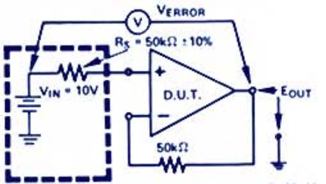
I.C. Insight

NOT BY DRIFT ALONE . . .

by Stan Harris

Voltage offset drift is commonly considered to be the most important factor limiting op amp accuracy at low frequencies, with drifts due to current bias and offset closely vying for second place. Recognizing (and perhaps overreacting to) the importance of low drift specifications, IC op amp manufacturers (and purveyors) have offered such popular devices as the SSS725E, the LM208A (and the BB3500E), which feature either low offset or bias current or low voltage drift. Analog Devices has recently (*Dialogue*, Vol. 6, No. 1) introduced the ultra-stable monolithic AD508K*, which not only has a $0.5\mu V/^\circ C$ offset drift and super-β input transistors, but also includes minimum gain of 10^6 and CMR of 110dB, to minimize *total error*, rather than simply win a drift-specification contest.

It has not been well-recognized that once drift (of both kinds) is greatly reduced (to the order of $1\mu V/^\circ C$), there are other sources of error that can no longer be neglected, particularly for high-accuracy non-inverting applications, and especially if ambient temperature varies over a reasonable range. These include finite-gain and common-mode errors.



BASIC CIRCUIT. DOES NOT SHOW POWER SUPPLY, COMPENSATION, OR ZEROING CONNECTIONS.

A particularly nasty transducer application that illuminates the problems of optimization is shown in the Figure: a unity-gain follower is driven by a 10V source with 50kΩ (±10%) internal resistance. The objective is to reproduce the source voltage and its variations at low impedance with the best possible accuracy, but at the low cost of a monolithic op amp, and with a minimum of external circuitry and "tweaking." The circuit in the Figure shows a model of such a source, in which the amplifier output can be directly compared with the open-circuit voltage.

To determine the major sources of error in the circuit and arrive at a basis for estimating worst-case error, an error budget is tabulated, based on specified (or estimated) worst-case amplifier parameters, for each of the amplifier types mentioned above, and for a representative low-cost amplifier, the AD741K.† Performance is considered over two ranges of temperature, +24°C to +45°C and 0 to +70°C. The amplifiers are nulled using their zero-adjust terminals (where provided), and are allowed a ±5% power-supply variation.

The results of this exercise tend to speak for themselves. The AD508 comes off quite well because of its balanced design; there is no single substantial source of error. The LM208AH is handicapped by lack of an offset adjustment terminal, but even so, gain, common-mode, and voltage drift errors make the overall sum at least twice that of the AD508. SSS725E is "done in" by its high bias and offset currents, as is the BB3500E, which is also beset by substantial gain, common-mode, and power-supply-sensitivity errors. The AD741K, despite its low price, is surprisingly not the worst performer, and should be considered seriously as a "best buy" for applications of this type in the 0.03% performance class.

FET-input IC's,§ while not listed here, should be mentioned, because their current errors are negligible, and they might seem an intuitive choice. Low drift-voltage types are costly, however, and high gain, CMR, and PSR, if available at all, would be quite expensive. The reader may wish, as an exercise, to compare performance of the AD508 with his favorite IC FET in the AD508's price class.

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I.C. OP AMP ERROR BUDGET ANALYSIS

Error Parameter (min or max)	T_A = +25°C to +45°C					T_A = 0°C to +70°C					
	AD508KH	LM208AH	SSS725EJ	BB3500E	AD741KH	AD508K	LM208A	SSS725E	BB3500E	AD741K	
GAIN	(10^6) 10μV	(80k) 125μV	(10^6) 10μV	(100k) 100μV	(50k) 200μV	(500k) 20μV	(Est 60k) 167μV	(800k) 12.5μV	(Est 70k) 143μV	(25k) 400μV	SPEC ERROR
$I_b \times \Delta R$ (5kΩ)	(10nA) 50μV	(2nA) 10μV	(80nA) 400μV	(50nA) 250μV	(75nA) 375μV	(15nA) 75μV	(Est 2.5nA) 12.5μV	(100nA) 500μV	(Est 75nA) 375μV	(120nA) 600μV	SPEC ERROR
$I_{OS} \times R$ (50kΩ)	(1nA) 50μV	(0.2nA) 10μV	(5nA) 250μV	(30nA) 1500μV	(10nA) 500μV	(1.6nA) 80μV	(Est 0.3nA) 15μV	(7nA) 350μV	(Est 45nA) 2250μV	(15nA) 750μV	SPEC ERROR
V_{OS}	(trim to 0) 0	(500μV) 500μV	(trim to 0) 0	(trim to 0) 0	(trim to 0) 0	(trim to 0) 0	(Est 730μV) 730μV	(trim to 0) 0	(trim to 0) 0	(trim to 0) 0	SPEC ERROR
$\Delta V_{OS}/\Delta T$ (see note)	(0.5μV/°C) 10μV	(5.0μV/°C) 100μV	(0.6μV/°C) 12μV	(1.0μV/°C) 20μV	(15μV/°C) 300μV	(0.5μV/°C) 35μV	(5.0μV/°C) 350μV	(0.6μV/°C) 42μV	(1.0μV/°C) 70μV	(15μV/°C) 1050μV	SPEC ERROR
CMR	(110dB) 32μV	(96dB) 160μV	(120dB) 10μV	(Est 96dB) 160μV	(90dB) 320μV	(100dB) 100μV	(96dB) 160μV	(115dB) 18μV	(Est 90dB) 320μV	(90dB) 320μV	SPEC ERROR
PSRR	(10μV/V) 30μV	(16μV/V) 48μV	(5μV/V) 15μV	(Est 50μV/V) 150μV	(15μV/V) 45μV	(15μV/V) 45μV	(16μV/V) 48μV	(7μV/V) 21μV	(Est 60μV/V) 180μV	(15μV/V) 45μV	SPEC ERROR
NOISE	Difficult to estimate because of specification non-uniformity. Range approximately from 2μV to 10μV, not a significant % of the total.										
TOTAL	182μV	953μV	697μV	2180μV	1740μV	355μV	1482μV	944μV	3338μV	3165μV	
PRICE (100 pcs)	$20.00	$14.95	$16.30	$20.00	$2.25	$20.00	$14.95	$16.30	$20.00	$2.25	

NOTE: $\Delta V_{OS}/\Delta T$ for the AD508K and SSS725E are specified with V_{OS} nulled. Nulling the BB3500E and AD741K may degrade $\Delta V_{OS}/\Delta T$ beyond the maximum spec.

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*For complete information on the AD508, use the reply card. Request G12.

†For data on the AD741K, request G13.

§For information on FET-input IC's from Analog Devices, request G14.

NOT BY DRIFT ALONE . . .

Chapter 2. The 741 Op Amp Family

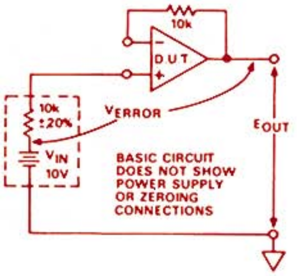
by Stan Harris

In Vol. 6, No. 2 (p. 12), we developed the thesis that for practical high-precision applications, the drift spec of an operational amplifier was but one of the specifications affecting accuracy, and not always the most important one at that.

We offered an example involving a simple unity-gain follower unloading a 10V precision signal source with an internal resistance of 50kΩ ±10%. An error budget compared the worst-case errors of a number of commercially-available comparably-priced "low-drift" op amps. It was gratifying (but hardly surprising) to find that the AD508H*, with its balanced optimized design, won handily over such competitors as the LM208AH, the SSS725EJ, and the BB3500E. What *was* a bit surprising, however, was to find that the AD741KH, costing less by an order of magnitude, was *not* the worst of the lot.

Thus encouraged, we decided to take a closer look at the 741* family. Besides the common, garden variety (AD)741 and (AD)741C, at their rock-bottom prices, Analog Devices also makes the higher-performance AD741J, AD741K, AD741L, and AD741S, for which only modest premiums are exacted.

We used for the comparison a unity-gain follower circuit, driven by a source having internal resistance of 10kΩ ±20%, and using a nominal 10kΩ bias-current compensating resistance in series with the negative input terminal. The results of the error-budget comparison are shown in the table. For performance over the commercial temperature range, the AD741K has better than 5X less error than 741C at 2½X the cost. Over the full "MIL" range, the AD741S has 3½X less error than 741 at less than twice the cost.



ERROR BUDGET ANALYSIS

PARAMETER		0 to +70°C				−55°C to +125°C	
		AD741C	AD741J	AD741K	AD741L	AD741	AD741S
Gain (G, V/V)	SPEC	15,000	25,000[1]	25,000	25,000	25,000	25,000[1]
Gain error (10^7μV/G)	ERROR	660	400	400	400	400	400
I_b (nA)	SPEC	800	400	120	100	1,500	250
I_b x R mismatch (μV)	ERROR	1,600	800	240	200	3,000	600
I_{OS} (nA)	SPEC	300	100	16	10	600	25
I_{OS} x 10kΩ error (μV)	ERROR	3,000	1,000	160	100	6,000	250
$\Delta V_{OS}/\Delta T$ (μV/°C)	SPEC[2]	25	20	15	5	25	15
ΔV_{OS} over temp. (μV)	ERROR	1,125	900	675	225	2,500	1,500
CMR = 20logCMRR (dB)	SPEC	70	80	90	90	70	80
CME = 10V/CMRR	ERROR	3,160	1,000	316	316	3,160	1,000
PSRR (μV/V)	SPEC	150	100	15	15	150	100
ERROR = 3 x PSRR (μV)[3]	ERROR	450	300	45	45	450	300
Total (Algebraic)	ERROR (μV)	10,000	4,400	1,800	1,300	14,500	3,950
Total (RMS)	ERROR (μV)	4,800	1,900	890	600	7,100	1,950
PRICE (100's) $U.S.		$1.00	$1.25	$2.25	$6.00	$2.00	$3.30

[1] For ±10V output into 1kΩ load.
[2] Not specified as a ratio, types 741 and 741C.
[3] Assuming ±5% power-supply change, 2 x 15 x 0.05 x 2 x PSRR.

WHAT IS A 741? (AN ANALOG DIATRIBE)

Users of 741's take them for granted: 741, 741C, TO-99, can, minidip, use them anywhere, get them anywhere, same specs, at the cheapest price. After all, a 741 is a 741 is a 741 . . . Right?

Not quite.

The μA741, as the historically-minded may recall, was Fairchild's answer to the National LM101A. Both were successful 2nd-generation op amps, but the 741 became the more popular (except for wideband applications) because of its internal compensation. Soon the number of suppliers of 741's mushroomed: five, ten, fifteen? twenty? It became the product with which a new supplier broke-in his linear process capability.

Curious thing about these suppliers: some make a pretty good 741; some make a pretty bad 741; some don't make a 741 at all. This isn't just a qualitative feel; there's hard engineering data to back it up. We can distinctly recall an evaluation of yet-another-741 by one of our engineers: "It's a good op amp . . . and if I were still designing systems, I might even use it . . . but it sure isn't a 741!" Call it I.C. design license; there are enough processing and design variations in existence to strongly suggest a policy of *caveat emptor* on the next "standard" 741 you meet. Here are a few manifestations of variety:

- Noise (to wit, *popcorn noise,* the erratic jump of bias current between two levels at random intervals). This kind of noise is process-oriented, and the fraction of units that exhibit it varies from lot to lot, but, in general, the manufacturers — both large and small — that supply low-noise 741's tend to do so consistently; and the guys that don't — again, both large and small — also tend to be consistent (sometimes with amplitudes as high as 150μV/100kΩ = 1.5nA).
- AC Performance Some 741's are said to be faster than the "ordinary" standard 741. One wonders whether this is by intent or by accident, since all it takes is a thicker oxide layer (i.e., less C) in the compensating capacitor. The fewer the pF's, the faster the device, but . . . the price you pay is possible instability (a) in tight feedback loops, or (b) if your circuit application has parasitic capacitive loads that a "slow" standard 741 takes in its stride. Such devices, in our book, are *not* 741's.
- Offset and drift The practice observed by all 741 manufacturers, of specifying a standard 741 (or 741C) for competitive purposes, deprives users of the highly-desirable $\Delta V_{OS}/\Delta T$ voltage-drift spec. However deplorable, it is an economic necessity: if you don't have a spec, you don't have to reject a 60μV/°C device for not meeting a 25μV/°C spec. The dilemma for the good guys is: if you have a process that can usually be depended on to produce mostly 10μV/°C units, how do you give your customers the benefit of the better spec, still remain price-competitive, and maintain some protection against "off" days?

Our solution is to label devices that are known to meet a

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*For information on AD508, and the AD741 family, request J10.

continued from page 11

20μV/°C specification (and other improved specs) AD741J, price them just a few cents higher, and still compete for the penny-pinching "don't-care" market with an AD741C (which is often a much better device than its name would indicate, but then again . . .). The beauty of this approach is that, as a bonus, we also get 15μV/°C AD741K's and 5μV/°C AD741L's, with other specs tightened, as the table shows. We also get much better feedback about our process from the large number of units that get extra testing. And finally, we get to publish some of the most-informative data sheets in the business.

A note to the user: with op amps that use simple differential-pair bipolar-transistor inputs, the lowest drift is experienced at the lowest offset. As the offset voltage is nulled out, the reduction of drift is commonly given as 3.3μV/°C/mV$_{OS}$. However, the 741 has a somewhat more-involved input circuit, and zeroing the amplifier may actually worsen the drift (then again, it may improve it, but we have to take Murphy's Law into account). Thus if low (e.g., zero) offset *and* low drift are needed, and the budget calls for a 741, the AD741K (2mV max) or the AD741L (0.5mV max) may be the answer for the commercial temperature range, and the AD741S (2mV max) for the "MIL" range.

- The dismal effects of economics The price-vs.-time curve for the 741 has been an apparent blessing to users; for producers, it has been a mixed curse, rewarding the efficient or the agile, penalizing the inefficient or the straightforward. Since profit (equal to price minus cost) is a key objective of producers, maintaining the equation's polarity positive requires that cost decrease as price decreases.

Sometimes, to keep cost coming down, a highly-motivated production manager might find it necessary to omit certain manufacturing cost items, such as 100% testing, or relax the test-limit guard bands, or loosen the AQL at outgoing Q.C. Don't scoff — it happens! If production efficiencies, that normally are realized by moving up the learning curve, don't occur, then corner cutting may appear to *some* to be the only way to keep profit margins reasonable (or, at least, positive). This may help to explain why — on an industrywide basis — as the price of the 741 has decreased, its quality appears to have declined (measured by increased lot rejections at users' incoming Q.C. and more field failures in systems).

Where does all this lead?

To a sober realization that many design engineers, component engineers, and buyers tend to regard use of the 741 as one regards breathing, or the ticking of a clock. That is, they don't pay much attention at all, until breathing gets difficult or the clock stops . . . until the old reliable 741 they were so familiar with is no longer reliable (or even familiar), the apparent saving due to the price war is no longer a saving, the new supplier's 741 doesn't act as it should, and the new design could use a little more accuracy than the standard 741 is specified to give.

The smart buyer no longer buys 741's on price alone (the cost of potentially-lower quality is more than a few cents per unit) but looks for variations of the 741 that are a cut above the average, and must have required extra care to be so identified.

Meet the AD741J, AD741K, AD741L, and AD741S!

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THE AD520: NOT AN OP AMP BUT AN INSTRUMENTATION AMPLIFIER

What is an instrumentation amplifier?

It is a device that accepts a voltage signal as an input and produces a linearly-scaled version at the output. It is a *closed-loop, committed, fixed-gain* amplifier, usually *differential*, with *high input impedance, low drift*, and *high common-mode rejection* over a wide range of frequencies; it is characterized by a set of specifications that describe *overall performance*.

The AD520*, introduced in Vol. 6, No. 1, is the only monolithic I.C. instrumentation amplifier known to us. However, there have been a number of monolithic I.C. amplifiers offered on the market as "instrumentation operational amplifiers," usually so-called because of their low drift or high CMR. However, it must be clearly understood that they are *open-loop, uncommitted, high-open-loop-gain* devices that must usually be connected in pairs or triads in a circuit involving a number of precision resistors, in order to work as instrumentation amplifiers. Furthermore, their specifications describe the *basic device performance*.

By the time they have been adapted to the application, a number of compromises will have been made that adversely affect cost, complexity, or performance of the assembled closed-loop, committed, fixed-gain circuit. In effect, the *user* (not the manufacturer) must be able to guarantee the overall performance.

By contrast, the AD520K, with a pair of low-T.C. resistors and a few added components (mostly capacitors) with non-critical parameters (Figure 1), will provide gain-of-1000 with CMR = 106dB (min, 1kΩ source unbalance, 0-100Hz), drift = 5μV/°C (max, r.t.i.), slew rate = 2.5V/μs (min), I_b = 40nA (max), at a device cost of $16 (100's).

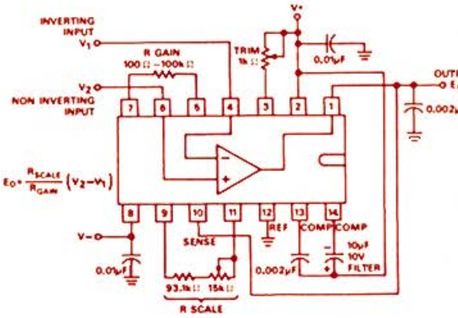

Figure 1. The AD520 in a Typical Application, Showing All Auxiliary Components

An interesting feature of the AD520 is the pair of feedback terminals, labeled *Sense* and *Reference*. They can be used to provide an output bias, current-controlled output (either floating or grounded), and high output current (via an inside-the-loop booster follower) without affecting accuracy. The already low drift can be reduced further by chopping the input signal and using the *Sense* and *Reference* terminals, with a *hold* circuit, to null out input offsets in the *feedback* circuit, without affecting response speed during the *hold* interval. More information on this technique will appear in a future issue of *Dialogue*.

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*For complete data (including 2 pages of specifications) on the AD520, use the reply card. Request **J11**.