Appendix 1

MODERN CALIBRATOR DESIGN

INTRODUCTION

In the design of a modern DC Voltage Calibrator (or the DC function of a Multifunction Calibrator) the traditional Resistance or Kelvin Varley dividers were discarded in favour of Times Division or PWM dividers. This fundamental design change was due to four problems associated with the use of a simple resistor chain, or a Kelvin Varley type divider:

1. **Mechanical complexity:** Requires many switch poles, very expensive, difficulty in programming and a tendency for the switch contacts to wear out.

2. **Very difficult to calibrate:** Requires a very large number of resistors that need to be fixed in set ratios. This requires the use of a Bridge Circuit, and therefore involves many tedious and time consuming individual adjustments, and a very high skill level.

3. **Very poor temperature coefficient:** With the large number of resistors involved, mechanical problems make it impossible to guarantee resistor tracking to better than 0.3ppm/°C. This results in poor linearity, and therefore poor accuracy away from the full range points.

4. **Non-monotonic:** It is best for a calibrators main divider to have a greater setting resolution than linearity. Switched resistor dividers have inherent transition points that can be in error by more than the dividers resolution.

In practice this means that when used like a potentiometer to set a null, or indeed a specific value, a "discontinuity" can occur which makes the specific point (value) required not available.

A very simple example: presume an output divider with decade ranges, a transition point at 1.01V (1.0% overrange) and a resolution of 0.0001V. The overall accuracy of the divider below this transition point could be 0.02% low, that is a setting of 1.0100V would result in an actual output of 1.0098V. Equally the next range (step) up could have an error of 0.11% high, therefore a setting of 1.0100V would provide an actual output of 1.0111V. That is the required output of 1.0100V is not available.

Two types of division can provide the required excellent linearity and stability :

1. **Inductive Division:** Based on turns ratio, the output can be very precisely set, inherently providing good linearity. However, inductive division still involves complex mechanical switching, and therefore still does not lend itself to remote programming.

2. **Times Division or Pulse Width Modulation:** Surprisingly, this simple concept, used for some time in power supplies, was not adopted in calibrators until Datron pioneered it's use in their model 4000 and 4000A DC Calibrators (1979).

TIMES DIVISION or PULSE WIDTH MODULATION (PWM)

As stated the concept is very simple. If a reference voltage is switched ON and OFF with a 50% duty cycle (equal mark - space ratio)) then the rectified output will be half that of the reference, as Figure 1.

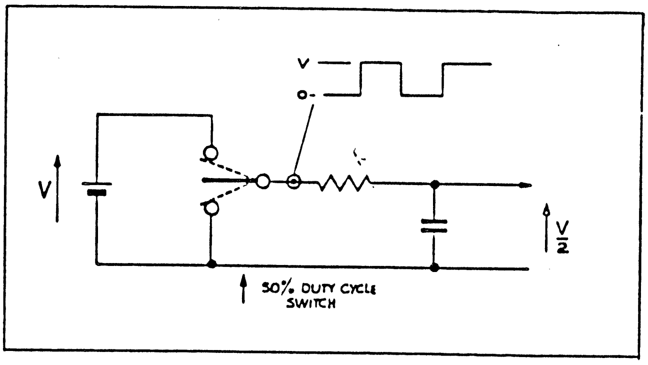


Fig.1

Determining the switch duty cycle (On/Off ratio) by digital counting, and presuming a perfect switch, then any average output voltage from zero to full reference value can be obtained, see Figure 2.

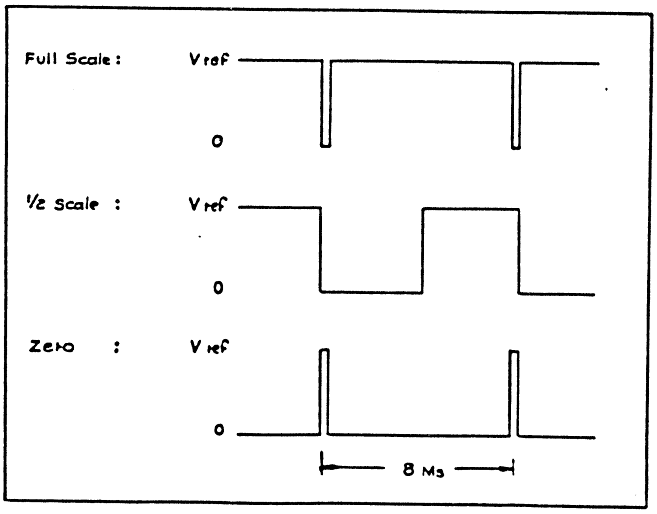


Fig.2

The use of a fixed reference (input) voltage simplifies the design of the divider. In the Datron's 480X series the reference voltage is 20.5V. Combining the reference divider with an output amplifier,and precision gain and attenuation, see Figure 3, provides for a full range of output voltages.

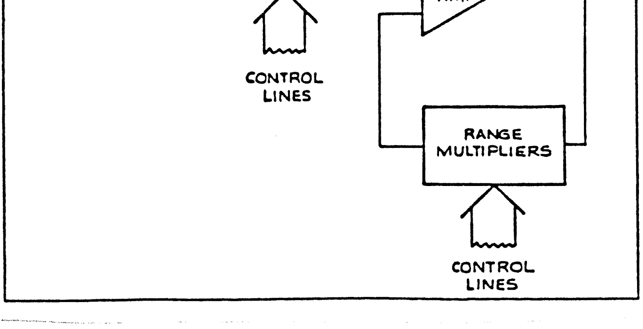


Fig.3

In practice, in order to avoid too high a clock frequency, two switches are used. Provision of a 1 part in $2x10^7$ resolution from a single switch would require an impractical 2.5 GHz clock frequency. The 480x series utilizes a "High Order" (course) switch resolving 1 part in $1x10^4$, (2mV in 20V) and a "Low Order" switch, combined with a 1000:1 divider, resolving 1 part in $2x10^3$ (1µV in 2mV). That is after summing, as Figure 4, provides for a composite resolution of 1 µV in 20V, or 1 part in 2×10^7.

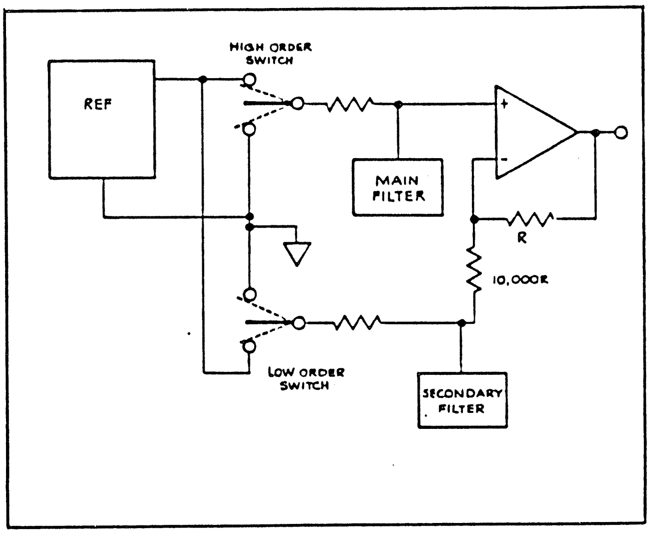


Fig.4

ANALOGUE SWITCH DESIGN

The mark space switch has to maintain relative switching edge stability to better than 1 nsec, which in practice is accomplished by using complementary JFET devices switching the basic Reference of 20.5V, A simplified version is shown in Figure 5.

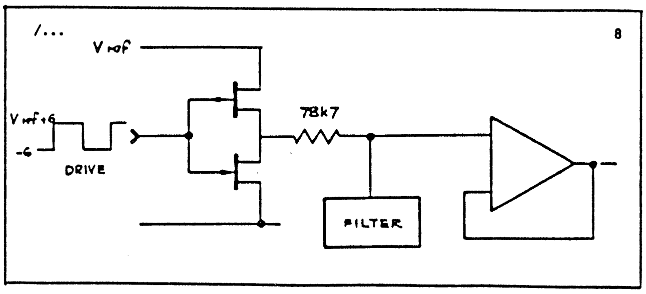
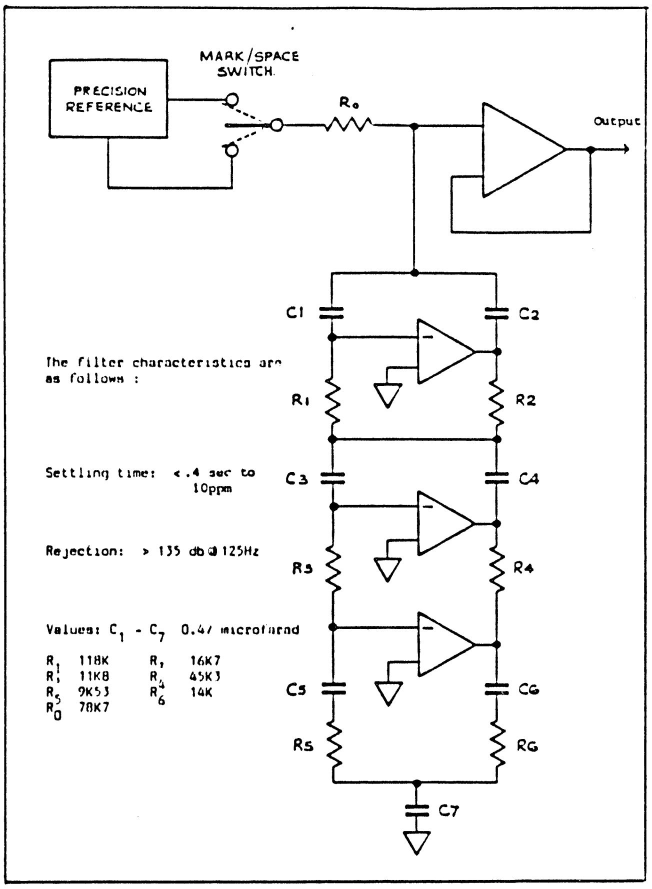


Fig.5

There are two essential factors in the design and operation of the switch:

1. **A fast switching rate makes the smoothing of the output waveform** (square wave to rectified DC) **easier, and settling time quicker, but adds to switching errors.**

The 480X design compromised on 125 Hz switching rate (this rate also has the advantage of not being the harmonic of any mains/utility supply frequency), and a seven pole Bessel filter which provides for a < 400 mS settling time (to 10 ppm), and a > 135 dB rejection at 125 Hz. See Figure 6 (over page).



The filter characteristics are as follows :

Settling time: < .4 sec to 10ppm

Rejection: > 135 db @ 125Hz

Values: C_1 - C_7 0.47 microfarad

R_1	118K	R_2	16K7
R_3	11K8	R_4	45K3
R_5	9K53	R_6	14K
R_0	78K7		

Fig.6

2. In order to be able to quantify the switch errors into a single parameter, it is essential that for any output from Zero to Full Range, the switch goes through a full On/Off cycle.

In theory of course zero could be obtained by holding the switch in the "off" condition, and full range by holding the switch in the "on" condition. However,as stated, this is neither desirable or indeed practical.

Referring back to Figures 2 (page 2) and 4 (page 3), ZERO is obtained by summing +2mV from the High Order switch, and -2mV from the Low Order switch. FULL RANGE (20V) is provided from the reference of 20.5V with a 40:1 mark space ratio.

By ensuring a full duty cycle for any output value, switching errors are reduced to the difference between the On and Off resistance of the switch, ΔR.(Figure 7)

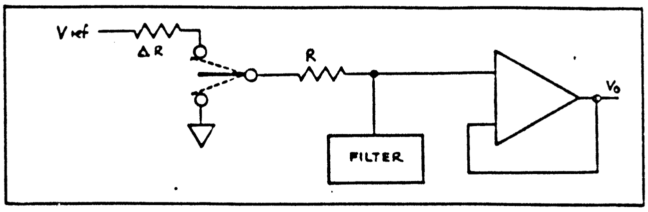


Fig.7

The output voltage for a duty cycle of x/n, where x is the desired output setting ,and n is the full scale setting (20,000,000 on a 4808 /4800),is given by the equation:

$$\frac{Vref - Vo}{R + \Delta R}\, x = \frac{Vo.\,(n-x)}{R}$$

The previous equation simplifies to:

$$Vo = \frac{Vref.\,x}{n + (n - x)\,\Delta R/R}$$

Now, the "ideal" output is given by:

$$Vo = Vref.\,x/n$$

The deviation from the ideal, ΔV is therefore

$$\Delta V = Vref\left[\frac{x}{n} - \frac{x}{n + (n - x)\,\Delta R/R}\right]$$

Since the uncalibrated error ΔV is known to be small, and therefore the value of ΔR/R is small, this equation can be further simplified to:

(i) $$\Delta V = Vref.\frac{(nx - x^2)}{n^2}\,\Delta R/R$$

NOTE, that this is a predictable square law error. (See Figure 8).

whose value tends to ZERO at: **x = n (Full Scale) and x = 0 (Zero)**

and whose value is MAXIMUM at: **x = n/2 (1/2 scale or Full Range)**

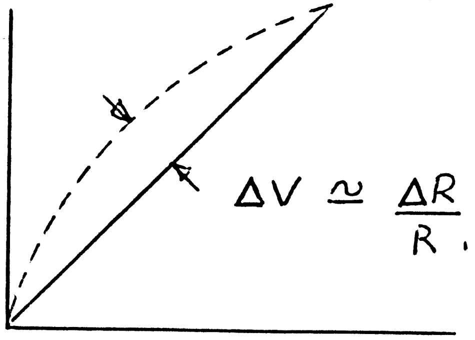


Fig.8

THEREFORE IN RESPECT of VERIFYING the LINEARITY of MODERN CALIBRATORS such as DATRON's 480X or 470X series 1/.2 Scale or FULL RANGE is the WORST CASE, that is 10V on the 10V Range (20V Full Scale).

ACTUAL CORRECTION

The magnitude of the error is easily measured at the Half Scale (Full Range) point using two near equal resistors as shown in Figure 9.

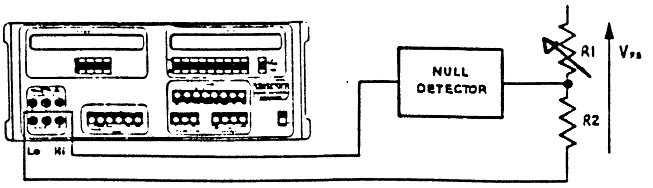


Fig.9

Vfs is set using an external low noise source to be equal to the FS output of the calibrator, the half scale (10V) is set and compared with the division point set by R1 (adjustable) and R2. This voltage ΔV1 is given by:

$$\Delta V1 = Vo - Vfs \frac{R2}{R1 + R2}$$

If R1 and R2 are reversed, a second measurement ΔV2 is obtained:

$$\Delta V2 = Vo - Vsf \frac{R1}{R1 + R2}$$

If the resisters are repeatably reversed, and R1 adjusted until the null meter is stable on the reversal of R1 and R2, then:

$$\Delta V1 = \Delta V2, \qquad \text{That is:} \qquad Vo - \frac{Vfs\ R2}{R1 + R2} = Vo - \frac{Vfs\ R1}{R1 + R2}$$

This has only one solution, R1 = R2 and therefore the mid point is exactly equal to Vfs/2, or full range on a Datron calibrator.

In practice the calibrator is then adjusted, using the Up/Down keys to obtain a "null", and thus the peak (worst case) 1/2 scale linearity error is defined and then loaded into the calibrators memory. The microprocessor then uses the equation (i) above, to correct for linearity at all points providing a typical linearity of 0.2 ppm, and a linearity stability of better than 0.05 ppm/ °C, with virtually no long term drift.

The lifetime linearity specification is 0.5 ppm/FS, but note that, differing from a DMM, absolute worst case is at full range. At 10% of range this will be < 0.1ppm/FS:
This can be proven by returning to equation (1) on page 5,where ΔV will be at:

$$\text{@ Full Range} = \frac{20.\,10 - 10^2}{20^2} \frac{\Delta R}{R} = \frac{1}{4} \frac{\Delta R}{R}$$

$$\text{@ 10\% Range} = \frac{20.\,1 - 1^2}{20^2} \frac{\Delta R}{R} = \frac{1}{20} \frac{\Delta R}{R}$$

This shows that the worst case linearity at 10% of range is 5X better than at full range.

CONCLUSIONS

The request for additional test points on the Datron 4950 MTS is not valid. The operation of Times Division or PWM, with it s inherent linearity, ensures that the absolute worst case nonlinearity, is at 1/2 scale. That is with a Datron calibrator which has a full scale of 19,999,99(9) (4805 6.5 digits), this absolute worst case nonlinearity is at "Full Range" (10V on the 10V range).

Moving away from full range, towards Zero or Full Scale the linearity improves by the square law.