Sensors and Transducers

E80 Spring 2014
Erik Spjut

Scientific & Engineering Measurements

- Scientific Measurements
  - What you measure *with* a rocket.
  - What are examples?
- Engineering Measurements
  - What you measure *about* a rocket.
  - What are examples?

Experimental Measurements

- Mass
- Force
- Acceleration
- Velocity
- Position
- Displacement
- Orientation
- Vibration

- EM Intensity
  - Radio
  - Microwave
  - IR
  - Visible
  - UV
  - X-ray
  - Gamma

Experimental Measurements II

- Temperature
- Pressure
- Flow Rate
- Composition
  - Partial Pressure
  - Humidity
  - Mass fraction
  - Mole fraction
  - pH
- Phases
  - Aerosols
  - Suspensions
  - Microstructure
- Sound
- Images
- Video

Experimental Measurements III

- Electrical
  - Voltage
  - Charge
  - Current
  - Resistance
  - Inductance
  - Capacitance
  - Power
- Time
- Frequency
- Phase
- Angular
  - Position
  - Velocity
  - Acceleration

Digikey's List of Sensors

- Accelerometers (1022 items)
- Accessories (3085 items)
- Amplifiers (277 items)
- Capacitive Touch Sensors, Proximity Sensor ICs (508 items)
- Color Sensors (111 items)
- Current Transducers (1440 items)
- Dust Sensors (11 items)
- Encoders (4042 items)
- Flex Sensors (3 items)
- Float, Level Sensors (313 items)
- Flow Sensors (162 items)
- Force Sensors (50 items)
- Gas Sensors (66 items)
- Gyroscopes (205 items)
- Image Sensors, Camera (313 items)
- Inclinometers (44 items)
- IrDA Transceiver Modules (291 items)
- LVDT Transducers (Linear Variable Differential Transformer) (47 items)
- Magnetic Sensors - Compass, Magnetic Field (Modules) (26 items)
- Magnetic Sensors - Hall Effect, Digital Switch, Linear, Compass (ICs) (2324 items)
- Magnetic Sensors - Position, Proximity, Speed (Modules) (879 items)
- Magnets (95 items)
- Moisture Sensors, Humidity (257 items)
- Motion Sensors, Detectors (PIR) (168 items)
- Multifunction (101 items)
- Obsolete/Discontinued Part Numbers (16 items)
- Optical Sensors - Ambient Light, IR, UV Sensors (561 items)
- Optical Sensors - Distance Measuring (36 items)
- Optical Sensors - Mouse (117 items)
- Optical Sensors - Photo Detectors - CdS Cells (38 items)
- Optical Sensors - Photo Detectors - Logic Output (128 items)
- Optical Sensors - Photo Detectors - Remote Receiver (1104 items)
- Optical Sensors - Photodiodes (925 items)
- Optical Sensors - Photoelectric, Industrial (2861 items)
- Optical Sensors - Photointerrupters - Slot Type - Logic Output (1126 items)
- Optical Sensors - Photointerrupters - Slot Type - Transistor Output (1115 items)
- Optical Sensors - Phototransistors (738 items)
- Optical Sensors - Reflective - Analog Output (323 items)
- Optical Sensors - Reflective - Logic Output (123 items)
- Position Sensors - Angle, Linear Position Measuring (937 items)
- Pressure Sensors, Transducers (25455 items)
- Proximity Sensors (3521 items)
- RTD (Resistance Temperature Detector) (60 items)
- Shock Sensors (11 items)
- Solar Cells (82 items)
- Specialized Sensors (311 items)
- Strain Gages (24 items)
- Temperature Regulators (3285 items)
- Temperature Sensors, Transducers (1374 items)
- Thermistors - NTC (4928 items)
- Thermistors - PTC (1257 items)
- Thermocouple, Temperature Probe (396 items)
- Tilt Sensors (50 items)
- Ultrasonic Receivers, Transmitters (78 items)
- Vibration Sensors (30 items)

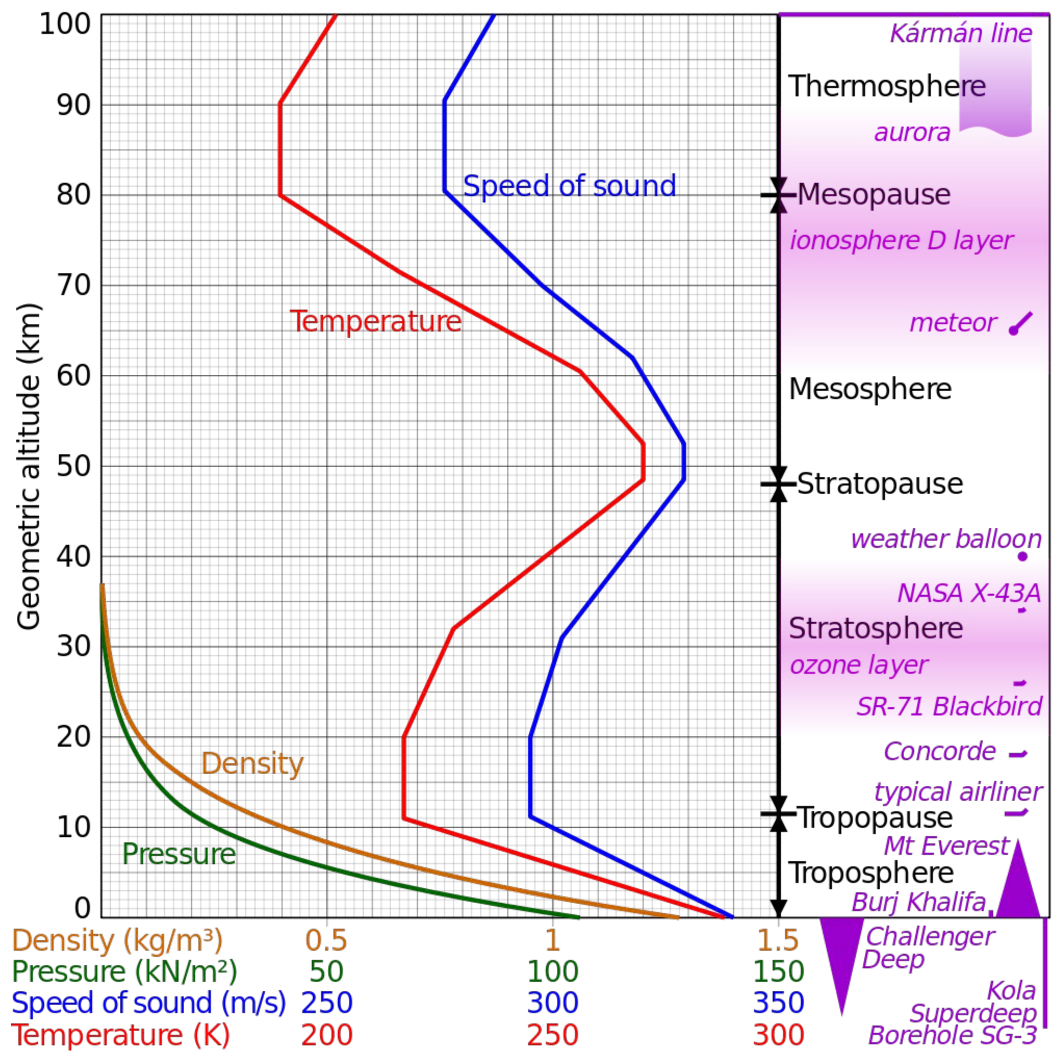
What Spec's Do We Care About?

- Quantity Measured
- Range or Span
- Accuracy
- Precision
- Noise
- Linearity
- Speed of Response
- Voltage Requirements
- Current Requirements
- Output Impedance
- Mounting Requirements

Example – Altimeter

- Measure Absolute Pressure and Calculate Altitude
  - What range of pressures do we need?
  - What accuracy do we expect?

Calculate Altitude from Pressure



US Standard Atmosphere

http://en.wikipedia.org/wiki/File:Comparison_US_standard_atmosphere_1962.svg

For the Troposphere

$$h = \frac{T_0}{-\left(dT/dh\right)} \cdot \left[1 - \left(\frac{P}{P_0}\right)^{\frac{-\left(dT/dh\right)\cdot R}{gM}}\right]$$

where

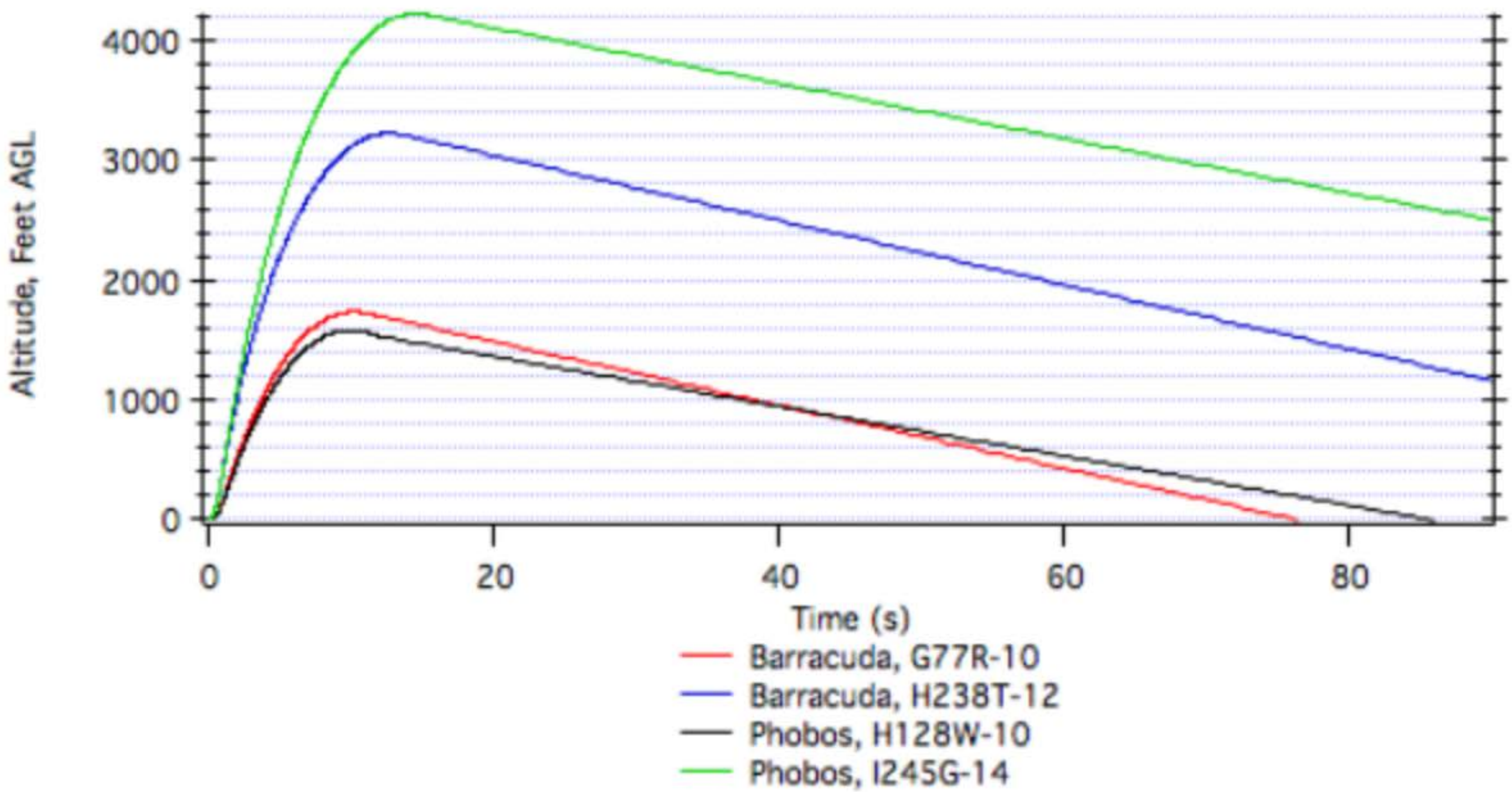
- h = geopotential altitude (above sea level) (in meters)
- P_0 = standard atmosphere pressure = 101325Pa
- T_0 = 288.15K (+15°C)
- dT/dh = –0.0065 K/m: thermal gradient or standard temperature lapse rate
- R = 8.31432 Nm/mol K (Current NIST value 8.3144621)
- g = 9.80665 m/s²
- M = 0.0289644 kg/mol

From 1976 US Standard Atmosphere

How Does Pressure Vary With Height?

Alt. (m)	Alt. (ft)	Alt. (mi)	P (Pa)	dP/dh (Pa/m)
0	0	0.000	101325	-12.01
200	656	0.124	98945	-11.78
400	1312	0.249	96610	-11.56
600	1969	0.373	94321	-11.34
800	2625	0.497	92076	-11.12
1000	3281	0.621	89874	-10.90
1200	3937	0.746	87715	-10.69
1400	4593	0.870	85598	-10.48
1600	5249	0.994	83522	-10.27
1800	5906	1.118	81488	-10.07
2000	6562	1.243	79494	-9.87
2200	7218	1.367	77540	-9.67
2400	7874	1.491	75624	-9.48
2600	8530	1.616	73747	-9.29

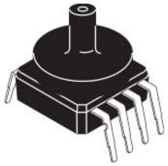
Calculate Flight Height



Assume 1 Mile AGL Max Alt

- Lucerne Valley at 3000 ft MSL, Claremont 1200 ft
- P_{ground} = 90 kPa
- P_{apogee} = 74 kPa
- Span = ΔP = 16 kPa
- Need to allow for Barometric Pressure Changes +7% to –13%
- P_{max} = MAX(104 kPa, 97 kPa)
- P_{min} = 64 kPa

MPXA6115AC7U



MPXA6115AC7U
CASE 482C

Operating Characteristics

Table 1. Operating Characteristics (V_S = 5.0 Vdc, T_A = 25°C unless otherwise noted, P1 > P2)

Characteristic	Symbol	Min	Typ	Max	Unit
Pressure Range	P_{OP}	15	—	115	kPa
Supply Voltage[1]	V_S	4.75	5.0	5.25	Vdc
Supply Current	I_o	—	6.0	10	mAdc
Minimum Pressure Offset[2](0 to 85°C) @ V_S = 5.0 Volts	V_{off}	0.133	0.200	0.268	Vdc
Full Scale Output[3](0 to 85°C) @ V_S = 5.0 Volts	V_{FSO}	4.633	4.700	4.768	Vdc
Full Scale Span[4](0 to 85°C) @ V_S = 5.0 Volts	V_{FSS}	4.433	4.500	4.568	Vdc
Accuracy[5](0 to 85°C)	—	—	—	±1.5	$\%V_{FSS}$
Sensitivity	V/P	—	45.0	—	mV/kPa
Response Time[6]	t_R	—	1.0	—	ms
Warm-Up Time[7]	—	—	20	—	ms
Offset Stability[8]	—	—	±0.25	—	$\%V_{FSS}$

From Freescale Data Sheet

Nominal Values

- $V @ P_{\mathrm{min}}$= 0.200 V + (64 kPa – 15 kPa)•0.045 V/kPa = 2.41 V
- $V @ P_{\mathrm{max}}$ = 0.200 + (104 kPa – 15 kPa)•0.045 V/kPa = 4.21 V
- Accuracy (Uncalibrated) ±1.5% V_{FS} = ±1.5%•4.7 V = ±0.071 V = ±1.57 kPa = ±157 m
- $t_{\mathrm{R10\%\text{-}90\%}}$ = 1.0 ms, τ = $t_{\mathrm{R10\%\text{-}90\%}}/\ln(9)$ = 0.46 ms

Output Impedance

- Can drive circuit with 0.5 mA at 4.7 V
- Impedance of driven circuit = V/I = 4.7 V/ 0.0005 A = 9400 Ω.
- Actual output impedance determined empirically. How?

Choices on Conditioning

- Data Logger
  - 0 V to 3.3 V
  - Input Impedance ~2200 Ω
  - 16 bit, 1 LSB = 3.3 V/2^{16} = 50 μV

1. Change gain so $V_{\max}$ = 3.3 V
   - 1 LSB = 50 μV = 0.16 m = 6 in
2. Change gain and offset so $V_{\min}$ = 0 V & $V_{\max}$ = 3.3 V
   - 1 LSB = 50 μV = 0.06 m = 2.4 in

Signal Conditioning

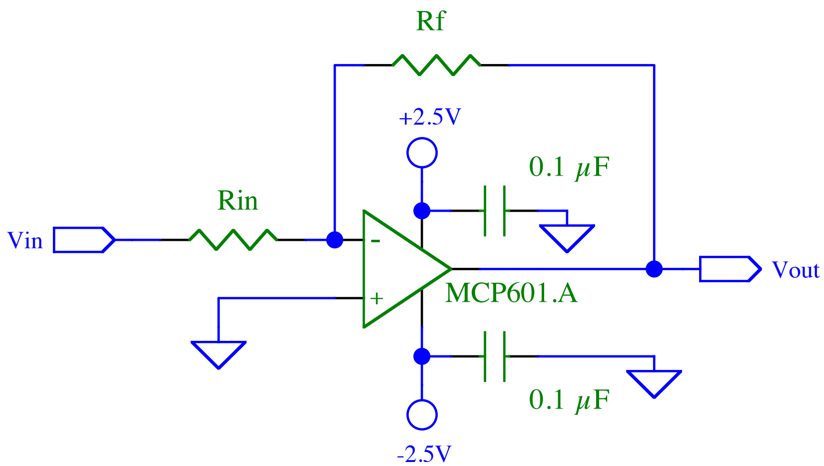
- Does it need a buffer amp? How would you know?
- How do you change the gain?
- How do you change the gain and offset?
- What about aliasing?

Single-Sided Circuits

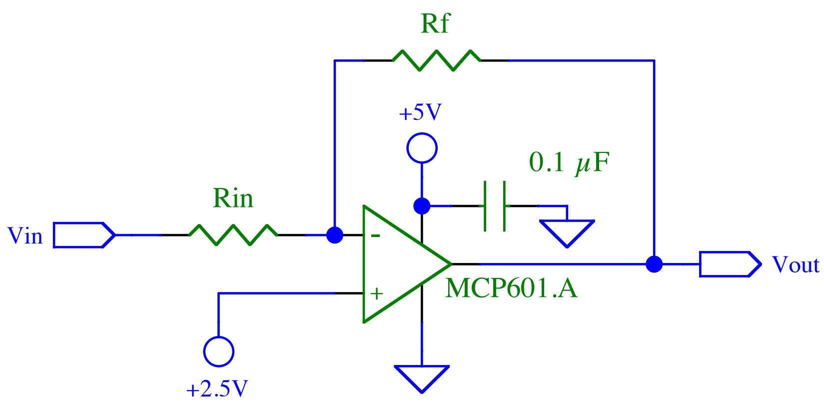
(Will visit again under Flight Hardware)

- Data logger expects 0 V to 3.3 V signals
- Classical op-amp circuit power ±15 V
- Low-voltage op-amp circuit power
  - ±1.4 V to ±3 V
  - 0-to-2.8 V to 0-to-6 V
- Signal offset
- Reference offset
- Virtual ground

Inverting Amps

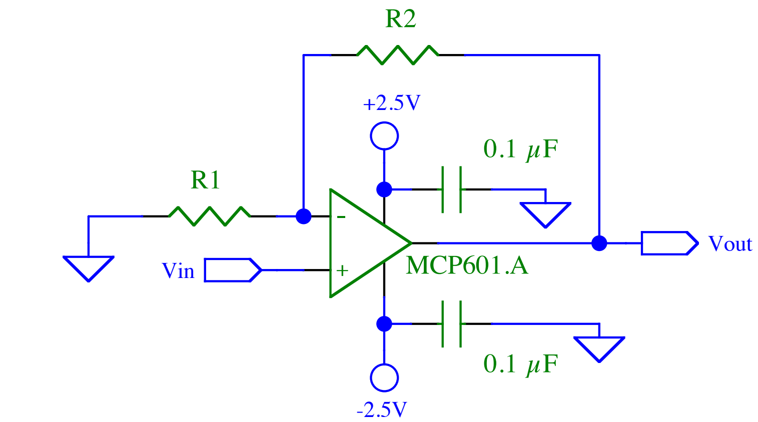


$$V_{\text{out}} = -\left(\frac{R_f}{R_{in}}\right)V_{in}$$

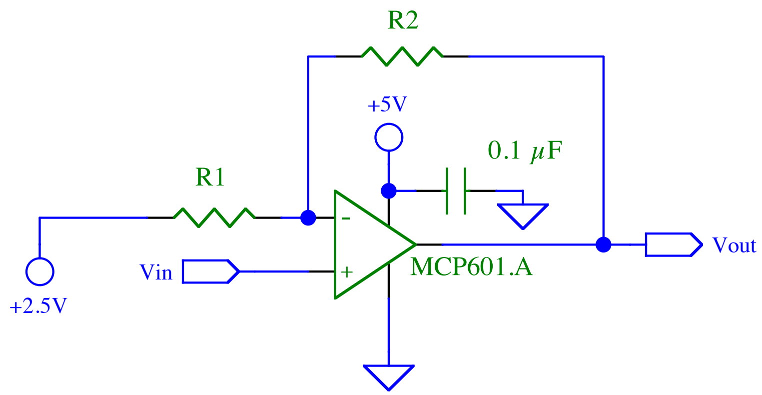


$$V_{\text{out}} = -\left(\frac{R_f}{R_{in}}\right)V_{in} + 2.5\left(1 + \frac{R_f}{R_{in}}\right)$$

Non-Inverting Amps



$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right) V_{in}$$



$$V_{out} = \left(1 + \frac{R_f}{R_{in}}\right) V_{in} - 2.5\left(\frac{R_f}{R_{in}}\right)$$

Can You do Single Sided for:

- Differential Amplifier?
- Integrator?
- Transimpedance Amplifier?
- Sallen-Key Filter?
- Bipolar sensor like piezoelectric vibration?

Example – Gas Sensor

- MQ-2 CH_4 Gas Sensor (Digikey, Parallax, or Pololu)

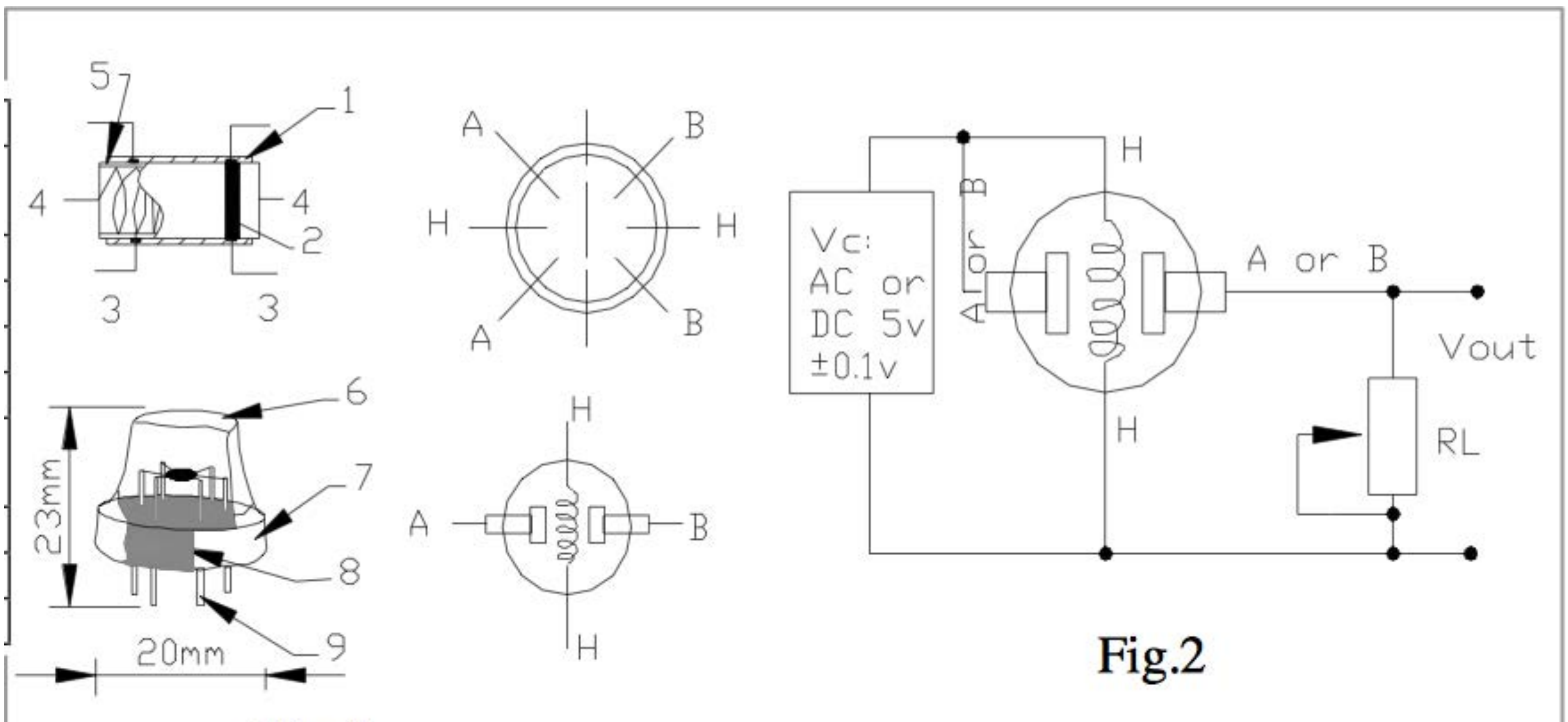


Fig. 1

Other Specs

SPECIFICATIONS

A. Standard work condition

Symbol	Parameter name	Technical condition
Vc	Circuit voltage	5V±0.1
V_H	Heating voltage	5V±0.1
R_L	Load resistance	can adjust
R_H	Heater resistance	33Ω±5%
P_H	Heating consumption	less than 800mw

C. Sensitivity characteristic

Symbol	Parameter name	Technical parameter	Remarks
Rs	Sensing Resistance	3KΩ-30KΩ (1000ppm iso-butane)	Detecting concentration scope: 200ppm-5000ppm LPG and propane 300ppm-5000ppm butane 5000ppm-20000ppm methane 300ppm-5000ppm H_2 100ppm-2000ppm Alcohol
α (3000/1000) isobutane	Concentration Slope rate	≤0.6	
Standard Detecting Condition	Temp: 20℃±2℃ Vc:5V±0.1 Humidity: 65%±5% Vh: 5V±0.1		
Preheat time	Over 24 hour		

Sensitivity

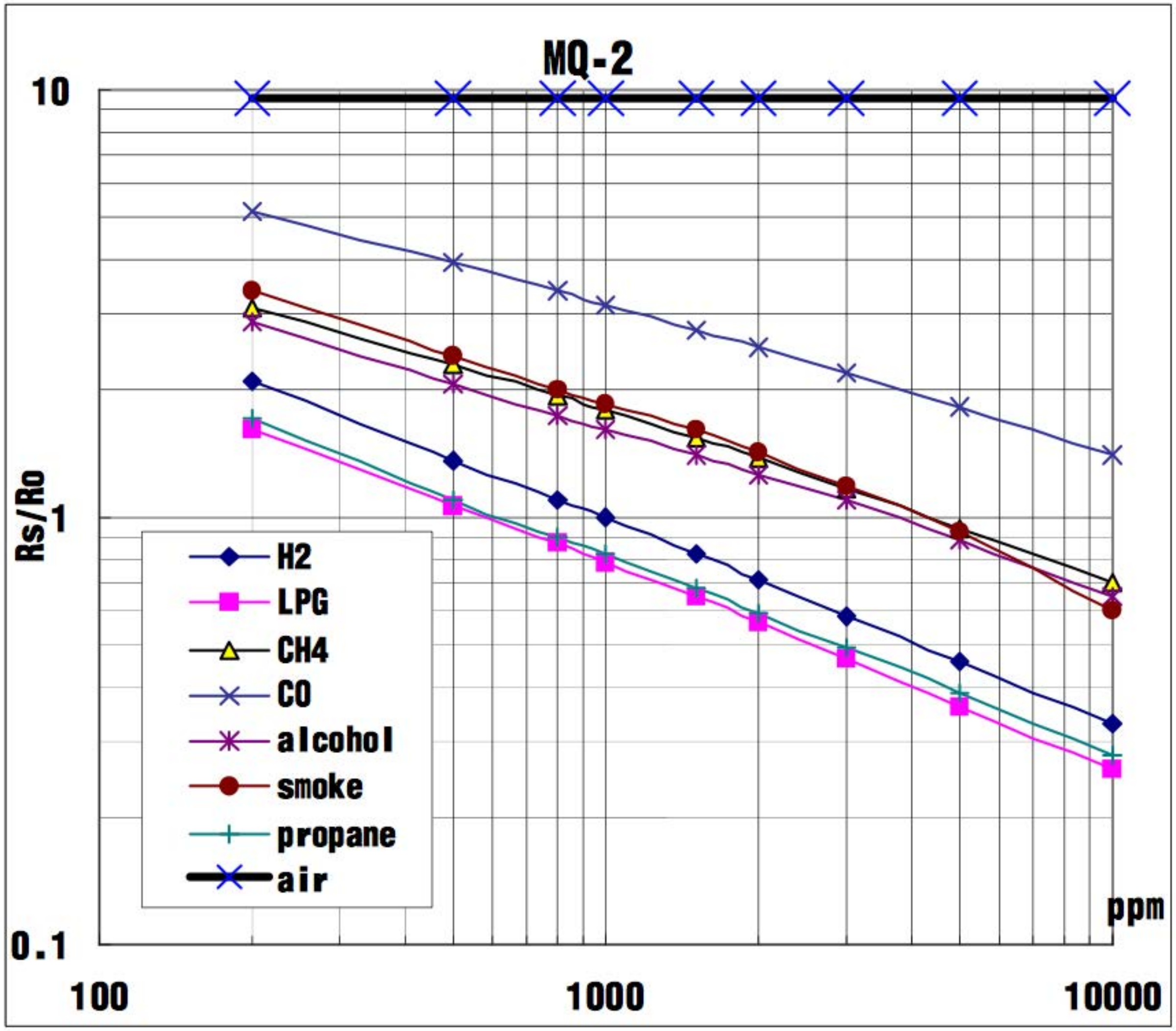


Fig.2 sensitivity characteristics of the MQ-2

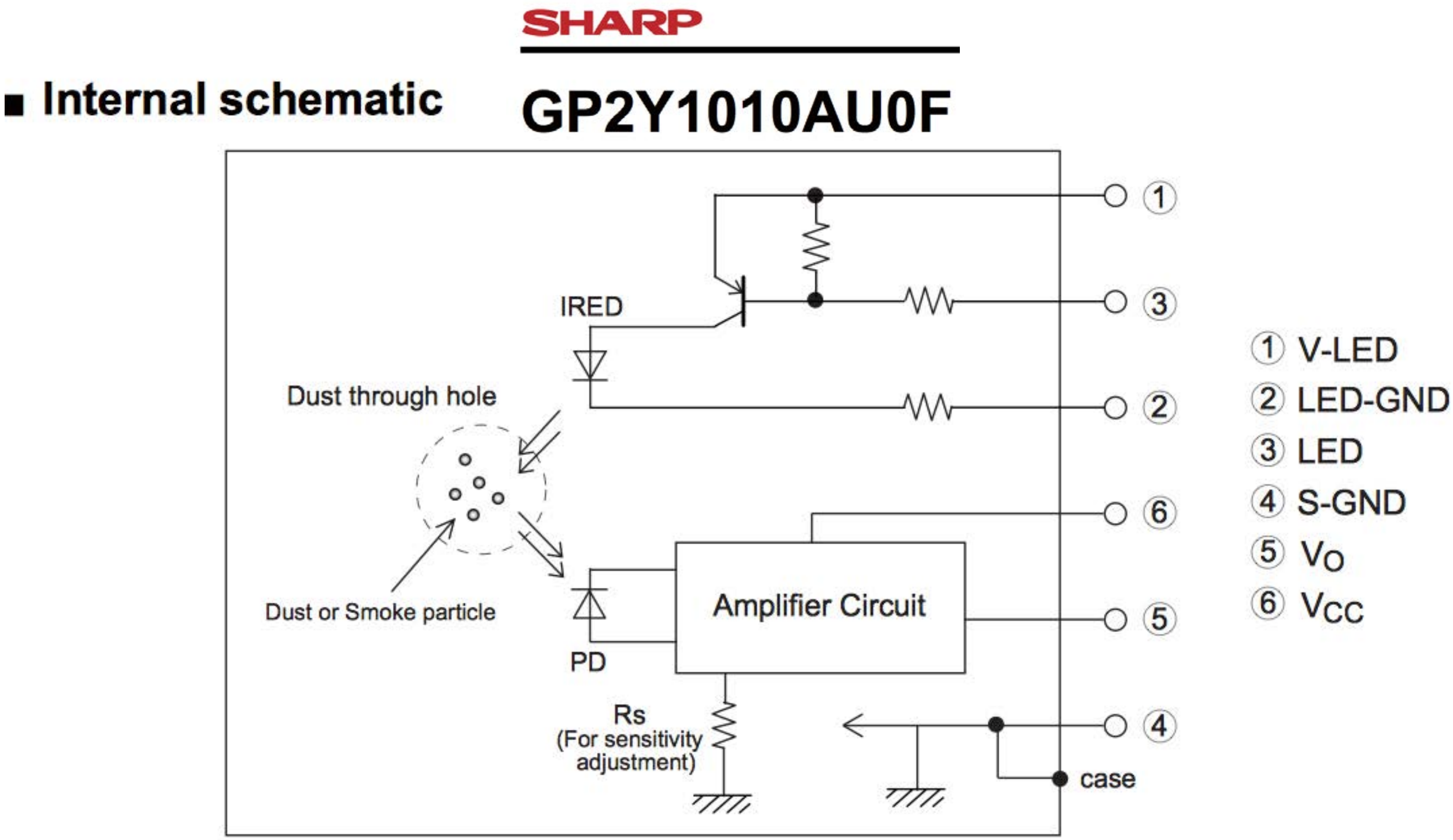
Power Calculations

- 5 V @ 800 mW = 160 mA.
- 5 V @ 33 Ω = 150 mA.
- Standard 9 V battery is ~250 mAh
  - Would last about 1 ½ hours
  - Separate battery for sensor and system.

Signal Conditioning

- Must get air to sensor.
- Resistance changes with gas concentration.
- Designed to work in voltage divider.
- Need R in range of approx. 3 kΩ to 30 kΩ.
- Need buffer amp.
- What is time constant?
- http://www.parallax.com/catalog/sensors/gas for more info

Example – Particle Sensor



Driving & Reading Circuits

Fig. 1 Input Condition for LED Input Terminal

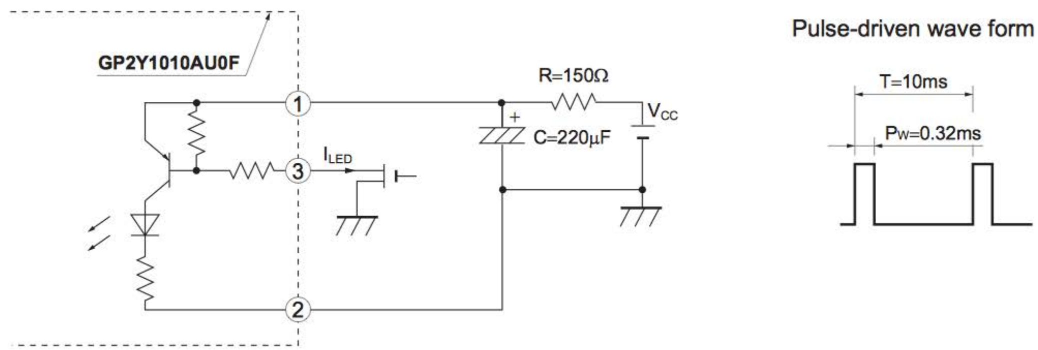
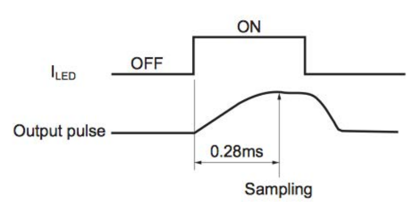
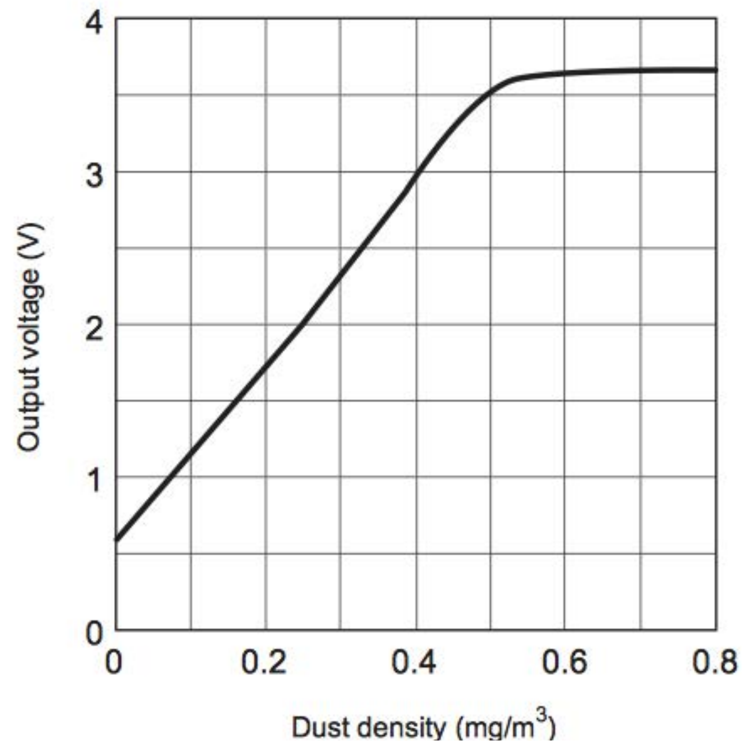


Fig. 2 Sampling Timing of Output Pulse



Output & Caution

Fig. 3 Output Voltage vs. Dust Density



10 Vibration influence

The sensor may change its value under mechanical oscillation. Before usage, please make sure that the device works normally in the application.

Driving Circuit

intersil *ICM7555,*

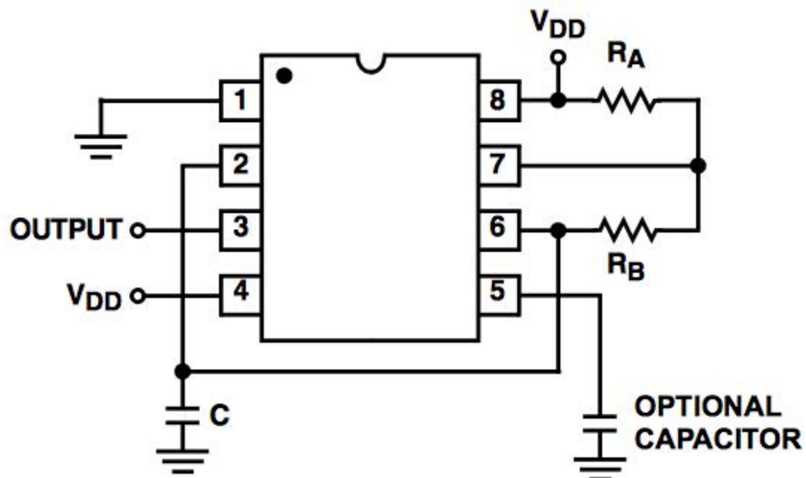


FIGURE 2B. ALTERNATE ASTABLE CONFIGURATION

The timer can also be connected as shown in Figure 2B. In this circuit, the frequency is:

$$f = 1.44/(R_A + 2R_B)C \qquad \text{(EQ. 2)}$$

The duty cycle is controlled by the values of R_A and R_B, by the equation:

$$D = (R_A + R_B)/(R_A + 2R_B) \qquad \text{(EQ. 3)}$$

Reading Circuit

- Pulse Width 0.32 ms
- Minimum 1 point
- Best 10 points
- Sample rate = 10/0.32 ms = 31.25 kSPS

Could You Do Better?

- IRED and Driver
- Photodiode & Reading Circuit
- Mechanical & Optical Chamber
- Start at http://en.wikipedia.org/wiki/Particle_counter for more information

Example – Humidity Sensor

- Check out Digikey
  - http://www.digikey.com/product-search/en?FV=fff4001e%2Cfff80274&mnonly=0&newproducts=0&ColumnSort=1000011&page=1&stock=0&pbfree=0&rohs=0&quantity=1&ptm=0&fid=0&pageSize=25
- Digital, I^2C – 18 s response time
- Capacitive – 15 s, 5 s response time
- Linear Voltage – 5 s response time

Digital, I^2C

- Need microcontroller, e.g., Arduino Pro Mini 328 - 3.3V/8MHz <Sparkfun>
- Power separately from data logger
- Must synchronize
- Must program

Capacitive

- How do you measure capacitance?
  - Put in a timer circuit
  - Put in an integrator
  - Put in a voltage divider

In a Timer Circuit

intersil® ***ICM7555,***

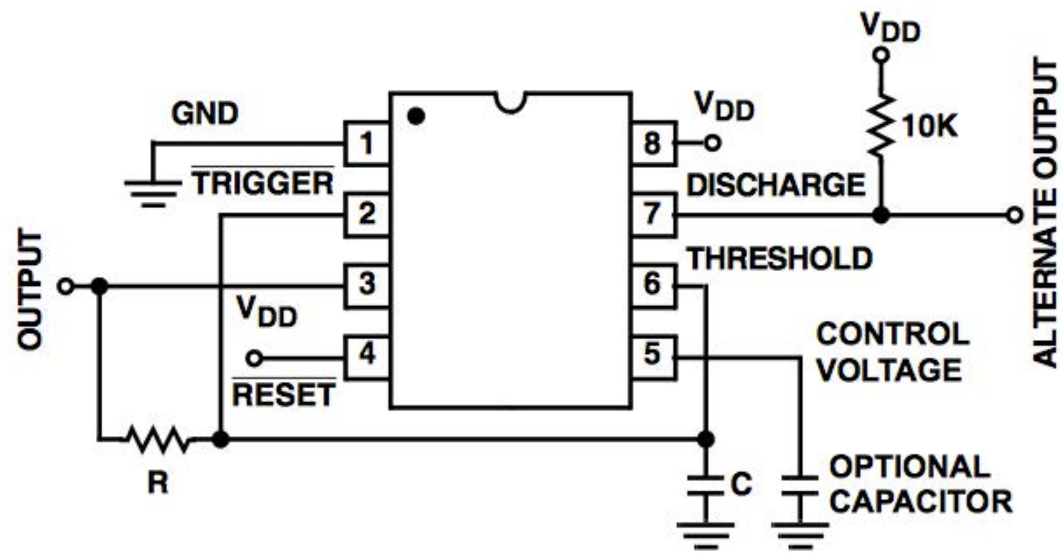


FIGURE 2A. ASTABLE OPERATION

$$f = \frac{1}{1.4\ RC} \qquad \text{(EQ. 1)}$$

Honeywell HIH-1000-002

HCH-1000 Series

Table 1. Specifications (T_A= 25 °C [77 °F], Input Voltage = 1 V_{RMS}, Frequency = 20 kHz)

Characteristic	Condition	Min.	Typ.	Max.	Unit
Normal capacitance	at 55 %RH	310	330	350	pF
Sensitivity	10 %RH to 95 %RH	0.55	0.60	0.65	pF/%RH
Humidity hysteresis	–	–	±2	–	%RH
Linearity	–	–	±2	–	%RH
Response time	30 %RH to 90 %RH	–	15	–	sec
Temperature coefficient	5 °C to 70 °C [41 °F to 158 °F]	0.15	0.16	0.17	pF/°C
Long-term stability (drift)	–	–	0.2	–	%RH/year
Operating temperature range	–	-40 [-40]	–	120 [248]	°C [°F]
Operating humidity range	–	0%	–	100%	RH
Operating frequency range	–	1	–	100	kHz

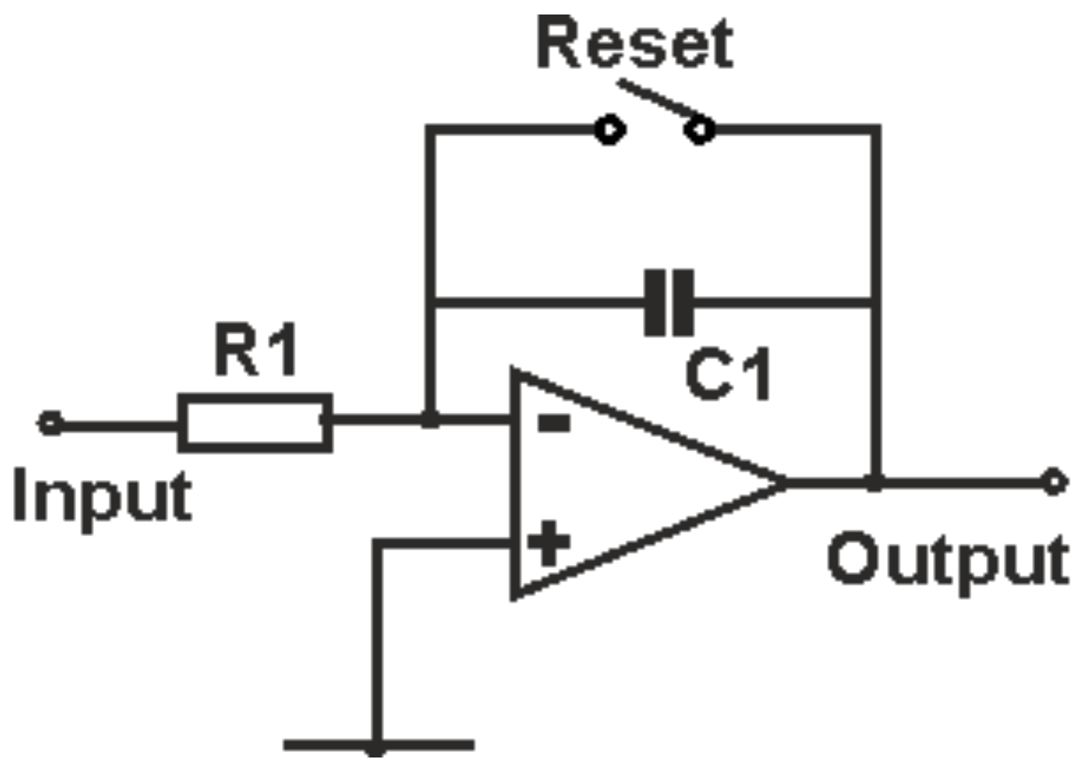
Measurement Calc's

R	200,000	Ω
C	330	pF
	3.3E-10	F
RC	0.000066	s
	66	µs
Angular Freq	15152	s^{-1}
Freq	2411	Hz

Sensitivity	0.6	pF/%RH
0% RH	297	pF
	2679	Hz
100% RH	357	pF
	2229	Hz
ΔF	450	Hz
ΔF/F	18.67%	Hz/Hz

The sample rate will need to be high enough to discriminate the frequency changes.

Integrator



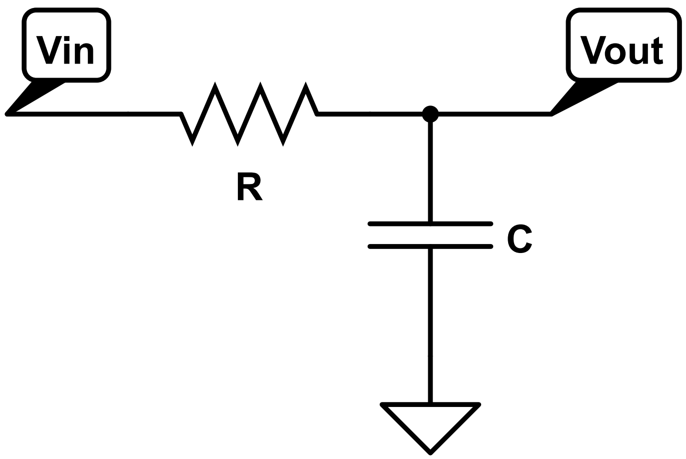
From: http://www.radio-electronics.com/info/circuits/opamp-circuits/operational-amplifier-integrator.php

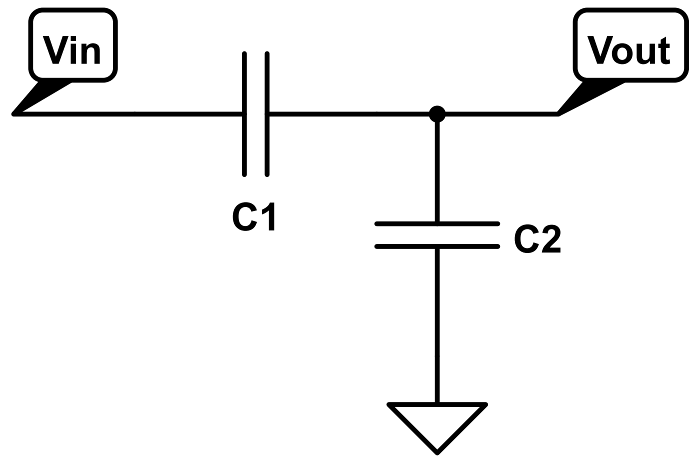
Issues

- Easiest input is constant voltage
  - Output is then a ramp
  - Calculate C from ramp slope or time to V_{set}.
- How control reset switch?
  - Solid State Relay
  - Signal Generator
  - Comparator

Voltage Divider

- Need sinusoidal input

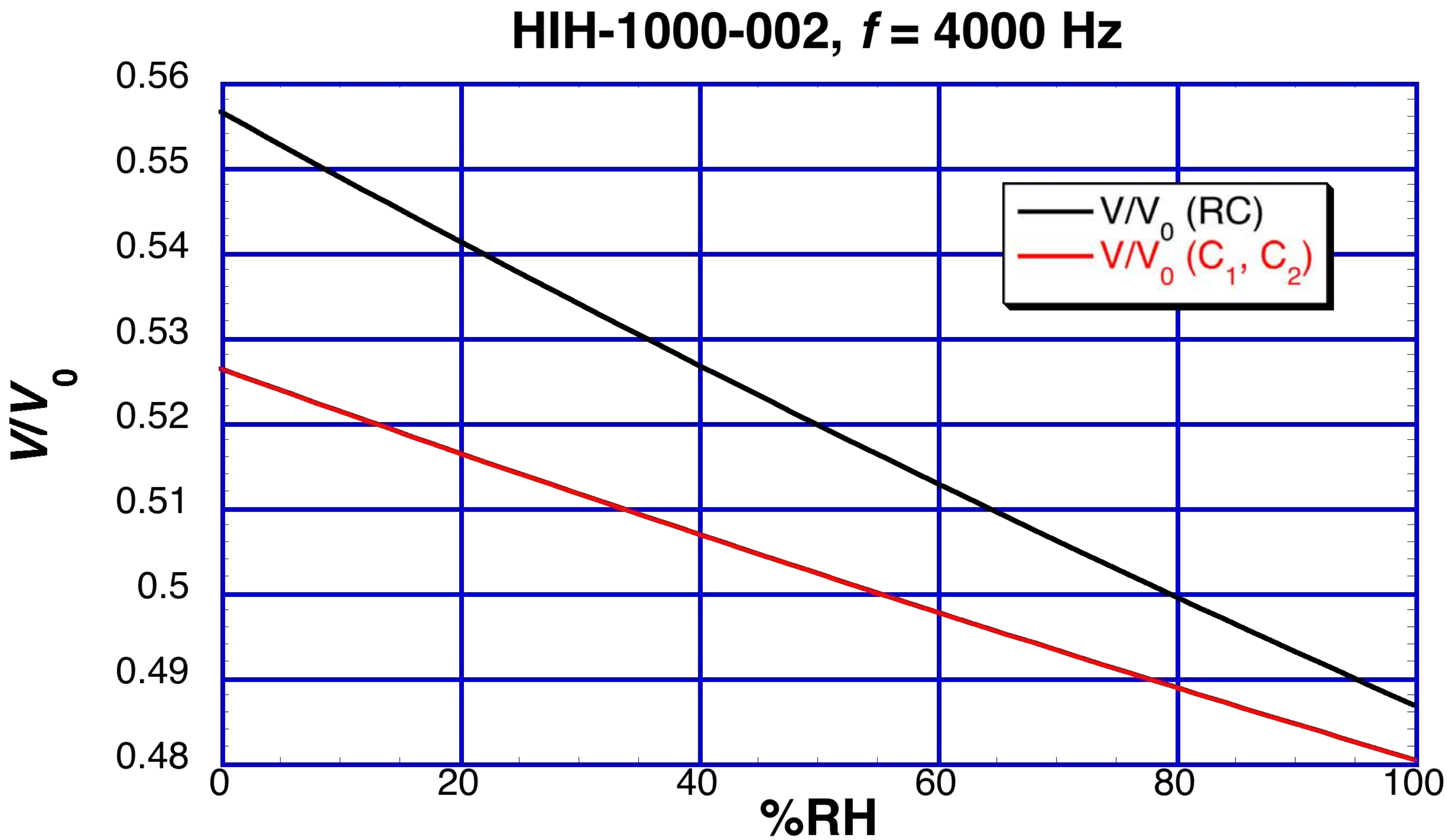




$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{1}{1 + jRC\omega}$$

$$\frac{V_{\text{out}}}{V_{\text{in}}} = \frac{\frac{1}{j\omega C_2}}{\frac{1}{j\omega C_1} + \frac{1}{j\omega C_2}} = \frac{1}{1 + {C_2}/{C_1}}$$

Voltage Divider Performance



How Do You Generate a Sine Wave?

XR-2206

EXAR *...the analog plus company™*

Monolithic
Function Generator

June 1997-3

FEATURES

- Low-Sine Wave Distortion, 0.5%, Typical
- Excellent Temperature Stability, 20ppm/°C, Typ.
- Wide Sweep Range, 2000:1, Typical
- Low-Supply Sensitivity, 0.01%V, Typ.
- Linear Amplitude Modulation
- TTL Compatible FSK Controls
- Wide Supply Range, 10V to 26V
- Adjustable Duty Cycle, 1% TO 99%

APPLICATIONS

- Waveform Generation
- Sweep Generation
- AM/FM Generation
- V/F Conversion
- FSK Generation
- Phase-Locked Loops (VCO)

GENERAL DESCRIPTION

The XR-2206 is a monolithic function generator integrated circuit capable of producing high quality sine, square, triangle, ramp, and pulse waveforms of high-stability and accuracy. The output waveforms can be both amplitude and frequency modulated by an external voltage. Frequency of operation can be selected externally over a range of 0.01Hz to more than 1MHz.

The circuit is ideally suited for communications, instrumentation, and function generator applications requiring sinusoidal tone, AM, FM, or FSK generation. It has a typical drift specification of 20ppm/°C. The oscillator frequency can be linearly swept over a 2000:1 frequency range with an external control voltage, while maintaining low distortion.

How Do You Generate a Sine Wave?

XR-2209
Voltage-Controlled Oscillator

EXAR ...*the analog plus company*™

June 1997–3

FEATURES

- Excellent Temperature Stability (20ppm/°C)
- Linear Frequency Sweep
- Wide Sweep Range (1000:1 Minimum)
- Wide Supply Voltage Range ($\pm$4V to $\pm$13V)
- Low Supply Sensitivity (0.1% /V)
- Wide Frequency Range (0.01Hz to 1MHz)
- Simultaneous Triangle and Squarewave Outputs

APPLICATIONS

- Voltage and Current-to-Frequency Conversion
- Stable Phase-Locked Loop
- Waveform Generation
  Triangle, Sawtooth, Pulse, Squarewave
- FM and Sweep Generation

GENERAL DESCRIPTION

The XR-2209 is a monolithic voltage-controlled oscillator (VCO) integrated circuit featuring excellent frequency stability and a wide tuning range. The circuit provides simultaneous triangle and squarewave outputs over a frequency range of 0.01Hz to 1MHz. It is ideally suited for FM, FSK, and sweep or tone generation, as well as for phase-locked loop applications.

The oscillator of the XR-2209 has a typical drift specification of 20ppm/°C. The oscillator frequency can be linearly swept over a 1000:1 range with an external control voltage.

Linear Voltage

Honeywell

HIH-5030/5031 Series

Low Voltage Humidity Sensors

DESCRIPTION

The HIH-5030/5031 Series Low Voltage Humidity Sensors operate down to 2.7 Vdc, often ideal in battery-powered systems where the supply is a nominal 3 Vdc.

The HIH-5030/5031 Series delivers instrumentation-quality RH (Relative Humidity) sensing performance in a competitively priced, solderable SMD.

Table 1. Performance Specifications (At 3.3 Vdc supply and 25 °C [77 °F] unless otherwise noted.)

Parameter	Minimum	Typical	Maximum	Unit	Specific Note
Interchangeability (first order curve)					
0% RH to 10% RH, 90% RH to 100% RH	-7	–	7	% RH	–
11% RH to 89% RH	-3	–	3	% RH	
Accuracy (best fit straight line) 11% RH to 89% RH	-3	–	+3	% RH	4
Hysteresis	–	2	–	% RH	–
Repeatability	–	±0.5	–	% RH	–
Settling time	–	–	70	ms	–
Response time (1/e in slow moving air)	–	5	–	s	–
Stability (at 50% RH in 5 years)	–	±1.2	–	% RH	1
Voltage supply	2.7	–	5.5	Vdc	2
Current supply	–	200	500	µA	–
Voltage output (1st order curve fit)	$V_{OUT}=(V_{SUPPLY})(0.00636(\text{sensor RH}) + 0.1515)$, typical at 25 °C				
Temperature compensation	True RH = (Sensor RH)/(1.0546 – 0.00216T), T in °C				
Output voltage temp. coefficient at 50% RH, 3.3 V	–	-2	–	mV/°C	–
Operating temperature	-40[-40]	See Figure 2.	85[185]	°C[°F]	–
Operating humidity (HIH-5030)	0	See Figure 2.	100	% RH	3
Operating humidity (HIH-5031)	0	See Figure 2.	100	% RH	–
Storage temperature	-50[-58]	–	125[257]	°C [°F]	–
Storage humidity	See Figure 3.			% RH	3

Specific Notes:

1. Includes stress outside of recommended operating zone.
2. Device is tested at 3.3 Vdc and 25 °C.
3. Non-condensing environment. When liquid water falls on the humidity sensor die, output goes to a low rail condition indicating no humidity.
4. Total accuracy including interchangeability is ±3 %RH.

General Notes:

- Sensor is ratiometric to supply voltage.
- Extended exposure to ≥90 % RH causes a reversible shift of 3 % RH.
- Sensor is light sensitive. For best performance, shield sensor from bright light.

Figure 4. Typical Output Voltage (BFSL) vs Relative Humidity (At 0 °C, 70 °C and 3.3 Vdc.)

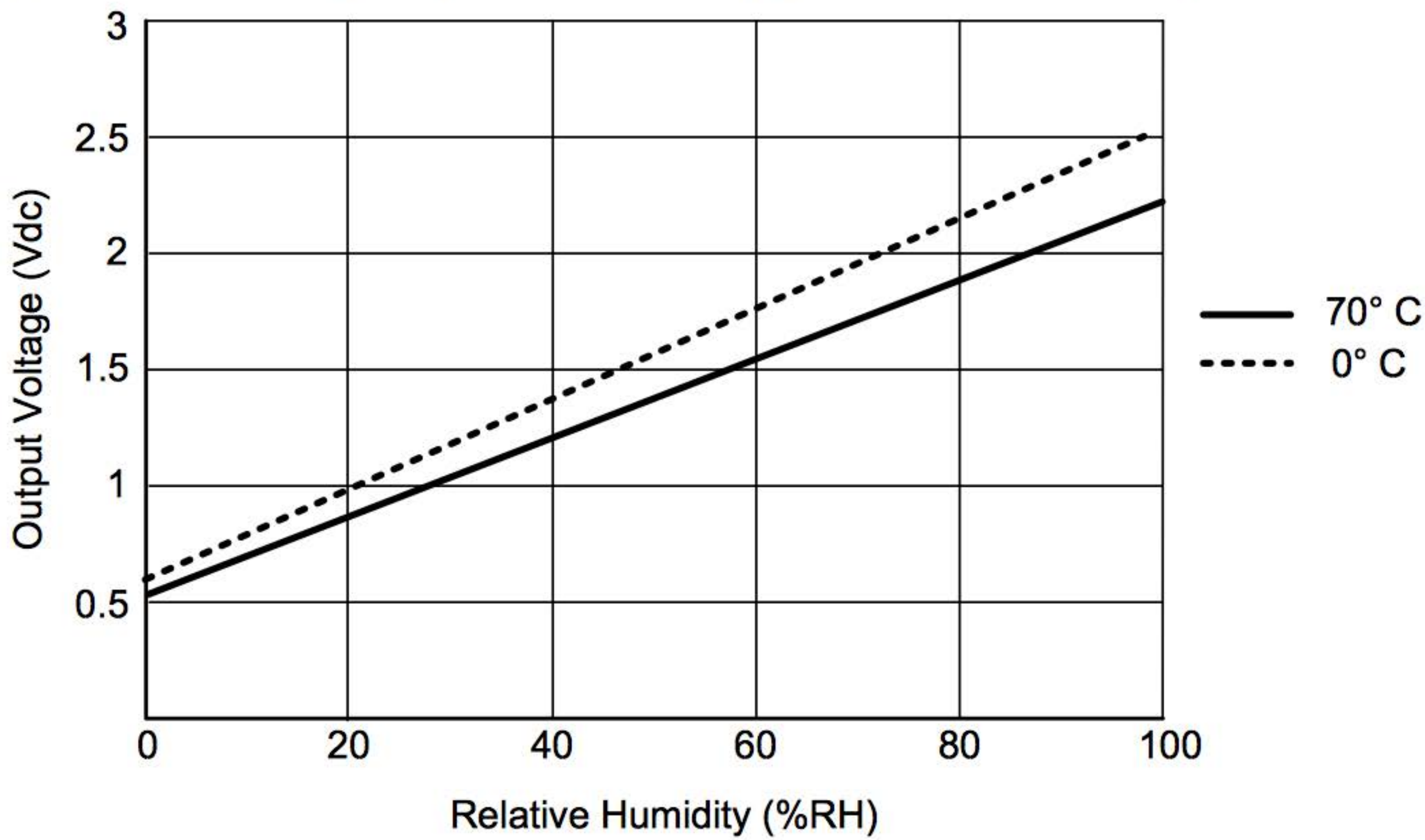
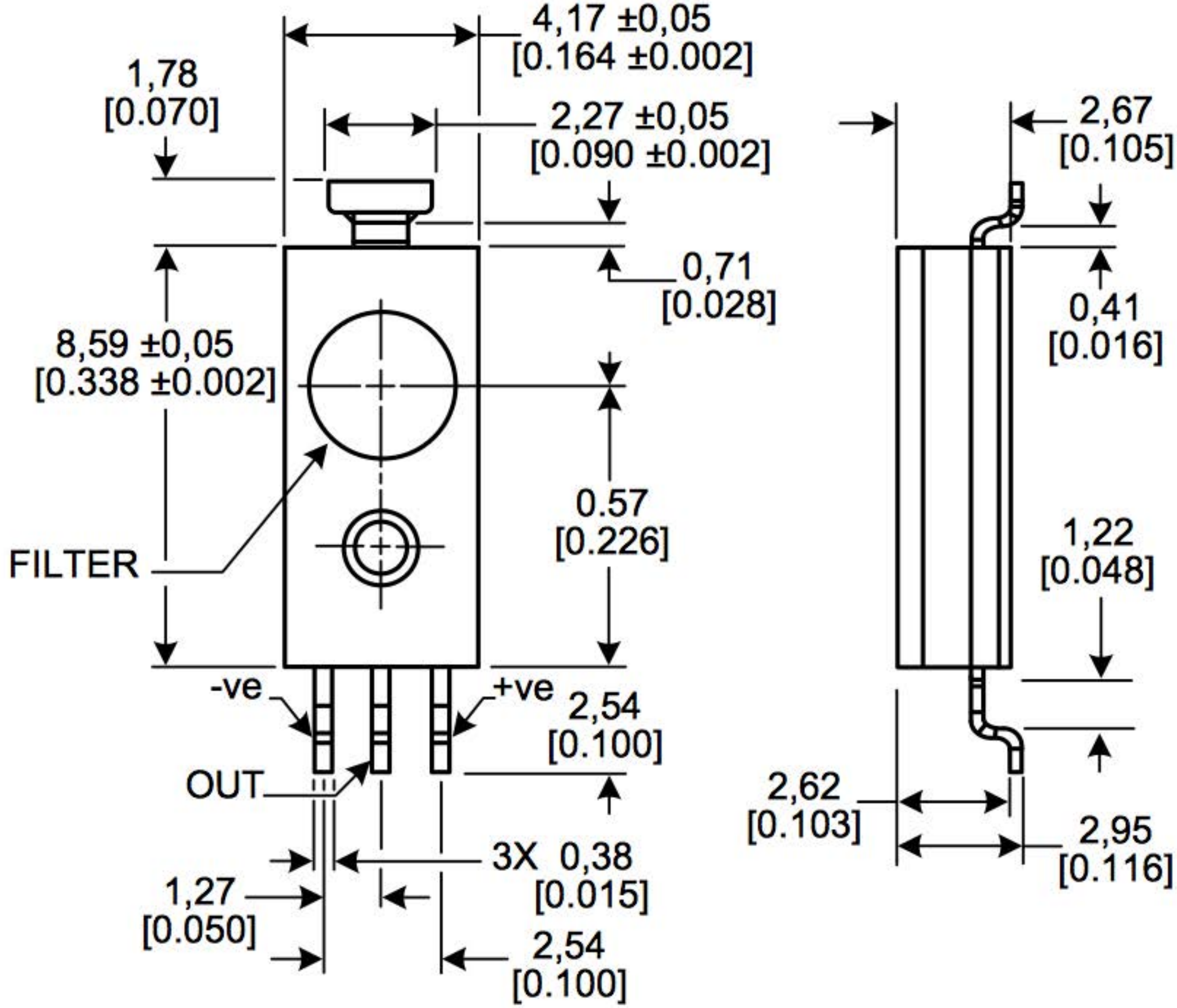


Figure 7. HIH-5031 Mounting Dimensions (For reference only. mm/[in])

The challenges are how and where to connect it, how and where to mount it, and how to get airflow over it.



Where to look for sensors

- Digikey: http://www.digikey.com
- Mouser: http://www.mouser.com
- Arrow: http://www.arrow.com
- Sparkfun: https://www.sparkfun.com
- Pololu: https://www.pololu.com
- Parallax: http://www.parallax.com