Alan Fisher's THERMAL SNOOPER

Original article by Alan Fisher, Huntsville, AL, July 28, 2009
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Figure 1 - A Thermal Snooper from the 1980s

This article first details the Thermal Snooper and then develops attributes and circuits for an improved, proposed Thermal Snooper II.

The article and Thermal Snooper has generally four major sections:

Sensor

A small silicone diode was exposed to the air stream. A small and constant forward current through the diode produced a small voltage across the diode. That voltage varies inversely with temperature.

Amplifier

A CMOS amplifier greatly amplified the small diode voltage changes and presented them to a threshold circuit.

Threshold Circuit

A threshold circuit determined what amount of amplified voltage change would cause a beep or boop indication.

Sounder Circuit

A sounder circuit turned beep and boop indications into a sound using a piezo-electric speaker.

SENSOR DIODE AND AMPLIFIER

The temperature sensor was a small silicone diode providing a rugged sensor. Most of the length of its leads were loosely coiled and exposed to the same air stream as the diode. A plated brass hood shaded these parts from direct sun light. A small and constant forward current through the diode produced a small voltage across the diode. That voltage varies inversely with temperature.

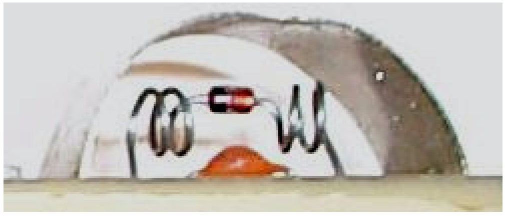

Figure 2 - Thermal Snooper sensing silicone diode

[The sensor and accompanying amplifier circuits are shown below:]

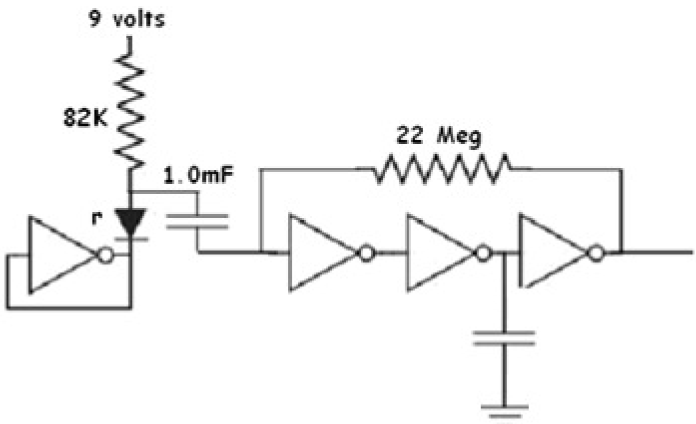

Figure 3 - Sensor diode circuit diagram

The four inverters shown are in a CMOS hex inverter CD4069UBE. The battery is 9 volts. The sensing diode is a 1N914 with a dynamic resistance of dE/dI = r. The values of "r" are calculated and shown later.

A CMOS operational amplifier could have been used but the CD4069 inverters were chosen for their simplicity and having six exactly matched ones on a chip.

When the input and output of such inverters are connected together, they come to a quiescent condition.

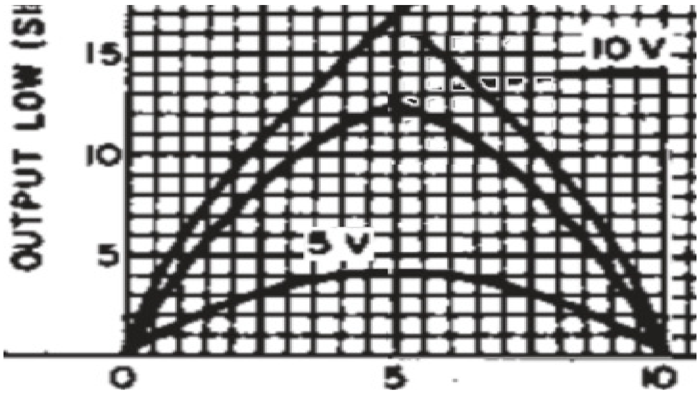

Figure 4 - Voltage/Current characteristics of the CD4096 inverter

This overlaid voltage/current characteristics of the CD4069 inverters show the quiescent condition for a ten-volt supply to be about 5.5 volts and 13 mA.

If the first two inverters share a common chip, their quiescent voltages are essentially identical so that the only voltage across the coupling capacitor is the small forward voltage of the sensing diode. At turn on, it is the charging of this capacitor that takes so long for the Snooper to settle down. That is the reason to minimize that voltage by sinking the diode's current to the quiescent voltage source instead of to the battery negative.

I am not sure exactly where, in the series of three inverters, the other capacitor was connected. I believe it was about 0.33 mF to limit the amplifier's gain above 1.0 kHz. That prevents high frequency oscillation of the amplifier.

Diode Temperature Relationship

[Now we calculate the value of dE/dI:]

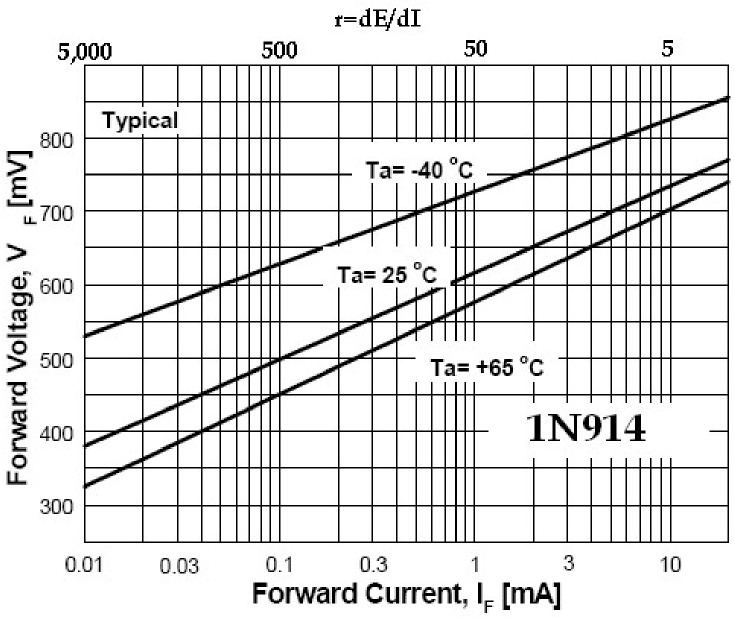

Figure 5 - Temperature relationship of the 1N914 diode

Calculating backward this indicates a sensor diode r = dE/dI = 1.11K caused by a forward current of 0.045 mA.

Replotting:

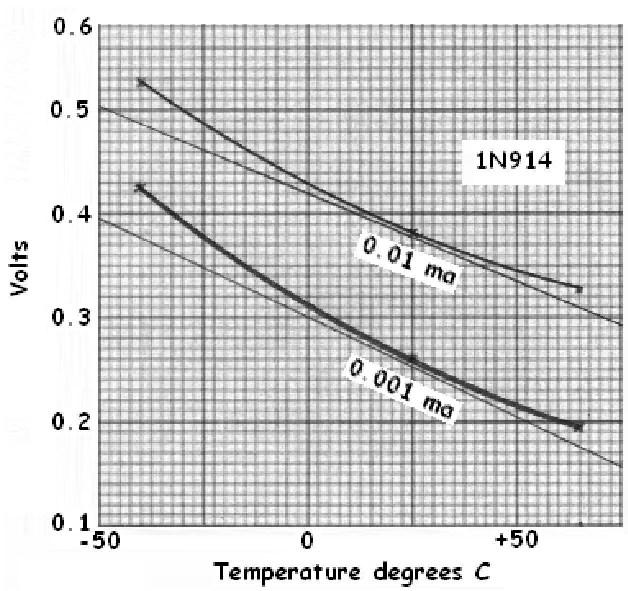

Figure 6 - Temperature and voltage relationship of the 1N914 diode

Calculating forward:

The above plot shows the diode's sensitivity to be 0.0020 volts/deg C, or 0.0036 volts/deg F.
0.0036 volts/deg F * 22,000K/1.11K = 71.4 volts/deg F comes out of the all-pass sensor amplifier.
1 / (71.4 volts/deg F) = 0.014 deg F/volt, or 0.007 deg F per 0.5 volt beep or boop.

But, the actual sensitivity is greatly reduced by two time constants. Firstly by the thermal time constant of the 1N914 diode and its coiled leads in the air stream. That has not as yet been measured, but is here assumed to be 1/3 second. Secondly by the time constant of the 1.0 mF input coupling capacitor and the r = 1.11K of the sensing diode. These cause a pass band with the following corner frequencies:

- Due to diode thermal time constant: $f_c = 1/[2\pi(1/3)] = 0.48$ Hz
- Due to 1.0 mF capacitor and r of 1.11K: $f_c = 1/2\pi(.00111) = 143$ Hz

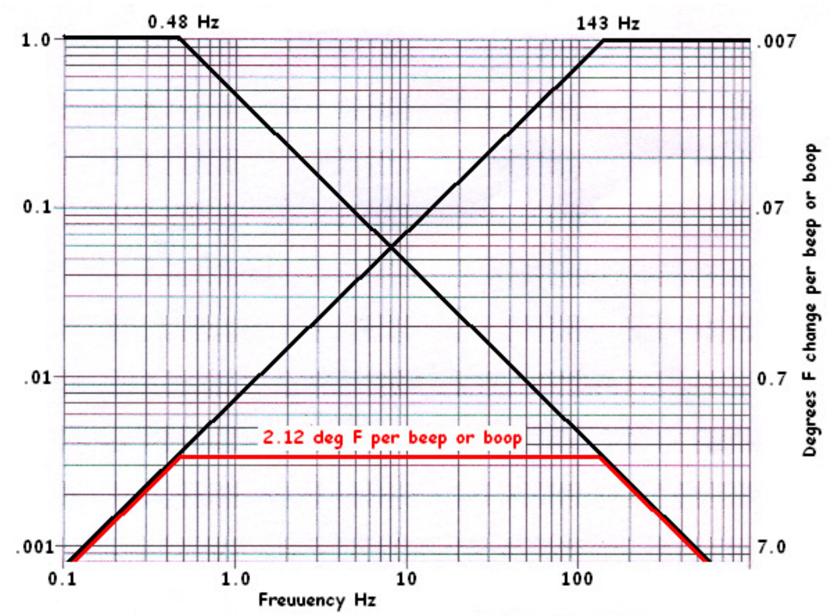

Figure 7 - Band pass and sensitivity of the sensor circuit

As may be seen, the actual sensitivity in the pass band is 2.12 deg F per beep or boop. When measured, if the thermal time constant of the diode is shorter than assumed, then the sensitivity will be greater. The actual response curve is asymptotic to the red lines and is 3-dB (0.707) down at the corner frequencies.

Looking at this log-log graph, note that a log-log square is formed. That is, the sensitivity is reduced by the same ratio as the corner frequencies. One is tempted to say let's reduce the diode current by a decade. That will increase "r" by a decade, to decrease the 143 Hz corner by a decade, to provide ten times the sensitivity. But that does not occur because the beginning sensitivity at the top of the graph is reduced a decade by the "r" in the amplifier gain calculation. The degrees per beep sensitivity is independent of sensor diode current.

Only increasing the 1.0 mF input capacitor or increasing or the 22 MΩ feedback resistor would increase the sensitivity out of this amplifier. Neither choice is desirable.

Open loop gain of each inverter

Much of the literature indicates a gain of 14 at 10 volts supply. However the gate transfer graph on a Harris data sheet shows a gain of 36. Those become 15 and 40 at 9 volts supply. An unloaded gain of 40 is closer to what I remember.

The intended closed loop gain in the above amplifier is 22,000K/1.11K =19,800.
153=3,375 not enough
403=64,000 enough

Thus the amplifier as I remember it would require the open loop gain of 40 for each inverter. So there is a big uncertainty here that needs to be measured. Use a 22 MΩ feedback resistor around a single inverter and a 600 Ω signal source producing no more than 4 volts peek-to-peak output. Then the ratio of the output to the input ac voltage is the open loop gain.

(But a diode current of 0.001 mA from a 3.9 MΩ resistor for an r=50K would work with the 15 gain. That results in a closed loop gain of 435 and a pass band from 0.48 to 3.2 Hz and the same sensitivity. Measuring the diode voltage on an operating Thermal Snooper with a oscilloscope will allow the current to be deduced.)

To be safe, I will use 15 as the open loop gain of each inverter in the sections that follow.

PREDICTING SIGNAL FREQUENCIES

The best method I could devise to forecast signal frequencies is shown in the following figure:

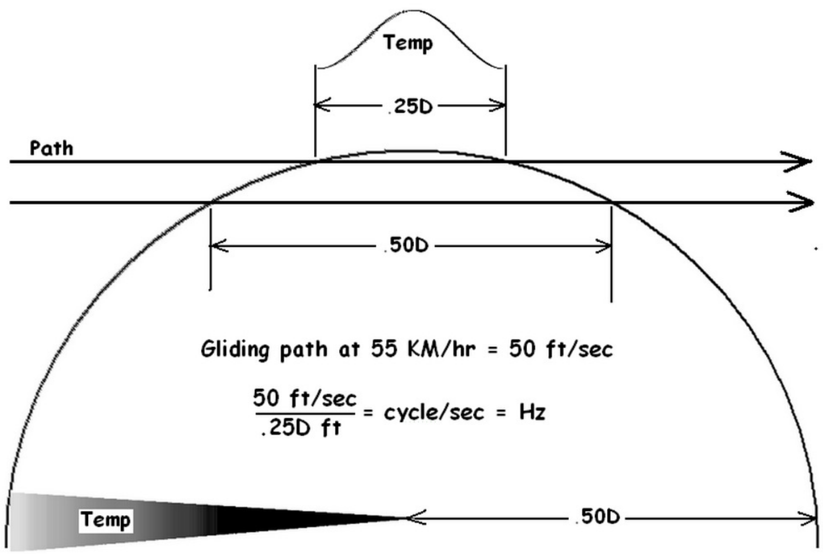

Figure 8 - Estimating Snooper frequency response needed when grazing various size thermals

The part circle shown represents the edge of an idealized thermal where the first detectable temperature rise occurs.

The lowest frequencies result from the biggest thermals and deepest graze. That is 0.2 Hz for D=500 ft and a .50D graze.
The highest frequencies result from the smallest thermals and shallowest graze. That is 0.8 Hz for D=250 ft and a .25D graze.

Thus for the idealized thermal, a snooper pass band from 0.2 to 0.8 Hz is indicated.   (The pass band of the Thermal Snooper instrument is thought to be about 0.5 to 3 Hz)

I estimate the thermal time constant for the diode sensor in the air stream is about 1/3 second causing a corner frequency in the snooper response of about 0.5 Hz. If that estimate is correct, it puts a corner frequency right in the middle of the desired pass band. So according to these forecasts, a compensating network in the amplifier is definitely needed.

MEASURUNG THERMAL SNOOPER SENSOR DELAY

The 1N914 sensor diode and its coiled leads require time to change temperature due to their thermal mass. The following test is suggested to measure that delay:

Provide a small forward current to the diode with leads coiled as in the Thermal Snooper. The ends of the leads should be fastened in an electrically insulated vise having a large thermal mass like the Snooper case. Or better yet, connect to the ends of the diode leads on an operating Snooper. Display the diode's forward voltage on a storage oscilloscope with very slow sweep. Turn on and adjust a variable speed hair drier to estimated hang gliding wind speed. Suddenly direct that hot air through the diode and coiled leads to record the delay on the oscilloscope.

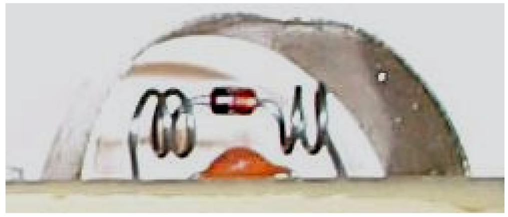

Figure 9 - Sensor head of the Snooper

This is what is expected: the change will be about 0.1 volts and “t” will be about 1/3 second.

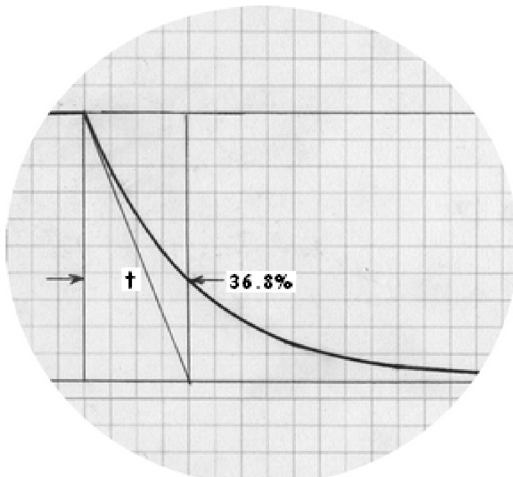

Figure 10 - Determination of change time

If the time constant “t” is significant to hang gliding sensing, compensation can be made for it in the response of a snooper amplifier. The corner frequency caused in the diode’s frequency response is: $f_c=1/(2\pi t)$

I would like to know the resulting time constant. A photograph of the response would be most helpful.

CAPACITOR AMPLIFIER WITH SWITCH / 0.5 VOLT DETECTORS

The capacitor amplifier is often called a charge amplifier. Here a switch establishes its starting charges.

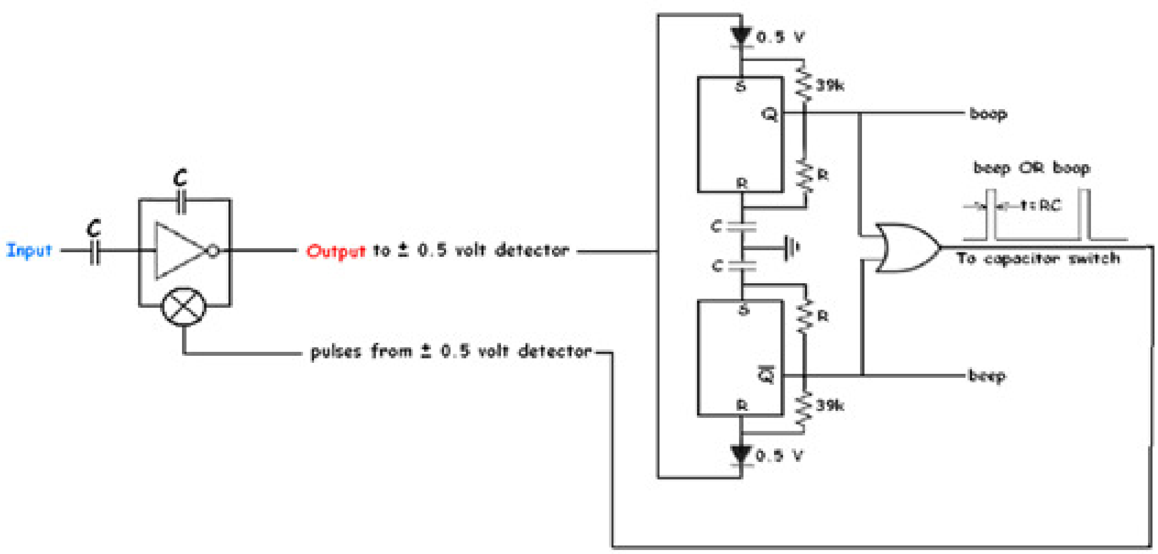

Figure 11 - Charge amplifier circuit

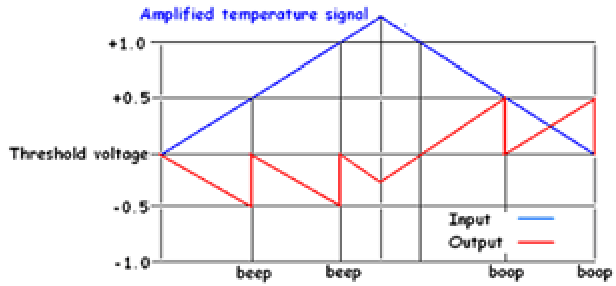

Figure 12 - Capacitor amplifier response

The (beep or boop) pulses from the ±0.5 volt detector cause the switch to connect the inverter output and input together for an instant. That forces both input and output to the threshold (quiescent) voltage and charges/discharges the capacitors accordingly. The result is shown in Figure 12. Thus, every 0.5 volt change in signal causes an indication. The switch is a CD4066 and the flip-flops are a CD4013 device.

SOUNDER CIRCUIT

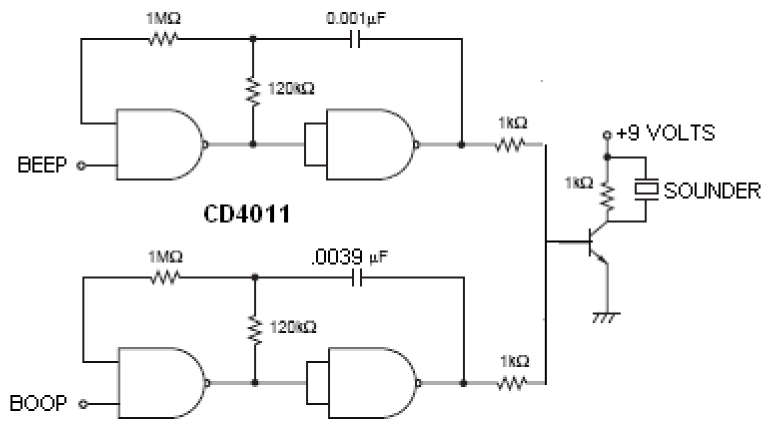

Figure 13 - Sounder circuit in the Snooper

The above circuits are from:
https://web.archive.org/web/20100602013135/http://www.murata.com/catalog/p15e6.pdf
Much information is available there about piezoelectric sounders.

DECENDING BETWEEN THERMALS

Decent rate is speed divided by glide ratio: 50ft/s / 20 = 2.5 ft/sec
Normal temperature change with altitude is: 0.0035 deg F/ft.
Resulting temperature ramp: 2.5 ft/sec * 0.0035 deg F/ft = 0.00875 deg F/sec

If snooper sensitivity is 0.5 deg F/ beep:
(0.5 deg F/ beep) / (0.00875 deg F/sec.) = 57 seconds per beep while descending.

Much more sensitivity would cause more frequent misleading beeps during such decent.

PROPOSED THERMAL SNOOPER II

In the preceding sections, the circuits and design of the Thermal Snooper have been documented and analyzed. (Some mostly minor errors were made in those articles.) Many aspects have now been looked into much deeper than when the original trial-and-error design was made. Thus good ideas for an improved Thermal Snooper II are at hand.

Several designs for the Thermal Snooper II have been nearly finalized and then rejected.

[This section has been reordered to present the proposed system in the same order as the original.]

Sensor and Preamp

If all the gain is put in the switched capacitor amplifier, the sensor diode may be directly connected to a unity gain preamp. Then the largest voltage the preamp must handle is the diode forward voltage, which will not saturate it.

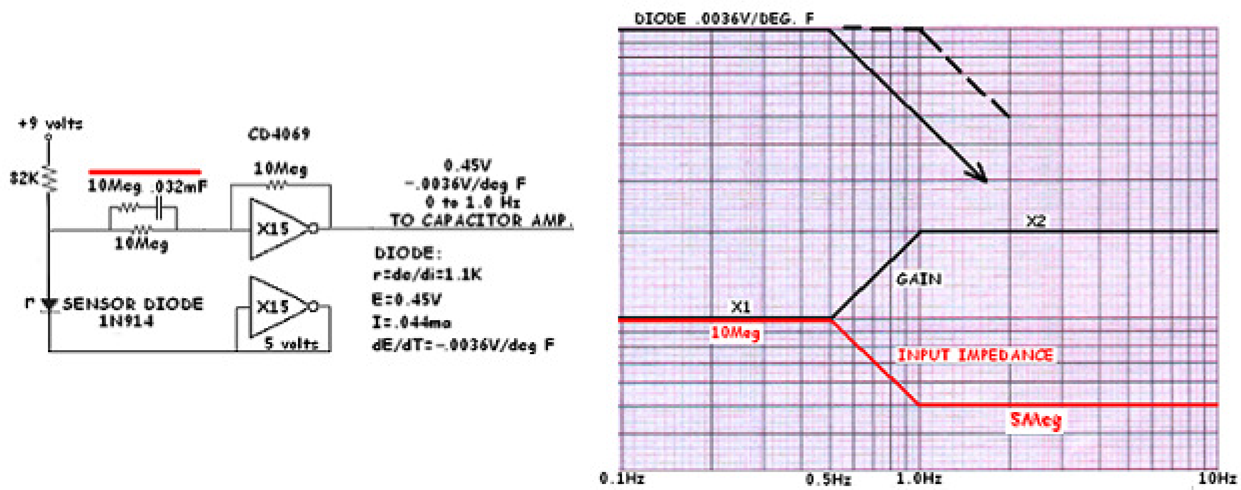

Figure 14 - Proposed Snooper II Preamp (left) and response (right).

The Preamp produces a step up in gain as shown in the graph. The rising gain from 0.5 to 1.0 Hz compensates for a sensor diode having an assumed thermal time constant of 0.32 seconds causing the 0.5 Hz corner frequency. When that time constant has been actually measured, the component values overlined in red will change somewhat. See section "MEASURUNG THERMAL SNOOPER SENSOR DELAY" for how to make that measurement.

With this compensation from 0.5 to 1.0 Hz, the result is a desirable flat pass band from 0 to 1.0 Hz. That is shown as dashed lines. (It is believed the pass band for the original Thermal Snooper was about 0.5 Hz to 3 Hz.)

All three 10 MΩ resistors may be 1.0 MΩ if the capacitor is changed to 0.32 mF.

(If you wish to use a CMOS operational amplifier for the Preamp, be careful. Most of them are unstable with a capacitance load.)

Charge Amplifier

A main problem was the large capacitor coupling the sensor diode signal to the amplifier. It was just not compatible with the very low signal frequencies predicted and also it caused a very long stabilization at turn on.

One interesting solution to that problem would use two matched sensing diodes and a differential amplifier. One of the diodes with coiled leads would be placed in the air stream and the other with short leads placed just below it and cemented with epoxy to the case. In the long term both diodes will come to the same temperature to cause no output from the differential amplifier. But due to the difference in the thermal time constants of the two diodes, the signals predicted for thermals would output from a compensated differential amplifier.

However a more elegant solution was recognized. If all the gain is put in the switched capacitor amplifier, the sensor diode may be directly connected to a unity gain preamp. Then the largest voltage the preamp must handle is the diode forward voltage, which will not saturate it. The following figure shows such a large gain capacitor amplifier:

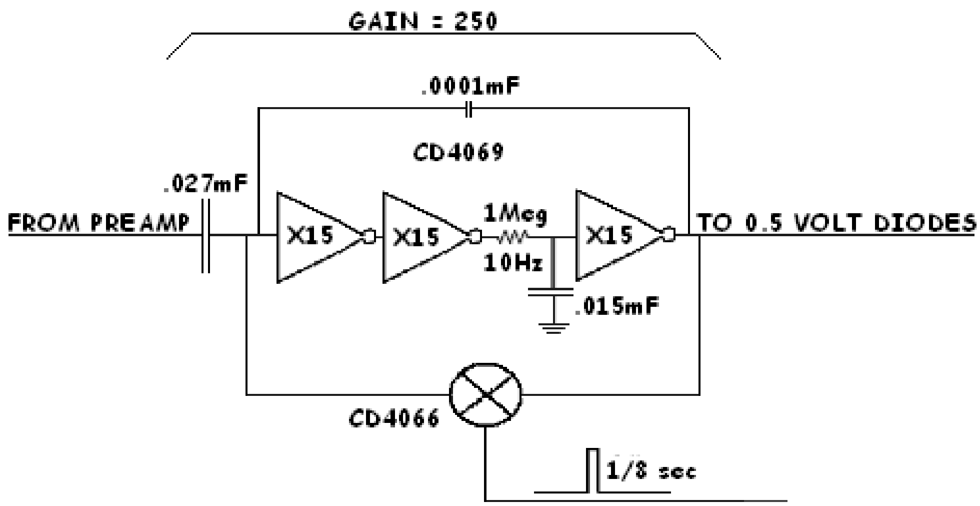

Figure 15 - Proposed Snooper II switched capacitor amplifier

The gain of 250 is calculated as follows:

$$\frac{1}{\left(\frac{0.0001}{0.027}\right)+\left(\frac{1}{153}\right)} = 250$$

The proposed preamp has unity gain. So the 0.027 mF capacitor is charged to the diode forward voltage the first time the switch is closed. Thereafter the output contains only changes in sensor diode voltage. Exactly what is desired!

The 0.0036 volts per deg F from the sensor diode becomes 0.90 volts per deg F out of the X250 amplifier. Inverting, that is 1.11 deg F per volt or 0.56 deg F per beep or boop with 0.5 volt thresholds. One half degree F per beep or boop is a great sensitivity. That is about four times more sensitive than the original snooper.

Refer to section “Threshold Detectors” for details of how the capacitor amplifier operates in conjunction with the 0.5 volt thresholds.

The 10 Hz RC filter should prevent high frequency oscillation as well as limit high frequency noise.

The capacitors need to be high quality stacked film types.

Threshold Detectors

Here is a preferred alternate circuit for the 0.5 volt detectors:

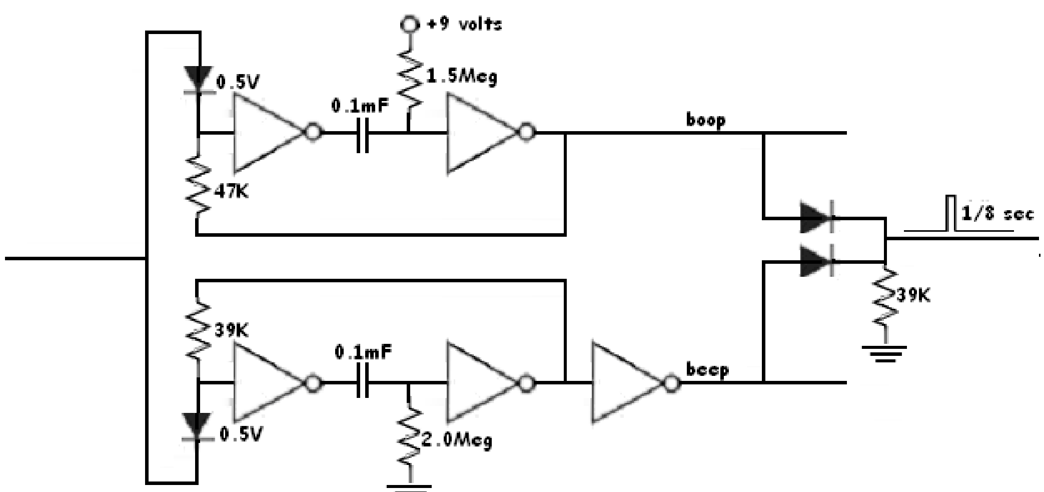

Figure 16 – Proposed Snooper II circuit for 0.5v detector

The diodes are 1N914's. If they perform as conceived, these Schmitt trigger circuits are better than the flip-flops in the original snooper circuit. For exact match of thresholds, the first inverters should be in the same CD4069 device as the capacitor amplifier inverter

If the third beep inverter is needed elsewhere, it may be replaced with an NPN transistor.

Sounder Circuit

Now for the beep OR boop circuits: [Editor's note: this did not change from the original, except for some discrete values]

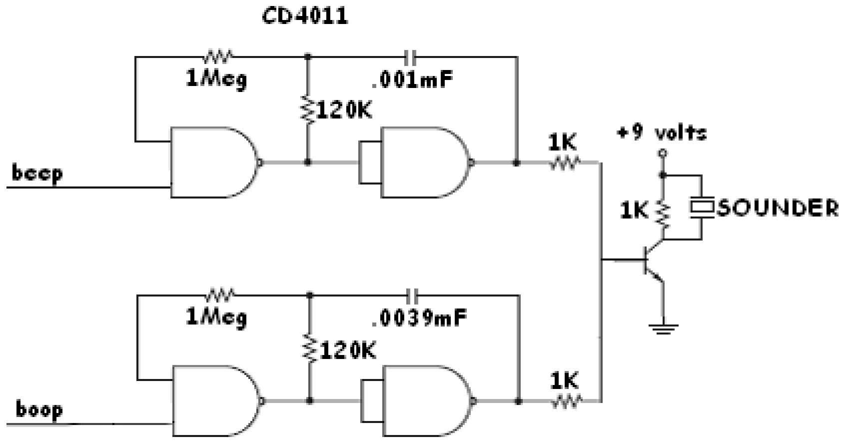

Figure 17 - Proposed Snooper II beep or boop circuit

The tone oscillators and sounder circuits were taken from:
https://web.archive.org/web/20100602013135/http://www.murata.com/catalog/p15e6.pdf

One should experiment with the capacitors at the NOR gates to find beep and boop tones that are pleasing and give a good sounder volume. The duration of the tones should be optimized also.

Summary

It is my hope that a capable individual or firm will produce this Thermal Snooper II.

- I do not wish any monetary return for my efforts.
- I will not fabricate it.
- I will freely offer advice and answer questions.
- Understand that the circuits presented in these articles are concepts and have not been proven to operate as conceived.

A prototype should be made and tested. Pilots who use the Thermal Snooper should do the testing. They can best judge if the improvements are real or imagined.

These schematic circuits, when combined, offer the following improvements over the original Thermal Snooper:

- Compensation for the thermal mass of the sensor diode.
- That allows a flat response to all signals predicted when grazing thermals.
- A high gain capacitor amplifier solves a basic design problem.
- Instant readiness at turn on.
- Four times greater sensitivity than the original Thermal Snooper.

Here is the combined schematic wiring diagram for the proposed Thermal Snooper II:

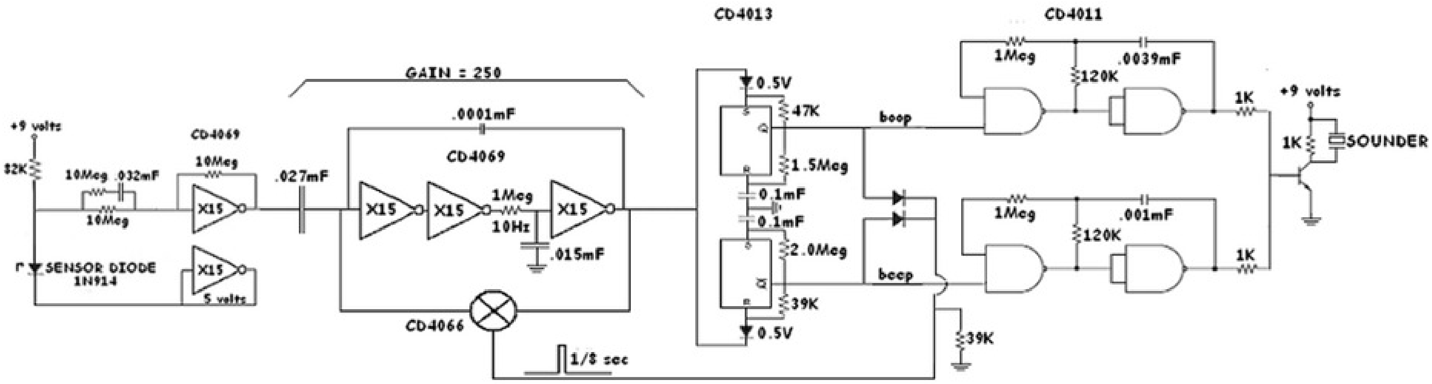

Figure 18 - Proposed Snooper II combined circuit [note: 0.5v flip-flop detectors from original circuit shown]

In order to better fit the schematic on one sheet, the flip-flop 0.5 volt detectors are shown instead of the Schmitt trigger 0.5 volt detectors that were proposed in Figure 16.

AFTERTHOUGHTS

Sounds

Beep/boop tone length and number of meaningful beeps and boops determine the highest usable signal frequency.

A good site to experience different tone lengths is:
http://www.dialabc.com/sound/generate/index.html?pnum=2567767272&auFormat=wavpcm8&toneLength=50&mtcontinue=Generate+DTMF+Tones
There you may listen to tone lengths of 300, 100 and 50 milliseconds. Try "0011".

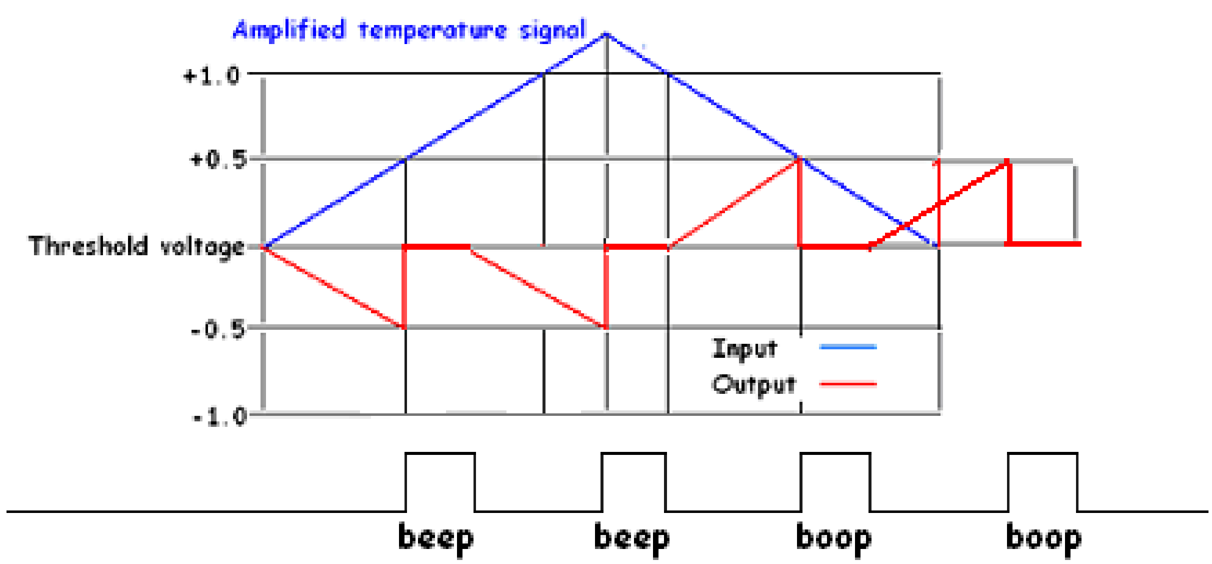

Figure 19 - Beep and boop determination

Choosing two beeps followed by two boops as the least meaningful indication:

That and a 100 millisecond beep/boop duration makes the above signal period 1 second or a 1 Hz pulse. So you see that with the beep/boop method of indication, a signal pulse much past 1 Hz is useless. If 50 millisecond beeps can be tolerated, then 2 Hz pulses may be recognized. But the signals predicted in "PREDICTING SIGNAL FREQUENCIES" were all less than 1 Hz. So the beep/boop signaling seems well suited to thermal detection.

Band Pass Filter Tuning

We have one inverter left over which may be used to either enable more sensitivity or increase the pass band. The following indicates more pass band is desirable.

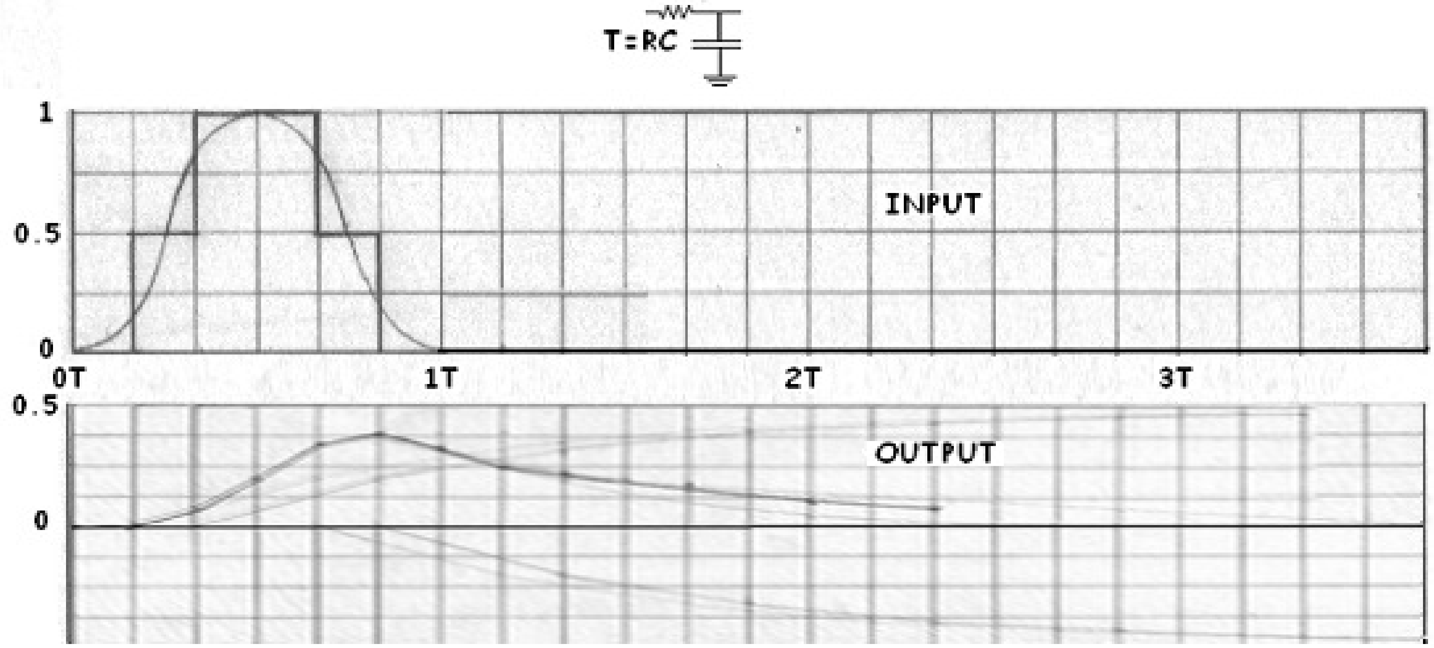

Figure 20 - Illustration of need for more band pass

I realize that the signals considered in these articles are not a single frequency but rather a raised cosine pulse like shown in the above figure.

This is a graphical solution for a raised cosine pulse applied to a low pass RC filter having the same corner frequency as the cosine. Make T=1 and this becomes the response of the proposed Thermal Snooper II to a 1 Hz raised cosine pulse. The output pulse rise is slower and the fall very much slower than the input. More importantly, the pulse amplitude is only four tenths of the input. This shows that the Thermal Snooper pass band needs to be greater than 1 Hz to better preserve the spectrum of a 1 Hz raised cosine pulse.

Let's try a band pass of 4.5 Hz. This is a crude graphical approximation, but it clearly indicates the advantage of increasing the band pass to 4.5 Hz.

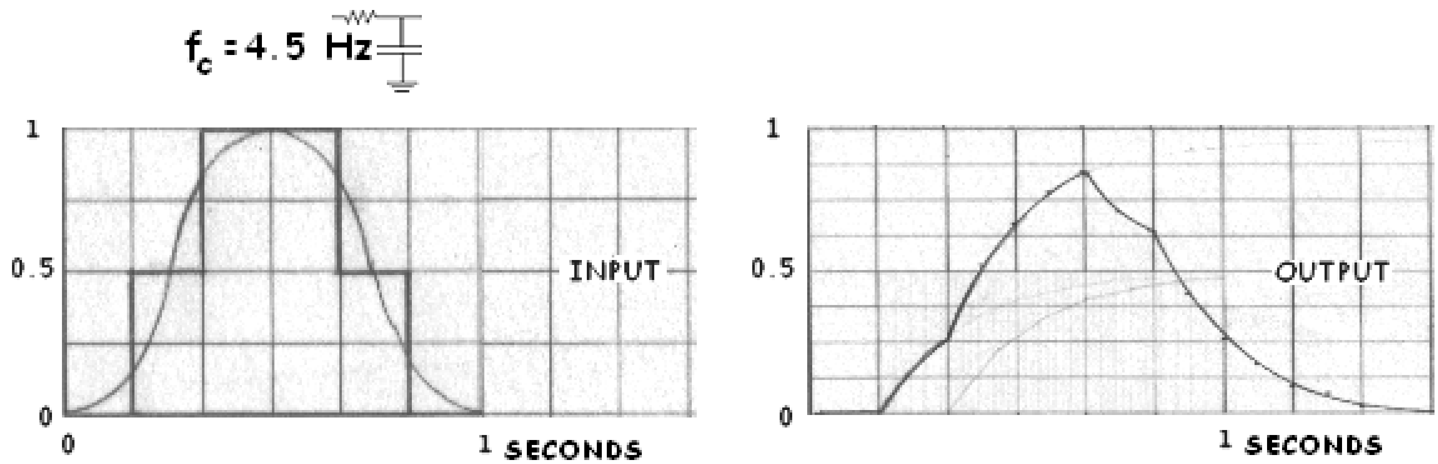

Figure 21 - Illustration of 4.5 Hz band pass

A 4.5 Hz Preamp

Based upon the above results, the extra gain should be used for diode thermal mass compensation to frequencies higher than the 1 Hz of the proposed Thermal Snooper II. Following is a Preamp that provides a pass band from 0 to 4.5 Hz. It is recommended the Thermal Snooper II use this better Preamp.

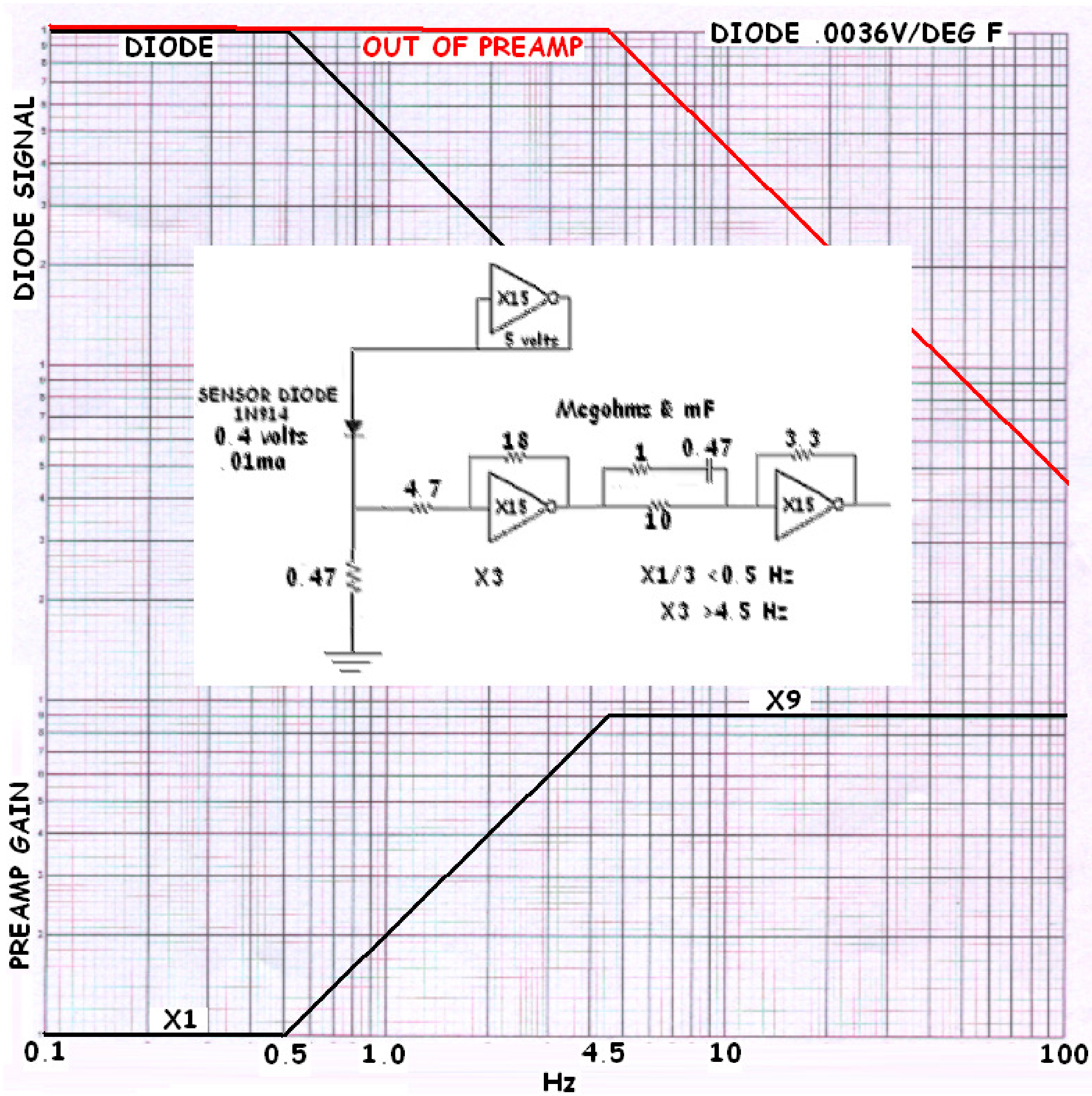

Figure 22 - New band pass recommended circuit values

As before, component values in the compensating network will need to be adjusted slightly once the thermal time constant of the diode is actually measured.

And should the open loop gain GOL of each inverter be more that 15, the input and feedback resistor values need to be recalculated to produce the desired closed loop gain GCL.

For the capacitor amplifier:

$$\frac{R_{IN}}{R_{FB}} = \left(\frac{1}{GCL}\right) - \left(\frac{1}{GOL}\right) \quad and \quad \frac{C_{FB}}{C_{IN}} = \left(\frac{1}{GCL}\right) - \left(\frac{1}{GOL}\right)$$

OPEN SOURCE FEEDBACK

July 28. 2009

For my day job I do temperature stabilization of diode lasers. The device shown [here] achieves well below single mK level. Based on this experience, I'd recommend the following:

1. Use a thermistor rather than a diode as temperature sensor. These devices are made for the purpose. A value of 10 kOhm should be fine.
2. Create the reference voltage that is applied across the sensor with a REF02, rather than simply take the general supply.
3. The version 2 idea to measure the difference of identical two-sensors in different thermal environment seems good to me.
4. Put the sensors in a wheatsone bridge. This minimizes the effect of variations in the reference voltage.
5. Use a resistor array for the reference resistors in the wheatstone bridge. Glue the array to a piece of aluminum. This minimizes errors due to temperature differences of the reference resistors.
6. Use a decent instrumentation amplifier to evaluate the wheatstone bridge. These devices are made for the purpose. LT1167 may be a reasonable choice. Using inverters for linear amplification is a hack.
7. No amplification stage should amplify more than about 100. Use more stages if more amplification is needed.
8. Use low offset, low drift opamps for the amplification stages. The classical choice would be OP07, which affordable, too.
9. The largest resistor value in the circuit should be 100 kOhm. With multi MOhm values, the Johnson noise of the resistors becomes a problem.
10. Use comparators to decide whether to beep, or boop, or fall silent. Again, these devices are made for the purpose. I'd choose the LM393.
11. Put the circuit in a rugged aluminium enclosure. E.g. Hammond 1590BB

Seems to me, that the temperature measurement hardware is the easy part. The real challenge is to evaluate the data in terms of decision making. Is a sudden increase in air temperature good, or bad, or what? Maybe other data should be taken into account. Has there been any flights with the snooper and vario logged in parallel?

---<kaimartin>---