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Longbase laser strainmeter measurements from the South Ramp of the Yucca Mountain facility

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Final Technical Report

Longbase Laser Strainmeter Measurements from the South Ramp of the Yucca Mountain Facility

Prepared for the U.S. DOE/UCCSN Cooperative Agreement Number DE-FC28-98NV12081,

Task 7: Establishment of a Long-Baseline Laser Strainmeter in the Exploratory Studies Facility

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1. Abstract

Under subcontract (DOE/UCCSN DE-FC28-98NV12081, Task 7) from the Seismological Laboratory of the University of Nevada-Reno, the University of California, San Diego (UCSD), has designed, installed, and operated a laser strainmeter (LSM) in the Exploratory Studies Facility (ESF) at Yucca Mountain, Nevada. This instrument provides precise deformation monitoring of the (proposed) repository block. This document describes the history of the installation, outlines the principles of operation of the system, documents the integral recording and control system and file formats used, and provides information on how QA has been implemented, with the aim of being a self-contained description which could be used (in conjunction with the data files at the TDMS) to understand the measurements made by the LSM. Appendix A gives the unique digital signatures for all data files submitted to the TDMS.

The instrument was installed along the south wall of the tunnel, between 69+46 m and 65+41 m (tunnel coordinates). The resulting azimuth (91°) provides good sensitivity to the posited long-term strains from geologic sources. Designing an instrument for the tunnel was a challenge, as was installing it, given the usual, strict local operating procedures; these two elements combined to increase substantially the overall time to completion, though the experience gained has put us in a good position for further work in this setting. We have fully documented (SN) all aspects of the installation, and have complete engineering plans of the LSM available (Appendix B).

The instrument began operating to QA standards on 2002:233 (August 21, 2002), and has recorded strain since that time, though with interruptions caused by the very strong shaking from the mining trains, which both caused sizeable gaps in the series and caused the lasers to degrade much more rapidly: both problems have been dealt with successfully. The instrument is producing quality records. Preliminary results from the laser strainmeter suggest that seismic waves and tides cause strains with no obvious anomalous response or nonlinearity; and that air-pressure changes can cause significant strains, with a response that depends on the spatial pattern of pressure applied. With the data so far available, we can constrain the long-term strain rate to be less than 0.2 $\mu\varepsilon$/yr. A longer-term record should greatly improve this constraint.

2. Introduction

This report describes work done by the University of California, San Diego (UCSD), under subcontract to the Seismological Laboratory of the University of Nevada-Reno, to install and operate a laser strainmeter (LSM) in the Exploratory Studies Facility (ESF) at Yucca Mountain, Nevada (DOE/UCCSN DE-FC28-98NV12081, Task 7). UCSD has designed and installed an LSM for deformation monitoring at Yucca Mountain, specifically in the south ramp of the ESF (**Figure 1**).

The value of this measurement to the Yucca Mountain Project is that the LSM is critical for understanding the short-term and long-term stability of the site; precise deformation monitoring is essential for understanding the hazard posed by the local tectonic environment, for helping to guide the engineering requirements for constructing a safe site, and for providing a baseline against which to observe warning signals from any significant future changes in tectonic, volcanic, or rock conditions. The LSM continuously monitors the repository-scale strains from all sources, complementing regional geodetic surveys at the facility by providing an independent check and much lower noise over a wide frequency range.

The strainmeter monitors the following:

- The baseline strain rate in the ESF; measuring this, and possible future changes, will provide a powerful check for strain-rate variations that might be associated with possible tectonic or volcanic events or potential repository activities. Continuous recording of strain thus provides

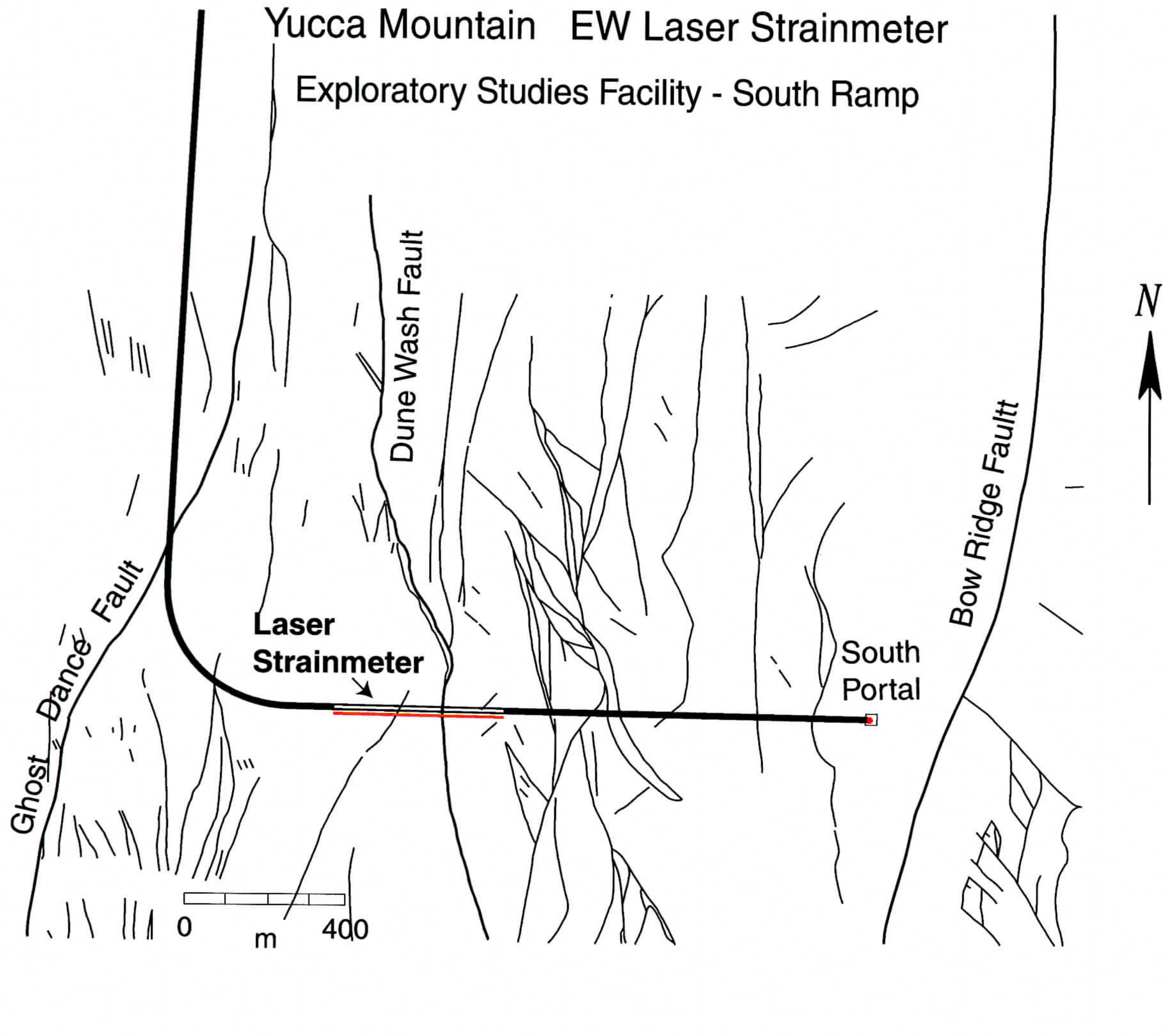

Yucca Mountain EW Laser Strainmeter
Exploratory Studies Facility - South Ramp
Dune Wash Fault
N
Bow Ridge Faultt
Ghost Dance Fault
Laser Strainmeter
South Portal
0
m
400

Figure 1

important data relevant to establishing performance compliance of the repository. The East-West LSM is installed with an orientation to provide good resolution of possible long-term strains.

- Strains associated with seismic waves, earth tides, and atmospheric pressure variations; analysis of these provides unique information on the bulk rock properties (e.g., elastic modulus) of the potential repository block, and any changes in them.
- Any strains from earthquakes (either from static deformations caused by (future) local earthquakes, or by triggered slip along nearby faults) or from volcanic activity (e.g., in Crater Flat); any such strains would be important in judging the integrity of the repository after such events.

3. Project History

For background we first provide a summary of how the project was originally organized, and the progress of the work; **Figure 2** shows (primarily) the steps at the site, though of course even more effort was spent on construction, testing, and assembly in our lab. The filled boxes are tasks completed. Note that while we have not yet completed the task of QA'ing our analysis software, this does not affect the data collected to this point, which does, in its raw form, satisfy QA, and can be retrospectively analyzed once the software qualification is complete.

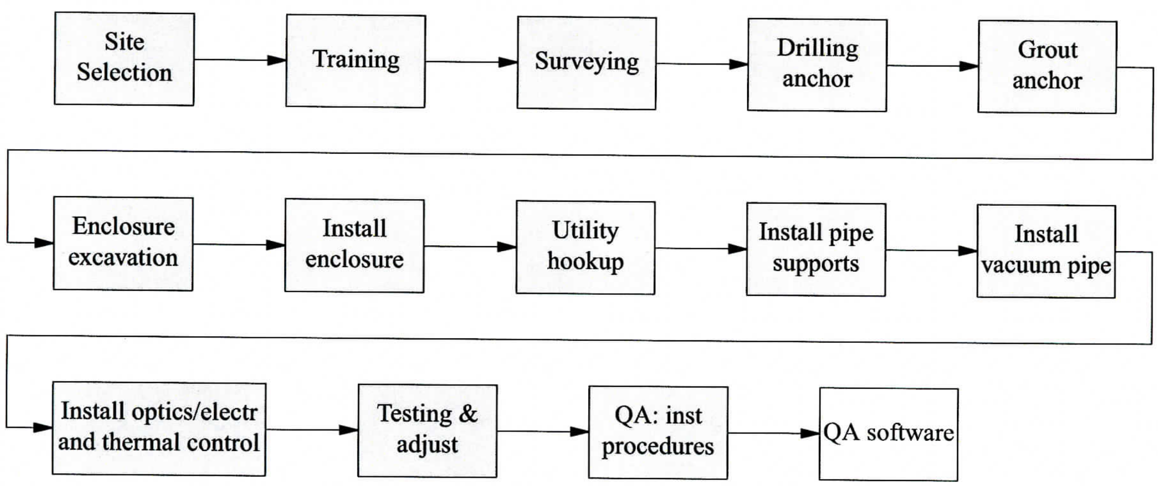


Figure 2

3.1. Phase I

This was the preparatory work, including site training, surveying, and instrument site-selection, Quality Assurance training, and (based on all this information) the main part of the instrument design and engineering.

Our introduction to the Exploratory Studies Facility was in 1999, with the objective of selecting a candidate instrument location. The basic instrument consists of a low powered laser projected through a several-hundred-meter long evacuated pipe, which is used to measure the displacements between two anchored end points. Extensive discussions and side-wall surveys led, in November 1999, to the selection of the South ramp as the best location (**Figure 1**). It is straight (save for one jog in a badly fractured area near 71+30 m), generally not heavily used, has large spans of sound rock, and is free of the complications of sidewall-supporting steel-sets, allowing the pipe to be mounted near the tunnel wall. We selected the longest straight section available toward the back of the South ramp (just before the tunnel begins its sweeping curve to the north). Over this section, the sidewalls are straight to within 5-7 cm. The pipe is centered 27 cm from the sidewall, and 1.4 m above the tunnel floor, well away from the traveled area. We had hoped to construct an instrument at least 300 m in length, and were able to achieve 405 m. In selecting the specific anchoring end-points we were guided both by onsite inspection and by the available (and extensive) geological mapping, from which we extrapolated the exposed geology back into the rock where the anchors were to be seated. For the east end of the instrument, at 69+46 m, we were limited by the fracturing tens of meters to the east and a contact surface below (and generally more extensive geologic variations to the east; see **Figure 1**); for the west end, at 65+41 m, by the greater density of small voids in the material going to the west, and by joints and contacts. The instrument does span one well mapped fault: the Dune Wash fault, at 67+88 m, with 52 meters of offset. The accepted view is that such minor faults are generally locked, and need not be considered as different from the surrounding material unless there is faulting on them. We do not expect any complicating signals from this fault.

Table 1: Strainmeter Dimensions and Coordinates

Location:	South Ramp of Exploratory Studies Facility South sidewall	
East-end anchor:	69+46 m	(tunnel coordinates)
West-end anchor:	65+41 m	
Length:	405 m long	
Slope:	2.6% (1.5°)	down-to-west
Azimuth:	91.0°	east of north
Coordinates:	36.828° N ;	-116.449° E
Elevation:	1120 m	(above mean sea level)

During this stage we also developed, working with the UCCSN QA staff, a basic outline for the QA aspects of the project:

A. The non-QA component: fabrication of the instrument.

B. A calibration period for verification of the installation.

C. Operating the instrument (requiring a Scientific Notebook, and eventually IP's)

D. Data processing, requiring QA'd software.

3.2. Phase II

This phase included fabrication of the bulk of the LSM instrument components, and all substantial site preparation work (site construction), which was carried out by YMP contract crews ("Crafts"), including the critical optical-anchor borehole work and alcove excavation (**Figure 3**). Borehole drilling for the LSM optical anchors began in December 1999, and was completed in January 2000. Two pairs of holes were drilled for "anchoring" each end of the 405 m-long instrument. Late in March 2000, we were provided with alignment-survey results for the candidate "anchoring" holes (each 15 m deep) and these results showed that the holes were curved beyond the specified tolerances. This led to an extensive effort (ultimately successful) to rework the downhole assemblies to make utilization of the holes possible; this is discussed further below.

Before we were familiar with the ESF we thought we could forego our normal end-structure enclosures, and hence did not identify them as a substantial element of the project. Most tunnel environments are exceptionally benign (e.g., very stable temperature), but because of the high activity level in the tunnel the environment there is as harsh as outdoors (except for rains). We thus felt obligated to propose sizable end-enclosures, which required tunnel excavation. Clearly, modifying the tunnel is not a minor

LASER STRAINMETER

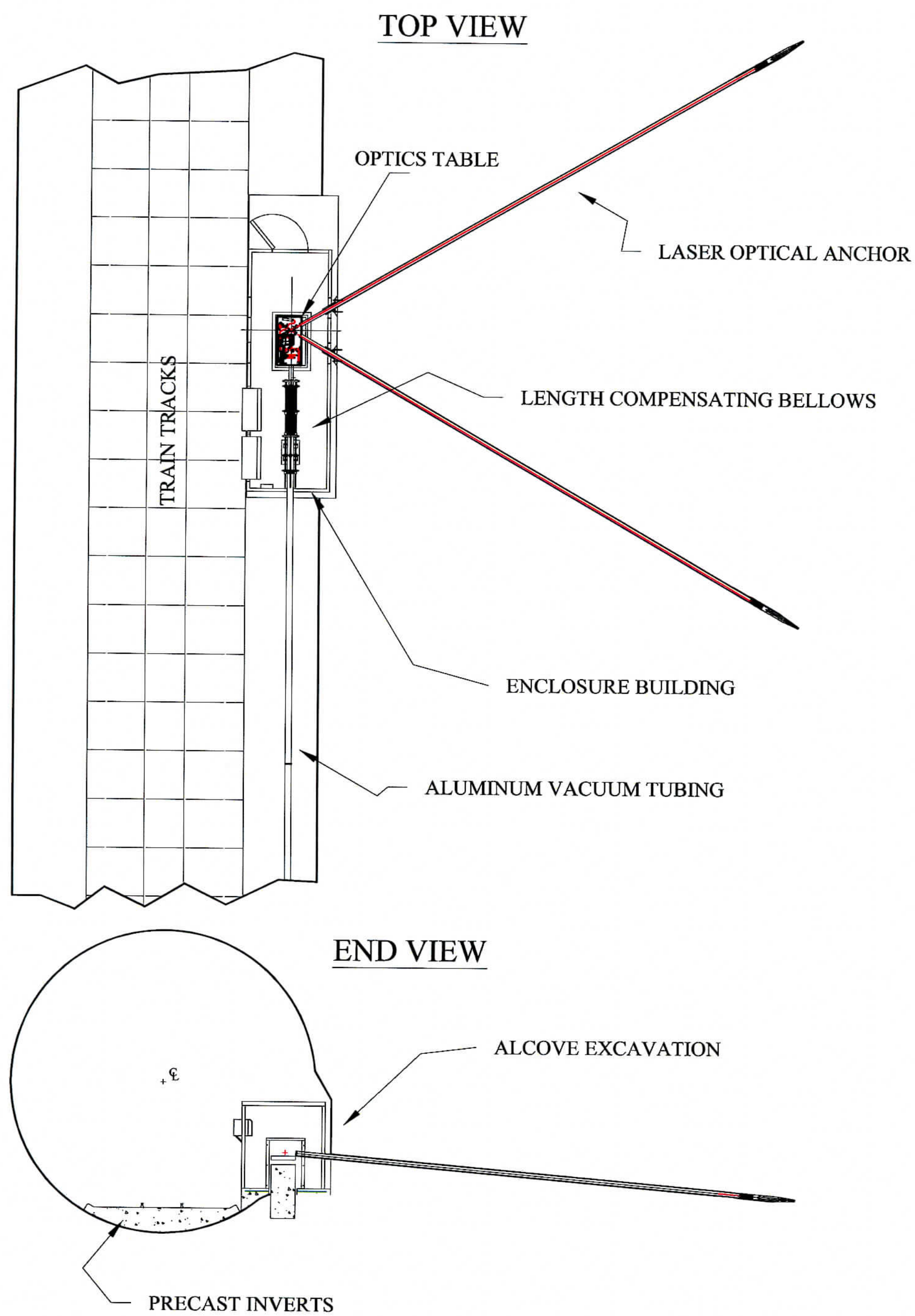


Figure 3

proposition. Our design work on both alcoves and buildings began early in 2000; this was an iterative exercise, as many of the constraints became clear only as plans were developed (**Figure 4**). Mining of the alcoves, which had to be rescheduled several times, began in October and was completed in November 2000. Concrete forming for the pads and end-monuments was completed in January 2001. Design and ordering of the specially-fabricated end-enclosures (built of allowable material, dimensioned for the pads, and highly insulated) was completed in May 2001, and the components for the buildings were delivered to the ESF site in July 2001.

Vacuum pipe supports (adjustable stanchions and rollers) were designed, fabricated by us, and installed by YMP personnel in the tunnel walls in March 2001. The vacuum pipe for the main strainmeter vacuum system (405 m long) was fabricated and delivered to our lab in San Diego for testing, ready for transportation to the site. Final assembly of the vacuum system was done in early 2002.

All of the electronic circuitry for the instrument was committed to printed circuit boards, with the aim of greatly improved reliability and ease of replacement (though this has been problematic).

3.3. Phase III

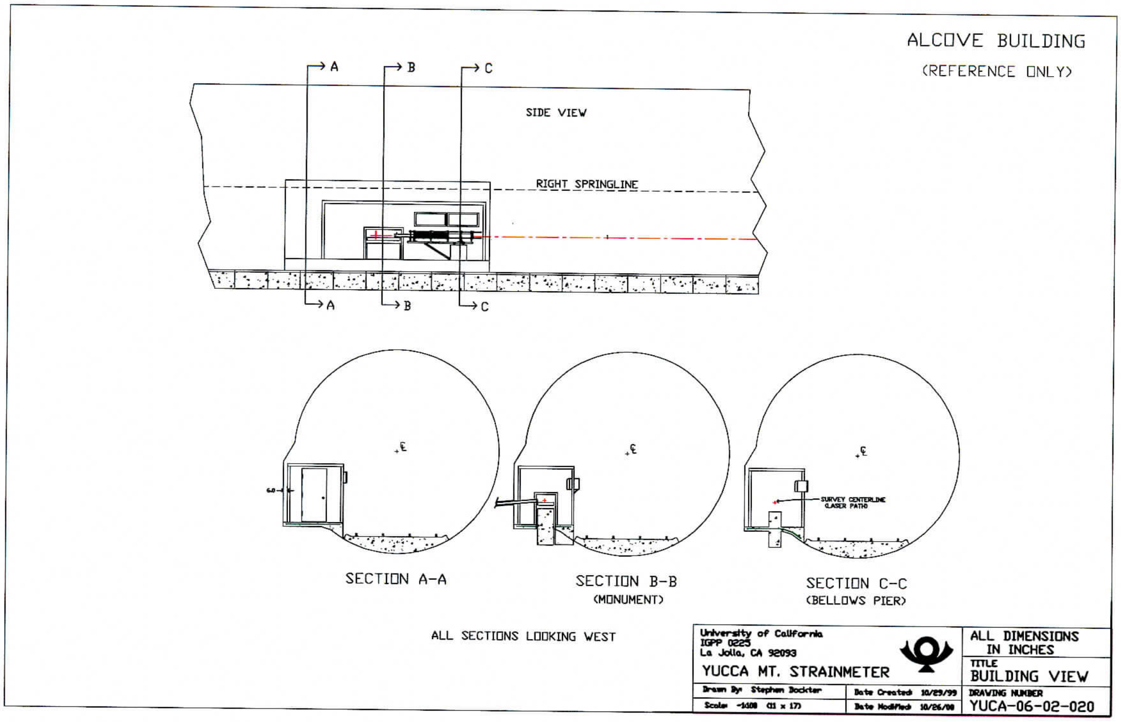
This was the instrument installation phase, including assembly of the instrument components at the ESF, and the initial operation and shake-down period.

The most technically challenging aspect of the instrument field installation was the cementing of the casing and optical-anchor canisters into the boreholes. Preparing for this took over a month and the actual field work required two week-long visits by a crew of four (plus considerable skilled support by YMP Crafts). This work was completed in April 2001.

Between July and September 2001, special steel sleeves were installed to protect the strainmeter's four end-point anchoring holes. The two (large) instrument end-enclosures were installed—custom fit; these hold all of the electronics and the delicate motion-sensing equipment. Power wiring was extended to and connected into the enclosures' circuitry, with plans for communication lines. We delivered the main vacuum tubing to the site. We also completed the design and ordering for all the major internal components. The manufacturer of the main sensing laser was having trouble achieving the specified frequency stability (earlier lasers did) and we worked with them on this. We completed the design-specification on the data-logging system for the strainmeter, and found (through UNR) a programmer to work on this.

In November 2001 we made two multiday field-trips to the site to lay out the end-to-end signal cabling, to install the Optical Anchor vacuum pipes (with their optics) into the four anchoring boreholes, and to install the vacuum-tube end-bellows and to begin the staging of the main 405-m of vacuum tubing—over most of its length, the most conspicuous part of the instrument. Because of its length, and the thermal expansion coefficient of the metal tubing, the vacuum-tube—secured only in the middle—requires length-absorbing bellows at each end. Without these, the ends would move as much as 5 cm and affect the observations. We continued to build the electronics and the optics-table components. We also continued to address noise problems with the state-of-the-art laser system, and work with the programmer on a data-logging system.

Between January and March 2002 we made three multiday trips to Yucca Mountain. The first trip was to complete the physical parts of the installation, most notably the vacuum system (both the main strainmeter tube and the four borehole tubes). This system, the largest and most complicated physical part of the strainmeter, worked as wanted, holding a good vacuum. The second trip focused on putting in the stages for the optical systems, and the third trip was to be assembly and alignment of the optics and


ALCOVE BUILDING
(REFERENCE ONLY)
SIDE VIEW
RIGHT SPRINGLINE
SECTION A-A
SECTION B-B
(MONUMENT)
SECTION C-C
(BELLOWS PIER)
ALL SECTIONS LOOKING WEST
University of California
IGPP 0225
La Jolla, CA 92093
YUCCA MT. STRAINMETER
ALL DIMENSIONS IN INCHES
TITLE
BUILDING VIEW
DRAWING NUMBER
YUCCA-06-02-020

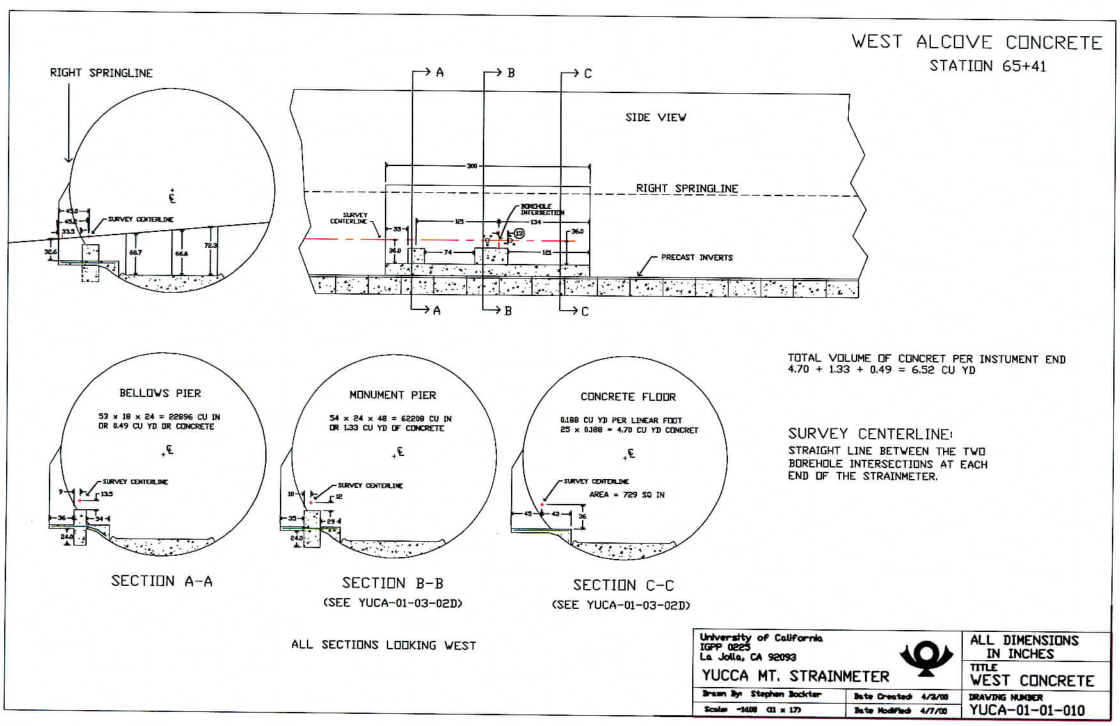

WEST ALCOVE CONCRETE
STATION 65+41
RIGHT SPRINGLINE
SIDE VIEW
PRECAST INVERTS
TOTAL VOLUME OF CONCRET PER INSTUMENT END
4.70 + 1.33 + 0.49 = 6.52 CU YD
BELLOWS PIER
53 x 18 x 24 = 22896 CU IN
OR 0.49 CU YD OR CONCRETE
MONUMENT PIER
54 x 24 x 48 = 62208 CU IN
OR 1.33 CU YD OF CONCRETE
CONCRETE FLOOR
0.188 CU YD PER LINEAR FOOT
25 x 0.188 = 4.70 CU YD CONCRET
AREA = 729 SQ IN
SURVEY CENTERLINE:
STRAIGHT LINE BETWEEN THE TWO
BOREHOLE INTERSECTIONS AT EACH
END OF THE STRAINMETER.
SECTION A-A
SECTION B-B
(SEE YUCA-01-03-02D)
SECTION C-C
(SEE YUCA-01-03-02D)
ALL SECTIONS LOOKING WEST
University of California
IGPP 0225
La Jolla, CA 92093
YUCCA MT. STRAINMETER
ALL DIMENSIONS IN INCHES
TITLE
WEST CONCRETE
DRAWING NUMBER
YUCA-01-01-010

Figure 4

test-bed operation of electronics. Both the second and third trips were severely impacted by tunnel working-practices. For the third trip, for which we had gathered our entire team at the site with the aim of preliminary instrument assembly and initial instrument operation, all personnel were required to quit the tunnel for an ESF safety stand-down, which then lasted for several weeks. Ultimately we had to undo and retrieve almost all of what we had brought, to carry out the assembly work in San Diego. In this period, work on the recording system progressed to the point of having a prototype data-logger ready for trial-use. We were also in contact with Ken Smith of UNR, who was working on providing precise time within the tunnel, and telemetry out of it [though this approach was ultimately dropped].

Between April and July 2002 we completed the installation of the laser strainmeter and began instrument shake-down and testing. In the first of three trips we introduced the optics (**Figure 5**) and established alignment of the laser systems; the second was for permanent cementing of the key optical elements and trials of the electronics; and the third trip to align the optics, connect the monitor-and-control electronics, and introduce the recording system. We worked extensively on the electronics and software, to see that it would meet the requirements of the system at Yucca Mountain. This included work on the recording-and-control system (**Section 4.3.2** and **Section 5**).

Assembly of the instrument and the initial test period was completed in July, 2002.

3.4. Phase IV

This phase includes (A) the long-term operation of, and (B) ongoing analysis of the data from this strainmeter installation. Of course, this is currently in progress; while the transition from testing to routine operation of a new system in an unusual setting is not always clear-cut, since 2002:233 recordings of the ESF's deformation have been collected to QA standards. In order to meet contract requirements we have submitted qualified raw data (**DID 007DA.001**, August 20, 2003) from then through 2003:099 to the Technical Data Archive Technical and Electronic Data Specialist. The strainmeter is continuing to operate and to monitor Yucca Mountain.

4. Principles of Strainmeter Operation

In this section we outline the principles of strainmeter operation, simplified from a detailed guide (Agnew and Wyatt, 2003) to long-base strainmeter design, data, and results, archived on the Web. Briefly, the strainmeter measures changes in distance between the two ends using an optical interferometer; at each end other interferometers, "optical anchors," secondarily measure the motions of the ends relative to points deep in the rock, away from the tunnel wall. These results then need further correction for variations in the optical path length, including any vacuum-pressure changes in the evacuated pipe which extends between the two ends, and any variation in the laser frequency.

The optical system used in the long-base strainmeters is a Michelson interferometer. A beam of light is sent to a beamsplitter where it is divided equally and goes to two reflectors, one local and one remote (in this case 405 m away); the returned beams meet and interfere at the beamsplitter, the interfered energy going (in part) to a detector. The intensity at the detector will vary with the path-length difference; measuring light to dark transitions (fringes) allows detection of movements of either arm of the interferometer. For the long-base strainmeter, the local arm is fixed on an optics table; the length-change measurement is thus made over the longer remote arm. Unless the interferometer arms are nearly equal in length, the light source must have an unusually narrow bandwidth (that is, a long coherence length). This means using a rather special kind of laser as a light source. For the optical anchor system the path lengths of the two arms are essentially equal, so the lasers for these can have a shorter coherence length, and much less stability.

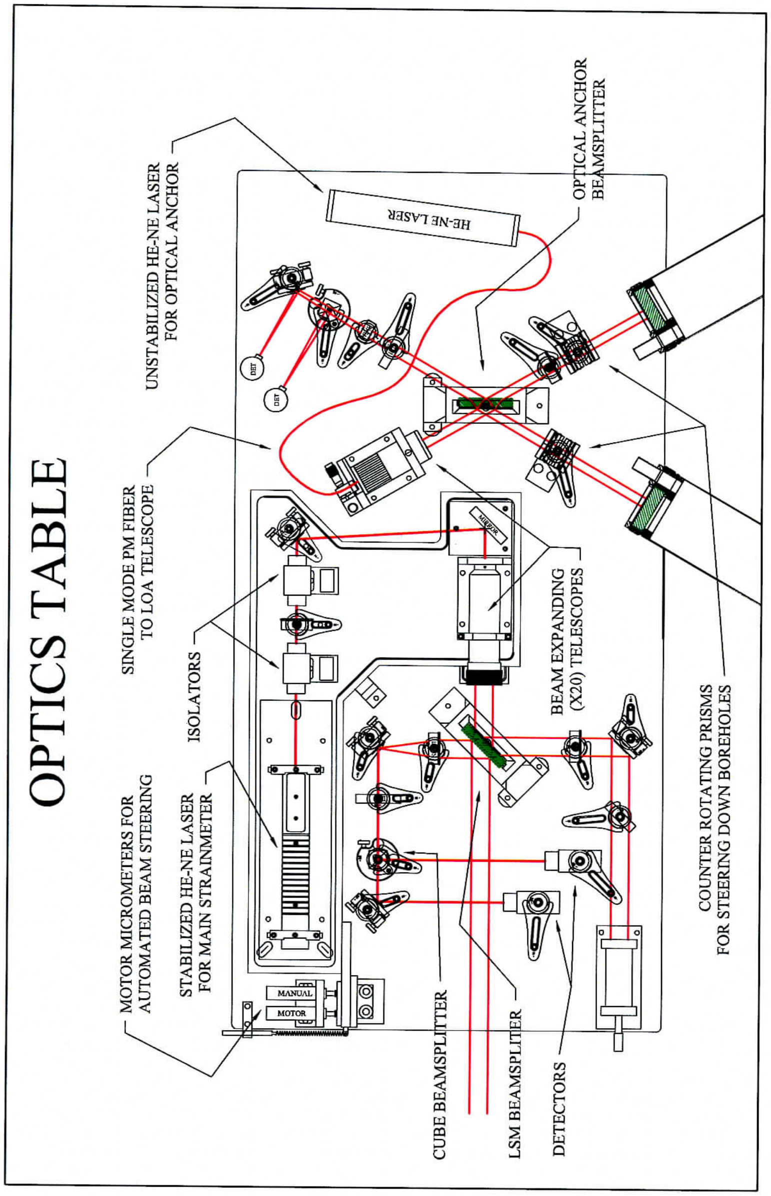

OPTICS TABLE
UNSTABILIZED HE-NE LASER FOR OPTICAL ANCHOR
HE-NE LASER
OPTICAL ANCHOR BEAMSPLITTER
SINGLE MODE PM FIBER TO LOA TELESCOPE
ISOLATORS
BEAM EXPANDING (X20) TELESCOPES
MOTOR MICROMETERS FOR AUTOMATED BEAM STEERING
STABILIZED HE-NE LASER FOR MAIN STRAINMETER
MANUAL
MOTOR
CUBE BEAMSPLITTER
LSM BEAMSPLITTER
DETECTORS
COUNTER ROTATING PRISMS FOR STEERING DOWN BOREHOLES

Figure 5

The strainmeter electronics converts the intensity changes at the detector into a recorded change in strain. The first step is actually taken in the optical system: one half of the beam sent to the local reflector has its phase retarded by 90°, so that half of the combined beam is in quadrature (90° phase-shifted) with the other half. Each half is then sent to a separate photodetector so that the available input is two intensity signals, separated by 90°. These can be thought of as the in-phase and quadrature part of a single complex-valued intensity. When displayed as x and y coordinates of a plot, the result of changes in length is to trace out a circle, a Lissajous pattern, with the direction of rotation determining if the path length to the remote mirror is increasing or decreasing. A complete rotation of the signal by 360° around the origin corresponds to a full-fringe change ($\lambda = 633.0$ nm, where λ is the wavelength of light) in optical round-trip path length. (In practice, because of differing depths of modulations of the two beams and imperfect phase retardation, this Lissajous pattern is not an exact circle; but unless it is badly distorted its rotation can still be measured.)

Because these in-phase and quadrature signals can vary with a high frequency (see the next section) they each are simply digitized with a single-bit system: a pair of comparators, whose four possible outputs then define, four quadrants of the complex intensity; at this level, the signal has been digitized to the nearest quarter-fringe. For this $\lambda/4 \div 2L$, with $L = 405$ m, gives 0.1954×10^{-9} $\Delta l/l$, or 0.1954 nanostrain per count. The fringe counting electronics is capable of operating at frequencies up to several MHz, but for digital recording at reasonable speeds some filtering of the signal is necessary to avoid aliasing. The output of the fringe counter therefore is used to drive a digital-to-analog voltage converter, whose output is passed through a single-pole lowpass filter and then redigitized. The standard "tectonic" recording system uses a filter with a time constant of 500 seconds; we also operate channels with shorter time constants, and different gains, for recording seismic waves: the gain is just a function of which bits from the counter are fed to the A-to-D, and the time constant just depends on the filter.

The system actually measures changes in the *optical* path lengths; if light travels through a medium of refractive index n, this is n times the physical length. To minimize the effect of varying n, the light path is kept evacuated; the system is pumped down to very low pressure routinely and permitted to gradually increase (with outgassing of the materials) to slightly higher pressures. This pressure variation is monitored and used as the input for a correction-series when processing the data. For temperatures typical in the tunnel the coefficient relating the vacuum pressure p (in Pascals) to the index of refraction is 2.73×10^{-9} $\Delta n/\Delta p$, and hence for apparent strain (given the instrument sensitivity per count, as listed above) 14 counts per Pa. The pressure is maintained below 10 Pa, such that corrections are limited to less than 140 counts, or strains of 27 nanostrains (approximately the level of the ever present earth tides).

For a Michelson interferometer with one much shorter arm, strain in the other arm (the long arm) and fractional changes in wavelength (or frequency) of the light used are indistinguishable so wavelength stability must be better than any deformation rates we hope to monitor. An objective for this installation is a wavelength stability of 1×10^{-8} $\Delta\lambda/\lambda$ yr^{-1} or better. Stability is usually given in frequency, and for a helium-neon laser a 1 MHz frequency change corresponds to a fractional frequency change (and apparent change in strain) of 2.1×10^{-9}. We currently use a polarization-stabilized laser which has proven to be stable enough and reasonably reliable; we employ an Iodine absorption-cell system for occasional checks of the stability of these systems.

4.1. Optical Anchor

The largest source of noise in any good deformation-measuring instrument is from the mechanism by which it is attached to the earth: a difficult problem, which we reduce with "optical anchors". At each end, a secondary interferometer is used to tie the end points on the tunnel wall to points deeper in the rock. Each interferometer measures along two equally angled boreholes, both lying in the same horizontal plane as the anchored strainmeter and intersecting at a common end point. We measure from this intersection point to retroreflectors cemented at the end of each 10 to 15 m deep hole; these, and a beam-splitter at the tunnel wall, form a Michelson interferometer (and, effectively, a shear strainmeter.) Because the interferometer arms in the optical anchor are of nearly equal length, an unstabilized multi-mode laser can be used as the source. The fringe-counting system is the same as for the main interferometer.

The long-term stability of the anchor depends on, primarily, the coupling of the anchor to the earth, which is controlled both by the quality of the installation and the integrity of the local geology (generally very good at locations away from surface/weathering exposed areas). We cement the remote reflectors in with expansive grout, but in the end, the stability is best indicated by the stability of the final results—quite good for YMP (**Section 7**).

The physical layout of the optical anchor is, at each end of the instrument, two boreholes, angled at 30° from the perpendicular to the wall, both in the plane aligned with the strainmeter axis (see, again, **Figure 3**). These holes need to intersect at a point directly in-line with the main strainmeter beam, and as close as possible to the main beam-splitter (or retroreflector). Each of the boreholes is cased with PVC pipe, with a 1.2 m stainless steel anchoring assembly threaded onto the end of the casing. The assemblies are cemented into place using non-shrink grout. Compliant material is attached to the bottom of the anchors to reduce axial loading caused by borehole rebound and deformation of the cement. The cementing grout is pumped through check valves in the bottom of the stainless steel assemblies and up the outside of the PVC casings until it reaches the surface.

Within the stainless steel anchoring assembly, a tapered and threaded insert serves as the mating surface to guide and secure the retroreflector housing. This housing is attached, by stainless steel bellows, to the end of a long stainless steel vacuum pipe. The bellows are required both to isolate the reflector housing from the vacuum pipe mechanically and to allow compensating pressure on both sides of the reflector. The last stage of assembly involves lowering the vacuum-pipe assembly into place and twisting it until the downhole reflector housing is secure.

4.2. Unanticipated Problems

As discussed above (**Section 3.2**), reworking of the overall physical layout of the strainmeter installation was one of the major problems we faced early on; in this, and for many other issues, we were challenged by the unfamiliar constraints on what could be allowed in the tunnel—though we are now more comfortable with them. Delays from auxiliary construction (one for over six months), and restricted tunnel access have also caused difficulties. This was offset by the high quality of help provided by the Test Coordination Office and by the work crews (Crafts). Their efforts contributed substantially to what has turned out to be a quality installation.

Perhaps the most challenging technical problem arose from the four optical-anchoring boreholes being less straight than expected. For a light beam to reach the hole bottom there must be a clear pathway; we faced both curved holes (3.8 cm out-of-line as opposed to the specified design-tolerance of 1.9 cm) and smaller holes than planned for. By redesigning the (many) downhole components, close surveying of the holes to optimize the fit of the equipment, and reselecting the anchoring points to shallower (but still adequate) depths, we were able to overcome this problem. The final selection of the anchoring depths was also influenced by logging of the holes, which showed areas of poor geology (extensive fracturing). **Table 2** lists the final depths.

Table 2: Optical Anchor Depths (in meters)

	East End		West End	
Hole	#1	#2	#3	#4
Drilled to:	15.3	15.3	15.2	15.5
Accessible:	14.5	15.4	15.2	14.4
Anchoring:	14.091	14.091	11.492	11.492

The major operational issue, which we have worked on but still face, has been the shaking caused by the mining trains as they pass immediately by the instrument end-structures (the track-support "inverts" come up to the instrument pad). Even before becoming familiar with the tunnel we expected that the passage of the trains would introduce transient signals, which could be smoothed over in the course of processing the data; but having witnessed the magnitude of the shaking on an alignment laser we became concerned that the passage of individual trains might actually cause instrument miscounting, with the ground deformed so much that the laser beam would become misaligned, no longer pointing accurately at the far end. This has indeed been so, and means that for each train passage (typically lasting less than a few tens of seconds) the record is disturbed and requires editing. Even with many train passages in a day, this (by itself) is manageable.

The trains, however, have caused an even greater problem, namely injury to and degradation of the laser; only recently have we found a way to circumvent this. The shaking is so severe as the train passes the main instrument enclosure that it seems to be stressing the laser. We are now operating our fourth laser in one year, whereas the expected laser lifetime is more than two years. Not all of the lasers have failed completely, but frequency-locking problems have developed to the point that swapping-out the lasers proved necessary. (Recognizing this unprecedented problem has been the single most difficult part of operating the strainmeter.) In July of this year (2003) we made an ambitious effort to physically isolate the main laser (suspending it from compliant springs) and route the laser light into the interferometer optics using optical fiber. For the laser-wavelengths involved and the demands of the system, this was a "research" type endeavor, and we're pleased to report success. In the course of 6 successive tunnel-trips we succeeded, and are now obtaining clean records.

A final problem worth noting has been infrequent miscounting of the interferometer fringes. This, as with the counting-disruptions associated with the trains, is readily edited, but at the cost of more time in the lab processing the data. With the initial objective of improving the servicability of the electronics, at the onset of this project we undertook to rework the electronic layout (though still using our long-proven design). In fact, this new layout has led to troubles and we are now actively working on a second generation of circuit cards. In the interim we have modified the cards in the field to suppress the problem, and added redundant electronics, all of which are currently operating properly. We are also working to improve an undesirable room-temperature response evident in some of the recorded signals.

4.3. Calibration to QA Standards

We next describe how we fulfill QA requirements on instrument operation and data handling—a plan resulting from extensive discussions with QA personnel from UCCSN. In the discussion below **boldface** indicates the few hardware items that are subject to QA verification (see also **Table 3**).

Table 3: Calibrated Equipment

Equipment	Model	S/N	BN ID
Winters Electro-Optics Iodine-Stabilized HeNe Laser	M-100	177	NIST
Hameg Frequency Counter and main frame	8021-3	21993P 24437 80013P 08308	008638
Wavetek Digital Multimeter	85XT	000410622	008639
Setra Air Pressure Gauge	270	1949519	000543
Alternative:	270	1368131	008838
Varian Vacuum Gauge and sensors	6522-08-515 6543-25-030	030505001	000542
Alternative: and sensors	6522-08-515 6543-25-030	960125011	008839

4.3.1. Calibrations at Instrument Site

4.3.1.1. Electronics and Recorder Verification

- Observe that each interference-fringe (light and dark bands of light) is a full revolution on a scope, and produces 4 counts. This simple observation checks all of the front-end electronics (pre-Fringe Counter electronics) involved in the signal pathway, implicitly. We have been writing such calibration observations in the Scientific Notebook, but we expect this activity to become an Implementing Procedure.
- Enter pairs of "counts" on the Fringe Counter front-panel thumbwheel switches and verify (subsequently) what is recorded by the logger, from our data storage archive(s). This arrangement provides a complete electronic-systems throughput check (a "Systems Check"). This calibration step involves writing down numbers and checking the recorded "raw" data. Again, this has started as Scientific Notebook material, and will become an Implementing Procedure.

4.3.1.2. Laser Frequency Measurements

- Perform regular checks of the instrument-illuminating laser's frequency, at least twice annually. For this we use a regularly calibrated Iodine absorption-cell HeNe (1) **Reference Laser** (*Winters Electro-Optics*, NIST traceable) and a transfer laser (to keep the Reference Laser safely at home; it is not meant to travel), and a regularly calibrated (2) **Frequency Counter**.

4.3.1.3. Routine Checks

- Monitor the main-tubing vacuum level, using a regularly calibrated (3) **Vacuum Gauge**. All that is required here is to note the level occasionally. Check other voltages using a regularly calibrated (4) **Voltmeter**. The voltmeter is mostly used for trouble-shooting, or initial setup. We also observe and optimize optical alignments. All notes are entered in the Scientific Notebook.

4.3.1.4. Ancillary Measurements

- Record the air pressure using a regularly calibrated (5) **Air Pressure Gauge**. This signal is recorded on the data logger. The throughput calibration on this involves noting voltages at the site and later checking the recorded observations.

4.3.2. Data Logging (and Control)

The logger is a PC-based system allowing remote control of a number of functions, as well as recording all the system (analog) voltages at 1 and 300 second sample-intervals. (**Figure 6** shows a screenshot of the front panel.) The complete, throughput, calibration of the main signals—one laser strainmeter signal and two laser optical anchor signals—are checked through the Electronics and Recorder Verification procedure described in Section 4.3.1.1. The logger also monitors two fixed reference voltages, as a continuous diagnostic of the recording system. These voltages are checked (using the calibrated voltmeter) during field visits and recorded in the Scientific Notebook.

The complete system, from strainmeter through recorder, functioned as designed in this reporting period. In addition, considerable progress was made in the remote/automated control of the strainmeter. **Table 4** presents specifications for the two components of the data-recording system: logging and control.

Table 4: Data Recorder and Instrument Control

Logger (autonomous operation):	
Recording:	continuous, and self-starting on power-up
Power:	operating on 1-hour power back-up (UPS system)
Number of channels:	32 minimum, expandable in multiples of 32
Analog range:	±10.000 V
Sensitivity:	0.3052 mV per least-count (16-bit digitizer)
Noise:	not to exceed 2 least counts
Timing:	accuracy to 1 s
Sampling:	1 s, and 300 s
Files:	day-based (described in detail below)
Tranfer:	automatic, daily 'zipping' and copy transfer
Monitor and Control (network access):	
Displays:	'front panel' display of all channel voltages
	graphical summary of last 48 hours
	graphical display of laser-alignment (Lissajous pattern)
Review:	independent access/display of all recorded (past) data
Reference voltage:	indicator of internal calibration status
Clock:	indicator of internal timing status
Recorder:	remote power-restart capable (external network device)
Beam steering:	fully automated steering of laser beam
Vacuum pump:	remote control of pump and valve
Laser control:	remote control of 'locking' status
Auxiliary:	24 (expandable to 96) digital control lines
Web access:	capable of near real-time transmission to Web site

4.3.3. Transmitting and Storing the Data

We use *gzip* to compress the files before transmission, since this includes a checksum. In order to comply with temporary-records storage requirements, we download a copy of the raw, 'zipped' data to the computer system at Scripps (UCSD) and maintain the original raw data on the computer located at the site. This operation is performed automatically, on a daily basis, shortly after the UTC day-boundary. Prior to removing any data from either the computer at the site or from the (duplicate) Scripps' system, the data are submitted to the Document Control Coordinator (DCC) in accordance with QAP-17.0, "Quality Assurance Records."

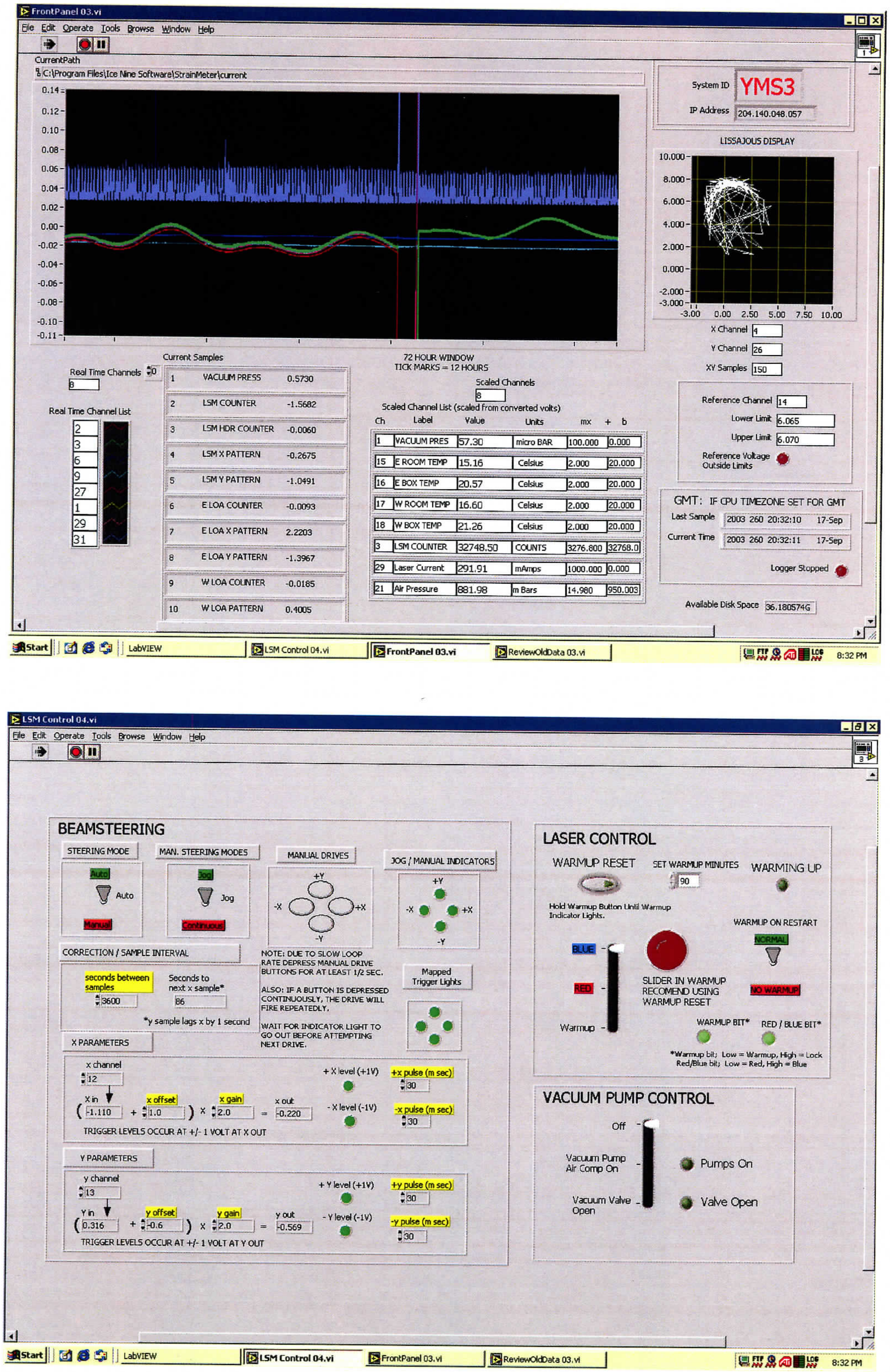

FrontPanel 03.vi
File Edit Operate Tools Browse Window Help
CurrentPath
C:\Program Files\Ice Nine Software\StrainMeter\current
System ID YMS3
IP Address 204.140.048.057
LISSAJOUS DISPLAY
X Channel 4
Y Channel 26
XY Samples 150
Real Time Channels
Real Time Channel List
Current Samples
1 VACUUM PRESS 0.5730
2 LSM COUNTER -1.5682
3 LSM HDR COUNTER -0.0060
4 LSM X PATTERN -0.2675
5 LSM Y PATTERN -1.0491
6 E LOA COUNTER -0.0093
7 E LOA X PATTERN 2.2203
8 E LOA Y PATTERN -1.3967
9 W LOA COUNTER -0.0185
10 W LOA PATTERN 0.4005
72 HOUR WINDOW
TICK MARKS = 12 HOURS
Scaled Channels
Scaled Channel List (scaled from converted volts)
Ch Label Value Units mx + b
1 VACUUM PRES 57.30 micro BAR 100.000 0.000
15 E ROOM TEMP 15.16 Celsius 2.000 20.000
16 E BOX TEMP 20.57 Celsius 2.000 20.000
17 W ROOM TEMP 16.60 Celsius 2.000 20.000
18 W BOX TEMP 21.26 Celsius 2.000 20.000
3 LSM COUNTER 32748.50 COUNTS 3276.800 32768.0
29 Laser Current 291.91 mAmps 1000.000 0.000
21 Air Pressure 881.98 m Bars 14.980 950.003
Reference Channel 14
Lower Limit 6.065
Upper Limit 6.070
Reference Voltage Outside Limits
GMT: IF CPU TIMEZONE SET FOR GMT
Last Sample 2003 260 20:32:10 17-Sep
Current Time 2003 260 20:32:11 17-Sep
Logger Stopped
Available Disk Space 36.180574G
Start LabVIEW LSM Control 04.vi FrontPanel 03.vi ReviewOldData 03.vi 8:32 PM
LSM Control 04.vi
File Edit Operate Tools Browse Window Help
BEAMSTEERING
STEERING MODE
Auto
Manual
MAN. STEERING MODES
Jog
Continuous
MANUAL DRIVES
JOG / MANUAL INDICATORS
+Y -X +X -Y
CORRECTION / SAMPLE INTERVAL
seconds between samples 3600
Seconds to next x sample* 86
*y sample lags x by 1 second
NOTE: DUE TO SLOW LOOP RATE DEPRESS MANUAL DRIVE BUTTONS FOR AT LEAST 1/2 SEC.
ALSO: IF A BUTTON IS DEPRESSED CONTINUOUSLY, THE DRIVE WILL FIRE REPEATEDLY.
WAIT FOR INDICATOR LIGHT TO GO OUT BEFORE ATTEMPTING NEXT DRIVE.
Mapped Trigger Lights
X PARAMETERS
x channel 12
X in x offset x gain x out
-1.110 1.0 2.0 -0.220
TRIGGER LEVELS OCCUR AT +/- 1 VOLT AT X OUT
+ X level (+1V) +x pulse (m sec) 30
- X level (-1V) -x pulse (m sec) 30
Y PARAMETERS
y channel 13
Y in y offset y gain y out
0.316 -0.6 2.0 -0.569
TRIGGER LEVELS OCCUR AT +/- 1 VOLT AT Y OUT
+ Y level (+1V) +y pulse (m sec) 30
- Y level (-1V) -y pulse (m sec) 30
LASER CONTROL
WARMUP RESET
SET WARMUP MINUTES 90
WARMING UP
Hold Warmup Button Until Warmup Indicator Lights.
WARMUP ON RESTART
NORMAL
NO WARMUP
BLUE
RED
Warmup
SLIDER IN WARMUP RECOMEND USING WARMUP RESET
WARMUP BIT* RED / BLUE BIT*
*Warmup bit; Low = Warmup, High = Lock
Red/Blue bit; Low = Red, High = Blue
VACUUM PUMP CONTROL
Off
Vacuum Pump Air Comp On
Vacuum Valve Open
Pumps On
Valve Open
Start LabVIEW LSM Control 04.vi FrontPanel 03.vi ReviewOldData 03.vi 8:32 PM

Figure 6

5. Data Description

In this section we describe the data so far provided to the TDA. This is raw data (as recorded) from the longbase laser strainmeter described above. Though preliminary processed results are available, the software for producing them has not yet been Qualified, so only raw data have been submitted. For many sorts of studies, these data are useful as they stand.

5.1. Files and File Naming

The data at the TDMS consists of a single zipped file, which when unpacked contains daily files of data sampled at 300-seconds (5 minutes) and 1 second, for the period between 2002:233 and 2003:099. The file names have the following forms:

YYYYDDD.1s.gz is a gzipped file of binary data recorded at 1-second interval beginning on year YYYY and day of year DDD: for example 2002246.1s.gz starts (and ends) on day 246 of 2002; note that 2002247.1s.gz starts on day 247 of 2002 but runs through day 266. In some cases a letter may follow the DDD to distinguish files written with different software versions on the same day.

YYYYDDD.5m.gz is a gzipped file of binary data recorded at 1-second intervals, and sampled every 5 minutes.

On January 28, 2003 the file names were augmented to:

YYYYDDD.CCCC.1s.gz where CCCC indicates the logger's location and ID; for example, 2003028.YMS3.1s.gz. is logger #3 at site YMS. The logger name was included starting with datalogger software version number 2.3.0.0 and higher, first installed at Yucca Mountain on day 28 of 2003.

YYYYDDD.CCCC.5m.gz is a gzipped file of binary data recorded at 1-second intervals, and sampled every 5 minutes,

5.2. File Formats

5.2.1. Versions

Slight changes to the file header formats (not the data) have occurred over time; the file format version is related to the software version as follows (the software is the version for which that file format was introduced).

Table 5: Datalogger Softwares

File Format Code#	Files	Software Version	Comments
#1	2002:233 through 2002:268a	2.2.0.2	
#2	2002:268b through 2003:027	2.2.0.7	Added sample interval to file header
#3	2003:028 through 2003:099	2.4.0.1	Software version not indicated in file header (still given as 2.2)

5.2.2. Binary Files

The binary (.1s and .5m) files have a 128-byte header, containing file-specific information, labels to allow cross-checking of the source of the file, and version and system identification information. All header information is stored in Little Endian (PC) byte order.

5.2.2.1. File Header Record

The header includes the following items:

Bytes 1–4: Binary file version number, which identifies the binary file format.

Bytes 5–8: Header size in bytes.

Bytes 9–12: End-of-file marker; data at or past this location is not valid.

Bytes 13–16: Last sample marker, gives the position in bytes of the start of the last valid sample record.

Bytes 17–20: 4-character system ID, used to identify the source of the data.

Bytes 21–24: Sample interval in seconds (added in Version 2).

Bytes 25–28: IP address of PC (added in version 3; before this just padding with zeroes).

Bytes 29–128: Padding with zeroes.

5.2.2.2. Data Records

Each data record consists of a 16-byte record header followed by the data. The record header information and data are stored in Big Endian (Sun/UNIX) byte order.

The header consists of the following:

Bytes 1–4: UNIX UTC time (seconds since 1 January 1970 00:00 UTC, ignoring leap seconds).

Bytes 5–6: Year

Bytes 7–8: Day of year (1-365, or 366 in leap years).

Bytes 9–10: Hour

Bytes 11–12: Minute

Bytes 13–14: Second

Bytes 15–16: Number of channels of data in record.

The header is followed by N 2-byte integer values, where N is the number of channels in the record header. The data are stored in counts, with the range ± 10 volts being -32768 to 32768 counts (0.3052 mV per count); the values are stored as 2's-complement 16-bit integers.

The datalogger channels (numbered 1 through 32) have particular signals (which have names) assigned to them, though some channels do not currently have a signal, and the assignment of channels to signals can (and has) changed with time. **Table 6** shows which signals have been assigned to each channel (for those channels with signals), and also the sensitivity (in physical units per count). Channels with no signals are not listed.

5.3. Description of Signals

The signals can be described as follows:

YM VAC: Pressure inside the vacuum system. Increasing values correspond to increasing pressure.

Table 6: Strainmeter Data Channels

Chan.	Signal	Units/Count	Units of Measurement	Type
1	YM VAC	3.05 10^{-4}	Pa	
2	YM LSM	1.954 10^{-10}	strain	
3	YM HDR	1.954 10^{-10}	strain	
4	YMSM LX	3.052 10^{-4}	V	Diagnostic
5	YMSM LY	3.052 10^{-4}	V	Diagnostic
6	YMOA E	1.954 10^{-10}	strain	
7	YMOA ELX	3.052 10^{-4}	V	Diagnostic
8	YMOA ELY	3.052 10^{-4}	V	Diagnostic
9	YMOA W	1.954 10^{-10}	strain	
10	YMOA WLX	3.052 10^{-4}	V	Diagnostic
11	YMOA WLY	3.052 10^{-4}	V	Diagnostic
12	YMSM BX	3.052 10^{-4}	V	Diagnostic
13	YMSM BY	3.052 10^{-4}	V	Diagnostic
14	YM VR#1	3.052 10^{-4}	V	Diagnostic
15	YM ERMTP	6.10 10^{-4}	°C	Diagnostic
16	YM EINTP	6.10 10^{-4}	°C	Diagnostic
17	YM WRMTP	6.10 10^{-4}	°C	Diagnostic
18	YM WINTP	6.10 10^{-4}	°C	Diagnostic
21	YM BARO (1)	4.57 10^{-1}	Pa	
24	YM VR#2	3.052 10^{-4}	V	Diagnostic
29	YMML FC (2)	3.052 10^{-4}	amp	Diagnostic
31	YMTS E (3)	3.052 10^{-4}	arbitrary	Diagnostic

(1) starting 2003:042:22:30; channel 21 not used before;
(2) starting 2002:309:19:00; channel 29 not used before;
(3) starting 2002:309:16:50; channel 31 not used before;
"Diagnostic" means that the signals can be used in judging data quality and performance, but are not themselves used to create the final results.

YM LSM: Strain between ends of the instrument (at locations 69+46 m and 65+41 m along the S wall of the S ramp tunnel), total length 405 m, filtered with a 500-s time-constant lowpass filter. Increasing values correspond to extensional strain.

YM HDR: Strain between ends of instrument (at locations 69+46 m and 65+41 m along the S wall of the S ramp tunnel), total length 405 m, filtered with a 2-s time-constant lowpass filter. Increasing values correspond to extensional strain.

YMSM LX: Output of the X-detector of the interference pattern for the main strainmeter measurement.

YMSM LY: Output of the Y-detector of the interference pattern for the main strainmeter measurement.

YMOA E: Motion of the East strainmeter point, measured by the optical anchor relative to a depth of 14.091 m. Increasing values correspond to extensional strain of the full instrument.

YMOA ELX: Output of the X-detector of the interference pattern for the East optical anchor measurement.

YMOA ELY: Output of the Y-detector of the interference pattern for the East optical anchor measurement.

YMOA W: Motion of the West strainmeter point, measured by the optical anchor relative to a depth of 11.492 m. Increasing values correspond to extensional strain of the full instrument.

YMOA WLX: Output of the X-detector of the interference pattern for the West optical anchor measurement.

YMOA WLY: Output of the Y-detector of the interference pattern for the West optical anchor measurement.

YMSM BX: Beam position voltage (x-component) for the main laser strainmeter beam.

YMSM BY: Beam position voltage (y-component) for the main laser strainmeter beam.

YM VR#1: Reference voltage to monitor datalogger stability; should register as 6.068 V.

YM ERMTP: Air temperature measured inside the East room of the laser strainmeter. Increasing values correspond to increasing temperature.

YM EINTP: Air temperature measured inside the East optics-table enclosure of the laser strainmeter. Increasing values correspond to increasing temperature.

YM WRMTP: Air temperature measured inside the West room of the laser strainmeter. Increasing values correspond to increasing temperature.

YM WINTP: Air temperature measured inside the West optics-table enclosure of the laser strainmeter. Increasing values correspond to increasing temperature.

YM BARO: Air pressure measured in the East room of the laser strainmeter. Increasing values correspond to increasing pressure.

YM VR#2: Reference voltage to monitor datalogger stability; should register as -6.068 V.

YMML FC: Current keeping main strainmeter laser (ML-1) locked to single frequency by changing tube length.

YMTS E: Train-sensing seismometer: a rectified and lowpassed output from a GS-20 geophone.

6. Data Processing

We outline here what is needed to convert the raw data to final processed results.

We, like other groups concerned with producing long time series of strain data, have developed fairly elaborate systems for processing raw strain data. We describe ours briefly here, with reference to the flowchart shown in **Figure 7**. This chart may seem a bit complex; we would emphasize that the procedures have been developed with the aim of utilizing the data for research, which has encouraged us to try to get the most information possible (including very small signals) from the recorded data—inevitably, not a simple task.

The upper part of **Figure 7** shows the procedure for an individual data series: we first remove as much "predictable" energy as possible, usually from a prediction of the tides. The resulting series is then edited using an interactive program which displays the data (raw or as edited) and allows it to be flagged as bad, and offset to remove jumps. This editing is of course a matter of judgement—aided by experience, and helped by examining supplementary information, notably records of environmental data (including the seismic record, to show local shaking from the trains), and also what we have called "metadata"—the whole range of records of what was done to the instrument, which we record in written form.

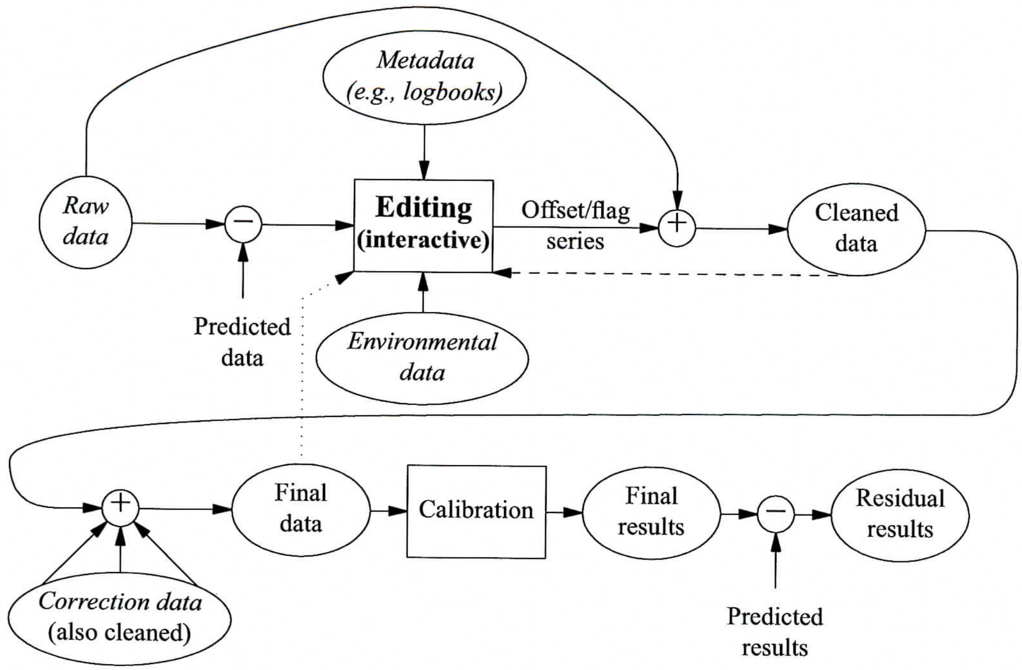


Figure 7

We note that because of the electronics problems mentioned above, some of the channels showed an unusually large number of offsets from miscounts. These are most easily detected by comparing the three main series; any unaccountable offset contained in only one is a miscount, and can be removed by applying an offset.

The result of the editing process is information about which parts of the time series to discard and what offsets to add to it. When the editing information is combined with the raw data, we have cleaned data. The dashed line in **Figure 7** expresses a kind of feedback which plays a role in the process: not infrequently, only after the data have been edited can subtle problems be identified which call for further editing. The next steps, shown in the lower part of **Figure 7**, are to combine the data series as needed to produce a final estimate; for example, the final strain time series from the laser strainmeter requires the cleaned strain to be combined with two optical anchor series, the pressure, and a correction for laser frequency.

For the strainmeter at Yucca Mountain, the primary time series are combined according to the formula

YM_HDR - (YMOA_E + YMOA_W)

(recorded strain, less the two end-point displacements) where **Table 6** gives the scale factors to be applied to these channels before combining them. The recorded vacuum pressure signal is not used directly but is included by subtracting a series of ramps with offsets at the times the vacuum pumps are run (see **Figure 10**: Vacuum correction). Because of the unusual number of laser changes in this particular period (2002:233 - 2003:099), the generally minor role of frequency correction, we have not attempted to estimate the drift of laser frequency, which is small over the times that each laser has been in. (Differences between the absolute wavelength of the different lasers do not affect the measurement, only variations once in use.) The recipe for the fully corrected signal, the measure of the repository strain, is

YM_HDR - (YMOA_E + YMOA_W) - YM_VAC - YM_Freq

7. Results

Finally, we describe some of the results from inspection of the data which demonstrate the successful operation of the strainmeter. Because the software is not yet QA-certified, the results we show are not QA, and are given for information only—but the processed QA'd data will not be significantly different from what we show here. (Note, however, that the data plotted in **Figure 9** do not depend on any processing, and are therefore Q.)

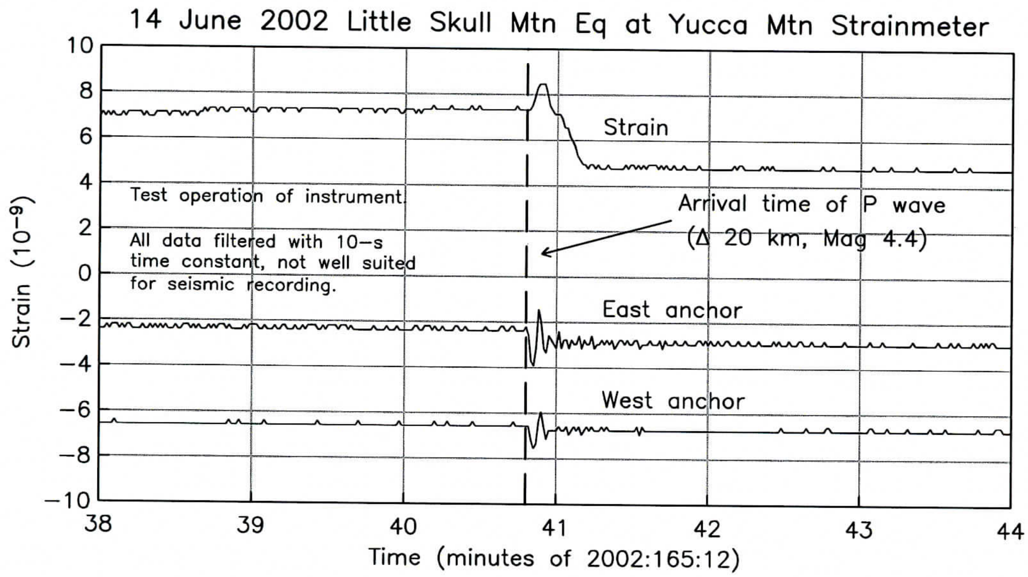


Figure 8 (Non-Q data, for information only. Ref: Figure 1 in UCSD portion of UNR OSPA No. 1990709.)

7.1. Earthquakes

In fact, the only significant earthquake close to the ESF during the period covered by this report was the magnitude 4.4 earthquake Little Skull Mountain earthquake of 14 June 2002. It was located at 36.7150 N, 116.3003 W, approximately 18 km southeast of the ESF, with a preliminary depth of 12 kilometers. This earthquake occurred in the aftershock zone of the M 5.6 Little Skull Mountain earthquake of June 1992. The area has been active since that earthquake, but this is the largest event in over 6 years. At the time (2002:165:12:40) the instrument had only just begun operation, and only in a preliminary testing mode, so these data are **not QA**—but we show them here for their intrinsic interest (**Figure 8**). The main instrument output (strain) at this time was heavily filtered, so we did not record the seismic waves, which were too high-frequency; since the data are only sampled every second, unfiltered data would have been aliased (as is suggested by the optical anchor records). The records show, however, nothing unusual in the response of the site to this (strong) local disturbance.

Worldwide there were approximately 6 earthquakes of magnitude 7.5 or greater in this reporting period whose signal was large enough to be of some value to characterizing site response. Only two events produced sizable signals: on 3 November 2002 (day 307) a magnitude 7.9 (Denali, Alaska); and on 22 January 2003 a magnitude 7.6 (Colima, Mexico), shown in **Figure 9**; note that this did not clip the

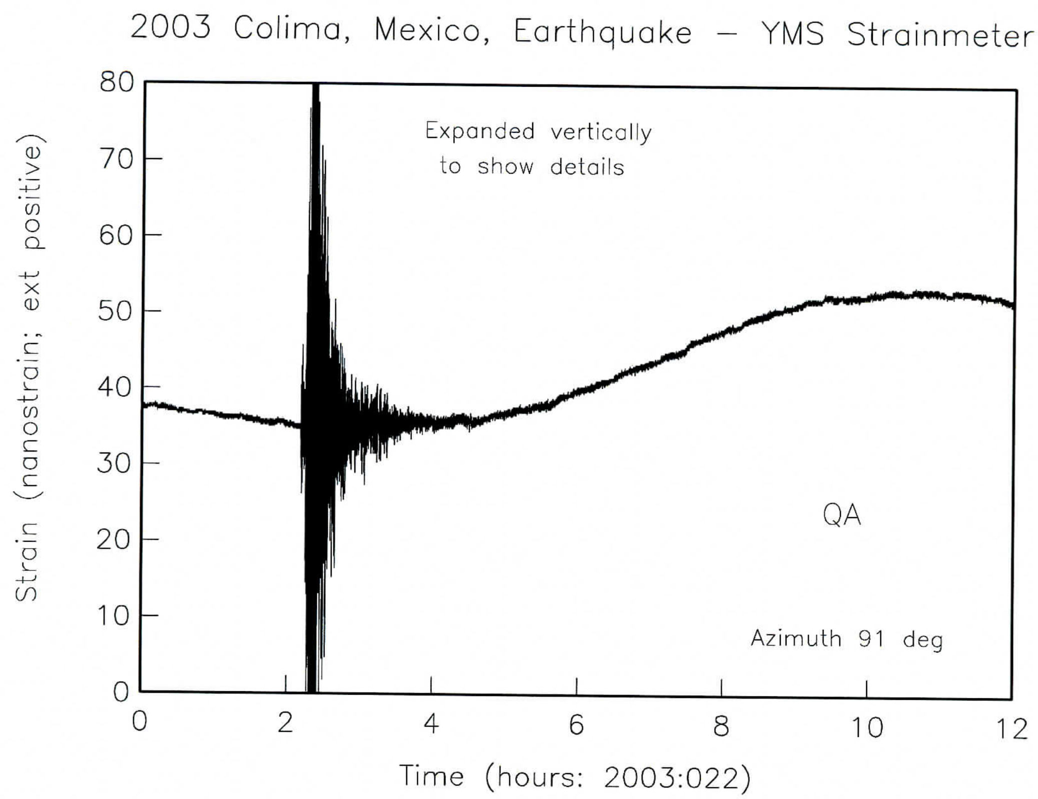


Figure 9 (Data derived from DID 007DA.001)

datalogger but has been scaled to show the underlying deformation. Observations from these events will be used, in conjunction with other signals (e.g., the recorded earth tides and air-pressure response, discussed below), to establish measures of repository-block bulk properties.

7.2. Tides, Air Pressure, Long-Term Strain

Prior to 2002:330 the data were significantly and routinely disturbed by laser-related problems stemming from passage of mine trains, a problem since reduced (though not eliminated) by the development and installation of another laser system. Nearly all short-period signals for the 100-day period from 2002:233 to 2002:330 are adequately recorded, but the longer period record is not well constrained. Other than this and a return of the laser troubles in the spring of 2003, the instrument has run with remarkably little trouble, providing a continuous record of strain with a resolution of 0.001 microstrain on a day-to-day basis—more than 100 times better than GPS over repository length scales. **Figure 10** presents both the de-tided repository strain record and the air pressure measured at the instrument, as edited; **Figure 11** presents some of the most recent data. The recorded earth tides match the theoretical tides well; there is no anomalous or nonlinear tidal response.

From the beginnings of operations we noticed an unusual response associated with the air pressure. The correlation of the two records is clear; the scaling factor is 1.0 nanostrain per mbar. Not so apparent is that for these long-period variations there is actually a delay of some 8 hours in the response of the strainmeter to the pressure. This response is much larger than anything we are familiar with from other strainmeter sites. Additional information is provided by the air-pressure changes from operation of the tunnel fans; when these are turned on or off the pressure at the instrument changes abruptly.

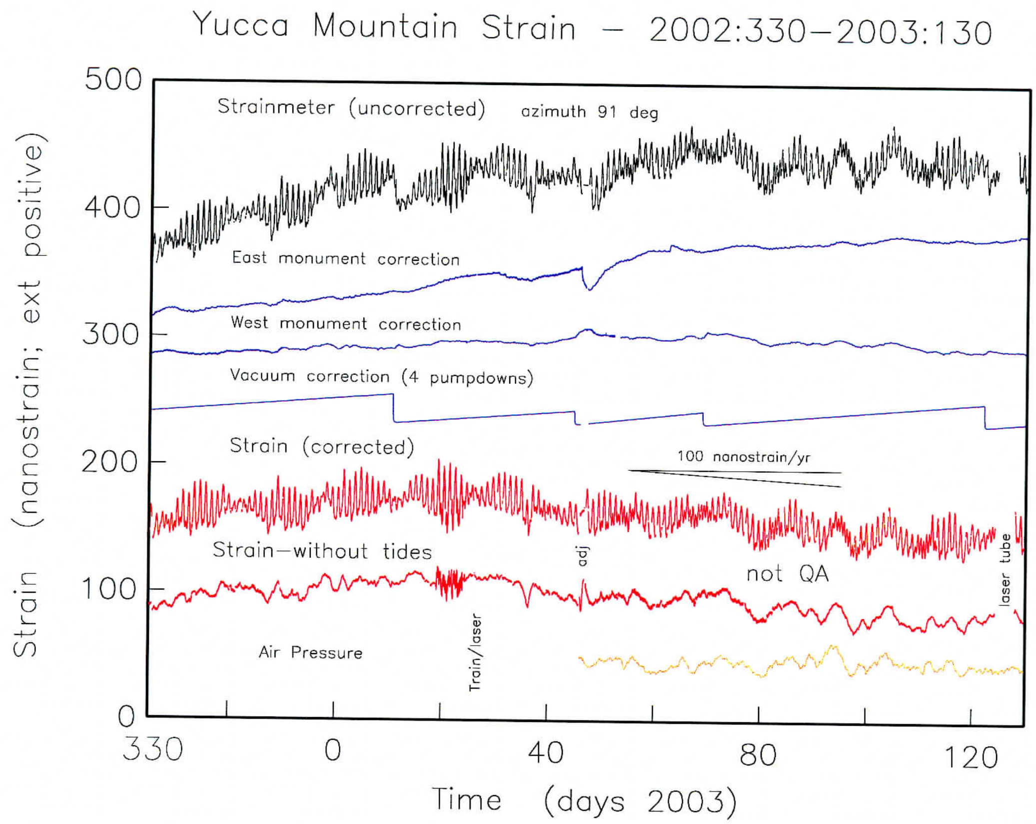


Figure 10 (Non-Q data, for information only. Data source: DID 007DA.001.)

Surprisingly the response from this source is stronger, immediate (without any delay), and has the opposite sign from that caused by outside air-pressure changes (-2.1 nanostrain per mbar). Modeling of these apparently disparate effects should prove valuable in understanding the response of the mountain to applied forces.

A major reason for the installation of the strainmeter at the ESF was that Wernicke *et al.* (1998), using GPS measurements from 1991 to 1997, found strain rates possibly an order of magnitude higher than average long-term rates indicated by the tectonic history of the region. The small number of sites involved in that study, the possibility of significant GPS monument instability, and the possible influence of postseismic deformation associated with the June 1992 $M_L = 5.6$, Little Skull Mountain earthquake on the reported strain-rate raised concerns about the applicability of the GPS results to issues concerning seismic and volcanic hazards. The strainmeter provides a completely independent measurement of the same quantity, with quite different error sources.

With only months of data for this reporting period and the likelihood of there being an annual variation in the deformation, the long-term East-West strain rate can be bounded only preliminarily ("Strain-without tides" in the figure), but it is certainly within ±0.2 microstrain per year, and could be much smaller. Since the estimated strain rate now found using continuous GPS is much smaller than the original Wernicke *et al.* estimate (G. Blewitt, pers. commun.), it will take more time for the strainmeter to be able to confirm (or not) the GPS-derived rate. However, this discrepancy between old and new GPS rates raises the possibility (though it is unlikely) that the strain rate can vary with time, which would pose

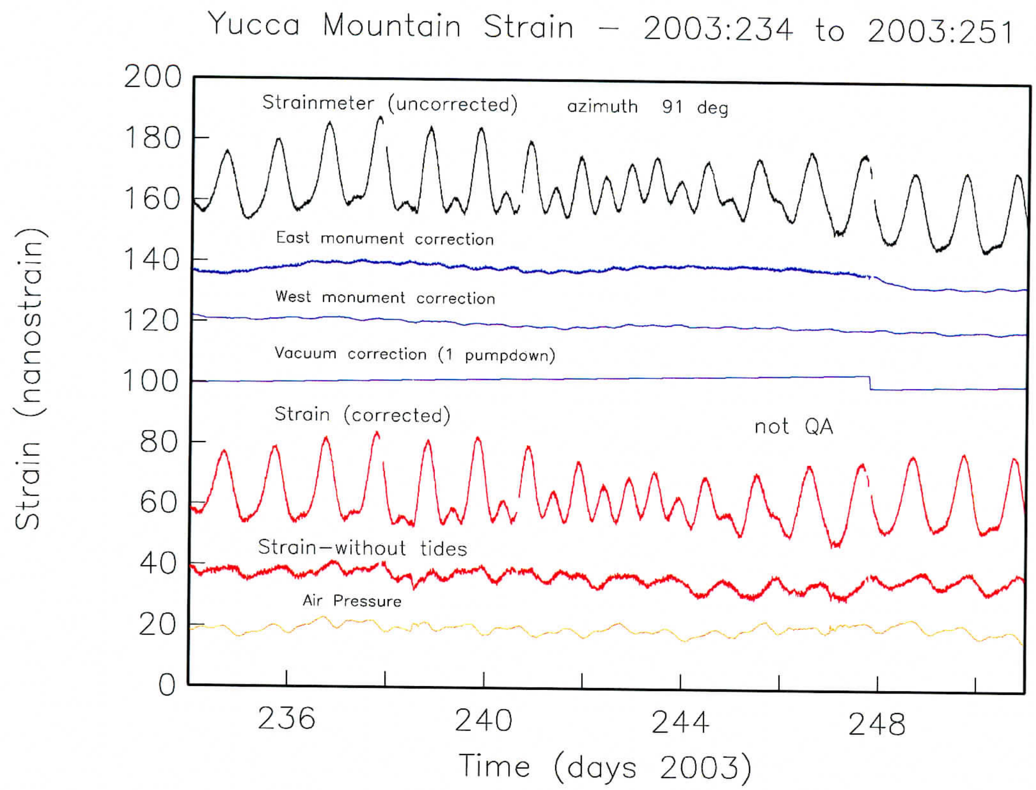


Figure 11 (Non-Q data, for information only. Ref: Figure 2 in UCSD portion of UNR OSPA No. 0404021.)

a major concern for the repository. The strainmeter's ability to detect such changes over periods of a year and less makes it an important part of the continued monitoring of the facility—this instrument, and the continuous GPS network, provide complementary measures which between them will measure the deformation in this area as well as is done anywhere.

References

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Wernicke, B., J.L. Davis, R.A. Bennett, P. Elosegui, M.J. Abolins, R.J. Brady, M.A. House, N.A. Niemi, and J.K. Snow, Anomalous strain accumulation in the Yucca Mountain area, Nevada, *Science*, **279**, 2096-2100, 1998.

Figure 8: See Figure 1 in the University of California, San Diego section of Proposal Number UNR OSPA No. 1990709 from the University of Nevada Reno Office of Sponsored Projects.

Figure 11: See Figure 2 in the University of California, San Diego section of Proposal Number UNR OSPA No. 0404021 from the University of Nevada Reno Office of Sponsored Projects.

Appendix A: MD5 Signatures for Files

Files of 1-second Data

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Files of 5-minute Data

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Appendix B: Strainmeter-Component-Plans

YMS Strainmeter

\Electrical

\01-Logger
- 01-01-010 Multiplexer box layout
- 01-02-010 Multiplexer rack layout

\02-Other Remote Control
- Master Control Block Diagram

\03-Beamsteering driver
- All drawings transferred to OrCad

\04-LOA Modulation driver
- All drawings transferred to OrCad

\05-Vacuum Control
- 05-01-010 Vacuum controller box
- 05-01-020 Vacuum controller box 2
- 05-01-030 Vacuum controller circuit (electric, air, and vacuum)
- 05-01-040 Vacuum pneumatics

\06-Thermal Control
- 06-01-010 TEM schematic
- 06-01-020 TEM control board layout
- 06-01-030 TEM installation layout
- 06-01-040 TEM parts
- 06-01-050 TEM assembly

\LOAs

\02-LOA 2000 Vacuum
- LOAS-02-01-010 4" LOA flange
- LOAS-02-01-020 System base (screws into canister)
- LOAS-02-01-021 System base hole x-y coordinates
- LOAS-02-01-030 1" reflector holder and retaining ring
- LOAS-02-01-031 Large (1.5") corner reflector holder
- LOAS-02-01-040 Pipe end flange (mate to bellows)
- LOAS-02-01-050 Bellows flange
- LOAS-02-01-060 LOA bellows design
- LOAS-02-01-070 Guide rods and parts
- LOAS-02-01-080 Window holder
- LOAS-02-01-090 Window retainer ring and vacuum hose flange
- LOAS-02-01-100 Vacuum tube hanger
- LOAS-02-01-110 LOA pipe lowering clamp
- LOAS-02-01-120 Install tool mod (older tool modified)
- LOAS-02-02-010 Bellows assembly
- LOAS-02-02-020 Vacuum hookup assembly
- LOAS-02-02-030 Vacuum pipe assembly
- LOAS-02-02-040 Bottom pipe assembly
- LOAS-02-02-050 Middle pipe assembly

- LOAS-02-02-060 Top pipe assembly
- LOAS-02-05-010 Length assembly worksheet

\03-LOA 2000 Casing

- LOAS-03-01-010 Anchor canister
- LOAS-03-01-020 Anchor canister base threads
- LOAS-03-01-030 Anchor canister frame parts
- LOAS-03-01-040 Anchor canister grout tube assembly
- LOAS-03-01-050 Grout cap
- LOAS-03-01-060 LOA PVC casing canister threads
- LOAS-03-01-070 PVC casing skids
- LOAS-03-01-080 1 1/4" pipe guides
- LOAS-03-01-090 Casing survey tool
- LOAS-03-02-010 Anchor canister assembly
- LOAS-03-02-020 Anchor canister skid assembly
- LOAS-03-02-030 Long socket assembly
- LOAS-03-03-010 Anchor canister in ground (cutaway)
- LOAS-03-03-020 Anchor canister in ground
- LOAS-03-03-030 Anchor canister loading views
- LOAS-03-05-010 Casing shim worksheet
- LOAS-03-05-020 Casing vs. borehole vs. vac tube worksheet
- LOAS-03-05-030 Casing vs. borehole vs. vac tube Advanced worksheet
- LOAS-03-05-050 Target worksheet

\Main Vacuum

\01-Main Pipe

- PIPE-01-01-010 5.5" tube 8 bolt flange
- PIPE-01-01-020 5.5" tube flange welding specifications
- PIPE-01-01-030 5.5" tube 4 bolt flange
- PIPE-01-01-040 5.5 and 6" tube O-ring overpressure rings
- PIPE-01-01-050 Pipe cradle layout and design

\03-Yucca Stanchions

- PIPE-02-01-010 5.5" pipe rollers
- PIPE-03-01-010 Yucca stanchions
- PIPE-03-01-020 Yucca layout tool (piercing point)
- PIPE-03-01-030 Yucca center clamp
- PIPE-03-02-010 Tunnel wall and layout view
- PIPE-03-02-020 Piercing point tool use
- PIPE-03-02-030 Center anchor layout
- PIPE-03-02-040 Yucca roller assembly

\04-Pump and Plumbing

- PIPE-04-01-020 Vacuum pump layout and plumbing
- PIPE-04-01-040 Yucca vacuum pump stand
- PIPE-04-01-050 LASM (GVS) pump stand

\05-Bellows

- PIPE-05-01-010 Bellows main brace
- PIPE-05-01-020 Bellows adapter plate
- PIPE-05-01-030 Bellows anti-torque brace
- PIPE-05-01-040 End window assembly
- PIPE-05-01-050 Tail piece assembly
- PIPE-05-02-010 Bellows assembly

\Optics

\01-Laser adapter
- OPTC-01-01-010 ML1-AL1 adapter
- OPTC-01-02-010 ML1 laser
- OPTC-01-02-020 ML1- AL1 adapter assembly

\02-Optics Table
- OPTC-02-01-010 48"x24" optics table (unmodified)
- OPTC-02-01-011 48"x24" optics table (modified for vertical LOA s)
- OPTC-02-01-011A Yucca optics table. No LOA holes (renumber).
- OPTC-02-01-012 Optic table legs and holders
- OPTC-02-01-013 Optics table feet
- OPTC-02-01-014 Yucca special flat foot (for tilted optics table)
- OPTC-02-01-020 Optic table hold downs
- OPTC-02-05-010 Optic table legs assembly
- OPTC-02-05-020 Yucca table assembly view (showing tilt)

\03-Beam Splitters
- OPTC-03-01-010 2" beamsplitter holder (for Newport beamsplitter)
- OPTC-03-01-020 3" beamsplitter holder (for BS Arch)
- OPTC-03-01-030 2" beamsplitter holder (for Coherent beamsplitter)
- OPTC-03-01-040 Telescope mount
- OPTC-03-01-050 LSM beamsplitter arch
- OPTC-03-01-060 LOA beamsplitter arch
- OPTC-03-01-070 Yucca LOA beamsplitter arch
- OPTC-03-01-080 Arch feet and legs
- OPTC-03-02-010 2" beamsplitter light path
- OPTC-03-02-020 Telescope mount assembly

\04-Reference Laser
- OPTC-04-02-010 Iodine laser to He-Ne laser test stand schematic

\05-Optics Layouts
- OPTC-05-02-010 Yucca optics layout (older version)
- OPTC-05-02-020 Yucca optics layout (presentation quality)
- OPTC-05-02-030 Yucca optics layout (side view)

\06-Laser Stage
- OPTC-06-01-010 Laser stage pivot and spring parts
- OPTC-06-01-011 Stage hold down parts
- OPTC-06-01-020 Steering arm and micrometer surfaces
- OPTC-06-01-030 Micrometer holders
- OPTC-06-01-040 Yucca laser stage
- OPTC-06-02-010 Yucca optics layout (move to Layouts)
- OPTC-06-02-020 Laser stage assembly
- OPTC-06-02-030 Yucca laser stage center of gravity worksheet

\07-LOA Scope Mount
- OPTC-07-01-010 Telescope base
- OPTC-07-01-020 Base cross bar
- OPTC-07-01-030 Leg and leg base
- OPTC-07-02-010 LOA scope mount assembly

\08-LOA Prism Steering

- OPTC-08-01-010 Unmodified rotary mount and motor micrometer
- OPTC-08-01-020 Micrometer bracket
- OPTC-08-01-030 Rotary mount modifications and steering arm ring
- OPTC-08-01-040 Spring plunger and ring assembly
- OPTC-08-01-050 Rotator mount
- OPTC-08-01-060 Rotator and wave plate mount
- OPTC-08-02-010 Range of motion worksheet
- OPTC-08-02-020 Assembly top view
- OPTC-08-02-030 Beam splitter to counter rotating prism layout worksheet
- OPTC-08-05-010 Prism motion and function worksheet

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\01-Site Drawings (note West = 65+41 and East = 69+46)

- YUCA-01-01-010 West alcove concrete. Layout and volumes
- YUCA-01-01-020 East alcove concrete. Layout and volumes
- YUCA-01-01-030 West monument and bellows piers construction detail
- YUCA-01-01-040 East monument and bellows piers construction detail
- YUCA-01-01-050 Monument pier detail. Showing relation between ground contact and slabs.
- YUCA-01-01-060 Concrete floor detail and rebar layout
- YUCA-01-01-070 West alcove excavation detail and volumes
- YUCA-01-01-080 East alcove excavation detail and volumes
- YUCA-01-02-010 Pipe roller layout. Tunnel position and various views.
- YUCA-01-02-020 Alcove / Building / Monument layout view.
- YUCA-01-02-030 Instrument layout. Top and side view.
- YUCA-01-03-010 East and West building cutaway view. (Contains two drawings.)
- YUCA-01-03-020 Top and end view showing full LOA depth to scale
- YUCA-01-03-030 End view showing full LOA depth to scale
- YUCA-01-05-010 West building placement layout guide
- YUCA-01-05-020 East building placement layout guide

\02-Strainmeter

- YUCA-02-01-010 East vault construction plans (ours)
- YUCA-02-01-015 East vault construction plans (contractors)
- YUCA-02-01-020 West vault construction plans (ours)
- YUCA-02-01-025 West vault construction plans (contractors)
- YUCA-02-01-030 LOA tube clamping collar
- YUCA-02-01-032 LOA tube clamp
- YUCA-02-01-033 LOA window end clamp (unfinished)
- YUCA-02-01-040 Instrument enclosure assembly drawing
- YUCA-02-01-041 Instrument enclosure assembly cutaway
- YUCA-02-01-042 Instrument panel construction plans
- YUCA-02-01-043 Instrument box fasteners and assembly
- YUCA-02-01-050 East instrument box modifications
- YUCA-02-01-060 West instrument box modifications
- YUCA-02-02-010 LOA tube clamping collar assembly and instructions

\03-LOA Layout

- YUCA-03-05-010 LOA layout instructions and definitions
- YUCA-03-05-020 Acceptable borehole drift
- YUCA-03-05-030 Angular drift allowances and drift from straight line

\04-Rail Cart

- YUCA-04-01-010 Rail cart assembly and frame construction

- YUCA-04-01-020 Push bar
- YUCA-04-01-030 Rail cart parts

\05-As Built Drawings
- YUCA-05-01-010 West concrete
- YUCA-05-01-020 East conctete
- YUCA-05-01-030 West pier detail (unfinished)
- YUCA-05-01-040 East pier detail (unfinished)

\99-Old and Unused
- LOA pipe installation supports
- YUCA-01-04-020 Tunnel tools. Various views of pipe layout, building layout and tunnel to pipe dimensions
- YUCA-01-02-020 Old building design
- YUCA-01-09-020 Alternate roller support design
- YUCA-01-09-010 Early tunnel cross section showing proposed pipe location
- YUCA-01-09-030 No vault strainmeter design layout (end view cross section)
- YUCA-99-09-040 No vault strainmeter design (top view)
- YUCA-99-09-090 20 shipping container strainmeter layout
- YUCA-99-09-080 20 shipping container layout
- YUCA-99-09-070 Another 20 shipping container layout
- YUCA-99-09-060 Early building tunnel layout
- YUCA-99-09-050 Micro building layout
- YUCA-99-09-100 Mico building layout detail. Building / Excavation / Concrete.