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Chopper Amplifier's PPM Stability Enables Electron Microsope To Scrutinize·Individual Molecules*

*Based on informal conversations with Robert Libbey, Design Engineer RCA, Camden, N.J.

Current source, based on ultra-stable operational amplifier, supplies lens current with 2.5 part-per-million stability, enables a new generation of electron microscopes to resolve better than 8 Angstroms. This article introduces electron microscope principles, illustrates the need for utmost current stability, and describes the current source design.

The electron microscope "sees" by using an electron beam as an ultra-short wavelength "light source." Owing to the dramatic reduction in diffraction effects afforded by its short-wave illumination, the instrument can resolve a thousandfold more finely than the best optical instrument. Evolution of the electron microscope during the past few decades has opened entirely new realms of exploration and study, and has enabled researchers to examine individual molecules and viruses not previously discernible with even the most powerful optical microscope.

Electronic engineers, so familiar with a heated cathode's random emission, may be forgiven for believing electron beams to exemplify particle rather than wave motion. Yet during 1924, deBroglie paralleled Einstein's earlier unification of wave and corpuscular light theories by showing that a beam of charged particles may also be represented by a wave motion of definite and calculable wavelength. In fact, the wavelength of an electron beam accelerated through 50,000 volts is roughly 0.05 Angstroms, or 5×10^{-10} centimeters. This is approximately six orders-of-magnitude shorter than the 4×10^{-5} centimeters for visible light at the ultra-violet end of the spectrum.

Electron microscopes have evolved at an explosive pace compared with the optical microscope's 300 years of development since Anton Leeuwenhoeck observed his first microbe. In 1926, Busch published theoretical calculations showing how an electrostatic field could focus an electron beam, thereby laying the foundations for geometrical optics. Bruche and Johannson built the first electrostatic instrument in 1932. Then also in 1932, Knoll and Ruska accelerated the pace by publishing the first experimental results obtained with an electron microscope employing magnetic lenses. The industry hasn't looked back since.

RESOLUTION

Diffraction effects, caused by mutual interference between phase-related wave-fronts, ultimately limit a microscope's ability to distinguish separate points on any object being viewed. Diffraction is directly related to wavelength, as Abbe's equation: $d = 0.62\lambda/n \sin\alpha$ demonstrates. This equation shows how resolution d improves as wavelength λ shrinks. The electron microscope's "light source," being several orders of magnitude shorter than visible light, improves resolution dramatically.

A good optical microscope can distinguish points separated by a distance roughly equal to half a wavelength. For a 4000 Angstrom light source, this works out to about 2000 Angstroms, or 0.0002 centimeters. The naked eye can resolve to about 0.02 centimeters. Compromises in the electron microscope between diffraction and spherical aberration effects yield an optimum resolution of about 8 Angstroms, or 8×10^{-10} centimeters. (Spherical aberration is minimized by a small aperture, diffraction is minimized by a large one.)

LENS COMPARISONS

Electron microscopes are virtually identical in fundamental principle to their optical counterparts, as the ray diagram, Fig. 1, shows. Lenses are arranged in conventional condenser, objective, and projection configurations for transmission microscopes of both types. Even so, the differences in practice are more marked than the similarities in principle.

An optical microscope's day-to-day performance depends primarily upon such basic factors as dimensional stability of lenses and structure. By contrast, an electron microscope's day-to-day resolving power is a much more delicate matter and depends upon far less tangible parameters than glass and metal configurations. Magnetic field geometry establishes the electron microscope's working efficiency, making magnetic stability, hence lens current constancy, analogous to the optical microscope's lens and structural stability.

The electron microscope exemplifies modern instrument trends towards increasing use of electrical rather than physical "dimensions." Sophisticated designs in many fields are using electronics to achieve new functions and improved accuracy. Examples occur in caesium cell frequency standards, particle accelerators, mass spectrometers, and doubtless many more. One commercial analytical balance even uses the pull of an accurately calibrated solenoid for fractional milligram resolution of sample weight. In all of these instances, utmost electrical stability is reflected directly in the instrument's usefulness. Because Analog Devices is participating with instrument manufacturers in the development of advanced electronic instrumentation, we've obtained RCA's permission to present the design and circuit details of the current source used in their new Model EMU4 microscope.

CURRENT SOURCE

Until recently, electronic circuitry imposed a final limitation on the routine performance of commercial electron microscopes. However, chopper stabilized amplifiers with better than $0.5\mu V/°C$ drift, and ultra-stable Zener diodes with comparable specifications, have elevated the performance of electronic circuits to at least the equal of the instrument's physical hardware. Oscilloscope users are aware that the focus knob on their instrument can stand a good deal of twiddling before the trace loses its definition. This slackness of focus is certainly not duplicated by an electron microscope capable of enlarging objects by 200,000 or more. At highest magnification levels a 10 PPM lens current drift drastically degrades resolving power and defeats the purpose of the original $50,000 to $500,000 expenditure.

BASIC CIRCUIT

The basic current source circuit that supplies lens current for the EMU4 microscope is analyzed in Fig. 2. The analysis shows how errors due to drift and noise reflect in output current deviations.

Compared with other current sources[1], this circuit has the advantage that its main amplifier operates with one input terminal grounded, simultaneously eliminating common mode errors and enabling a chopper stabilized operational amplifier to establish the basic stability. Too, the current booster circuit can be a simple emitter follower or Darlington pair enclosed within the feedback loop. Equivalent booster drift, when reflected back to the reference source, is then reduced by the chopper amplifier's 10^8 gain to negligible proportions compared with the chopper amplifier's own drift.

Penalties paid for these simplifications include a somewhat increased overall drift gain, and the need for a floating load. Since the lens coil is isolated from ground anyway, the floating load condition imposes no extra problems. Similarly, chopper amplifiers can be selected for ample margin of stability over the increased drift gain.

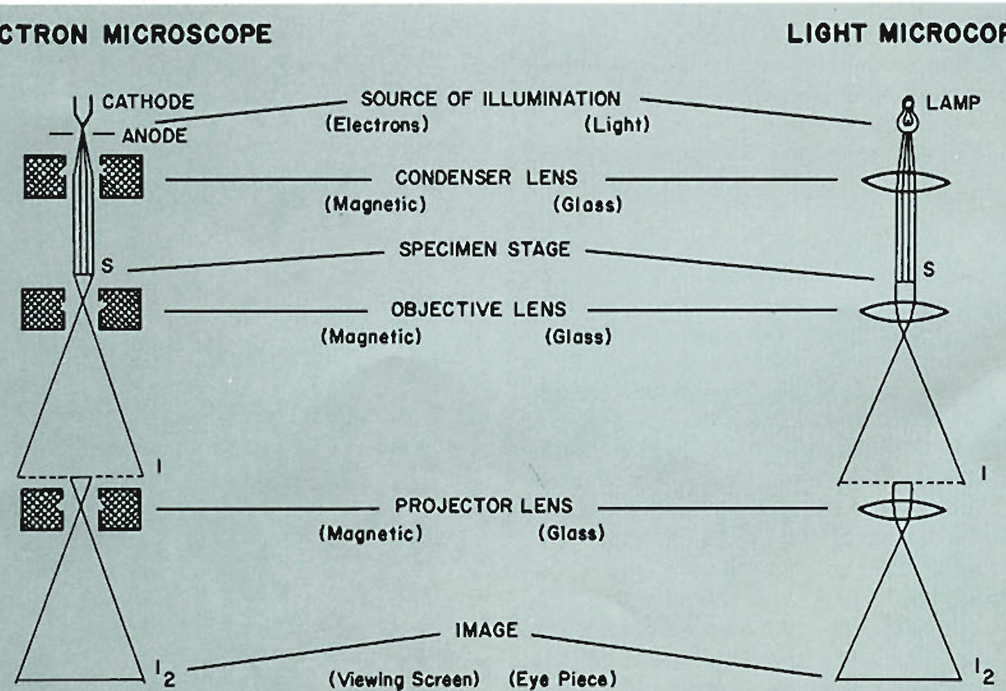


FIGURE 1. Electron microscope compared to their optical counterparts.

[1] *Current Sources, by Bill Miller, Analog Dialogue No. 1 (Available on request from Analog Devices, Inc.)*

ACTUAL CIRCUIT

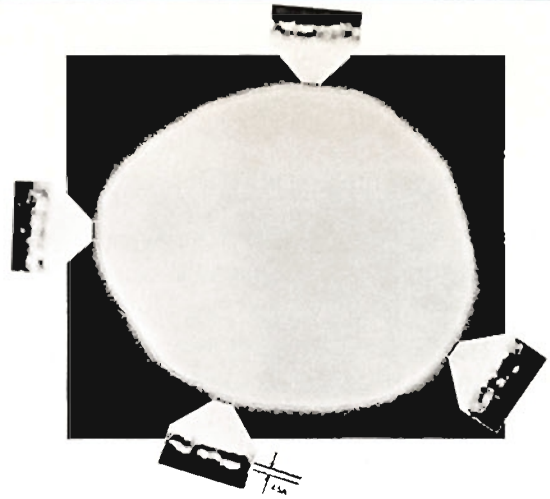
Owing to the relative wide range of voltage needed by the lens coil, the booster amplifier is not a simple emitter follower, but increases output voltage from the chopper amplifier's −6 volts to roughly 50 volts at maximum coil current. Additionally, the Darlington configuration raises output current to nearly 300 milliamps.

The design procedure for such a circuit is first of all to establish a theoretical paper "Bode" design, then produce a simple prototype for error measurement and diagnosis. The next step is to add voltage and current amplifiers to the circuit, introduce long leads and control switches, then check for frequency and phase stability, as well as dc stability. Frequency-stabilizing capacitors are introduced to ensure operating stability under all operating conditions, including switching transients.

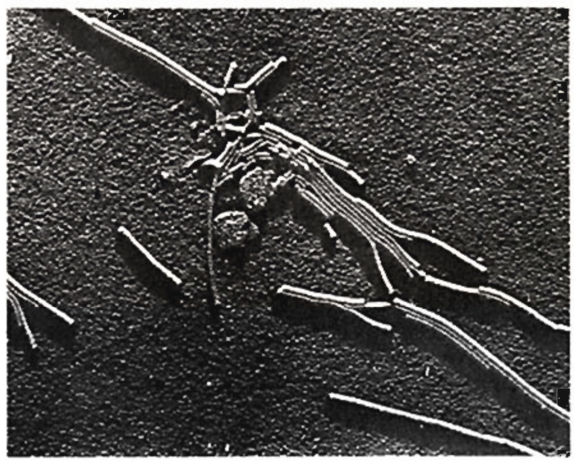
Feedback resistors should be low noise types (they should be checked by the "current noise" method), and must afford stability commensurate with the circuit's final specifications. Operating the resistors at low dissipation levels, and in a uniform temperature environment, are important design factors.

Temperature compensated Zeners operated in the proper temperature environment (but without constant temperature oven), provide about 1 ppm short-term stability. The amplifier drift, as shown in Fig. 3, can be well below this value for the 5°C temperature range.

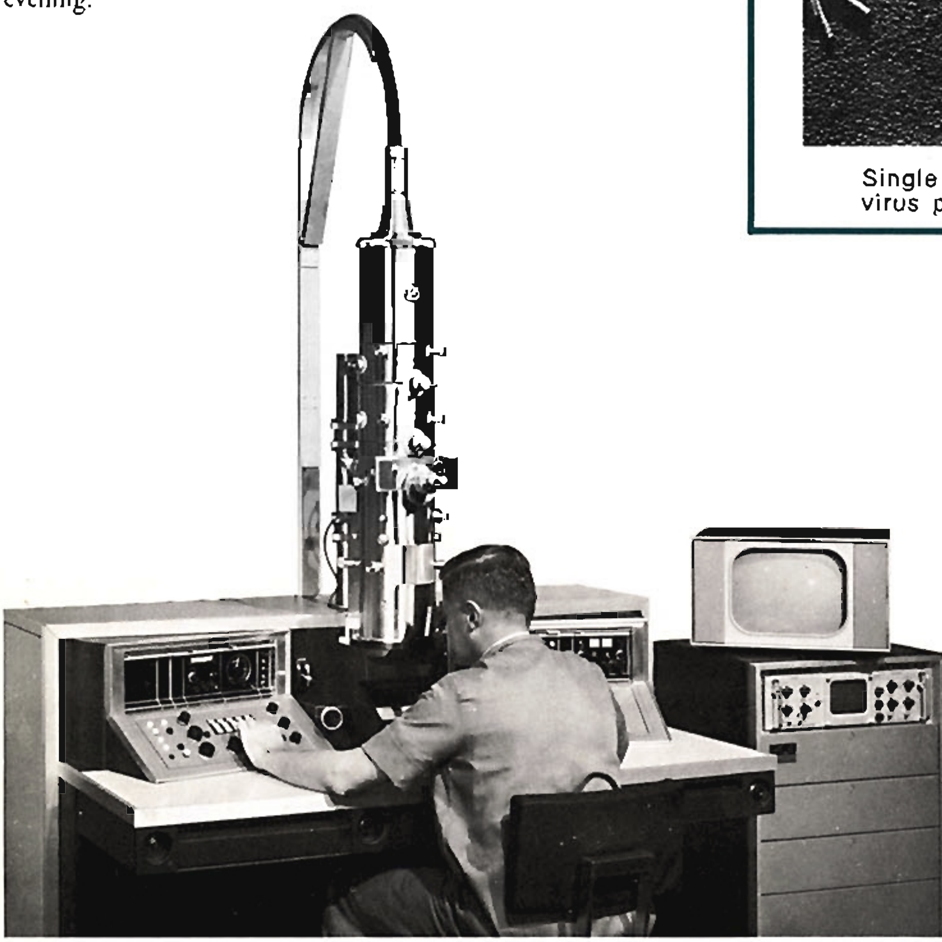
Overall performance of the circuit meets the worst-case current drift specifications of 2.5 parts-per-million deviation over the one-minute exposure interval needed by some image photographic processes. Generally speaking, a one-second exposure is adequate, making the 2.5 ppm drift specification ample. Long-term stability of the lens current output is about 10 ppm/hour, and its state-of-the-art repeatability enables operators to start the morning's work where they left off the previous evening.



Hole in carbon film showing 45°A fringe. Magnification 400,000x; wedged areas 2,000,000x.



Single molecule of tobacco mosaic virus protein.

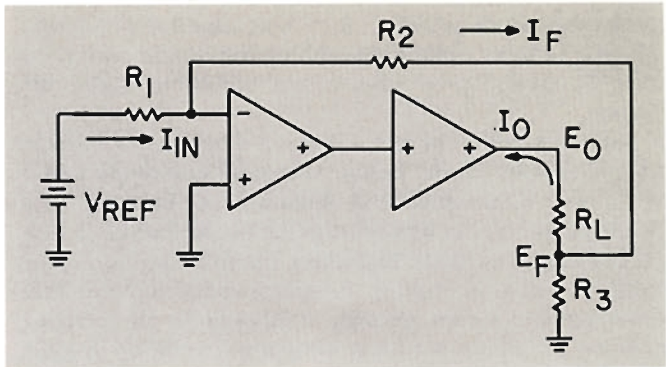


Heralding a new generation in electron microscopes — The RCA EMU-4.

FIGURE 2. ANALYSIS OF CURRENT SOURCE'S OUTPUT VOLTAGE AND CURRENT

Analysis for determining current source's output current and output voltage in terms of Reference voltage and circuit values.

The analysis is based on the equality between input current I_{in} and feedback current I_f that prevails during steady-state operation.



VOLTAGE OUTPUT

The summing junction potential is very nearly zero (virtual ground principle), so that input current $I_{in} = V_{ref}/R_1$, and

feedback current $I_f = E_f / \left(R_2 + \frac{R_3 R_L}{R_3 + R_L} \right)$

Since $I_{in} = I_f$, $V_{ref}/R_1 = E_f / \left(R_2 + \frac{R_3 R_L}{R_3 + R_L} \right)$

The artificial thevenin voltage, designated E_f, can also be expressed in terms of amplifier output voltage by:

$$E_f = E_o \left(\frac{R_3}{R_L + R_3} \right)$$

This expression for E_f can be substituted in the identity $I_{in} = I_f$, enabling the amplifier output voltage to be defined in terms of reference voltage V_{ref}.

Accordingly, $V_{ref}/R_1 = \left(\frac{E_o R_3}{R_3 + R_L} \right) \div \left(R_2 + \frac{R_3 R_L}{R_3 + R_L} \right)$

Output voltage expressed explicitly becomes

$$E_o = \frac{V_{ref}}{R_1} \left(\frac{R_2 R_3 + R_2 R_L + R_3 R_L}{R_3} \right)$$

Conventionally, amplifier output voltage is expressed in terms of the ratio between feedback resistor R_2 and input resistor R_1. The current source's output voltage can be manipulated into this conventional form too.

$$\text{Thus, } E_o = V_{ref} \left(\frac{R_2}{R_1} \right) \left(1 + \frac{R_L}{R_3} + \frac{R_L}{R_2} \right)$$

$$= V_{ref} \left(\frac{R_2}{R_1} \right) \left(1 + R_L/\text{Parallel combination of } R_2 \text{ and } R_3 \right)$$

CURRENT OUTPUT

The amplifier's output current flows through load resistor R_L then divides between the parallel combination of R_3 and R_2, both of which, to all intents and purposes, have one terminal grounded. Consequently, $I_o = E_o / \left(R_L + \frac{R_2 R_3}{R_2 + R_3} \right)$

Substituting the expression for output voltage in the above equation gives

$$I_o = V_{ref} \left(\frac{R_2}{R_1} \right) \left(1 + \frac{R_L}{R_3} + \frac{R_L}{R_2} \right) \div \left(R_L + \frac{R_2 R_3}{R_2 + R_3} \right)$$

which can be simplified by algebraic juggling to

$$I_o \cong \frac{V_{ref}}{R_1} \left(1 + \frac{R_2}{R_3} \right) \cong \frac{V_{ref}}{R_1} \left(\frac{R_2}{R_3} \right) \text{ for } R_2 >> R_3$$

This expression shows that so long as R_2 is much larger than R_3, output current varies linearly with the values of R_2. Further, output current is independent of the actual values of load resistance R_L, provided that this resistance is small enough to allow the amplifier to operate within its normal output voltage range.

ERROR CONSIDERATIONS

Output current deviations are caused by voltage and current drifts within the amplifier, and also by the amplifier's voltage and current noise. An analysis of the output current deviations produced by these effects proceeds from the assumption that noise and drift errors can be referred to the input circuit as small deviations in reference voltage, V_{ref}. In effect, the amplifier's noise and drift may be represented as small voltage generators acting in series with the reference source, and having net voltage ΔV_{ref} producing voltage errors amounting to ΔV_{ref}.

Load current variations caused by input voltage variations ΔV_{ref} can be found by differentiating the output current expression with respect to reference or input voltage.

$$\text{Thus, } \frac{dI_o}{dV_{ref}} = \frac{d}{dV_{ref}} \left[\frac{V_{ref}}{R_1} \left(1 + \frac{R_2}{R_3} \right) \right]$$

$$= \frac{1}{R_1} \left(1 + \frac{R_2}{R_3} \right) = \frac{I_o}{V_{ref}}$$

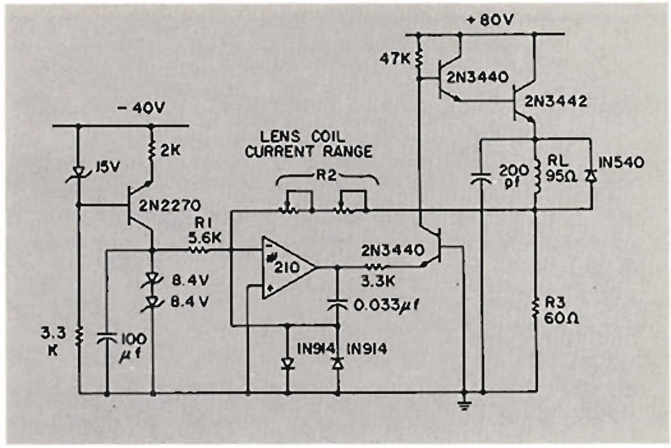
And because $\frac{dI_o}{dV_{ref}} \cong \frac{\Delta I_o}{\Delta V_{ref}}$, $\Delta I_o = \Delta V_{ref} \left(\frac{I_o}{V_{ref}} \right)$

Or in other words, the proportionate current change is equal to the proportionate input voltage change: $\frac{\Delta I_o}{I_o} = \frac{\Delta V_{ref}}{V_{ref}}$

This means that a 10 part-per-million increase in reference voltage creates a 10 part-per-million increase in output current. (A numerical error analysis for a practical current source is worked out in Fig. 3)

FIGURE 3. CURRENT SOURCE CIRCUIT SUPPLIES HIGHLY STABLE LENS CURRENT FOR RCA'S MODEL EMU4 ELECTRON MICROSCOPE.

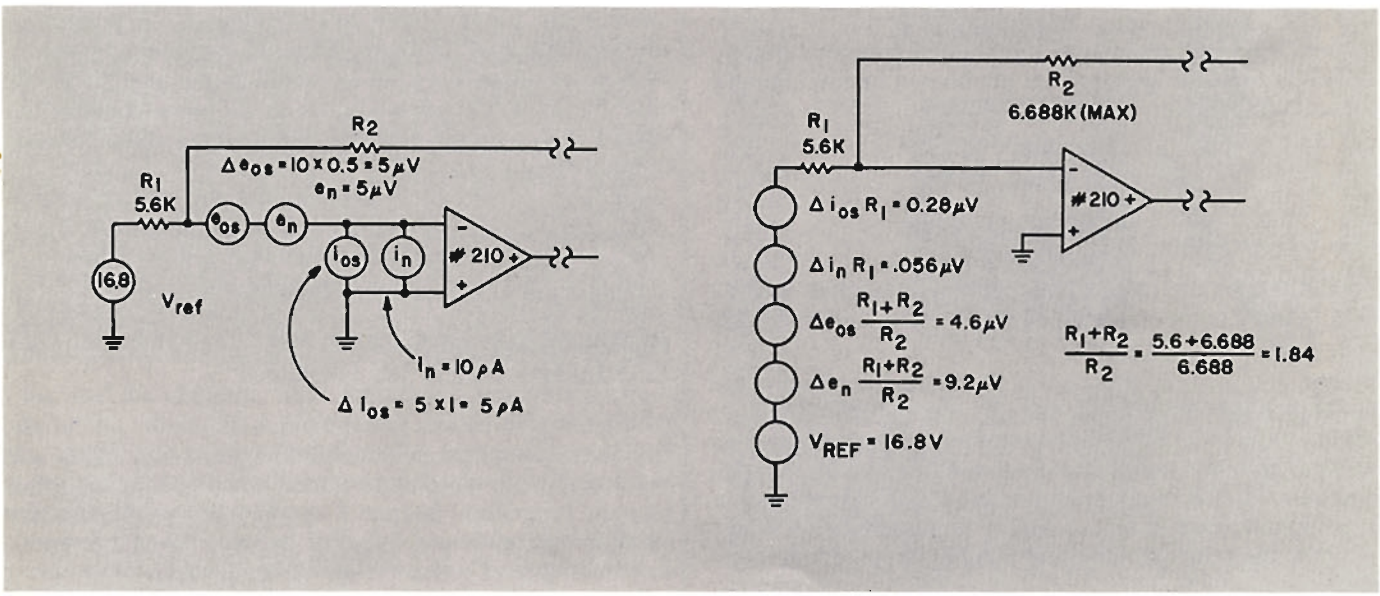
Short terms stability of better than 2.5 ppm is derived basically from Model 210 chopper stabilized op amp. Booster circuit raises output voltage and current to as high as 50 volt 300mA from the amplifier's basic ±10 volt, 20mA.



CALCULATION OF ERRORS

Numerical values for output current error are determined for a given temperature range from the worst-case drift and noise figures quoted in the amplifier's specification tables. For Model 210 these are $0.5\mu V/°C$ and $1pA/°C$ drift, and $5\mu V$ and $10pA$ peak-to-peak noise, respectively. Although noise is practically independent of temperature for small environmental ranges, the voltage and current offsets caused by a 5°C variation around room temperature amount to $5 \times 0.5 = 2.5\mu V$ and $5 \times 1 = 5pA$. These values for noise and offset have been inserted into the equivalent current source circuit below (left). When referred to the reference source (instead of the actual amplifier terminals), the noise and offset values are modified by the potentiometric effect of circuit components, leading to the equivalent error voltage generators as shown in the illustration below (right).

The sum of voltage and current offset errors, and also the sum of voltage and current noise errors, both as proportions of the reference voltage, give a measure of the output current error directly. The calculations are performed here for the actual electron microscope lens current supply (top).



DRIFT ERRORS

Sum of voltage and current offset errors due to 5°C temperature variation, are referred to input as: —

$$\Delta e_{os}\left(\frac{R_1+R_2}{R_2}\right) + \Delta i_{os}R_1$$

$$\cong 4.6\mu V + 0.28\mu V \cong 4.63\mu V$$

Offset error as a proportion of circuit input error $\Delta V_{ref}/V_{ref}$

$= 4.63 \times 10^{-6}/16.8 = 0.28$ parts/million

NOISE ERRORS

Sum of voltage and current noise errors in the frequency range DC to 1Hz, are referred to the input as: —

$$e_n\left(\frac{R_1+R_2}{R_2}\right) + i_{os}R_1$$

$$\cong 9.2\mu V + 0.56\mu V \cong 9.26\mu V$$

Noise error as a proportion of circuit input error $\Delta V_{ref}/V_{ref}$

$= 9.26 \times 10^{-6}/16.8 = 0.55$ppm

CONCLUSION

Drift errors for the 5°C temperature range, happen to be half the error caused by noise for the amplifier. Ambient temperature varies relatively slowly, so that for short-term exposure periods of a few minutes, noise will be the predominant cause of lens current deviation.

The 0.83ppm amplifier error combined with the 1ppm Zener diode error provide better than the 2.5ppm design goal.