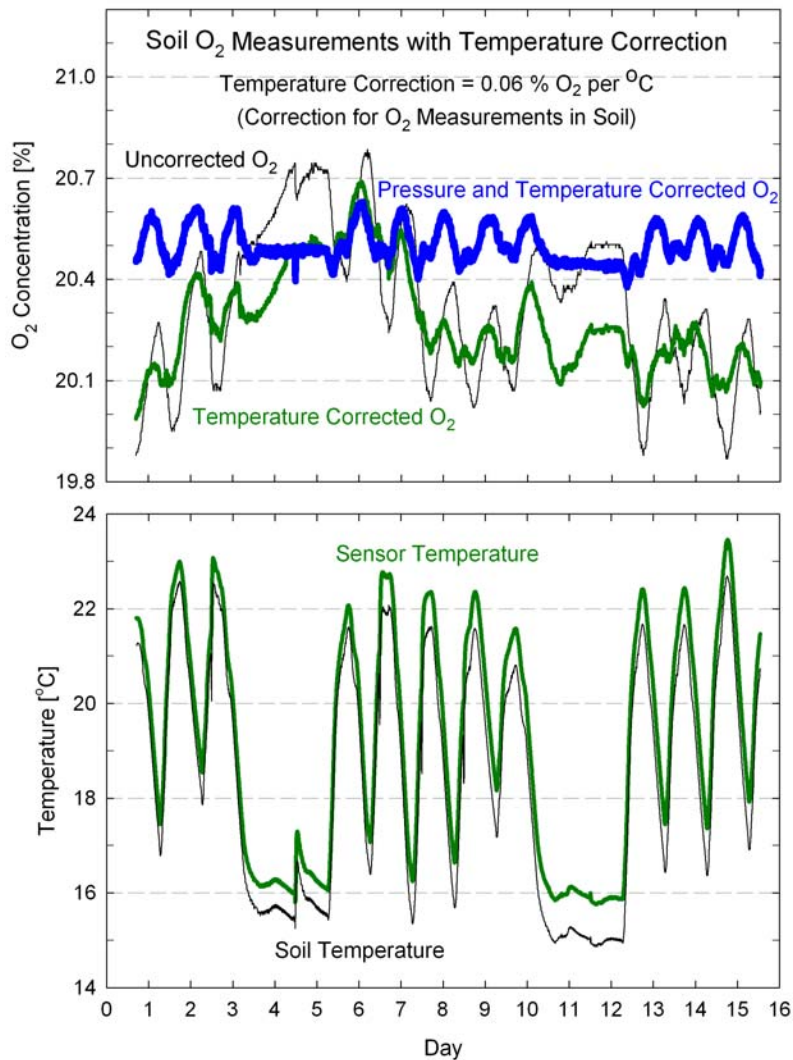
The correction for the effect of temperature on the solubility of CO<sub>2</sub> in water should be made for measurement of O<sub>2</sub> in soil. The solubility of CO<sub>2</sub> in water decreases with increasing temperature, and the resulting increase in CO<sub>2</sub> in the soil gas causes O<sub>2</sub> molecules to be displaced. If the CO<sub>2</sub> concentration in the soil gas is 1%, this effect decreases the output by **0.05% per °C** increase in temperature. The solubility of O<sub>2</sub> is also temperature dependent, but O<sub>2</sub> solubility in water is 30 times less than CO<sub>2</sub> solubility in water, thus the O<sub>2</sub> solubility effect can be ignored.

The water vapor dilution effect and the CO<sub>2</sub> solubility effect both decrease the sensor output. Their combined effects cause the output of the O<sub>2</sub> sensor to *decrease 0.09% per °C* increase in temperature. This combined effect offsets the **0.03% per °C increase** in output that occurs in dry air. Thus the net temperature effect in soil is a decrease in output of the O<sub>2</sub> sensor by **0.06% per °C** increase in temperature. For example, if an O<sub>2</sub> sensor were calibrated to read 20.95% O<sub>2</sub> at 25 °C then the sensor would read 21.25% O<sub>2</sub> at 30 °C [20.95 + 0.06\*(30-25)] and 20.65% O<sub>2</sub> at 20 °C [20.95 + 0.06\*(20-25)]. The equation to correct O<sub>2</sub> measurements in soil for temperature is:

$$\% \text{ O}_2 = \text{measured } \% \text{ O}_2 + 0.06 \% \text{ O}_2 / ^\circ\text{C} * (\text{measured } ^\circ\text{C} - \text{calibrated } ^\circ\text{C}).$$

## Example of Temperature Correction in Soil

The Figure below shows simultaneous O<sub>2</sub> in soil and temperature measurements, and the temperature correction described above applied to the O<sub>2</sub> measurements and the pressure-corrected O<sub>2</sub> measurements. As with the pressure correction, the data show the improvement in the measurement as a result of the temperature correction. When both corrections are applied the standard deviation is 0.05% O<sub>2</sub>. The reason the sensor temperature is always slightly warmer than the soil temperature is because there is a small heater to prevent condensation on the sensing element.



# Wiring Instructions for Omega EWS-BP-A Barometric Pressure Transducer

The Omega EWS-BP-A Barometric Pressure Transducer yields a voltage output, ranging from 1-5 volts, which is linearly dependent on barometric pressure. The sensor can be easily connected to a datalogger. To make measurements, port 1 on the sensor is connected to a 12 volt DC power source and port 3 is connected to the high port of a differential channel on the datalogger. A 250Ω resistor should be jumpered across the high and low ports of the differential channel (A 250Ω should be used with dataloggers capable of measuring a 1-5 volt range. A 100Ω resistor can be used to yield a 0.4-2 volt range.). The low port of the differential channel should be jumpered to analog ground. The calibration between the measured voltage output of the sensor and the barometric pressure is found in the EWS-BP-A User's Guide (<http://www.omega.com/manuals/manualpdf/M3502.pdf>) (The calibration in the manual is for a 1-5 volt range. If a 100Ω resistor is used to produce a 0.4-2 volt range, the calibration must be scaled accordingly).

## Appendix

### Example Campbell Scientific Datalogger Program for O2 Measurements with Apogee Models O2S, O2S-D, and O2S-F (Oxygen Sensors). All comments are in bold text.

```
:{CR10X}  
*Table 1 Program  
01: 1      Execution Interval (seconds)
```

#### Instruction to measure the mV output of the O2 sensor and calculate the O2 concentration (in %).

```
1: Volt (Diff) (P2)  
1: 1      Reps  
2: 24     250 mV 60 Hz Rejection Range (mV range is dependent on the sensor; standard sensor or fast-response sensor)  
3: 1      DIFF Channel  
4: 1      Loc [ Uncor_O2 ]  
5: 0.419  Mult (the multiplier is sensor specific and is determined via calibration; procedure is explained below)  
6: 0.0    Offset
```

#### Instruction to measure the mV output of the Omega EWS-BP-A Barometric Pressure Transducer and calculate barometric pressure. Multiplier and offset are calculated from the calibration information given in the EWS-BP-A User's Guide.

```
2: Volt (Diff) (P2)  
1: 1      Reps  
2: 25     2500 mV 60 Hz Rejection Range  
3: 2      DIFF Channel  
4: 2      Loc [ BP_kPa ]  
5: 0.02385 Mult (multiplier and offset listed here are adjusted for use with a smaller voltage measurement range)  
6: 60.804 Offset
```

#### Instruction string to measure the resistance of the thermistor and calculate the sensor body temperature. See the Instruction Manual for the Campbell Scientific Model 109-L Temperature Sensor for further details.

```
3: AC Half Bridge (P5)  
1: 1      Reps  
2: 25     2500 mV 60 Hz Rejection Range (the range should at least match the excitation)  
3: 5      SE Channel  
4: 1      Excite all reps w/Exchan 1  
5: 2500   mV Excitation  
6: 3      Loc [ mV_ther ]  
7: 1.0    Mult  
8: 0.0    Offset
```

4:  $Z=1/X$  (P42)  
 1: 3 X Loc [ mV\_thrm ]  
 2: 4 Z Loc [ 1\_mV\_ther ]

5:  $Z=X+F$  (P34)  
 1: 4 X Loc [ 1\_mV\_thrm ]  
 2: -1.0 F  
 3: 5 Z Loc [ 2\_mV\_thrm ]

6:  $Z=X*F$  (P37)  
 1: 5 X Loc [ 2\_mV\_thrm ]  
 2: 24900 F  
 3: 6 Z Loc [ R\_thrm ]

7:  $Z=LN(X)$  (P40)  
 1: 6 X Loc [ R\_thrm ]  
 2: 7 Z Loc [ ln\_R\_thrm ]

8:  $Z=X*F$  (P37)  
 1: 7 X Loc [ ln\_R\_thrm ]  
 2: 0.001 F  
 3: 8 Z Loc [ Scaled\_R ]

9: Polynomial (P55)  
 1: 1 Reps  
 2: 8 X Loc [ Scaled\_R ]  
 3: 9 F(X) Loc [ SH\_coeffs ]  
 4: .001129 C0  
 5: .234108 C1  
 6: 0.0 C2  
 7: 87.7547 C3  
 8: 0.0 C4  
 9: 0.0 C5

10:  $Z=1/X$  (P42)  
 1: 9 X Loc [ SH\_coeffs ]  
 2: 10 Z Loc [ SB\_temp\_K ]

11:  $Z=X+F$  (P34)  
 1: 10 X Loc [ SB\_temp\_K ]  
 2: -273.15 F  
 3: 11 Z Loc [ SB\_temp\_C ]

**Instruction string to correct the O2 measurement for the pressure effect. -86.0 is the barometric pressure [kPa] at calibration and -0.245 is the correction factor [% O2 per kPa] for barometric pressure effects.**

12:  $Z=X+F$  (P34)  
 1: 2 X Loc [ BP\_kPa ]  
 2: -86.0 F  
 3: 12 Z Loc [ BP\_diff ]

13:  $Z=X*F$  (P37)  
 1: 12 X Loc [ BP\_diff ]  
 2: -0.245 F  
 3: 13 Z Loc [ BP\_cor ]

14:  $Z=X+Y$  (P33)  
 1: 1 X Loc [ Uncor\_O2 ]  
 2: 13 Y Loc [ BP\_cor ]  
 3: 14 Z Loc [ O2\_BP\_cor ]



**Instruction string to correct the pressure-corrected O2 measurement for the temperature effect. -20.0 is the temperature [degrees C] at calibration and 0.060 is the correction factor [% O2 per degree C] for temperature effects in soil. The correction factor is -0.030 [% O2 per degree C] for temperature effects in air.**

```
15: Z=X+F (P34)
1: 11      X Loc [ Temp_C  ]
2: -20.0   F
3: 15      Z Loc [ T_diff  ]
```

```
16: Z=X*F (P37)
1: 15      X Loc [ T_diff  ]
2: 0.060   F
3: 16      Z Loc [ T_cor   ]
```

```
17: Z=X+Y (P33)
1: 14      X Loc [ O2_BP_cor ]
2: 16      Y Loc [ T_cor   ]
3: 17      Z Loc [ O2_T_cor ]
```

End Program

**Explanation of labels used in the program:**

**Uncor\_O2** = uncorrected O2 concentration in percent.  
**BP\_kPa** = barometric pressure in kPa.  
**mV\_thrm** = mV output of the thermistor.  
**1\_mV\_thrm** = first step in converting the mV output of the thermistor to resistance.  
**2\_mV\_thrm** = second step in converting the mV output of the thermistor to resistance.  
**R\_thrm** = resistance of the thermistor.  
**ln\_R\_thrm** = natural log of the resistance of the thermistor.  
**Scaled\_R** = intermediate step in converting the natural log of the resistance to temperature.  
**SH\_coeffs** = application of the Steinhart and Hart coefficients to convert the scaled resistance to the reciprocal of temperature.  
**Temp\_K** = internal sensor temperature in Kelvin.  
**Temp\_C** = internal sensor temperature in degrees Celsius.  
**BP\_diff** = barometric pressure difference between time of measurement and calibration.  
**BP\_cor** = barometric pressure correction factor.  
**O2\_BP\_cor** = O2 concentration corrected for barometric pressure effects.  
**T\_diff** = temperature difference between time of measurement and calibration.  
**T\_cor** = temperature correction factor.  
**O2\_T\_cor** = pressure-corrected O2 concentration corrected for barometric pressure effects.

**Wiring Instructions for Apogee Model O2S, O2S-D, and O2S-F (Oxygen Sensors).**

**Red Wire** = high side of differential channel (positive lead for O2 sensor)  
**Black Wire** = low side of differential channel (negative lead for O2 sensor)  
**Clear Wire** = analog ground (ground for O2 sensor)  
**Green Wire** = high side of single-ended channel (positive lead for thermistor)  
**Orange Wire** = analog ground (negative lead for thermistor)  
**White Wire** = excitation channel (excitation for thermistor)  
**Yellow Wire** = 12V port (positive lead for heater)  
**Blue Wire** = ground (negative lead for heater)

**Calibration Instructions for Apogee Model O2S, O2S-D, and O2S-F (Oxygen Sensors).**

Measure the mV output of the sensor while it is open air. Divide the O2 concentration in air, 20.95 % O2, by the mV output to yield the multiplier. For example, if the mV output in air was 50.0 mV, then the calibration factor would be 20.95 % O2 / 50.0 mV = 0.419 % O2 per mV. Multiply this calibration factor by the measured mV output to determine the % O2 (Instruction 1 above).