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The Design and Performance of a Low-cost Strong-motion Sensor Using the ICS-3028® Micromachined Accelerometer

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Open-file Report 98-109

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On-line Versions

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Introduction

The severity of earthquake ground shaking varies tremendously over very short distances (Figures 1*a-c*). Within a distance of as little as 1 km from the nearest station, one knows little more than what can be obtained from an attenuation relation, given only distance from the fault rupture and the geology of the site. For example, if some station measures 0.5 g peak ground acceleration (PGA), then at a distance of 1 km from that site, under otherwise identical conditions, the shaking has one chance in three of being under 0.36 g or over 0.70 g, based on the curve shown in Figures 1*a,c*. Similarly, pseudovelocity (PSV) response spectra have a 5% chance of differing by 2× at 1 km distance (Figure 1*b*). This variance can be the difference between moderate and severe damage.

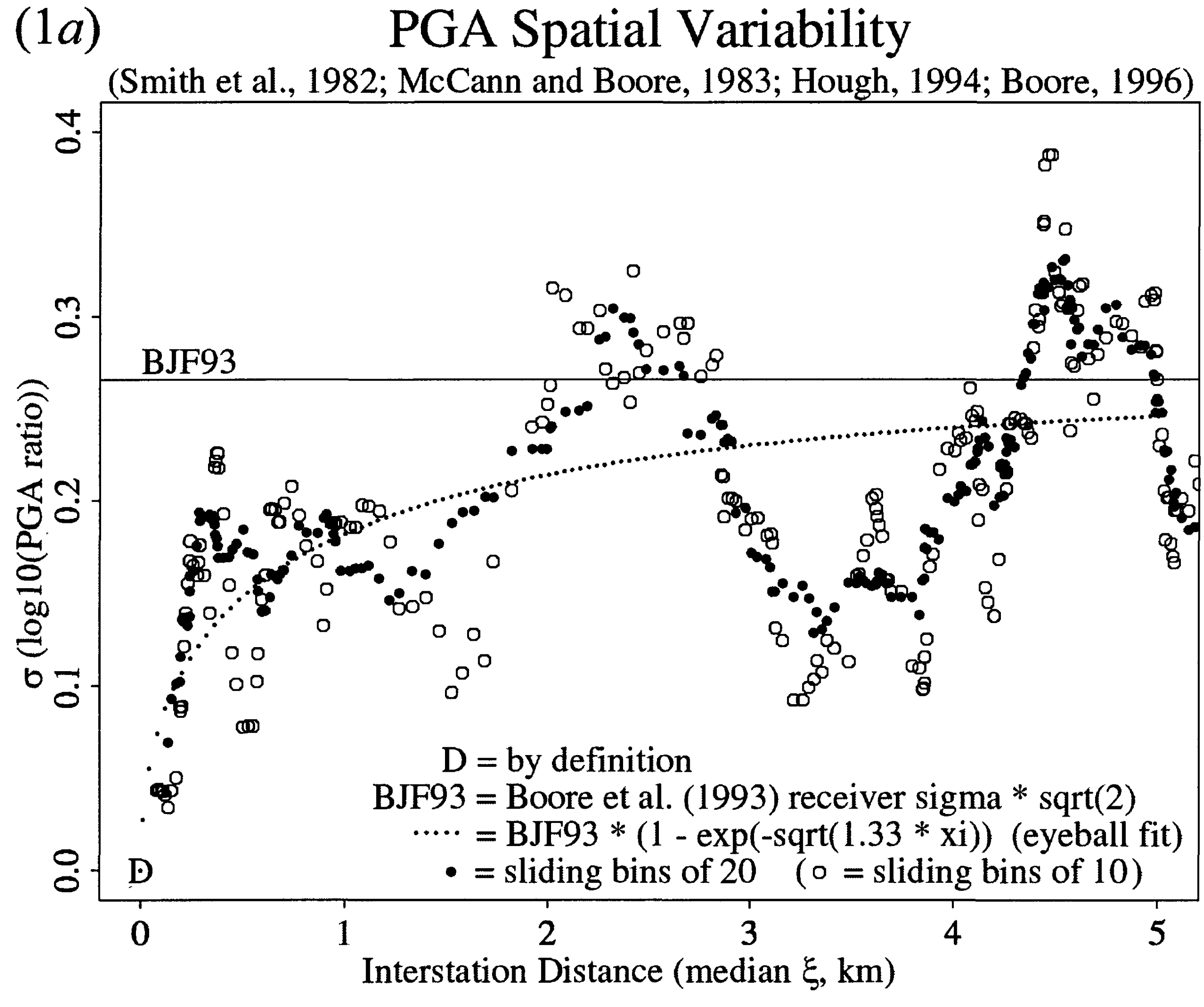


Figure 1. The spatial variability of strong ground motion, expressed as the log-normal standard deviation (σ) between neighboring stations separated by ξ km. These results are compiled from the literature, in some instances recast or evaluated by the author. Sources cited on Figures. (*a*) Peak ground acceleration.

Hence, there are critical needs, both in emergency response and in mitigation (prediction of shaking strength, building codes, structural engineering), to sample ground shaking densely enough to identify individual neighborhoods suffering localized, strong shaking. These needs imply a spatially dense network of strong-motion seismographs, probably numbering thousands of sites in an urban region the size of the San Francisco Bay Area, California (Figure 1*c*). It has not been economically feasible to field that many instruments, since existing ones cost many thousands of dollars apiece. For example, there are currently just a few dozen digital free-field instruments in the Bay Area. This paper is one step toward a solution to this conundrum. I demonstrate that a recently developed class of accelerometers, those constructed from silicon by "micromachining" (a process similar to integrated circuit fabrication), is now capable of resolving ground motion with the necessary accuracy while greatly lowering both acquisition and maintenance costs.

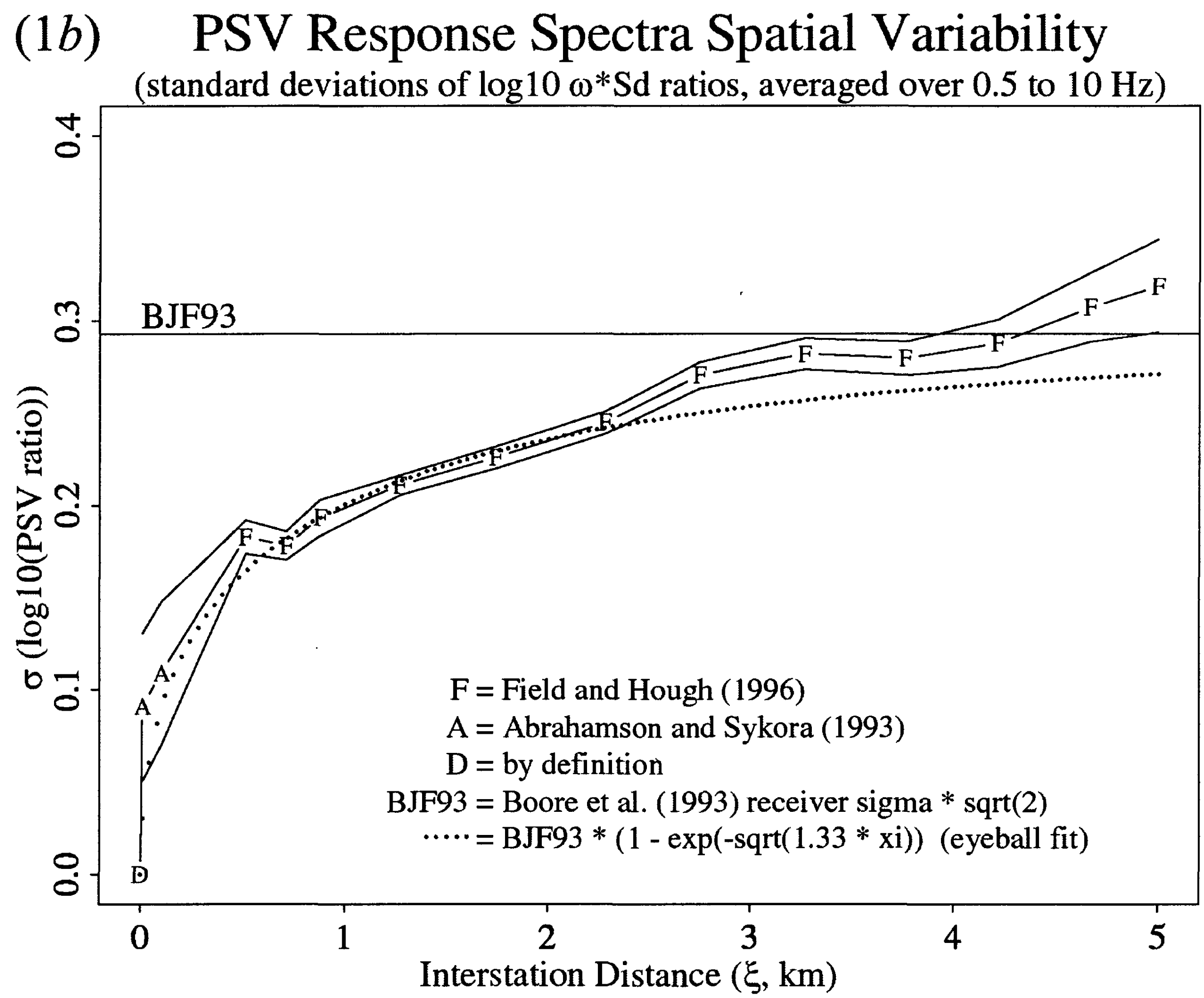


Figure 1 (cont.). (*b*) Pseudo-velocity response spectra (5% damped) averaged from 0.5 to 10 Hz.

Specifically, I describe the design and performance of a moderate-cost micromachined silicon accelerometer system combining the EG&G ICSensors ICS-3028® ($76 in quantity 500; ±2-g version) with a power-supply, amplifier, and filter system designed by the U.S. Geological Survey and one of its contractors (cf. **Acknowledgements**). I estimate that a completed three-component set including temperature sensor will cost about $550 parts plus labor in modest quantity (Table 1), compared to a retail cost of about $2700 for one of the commonest state-of-the-art strong-motion sensors used in seismology. Our sensor system is intended for use in low- to moderate-cost earthquake strong-motion seismographs in urban and suburban areas and lifeline corridors, where cultural ground noise often reaches over 50 μg peak-to-peak (PTP), and possibly along fault lines to aid early-warning systems. (One g is the acceleration due to gravity, 980.665 cm/s^2.) This sensor/amplifier system also has potential application in developing countries and other cost-sensitive installations, as well as general application to acceleration problems in the band above ≈0.1 Hz. We offer this design and these test results to further these aims.

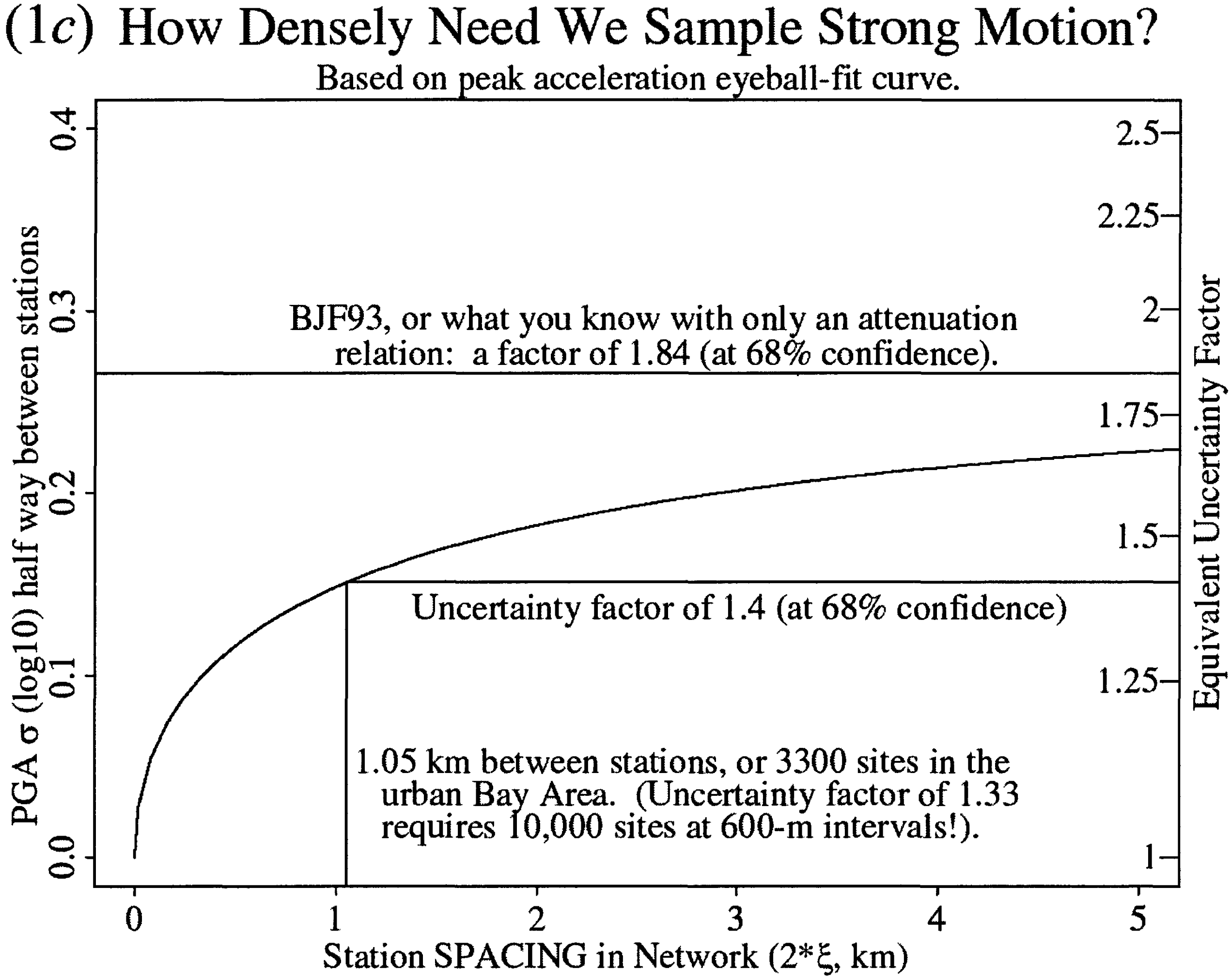


Figure 1 (cont.). (*c*) Recasting of the eyeball-fit curve from (*a*) to give PGA uncertainty examples. The "Equivalent Uncertainty Factor" corresponds to one standard deviation and is multiplicative.

Design

Figures 3*a* and 3*b* show our schematics, a single-ended design. Figure 4*a* shows the equivalent printed-circuit board.

The sensor itself (Figure 2) is an open-loop accelerometer based on a piezoresistive Wheatstone bridge. It is not temperature compensated and is quite sensitive to temperature (for gain, typically −0.15% of full scale (FS) per °C, or about −0.03 g over +10 °C in the 2-g devices we use). Each sensor is calibrated individually by the manufacturer (EG&G ICSensors, Inc.®, Milpitas, California) and supplied along with calibration-resistor values and related information. To build one of these sensors, a square section of silicon wafer is etched nearly free of its surroundings, remaining attached by four thin cantilever beams near the corners of the square. This proof mass is blocked from damaging overrange excursions by two more etched wafers, one fused to each face of the proof-mass wafer. Boron doping of the high-strain parts of the springs creates the bridge resistors, which are organized into a bridge circuit in a manner that cancels signals from rotations and cross-axis accelerations.

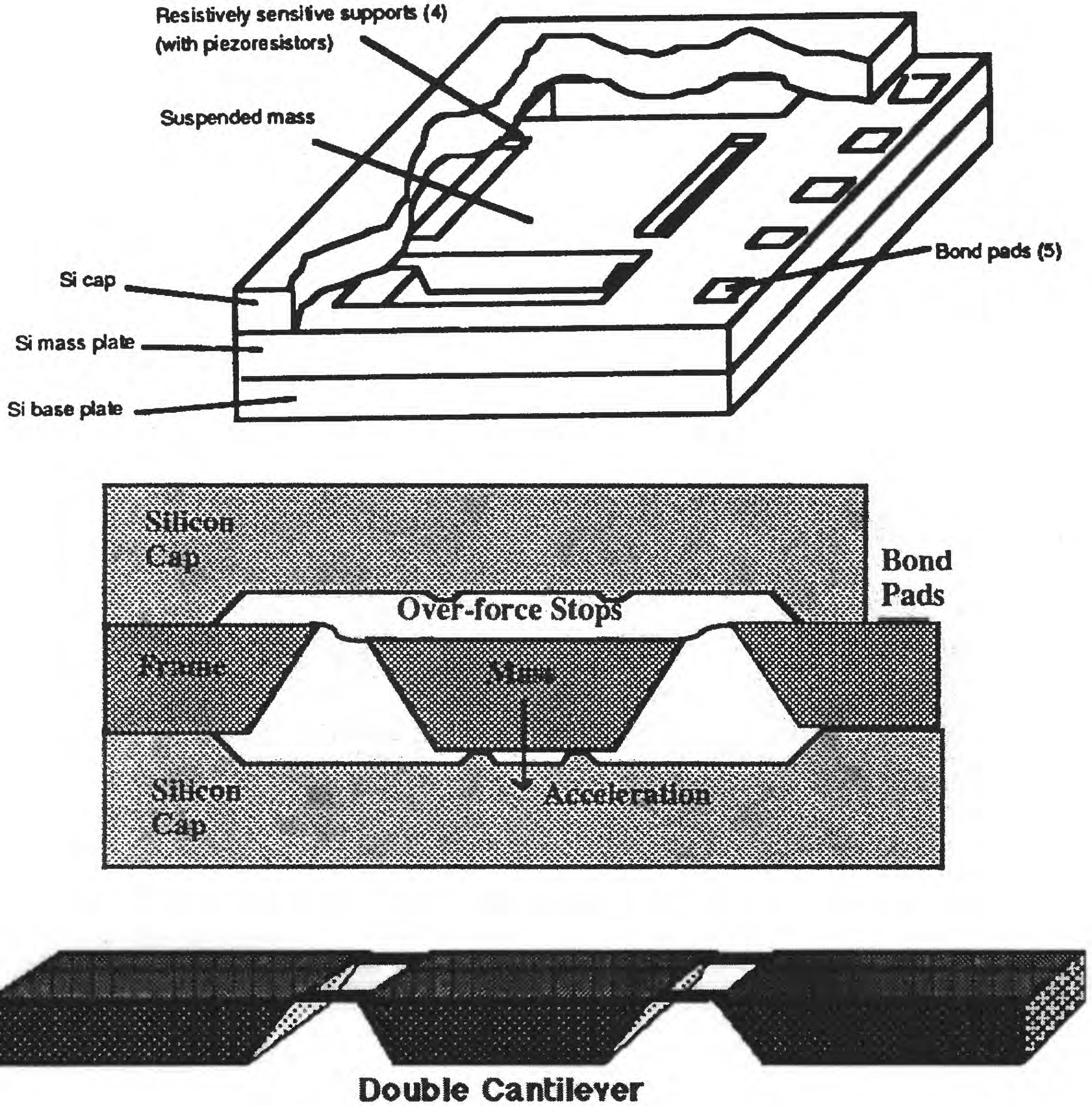


Figure 2. Diagrams of typical ICSensors® accelerometers (courtesy of ICSensors® Inc.). (*Top*) Cut-away perspective view of the entire device. (*Center*) Cross-section of the entire device. "Acceleration" is the negative of the acceleration vector. (*Bottom*) Proof-mass quad-cantilever design (sometimes called a "double" cantilever).

With a 5-V supply to the bridge, sensitivities are nominally 10 mV/g, though varying from one accelerometer to another by about ±20%. Resonant frequency is nominally 1 kHz, with similar variability, and damping is roughly 0.7, provided by viscous flow of the gas between the proof mass and the overrange stops on either side of it. Since the natural period is well outside the seismic-signal range, its variability and that of damping will not have a significant effect on the data.

Each arm of the Wheatstone bridge is nominally 4 kΩ, however slight process variability from one place to another across the wafer leads to imbalances between the arms. A low-valued resistor pair at either R1/R11 (R_{ZB1}) or R2/R12 (R_{ZB2}; Figure 3*a*) corrects the resulting offset in the 0-g output. (A parallel pair aids accurate matching of very low values, typically a few Ohms.) The other pair is to be shorted, generally with a zero-Ohm resistor.

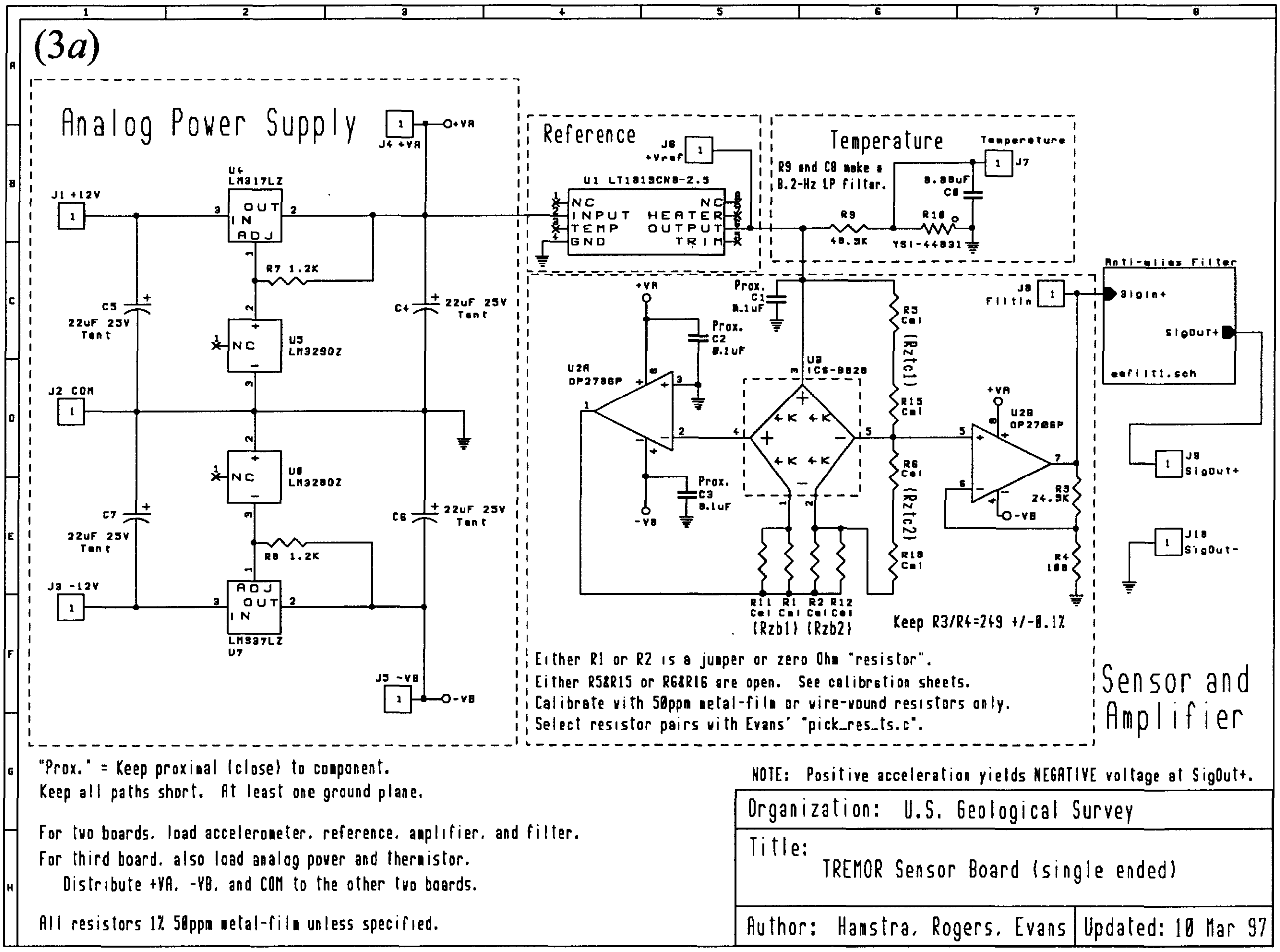


Figure 3. Schematic of the USGS low-cost strong-motion accelerometer signal-conditioning circuit. (*a*) Main part of the circuit. A PostScript® file containing this schematic is available *via* anonymous ***ftp*** from "andreas.wr.usgs.gov" at "~ftp/pub/outgoing/evans/OFR_98_109/ampfilt1.ps".

Another resistor pair at either R5/R15 (R_{ZTC1}) or R6/R16 (R_{ZTC2}) compensates the temperature drift of the zero level. (A series pair aids accurate matching of large values, typically on the order of 1 MΩ.) The other pair is to be left open.

All compensating resistors, indeed all resistors in this design, ***must*** be metal-film resistors with low temperature coefficients. All compensating resistors must be close to the sensor to minimize noise pickup and prevent parasitic oscillations in U2. (Wire-wound resistors are likely to induce such oscillations and carbon resistors are very noisy and temperature sensitive.) We use 1-% metal-film resistors with 50-ppm temperature coefficients (2¢ each in quantity 200). Selection of these resistors can be onerous since they are unique for each sensor. However the sensor manufacturer has indicated willingness to provide laser-trimmed compensating resistors for no additional cost in bulk purchases (cf. **Manufacturing Issues**). A simple brute-force C-language computer program for selecting optimal resistor pairs from standard sets is given in **Appendix A**.

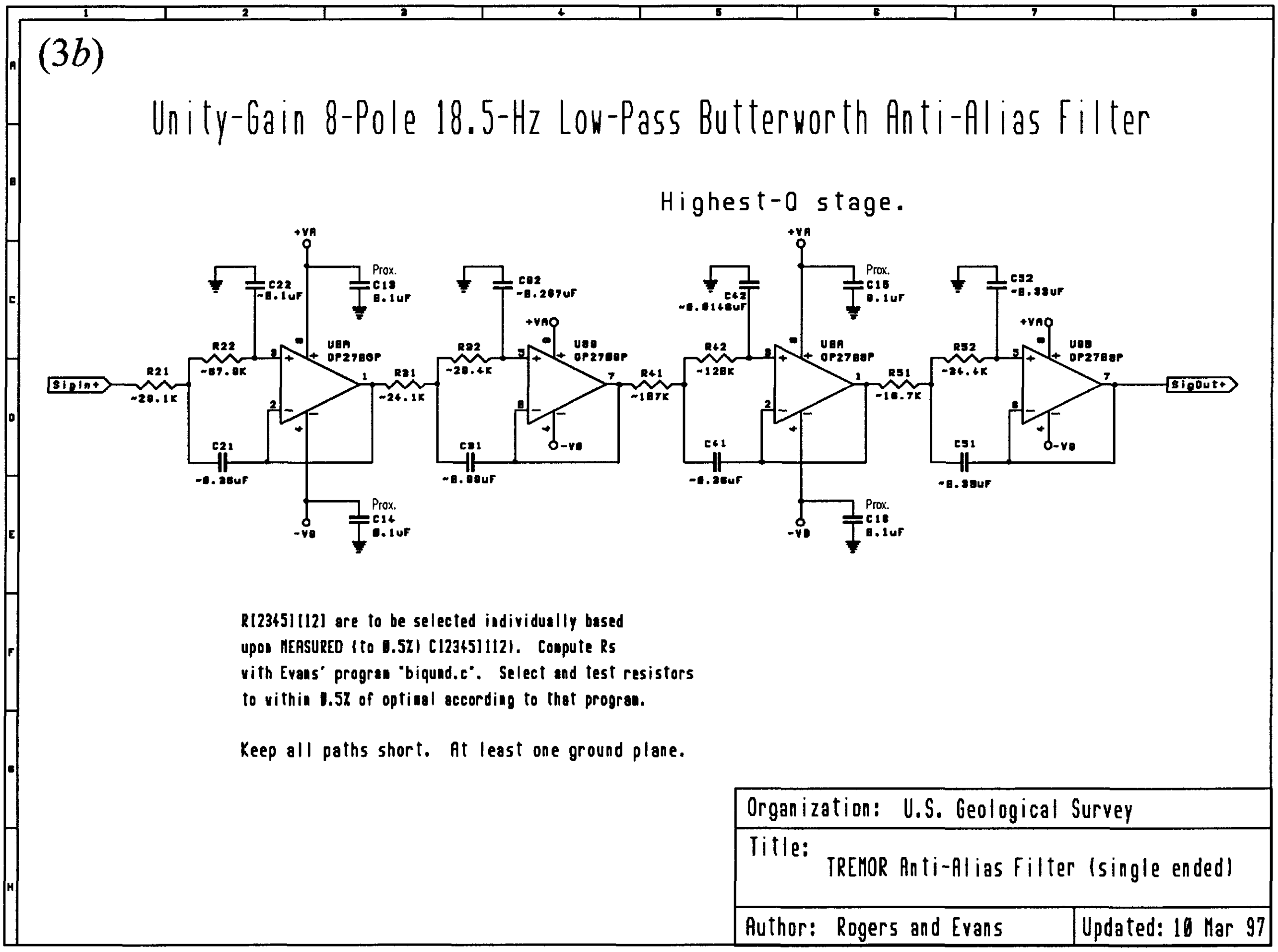


Figure 3 (cont.). (*b*) Anti-alias filter. A PostScript® file containing this schematic is available via anonymous *ftp* from "andreas.wr.usgs.gov" at "~ftp/pub/outgoing/evans/OFR_98_109/aafilt1.ps".

Because analog compensation circuits for the temperature-dependence of sensitivity use one or more diodes or transistors, they produce too much noise in the most critical part of the circuit. (The ICS-3052®, equivalent to an ICS-3028® but with internal laser-trimmed compensating resistors and transistors, is significantly noisier than the circuit shown here. However, it may be possible to use a "super matched pair" of transistors in this application, since these are in fact many transistors in parallel and yield a significant reduction in noise.) We have elected to use digital post-acquisition temperature compensation. We minimize temperature variations in space and time by placement of all sensors and signal conditioning circuits on a small, insulated, isothermal aluminum-mounting block (Figure 4*b*). This block also ensures orthogonality of the three accelerometers.

To measure temperature near the accelerometers we include a precision negative-temperature-coefficient (NTC) thermistor (YSI® model 44031). These low-cost sensors are accurate to ±0.2 °C after ten years and easily resolve to 0.001 °C. The resistance of an NTC thermistor is a highly nonlinear function of temperature (empirically modeled by a log-cubic relation). A C-language program to convert the output of this circuit (at J7) from mV to °C is given in **Appendix B**. It is intended for use in post-acquisition compensation of accelerometer sensitivity.

(4*a*)

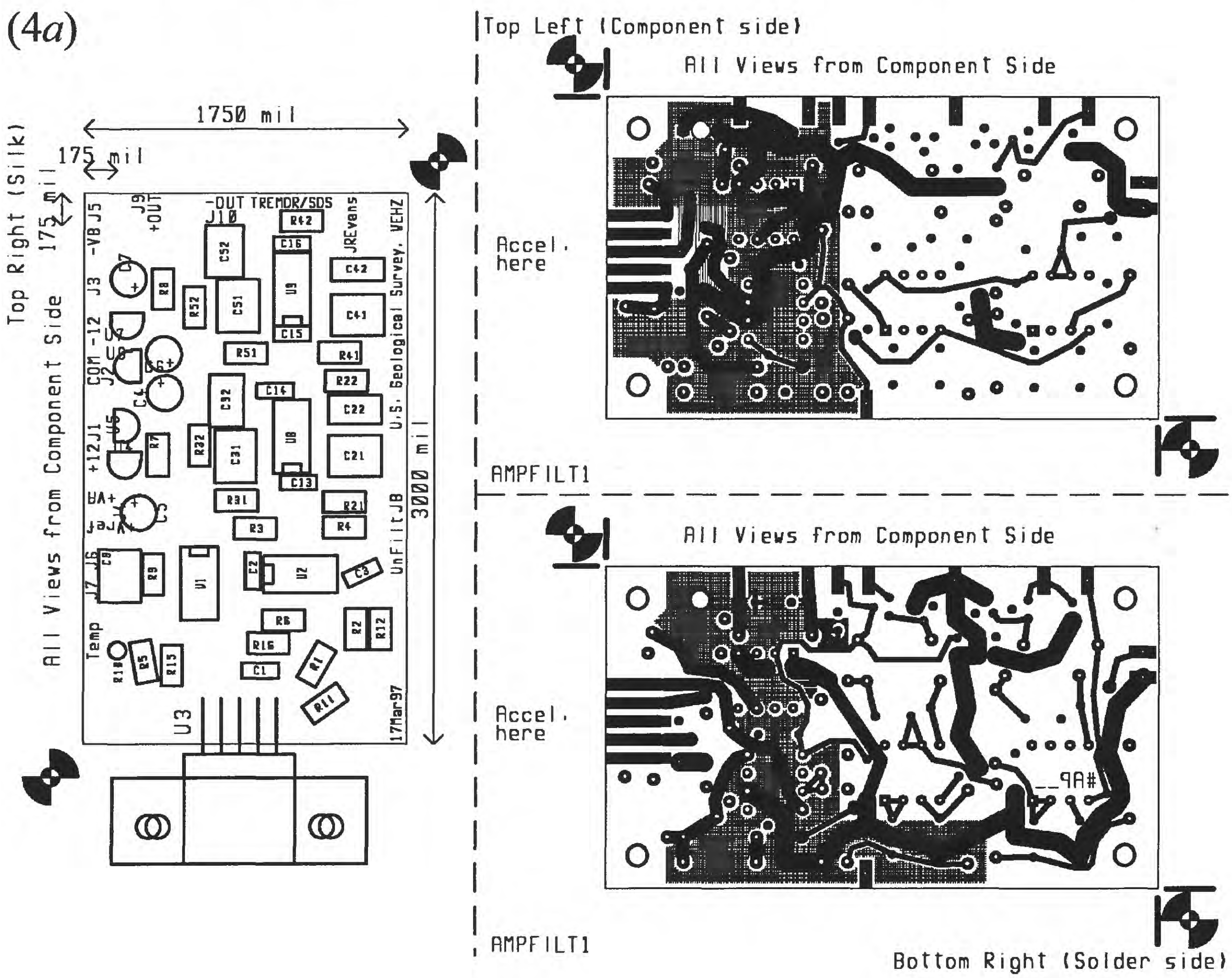


Figure 4. (*a*) Printed circuit board for the circuit in Figure 3. *Left:* component-side silkscreen; *top right:* component-side copper; *bottom right:* solder-side copper. All views are from component side. Accelerometer outline below silkscreen is intended to be outside the board, directly attached to the aluminum block with leads Z-bent upward to meet the board. It can also be 90° to the board with leads bent around that corner. As drawn, positive acceleration axis is out of page toward viewer. Gerber® plot files are available on "andreas.wr.usgs.gov" at files "~ftp/pub/outgoing/evans/OFR_98_109/*.ger". Use "binary" *ftp* to a PC. (*b*) Isothermal aluminum block for sensor mounting (Figure 4*b* is on page 11). This diagram is available as a PostScript® file in "~ftp/pub/outgoing/evans/OFR_98_109/TREMOR_Al_Block.ps".

A low-noise 2.5-V reference, U1 (LT1019CN8-2.5®), drives both the bridge and the thermistor circuit. Capacitor C1 further limits noise input to the bridge; it should be close to the sensor, with a very short run to the ground plane, and should be of type X7R ceramic. Half of the main gain stage, U2A (a bipolar PMI®/Analog Devices® OP270GP®), drives the negative input of the bridge to about −2.5 V, forcing the positive output of the bridge at pin 4 to ground and thereby doubling the range of output at pin 5. That negative output is amplified in non-inverting amplifier U2B, with a nominal gain of 250×. (Note that this arrangement yields ***negative voltage for positive accelera-***

tion. An inverting amplifier is inappropriate because it would pull pin 5 to ground and load the bridge. However, rearrangement of this part of the circuit for positive-positive output is possible.) The gain resistors should be of the same type as the compensating resistors. In practice, I have selected individual gain resistors to give about the same output sensitivity (2.5 V/g) in order to optimize use of an ADC's dynamic range (cf. **Manufacturing Issues**). As with C1, all op-amp-decoupling capacitors (C2, C3, and C13 through C16) must be proximal to the device served and to the ground plane and of type X7R ceramic.

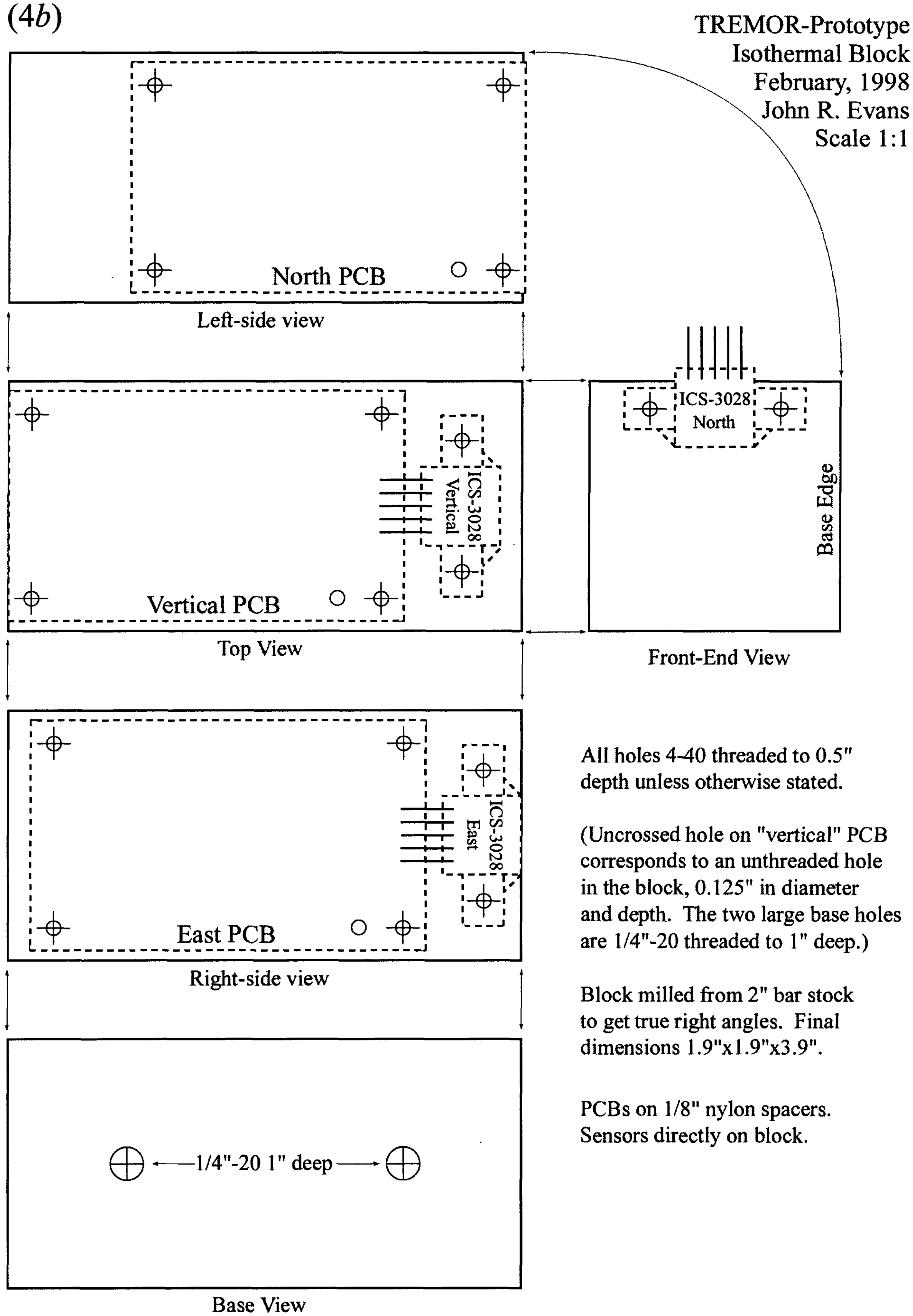
The output of the main gain stage, U2B pin 7, goes to an 8-pole Butterworth low-pass filter for anti-alias filtering (Figure 3*b*). The design used here is a bi-quad configuration. We currently use 5% capacitors and individually tune the filters by selecting matching resistors. The C-language program in **Appendix C** aids this selection. (In mass production one would use 2% capacitors with standard 1% resistors to achieve adequate tuning consistency without custom part selection.) In the temperature circuit, R9 and C8 provide anti-alias filtering by forming a one-pole filter appropriate to the decimated sampling rate of that channel. All filter capacitors must be of low-impedance film type; we have used Panasonic® Series V to date, but similar varieties would be appropriate.

Alternatively, one might be able to use a switched-capacitor filter for anti-alias filtering, if the clock of that filter were synchronized with the clock of a subsequent Σ–Δ or fast multi-slope ADC to eliminate clock feed-through noise (R. Jarnot, personal communication, 1998). Such designs are likely to be simple (less expensive) and lower in power use. In another alternative, a much more modest anti-alias filter combined with the inherent over-sampling of Σ–Δ ADCs could significantly lower parts costs and manufacturing complexity. This technique has been used in other seismographs. The power supply on the left side of Figure 3*a* provides quiet power to the signal conditioning circuitry, nominally at ±8.2 V. It uses low-cost low-noise linear components. Input to this circuit is about ±12 V. Total power consumption for a three component set of accelerometers is very nearly 1 W, and nearly all of it goes to driving the OP270GPs®. Hence, this power level could be reduced by half or more by using low-noise CMOS op-amps in the Butterworth filter, however use of the OP270GP® in the primary gain stage (U2) is crucial to system noise performance.

Various dual-use input/output pads (J2, J4, J5, and J6) are provided to allow sharing of the power supply and voltage reference. The printed-circuit board in Figure 4*a* is used in sets of three, one per acceleration channel (e.g., vertical, North, East). Only one board needs to be loaded with a thermistor and power supply, with the other boards powered by jumpering J2, J4, and J5 between all boards. The voltage reference can be shared similarly, though we have not done so initially to avoid noise pickup in the jumpers. A redesign for a three-component surface-mount board using only one voltage reference would be appropriate in manufactured versions. In any case, ground planes must be provided in the low-level-signal parts of any board, as they are in our prototypes (Figure 4*a*). An internal, grounded aluminum box in our prototype accelerographs supplies additional shielding for this single-ended sensor block, with all digital circuits kept outside that internal shield box.

Lastly, avoid stressing the accelerometers during mounting. For example do not shim them for orientation. The manufacturer recommends mounting them flat on a machined aluminum block with screws tightened to 6 foot-pounds per inch of screw length (for 4-40 screws). Stressing the mount can stress the silicon of the accelerometer and cause large offsets in the output signal. It can also induce "oil canning" nonlinearity—kinking of the cantilever springs causing the proof mass to hang up.

(4*b*)



All holes 4-40 threaded to 0.5" depth unless otherwise stated.

(Uncrossed hole on "vertical" PCB corresponds to an unthreaded hole in the block, 0.125" in diameter and depth. The two large base holes are 1/4"-20 threaded to 1" deep.)

Block milled from 2" bar stock to get true right angles. Final dimensions 1.9"x1.9"x3.9".

PCBs on 1/8" nylon spacers. Sensors directly on block.

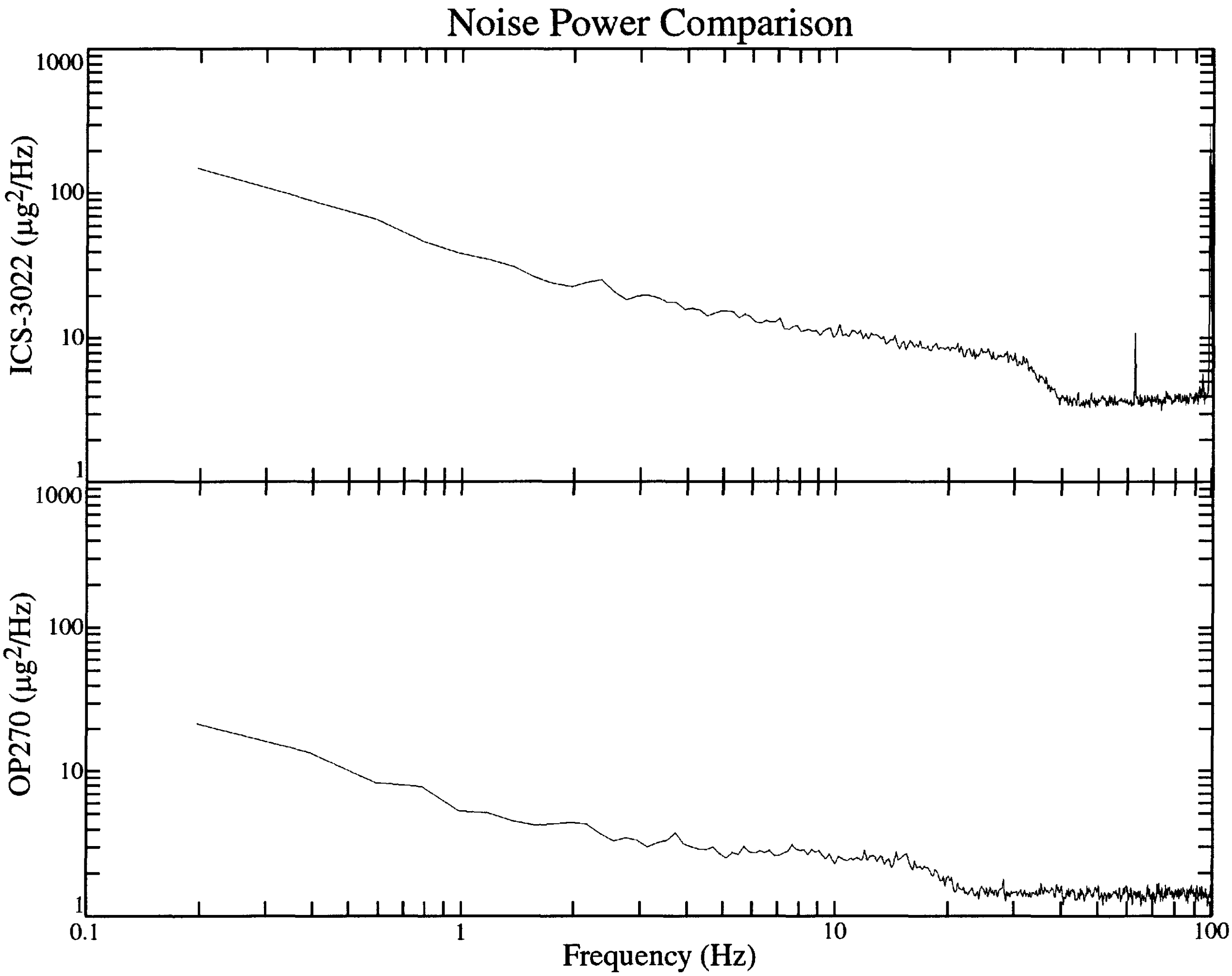


Figure 5. Noise power spectra for the complete system (*top*), with an ICS-3022® accelerometer. (*Bottom*) Equivalent noise spectrum with the accelerometer replaced by a dummy bridge of 4KΩ metal-film resistors. (Data for these two spectra were taken at the same sample rate (200 sps) but with different anti-alias filter corners. Each is an ensemble average of the spectra from many noise samples.) The spikes above 60 Hz and just below 100 Hz in the upper plot were probably caused by noise from the inverter used for power at our rural vault site. The lower plot was derived in the laboratory using line power.

Performance

Noise performance of this sensor system is shown Figures 5 to 7. Figure 5 (*top*) gives the noise power spectrum for the entire system, from the ICS-3022® accelerometer through anti-alias filter, taken at a quiet rock vault where ground noise is known to be far below intrinsic sensor noise levels. (The ICS-3022® is identical to the ICS-3028® except for packaging details like mounting plates and pins.) It reveals *1/f* noise with two corner frequencies, at about 2 Hz and somewhere above the anti-alias corner frequency. Since the noise level of the same system with a dummy bridge replacing the sensor is about a factor of five to ten quieter (Figure 5, *bottom*), the principal limiting noise source appears to be non-Johnson noise in the resistors of the sensor's Wheatstone bridge. The likely source of this noise is surface imperfections in the doped resistors and interconnects (R. Jarnot, personal communication, 1997). Manufacturing changes subsequent to the acquisition of our test samples may have improved this noise figure, but this conjecture is untested.

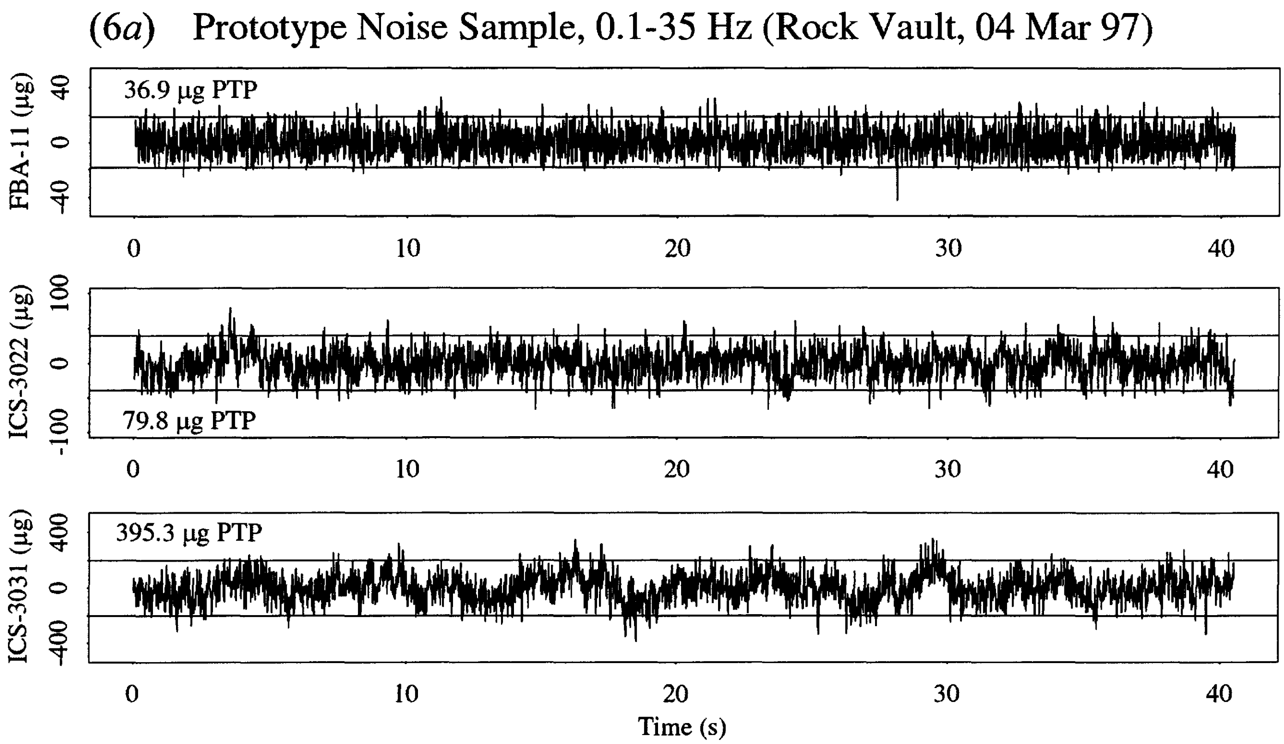


Figure 6. Noise samples for the complete system for (*top*) FBA-11® (limited here by noise in our test apparatus); (*center*) an ICS-3022®; and (*bottom*) a lower cost device, the ICS-3031®. Note the differing amplitude scales. PTP noise amplitude is defined as $\pm 2\sigma$. (*a*) Signals in the band 0.1 to 35 Hz.

Equivalent noise samples in the time domain are shown in Figures 6*a* and 6*b*. These correspond to the desired bandwidth, 0.1 to 35 Hz, and the minimum acceptable bandwidth, 0.5 to 10 Hz, for strong-motion seismology and structural engineering. Simultaneous noise samples are shown for an FBA-11® (limited by our test-system noise level) and a lower-cost silicon accelerometer, the ICS-3031®, using the same signal conditioning circuit as the ICS-3022®. For comparison, the noise level we measured in Pasadena (one block from a major freeway) was on the order of 100 μg PTP. Noise levels measured in a quiet residential neighborhood of Palo Alto, California, were about 40 μg PTP on soft soil about 1 km from a freeway. (These samples were taken with a horizontal FBA-11® sensor. They were estimated visually—possibly under estimated—using an oscilloscope.) In the Palo Alto case, the footsteps of a worker about 20 m away were clearly visible with the ICS-3022®.

The ICS-3022® (hence, the ICS-3028®) clearly justifies an 18-bit ADC, given its broadband signal-to-noise ratios. These ratios (4σ/4-g) are 15.6 bits (0.1 to 35 Hz) and 16.3 bits (0.5 to 10 Hz). If signal-to-noise is instead defined as RMS/2-g, those values become 16.6 and 17.3 bits (100 and 104 dB). Using a third signal-to-noise definition (RMS(noise)/RMS(4-g PTP sine wave)), the values become 16.1 and 16.8 bits (97 and 101 dB).

Tests of sensor linearity are partially complete. However, we can limit the nonlinearity of sensor output *versus* static acceleration in a tilt test (Figure 8) to the inherent accuracy of our tilt table (about 0.1 %FS). Indeed, the results of our tilt tests for a research-grade accelerometer (Kinemetrics® FBA-11®) are indistinguishable from those of the ICS-3028® family—our tilt table limits both results. We can also limit hysteresis to about 0.02% FS with the sensor axis oriented in the horizontal plane, which compares well with the manufacturers claim of 0.01 to 0.02% FS (G. Rendla, personal communication, 1996). This limit happens to be the same as the (informal) specification for the FBA-11®. More sensitive tests for this type of hysteresis are planned. Tests of temperature compensation for sensitivity also have not been completed. We intend to do such tests to verify the manufacturer's calibration. Preliminary tests suggest at least gross similarity, but are insufficient to test the veracity of those calibrations.

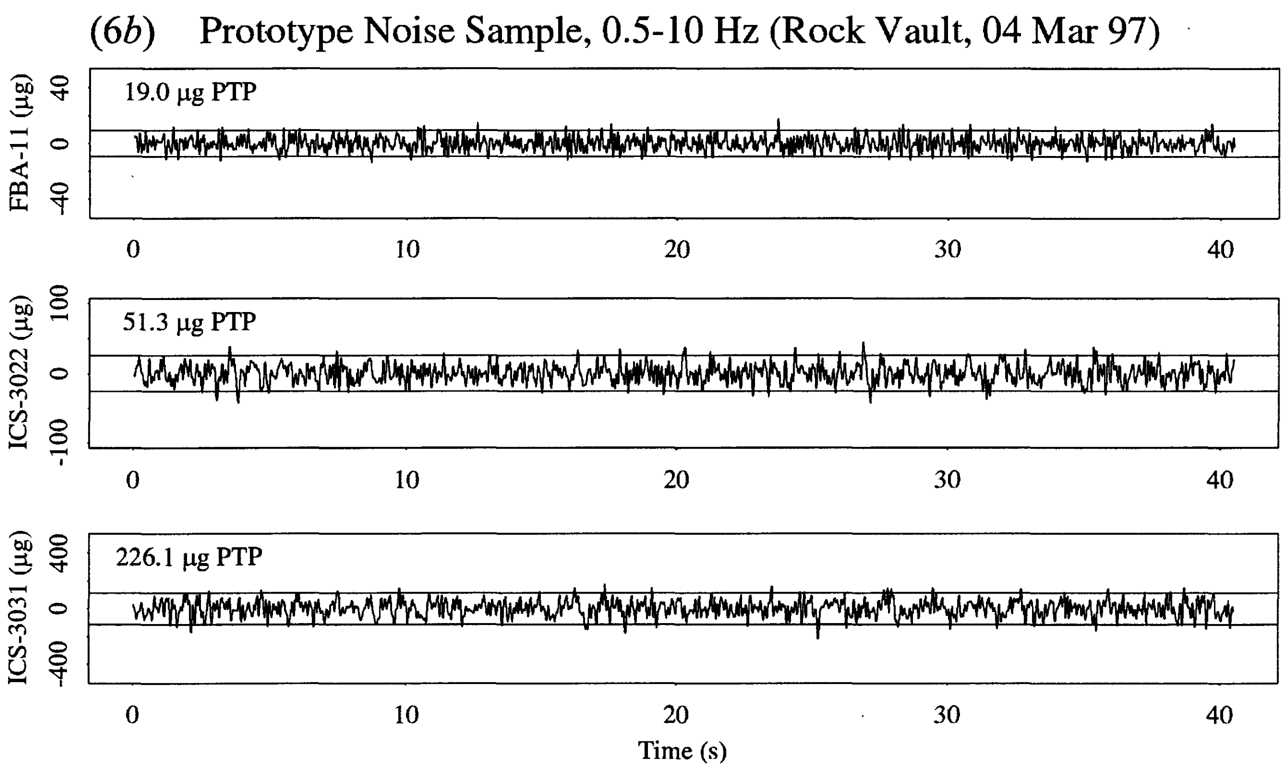


Figure 6 (cont.). (*b*) Signals in the band 0.5 to 10 Hz.

Tests of cross-axis sensitivity also remain to be done. The manufacturer's specification is ±3% FS (and typically ±1% FS). Spot checks of sensor orientations agree with the manufacturer's claim of 2° accuracy, with all examples tested being well within that limit. The manufacturer subsequently improved orientation accuracy and now claims 1° orientation accuracy. Appropriate goals are ±1-% FS cross-axis sensitivity and 1° orientation accuracy.

In the process of finding an amplifier that does not contribute significantly to system noise, we tested many models in several configurations. We found the OP270GP® to be both quiet and stable. The noise spectra for this and two other amplifiers (installed in our Figure-3 circuit with a dummy bridge) are compared in Figure 7. The spectrum for the LT1007® is suspect because longer leads needed for these (single) op amps induced a parasitic oscillation in U2. The LT1124® and OP270® did not oscillate and can be compared directly. We chose the latter because its spectrum is slightly less red than that of the LT1124®. However, either device is adequate.

In short, the sensor, not the amplifier, currently limits performance. In any case, the resulting noise figure is quite adequate for urban strong-motion recording.

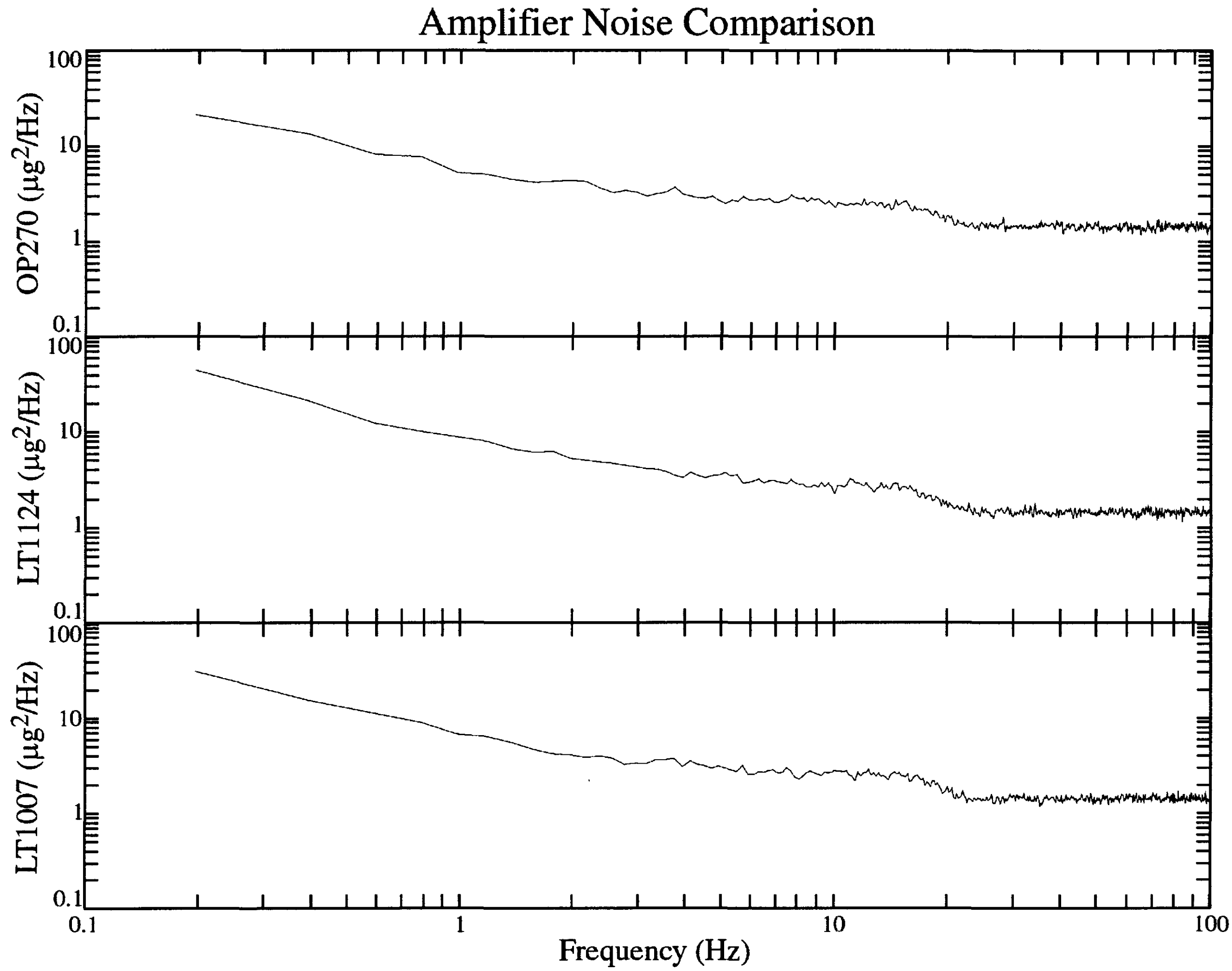


Figure 7. Noise power spectra for three models of operational amplifier, with a dummy bridge in place of the accelerometer, as in Figure 5 (*bottom*). Result for the LT1007® is suspect because our jumpers used with that model induced a parasitic oscillation.

Operational Issues

A number of operational issues arise with this sensor. In particular, one must lower the rate of temperature change within the sensors and assure nearly homogeneous temperature across each sensor and between the accelerometers and the thermistor. These goals can be met easily by (1) placing all four devices in close contact with a small aluminum block, (2) making thermal contact between this block and the underlying concrete slab or rock of a site, and (3) insulating this block from the air. In practice, we insulate in two layers, one between the internal shield box of the sensors and the outer box of the instrument and the other around the whole instrument. The latter is made from two-inch-thick semi-rigid polyisocyanurate foam board with aluminum-foil facings, a common housing-construction material (e.g., Celotex® Tuff-R®). It is easily sawed with bandsaw or jigsaw, and assembled with adhesive caulking. Hand, arm, eye, and breathing protection should be worn since this material seems to contain fiberglass for strength. We attach the prototype instrument to the concrete slab and cover it with a skirted box of this foam. The box's skirt is attached to the concrete with a removable adhesive, such as DAP® Fun•Tak® or Seal 'N Peel® removable caulking. If manufactured in bulk, an equivalent enclosure could doubtless be custom molded to shape at very low cost.

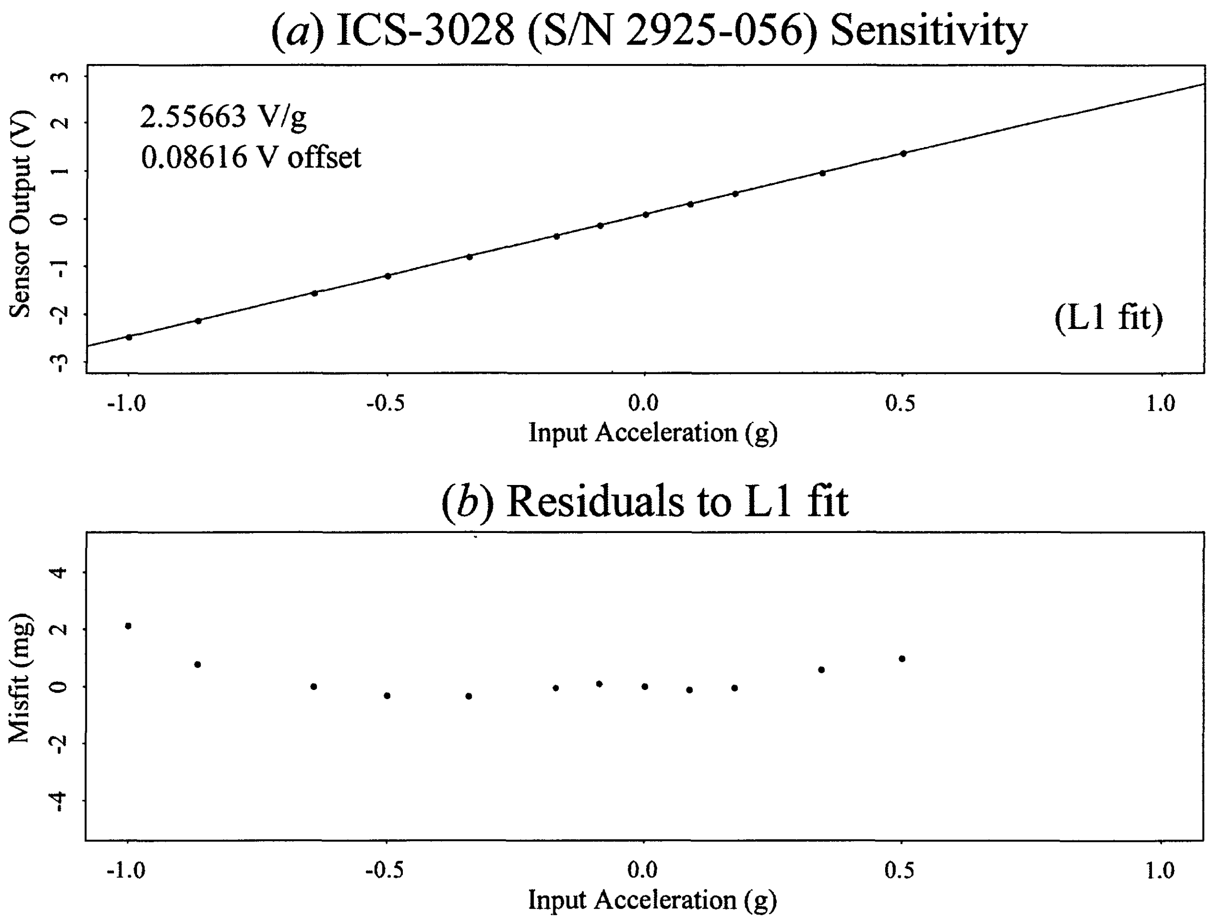


Figure 8. Tilt-table calibration and linearity test for an ICS-3028®. Apparent nonlinearity is probably due to imperfections in the tilt table. In any case, the largest apparent diversion from linear response is at −1 g, and is about 0.1% FS.

For the very large networks envisioned, maintenance costs are crucial and likely to exceed acquisition costs within a few years of operation. Keys to lowering maintenance costs are robustness of the instruments and sensors, non-challenging environments, and routine state-of-health (SOH) messaging. The latter allows one to leave an instrument untended indefinitely, visiting a site only when the SOH message (or lack of a message) indicates a need for repair. This messaging presupposes some low-cost telecommunications link for SOH messages, the same link required for real-time messaging in support of Emergency Services. Robustness in the partially controlled environments envisioned (mostly school closets and private garages) requires that the sensor and other parts of the instrument withstand occasional impacts by furniture, 2×4 studs, teenagers, dogs, etc., without damage and preferably without triggering. Similarly, washing machines, vehicles, and other sources of vibration must not affect the instrument significantly (preliminary field tests suggest these noise sources are tractable). Silicon accelerometers by this manufacturer are extremely robust, including for shock (at least 1000 g), vibration (400 g RMS), and spring sagging (none detectable in decade-old test articles). They do have some weakness to corrosion of metal interconnect parts, hence require a dry atmosphere within the instrument. This atmosphere can be maintained by desiccant and by introducing a small piece of dry ice just prior to instrument closure. The sublimating CO_2 displaces Oxygen and water vapor from the container (K. Young, personal communication, 1997). The trigger currently has a modest minimum-duration criterion in addition to a triggering threshold. The former is designed to avoid triggers caused by impacts on or near the instrument. The foam insulation also provides a significant crush zone.

The most likely component to fail is the backup batteries, which probably should be sintered-electrode NiMH D-cells (e.g., Varta Batteries AG® or Universe Power Sources (Huan Yu US) Ltd.®). These were designed for the emergency-lighting industry and are rated for five years continuous float charging. In seismic applications they probably can be used for longer periods. By combining such non-toxic cells with careful design, one might be able to have the homeowner or other local representative replace the batteries when indicated by the SOH message and simply discard the old ones in their normal garbage stream.

I know of no calibration method that will work for these sensors other than tilt testing; they lack other means to deflect the mass. The absence of measurable spring sag and the use of diffused resistors in the bridge suggest that sensitivity will change only very slowly. However, this issue remains open.

We intend to operate most of these instruments at "free field" sites, relatively unaffected by soil-structure interactions. As a practical matter, truly open sites are rare in urban areas and even less often secure from weather and vandals. In practice, we will compromise by using one- and two-story buildings, where possible of light construction (e.g., wood-frame). These are commonly regarded as having little effect on earthquake signals (W. Joyner, personal communication, 1997). Initial feedback from likely hosts suggests that siting on grade-level slabs in the garages of private homes is the most viable solution, with janitors' closets in schools a likely alternative.

Manufacturing Issues

Issues of manufacturability have been mentioned at various points throughout this report. Here we collect and elaborate on these issues.

Individual selection of sensor-calibration resistors is the most serious issue to be solved before low-cost mass-production could begin. The selection process is labor intensive and vulnerable to human error. Luckily, the manufacturer has indicated willingness (at least at 10,000-quantity purchases) to make certain custom modifications to the design and testing of these devices. In particular, they already offer a similar device, the ICS-3052®, which has laser-trimmed Ruthenium calibration resistors integrated with the accelerometer package. This device also contains a transistor pair, used in temperature-compensating sensitivity. Our design would simply leave out this transistor pair—call the result an "ICS-305*x*". The manufacturer has indicated willingness to offer such a device at the same price. If, in addition, one more pin could be added to the design, then a calibrating resistor now used in conjunction with these transistors could be used instead to provide

R3 of Figure 3*a*, the gain-setting resistor. This change would allow easy correction for gross sensitivity differences between individual sensors. The addition of this sixth pin is problematic, however, requiring more significant retooling and redesign. It is not clear whether the manufacturer would undertake it without a price change. Changing from an 18- to a 19-bit ADC would obviate the need for this sixth pin and could well prove less expensive. Sensitivity corrections would then be made in the same post-acquisition process as are temperature corrections.

The manufacturer has also indicated willingness to customize their testing procedure to suit the needs of a large purchase. I suggest in-circuit testing using the final amplifier design. This change would minimize the degree of inference required for subsequent digital compensation. Furthermore, it may be desirable to get testing in three orientations, –1 g, 0 g, +1 g, and at more temperature points than is standard (perhaps at –10°, 5°, 20°, and 40° C).

Filter components would not be custom-selected in any final design. With more lead-time, 2% capacitors can be ordered, which when combined with 1% resistors would provide adequate tuning precision. The alternative design suggestions in **Design** could lower power, cost, and complexity still further.

Orientation of the accelerometer's active axis should be adequate without shimming or other corrections. Those we have checked were well within the ±2° tolerance then specified by the manufacturer. That specification is now ±1°, which is adequate for seismology. Furthermore, shimming stresses the accelerometer and causes large offsets in its output and may also induce nonlinear behaviors. Simply attach the sensors flat on the faces of a rectilinear aluminum block.

The thermistor used to sense this block's temperature should be of high quality. YSI® Inc. has very tight closed-loop quality control allowing it to guarantee ±0.1 °C accuracy when purchased across all examples of certain models (e.g., model 44031) and ±0.2 °C after ten years deployment. Their price depends very strongly on quantity; at the large quantities envisioned here they would cost a few dollars apiece for the raw, epoxy encapsulated version. This version is difficult to handle since it is small and has very fine leads. However, numerous packaging options are available, including surface-mounting and threaded-insert versions. The latter (e.g., YSI 093) probably is the most cost-effective solutions.

In any production version one would probably use surface-mount techniques and redesign the board of Figure 4*a* into a three-component version with better I/O connectors. This change would reduce the parts count, for example by sharing one voltage reference (U1) among all sensors. It probably is not appropriate to use connectors to attach the accelerometers to this board because the signal levels are so low in that part of the circuit and because the bimetal-junction count probably would increase, causing larger temperature-induced signal offsets. The isothermal mounting block and shield box probably would be integrated into a single unit of cast aluminum or conductive polymer. Indeed, a complete two-chamber box with mounts may be appropriate. All envisioned digital circuitry for a low-cost instrument would fit on a single board as well so the completed instrument should be very compact.

Conclusions

As shown by *Evans and Rogers* (1995), even far noisier sensors are adequate for attenuation relation studies; certainly the noisier sensors are also adequate for Emergency Services needs. We have shown that the ICS-3028® is capable of much more, of reaching below urban background noise levels. In other words, it is capable of measuring all the seismic signal there is to record in such environments, with the possible exception of long period signals (Figure 5). It opens the door to serious research in seismology and structural engineering, research with direct impacts on life safety.

Manufacturing issues can be overcome in large purchases by inclusion of laser-trimmed compensating resistors inside the sensor package. Sensor robustness promises long field life even in imperfectly controlled environments, such as schools and the garages of private homes.

In short, micromachined silicon accelerometers admit a new paradigm in strong-motion seismology. We can look forward to a day where the necessarily few high-grade research instruments are augmented by spatially dense networks of robust, low-cost instruments. With these, we could produce the equivalent of Doppler weather radar, showing earthquake-shaking "storms" and the badly shaken "squall lines" within them. Emergency Services can then both estimate overall needs and direct scarce resources optimally to those most in need. Seismologists could finally make and test detailed shaking models for predictive purposes. And structural engineers and seismologists could finally unravel the effects of shaking, design, construction, and maintenance upon structural vulnerability. The need for such arrays and their usefulness in response and mitigation are incontrovertible.

Acknowledgements

This work is part of the TREMOR/SOS Project, funded by the USGS Earthquake Hazards Reduction Program. We are grateful for their support even in times of very lean budgets.

John Rogers, with minor help from the author, performed the initial design and operational-amplifier selection. This effort led to the selection of the OP270GP® dual amplifier for its superior noise performance, which is both low and fairly white. The design of the voltage reference, power-supply, and amplifier now used is that of Robert H. Hamstra Jr., a private consultant specializing in low-noise instrumentation, while he was under contract to the USGS. He went far beyond the call of duty and taught this author many essentials of good instrumentation design. Dr. Robert Jarnot of JPL provided critical reviews of the design and of this paper and gave important insights into crucial design issues. The anti-alias filter is a joint effort of John Rogers, Gray Jensen, and the author, all of the USGS. Testing was performed at various stages by the author, John Rogers, Bill Robinson, and John Coakley, all of the USGS. We are grateful for the contribution of Bill Robinson's time and expertise by the USGS Marine Facility. ICSensors® Inc. kindly supplied the diagrams comprising Figure 2. Sensor-in-circuit noise tests were done at a USGS seismometer vault on the Gerber-Wells Ranch with the kind permission of Helen Gerber and her family. Willie Lee provided insights, comments, facilities, and an occasional kick in the pants—I limp gratefully. Throughout it all, Paul Spudich provided essential insight, guidance, support, and tactical skill.

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Table 1—Parts Listing and costs

Parts Cost for TREMOR Accelerometer Three-component Sets								
			For 10 Units			For 1000 Units		
Use Qty	**Reference**	**Value**	**Unit Price**	**Buy Qty**	**Total**	**Unit Price**	**Buy Qty**	**Total**
3	U3	ICS-3028	$90.00	25	$270.00	$66.00	3,000	$198.00
1	Al mounting block	Block	$71.00	7	$71.00	$13.00	1,000	$13.00
3	U2	OP270GP	$3.37	100	$10.11	$2.13	10,000	$6.39
3	R3	24.9 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R4	100	$0.02	200	$0.06	$0.012	1,000	$0.04
24	R1,2,5,6,11,12,15,16	Calibration	$0.02	200	$0.48	$0.012	1,000	$0.29
9	C1,2,3	0.1 uF	$0.2128	100	$1.92	$0.127	1,000	$1.14
3	J8	FiltIn	$0.00	N/A	$0.00	$0.00	N/A	$0.00
	Accelerometer Section Parts			**76.1%**	**$353.63**		**80.5%**	**$218.89**
6	U8,U9	OP270GP	$3.37	100	$20.22	$2.13	10,000	$12.78
12	C13,14,15,16	0.1 uF	$0.2128	100	$2.55	$0.127	1,000	$1.52
3	R21	28.1 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R22	67.5 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R31	24.1 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R32	29.4 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R41	107 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R42	120 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R51	16.7 K	$0.02	200	$0.06	$0.012	1,000	$0.04
3	R52	34.4 K	$0.02	200	$0.06	$0.012	1,000	$0.04
12	C21,31,41,51	0.39 uF	$0.265	100	$3.18	$0.138	10,000	$1.66
3	C22	0.1 uF	$0.174	10	$0.52	$0.087	1,000	$0.26
3	C32	0.267 uF	$0.252	10	$0.76	$0.125	1,000	$0.38
3	C42	0.0148 uF	$0.135	10	$0.41	$0.067	1,000	$0.20
3	C52	0.33 uF	$0.285	10	$0.86	$0.142	1,000	$0.43
3	J9	SigOut+	$0.00	N/A	$0.00	$0.00	N/A	$0.00
3	J10	SigOut-	$0.00	N/A	$0.00	$0.00	N/A	$0.00
	Filter Section Parts			**6.2%**	**$28.97**		**6.4%**	**$17.51**
1	U1	LT1019CN8-2.5	$4.58	25	$4.58	$3.70002	1,000	$3.70
1	R10	Threaded 44031	$35.46	10	$35.46	$16.80	1,000	$16.80
0	R10, alternate	Bare YSI-44031	$12.00	1	$0.00	$6.30	1,000	$0.00
1	R9	49.9 K	$0.02	200	$0.02	$0.012	1,000	$0.01
1	C8	0.39 uF	$0.265	100	$0.27	$0.138	10,000	$0.14
1	J6	Vref	$0.00	N/A	$0.00	$0.00	N/A	$0.00
1	J7	Temperature	$0.00	N/A	$0.00	$0.00	N/A	$0.00
	Temperature and Vref Parts			**8.7%**	**$40.33**		**7.6%**	**$20.65**

Table 1 (cont.)

1	U4	LM317LZ	$0.45	25	$0.45	$0.2394	250	$0.24
2	U5,U6	LM329DZ	$0.75	25	$1.50	$0.399	250	$0.80
1	U7	LM337LZ	$1.30	25	$1.30	$0.691	250	$0.69
2	C4,C6	22uF 16V Tant	$0.735	10	$1.47	$0.366	1,000	$0.73
2	C5,C7	22uF 25V Tant	$1.488	10	$2.98	$0.74	1,000	$1.48
2	R7,R8	1.2K	$0.02	200	$0.04	$0.012	1,000	$0.02
1	Printed-circuit board	PCB	$12.12	51	$12.12	$4.00	1,000	$4.00
1	Al shield box	Box	$22.00	1	$22.00	$7.06	1,000	$7.06
3	J2	COM	$0.00	N/A	$0.00	$0.00	N/A	$0.00
3	J1	+12V	$0.00	N/A	$0.00	$0.00	N/A	$0.00
3	J3	-12V	$0.00	N/A	$0.00	$0.00	N/A	$0.00
3	J4	+VA	$0.00	N/A	$0.00	$0.00	N/A	$0.00
3	J5	-VB	$0.00	N/A	$0.00	$0.00	N/A	$0.00
	Power and Miscellaneous Parts			**9.0%**	**$41.86**		**5.5%**	**$15.02**
	Parts Total				**$464.78**			**$272.08**
1	Assembly Labor (a wild guess)		$100.00	10	$100.00	$50.00	1,000	$50.00
	Grand Total				**$564.78**			**$322.08**
			Parts Cost with Alternative Sensor					
3	U3	ICS-3031	$58.00	25	$174.00	$26.00	3,000	$78.00
	Parts Total Using ICS-3031				**$368.78**			**$152.08**

Appendix A—C Program for Selecting Compensating Resistor Pairs

The following software is available via anonymous ***ftp*** at “andreas.wr.usgs.gov” in file ~ftp/pub/outgoing/evans/OFR_98_109/pick_resistors_ts.c.

```
/*
 * PICK_RESISTORS_TS()
 *
 * Given a target resistance, pick resistors for a network of either
 * one parallel pair ("-p", the default) or one series pair ("-s")
 * from the 1% metal-film resistors IN THE TREMOR/SOS STOCK to match
 * the desired value as closely as possible.  Schematic:

     ----------*---R1---*----------
               |        |             ==    -----R-----    (DEFAULT)
               *---R2---*

 * OR

     ------*---R1---*---R2---*------    ==    -----R-----

 * Simply searches ALL available permutations for the best match,
 * ignoring issues of precision.  First searches single-resistor
 * solution, then two-resistor solutions, returning whichever is
 * better (i.e., a more precise match).
 *
 * USAGE:  pick_res_ts [-p | -s] < R_in_Ohms ... > result_file
 *
 * AUTHOR:  JREvans, USGS, January 14, 1997.
 *
 * DEBUG:
 *
dbxtool -I . sun4/pick_res_ts
stop in main
 *
 * RUNS:
 *
/bin/rm -f Rz*.out
pick_res_ts -s < Rztc1.in > Rztc1.out
pick_res_ts -s < Rztc2.in > Rztc2.out
pick_res_ts -p < Rzb1.in > Rzb1.out
pick_res_ts -p < Rzb2.in > Rzb2.out
 *
 */

#include <stdio.h>
#include <string.h>
#include <math.h>

#define   streq     !strcmp
#define   TRUE      1
#define   FALSE     0
#define   PARALLEL  0
#define   SERIES    1

#define    PAR_VAL(R1, R2)   ( (double)1.0 / (( (double)1.0 / ((double)R1) ) + ( (dou-
ble)1.0 / ((double)R2) )) )

#define   SER_VAL(R1, R2)   ( ((double)R1) + ((double)R2) )
```

```
#define    FRAC_ERR(R1, R2) ( fabs( (double)1.0 - ((double)R1 / (double)R2) ) )
#define    TOLERANCE ((double)0.005)      /* Acceptable Fractional error      */

      /*
       * The TREMOR/SOS stock of 1% (50 ppm temperature sensitivity) metal-film
       * resistors (mainly at 2% intervals).  This stock is in Room 8B03.  A
       * few higher values available only from the CalNet (200 ppm) stash.
       */

/* In Ohms */
#define   N_TABLE   (312)
static double r_table[N_TABLE] = {
            /* TREMOR/SOS special buys: */
            0.0, 1.00, 1.47,

            /* TREMOR/SOS dense stash (mainly for Rzb[12]): */
            4.02, 4.75, 10, 10.2, 10.5, 10.7, 11, 11.3, 11.5, 11.8, 12, 12.1,
            12.4, 12.7, 13, 13.3, 13.7, 14, 14.3, 14.7, 15, 15.4, 15.8, 16,
            16.2, 16.5, 16.9, 17.4, 17.8, 18, 18.2, 18.7, 19.1, 19.6, 20, 20.5,
            21, 21.5, 22, 22.1, 22.6, 23.2, 23.7, 24, 24.3, 24.7, 24.9, 25.5,
            26.1, 26.7, 27, 27.4, 28, 28.7, 29.4, 30, 30.1, 30.9, 31.6, 32.4,

            /* TREMOR/SOS light stash: */
            33, 33.2, 34, 36, 39, 43, 47, 51, 56, 59, 62, 68, 75, 82, 88.7,
            100, 110, 120, 130, 140, 150, 165, 180, 200, 220, 240, 270, 300,
            330, 350, 390, 430, 470, 510, 560, 590, 620, 680, 750, 820, 910,
            1000, 1100, 1200, 1300, 1400, 1500, 1600, 1800, 2000, 2200, 2400,
            2700, 3000, 3300, 3600, 3900, 4320, 4700, 5100, 5600, 5900, 6200,
            6800, 7500, 8200,

            /* TREMOR/SOS dense stash (mainly for anti-alias filters): */
            8800, 8870, 9090, 9100, 9310, 9530, 9760, 10000, 10200, 10500,
            10700, 11000, 11300, 11500, 11800, 12000, 12100, 12400, 12700,
            13000, 13300, 13700, 14000, 14300, 14700, 15000, 15400, 15800,
            16000, 16200, 16500, 16900, 17400, 17800, 18000, 18200, 18700,
            19100, 19600, 20000, 20500, 21000, 21500, 22000, 22100, 22600,
            23200, 23700, 24000, 24300, 24900, 25500, 26100, 26700, 27000,
            27400, 28000, 28700, 29400, 30000, 30100, 30900, 31600, 32400,
            33000, 33200, 33600, 34000, 34800, 35700, 36000, 36500, 37400,
            38300, 39000, 39200, 40200, 41200, 42200, 43000, 43200, 44200,
            45300, 46400, 47000, 47500, 48700, 49900, 51000, 51100, 52300,
            53600, 54900, 56000, 56200, 57600, 59000, 60400, 61900, 62000,
            63400, 64900, 66500, 68000, 68100, 69800, 71500, 73200, 75000,
            76800, 78700, 80600, 82000, 82500, 84500, 86600, 88700, 90900,
            91000, 93100, 95300, 97600, 100000, 102000, 105000, 107000,
            110000, 113000, 115000, 118000, 120000, 121000, 124000, 127000,
            130000, 133000, 137000, 140000, 143000,

            /* TREMOR/SOS light stash: */
            150000, 160000, 180000, 200000, 220000, 240000, 270000, 300000,
            330000, 340000, 360000, 390000, 430000, 470000, 511000, 560000,
            590000, 620000, 680000, 750000, 820000, 909000,
            1000000, 1500000, 2200000,

            /* CalNet stash: */
            1100000, 1300000, 1430000, 1580000, 1700000, 1760000, 1900000,
            1910000, 2150000, 2430000, 2610000, 2870000, 4750000, 5230000,
            5900000, 8060000, 8250000, 10500000, 21000000
      };

     void      stash();              /* Defined below */

main(argc, argv)
```

```
	int       argc;
	char      **argv;
{
	int       ii, jj, geometry;
	double    R, Rnow, Rbest;
	double    R1, R2, R1best, R2best;

	(void)printf("\nMainly from TREMOR/SOS stashes of 1%% resistors in Room 8B03.\n");
	(void)printf("(Some higher values are only in the CalNet stash in Room 7B25.)\n");

	if (argc >= 2) {
		if (streq(argv[1], "-s"))
			geometry = SERIES;
		else if (streq(argv[1], "-p"))
			geometry = PARALLEL;
		else
			geometry = PARALLEL;
	}


	/* Reproduce schematic */

	if (geometry == PARALLEL) {
		(void)printf("\nParallel pair:\n");
		(void)printf("----------*---R1---*----------\n");
		(void)printf("          |        |\n");
		(void)printf("          *---R2---*\n\n");
	} else {
		(void)printf("\nSeries pair:\n");
		(void)printf("------*---R1---*---R2---*------\n\n");
	}

	/* Solve */
	while (scanf("%lf", &R) != EOF) {

		(void)printf("For %.2lf Ohms:\n", R);
		(void)printf("--------------------\n");

		/* ***************************************** */
		/* First find best SINGLE-resistor match ... */

		Rbest = r_table[0];
		R1best = r_table[0];
		R2best = (double)0.0;     /* flag as "null" */

		for (ii = 1 ; ii < N_TABLE ; ii++) {
			/* Test fractional error */
			if (FRAC_ERR(r_table[ii], R) < FRAC_ERR(Rbest, R)) {
				Rbest = r_table[ii];
				R1best = r_table[ii];
			}
		}

		/* ****************************************** */
		/* ... then permute over all available PAIRS. */
		for (ii = 0 ; ii < N_TABLE ; ii++) {
			for (jj = ii ; jj < N_TABLE ; jj++) {

				if (geometry == PARALLEL)
					Rnow = PAR_VAL(r_table[ii], r_table[jj]);
				else
					Rnow = SER_VAL(r_table[ii], r_table[jj]);
```

```
                    /* Test fractional error */
                    if (FRAC_ERR(Rnow, R) < FRAC_ERR(Rbest, R)) {
                         Rbest = Rnow;
                         R1best = r_table[jj];
                         R2best = r_table[ii];
                    }
               }
          }

          /* ************* */
          /* Return result */

          (void)printf("R1 = %.2lf Ohms", R1best);
          (void)stash(R1best);

          if (R2best == (double)0.0)
               if (geometry == PARALLEL)
                    (void)printf("R2 = Open (Inf Ohms)\n");
               else
                    (void)printf("R2 = Short (0 Ohms)\n");
          else {
               (void)printf("R2 = %.2lf Ohms", R2best);
               (void)stash(R2best);
          }

          if (geometry == PARALLEL)
               (void)printf("------PARALLEL------\n");
          else
               (void)printf("-------SERIES-------\n");

          (void)printf("Yields %.2lf Ohms.\n", Rbest);

          (void)printf("Error = %.2lf Ohms (%.2lf%%)",
               Rbest - R, (double)100. * FRAC_ERR(Rbest, R));
          if (FRAC_ERR(Rbest, R) > TOLERANCE)
               (void)printf(" \t***ERROR OVER %.1lf%%***\n\n\n",
                    TOLERANCE * (double)100.);
          else
               (void)printf(".\n\n\n");
     }
     exit(0);
}

void
stash(RR)
     double    RR;
{
     if (           (RR <= (double)32.4)
               || (RR >= (double)8800. && RR <= (double)143000.)
          )
          (void)printf(" \t(T/S dense collection)\n");

     else if (      (RR >= (double)33. && RR <= (double)8200.)
               || (RR >= (double)150000. && RR <= (double)1000000.)
               || (RR == 1500000)
               || (RR == 2200000)
          )
          (void)printf(" \t(T/S sparse collection)\n");

     else
          (void)printf(" \t(CalNet main collection)\n");
}
```

Appendix B—C Program for Computing Temperature from NTC Thermistor

The following software is available via anonymous ***ftp*** at "andreas.wr.usgs.gov" in file ~ftp/pub/outgoing/evans/OFR_98_109 /Thermistors.c.

```
/*
 * YSI 44031 thermistor using their test points at 0, 25, and 40 C from
 * "Temperature Sensors and Probes, 1993, p. 11 and their algorithm on p.
 * 74 (their BASIC program, but done on HP calculator).
 *
 * MAKE:  make -f Makefile.Thermistors install
 *
 * USAGE:  Thermistors [-v | -mv] [-R0 non_default_R0_in_Ohms]
 *       < file_of_measurements > file_of_temperatures
 *
 * Argument interpreter is stupid--the order of the arguments is
 *       NOT flexible.
 *
 * If "-v" option, file_of_resistances contains VOLTAGES measured by
 * final-design (17 Jan 97) circuit with 49.8K R0 and 2.50 Vref.  If
 * "-mv", assumes millivolts rather than volts, and makes a terse output
 * of only the equivalent Celsius temperature.  Hence, "-mv" makes a
 * simple filter to change Lawson data to temperature.  If neither "-mv"
 * nor "-v", assumes values are resistances in Ohms.
 *
 * If "-R0" (note zero, not letter O) then the reference resistance
 * is changed from 49.8K to what is given in the next argument.
 *
 * J.R.Evans, USGS, Menlo Park.  Last modified 21 May 97.
 */

#include <stdio.h>
#include <math.h>

#define R0_dflt      ((double)49800.0)    /* in series with thermistor      */
#define Vref  ((double)2.50)              /* across series pair             */

main(argc, argv)
       int    argc;
       char   *argv[];
{
       double temperature, resistance, voltage, lr, degF, R0;

       double aa = 1.034034113e-03;
       double bb = 2.383800240e-04;
       double cc = 1.592455177e-07;

       R0 = R0_dflt;

       while (scanf("%lf", &resistance) == 1) {

              /* If reference resistance is not the default */
              if (argc >= 3 && !strcmp("-R0", argv[1]))
                     R0 = atof(argv[2]);
              if (argc >= 4 && !strcmp("-R0", argv[2]))
                     R0 = atof(argv[3]);

              /* If really a voltage, compute resistance */
              if (argc >= 2 && !strcmp("-v", argv[1])) {
                     voltage = resistance;
```

```
                resistance = voltage * R0 / (Vref - voltage);
                printf("V = %.1lf mV --> ",
                        (double)1000. * voltage);
        }

        /* If really an mV voltage, compute resistance */
        if (argc >= 2 && !strcmp("-mv", argv[1])) {
                voltage = resistance / (double)1000.;
                resistance = voltage * R0 / (Vref - voltage);
        }

        /* Now digest a resistance */

        lr = log(resistance);
        temperature = (double)1.0 /
                ( aa + bb * lr + cc * lr * lr * lr );
        temperature = temperature - (double)273.15;
        degF = 32.0 + (temperature * 9.0 / 5.0);

        if (argc >= 2 && !strcmp("-mv", argv[1]))
                printf("%.3lf\n", temperature);
        else
                printf("R = %.0lf ohms --> T = %.2lf C, %.2lf F\n",
                        resistance, temperature, degF);
    }
    exit(0);
}
```

Appendix C—C Program for Computing Filter Component Values

The following software is available via anonymous *ftp* at "andreas.wr.usgs.gov" in file ~ftp/pub/outgoing/evans/OFR_98_109 /biquad.c.

```
/*
 * Use the method of Johnson, Johnson, and Moore, A Handbook of
 * Active Filters, Prentice-Hall, 1980, to tune an 8th-order (gain=1)
 * Butterworth low-pass filter, given imperfect (5%) capacitors
 * near their ideal values.  (Reverse their naming of C1 and C2.
 * Than is, "C1" <---> "C2".  Also move their stage 1 (A) to my
 * stage C since it is high-Q and can clip.)
 *
 * USAGE:  biquad > out_file (and answer questions)
 *
 * AUTHOR:  JREvans, USGS, Menlo Park, 12Dec96.
 */

#include <stdio.h>
#include <math.h>

#define BstageA     ((double)1.111140)
#define BstageB     ((double)1.662939)
#define BstageC     ((double)0.390181)
#define BstageD     ((double)1.961571)

#define CstageA     ((double)1.000000)
#define CstageB     ((double)1.000000)
#define CstageC     ((double)1.000000)
#define CstageD     ((double)1.000000)

#define MICRO ((double)0.000001)
#define KILO  ((double)1000.0)

main()
{
        double BB[4];
        double CC[4];

        double fcorner, wcorner;
        double C1, C2, R1, R2;

        char   sn[128];

        int    ii;
        char   stage[4];
        int    aka[4];  /* decade portion of new part name */

        while(1) {

                BB[0] = BstageA;
                BB[1] = BstageB;
                BB[2] = BstageC;
                BB[3] = BstageD;
                CC[0] = CstageA;
                CC[1] = CstageB;
                CC[2] = CstageC;
                CC[3] = CstageD;
                stage[0] = 'A'; aka[0] = 2;
                stage[1] = 'B'; aka[1] = 3;
```

```
            stage[2] = 'C'; aka[2] = 4;
            stage[3] = 'D'; aka[3] = 5;

            fprintf(stderr, "Give serial number:  ");
            if (gets(sn) == NULL)
                  break;
            printf("\n-------------------\nSerial number:  \"%s\".\n", sn);

            fprintf(stderr, "Give corner frequency (Hz):  ");
            scanf("%lf", &fcorner);
            wcorner = (double)6.283185308 * fcorner;        /* 2*pi */

            printf("Gain 1 eight-pole Butterworth lowpass, corner at %.2lf Hz:\n",
fcorner);

            for(ii = 0 ; ii < 4 ; ii++) {

                  fprintf(stderr, "Give C1 (preferably near %.3lf uF):  ",
                        10.0 / fcorner);
                  scanf("%lf", &C1);
                  C1 = C1 * MICRO;

                  fprintf(stderr,
                        "Give C2 (MUST be <= %.5lf uF, preferably the largest):  ",
(BB[ii] * BB[ii] * C1) / (double)4.0 / MICRO);
                  scanf("%lf", &C2);
                  C2 = C2 * MICRO;

                  R1 = (double)2.0 / (
                        wcorner * (
                              BB[ii] * C1 +
                              sqrt(
                                    BB[ii] * BB[ii] * C1 * C1 -
                                    (double)4.0 * CC[ii] * C1 * C2
                                    )
                              )
                        );

                  R2 = (double)1.0 / (
                        CC[ii] * C1 * C2 * R1 * wcorner * wcorner
                        );

                  printf("\nC1%c (C%1d1) = %.5lf uF, ",
                        stage[ii], aka[ii], C1 / MICRO);
                  printf("\tR1%c (R%1d1) = %.3lf KOhms.\n",
                        stage[ii], aka[ii], R1 / KILO);
                  printf("C2%c (C%1d2) = %.5lf uF, ",
                        stage[ii], aka[ii], C2 / MICRO);
                  printf("\tR2%c (R%1d2) = %.3lf KOhms.\n\n",
                        stage[ii], aka[ii], R2 / KILO);

                  /* Clear input buffer to NEWLINE */
                  (void)gets(sn);
            }
      }
}
```