Using $f_1 = 1/(10 \times 3600)$ (T = 1 hour = 3600 seconds) and an amplifier bandwidth of five kHz, the root mean-square values of the amplifier's voltage- and current-noise sources are 0.90 microvolts and 49 picoamperes, respectively.

An error model for the multiplexer and amplifier portion of the system is shown in Figure 9; this model includes the noise of the amplifier feedback resistors. In our flying-capacitor multiplexer, the capacitor is so large that the current-noise source does not develop any appreciable signal across the capacitor. However, the noise current does flow through the feedback resistors and adds to the total noise at the amplifier input. Simple circuit analysis yields the total input noise voltage:

$$
\sqrt{V_n^2} = \sqrt{V_{na}^2 + 9.99 \times 10^{-5} I_{na}^2 + 0.99 V_{na}^2 + (V_{na}/4 \times 10^5)}
$$

$$
= \sqrt{8.1 \times 10^{-13} + 2.4 \times 10^{-17} + 1.2 \times 10^{-14} + 6.5 \times 10^{-15}}
$$

$$
= 0.91 \mu V.
$$

On the input side of the multiplexer, the noise voltage of the source resistors adds to the thermocouple signal. However, because the capacitor and source resistances form a low-pass filter with a very low cut-off frequency (0.6 Hz for the system of Figure 9), the noise signal stored on C is negligible.

In other types of multiplexer systems, the noise current of the amplifier flows both through the 'on' resistance of the multiplexer switches and through the source resistance to produce an additional noise signal. This voltage and the noise voltages of the source and multiplexer resistances each add quadratically to the total noise at the amplifier input.

In our system, we are trying to measure voltages to within three microvolts, but we have a peak-to-peak noise of more than five microvolts corrupting our signal. Thus, noise will cause the ADC output to vary randomly by two LSBs. In higher-resolution systems, the effects of internal system noise become progressively more pronounced.

We can reduce the effect of noise on the measurements by a factor of $\sqrt{n}$, by averaging $n$ samples of the signal. Averaging 100 samples reduces the noise contribution by a factor of 10.

One hundred readings of a 50-microsecond successive approximation ADC require five milliseconds, plus a significant software overhead to take the extra readings and average the results. With 100 samples, the RMS input noise voltage is reduced to less than 0.1 microvolt.

On the other hand, an integrating ADC automatically averages the signal during the first integration period. Integrating for T milliseconds is equivalent to reducing the upper frequency limit to $\frac{1}{4}T$ Hz. Hence, a converter which integrates for 10 milliseconds will have an effective bandwidth of 25 Hz! The equivalent RMS value of the input noise voltage, calculated with the equation above, will then be 0.06 microvolt. Thus, the apparent speed disadvantage of a dual-ramp converter, particularly in high-resolution systems, is not as significant as one may first believe.

*For a single-pole amplifier, the effective bandwidth for noise is $\pi/2$ times the amplifier bandwidth ($f_2 = 5000 \pi/2$).

Another method is to reduce the noise bandwidth of the system by reducing the amplifier bandwidth. As shown earlier, the time dedicated to amplifier settling can be increased to 10 milliseconds and still easily meet the 16-SPS system speed requirement. The corresponding bandwidth of 154 Hz reduces the equivalent noise signal to 0.2 microvolts, which is negligible.

In a system which includes a sample-and-hold, the noise of that component must be included. The power spectrums of its voltage and current noise will be similar to those listed in Table 1. However, a sample-and-hold is usually a wide-band amplifier and may have a bandwidth of many MHz. Hence, the RMS values of its voltage- and current-noise generators can be fairly large. The sample-and-hold is usually placed after the instrumentation amplifier so that it samples only high-level signals. In most systems its noise will then be negligible. In any case, the noise voltage may be calculated and compared to the signal voltage to determine if it is a significant source of error.

**Errors due to repetitive sampling**

Subtle errors are introduced into a measurement because we are repetitively sampling each input signal.