# A Low-Cost High-Precision 700,000-Count Panel Meter

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This article describes the implementation of a low-cost 700,000-count panel meter using the MSC1200 that embeds a 24-bit delta-sigma ADC, and an enhanced 8051 CPU.

The goal of this project was to develop a low-cost high-precision panel meter. Normally, low cost and high precision are conflicting project requirements; however, with the introduction of CPUs with an embedded high-resolution delta-sigma ADC, such a goal became absolutely possible.

Panel meters are widely used for industrial applications. All that is needed is an external power supply to display the value on an analog signal LED. Most panel meters in the market range from 3 to 4½ digits and meters with a higher resolution are rare. Moreover, the price for a 4¼ digits panel meter is not trivial but this project implements a panel meter using an 8-digit LED with a resolution of 6½ digits.

To define the specifications of the project we referenced an industrial-standard bench top meter manufactured by Hewlett Packard: model HP3458A. This meter accepts an input voltage range of ±2.5V and we set target accuracy and resolution at 10 µV. These requirements translate to a half-million count meter (dividing full-scale voltage with the accuracy voltage). We'll describe the detail specifications of the final implementations later.

Next, we’ll describe the panel meter hardware and firmware implementations, and then the challenges to achieve the target precision.

## Hardware

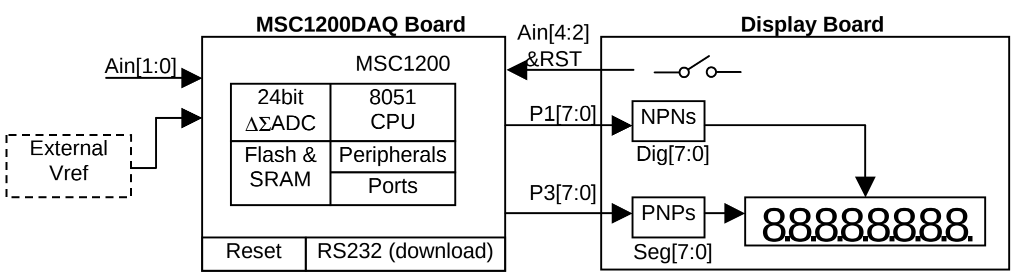



**Fig. 1: MSC1200 Panel Meter Block Diagram**

This prototype (block diagram in Fig. 1) was used to test the feasibility of implementing a low-cost high-resolution meter including three modules: the CPU-ADC board, the panel display board, and the optional external reference voltage board. Fig. 2 pictures the MSC1200 panel meter.

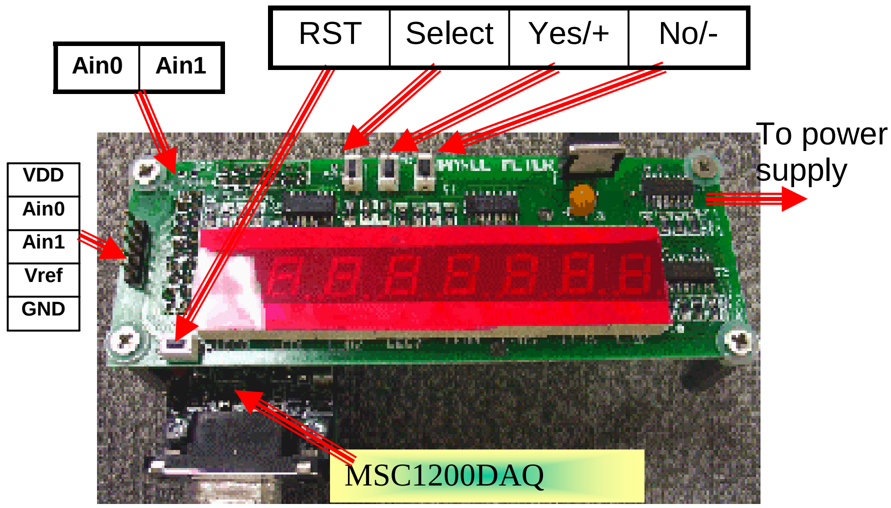



**Fig. 2: MSC1200 Panel Meter and MSC1200DAQ Board**

The heart of the panel meter is a single chip microprocessor with a built-in ADC. We selected the MSC1200 which embeds a 24-bit delta-sigma ADC, an 8 bit 8051 CPU, communications peripheral and ports. The MSC1200 is located on the MSC1200DAQ board and a complete schematic for this board is shown at the end of this article. The RS232 port for in this board is for downloading source code and once completed is not used again.

The MSC1200 has an internal, programmable 1.25-V or 2.5-V reference voltage although an external voltage may be used for some applications (which we will explain later), and here the MSC1200 panel meter board provides such an external reference.

### Seven Segment Display

A 7-segment LED module with common-anodes is used and Fig. 3 shows the configuration. (Common-cathode types could also be used with minor hardware and software modifications.

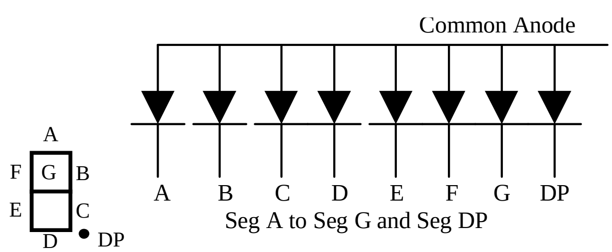



**Fig. 3: Typical Common-Anode 7-Segment LED**

The interconnection between the CPU ports and the LED display is depicted in Fig. 4. Each common line of the 7-segment LED module is controlled by a CPU port pin and when the common line is active, a digit is selected. Since we want to display 8 digits, 8 port pins (P1.0 to P1.7) are required to control the

8 digits. There are 7-segments and a decimal point (DP) for each digit. Since we are scanning every digit the same segment of every digit is connected together and controls each segment with a CPU port pin. For example, segment A of every digit is connected together so eight port pins (P3.0 to P3.7) are used to control the eight segments (including DP) of every digit. A total of 16 CPU port pins are used for LED display control. The complete schematic is shown at the end of this article (use the magnifying feature in the toolbar of Adobe Reader for clarity).

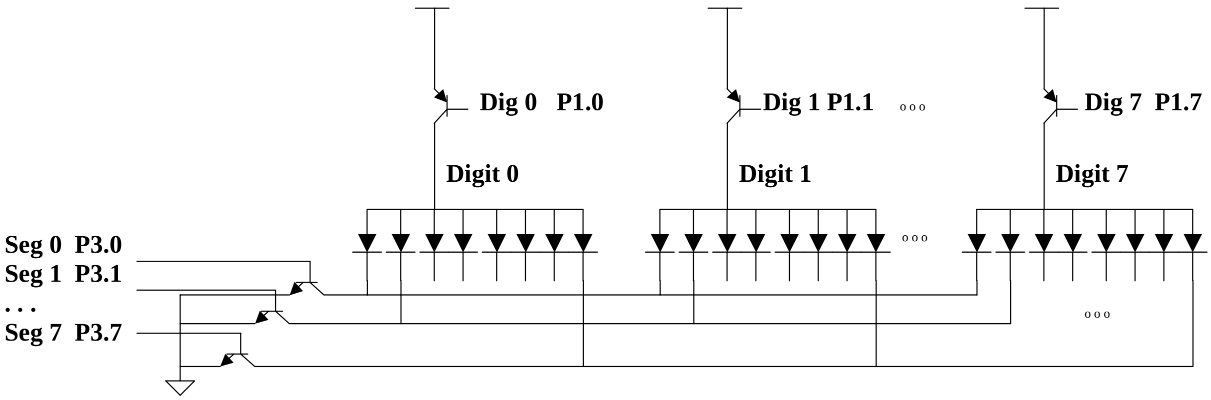



**Fig. 4: Interconnection For The 8 Digits**

To get sufficient brightness from each segment the LED module specifies a typical 2.6 V forward voltage and 25 mA of quiescent current. The scanning method turns on one digit at a time so no more than 8 segments can turn on at any instant. With 25 mA per segment the peak current would be 200 mA on the common-anode line. Each output pin of MSC1200 is capable of driving 32 mA with around 1.5 V drop from a 5-V rail. To meet the LED current/voltage requirements, bipolar transistors are used to drive the digit and segment lines. As shown (Fig. 4, again), pnp transistors are used for digit drivers and npn transistors are used for segment drivers. Quad packages were used.

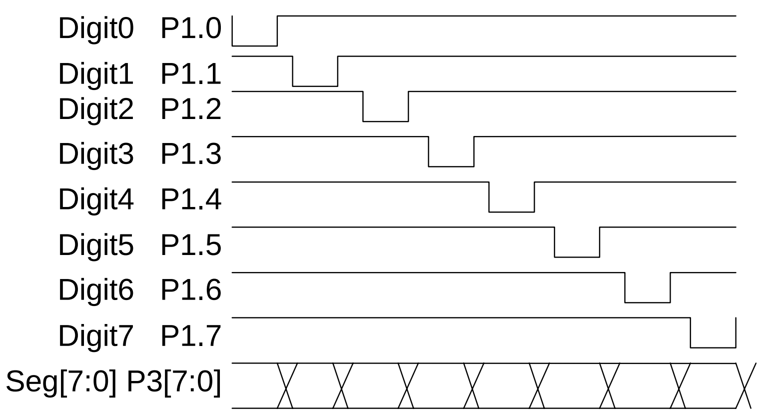



**Fig. 5: LED Digits Scanning Sequence**

Fig. 5 shows the LED digit scanning sequence. The on time for each digit is almost 1 ms so it takes 8 ms to complete scanning of the 8 digits. A display refresh rate of over 25 Hz is sufficient for a flicker-free display, so the 125 Hz used was more than sufficient. If any two of the digit-control pins (Digit0 to Digit7 (Fig. 5, again) were switched together, it is possible to have two digits turn-on together for a short time. To avoid unwanted displays, on-time delay is added to ensure transitions during the off period.

**Software**

The internal 12-MHz oscillator is used so there is enough CPU bandwidth to:

1) Perform the extensive floating-point calculation needed to manipulate the 24-bit ADC
2) Process the complex display formatting. Even though the clock will drift with supply voltage and ambient temperature, neither the ADC performance nor the display scanning are affected

This CPU has 8 kbyte of Flash memory and 256 byte of SRAM (there was only 128 byte on the original silicon). We used 7 kbyte of the Flash for source code, non-volatile parameters storage, and 127 byte of SRAM.

The software for the project consists mostly of the console interface and the ADC.

**Console Interface: LED Display**

The panel meter console interface software includes the LED display and input functions. As shown in Fig. 5 LED scanning is updated every 1 ms and the system timer is configured to generate 1 ms interrupts. The display can only be updated at the end of every complete 8 digit scan, avoiding noticeable, abrupt changes. 8051 C compilers (The Raisonance compiler was used here) allows the programmer to provide his custom *putchar()* function that works with the *printf()* function. The *printf()* of the C library typically sends output characters to the 8051 serial port. The custom *putchar()* redirects the *printf()* outputs to any output console hardware, in this case to the LED panel display, and performs the following:

- It updates the display buffer for the LED scanning interrupt service routine
- It formats the floating decimal point results (the HP bench top DMM displays the decimal point at a fixed location
- It can round the output values to achieve stable readings for signal levels of a few µV

With only 7-segments per digit many character patterns can still be displayed, including the basic number characters, almost all the letters of the alphabet, plus a few other symbols.

**Console Interface: Input Keys**

As described before, the LED segments and digit control require 16 port pins using both ports on the MSC1200 so no other port pin is available for reading input keys. To implement the function input keys, the additional multiplexed inputs of the ADC pins are used. Fig. 2 shows the three function-select keys {Select, Yes/+, No/-} which provide the following features:

- Gain calibration
- Internal or external reference selection
- Programmable gain amplifier settings
- Number of averaging conversion results
- Some other display formatting options

These configuration results fit into the 64-byte per page on-chip Flash memory, so only one page is required. Flash memory has to be erased by the page, unlike EEPROM where erase can be byte-by-byte; one way to update one of the parameters could be to backup the FLASH page into SRAM, modify the parameter(s) being changed in SRAM and then write it back to the FLASH. But that requires 64 byte of SRAM which can be scarce. Here, instead we use two pages of FLASH which we call *ping* and *pong* in the code: to update a parameter copy the content of *ping* plus the new parameter into *pong*, then erase *ping*. Similarly you could write to *ping* and delete *pong*.

**ADC Conversion**

The built-in 32-bit hardware averaging-filter, conforming to the IEEE 32-bit floating-point format, can be used on the ADC conversion results, and the Raisonance compiler supports the IEEE floating-point library. This includes 23 bits of mantissa, 8 bits of exponent and a sign bit and although mantissa support is less than the 24-bit conversion it is sufficient for this application, with the ADC routine detecting and reporting the overflow and underflow conditions.

**Achieving High Precision**

First, we concentrate on enhancing the resolution of the panel meter and then we can use gain and offset calibrations to achieve the targeted accuracy specifications. The resolution of the ADC is affected by many factors, but there are also many that do not affect it.

The Δ-Σ ADC oversamples the input analog signal typically at the rate of the modulation clock (ModClk), and uses the decimation filter to remove high frequency noise. The 32-bit filter then averages the conversion results. The initial settings were:

- Enable the internal 2.5-V reference
- Set the ModClk to 15.7 kHz
- Set the filter to decimate at the ratio of 2047 (the maximum ratio)
- Set the averaging filter to take the average of every two ADC conversion results

The ADC is set to bipolar so each LSB is equivalent to $(2.5 \text{ V} \times 2) \div 2^{24} = 298$ nV. The ADC conversion rate is calculated by ModClk ÷ decimation = 15.7 kHz ÷ 2047 = 7.7 sample/s. In this setting the filter is averaging 2 conversion results and the data rate is halved (3.8 sample/s).

The resolution of the ADC with these settings needs to be seen and there are different methods to estimate it. A common one is to acquire a large number of data, calculate the standard deviation (σ) and use it to represent the resolution; another is to leave the machine running for a long time and use the peak-to-peak value of the readings (statistically 6σ) to represent the resolution. Here, the peak-to-peak readings of 50 display results were recorded, giving a result between one σ and six σ. This represents a stable reading over tens of seconds, typical of the use of panel meters.

A Data Precision 8200 was used as the input voltage source and four different dc voltages were applied, spanned over full-scale (FS) range. The peak-to-peak voltage of 50 display results were measured at each applied voltage level and Fig. 6 shows the noise levels. When the input is close to zero there is less than 7 µVp-p of noise, but close to FS there is over 150 µVp-p; the first step is to reduce the low input signal noise and to then tackle the higher input noise.

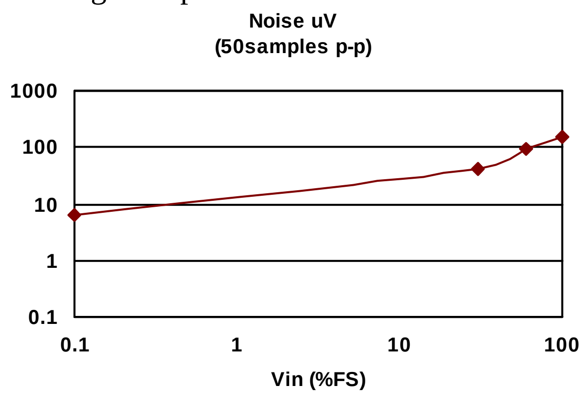



**Fig. 6: Noise Levels For Basic Set-Up**

## Switching Noise

Switching noise is a major problem in high-precision equipment and possible sources, that may affect the conversion results, are SPS noise, LED display noise, and CPU noise. A 6-V dc SPS was used for this project and a 5-V linear regulator further regulates the supply. Measuring the regulator output voltage, 200 mVp-p noise was at the output of the linear regulator (see Fig. 7) but as it was at a high frequency (relative to the conversion rate), it can be filtered by the digital filters.

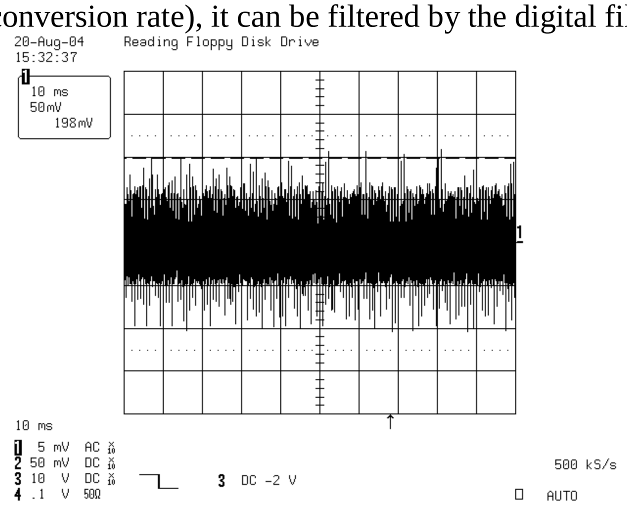



**Fig. 7: 200-mV Noise At Power Supply Regulator Output**

## Higher ModClk And Extra Averaging

A common technique to reduce high-frequency noise on conversion results is with extra filtering, but that slows down the conversion rate and the input response time. But these can be countered using a higher sampling rate, proportional to ModClk, giving a higher data rate anal allowing for additional filtering.

Initially ModClk was set to 15.7 kHz and in the MSC1200 a ModClk at any speed less than 100 kHz has no effect on conversion accuracy. Setting the clock at 86.4 kHz increased the data rate 5.5 times and the filter was set to average over 32 conversions instead of 2. Using the calculation we used before of (ModClk ÷ Decimation Ratio) ÷ Conversions Averaged, the sampling rate is 1.3 sample/s.

The system noise reduced from 7 µV to 2 µV at low input levels (see Fig. 8) but the noise only marginally improved at FS, because of noise from the reference.

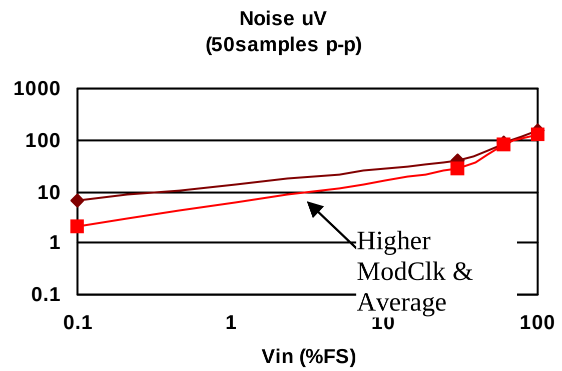



**Fig. 8: Noise Level With Faster Clock And Additional Averaging**

## Internal Reference Voltage Noise

The MSC1200 internal reference voltage has peak-peak noise of 150 µV over 10 minutes (see Fig. 9) matching the numbers obtained from the complete system, ranging from 0.1 Hz to 10 Hz.

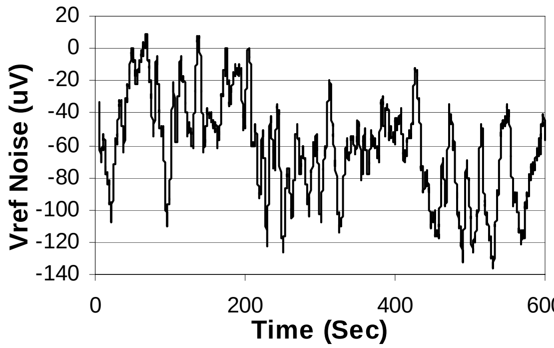
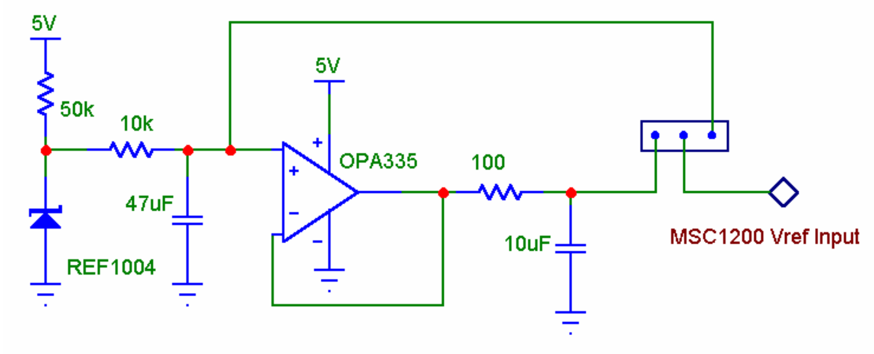



**Fig. 9: Noise From Internal Reference Over 10 Minutes**

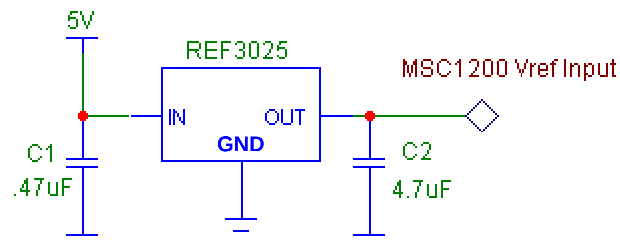
The answer is to use an external reference source.

**External Reference: 8 µVp-p**

Two 2.5-V external reference voltage parts, REF1004 (see Fig. 10a) and REF3025 (see Fig. 10b) were selected for comparison.




(a)




(b)

**Fig. 10: Reference Circuits With REF1004 (a) And REF3025 (b)**

The measured noise for 50 samples at FS were 8 µVp-p and 28 µVp-p, respectively (see Fig. 11)

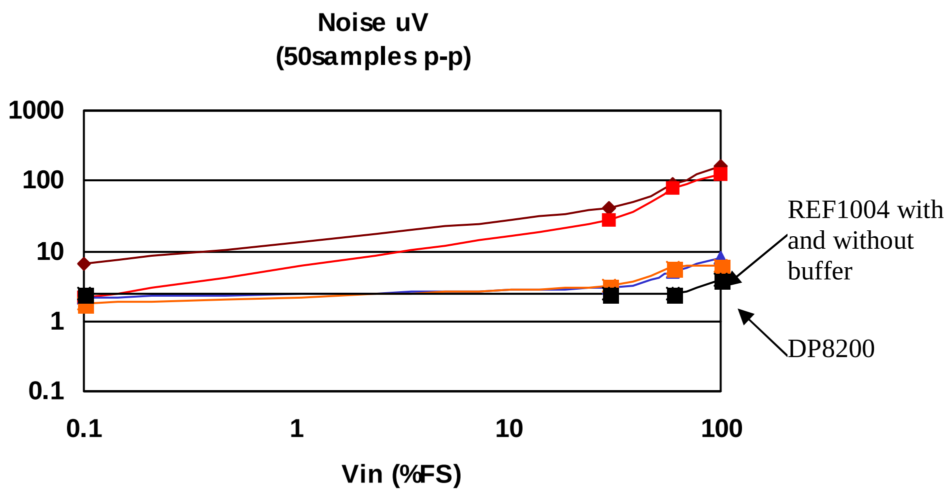



**Fig. 11: Reduced Noise Using External REF1004 And DP8200**

8 µVp-p is a 20 times noise reduction! When an OPA335 buffer is added to the REF1004 there is an additional, mild, noise reduction. This is what was used in the final design.

Checking the low-frequency drift of the REF1004, its output was measured over 10 minutes (Fig. 12). The reference, because of the highly-filtered output, takes almost 2 minute to settle; once it does it drifts by 40 µVp-p over the next 8 minutes. (The data sheet spec is that it has a 50 µV drift per °C.)

The last experiment for an external reference was to use a second Data Precision 8200 voltage source, when noise was measured down at 4 µVp-p, showing that how much you are willing to pay for your reference does count!

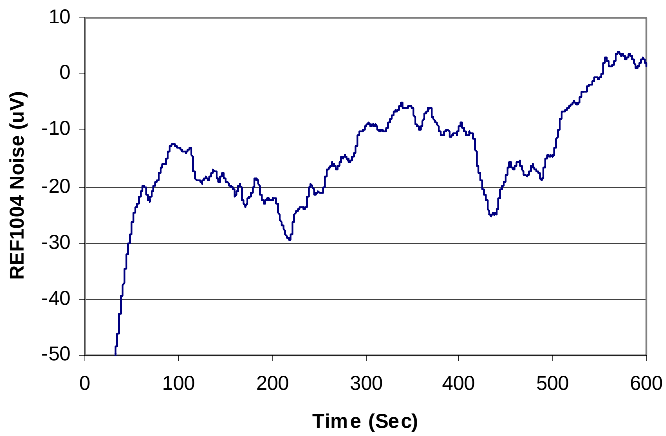



**Fig. 12: After-Settling Peak-Peak Noise Of 35 µV**

## Meter Accuracy

We now have a meter with 2 µV to 8 µV resolution for 0 to 0.3FS small signals and 0.3FS to FS large signals. To calibrate FS a voltage close to it is applied and the calibration routine used to match the conversion readings with the DP8200. The five calibration ranges (100 mV, 10 mV, 1 mV, 100 µV and 10 µV) allow manual calibration to the nearest 10 µV. The panel meter and an HP3458A are compared to the reading of the voltage source (Fig. 13) and the panel meter matches the HP reading within 1 µV.

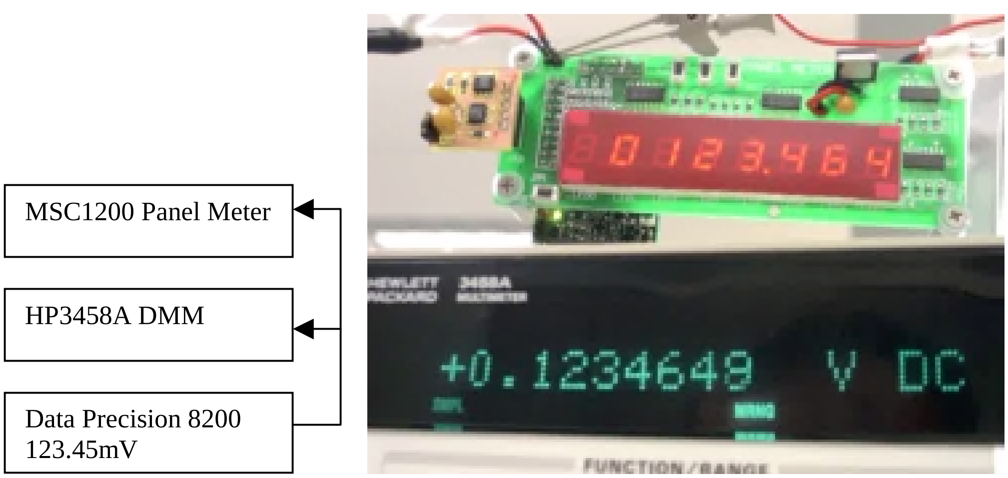



**Fig. 13: Panel Meter Matches HP3458A Within 1 µV**

**Conclusions**

In the course of this other factors were found that may or may not affect performance.

Noticeable improvements:

- Adding noise filter cap 0.01 µF right at the differential inputs of the analog input
- Using L-100 µH/C-2 µF filter for the analog power supply for MSC1200

No change in performance:

- Adjusting decimation ratio to reject 60Hz
- Adjusting LED display refresh rate to multiple of 60Hz
- Adding more than 1 µF on MSC1200 digital power supply
- Adding a separate linear regulator for LED drivers and MSC1200

Degrading performance:

- Using switching power supply

Note: These observations may not apply to another project.

The panel meter precision improvements over different techniques are summarized in Table:. The column titled low (high) level signal sensitivity refers to the peak-peak noise when the input signal is within (above) 20% of the FS. The column titled Full Scale Resolution (Counts) is calculated from the voltage of a LSB, the FS voltage and the high-level signal sensitivity.

| Configuration | Low Level Signal Sensitivity (uV) | High Level Signal Sensitivity (uV) | Full Scale Resolution (Counts) |
|---|---|---|---|
| **Int. Vref** | 6.6 | 156.8 | 31,895 |
| **Int. Vref + Avg** | 2.1 | 123.4 | 40,524 |
| **REF1004 + Avg** | 2.1 | 8.0 | 621,378 |
| **REF1004 + Avg/ Buf** | 1.8 | 6.0 | 838,860 |
| **DP8200 + Avg** | 2.4 | 3.9 | 1,290,555 |

**Table: Precision Improvement Summary**

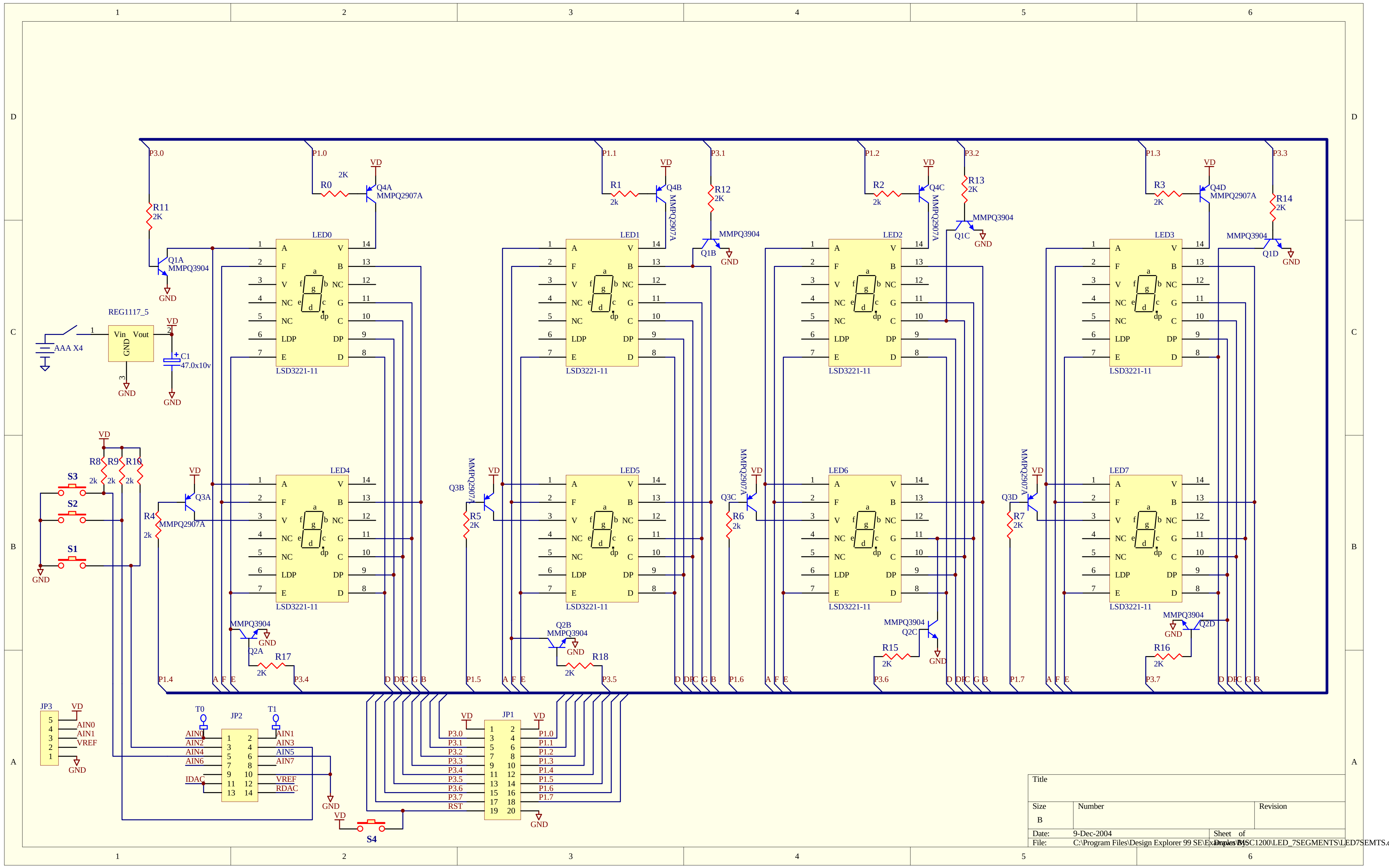
Using the REF1004 (with buffer) plus averaging we are getting an over-800,000 counts resolution, which reduces to 700,000 counts when the rounding function is turned on to reduce digit flickering.

The following performance was obtained from the panel meter for a BOM cost of $40:

- Accuracy: <5 ppm
- Resolution: 6½ digits
- Sensitivity: <2 µV
- Full Scale Range: ±2.5 V
- Readings/second: 1+ sample/s
- Overflow/Underflow Indicator

**References**

SBAS289D MSC1200: Precision ADC and DAC with 8051 Microcontroller and Flash Memory (Rev. D) (msc1200y3.pdf, 834 kbyte) 02 Sep 2004
PDS-1172 Micropower Voltage Reference (ref1004-2.5.pdf, 68 kbyte) 27 Sep 2000
SBVS032E REF30xx: 50 ppm/°C Max, in SOT-23-3 Voltage Reference (Rev. E) (ref3025.pdf, 309 kbyte) 24 Mar 2004



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LED2
LED3
LED4
LED5
LED6
LED7
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F
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B
G
C
DP
D
MMPQ3904
MMPQ2907A
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Q1B
Q1C
Q1D
Q2A
Q2B
Q2C
Q2D
Q3A
Q3B
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R14
R15
R16
R17
R18
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2k
VD
GND
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P3.1
P3.2
P3.3
P3.4
P3.5
P3.6
P3.7
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P1.2
P1.3
P1.4
P1.5
P1.6
P1.7
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Vin
Vout
AAA X4
C1
47.0x10v
S1
S2
S3
S4
JP1
JP2
JP3
T0
T1
AIN0
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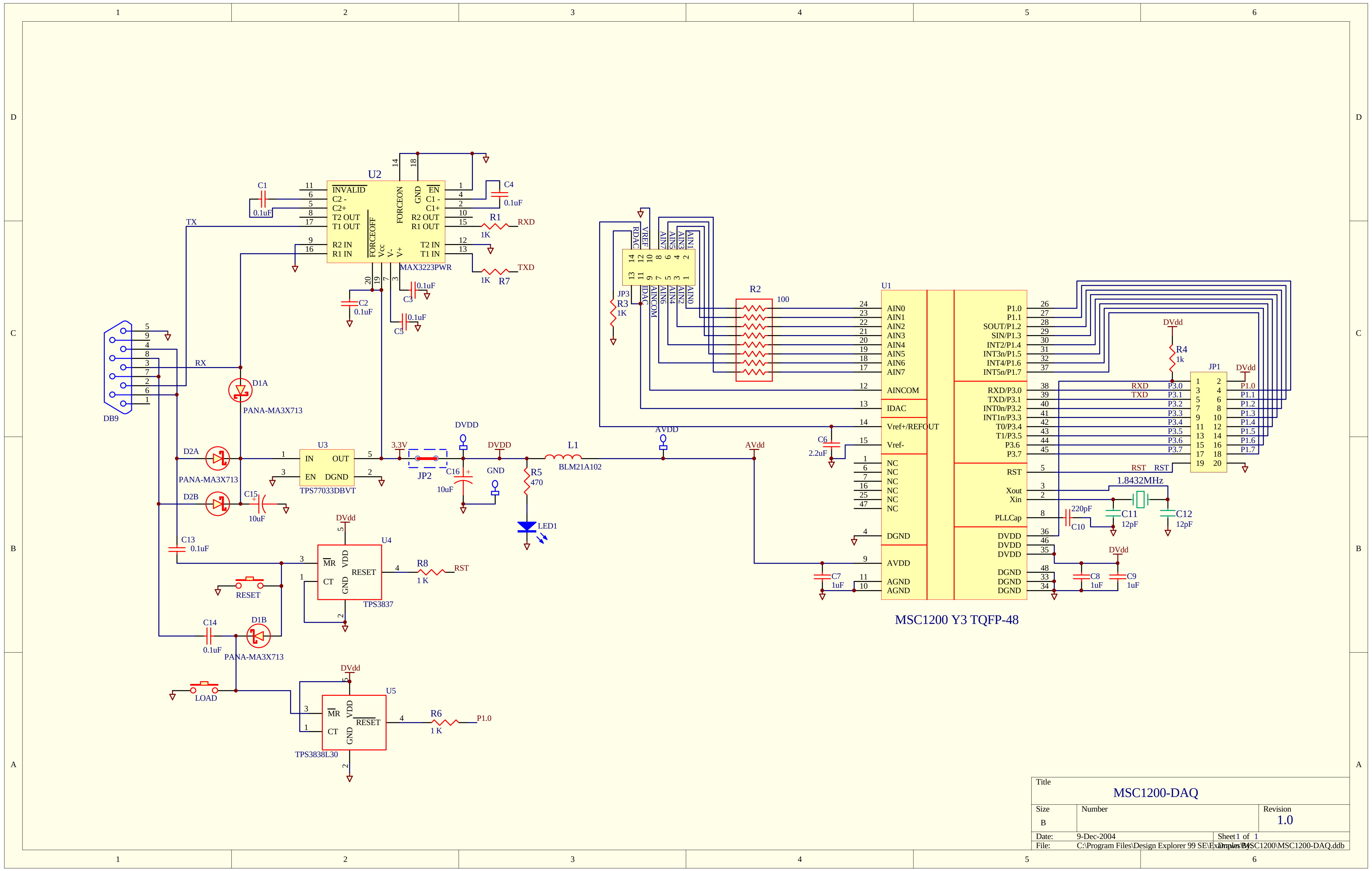
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C3 0.1uF
C4 0.1uF
C5 0.1uF
R1 1K
R7 1K
RXD
TXD
TX
RX
DB9
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D2A
D2B
D1B PANA-MA3X713
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C13 0.1uF
C14 0.1uF
U3 TPS77033DBVT
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OUT
EN
DGND
3.3V
JP2
DVDD
C16 10uF
GND
R5 470
LED1
L1 BLM21A102
AVDD
AVdd
U4 TPS3837
MR
CT
VDD
GND
RESET
R8 1 K
RST
U5 TPS3838L30
R6 1 K
P1.0
LOAD
DVdd
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R3 1K
R2 100
U1
MSC1200 Y3 TQFP-48
AIN0
AIN1
AIN2
AIN3
AIN4
AIN5
AIN6
AIN7
AINCOM
IDAC
Vref+/REFOUT
Vref-
NC
DGND
AVDD
AGND
P1.0
P1.1
SOUT/P1.2
SIN/P1.3
INT2/P1.4
INT3n/P1.5
INT4/P1.6
INT5n/P1.7
RXD/P3.0
TXD/P3.1
INT0n/P3.2
INT1n/P3.3
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