

# Techniques for Noise Measurements in Precision Series References



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## ABSTRACT

This application note describes low flicker noise (0.1 Hz to 10 Hz band) measurement methodology and test setup recommendations for precision series references. Low noise measurement requires ultra-low setup noise, which can be achieved by selecting low-noise BOM for the band pass filter and proper design or layout techniques. The lowest noise reference [REF54250CDR](#) (flicker noise = 275 nV pk-pk with 100  $\mu$ F capacitor on NR pin) is used to illustrate the component selection and board design to measure the noise floor with < 1.5% error from the measurement setup.

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## Trademarks

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## 1 Introduction

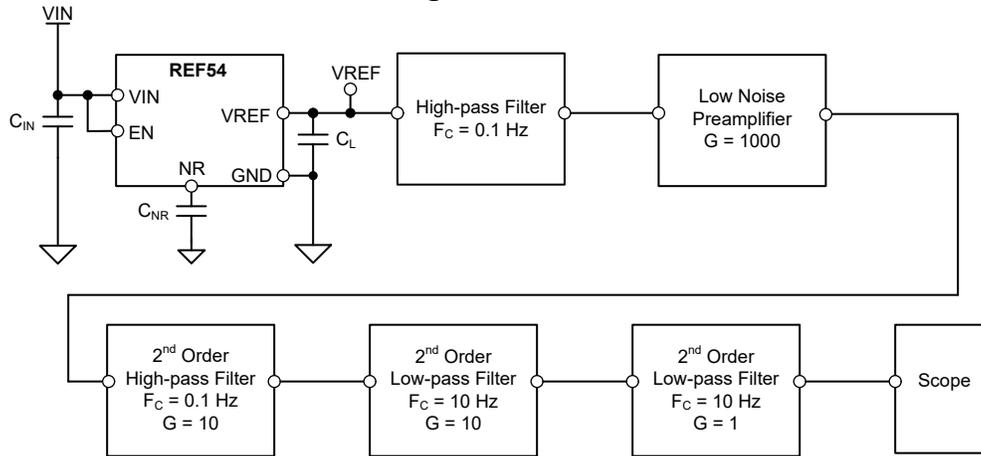
Noise of the reference couples with the data converter's quantization error and impacts the resolution of the overall signal chain. Designers must keep the reference noise sufficiently small so that the reference noise does not affect the resolution of the signal chain. This becomes very critical for high-precision systems such as medical imaging, precision weigh scales for chemical and pharmaceutical labs, seismic measurement equipment, and high precision test and measurement equipment where the ENOB of the system is greater than or equal to 20 bits. These systems typically use an active filter for high-frequency thermal noise; however, designing a low pass filter with less than 10 Hz cut-off frequency is impractical due to high capacitor requirement and slow response. Therefore these applications choose the reference with the best possible flicker noise for signal chain requirement. The accurate measurement is critical so that the designer is not constrained to over design the precision signal chain part and achieve faster system response.

## 2 Flicker Noise Measurement Method

A voltage reference data sheet specifies flicker noise from  $0.1\text{ Hz}$  to  $10\text{ Hz}$  frequency band in the units of *peak to peak* variation over 10 seconds. A simple method is to measure this noise on DMM for 10 seconds with an averaging time of 100 ms ( $1/10\text{ Hz}$ ) to capture peak to peak response. The peak to peak noise from the reference signal gets coupled with the DMM signal chain noise (around  $0.5\text{ }\mu\text{V}$  measured at TI lab for HP3458A at 10 V range). SNR of this method is not good enough for ultra-low noise high precision references, such as [REF7012](#), which has flicker noise =  $312\text{ nV}$  pk-pk over 10 seconds, or [REF54250CDR](#) has  $275\text{ nV}$  pk-pk ( $0.11\text{ ppm}_{pp}$ ) noise with  $100\text{ }\mu\text{F}$  capacitor on NR pin as the DMM's signal chain noise is more than the device noise.

Pre-amplify the reference noise to improve SNR of the measurement setup. This requires eliminating the DC and providing sufficient gain to noise signal as shown in [Figure 3-1](#). [Section 3](#) discusses the filter design to measure flicker noise with high SNR.

### 3 0.1 Hz to 10 Hz Band Pass Filter Design for Reference Noise Measurement



**Figure 3-1. Flicker Noise Test Setup Block Diagram**

Minimum noise specification of REF54250 is 400 nVpk-pk. To have the measurement error be less than 1.5%, calculate the maximum allowed setup noise as follows:

$$\text{Setup Noise} < = 275 \times \sqrt{(1.015^2 - 1^2)} < = 47 \text{ nV}_{pk-pk} \quad (1)$$

The first stage high pass filter's resistor and first stage pre-amplifier noise (referred to as setup noise) gets directly coupled to the reference noise signal. Consequently, these two elements are the major error contributors to the total setup noise budget. Reference noise is amplified 1000 times in the first stage so the impact from subsequent stages setup noises are minimal. Hence, we assign greater than 98% of the budget to this stage. The high pass filter is designed with a 50 Ω resistor so that KT noise contribution of the resistor is minimal.

$$\text{Flicker noise of } 50 \Omega \text{ high pass resistor } (n_{50 \Omega}) = 18.92 \text{ nV}_{pk-pk} \quad (2)$$

The next step is to design a low noise pre-amp with a gain of 1000 which can meet the target spec of noise from first stage op-amp. OPA189 is an excellent choice in TI's portfolio of ultra-low noise and offset op-amps. We need to connect 8 op-amps in parallel to comfortably achieve the target spec of << 56nVpk-pk.

$$\text{Opamp FlickerNoise}(n_{opa}) = \frac{100 \text{ nV}_{pk-pk}}{\sqrt{8}} = 35.35 \text{ nV}_{pk-pk} \quad (3)$$

The gain of 1000 is realized by 10 Ω and 10 KΩ resistors. This equals to 10 Ω in noise contribution. The noise contribution by the 10 Ω resistor gets divided by √8 times.

$$\text{Flicker noise of } 10 \Omega \text{ gain resistor } (n_{10 \Omega}) = 3 \text{ nV}_{pk-pk} \quad (4)$$

Total noise contributed by first stage is RMS sum of equation 1, 2 and 3.

$$\text{Noise floor of first stage } (n_{\text{First}}) = \sqrt{(n_{opa}^2 + n_{50 \Omega}^2 + n_{10 \Omega}^2)} = 40.3 \text{ nV}_{pk-pk} \quad (5)$$

Current noise of the op-amp is ignored in this calculation as the impact is insignificant (current noise density = 165 fA/√Hz). Impact of later stage noise gets divided by greater than or equal to 1000 times. Therefore, the impact is not significant. This circuit contributes less than 1.5 % error in REF54250CDR noise measurement.

The second stage is a Sallen-Key high-pass filter of 0.1 Hz with a gain of 10 and damping ratio of 1 which provides 60 dB over all roll-off at 0.1 Hz high-pass. The next two stages are a multi-feedback 10-Hz low pass filter with an overall gain of 10 to provide roll-off of 80 dB at 10 Hz as shown in [Figure 3-3](#). The noise is gained 10<sup>5</sup> times and captured on the scope over a 10 second window with sampling frequency >> 20 samples a second to avoid aliasing.

### 3.1 Filter Schematic

This band pass filter has been simulated with TI-TINA to verify the frequency response.

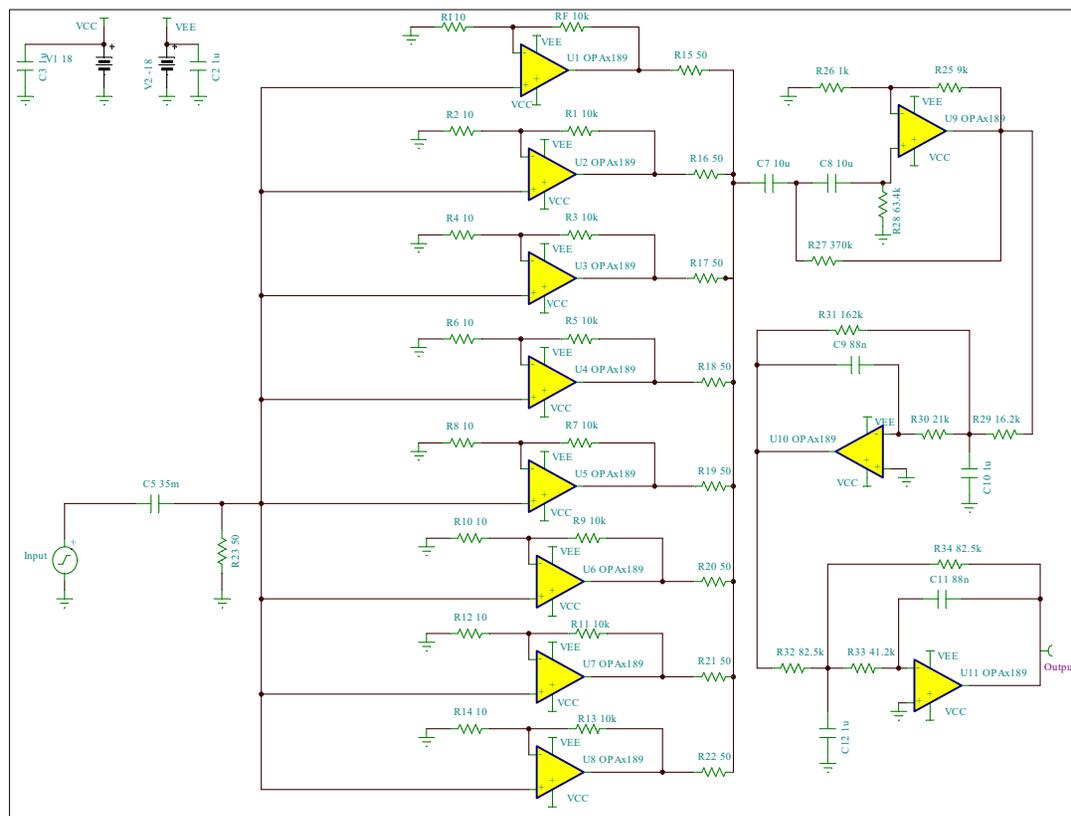


Figure 3-2. Filter Schematic in TINA- TI

### 3.2 TINA - TI simulations

The filter has been designed with a damping factor of 1, lower cutoff frequency of 0.1 Hz with roll off of 60 dB, and higher cutoff frequency is 10 Hz with 80 dB decade roll off. The pass band gain is 100 dB.

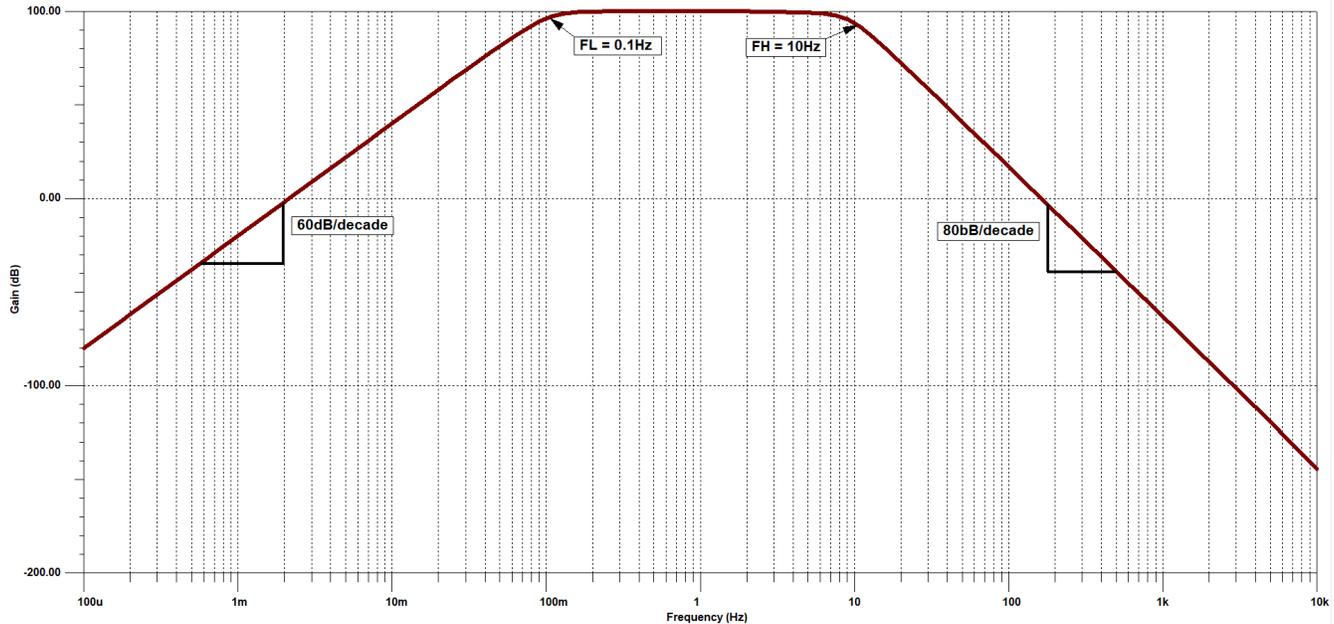


Figure 3-3. Frequency response of band pass filter

### 3.3 Component Selection

- First Stage High Pass Filter:** Noise of resistor at first stage high pass filter is critical as this noise directly couples with the reference noise. A small value resistor (50 ohms) and a bulk capacitor (32 mF) was chosen to design the first stage high pass filter to minimize the thermal noise from the resistor. A Vishay bulk metal foil resistor was chosen for first stage 0.1-Hz high-pass filter as the resistor has the best noise figure by construction. Two 100-Ω bulk metal foil resistors (0.25 W) are kept in parallel to reduce the impact of current (excess, flicker) noise as this noise can be reduced by reducing the current and increasing the volume of resistive material. Four low-leakage electrolyte capacitors are used to realize 32 mF capacitance with a stable capacitance over an entire frequency range. These bulk capacitors need a minimum of 12 hours dielectric soaking time to provide stable measurement. First stage gain resistors are metal foil resistors as these resistors are good in terms of noise performance. Eight OPA189s have been connected in parallel through 50-ohm metal film resistors to reduce the noise by sqrt (8) times.
- Later Stages:** The first stage high pass filter is followed by one Sallen-Key 0.1 Hz HPF with gain 10 and 2 stages of multi-feedback low-pass filter with over all gain 10 and 10 Hz cutoff frequency. The signal is already amplified by 1000 times, which allows relaxation in component selection for later stages. The resistance is higher and capacitance is lower in later stages as thermal noise of the resistors is suppressed by greater than or equal to 100 times. Please refer to [Table 5-1](#) for the exact values. All the capacitors are film capacitors as the aging spec is tight and property of filter does not change over time. All the resistors are metal film in this stage as this type exhibits excellent thermal noise property. OPA189 has been used in all the stages due to the ultra-low noise and offset stability.
- Power Stage:** DC power supply E3631 is used for this measurement. This is fed to low noise LDO through an LC filter to get a stable power supply with very good PSRR measurement. This topology makes sure that there is minimum impact of supply in the measured noise of the reference.

## 4 Measurement Setup

The filter board is kept in a metal box to avoid any EMI. All the cables that carry VREF or noise are shielded cables.

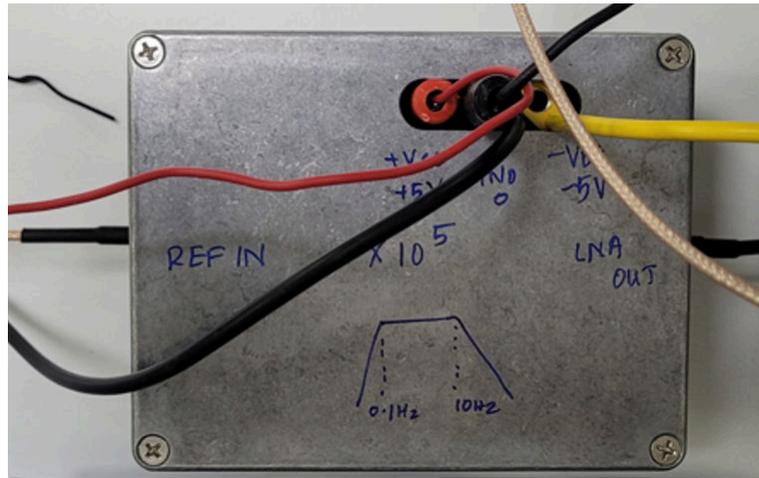


Figure 4-1. Metal Box for Noise Filter to Avoid External Interference

The output was terminated with  $50\ \Omega$ , and we kept the setup on for 12 hours to measure the noise floor. The typical noise floor of the board is 40 nV pk-pk which introduces  $<1.5\%$  error in the lowest noise measurement.

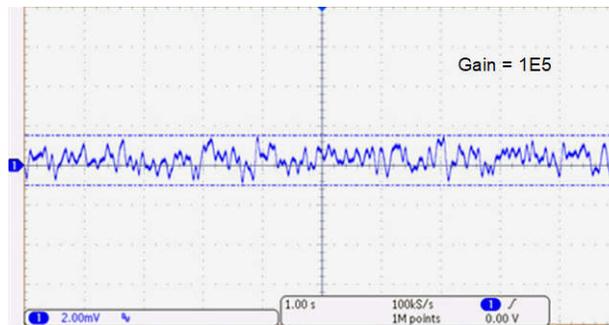
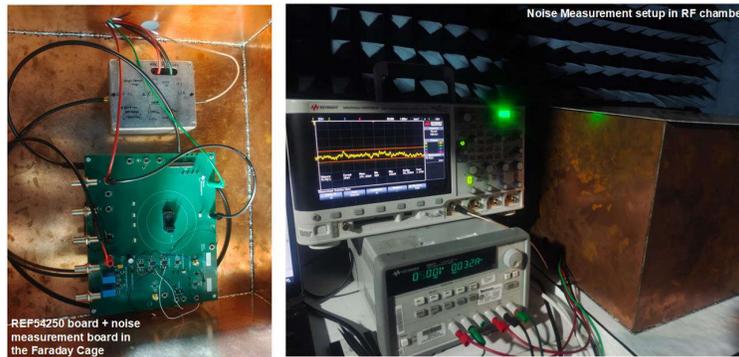


Figure 4-2. Typical Noise Floor of the Filter Board

### 4.1 REF54250CDR Noise Measurement Setup

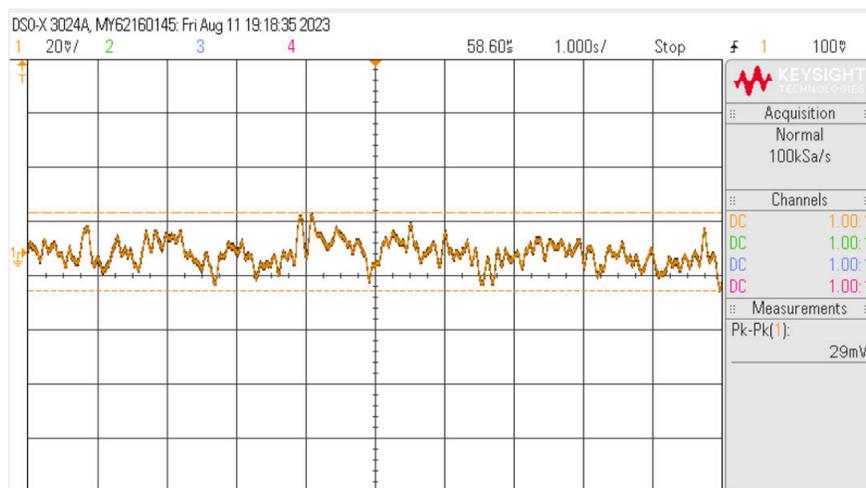
The output of REF54250CDR is connected to the filter board and both are kept in a Faraday cage inside RF chamber as shown in figure Figure 4-3. RF chamber cancels the echo, which avoids the coupling of any surrounding disturbance. Low PSRR power supply E3631 is used to power up the REF54250CDR and the noise board. Noise measurement has been done with a  $100\ \mu\text{F}$  capacitor connected on the NR pin and no capacitor connected to the NR pin. Time domain plot is captured on the scope with sampling frequency = 100 k samples a second ( $\gg 20$  samples a second) for 10 seconds to capture the impact of 0.1 Hz to 10 Hz on peak to peak noise

An oscilloscope is used to analyze the time domain plot with high density. If the user wants to measure peak to peak noise, then 8.5 digit DMM is a better alternate as DMM has better ADC resolution and has options for differential probing to avoid any possibility of scope ground noise injection. Users can record the value with 100 samples a second for a period of 10 seconds and get peak to peak variation.



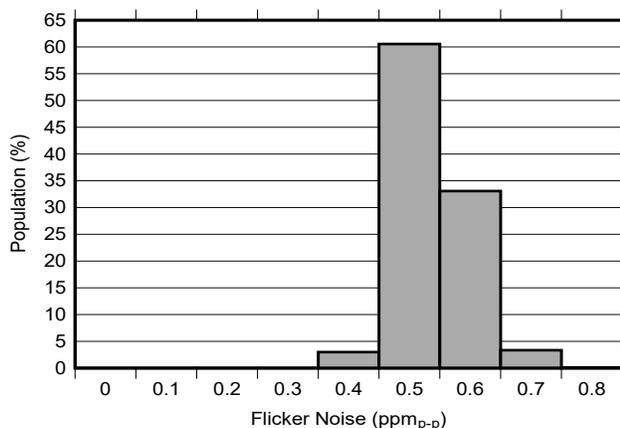
**Figure 4-3. REF54250 Noise Measurement Setup**

Figure 4-4 shows a typical measurement plot of REF54250CDR with a 100  $\mu$ F capacitor on NR pin.

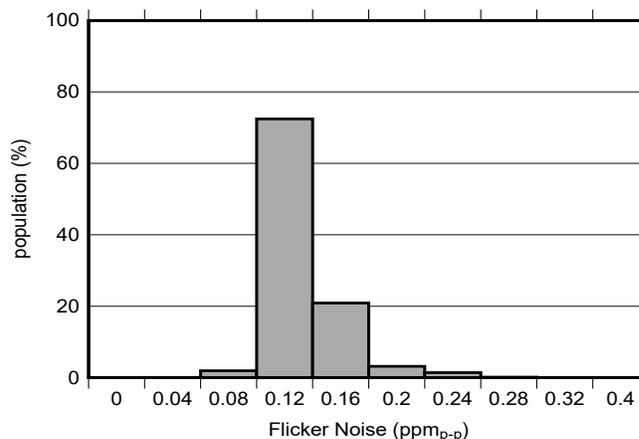


**Figure 4-4. REF54250 Noise Plot With 100  $\mu$ F Capacitor on NR Pin**

Typical flicker noise for REF54250CDR with 100  $\mu\text{F}$  NR pin capacitor is measured as 275 nV *pk-pk* (0.11 *ppm<sub>pp</sub>*). 40 nV *pk-pk* noise from the filter board contributes 1.5% error in the noise measurement. REF54250CDR has 1.125  $\mu\text{V}$  *pk-pk* (0.45 *ppm pk-pk*) flicker noise with open NR pin condition, which has less than 0.1% error from setup noise.



**Figure 4-5. 0.1-Hz to 10-Hz Voltage Noise (C<sub>NR</sub> = Open )**



**Figure 4-6. 0.1-Hz to 10-Hz Voltage Noise (C<sub>NR</sub> = 100  $\mu\text{F}$ )**

## 5 Filter Board Design

### 5.1 Schematic

VCC (+ve supply) and VEE (-ve supply) required for op-amps are connected at banana jack J2, J3 and J4. This is passed through pi filter and low noise LDO [TPS7A47](#) (+12 V) and [TPS7A3301RGWT](#) (-12 V) as shown in [Figure 5-1](#) to get noise free power for the op-amps used for the filter.

TPS7A47 and TPS7A33 are designed for high-accuracy and high-precision instrumentation applications where clean voltage rails are critical to maximize system performance. For applications where positive and negative high-performance rails are required, consider using these high voltage, ultra low noise, and low dropout linear regulators.

### 5.1.1 Schematics Images

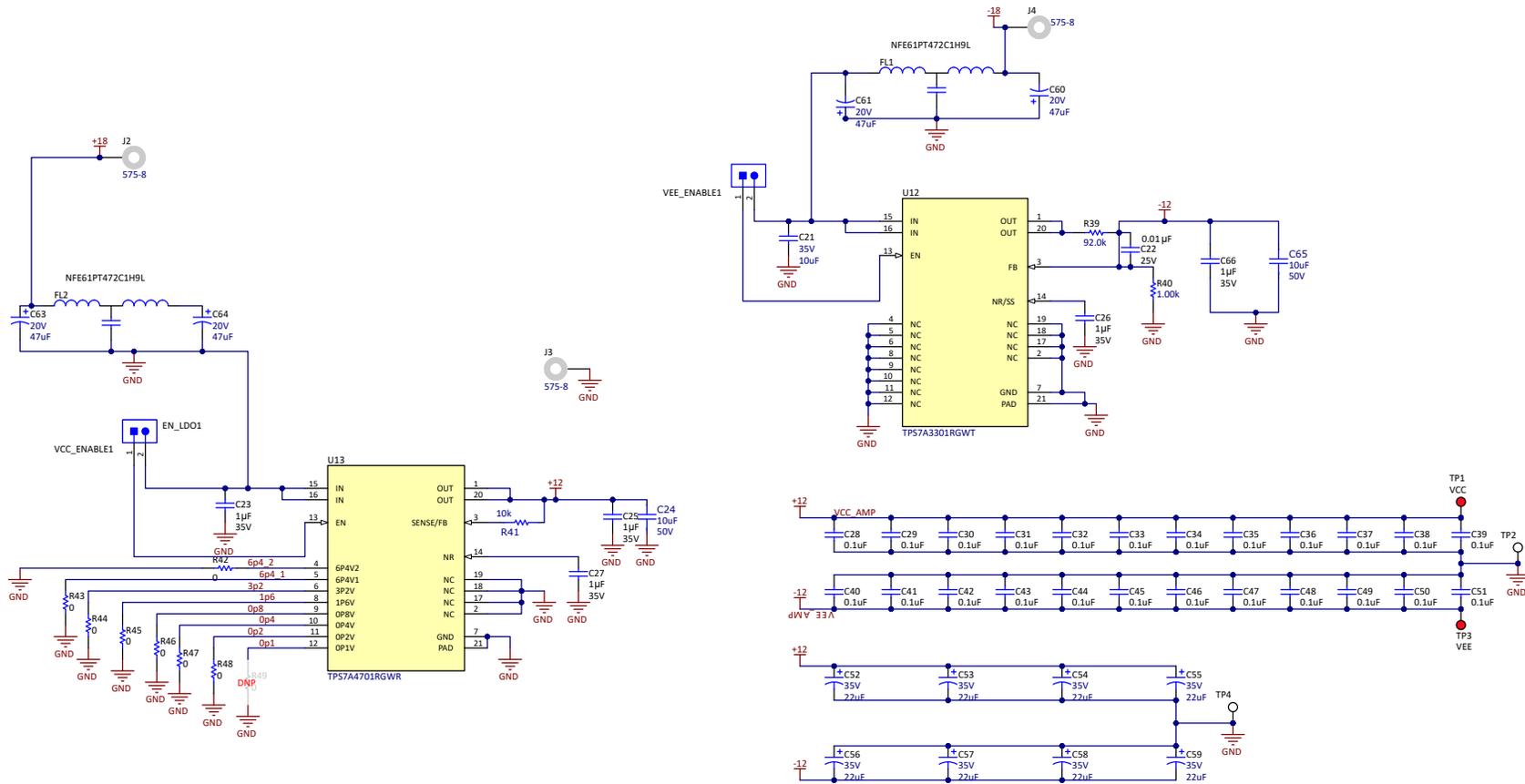


Figure 5-1. Power Stage for the Filter

Figure 5-2 shows the schematic for the 0.1 Hz to 10 Hz band pass filter as discussed in Section 3.2.

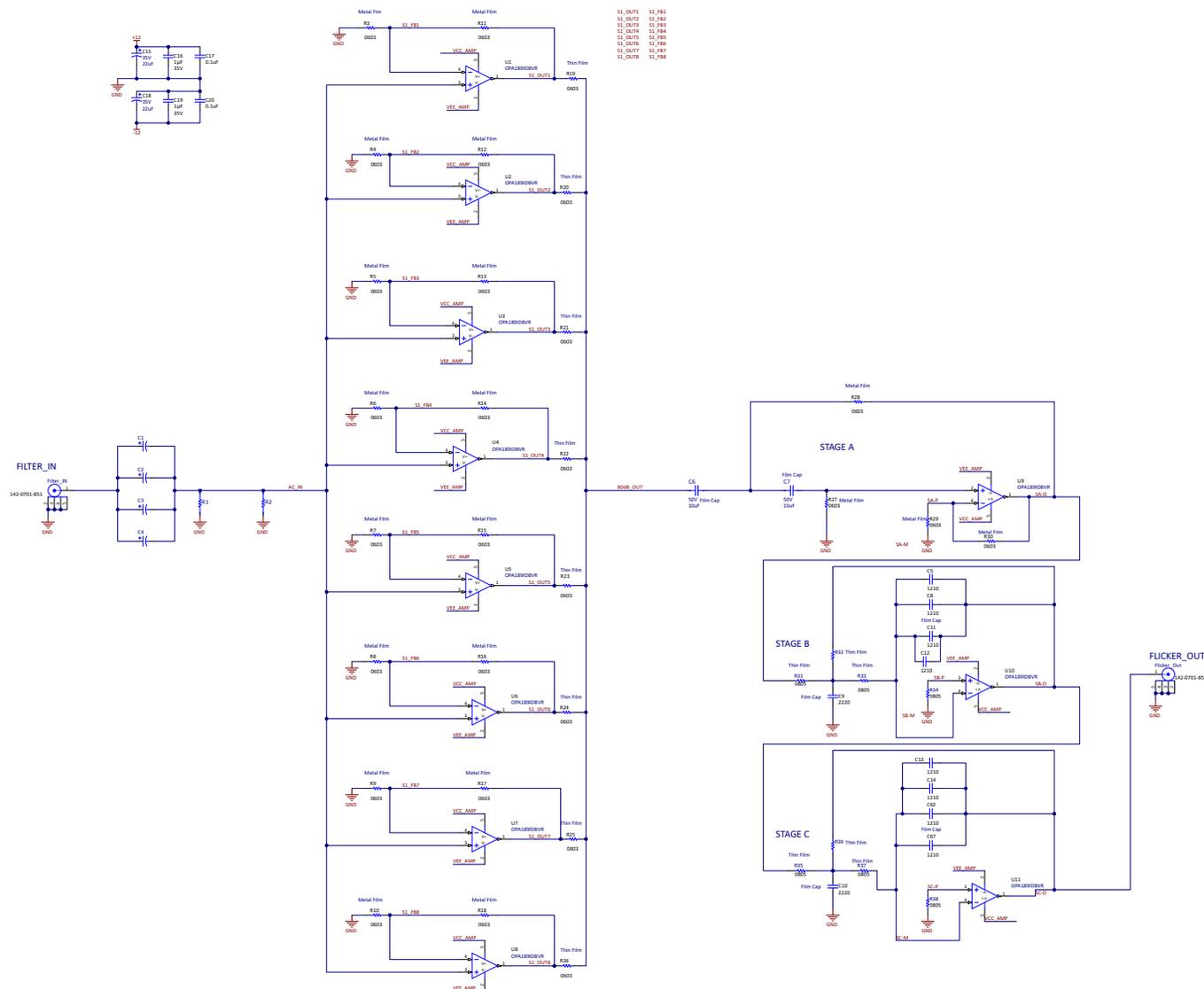


Figure 5-2. 0.1 Hz to 10 Hz Band Pass Filter Implementation

## 5.2 Layout

This is a four layer board. All the critical signals are routed in the top layer as shown in Figure 5-3. The power stage and 0.1 Hz to 10 Hz band pass filter are EMI shielded separately. The grounds for the band pass filter and the power stage are connected only at one place to verify that any power supply noise (ground return path) does not couple with critical signal in filter stage. Critical signals are ground shielded. Input and output are SMA connectors to avoid impact of EMI. All the signals for parallel op-amps in the first stage are routed with symmetry to avoid any mismatch between them. Second layer (Figure 5-4) is complete GND layer for decoupling. Power signal is routed in the third layer (Figure 5-5) for all the op-amps. Two of the four big electrolyte capacitors in first stage 0.1 Hz high pass filter are placed in the bottom layer (Figure 5-6) to save space. The bottom layer has low frequency bypass capacitors at all the corners of the shielded region.

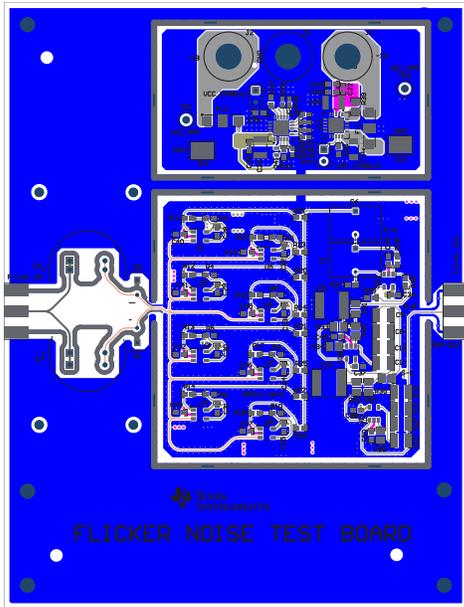


Figure 5-3. Top Layer - Critical Signals

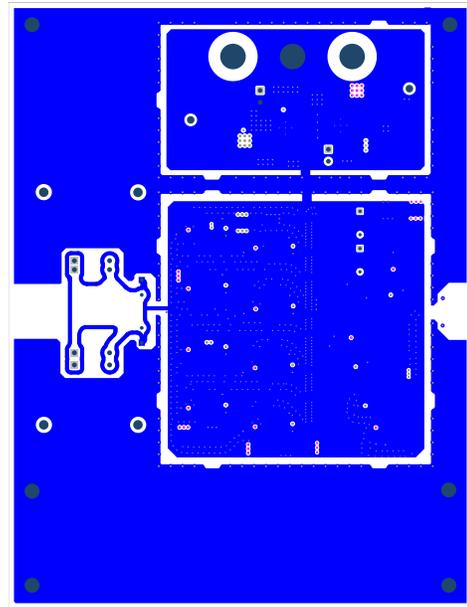


Figure 5-4. Second Layer - GND

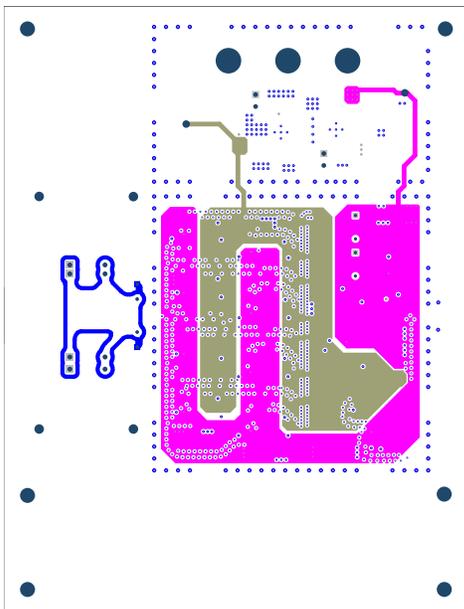


Figure 5-5. Third Layer - Power Plane

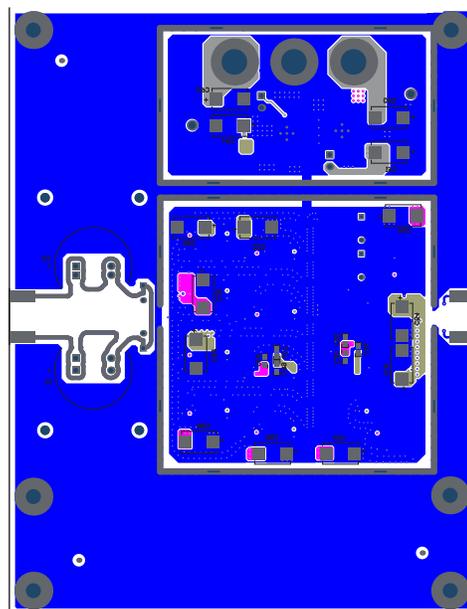


Figure 5-6. Bottom Layer

### 5.3 Bill of Materials

**Table 5-1. Bill of Materials**

Designator	Quantity	Value	Description	Package Reference	Part Number	Manufacturer
IPCB1	1		Printed Circuit Board		XXX###	Any
C1, C2, C3, C4	4	8200 $\mu$ F	CAP, AL, 8200 $\mu$ F, 16 V, $\pm$ 20%, TH	D16 x L35.5 mm	EKY160ELL822MM P1S	Chemi-Con
C5, C8, C11, C12, C13, C14, C62, C67	8	0.022 $\mu$ F	CAP FILM 0.022 $\mu$ F 5% 50 VDC 1210	1210		
C6, C7	2	10 $\mu$ F	10 $\mu$ F Film Capacitor 30 V 50 V Polyester, Polyethylene Terephthalate (PET), Metallized Radial	RADIAL	MKS2B051001N00J SSD	WIMA
C9, C10	2	1 $\mu$ F	CAP FILM 1 $\mu$ F 5% 63 VDC 2220	2220	LDEDD4100JA0N00	
C15, C18, C52, C53, C54, C55, C56, C57, C58, C59,	10	22 $\mu$ F	CAP, TA, 22 $\mu$ F, 35 V, $\pm$ 10%, 0.275 $\Omega$ , SMD	7343-43	T495X226K035ATE 275	Kemet
C16, C19, C23, C25, C26, C27, C66	7	1 $\mu$ F	CAP, CERM, 1 $\mu$ F, 35 V, $\pm$ 10%, X7R, 0603	0603	C1608X7R1V105K0 80AC	TDK
C17, C20, C28, C29, C30, C31, C32, C33, C34, C35, C36, C37, C38, C39, C40, C41, C42, C43, C44, C45, C46, C47, C48, C49, C50, C51,	36	0.1 $\mu$ F	CAP, CERM, 0.1 $\mu$ F, 50 V, $\pm$ 10%, X7R, 0603	0603	GRM188R71H104K A93D	MuRata
C21	1	10 $\mu$ F	CAP, CERM, 10 $\mu$ F, 35 V, $\pm$ 10%, X7R, 1206_190	1206_190	GMK316AB7106KL-TR	Taiyo Yuden
C22	1	0.01 $\mu$ F	CAP, CERM, 0.01 $\mu$ F, 25 V, $\pm$ 10%, X7R, 0402	0402	CL05B103KA5NNN C	Samsung Electro-Mechanics
C24, C65	2	10 $\mu$ F	10 $\mu$ F $\pm$ 10% 50 V Ceramic Capacitor X7R 1210 (3225 Metric)	1210	UMK325AB7106KM HP	Taiyo Yuden
C60, C61, C63, C64	4	47 $\mu$ F	CAP, Tantalum Polymer, 47 $\mu$ F, 20 V, $\pm$ 20%, 0.055 $\Omega$ , 7343-20 SMD	7343-20	20TQC47MYF	Panasonic
EN_LDO1	1		Shunt, 2.54 mm, Gold, Blue	Shunt, 2.54 mm, Blue	60900213621	Würth Elektronik
FID1, FID2, FID3,	4		Fiducial mark. There is nothing to buy or mount.	N/A	N/A	N/A
Filter_IN, Flicker_Out,	2		Connector, End launch SMA, 50 $\Omega$ , SMT	SMA End Launch	142-0701-851	Cinch Connectivity
FL1, FL2	2	4700 pF	Filter LC High freq 4700 PF, 2706	6.8 x 1.6 mm	NFE61PT472C1H9L	MuRata

Table 5-1. Bill of Materials (continued)

Designator	Quantity	Value	Description	Package Reference	Part Number	Manufacturer
H1, H2, H3, H4, H5, H6	6		Machine Screw, Round, #4-40 x 1/4, Nylon, Philips panhead	Screw	NY PMS 440 0025 PH	B&F Fastener Supply
H7, H8, H9, H10, H11, H12	6		Standoff, Threaded, 1.5", 4-40, Aluminum	1/4 Round Female Standoff	3483	Keystone
J2, J3, J4	3		Standard Banana Jack, Uninsulated, 8.9 mm	Keystone575-8	575-8	Keystone
R1, R2,	2	100	Ultra-High Precision Resistor Metal Foil 100 $\Omega$ 0.01% Bulk	RADIAL	Y1073100R000T9L	Vishay Precision Group
R3, R4, R5, R6, R7, R8, R9, R10,	8	10	10 $\Omega$ $\pm$ 0.5% 0.1 W, 1/10 W 0603 Metal Film	0603	RN73H1JTDD10R0 D25	KOA Speer Electronics, Inc.
R11, R12, R13, R14, R15, R16, R17, R18	8	10 k	10 k $\Omega$ $\pm$ 0.5% 0.1 W, 1/10 W 0603 Metal Film	0603	RN73H1JTDD1002D 25	KOA Speer Electronics, Inc.
R19, R20, R21, R22, R23, R24, R25, R26	8	49.9	49.9 $\Omega$ $\pm$ 0.5% 0.1W, 1/10W Chip Resistor 0603 Metal Film	0603	RN73H1JTDD49R9 D25	KOA Speer Electronics, Inc.
R27	1	63.4 k	63.4 k $\Omega$ $\pm$ 0.5% 0.1 W, 0603 Metal Film	0603	RN73H1JTDD6342D 25	KOA Speer Electronics, Inc.
R28	1	370 k	370 k $\Omega$ $\pm$ 1% 0603 Metal Film	0603	RN73H1JTDD3703F 100	KOA Speer Electronics, Inc.
R29	1	100	RES 100 $\Omega$ 0.1% 1/10 W 0603	0603	RN73H1JTDD1000B 25	KOA Speer Electronics, Inc.
R30	1	910	RES SMD 910 OHM 0.1% 1/10 W 0603	0603	ERA-3YEB911V	Panasonic Electronic Components
R31	1	16.2 k	16.2 k $\Omega$ $\pm$ 0.1% 0.125 W, 1/8 W Chip Resistor 0805 (2012 Metric) Automotive AEC-Q200, Moisture Resistant Thin Film	0805	RN73R2ATDD1622B 25	KOA Speer Electronics, Inc.
R32	1	162k	162 k $\Omega$ $\pm$ 0.1% 0.125 W, 1/8 W Chip Resistor 0805 (2012 Metric) Automotive AEC-Q200 Thin Film	0805	ERA-6AEB1623V	Panasonic Electronic Components
R33	1	21 k $\Omega$	21 k $\Omega$ $\pm$ 0.1% 0.125 W, 1/8 W Chip Resistor 0805 (2012 Metric) Thin Film	0805	RT0805BRD0721KL	YAGEO
R34, R38	2	0	0 $\Omega$ Jumper Chip Resistor 0805 (2012 Metric) Automotive AEC-Q200 Thick Film	0805	RMCF0805ZT0R00	Stackpole Electronics Inc

**Table 5-1. Bill of Materials (continued)**

Designator	Quantity	Value	Description	Package Reference	Part Number	Manufacturer
R35, R36	2	82.5 k $\Omega$	82.5 $\Omega$ $\pm$ 0.1% 0.125W, 1/8 W Chip Resistor 0805 (2012 Metric) Automotive AEC- Q200 Thin Film	0805	ERA-6AEB8252V	Panasonic Electronic Components
R37	1	41.2 k $\Omega$	41.2 k $\Omega$ $\pm$ 0.1% 0.125 W, 1/8 W Chip Resistor 0805 (2012 Metric) Automotive AEC- Q200 Thin Film	0805	ERA-6AEB4122V	Panasonic Electronic Components
R39	1	92.0 K $\Omega$	RES, 92.0 k, 0.1%, 0.125 W, 0805	0805	RT0805BRD0792KL	Yageo America
R40	1	1.00 k	RES, 1.00 k, 0.1%, 0.1 W, 0603	0603	RT0603BRD071KL	Yageo America
R41	1	10 k	10 k $\Omega$ $\pm$ 0.1% 0.1 W, 1/10 W Chip Resistor 0603 (1608 Metric) Automotive AEC- Q200 Thin Film	0603	ERA-3AEB103V	Panasonic
R42	1	0	RES, 0, 5%, 0.1 W, 0603	0603	RC0603JR-070RL	Yageo
R43, R44, R45, R46, R47, R48	6	0	RES, 0, 5%, 0.063 W, AEC- Q200 Grade 0, 0402	0402	CRCW04020000Z0 ED	Vishay-Dale
TP1, TP3	2		Test Point, Multipurpose, Red, TH	Red Multipurpose Testpoint	5010	Keystone
TP2, TP4	2		Test Point, Compact, SMT	Testpoint_Keysto ne_Compact	5016	Keystone
U1, U2, U3, U4, U5, U6, U7, U8, U9, U10, U11	11		14 MHz, MUX- friendly, low-noise, zero-drift, RRO, CMOS precision operational amplifier, DBV0005A (SOT-23-5)	DBV0005A		Texas Instruments
U12	1		Vin -3 V to -36 V, -1 A, Ultra-Low- Noise, High-PSRR, Low-Dropout Linear Regulator, RGW0020A (VQFN-20)	RGW0020A	TPS7A3301RGWT	Texas Instruments
U13	1		36 V, 1 A, 4.17 $\mu$ VRMS, RF Low- Dropout (LDO) Voltage Regulator, RGW0020A (VQFN-20)	RGW0020A	TPS7A4701RGWR	Texas Instruments
VCC_ENABLE1, VEE_ENABLE1	2		Header, 100 mil, 2x1, Tin, TH	Header, 2 PIN, 100 mil, Tin	PEC02SAAN	Sullins Connector Solutions
R49	0	0	RES, 0, 5%, 0.063 W, AEC- Q200 Grade 0, 0402	0402	CRCW04020000Z0 ED	Vishay-Dale

## 6 References

- Texas Instruments, [TI Precision Designs: Verified Design 0.1Hz to 10Hz Noise Filter](#) verified design.
- Vishay Precision Group, [Ultra High Precision, Z-Foil Audio Resistor Minimizes Noise and Distortion in the Signal Path with TCR of  \$\pm 0.05\$  ppm/ \$^{\circ}\$ C, Tolerance to  \$\pm 0.005\$  % and High Linearity or Low Voltage Coefficient of Resistance \(VCR\) of 0.1 ppm/V](#) document.
- Texas Instruments, [TPS7A33 –36-V, 1-A, Ultralow-Noise Negative Voltage Regulator](#) data sheet.
- Texas Instruments, [TPS7A4701RGWR](#) product.
- Texas Instruments, [OPAx189 Precision, Lowest-Noise, 36-V, Zero-Drift, 14-MHz, MUX-Friendly, Rail-to-Rail Output Operational Amplifiers](#)

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