Addition of Strain to Targeted GPS Clusters

- New Issues for

Large Scale Borehole Strainmeter Arrays

Mick Gladwin , Ross Gwyther and Rhodes Hart(C.S.I.R.O.,. Australia)

SUMMARY

Deployment of high density borehole tensor strain arrays is a crucial component of the PBO initiative, based on the complementary nature of these data to long baseline tectonic strain observations from intensive GPS arrays. We detail here the issues which must be addressed in establishing large scale arrays of borehole tensor strainmeters. These issues have previously been unimportant because the current scale of borehole strainmeter campaigns has been small. These key new issues center on

- **Development of a larger skilled cohort of researchers and technical support staff**
- **Production of instruments**
- **Deployment strategies and procedures**
- **Data archiving standards and protocol**
- **Data interpretation procedures**

Solutions to these issues are well defined, but need early planning for effective implementation at the proposed scale of the PBO.

Background

Major progress in tectonic and geodetic studies have been achieved through use of either seismic instruments or GPS instruments. The domains of measurement these instruments cover are shown in Figure 1. Many different types of instruments are used and all instrument technologies and acceptable performance standards are well established. Deployments of each type of instrument are in the thousands, there is widespread experience of instrument installation, operation, and data collection by many field personnel. Both seismic and GPS instrument technologies are commercially available instruments and can be regularly and routinely used with relatively little modification for field deployment.

Borehole strainmeters have been demonstrated to deliver critical deformation data in a complementary domain of measurement to that of GPS and seismics, as illustrated in Figure 1. In contrast to GPS and seismic instruments, borehole strain instruments are extremely sparsely deployed. There

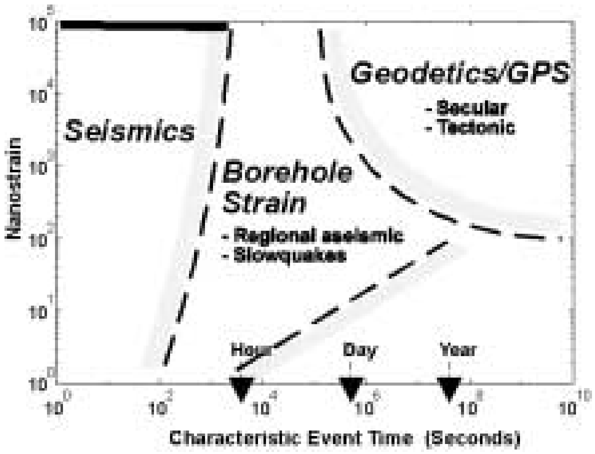


Figure 1

are in total only approximately 14 operating borehole dilatometers, and 7 operating borehole tensor strainmeters in the US (all in California).

Intrinsically these technologies are themselves mature. There has been a relatively long experience in their operation - the DTM group has operated dilatometers in Japan and the US since 1965, the Menlo Park USGS group has operated their dilatometers since 1979. Our Australian (University of Queensland and CSIRO) group has operated borehole tensor strainmeters since 1968 in Australia, and since 1983 in USA. This experience, however, has been limited to the very small number of researchers and support technicians involved. The instruments have up until now been constructed in-house, and the researchers involved in analysing the borehole strain data have highly specialised knowledge of instrument design, construction, specialised deployment procedures, and data processing.

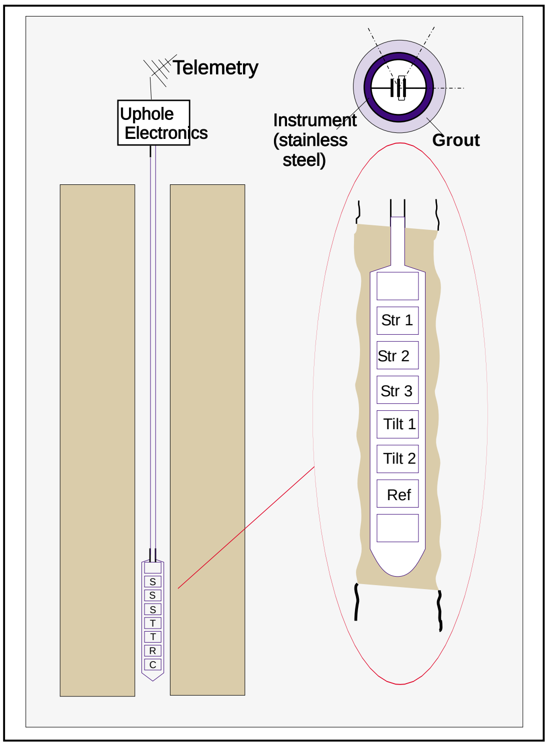
Borehole strainmeters are not currently a technology which can purchased off-the-shelf and employed readily by a wide number of research workers. The current situation can be summarised by the following table:

Current Instruments	
GPS and Seismic	**Borehole Strainmeters**
• *many instruments* • *many researchers* • *many specialized technical support staff available* • *many commercial sources available*	• *few instruments* • *few researchers* • *few specialized technical support staff* • *specialist construction*

For installation of some 200 borehole strainmeters at say a rate of one per week beginning in 2002, we need to address these issues by a focussed plan over the next two years which will guarantee effective and reliable deployments.

A Typical Borehole Strain Site

A typical borehole strainmeter installation involves considerable costs associated with permitting and drilling a borehole to approximately 200 m into competent rock. The instrument is installed into an expansive grout, and the borehole needs to be grouted to the surface to prevent contamination of the signal with groundwater migration. The borehole can be multiply used by installation of other instruments (eg piezometers, seismometers above the strain instrument provided these are deployed at the time of installation, and are sufficiently removed from the strainmeters (mechanically and electronically). Data from the downhole instrument are processed at the surface into short term averages typically sampled at five minutes to 30 minutes.



Some sites have "high" frequency sampling capability (typically to a few tens of Hz). The data are locally recorded and in near real time transmitted via satellite (GOES currently) to data collection facilities currently located at Menlo Park.

Instrumental stability of the tensor strainmeter including properties of the grouted inclusion is currently demonstrated at better than 100 nanostrain per year. For a typical borehole instrument (say 100 mm), measurements of strain to one nanostrain imply sensitivity to diameter changes of 100 picometers or changes of volume of approximately 30 micro-cubic centimeters. These figures necessitate highly accurate machining, construction and deployment procedures and demand very high reliability downhole miniature electronics and mechanical systems.

Cohort of skilled researchers/technical support

As mentioned there is a critically small number of researchers who have hands-on experience of borehole strainmeters (perhaps less than 10 in total) in the US and Australian groups, and there is a similar small number of specialist technical support staff. These numbers are inadequate to support a program involving 200 installed new strainmeters.

In the new world, the researchers will need to be freed of the obligations of actual production and deployment processes. Their construction and deployment expertise will need to be transferred to commercial suppliers and to specialist deployment teams. They will need to remain responsible initially for monitoring standards of production and deployment.

There will be need for aggressive involvement in the development of research programs at a wide range of institutions which will ultimately provide the cohort of post-graduates with experience and focus on borehole strain data analysis.

We recommend:

- Establishment of **research streams in borehole strain analysis and interpretation** in research institutions currently proposing programs which include strainmeter components to provide the new and complementary expertise for integration with GPS studies.
- Provision of **some PBO funds into post-graduate research scholarships** specifically targeted on borehole strain which will allow emerging graduates to visit experienced institutions for extended periods.
- Provision of **transitional training funds** to enable current researchers expertise in manufacture and deployment to be transferred to manufacturing companies and deployment teams

Production of instruments

Production of 300 instruments (175 along the San Andreas, 25 in volcanic settings, and 100 in off-fault clusters) over a five year timeframe will require construction and deployment of a little more than one(1) instrument per week over that whole time period or about two per week during the field season. This is well within capability for small scale commercial instrument makers who need to have produced production prototypes by 2001 and be tooled up for production by 2002. Standards of production quality and quality management procedures need to be put in place because the design instrument lifetime needs to be a minimum of approximately 20 years.

We recommend:

- Establishment of commonly accepted **standards for instrument specification**
- Definition of the **quality control procedures** to be used by the program.
- Early identification of **instrumentation companies** willing to enter into contracts for instrument manufacture and appropriate production licensing agreements from the principal instrument designers.

Deployment strategies/procedures

There is a considerable degree of experience amongst a small number of researchers in instrument siting decisions, and deployment procedures. To meet a goal of 1 instrument deployment per week, the PBO consortium will need to establish two suitably equipped deployment teams of four persons each with specialized skills transferred from the current workers in this field. However there is a critical need for the current borehole strainmeter specialists to be involved in an advisory capacity in the operations of these teams, both to make use of current experience, and also to guarantee effective transfer this knowledge to the deployment team personnel.

Siting strategies must include decisions in regard to rock quality, site security and access, topography (data corrections to account for topographic influence are of order 10% in moderate topography), specification of boreholes to be drilled, identification of surrounding geological conditions such as local faults, knowledge of local groundwater levels and conditions. There needs to be a significant commitment to planning and permitting for these arrays.

When planning array spacing, instrument distance from the fault trace is critical. Combination of the 3 independent strain tensor components from each instrument enables identification of source dimensions. Thus, shallow sources can be identified by instruments relatively close to the fault, and to each other. Identification of deep sources requires instruments at distances of the same order as the source depth. As a general rule instruments should not be less than 1 km from the fault, since characteristics in the immediate fault zone will perturb observed data. At a minimum for the major parts of the San Andreas, two rows of instruments will be required: one set at 2-3km from the fault, and one set at 8-10km . Spacing of the inner set at 5km, and spacing of the outer set at 10km. For the subduction areas, instrument spacing will be broader. All array planning needs to be performed by the use of forward modeling of deformation field expected slip distributions.

We recommend:

- Establishment of at least two **deployment teams** to carry out all instrument deployments. These teams will require specialised equipment.
- A siting committee will be required for each local array to insure appropriate deployment strategies for the particular tectonic environment.
- Training funds to enable **involvement by one or more of the current specialists** in borehole strainmeters, in both siting strategies, and deployment trips.

Data Archive methodology

Current publicly accessible data archive procedures for GPS and seismic data are well established and routinely implemented. In contrast, while data archiving procedures for relatively low frequency sampled time-series data from instruments such as strainmeters have been well defined and implemented by current strain groups, these need to be made available to the broader community in a unified system.

In addition to expected instrumental noise, borehole strainmeter data inherently contain occasional perturbations which are not related to the measured strain, for example instrument resets, outliers due to power failures, etc. These perturbations are regularly cleaned from current data sets before archiving. Suitably qualified staff need to be committed to preservation of archival standards and preliminary cleaning of data.

Currently established **protocols for regular pre-cleaning of instrumental data** before archiving need to be mandated. Decisions must be made in relation to **the types of data archived** for public access (raw components, processed strain data), and uniform **data formats for storage.** There is a need to create and standardize basic data presentation software which provides robust handling of complete and incomplete data sets with reliable handling of time tags and sample frequencies. An excellent model for defining the functionality of this software is the USGS internal package **xqp** which currently runs on UNIX systems only and accesses data stored in standard “bottles”. The package provides a good platform for integration of other data sets (eg water wells, rainfall, atmospheric pressure which are often sampled under different measurement regimes).

Data Interpretation

The specific characteristics of borehole strainmeters are critical to a good understanding of the observed data. Some of the issues to be included in processing and analysis are the following:

- **Preparation of standardized coordinate transformation matrices** to present the data in array coherent and map oriented coordinates.
- **Calibration procedures** which include the cross-coupling effects of shear and areal strain (see companion paper ***Strainmeter Calibration***, Agnew, Wyatt & Gladwin).
- Finite element **modeling of local geological and topographic features**, to determine matrices expressing these influences on observed data (typically these effects are of order 10%).
- Procedures for **removal of the exponential signals** normally present in data as a result of grout cure and long term inclusion creep.
- The **crucial influence of groundwater level changes**, which have significant impact on observed strain data due to thermoelastic effects. (see companion paper ***Fluid Pressure Data – a Complement to Borehole Strain***, by Roeloffs)