Introduction

The Force Balance Broad Band vertical seismometer was designed to provide an excellent balance between cost/complexity and performance. Its mechanical design is relatively simple and rugged and can be duplicated by anyone who has some basic metalworking equipment and the skill to use it. The electronics are contained on a single PC board using a circuit which is adequate to give excellent performance, though no more complex than required.

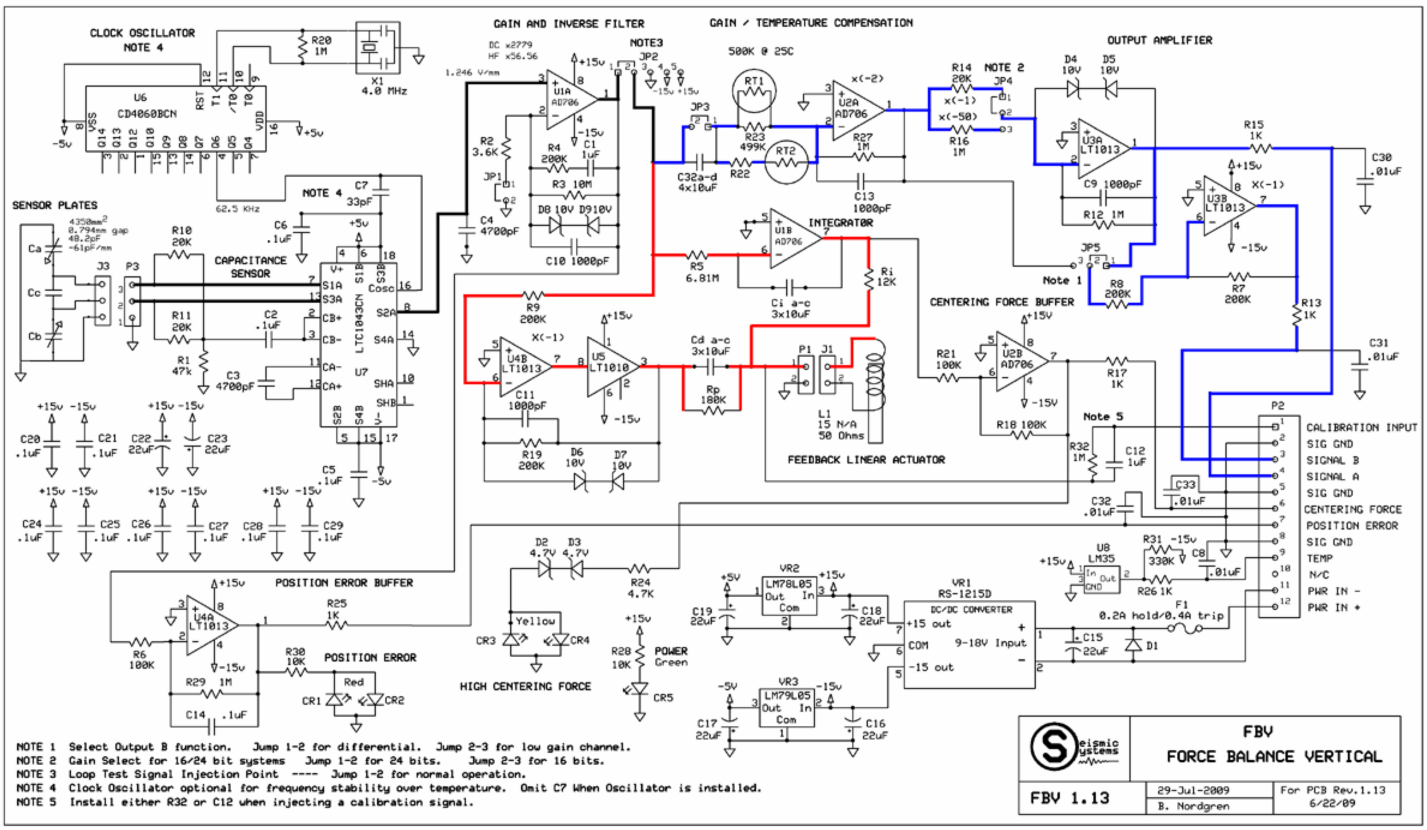
The mechanical design uses an astatic spring configuration, but unlike the most elegant commercial instruments the spring is made from stainless steel rather than from an exotic low TC of Elasticity alloy. This means that the instrument response to the rate of temperature change will be perhaps 10x larger than the best sensors of equivalent bandwidth, but still quite reasonable. In addition, by removing a jumper, the output can be passed through a 1/125 Hz single-pole high-pass filter, which will hide essentially all temperature variation effects. In addition the design is such that it should not need to be mechanically re-balanced over its full operating temperature range.

The internal noise of the FBV is somewhat higher than the expensive commercial verticals, but in all but the quietest locations will not be seen above the seismic background. Side-by-side tests against a high quality instrument (Trillium 40) show virtually identical waveforms, both when displaying seismic background signals as well as larger seismic events.

The mechanical elements are designed to be field-reparable, requiring only tools which can be obtained at any small hardware store. And all parts, mechanical and electronic are readily constructed or are available from on-line sources.

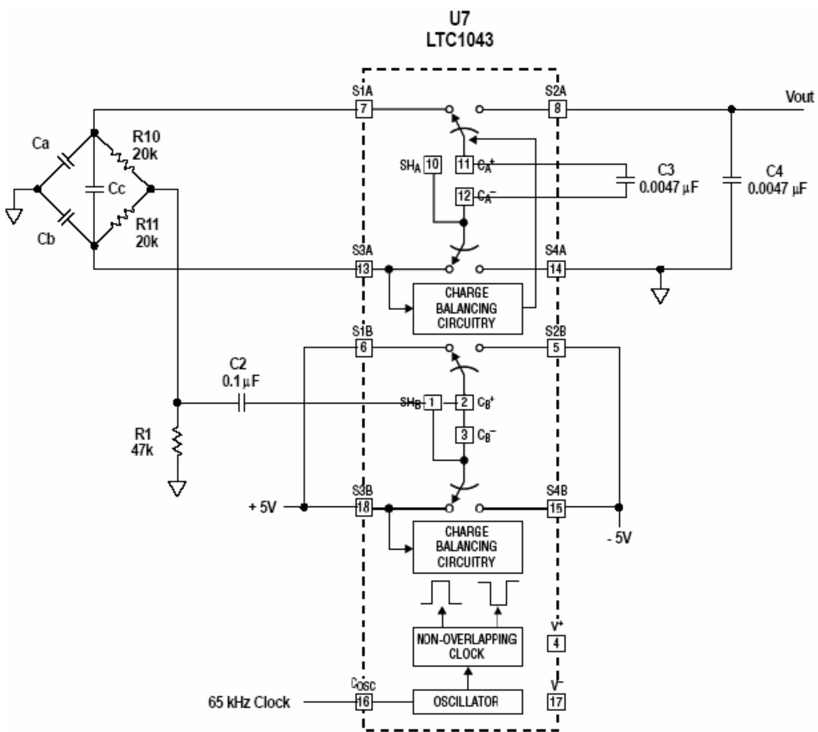
Circuit Overview

Following is an overview schematic which shows the major signal paths. The heavy black lines trace the forward, ‘A’, portion of the loop, starting at the capacitive position sensor and ending at the output of the feedback loop. The red lines trace the feedback branches of the loop, the ‘B’ path, starting at the loop output and ending at the force feedback coil. The blue lines trace the signal from where it exits the loop, through several stages of amplification to the output terminals.



Capacitive Sensor

The capacitive sensor consists of two sensor plates, copper foil layers, on opposite sides of a stationary printed circuit board. Above and below the PC board are two moving, grounded plates which form capacitors Ca and Cb, and which change value as the moving plates change position. As the boom moves up, Ca decreases in value while Cb increases. The difference in capacitance is detected and amplified by U7 and its associated circuits. Cc is a stray capacitance of about 130 pF formed by the circuit board dielectric between the driven electrode plates of Ca and Cb.

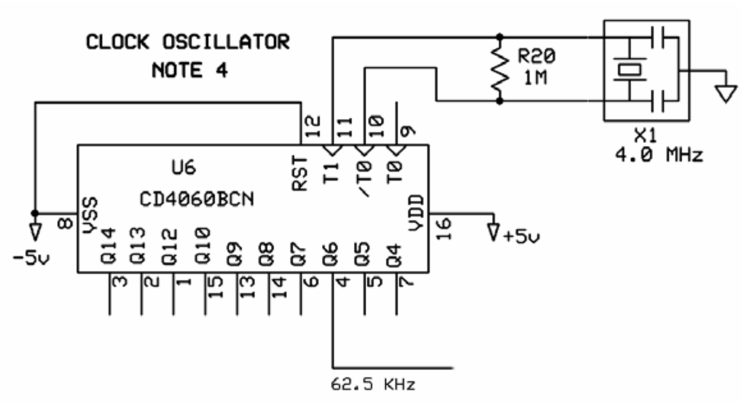


The area of each capacitor plate is approximately 4350 mm^2 and when centered, their separation from the grounded plates is about 1/32" or 0.79mm, making the capacitance of each about 48.2 pF. As the boom moves a small distance from its rest position, the capacitor values change at a rate of 61pF/mm of motion, one increasing and one decreasing, though in practice, with feedback active, that motion will only be few micrometers or even less.

Although Ca, Cb, R10 and R11 may be viewed as a bridge circuit, they are more easily analyzed as a switched-capacitor, charge transfer problem. U7, via C2, R10 and R11, applies a 62.5kHz, 5V peak square wave to both Ca and Cb. Each half cycle of 8.0 μs is sufficient to fully charge Ca and Cb. But if their values are slightly different, on the positive half cycle there will be a small difference in the charge transferred to each, and therefore a small net charge gets transferred to C3. On the negative half cycle a portion of that charge is transferred to output capacitor C4.

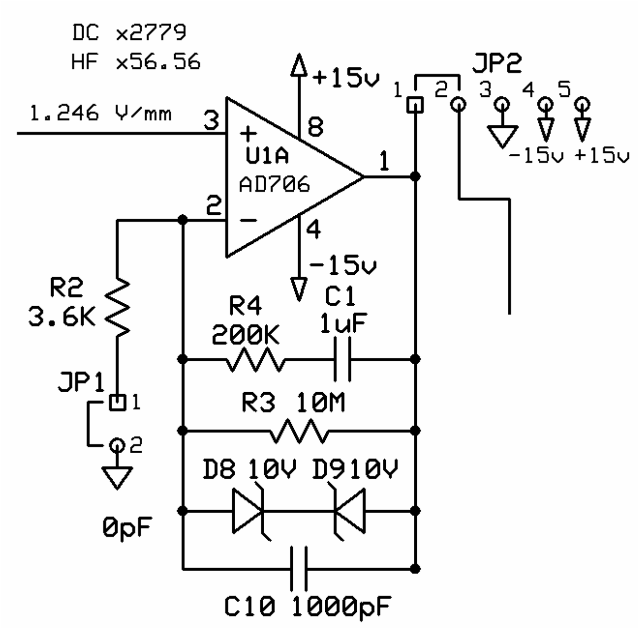
The result is that any unbalanced capacitance creates a voltage across the output capacitor of about 1.3V per mm of sensor motion. The 62.5kHz clock frequency and the capacitor values used, result in a transfer function pole having a time constant of about 0.52ms, representing a frequency roll off at 306 Hz.

External Clock



Since the gain of the sensor circuit is proportional to frequency it is desirable to maintain close control of the clock frequency. Therefore provision was made to install a higher stability clock in place of the LTC1043 internal oscillator. The clock is obtained by dividing down a 4MHz ceramic resonator to obtain the 62.5kHz signal.

Gain and Inverse Filter

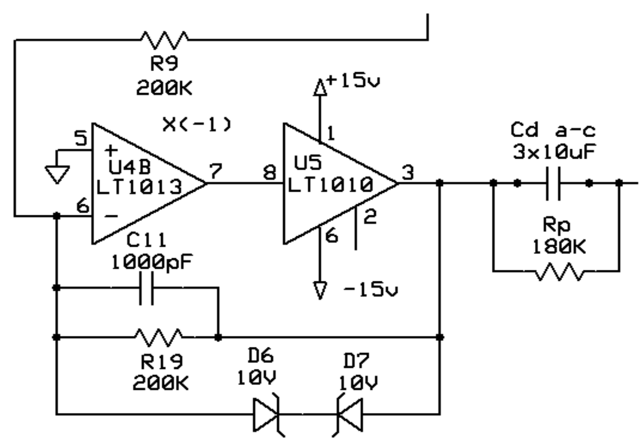


Amplifier U1A provides the remainder of the gain in the forward-directed portion of the feedback loop. This is a frequency-shaped, high-stability amplifier, providing a gain of 56.6 at all frequencies of interest, with an additional gain at DC of 49, making the DC gain equal to 2779. At a frequency of about 0.016 Hz the gain begins to fall, leveling out again at about 0.8 Hz. This frequency characteristic has been called the 'inverse filter' and it is designed to compensate for the loss of loop gain at the low end of the instrument operating band due to the falling velocity response of the spring portion of the spring-mass, with decreasing frequency.

Jumper JP1 may be removed to reduce the amplifier gain to 1 for testing and adjustment purposes.

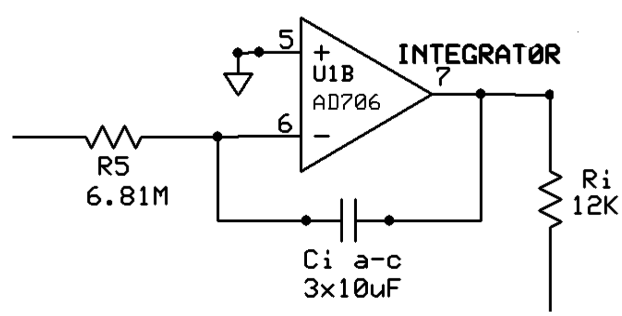
Jumper JP2 is used to provide an insertion point for a test signal, applied in such a way that the loop can still remain active. After removing the 1-2 jumper a plug can be installed on JP2 to connect and power a test adapter which consists mainly of an instrumentation amplifier.

Derivative Inverter-Buffer



In order to match the signal polarity of the integrator, the signal to the Derivative and Proportional branches is inverted by U4B and U5. Buffer U5 is needed in order to properly drive the derivative capacitor Cd in series with L1, the Feedback Linear Actuator coil, which, at 50Hz represent a combined load impedance of 117 ohms– too low to be directly driven by an ordinary op-amp output.

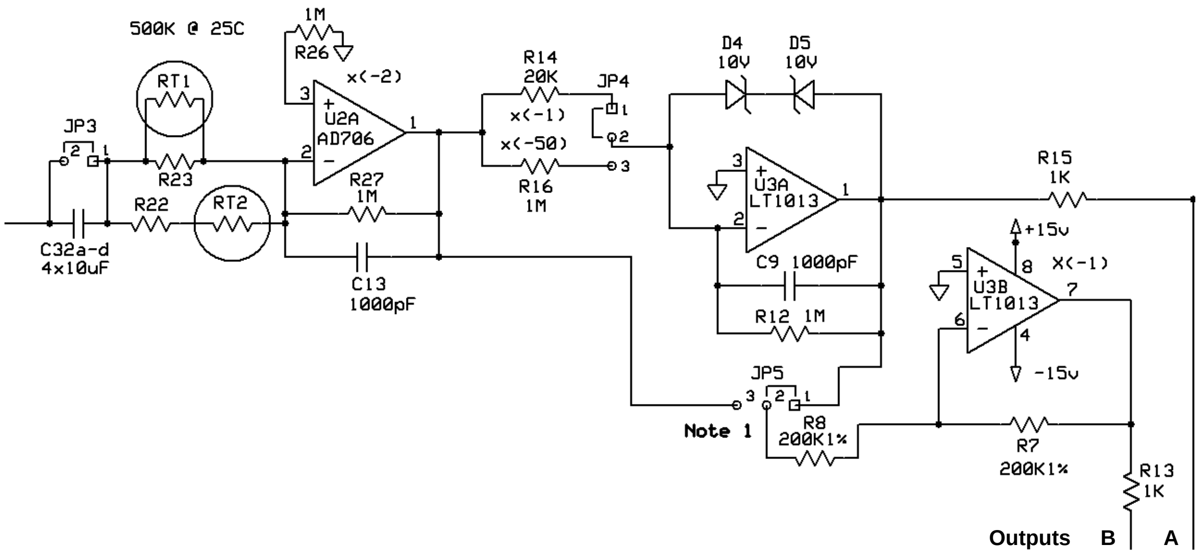
Integrator



The integral feedback branch is constructed using a feedback integrator circuit built around a high-stability amplifier.

Ri, the integral scaling resistor determines the relative strength of the integral feedback. It also represents a limit on how much unbalance force the integrator can handle, and it is designed to be able to compensate for the force change of the steel spring over the expected operating temperature range.

Output Amplifiers



These amplifiers are driven by the output of the feedback loop and are intended to provide flexibility in the choice of output signals and to isolate the feedback loop from the output connections.

The input network for U2A, consisting of R22, R23, RT1 and RT2 is designed to have a resistance of about 500k at 25°C, giving U2A a nominal gain of -2. It is used to compensate for the instrument sensitivity change resulting from changes in the force transducer due to the effect of changing temperature on its magnet strength.

Jumper JP3 allows for the selection of either DC or AC coupling, providing AC coupling when it is removed. The AC coupled mode is useful in situations where temperature variation of the instrument can not be well controlled. When AC coupled, all variations having a period much longer than 125 seconds, which should include most temperature effects, will be masked.

Jumpers JP4 and JP5 reconfigure the amplifiers to allow for single ended or differential outputs and provide for setting the instrument sensitivity to values appropriate for either 16-bit or 24-bit A/D converters. When using the 16-bit single-ended mode, a second, lower gain output is available which can be connected to another A/D channel. Although this second output is 50x less sensitive, it also provides a 50x higher clipping level, equal to that available when using a 24-bit digitizer. Note that the Differential outputs are, in fact, both ground-referenced. They are not floating and might better be termed ‘Balanced’.

The following tables show, for the different jumper configurations, what performance will be obtained for the two outputs A and B, in terms of output amplifier gain, instrument mid-band generator constant and clipping levels.

Output Amplifier Gain Following Loop					
Mode	JP4	JP5	Signal A	Signal B	Differential
16-bit	2-3	2-3	x 100	x 2	---
16-bit differential	2-3	1-2	x 100	x -100	x 200
24-bit	1-2	2-3	x 2	x 2	---
24-bit differential	1-2	1-2	x 2	x -2	x 4

Loop Generator Constant A_g - V / m/s 333

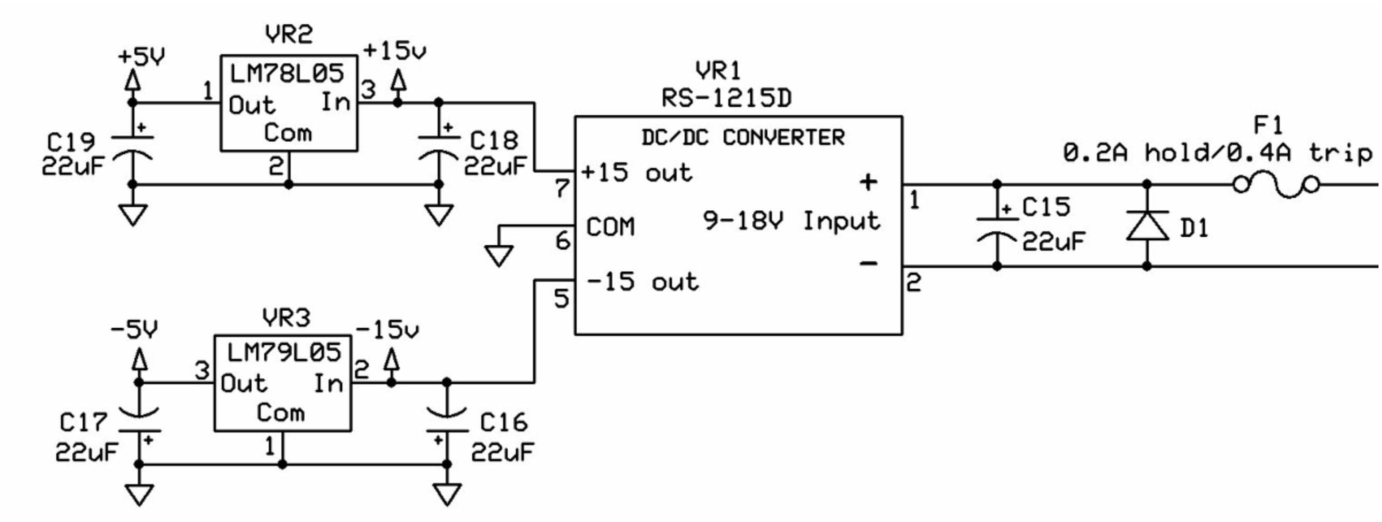
Instrument Generator Constant V / m/s					
Mode	JP4	JP5	Signal A	Signal B	Differential
16-bit	2-3	2-3	33,300	666	---
16-bit differential	2-3	1-2	33,300	-33,300	66,600
24-bit	1-2	2-3	666	666	---
24-bit differential	1-2	1-2	666	-666	1,332

Clipping Velocity for 10V Digitizer Input - m/s					
Mode	JP4	JP5	Signal A	Signal B	Differential
16-bit	2-3	2-3	3.00E-04	1.50E-02	---
16-bit differential	2-3	1-2	---	---	1.50E-04
24-bit	1-2	2-3	1.50E-02	1.50E-02	---
24-bit differential	1-2	1-2	---	---	7.51E-03

Power Supply

The power supply uses a voltage regulated DC/DC converter, VR1, to provide DC isolation from the external power source, whose voltage may vary over a range which includes the voltage range of a 12V lead-acid battery. The converter provides supply voltages of + and – 15 Volts, which are also regulated by regulators VR2 and VR3 down to + and – 5 Volts for those circuits which require the lower, better regulated voltages.

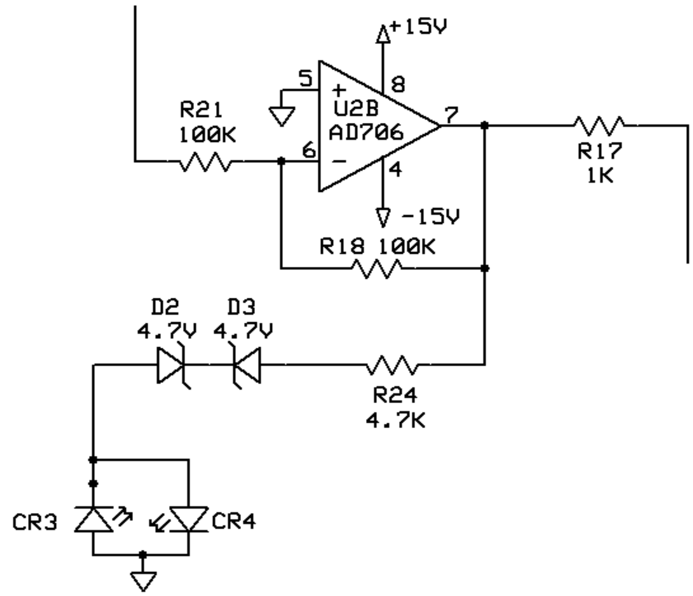
Input protection is provided by resettable PTC device, F1, which has a nominal operating current rating of 0.2A and a trip rating of 0.4A. Diode D1 protects against reversed polarity conditions. Normal input current draw is approximately 60 mA.



Auxiliary Circuits

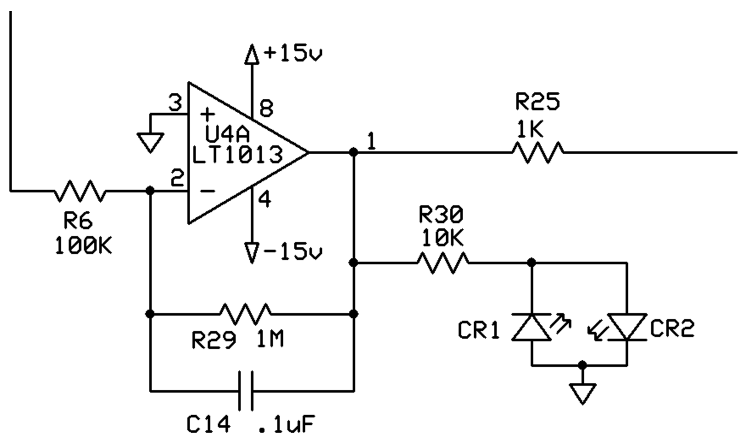
Centering Force Buffer

The centering force buffer amplifier, U2B is driven by the output of the Integrator circuit. With a gain of -1 it provides a test signal 'CF' to the output connector P2. This signal reflects the amount of mechanical imbalance which is being offset by the integrator. If this signal becomes too large the instrument should be mechanically re-balanced. Also, the circuit board contains two LED's, CR3 and CR4, which indicate when the Centering Force signal exceeds approximately +/- 7V. If the instrument is being operated with the circuit board hidden by a cover, R24 may be lifted to reduce possible current drain.



Position Error Buffer

The position error buffer amplifier, U4A is driven by the output of the feedback loop. It is useful when initially setting up the instrument, usually with jumper JP1 removed. During normal operation the position error signal 'PE' on the output connector P2, will be a filtered, low-amplitude version of the instrument output. However, it has the advantage of always being DC coupled so that it shows DC errors which would not be visible if the instrument had been AC coupled by removing jumper JP3. If the instrument is being operated with the circuit board hidden by a cover, R30 may be lifted to reduce possible current drain.



Temperature Sensor

A temperature sensor device, U8, is included, which provides a voltage signal 'T' on the output connector, P2, in order to track the board temperature. This is calibrated for 10 mV/°C, so that 25°C is indicated by an output of 250mV.