# Performance Verification of Low Noise, Low Dropout Regulators

## Silence of the Amps

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## Introduction

In an increasing trend, telecommunications, networking, audio and instrumentation require low noise power supplies. In particular, there is interest in low noise, low dropout linear regulators (LDO). These components power noise-sensitive circuitry, circuitry that contains noise-sensitive elements or both. Additionally, to conserve power, particularly in battery driven apparatus such as cellular telephones, the regulators must operate with low input-to-output voltages.[1] Devices presently becoming available meet these requirements (see separate section, "A Family of $20\mu V_{RMS}$ Noise, Low Dropout Regulators").

## Noise and Noise Testing

Establishing and specifying LDO dropout performance is relatively easy to do. Verifying that a regulator meets dropout specification is similarly straightforward. Accomplishing the same missions for noise and noise testing is considerably more involved. The noise bandwidth of interest must be called out, along with operating conditions. Operating conditions can include regulator input and output voltage, load, assorted discrete components, etc. Low noise performance is effected by numerous subtleties; changes in operating conditions can cause unwelcome surprises.[2] Because of this, LDO noise must be quoted under specified operating and bandwidth conditions to be meaningful. Failure to observe this precaution will result in misleading data and erroneous conclusions.

## Noise Testing Considerations

What noise bandwidth is of interest and why is it interesting? In most systems, the range of 10Hz to 100kHz is the information signal processing area of concern. Additionally, linear regulators produce little noise energy outside this region.[3] These considerations suggest a measurement bandpass of 10Hz to 100kHz, with steep slopes at the band limits. Figure 1 shows a conceptual filter for LDO noise testing. The Butterworth sections are the key to steep slopes and flatness in the passband. The small input level requires 60dB of low noise gain to provide adequate signal for the Butterworth filters. Figure 2 details the filter scheme. The regulator under test is at the diagram's center.[4] A1-A3 make up a 60dB gain highpass section. A1 and A2, extremely low noise devices ($<1nV\sqrt{Hz}$), comprise a 60dB gain stage with a 5Hz highpass input. A3 provides a 10Hz, 2nd order Butterworth highpass characteristic. The LTC®1562 filter block is arranged as a 4th order Butterworth lowpass. Its output is delivered via the $330\mu F$-$100\Omega$ highpass network. The circuit's output drives a thermally responding RMS voltmeter.[5] Note that all circuit power is furnished by batteries, precluding ground loops from corrupting the measurement.

## Instrumentation Performance Verification

Good measurement technique dictates verifying the noise test instrumentation's performance. Figure 3's spectral plot of the filter section shows essentially flat response in the 10Hz to 100kHz passband with abrupt slopes at the band extremes. Figure 4, expanding the vertical scale to

**Note 1:** See Appendix A, "Architecture of a Low Noise LDO," for design considerations of these devices.

**Note 2:** See Appendix D, "Practical Considerations for Selecting a Low Noise LDO."

**Note 3:** Switching regulators are an entirely different proposition, requiring very broadband noise measurement. See Reference 1.

**Note 4:** Component choice for the regulator, more critical than might be supposed, is discussed in Appendix B, "Capacitor Selection Considerations."

**Note 5:** The choice of RMS voltmeter is absolutely crucial to obtain meaningful measurements. See Appendix C, "Understanding and Selecting RMS Voltmeters."

## A FAMILY OF 20$\mu$V$_{RMS}$ NOISE, LOW DROPOUT REGULATORS

Telecom and instrumentation applications often require a low noise voltage regulator. Frequently this requirement coincides with the need for low regulator dropout and small quiescent current. A recently introduced family of devices addresses this problem. Figure A shows a variety of packages, power ranges and features in three basic regulator types. The SOT-23 packaged LT®1761 has only 20$\mu$V$_{RMS}$ noise with 300mV dropout at 100mA. Quiescent current is only 20$\mu$A.

### Applying the Regulators

Applying the regulators is simple. Figure B shows a minimum parts count, 3.3V output design. This circuit appears similar to conventional approaches with a notable exception: a bypass pin (BYP) is returned to the output via a 0.01$\mu$F capacitor. This path filters the internal reference's output, minimizing regulator output noise. It is the key to the 20$\mu$V$_{RMS}$ noise performance. A shutdown pin ($\overline{\text{SHDN}}$), when pulled low, turns off the regulator output while keeping current drain inside 1$\mu$A. Dropout characteristics appear in Figure C. Dropout scales with output current, falling to less than 100mV at low currents.

These devices provide the lowest available output noise in a low dropout regulator without compromising other parameters. Their performance, ease of use and versatility allow use in a variety of noise-sensitive applications.

| REGULATOR TYPE | OUTPUT CURRENT | RMS NOISE (10Hz to 100kHz) $C_{BYP} = 0.01\mu F$ | PACKAGE OPTIONS | FEATURES | QUIESCENT CURRENT | SHUTDOWN CURRENT |
|---|---|---|---|---|---|---|
| LT1761 | 100mA | 20$\mu$V$_{RMS}$ | SOT23-5 | Shutdown, Reference Bypass, Adjustable Output; SOT23 Package Mandates Selecting Any Two Features | 20$\mu$A | <1$\mu$A |
| LT1762 | 150mA | 20$\mu$V$_{RMS}$ | MSOP-8 | Shutdown, Reference Bypass, Adjustable Output | 25$\mu$A | <1$\mu$A |
| LT1962 | 300mA | 20$\mu$V$_{RMS}$ | MSOP-8 | Shutdown, Reference Bypass, Adjustable Output | 30$\mu$A | <1$\mu$A |
| LT1763 | 500mA | 20$\mu$V$_{RMS}$ | SO-8 | Shutdown, Reference Bypass, Adjustable Output | 30$\mu$A | <1$\mu$A |
| LT1963 | 1.5A | 40$\mu$V$_{RMS}$ | SO-8, SOT223-3, DD-5, TO220 | Shutdown, Adjustable Output, Fast Transient Response | 1mA | <1$\mu$A |
| LT1764 | 3A | 40$\mu$V$_{RMS}$ | DD-5, TO220 | Shutdown, Adjustable Output, Fast Transient Response | 1mA | <1$\mu$A |

**Figure A. Low Noise LDO Family Short-Form Specifications. Quiescent Current Scales with Output Current Capability, Although Noise Performance Remains Nearly Constant**
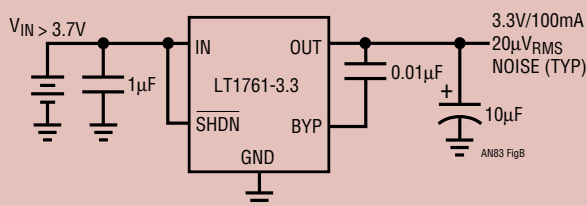


**Figure B. Applying the Low Noise, Low Dropout, Micropower Regulator. Bypass Pin and Associated Capacitor are Key to Low Noise Performance**
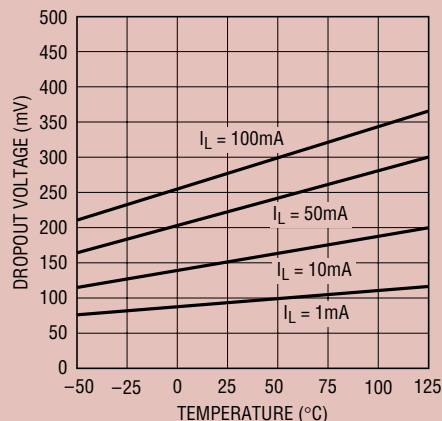


**Figure C. Figure B's Dropout Voltage at Various Currents**

1dB/division, reveals some flatness deviation but well within 1dB throughout nearly the entire passband. Grounding the filter's input determines the tester's noise floor. Figure 5 shows less than $4\mu V_{P-P}$, corresponding to a $0.5\mu V_{RMS}$ voltmeter reading. This is only about 0.5% of full scale ($100\mu V_{RMS}$), contributing negligible error. These results assure the confidence necessary to proceed with regulator noise measurement.

## Regulator Noise Measurement

Regulator noise measurement begins with attention to test setup details. The extremely low signal levels require attention to shielding, cable management, layout and component choice.[6] Figure 6a is the bench arrangement. The photo shows the completely shielded environment required to obtain faithful noise measurements. The metal can[7] encloses the regulator under test and its internal battery power supply. A BNC fitting (photo lower center) connects the regulator output to the noise filter test circuit (black box). Note that the monitoring oscilloscope and voltmeter are not simultaneously connected to the output, precluding ground loops which would corrupt the measurement.

Figure 6b details the regulator enclosure with its cover removed. The battery supply is visible; the regulator occupies the can center. The BNC fitting connecting the noise filter box (lower left) eliminates triboelectric disturbances a cable might contribute.

Figure 6c is the noise test circuit box. Functions are as labeled in the photo. The two capped BNC connectors (box lower) are unused box entries.

Figure 7's oscilloscope photo shows an LT1761 regulator's noise measured at the filter output. Monitoring this point with the RMS voltmeter shows a $20\mu V_{RMS}$ reading. Figure 8's spectral plot of this noise indicates diminished power above 1kHz, in accordance with expected regulator noise density. Figure 9 shows more complete spectral noise density data for three regulator types. Noise power decays uniformly with increasing frequency, although the three regulators show some dispersion below 200Hz.

## Bypass Capacitor ($C_{BYP}$) Influence

The regulator's internal voltage reference contributes most of the device's noise. The reference bypass capacitor filters reference noise, precluding it from appearing, in amplified form, at the output.[8] Figure 10 is a study of regulator noise vs various values of $C_{BYP}$. 10a shows substantial noise for $C_{BYP} = 0\mu F$, while 10d displays nearly $9\times$ improvement with $C_{BYP} = 0.01\mu F$; intermediate values of $C_{BYP}$ (10b and 10c) produce commensurate results.

## Interpreting Comparative Results

Figure 11's photos compare an LT1761-5's output noise (11d) with three other regulators (11a, 11b and 11c). These three devices are manufacturer specified for low noise performance, but the photos do not indicate this. The seeming contradication is probably due to ambiguity in testing methods or specifications. For example, inappropriate choice of test equipment (see Appendix C) or measurement bandwidth can easily cause huge ($5\times$) errors. This uncertainty mandates the noise testing described to insure realistic conclusions.

**Note 6:** Capacitor choice is discussed in Appendix B, "Capacitor Selection Considerations."

**Note 7:** The cookies were excellent, particularly the thin ones with sugar on top.

**Note 8:** See Appendix A, "Architecture of a Low Noise LDO," for details.
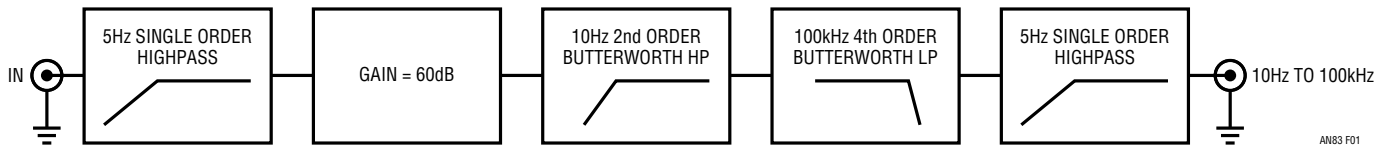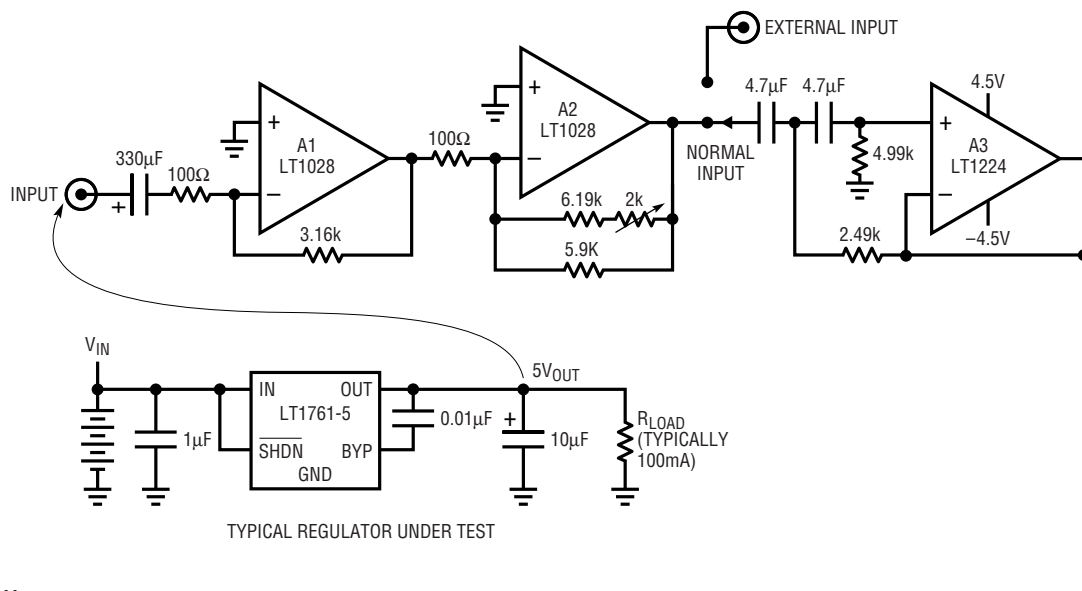
**Figure 1. Filter Structure for Noise Testing LDOs. Butterworth Sections Provide Appropriate Response in Desired Frequency Range**



ALL RESISTORS 1% METAL FILM
4.7μF CAPACITORS = MYLAR, WIMA MKS-2
330μF CAPACITORS = SANYO OSCON
±4.5V DERIVED FROM 6AA CELLS
POWER REGULATOR FROM APPROPRIATE
NUMBER OF D SIZE BATTERIES

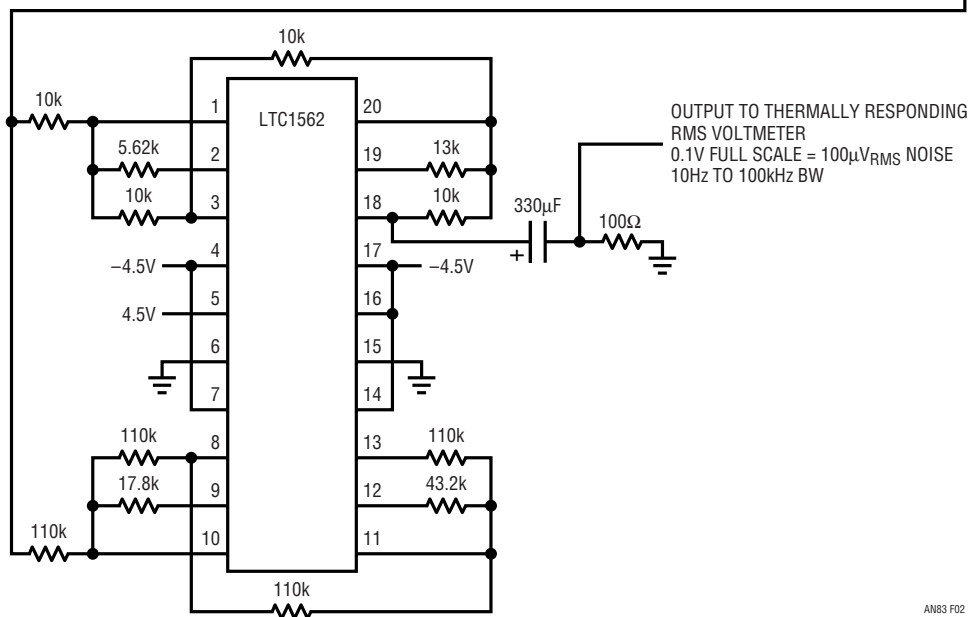OUTPUT TO THERMALLY RESPONDING
RMS VOLTMETER
0.1V FULL SCALE = 100μV$_{RMS}$ NOISE
10Hz TO 100kHz BW

**Figure 2. Implementation of Figure 1. Low Noise Amplifiers Provide Gain and Initial Highpass Shaping. LTC1562 Filter Supplies 4th Order Butterworth Lowpass Characteristic**
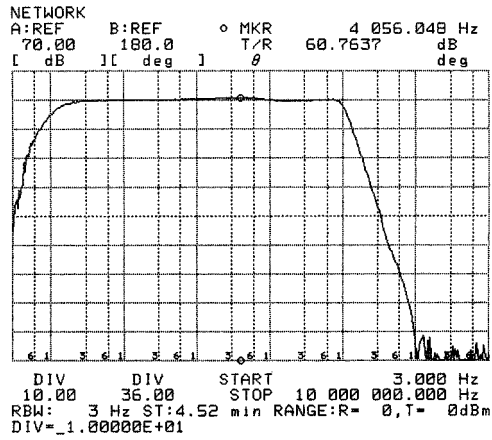
```
NETWORK
A:REF      B:REF      ○ MKR      4 056.048 Hz
 70.00      180.0      T/R   60.7637      dB
[  dB  ][  deg  ]      θ                   deg
```

```
  DIV        DIV      START        3.000 Hz
 10.00      36.00      STOP  10 000 000.000 Hz
RBW:  3 Hz ST:4.52 min RANGE:R=  0,T=  0dBm
DIV=_1.00000E+01
```

AN83 F03.eps

**Figure 3. HP-4195A Spectrum Analyzer Plot of Filter Characteristics. Filter Performance Is Nearly Flat Over Desired 10Hz to 100kHz Range with Steep Rolloff Outside Bandpass Region**



```
NETWORK
A:REF      B:REF      ○ MKR      4 056.048 Hz
 65.00      180.0      T/R   60.7637      dB
[  dB  ][  deg  ]      θ                   deg
```

```
  DIV        DIV      START        3.000 Hz
 1.000      36.00      STOP  10 000 000.000 Hz
RBW:  3 Hz ST:4.52 min RANGE:R=  0,T=  0dBm
DIV=_1.00000E+00
```

AN83 F04.eps
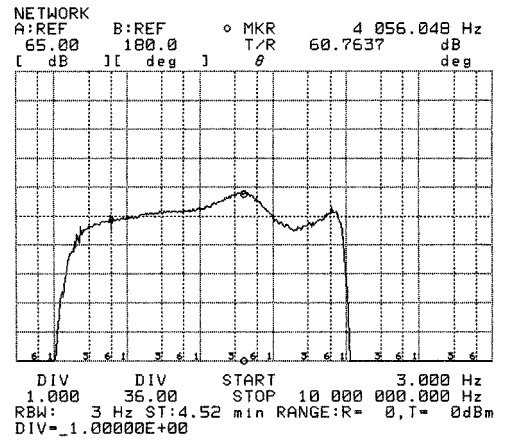
**Figure 4. Expanded Scale Examination of Passband Shows Flatness within 1dB Over Almost Entire Measurement Range**



2μV/DIV

1ms/DIV

AN83 F05
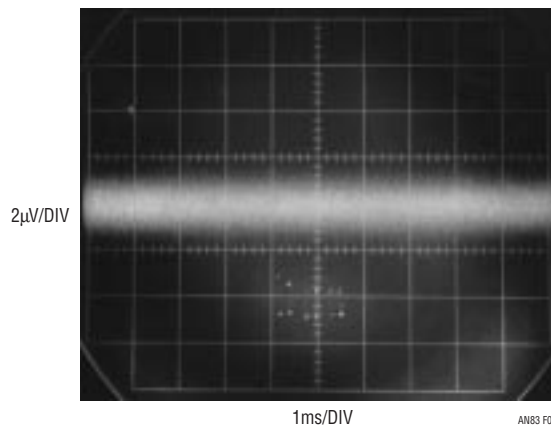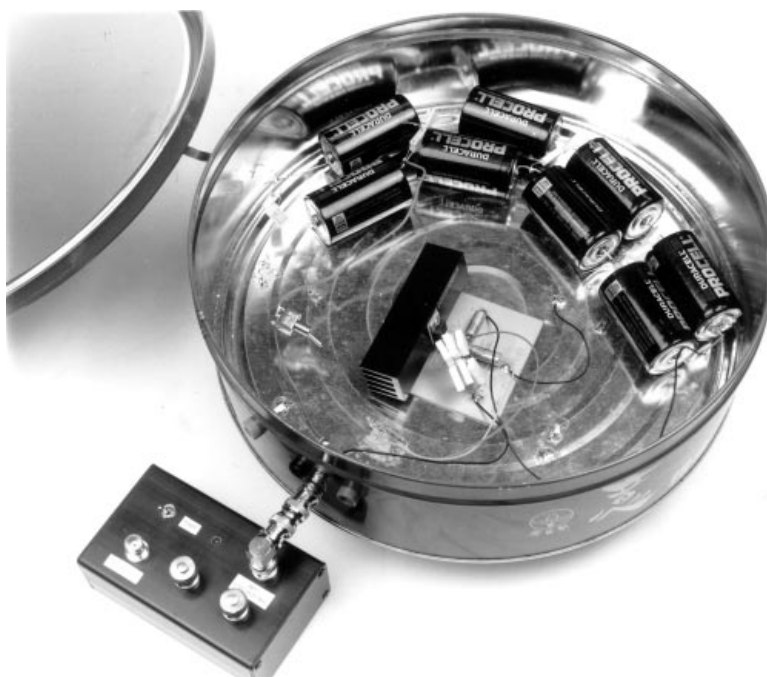
**Figure 5. <4μV$_{P-P}$ Test Setup Noise Residue Corresponds to About 0.5μV$_{RMS}$ Measurement Noise Floor**

**Figure 6a. LDO Noise Measurement Bench Setup. Shielded Can Contains Regulator; Noise Filter Circuitry Occupies Box at Photo Lower Center. Oscilloscope and RMS Voltmeter Are Not Simultaneously Connected, Precluding Ground Loop from Corrupting Measurement**



**Figure 6b. Shielded can with Cover Removed. LDO Under Test Occupies Center. D-Cells Provide Power, Eliminate Potential Ground Loop. BNC Fitting (Photo Lower Left) Connects Output to Filter Circuit Test Box, Minimizing Triboelectric Based Errors**
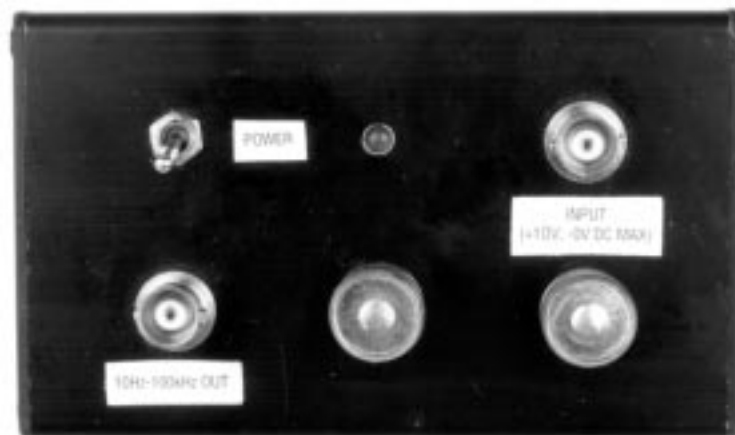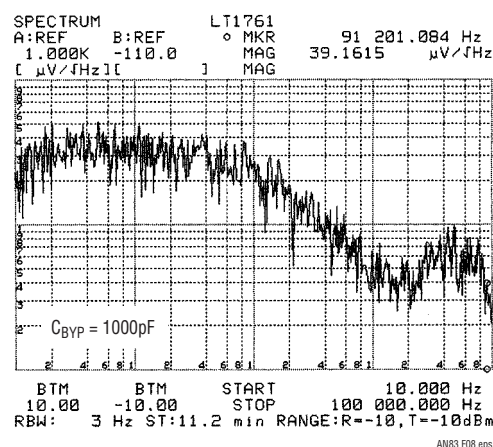
AN83 F06b

**Figure 6c. Noise Filter Test Box Is Fully Shielded. Connections Are As Indicated.
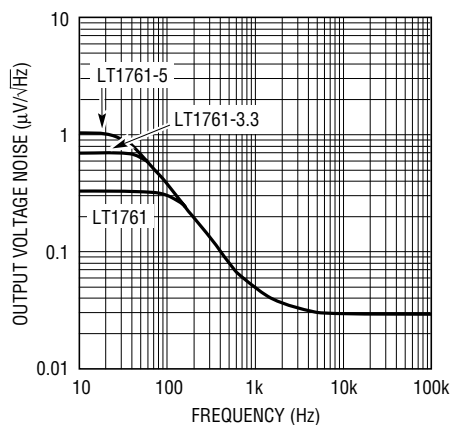Capped BNC Fittings (Photo Low Center and Right) Are Unused Entries**



1ms/DIV
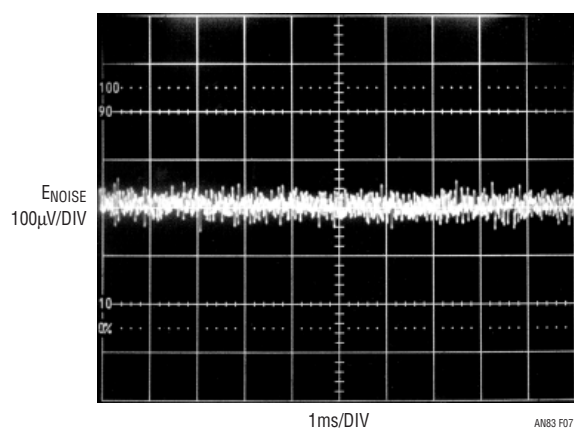
AN83 F07

**Figure 7. LT1761 Output Voltage Noise in a 10Hz to
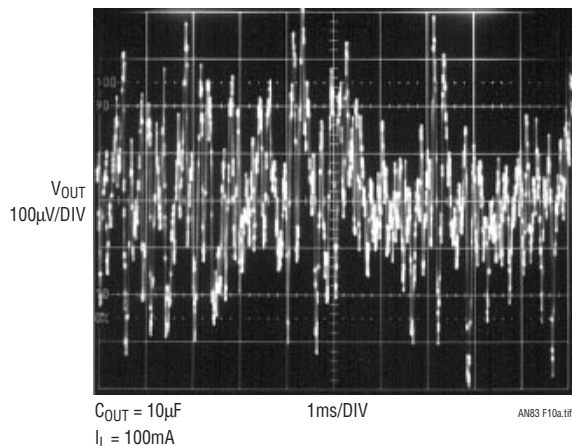100kHz Bandwidth. RMS Noise Measures 20$\mu V_{RMS}$**



AN83 F08.eps

**Figure 8. Noise Spectrum Plot Shows
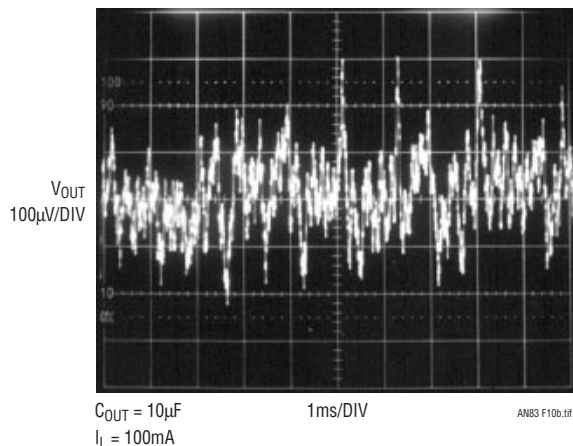Diminishing Power Above 1kHz**



AN 83 F09

**Figure 9. Output Noise Spectral Density Data Curves
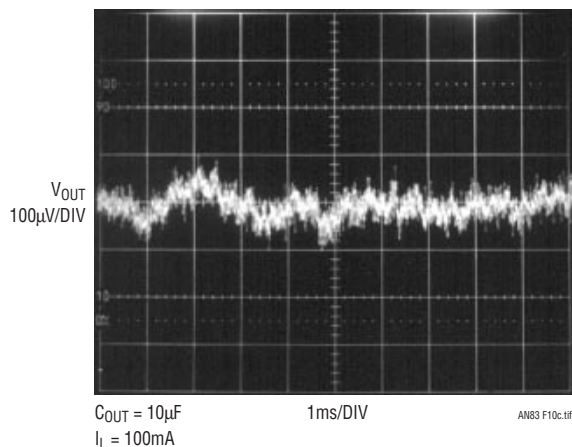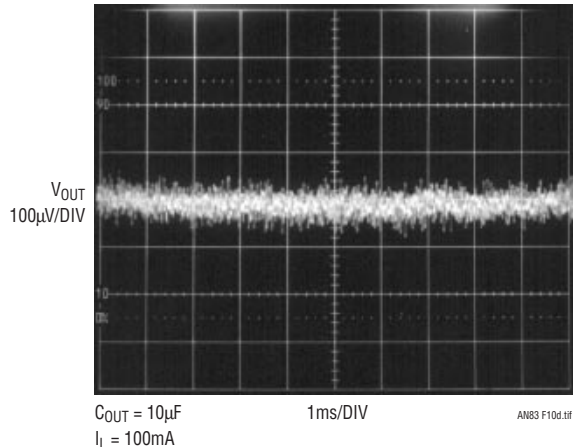for Three Regulators Show Dispersion Below 200Hz**

$C_{OUT} = 10\mu F$  1ms/DIV  AN83 F10a.tif
$I_L = 100mA$

**(10a) LT1761-5**
**10Hz to 100kHz Output Noise**
**$C_{BYP} = 0$**



$C_{OUT} = 10\mu F$  1ms/DIV  AN83 F10b.tif
$I_L = 100mA$

**(10b) LT1761-5**
**10Hz to 100kHz Output Noise**
**$C_{BYP} = 100pF$**



$C_{OUT} = 10\mu F$  1ms/DIV  AN83 F10c.tif
$I_L = 100mA$

**(10c) LT1761-5**
**10Hz to 100kHz Output Noise**
**$C_{BYP} = 1000pF$**



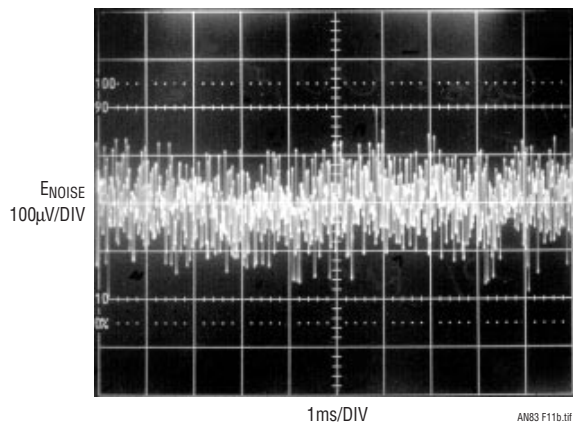$C_{OUT} = 10\mu F$  1ms/DIV  AN83 F10d.tif
$I_L = 100mA$

**(10d) LT1761-5**
**10Hz to 100kHz Output Noise**
**$C_{BYP} = 0.01\mu F$**

**Figure 10. Regulator Noise for Various Bypass Capacitor**
**($C_{BYP}$) Values. Noise Decreases with Increasing $C_{BYP}$**
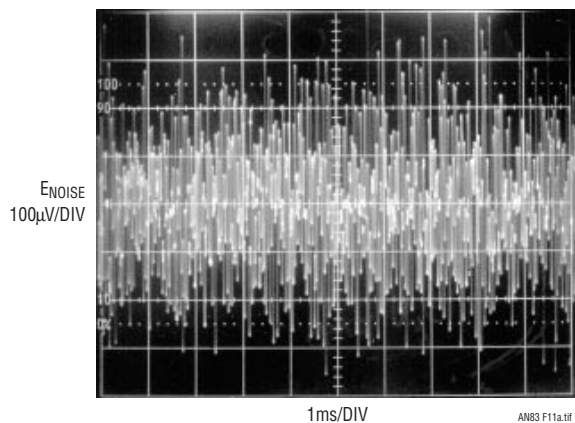
(11a) Manufacturer "MI" Output Voltage Noise (5V Output)



(11b) Manufacturer "NS" Output Voltage Noise (5V Output)
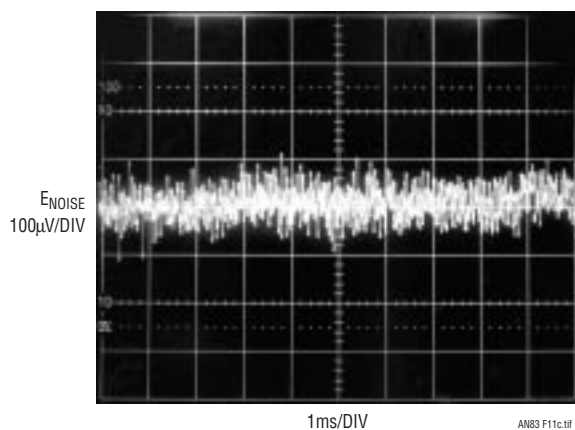


(11c) Manufacturer "MA" Output Voltage Noise (5V Output)



(11d) LT1761-5 Output Voltage Noise (5V Output)

**Figure 11. Noise for LT1761-5 vs Three Other Devices.**
**"C" Is Specified for RMS Noise Figure Approaching the LT1761-5,**
**but in a Restricted Noise Measurement Bandwidth. Caveat Emptor!**

## REFERENCES

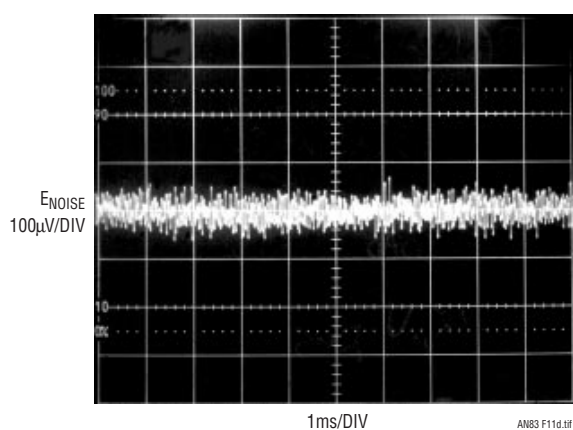1. Williams, J., "A Monolithic Switching Regulator with 100µV Output Noise," Linear Technology Corporation, Application Note 70, October 1997.

2. Sheingold, D. H. (editor), "Nonlinear Circuits Handbook," 2nd Edition, Analog Devices, Inc., 1976.

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4. Williams, J., "Practical Circuitry for Measurement and Control Problems," "Broadband Random Noise Generator," "Symmetrical White Gaussian Noise" Appendix B, Linear Technology Corporation, Application Note 61, August 1994, pp. 24–26, pp. 38–39.

5. General Radio Company, Type 1390B Random Noise Generator Operating Instructions, October 1961.

6. Hewlett-Packard Company, "1968 Instrumentation. Electronic—Analytical—Medical," AC Voltage Measurement, Hewlett-Packard Company, 1968, pp. 197–198.

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12. O'Neill, P.M., " A Monolithic Thermal Converter," H.P. Journal, May 1980.

13. Williams, J., "A Fourth Generation of LCD Backlight Technology," "RMS Voltmeters," Linear Technology Corporation, Application Note 65, November 1995, pp. 82–83.

14. Tektronix, Inc., "Type 1A7A Differential Amplifier Instruction Manual," Check Overall Noise Level Tangentially, 1968, pp. 5-36 and 5-37.

## APPENDIX A

### ARCHITECTURE OF A LOW NOISE LDO

**Noise Minimization**

The low noise LDOs use Figure A1's scheme, with special attention to minimizing noise transmission within the loop and from unregulated input. The internal voltage reference's noise is filtered by $C_{BYP}$. Additionally, the error amplifier's frequency response is shaped to minimize noise contribution while preserving transient response and PSRR. Regulators which do not do this have poor noise rejection and transient performance.

**Pass Element Considerations**

Extremely low dropout voltage requires considering the pass element. Dropout limitations are set by the pass elements on-impedance limits. The ideal pass element has zero impedance capability between input and output and consumes no drive energy.

A number of design and technology options offer various trade-offs and advantages. Figure A2 lists some pass element candidates. Followers offer current gain, ease of loop compensation (voltage gain is below unity) and the drive current ends up going to the load. Unfortunately, saturating a follower requires voltage overdriving the input (e.g. base, gate). Since drive is usually derived directly from $V_{IN}$, this is difficult. Practical circuits must either generate the overdrive or obtain it elsewhere. Without voltage overdrive, the saturation loss is set by $V_{BE}$ in the bipolar case and channel on-resistance for MOS. MOS channel on-resistance varies considerably under these conditions, although bipolar losses are more predictable. Note that voltage losses in driver stages (Darlington, etc.) add directly to the dropout voltage. The follower output used in conventional 3-terminal IC regulators combines with drive stage losses to set dropout at 3V.

Common emitter/source is another pass element option. This configuration removes the $V_{BE}$ loss in the bipolar case. The PNP version is easily fully saturated, even in IC form. The trade-off is that the base current never arrives at the load, wasting power. At higher currents, base drive losses can negate a common emitter's saturation advantage. As in the follower example, Darlington connections exacerbate the problem. Achieving low dropout in a monolithic PNP regulator requires a PNP structure that attains low dropout while minimizing base drive loss. This is particularly the case at higher pass currents. Considerable effort was expended in this direction in the LT176X through LT196X designs.

Common source connected P-channel MOSFETs are also candidates. The do not suffer the drive losses of bipolars, but typically require volts of gate-channel bias to fully saturate. In low voltage applications this may require generation of negative potentials. Additionally, P-channel devices have poorer saturation than equivalent size N-channel devices.

The voltage gain of common emitter and source configurations is a loop stability concern but is manageable.

Compound connections using a PNP driven NPN are a reasonable compromise, particularly for high power (beyond 250mA) IC construction. The trade-off between the PNP $V_{CE}$ saturation term and reduced drive losses over a conventional PNP structure is favorable. Also, the major current flow is through a power NPN, easily realized in monolithic form. The connection has voltage gain, necessitating attention to loop frequency compensation. Regulators utilizing this pass scheme can supply up to 7.5A with dropouts below 1.5V (LT1083 through LT1086 series).

Readers are invited to submit results obtained with our emeritus thermionic friends, shown out of respectful courtesy.

## Dynamic Characteristics

The LT176X through LT196X's low quiescent currents do not preclude good dynamics. Usually, low quiescent power devices are associated with slow dynamics and instability. The devices are stable (no output oscillation) even with low ESR ceramic output capacitors. This contrasts with conventional LDO regulators that often oscillate with ceramic capacitors.
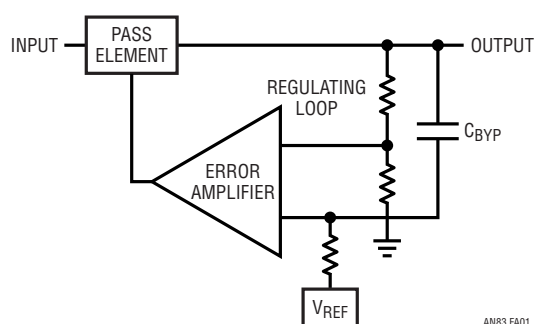
The internal architecture provides an added bonus in transient performance when the 0.01µF noise capacitor is added. Transient response for a 10mA to 100mA load step with a 10µF output capacitor appears in Figure A3 with the capacitor deleted. Figure A4 shows the same situation with the 0.01µF bypass capacitor in place. Settling time and amplitude are markedly reduced.



**Figure A1. Simplified Low Noise LDO Regulator. Voltage Reference Is Filtered by C$_{BYP}$, Isolating Noise from Regulating Loop. Error Amplifier's Frequency Compensation Prevents Transmission of Input Noise While Preserving Transient Response**
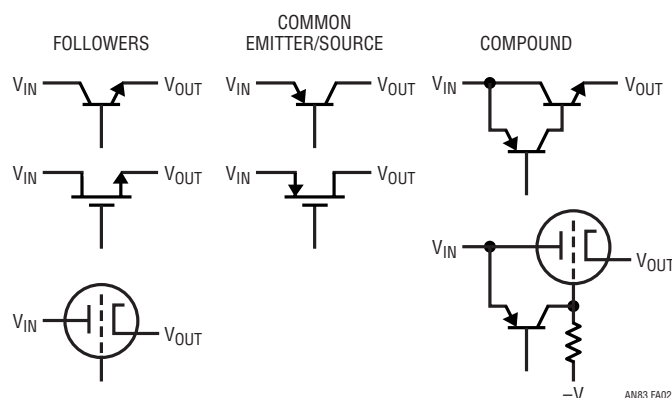


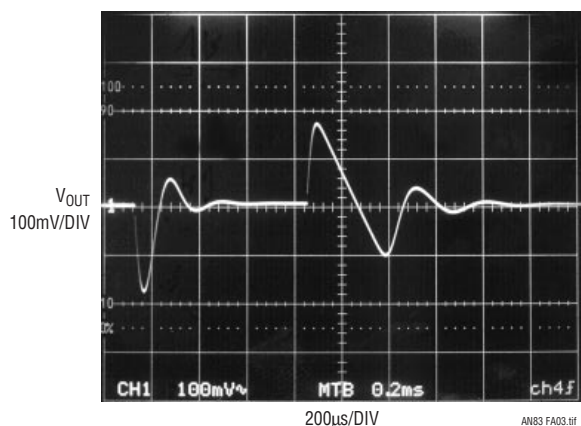**Figure A2. Linear Regulator Pass Element Candidates**



200µs/DIV

**Figure A3. Transient Response without Noise Bypass Capacitor**
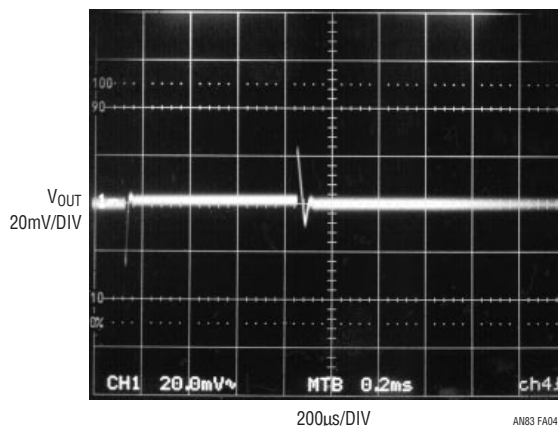


200µs/DIV

**Figure A4. Noise Bypass Capacitor Improves Transient Response. Note Voltage Scale Change**

## APPENDIX B

### CAPACITOR SELECTION CONSIDERATIONS

**Bypass Capacitance and Low Noise Performance**

Adding a capacitor from the regulators $V_{OUT}$ to BYP pin lowers output noise. A good quality low leakage capacitor is recommended. This capacitor bypasses the regulator's reference, providing a low frequency noise pole. A 0.01µF capacitor lowers the output voltage noise to 20µV$_{RMS}$. Using a bypass capacitor also improves transient response. With no bypassing and a 10µF output capacitor, a 10mA to 500mA load step settles within 1% of final value in under 100µs. With a 0.01µF bypass capacitor, the output settles within 1% for the same load step in under 10µs; total output deviation is inside 2.5%. Regulator start-up time is inversely proportional to bypass capacitor size, slowing to 15ms with a 0.01µF bypass capacitor and 10µF at the output.

**Output Capacitance and Transient Response**

The regulators are designed to be stable with a wide range of output capacitors. Output capacitor ESR affects stability, most notably with small capacitors. A 3.3µF minimum output value with ESR of 3Ω or less is recommended to prevent oscillation. Transient response is a function of output capacitance. Larger values of output capacitance decrease peak deviations, providing improved transient response for large load current changes. Bypass capacitors, used to decouple individual components powered by the regulator, increase effective output capacitor value. Larger values of reference bypass capacitance dictate larger output capacitors. For 100pF of bypass capacitance, 4.7µF of output capacitor is recommended. With 1000pF of bypass capacitor or larger, a 6.8µF output capacitor is required.

Figure B1's shaded region defines the regulator's stability range. Minimum ESR needed is set by the amount of bypass capacitance used, while maximum ESR is 3Ω.

**Ceramic Capacitors**

Ceramic capacitors require extra consideration. They are manufactured with a variety of dielectrics, each with different behavior across temperature and applied voltage. The most common dielectrics are Z5U, Y5V, X5R and X7R. The Z5U and Y5V dielectrics provide high capacitance in a small package, but exhibit strong voltage and temperature coefficients as shown in Figures B2 and B3. Used with a 5V regulator, a 10µF Y5V capacitor shows value as low as 1µF to 2µF over the operating temperature range. The X5R and X7R dielectrics have more stable characteristics and are more suitable for output capacitor use. The X7R type has better stability over temperature, while the X5R is less expensive and available in higher values.
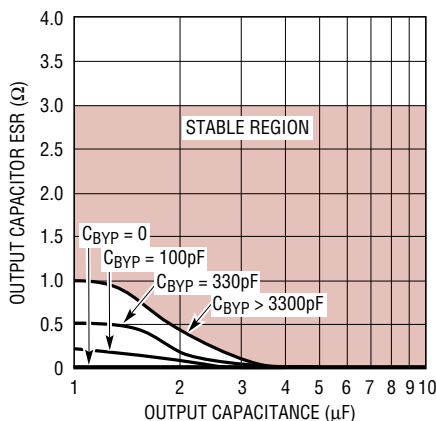


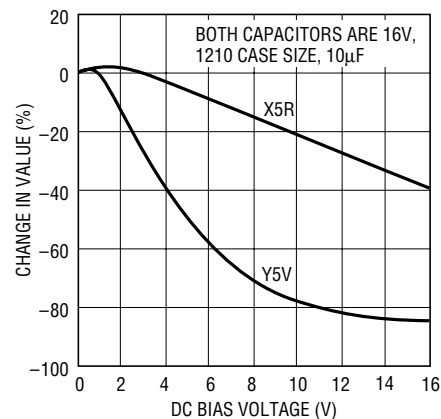Figure B1. Regulator Stability for Various Output and Bypass (C$_{BYP}$) Capacitor Characteristics



Figure B2. Ceramic Capacitor DC Bias Characteristics Indicate Pronounced Voltage Dependence. Device Must Provide Desired Capacitance Value at Operating Voltage

Voltage and temperature coefficients are not the only problem sources. Some ceramic capacitors have a piezoelectric response. A piezoelectric device generates voltage across its terminals due to mechanical stress, similar to the way a piezoelectric accelerometer or microphone works. For a ceramic capacitor the stress can be induced by vibrations in the system or thermal transients. The

resulting voltages produced can cause appreciable amounts of noise, especially when a ceramic capacitor is used for noise bypassing. A ceramic capacitor produced Figure B4's trace in response to light tapping from a pencil. Similar vibration induced behavior can masquerade as increased output voltage noise.
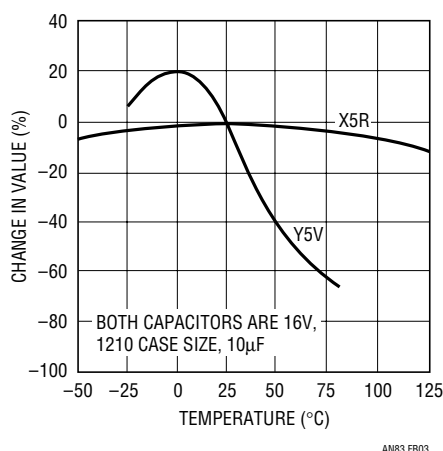


**Figure B3. Ceramic Capacitor Temperture Characteristics Show Large Capacitance Shift. Effect Should Be Considered When Determining Circuit Error Budget**
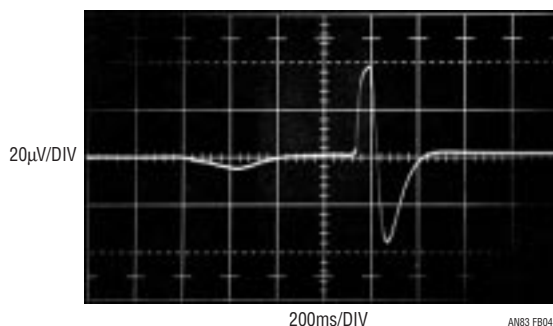


**Figure B4. A Ceramic Capacitor Responds to Light Pencil Tapping. Piezoelectric Based Response Approaches 80$\mu$V$_{P-P}$**

## APPENDIX C

### UNDERSTANDING AND SELECTING RMS VOLTMETERS

The choice of AC voltmeter is absolutely crucial for meaningful measurements. The AC voltmeter must respond faithfully to the RMS value of the measured noise. The majority of AC voltmeters (including DVMs with AC ranges) are *not* capable of doing this. This includes instruments with "true RMS" AC scales. As such, selecting an appropriate instrument requires care. The selection process begins with a basic understanding of AC voltmeter types.[1]

### AC Voltmeter Types

There are three basic AC voltmeter types. They include rectify and average, analog computing and thermal. The thermal approach is the only one that is inherently accurate, regardless of input waveshape. This feature is particularly relevant to noise RMS amplitude determination.

### Rectify and Average

The rectify and average scheme (Figure C1) applies the AC input to a precision rectifier. The rectifier output feeds a simple RC averager which is gain scaled, providing the output. In practice, gain is set so the DC output equals the RMS value of a sine wave input. If the input remains a pure sine wave, accuracy can be quite good. However, nonsinosoidal inputs cause large errors. This type voltmeter is only accurate for sine wave inputs, with increasing error as the input departs from sinosoidal.

**Note 1:** Another way to approximately measure RMS AC noise using an oscilloscope is the tangential method. See Reference 14.

## Analog Computation

Figure C2 shows a more sophisticated AC voltmeter method. Here, the instantaneous value is (ideally) continuously computed by an analog computational loop. The DC output follows the equation noted, resulting in much better accuracy as input waveshape varies. Almost all commercial implementations of this approach utilize logarithmically based analog computing techniques. Unfortunately, dynamic limitations in the ZY/X block dictate bandwidth restrictions. These circuits typically develop significant errors beyond 20kHz to 200kHz.

## Thermal

The thermally based AC voltmeter is inherently insensitive to input waveshape, particularly suiting it to noise RMS amplitude measurement. Additionally, high accuracy at bandwidths exceeding 100MHz is achievable. Figure C3 diagrams the classic thermal scheme.[2] It is composed of matched heater-temperature sensor pairs and an amplifier. The AC input drives a heater, warming it. The temperature sensor associated with this heater responds, biasing the amplifier. The amplifier closes its feedback loop by driving the output heater to warm its associated temperature sensor. When the loop closes, the heaters are at the same temperature. This "force-balance" action results in the DC output equalling the input heater's RMS heating value—the fundamental definition of RMS. Changes in waveshape have no effect, as they are effectively downconverted to heat. This "first principles" nature of operation makes thermally based AC voltmeters ideal for quantitative RMS noise measurement.

## Performance Comparison of Noise Driven AC Voltmeters

The wide performance variation of the above methods, and even within a method, mandates caution in selecting an AC voltmeter. Comparing AC voltmeters intended for use in RMS noise measurements is illuminating. Figure C4 shows a simple evaluation arrangement. The noise generator drives the external input of text Figure 2, producing a suitably band passed input at the voltmeter under test.[3]
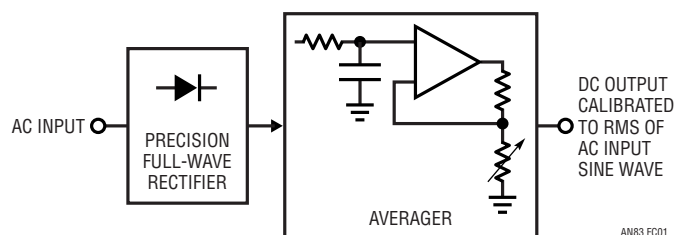


**Figure C1. Rectify-and-Average Based AC-DC Converter. Gain Is Set So DC Output Equals RMS Value of Sine Wave Input. Nonsine Inputs Produce Errors**
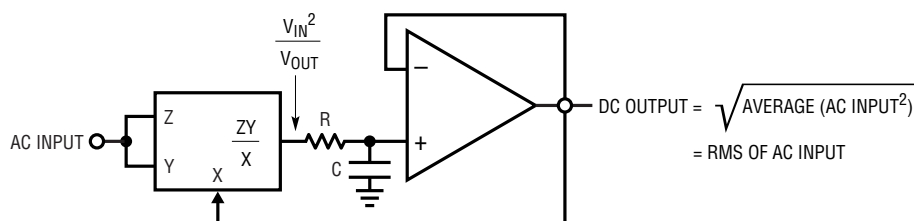


FIGURE DERIVED FROM REFERENCES 2 AND 3

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**Figure C2. Analog Computer Based AC-DC Converter. Loop Continuously Computes Input's RMS Value. Bandwidth Limitations Produce High Frequency Errors**

**Note 2:** See the References section for publications covering thermal AC–DC conversion.

**Note 3:** Noise generators are worthy of study and considered in References 4 and 5.

Figure C5 shows results for 20 voltmeters. Four of the voltmeters are thermal types; the remainder utilize logarithmic analog computing or rectify and average AC-DC conversion. The four thermal types agreed well within 1%. In fact, three of the thermal types were within 0.2%, while the fourth (HP3400A), a metered instrument, is only readable to 1%. The other 16 voltmeters showed errors up to 48% relative to the thermal group! Note that the errors cause lower readings than are actually warranted; a poorly chosen voltmeter will give unfairly optimistic readings.

The lesson here is clear. It is essential to verify AC voltmeter accuracy before proceeding with RMS noise measurement. Failure to do so may cause highly misleading "results."

### Thermal Voltmeter Circuit

It is sometimes desirable to construct, rather than purchase, a thermal voltmeter. Figure C6's circuit is applicable to noise measurement. Text Figure 2's filter feeds A1. A1's output biases A2, which provides additional AC gain. The LT1088 based RMS/DC converter is made up of matched pairs of heaters and diodes and a control amplifier. The LT1206 drives R1, producing heat which lowers D1's voltage. Differentially connected A3 responds by driving R2, via Q3, to heat D2, closing a loop around the amplifier. Because the diodes and heater resistors are matched, A3's DC output is related to the RMS value of the input, regardless of input frequency or waveshape. In practice, residual LT1088 mismatches necessitate a gain trim, which is implemented at A4. A4's output is the circuit output.

Start-up or input overdrive can cause A2 to deliver excessive current to the LT1088 with resultant damage. C1 and C2 prevent this. Overdrive forces D1's voltage to an abnormally low potential. C1 triggers low under these conditions, pulling C2's negative input low. This causes C2's output to go high, putting A2 into shutdown and terminating the overload. After a time determined by the RC at C2's input, A2 will be enabled. If the overload condition still exists, the loop will almost immediately shut A2 down again. This oscillatory action will continue, protecting the LT1088 until the overload condition is removed.

To trim this circuit, connect its input to a 10mV$_{RMS}$, 100kHz signal. Set the 500Ω adjustment for exactly 100mV DC out. Next, apply a 100kHz, 100mV$_{RMS}$ input and trim the 10k potentiometer for 1V DC out. Repeat this sequence until the adjustments do not interact. Two passes should be sufficient.
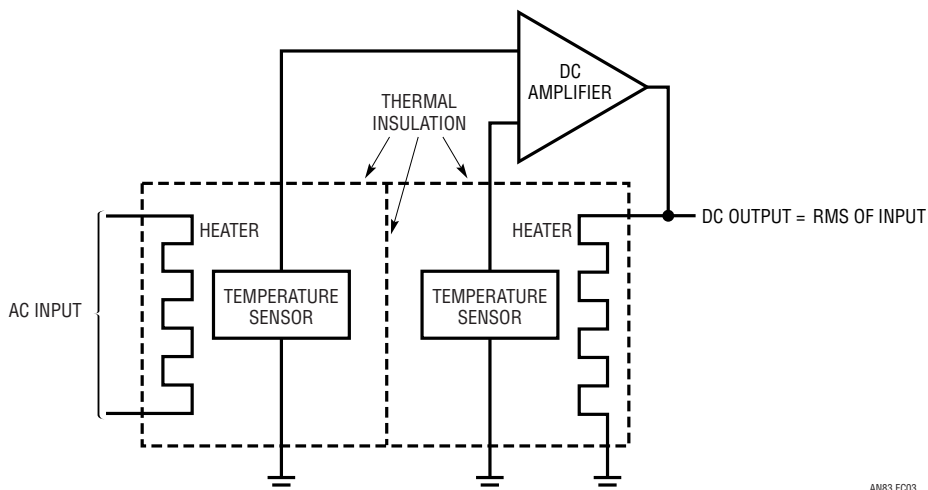


**Figure C3. Thermally Based AC-DC Converter Converts AC Input to Heat. Remaining Circuitry Determines DC Value (Output) Required to Produce Identical Heating. Error Is Extraordinarily Low, Even at Waveshape and Bandwidth Extremes**
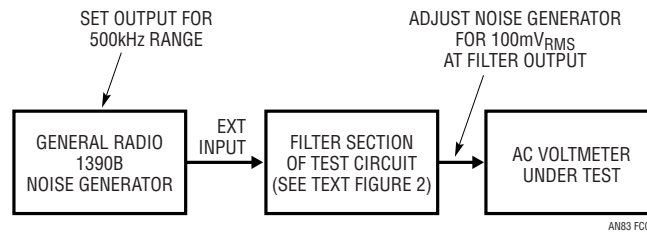
SET OUTPUT FOR
500kHz RANGE

ADJUST NOISE GENERATOR
FOR 100mV$_{RMS}$
AT FILTER OUTPUT

GENERAL RADIO
1390B
NOISE GENERATOR

EXT
INPUT

FILTER SECTION
OF TEST CIRCUIT
(SEE TEXT FIGURE 2)

AC VOLTMETER
UNDER TEST

AN83 FC04

**Figure C4. Arrangement for Evaluating AC Voltmeters. Noise Source, Filtered by Figure 2's Circuit, Drives the Voltmeter**

| VOLTMETER TYPE OR SAMPLE NUMBER | READING IN MILLIVOLTS | ERROR IN % | AC-DC CONVERSION METHOD |
|---|---|---|---|
| HP3403C | 100 | 0 | Thermal |
| HP3400A | 100 | 0 | Thermal |
| Fluke 8920A | 100 | 0 | Thermal |
| LTC Special (See Figure C6) | 100 | 0 | Thermal |
| 1 | 84 | −16 | Log |
| 2 | 85 | −15 | Rect-Avg |
| 3 | 84 | −16 | Rect-Avg |
| 4 Fluke 8800A | 90 | −10 | Rect-Avg |
| 5 HP3455 | 100 | 0 | Log |
| 6 HP334 | 92 | −8 | Rect-Avg |
| 7 Handheld | 52 | −48 | Rect-Avg |
| 8 HP3478 | 100 | 0 | Log |
| 9 Inexpensive Handheld | 56 | −44 | Rect-Avg |
| 10 HP403B | 93 | −7 | Rect-Avg |
| 11 HP3468B | 93 | −7 | Log |
| 12 | 80 | −20 | Rect-Avg |
| 13 | 72 | −28 | Rect-Avg |
| 14 | 62 | −38 | Rect-Avg |
| 15 Fluke 87 | 95 | −5 | Log |
| 16 HP34401A | 93 | −7 | Log |

**Figure C5. Results of AC Voltmeter Evaluation. Four Thermally Based Types Agree within 1%. Other Instruments Show Relative Error As Large As 48%**

**Figure C6. Inexpensive Thermally Based RMS Voltmeter Suitable for LDO Noise Measurement**

**APPENDIX D**

## PRACTICAL CONSIDERATIONS FOR SELECTING A LOW NOISE LDO

Any design has particular requirements for a low noise LDO; every individual situation should be carefully examined for specific needs. However, some general guidelines apply in selecting a low noise LDO. Significant issues are summarized below.

*Current Capacity*
Insure the regulator has adequate output current capacity for the application, including worst-case transient loads.

*Power Dissipation*
The device must be able to dissipate whatever power is required. This effects package choice. Usually, the $V_{IN}$-$V_{OUT}$ differential is low in LDO applications, obviating this issue. Prudence dictates checking to be sure.

*Package Size*
Package size is important in limited space applications. Package size is dictated by current capacity and power dissipation constraints. See the preceding paragraphs.

*Noise Bandwidth*
Insure that the LDO meets the system's noise requirement over the entire bandwidth of interest. 10Hz to 100kHz is realistic, as information usually occupies this range.

*Input Noise Rejection*
Insure that the regulator can reject input related disturbances originating from clocks, switching regulators and other power bus users. If the regulator's power supply rejection is poor, its low noise characteristics are useless.
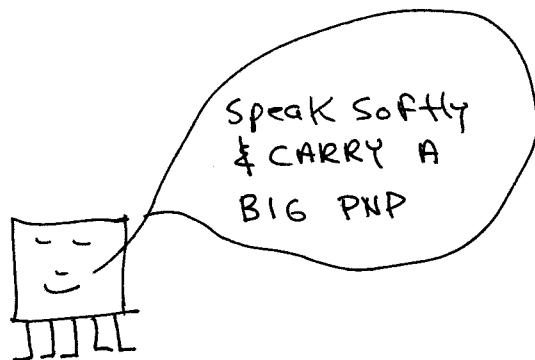
*Load Profile*
Know the load characteristics. Steady state drain is obviously important, but transient loads must also be evaluated. The regulator must maintain stability and low noise characteristics under all such transient loads.

*Discrete Components*
The choice of discrete components, particularly capacitors, is important. The wrong capacitor dielectric can adversely effect stability, noise performance, or both. See Appendix B, "Capacitor Selection Considerations."

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