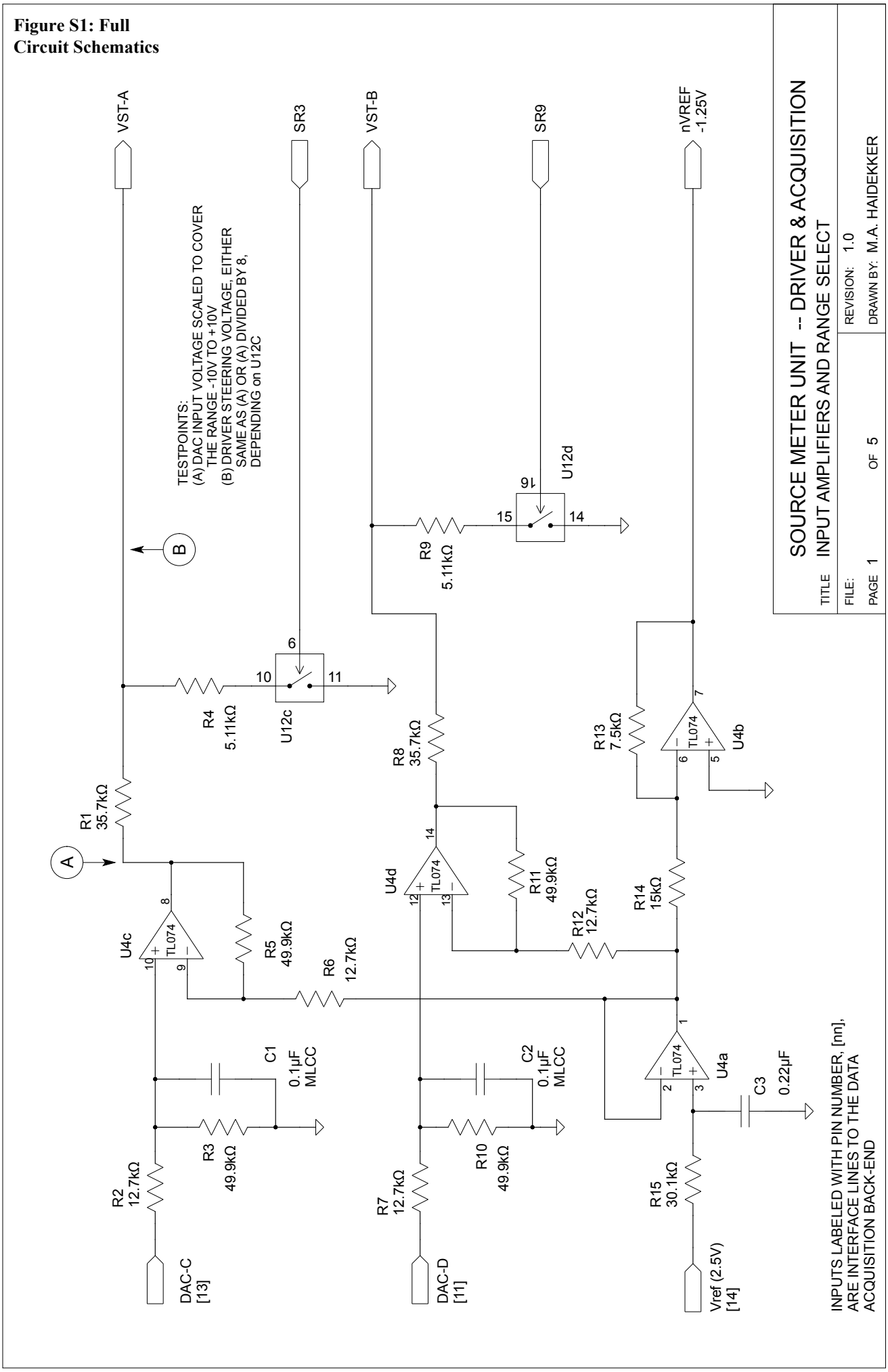
**Supplementary Materials**

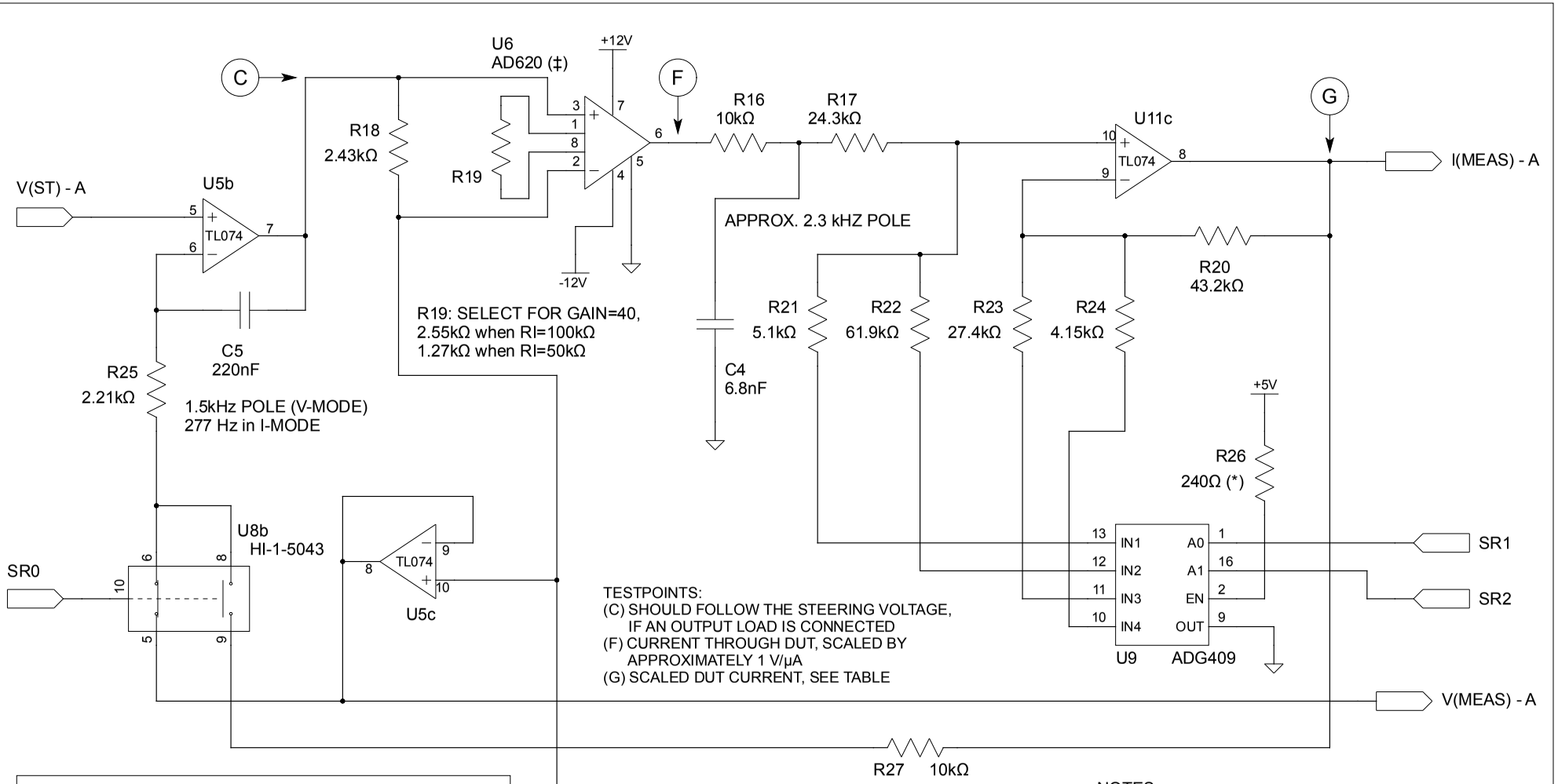
**Table S1: Bill of Materials with Sources and Approximate Costs**

| Line Item | Component | Manufacturer | Description | # | $ |
|---|---|---|---|---|---|
| 1 | 12.7 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 4 | $0.40 ($9.90 for 100) |
| 2 | 49.9 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 4 | $0.20 ($5.10 for 100) |
| 3 | 35.7 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 4 | 30.1 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 11 | $1.10 ($9.90 for 100) |
| 5 | 15 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 1 | $0.06 ($5.90 for 100) |
| 6 | 7.5 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 1 | $0.06 ($5.90 for 100) |
| 7 | 2.43 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.80 for 100) |
| 8 | 61.9 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 9 | 5.11 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.13 ($6.60 for 100) |
| 10 | 2.21 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 11 | 27.4 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 12 | 43.2 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.16 ($8.30 for 100) |
| 13 | 5.1 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.13 ($6.60 for 100) |
| 14 | 4.15 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 15 | 24.3 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 16 | 10 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 4 | $0.12 ($6.20 for 100) |
| 17 | 240 Ω Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 8 | $0.10 ($4.90 for 100) |
| 18 | 2.55 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.20 ($9.90 for 100) |
| 19 | 1.27 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.16 ($8.30 for 100) |
| 20 | 2.15 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.12 ($5.90 for 100) |
| 21 | 1.5 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.12 ($5.90 for 100) |
| 22 | 390 Ω Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 2 | $0.10 ($4.90 for 100) |
| 23 | 1 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 1 | $0.06 ($5.80 for 100) |

| | | | | | |
|---|---|---|---|---|---|
| 24 | 4.7 kΩ Resistor | Vishay | Metal Film Resistor, Rated ¼ W, 1% Tolerance | 3 | $0.20 ($6.60 for 100) |
| 25 | 0.1 uF Capacitor | Murata | Multilayer Ceramic Capacitor - Leaded | 4 | $0.26 ($6.40 for 100) |
| 26 | 0.22 uF Capacitor | Murata | Multilayer Ceramic Capacitor - Leaded | 4 | $0.42 ($10.40 for 100) |
| 27 | 6.8 uF Capacitor | Murata | Multilayer Ceramic Capacitor - Leaded | 2 | $0.20 ($10.10 for 100) |
| 28 | 470 uF Capacitor | Vishay | Aluminum Electrolytic Capacitor - Radial Leaded | 3 | $4.56 |
| 29 | 1000 uF Capacitor | Vishay | Aluminum Electrolytic Capacitor - Radial Leaded | 1 | $3.86 |
| 30 | 4.7 uF Capacitor | Vishay | Aluminum Electrolytic Capacitor - Radial Leaded | 2 | $3.46 |
| 31 | TL074 | Texas Instruments | Quad Low-Noise J-FET Input Operational Amplifier | 12 | $1.75 |
| 32 | AD7998 | Analog Devices | Analog to Digital Converter, 8-channel, 12-bit | 4 | $23.04 |
| 33 | ADG513 | Analog Devices | Precision Quad-SPST Switch, Noninverting | 4 | $16.00 |
| 34 | ADG409 | Analog Devices | Multiplexer Switch IC, 4-channel, +/- 15V | 4 | $38.84 |
| 35 | AD620 | Analog Devices | Instrumentation Amplifier, Gain 1-10000 | 2 | $22.76 |
| 36 | HI-1-5043 | Harris / Texas Instruments | Analog Switch IC, 16-channel | 6 | $60.00 |
| 37 | DG411 | Analog Devices | Quad-SPST Analog Switch IC | 1 | $13.19 |
| 38 | DG413 | Analog Devices | Quad-SPST Analog Switch IC | 1 | $13.19 |
| 39 | SN74HC595 | Texas Instruments | 8-Bit Shift Register with 3-State 8-Bit Output Register | 2 | $1.00 ($13.50 for 25) |
| 40 | SSA36 | OnSemi | Schottky Barrier Rectifier | 1 | $0.37 |
| 41 | ULN2003 | Texas Instruments | Darlington Transistor Low Power Relay Driver | 2 | $1.14 |
| 42 | LED | Jameco ValuePro | Light-emitting Diode Standard Diffuse | 3 | $0.20 ($6.55 for 100) |
| 43 | BNC Connector | Jameco ValuePro | PCB Mount, Right Angle | 2 | $4.38 |
| 44 | BNC Connector | Jameco ValuePro | Panel Mount | 2 | $3.90 |
| 45 | AD5694 | Analog Devices | Digital to Analog Converter, Quad, 12-Bit | 2 | $24.75 |
| 46 | Omron G5V-2 | Omron | General Purpose Relay, 5 VDC, Non-Latching, 2A, 125 VAC/DC | 1 | $3.55 |
| 47 | 3-Pin Jumpers | Jameco ValuePro | From 36-Pin 0.1” Breakaway Header, Straight | 1 | $0.99 |
| 48 | Protoboard | Jameco ValuePro | PT Series Prototyping Board with 5 Power Buses | 1 | $9.45 |
| 49 | Rat Wire | Jameco ValuePro | Wire Wrap 100 Feet 30 AWG | 6 | $100 |
| Total | | | | | $356.08 |

**Figure S1: Full Circuit Schematics**






CURRENT SENSE & FEEDBACK SCALER

| RANGE | I(max) | U6 out | U11c out | GAIN V/µA |
|---|---|---|---|---|
| 00 | 100µA | 9.81V | 1.27V | 0.00127 |
| 01 | 20µA | 1.96V | 1.26V | 0.0631 |
| 10 | 5µA | 0.49V | 1.25V | 0.2528 |
| 11 | 1µA | 0.098V | 1.18V | 1.184 |

NOTES:

RESISTORS MARKED (*) ARE PART OF A DIP ARRAY

‡ OTHER INSTRUMENTATION AMPLIFIERS ARE ALLOWABLE BUT MAY REQUIRE ADJUSTING THE AVLUE OF R19.

# SOURCE METER UNIT -- DRIVER & ACQUISITION

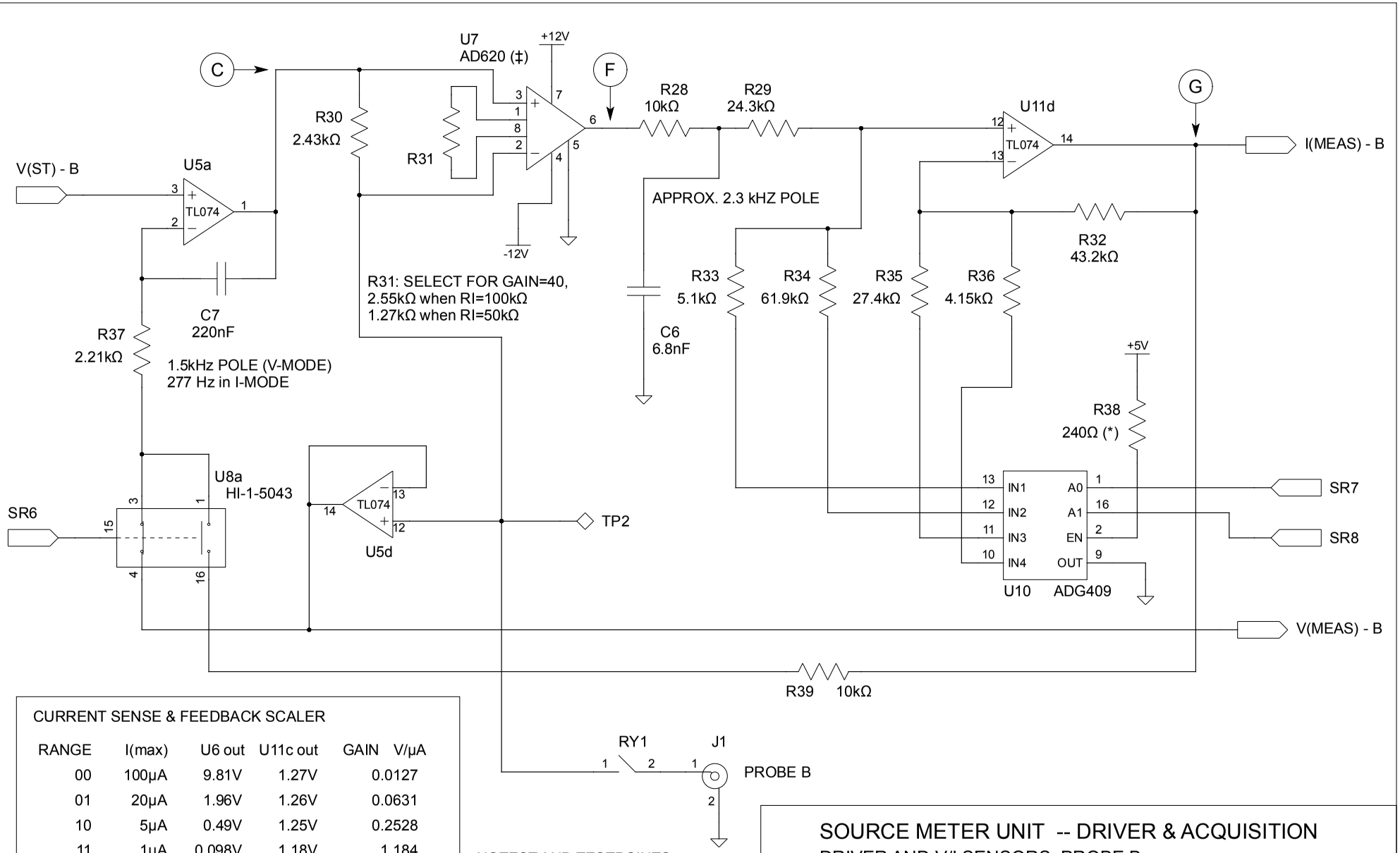
TITLE DRIVER AND V/I SENSORS, PROBE A

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CURRENT SENSE & FEEDBACK SCALER

| RANGE | I(max) | U6 out | U11c out | GAIN V/µA |
|---|---|---|---|---|
| 00 | 100µA | 9.81V | 1.27V | 0.0127 |
| 01 | 20µA | 1.96V | 1.26V | 0.0631 |
| 10 | 5µA | 0.49V | 1.25V | 0.2528 |
| 11 | 1µA | 0.098V | 1.18V | 1.184 |

NOTEST AND TESTPOINTS:
SEE SHEET 2

# SOURCE METER UNIT -- DRIVER & ACQUISITION

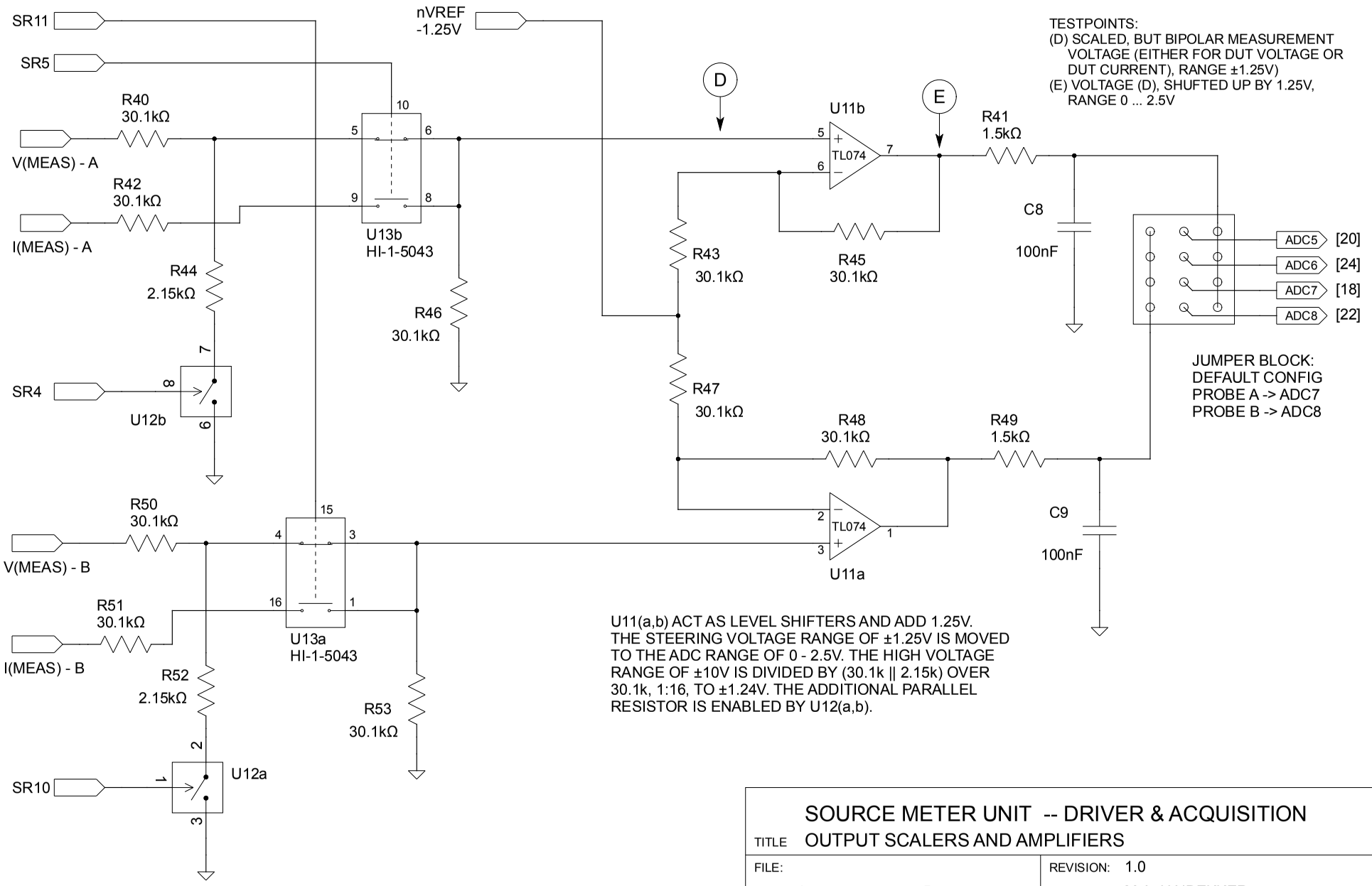
TITLE DRIVER AND V/I SENSORS, PROBE B

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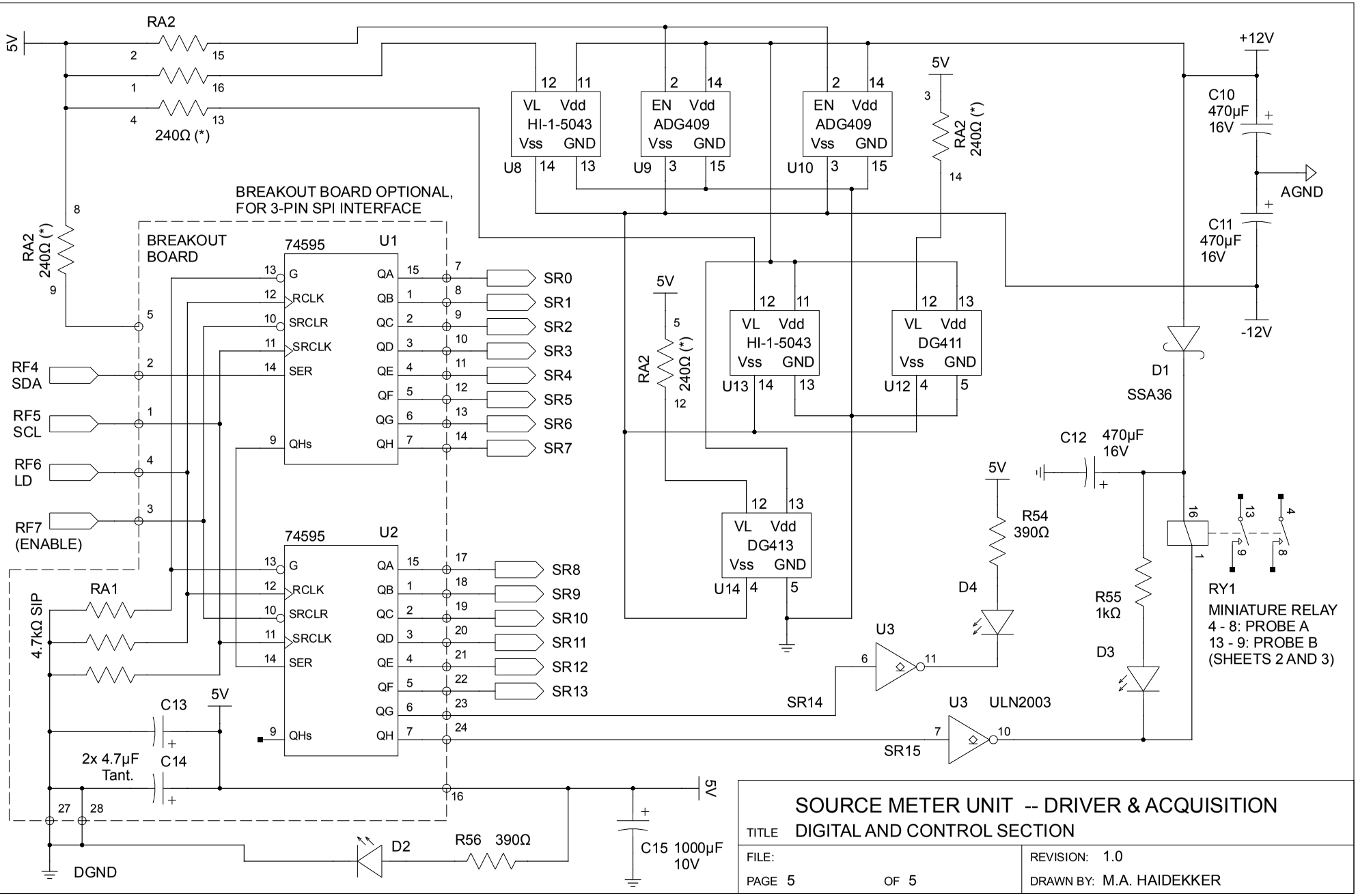
DRAWN BY: M.A. HAIDEKKER




# SOURCE METER UNIT -- DRIVER & ACQUISITION

TITLE OUTPUT SCALERS AND AMPLIFIERS

| | |
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| FILE: | REVISION: 1.0 |
| PAGE 4 OF 5 | DRAWN BY: M.A. HAIDEKKER |




# SOURCE METER UNIT -- DRIVER & ACQUISITION

TITLE DIGITAL AND CONTROL SECTION

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PAGE 5 OF 5

REVISION: 1.0

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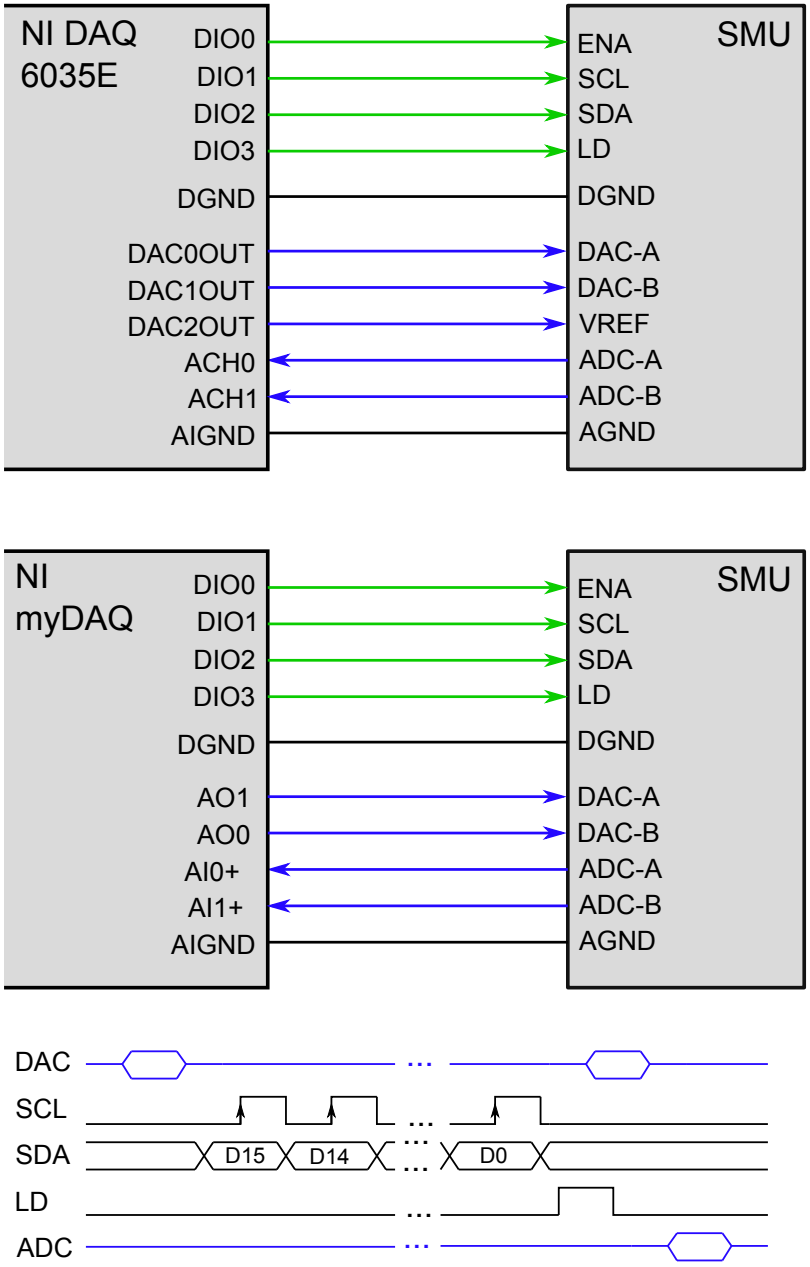



**Figure S2: Interfacing examples of the SMU with two examples of commonly used data acquisition systems.** (A) The first example is a National Instruments multi-channel analog/digital PCI card NI DAQ 6035E. (B) The second example is a low-end USB DAQ module, NI MyDAQ. As indicated in Figure 4, four analog signals are required. The digital signals can be provided by a four-wire SPI-type interface (Page 5 of Figure S1). The timing diagram for the SPI interface is provided in (C): The digital lines are shifted into the serial data line (SDA) LSB-first, and with a fixed 16-bit length. Each rising edge of the clock (SCL) samples the SDA input. Once all 16 bits are transferred, LD must be pulsed high for a few microseconds to propagate the input register to the outputs. The analog levels from the DAC can be updated both before or after the serial data transfer, but the analog acquisition (ADC) must take place after the digital transfer and the application of the DAC levels. Notably, the loop (Figure 6a) can be executed after the modes have been set once through the SPI interface, and merely updates of the DAC are needed. For an explanation of the 16 bits, see Table S2.

**Table S2: Function of the SPI Interface Bits (see also Table 2)**

| Bit | Label in Schematics | Function |
|---|---|---|
| 0 (LSB) | SR0 | Probe A control mode (0: controlled voltage, 1: controlled current) |
| 1, 2 | SR1, SR2 | Probe A, two-bit current range select (00: ±100µA; 01: ±25µA; 10: ±5µA; 11: ±1µA) |
| 3 | SR3 | Probe A input voltage scaler (0: ±10V; 1: ±1.25V) |
| 4 | SR4 | Probe A output voltage scaler (0: ±1.25V; 1: ±10V) |
| 5 | SR5 | Probe A measurement output (0: voltage, 1: current) |
| 6 | SR6 | Probe B control mode (0: controlled voltage, 1: controlled current) |
| 7, 8 | SR7, SR8 | Probe B, two-bit current range select (00: ±100µA; 01: ±25µA; 10: ±5µA; 11: ±1µA) |
| 9 | SR9 | Probe B input voltage scaler (0: ±10V; 1: ±1.25V) |
| 10 | SR10 | Probe B output voltage scaler (0: ±1.25V; 1: ±10V) |
| 11 | SR11 | Probe B measurement output (0: voltage, 1: current) |
| 12 | | Not used, reserved for future extensions |
| 13 | | Not used, reserved for future extensions |
| 14 | SR14 | Signal LED, can be used to diagnose the interface |
| 15 | SR15 | Output relay (0: Disconnect probe outputs from circuit, 1: Connect probe output to circuit) |