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Long-baseline fluid tiltmeter for seismotectonic studies of Mexican subduction zone

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RESUMEN

Un inclinómetro de agua de base larga (LBT) se construyó en la costa del océano Pacífico de México para realizar observaciones de inclinación de alta precisión en una área de la zona de subducción, la cual aparentemente está en fase de deformación intersísmica-presísmica. El continuo monitoreo de la inclinación complementará las mediciones de GPS y de la deformación vertical (por nivelación) en esta área con datos continuos de alta precisión. La interfase sismogénica entre las placas tectónicas en la zona de subducción está razonablemente bien determinada a partir de la sismicidad local y de anomalías gravimétricas. La combinación de observaciones geodésicas y de sismicidad permiten monitorear la evolución de la deformación en los límites superior e inferior de la zona sismogénica en la cual es probable la ocurrencia de un sismo de M~7.0. Los datos del LBT se usarán de manera inmediata para aprender mucho acerca del proceso de carga tectónica que excita la ruptura sísmica. Los principios, características técnicas y el procedimiento de instalación del LBT, así como algunas observaciones preliminares y resultados son presentados.

PALABRAS CLAVE: Inclinómetro de base larga, subducción, deformación intersísmica, brecha sísmica.

ABSTRACT

A long-baseline water tiltmeter (LBT) was constructed on the Pacific coast of Mexico to provide high precision tilt observations in a section of the subduction zone apparently undergoing interseismic-preseismic deformation phase. Continuous tilt complements GPS and vertical displacement (leveling) measurements by providing higher precision and continuous data. The plate interface is reasonably well located from local seismicity and gravity anomalies. Integrated geodetic and seismicity observations enabled us to monitor the strain near the upper and lower ends of a seismogenic zone on which a future M~7.0 earthquake is nucleating. Predicting the future rupture may be possible because the instrument is two orders of magnitude more sensitive than other monitoring devices in the region. Main principles, technical features and installation procedure of the water LBT and some preliminary observations and results are presented.

KEY WORDS: Long-base tiltmeter, subduction, interseismic deformation, seismic gap.

INTRODUCTION

The 5-7 cm/year convergence between the Cocos and North American plates on the southern Mexican coast (DeMetz *et al.*, 1994) generates M>7 earthquakes every few years, and M>8 earthquakes at intervals of 30-100 years. The rupture dimensions of these events form characteristic zones, often terminated by the inferred locations of subducted fracture zones or other bathymetric irregularities that can be traced offshore (Kostoglodov and Ponce, 1994). These earthquakes can produce significant shaking in Mexico City. In 1985 the Mw=8.1 Michoacán earthquake caused about 10 000 fatalities (UNAM Seismology Group, 1986).

The two seismic gaps along the Pacific coast of Mexico closest to Mexico City are the NW and SE Guerrero gaps (Figure 1). Though the SE gap failed in the 1957 event (apparent recurrence 4-5 decades), the NW gap has an incomplete history of previous ruptures. The last big event probably was in 1911 (Nishenko and Singh, 1987). Some assessments of the seismic hazard potential of the NW Guerrero Gap assign a maximum probable magnitude of Mw 8-8.4 (Suárez *et al.,* 1990), however, it should not be regarded as an unambiguous estimate.

The coastal area around Acapulco City may be a smaller but significant seismic gap, which ruptured with two successive Mw 7.1, 7.0 events in 1962. The rupture zones of these earthquakes were recently ascertained by tsunami data modeling (Ortiz *et al.,* 2000). The configuration of the plate interface was inferred from gravity modeling (Kostoglodov *et al.,* 1996, Peláez, 1999). Campaign GPS since 1992, and

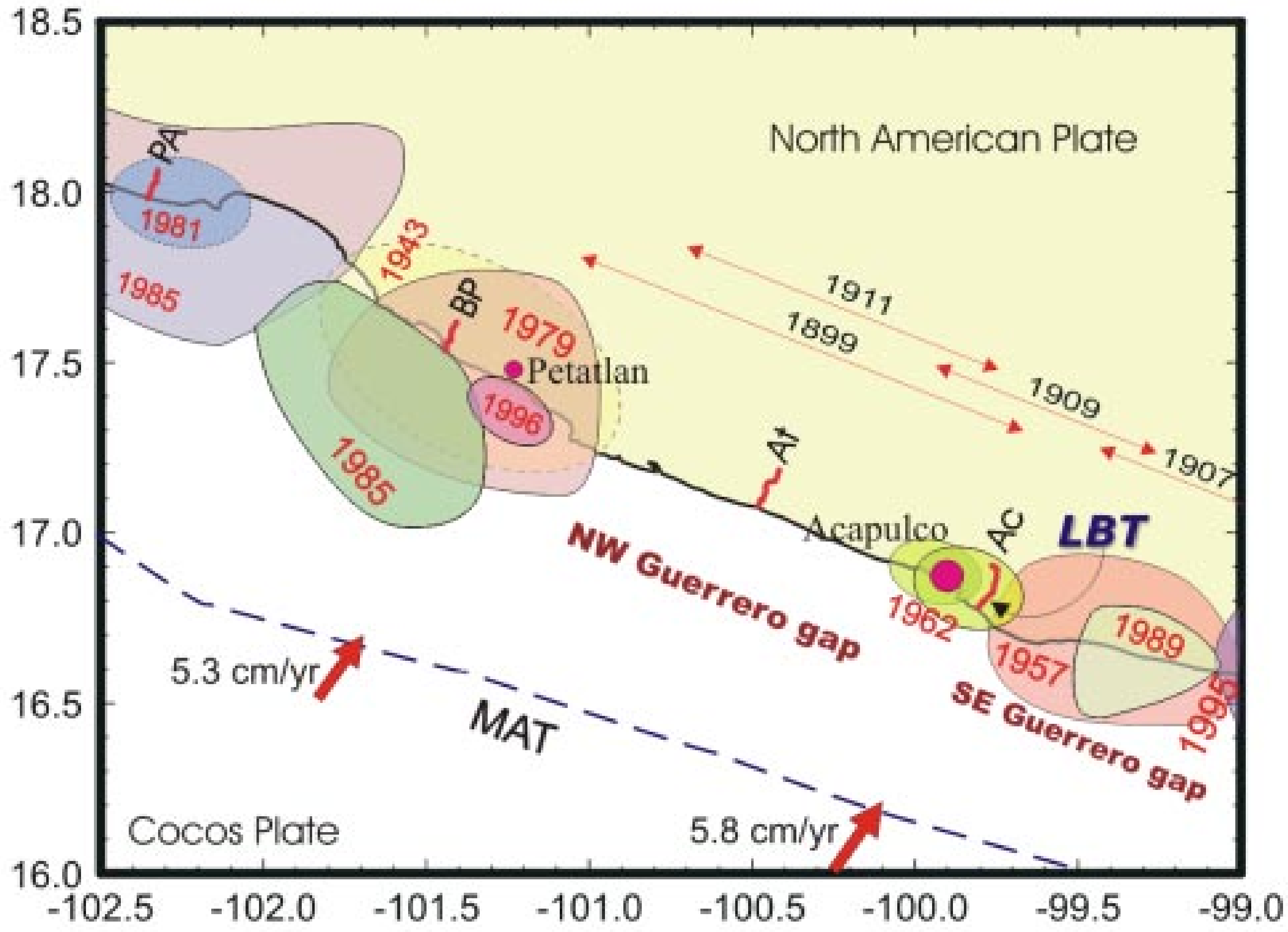


Fig. 1. Major seismic gaps along the Pacific coast of Mexico. Shaded areas annotated with a year are rupture zones of recent large thrust earthquakes. Thin arrows indicate the approximate rupture length of large earthquakes in 1899, 1907, 1909, and 1911. Solid arrows are vectors of the Cocos – NA convergence velocities according to the NUVEL 1A model (DeMets *et al.,* 1994). MAT – Middle America trench. LBT mark with a thin arrow show a location of the tiltmeter. Annotated short lines (PA, BP, At, and Ac) are leveling profiles.

precise leveling since 1995, observations have been regularly carried out to determine the location and width of the locked seismogenic segment on the interplate contact zone (Kostoglodov *et al.,* 2001). There are some indications of transient aseismic slip and migration of the upper and lower edges of the inferred locked seismogenic zone (continuous GPS observation and repeated leveling) in the subduction zone close to Acapulco (Lowry *et al.,* 2001).

Very low interseismic and transient-slip strain rates complicate a reliable detection of this process using campaign GPS and leveling. Higher precision methods are needed to monitor 1 µstrain/yr or <1 µradian/yr deformation in near real time. One of the approaches that can meet these requirements is an employment of long-baseline fluid tiltmeter (LBT) at locations where maximum tilt signals may be occurring. Fortunately we may readily identify these locations in the coastal area. The sensitivity of this instruments is ~10 nrad (Bilham *et al.,* 1982) which is (depending on the noise level) sufficient to resolve secular tilt fluctuations of ~0.1 µrad.

The first experimental water LBT (~500 m long) on the Guerrero coast was designed by Roger Bilham and built by the Instituto de Geofísica, UNAM by the end of May 1999 (Appendix). Technical problems and a number of construction errors have delayed the continuous operation of the LBT for one year. The accumulated continuous data record permits us to estimate the main characteristics of the LBT and realize its relevance for seismotectonic studies of the Mexican subduction zone.

THE LONG-BASE FLUID TILTMETER: PRINCIPLES OF OPERATION AND DESIGN

It is well known that surface noise often mask slow deformation of the Earth's surface associated with tectonic processes. Tectonic signals are 1 µrad/year or less, whereas thermal signals and the effects of rainfall may exceed 1 µrad/day. To control the noise two strategies are commonly used. The first is to install the tiltmeter at depths greater than 10 m, and the second is to construct tiltmeters that are long compared to the wavelengths of surface tilts. In practice a compromise solution is adopted: the tiltmeter is installed at shallow depth but indexed to points >10 m below the Earth's surface. Such installations are known as long-baseline tiltmeters (LBT).

A long-baseline tiltmeter is a fluid-filled pipe terminated by two reservoirs, in which the relative height difference of the free surface of the fluid yields a measure of the Earth's surface tilt. Many long baseline tiltmeters have been developed in the past century using mercury or water, and using various types of fluid level detectors to measure the tilt. Typical tilt sensitivities of these instruments are of 1 nanoradian (1 nrad or 0.001 µrad). With careful installation, noise level for annual periods is less than 50 nrad, and for daily periods less than 5 nrad.

The principle of operation of the LBT is that the surface of an isothermal fluid at rest is an equipotential surface, against which tilts of the Earth's surface are measured (Figure 2). Planar tilt results in the rise of fluid at one end and a corresponding identical drop in fluid level at the opposite end. The changes in level are detected using displacement transducers attached to floats or laser interferometers.

All types of tiltmeters are affected by thermal variations, instrumental noise and noise arising from attaching the tiltmeter to the Earth's surface. Many of these thermal sources do not increase with the size of the tiltmeter (thermoelastic strain is a typical exception). Thus by making the instrument very large, and hence increasing the relative displacements, *D*, (Figure 2) associated with a given tilt signal, the signal-to-noise ratio increases linearly with the length *L* of the tiltmeter. Long-base fluid tiltmeters are limited in size only by the wavelength of the signal. Suitable lengths for volcano studies are 200 m to 500 m. For subduction zones where wavelengths are tens of km, instruments up to 1 km length can be considered. No special tunnels are needed for these installations; the water pipe is buried horizontally at 1-1.5 m depth in the soil. Vaults are used to mount and access the transducers. The sensitivity of a 1 km long water tube tiltmeter is about 1000 times higher than that of GPS measurements over the same distance, assuming 5 mm vertical GPS noise.

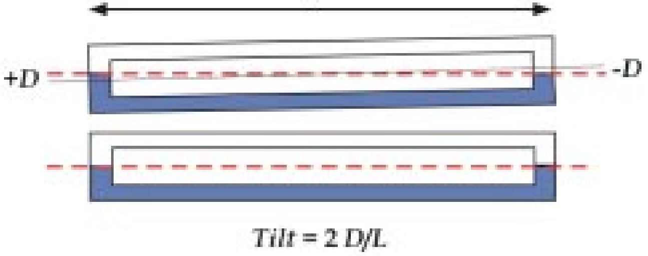


Fig. 2. Principle of the water LBT. Dashed horizontal line is an equipotential surface, which is used as a reference for the deforming Earth's surface (thin line in the top drawing).

The signal-to-noise level of all tiltmeters is period dependent. At yearly and longer periods, noise is introduced by thermoelastic signals generated near the Earth's surface, and by loading from long-period tidal variations in the oceans. The secular stability of a long-baseline tiltmeter anchored at depths of the order of 10 m is typically better than 0.1 µrad. The seasonal stability (weeks to months) is of the order of 0.01 µrad (10 nrad), and the noise level at hourly to daily periods is 1-5 nrad. The decreasing noise level over shorter time intervals is linked to reductions in the amplitudes of atmospheric and oceanic forcing functions (mass redistribution, water loading, soil expansion, temperature and pressure). This is an example of the "infra-red catastrophe" for surface signals.

Tiltmeter geometry

Of the three known types of long-baseline tiltmeters (Figure 3), only the half-filled water pipe type has clear advantages in long-term stability and immunity to thermal variations in the fluid. This tiltmeter in Geometry A (Figure 3) was introduced by A. A. Michelson in 1918 to measure the Earth's rigidity. Geometry B is typical of water-tube tiltmeters in tunnels and mines but is not suited to locations near the Earth's surface where temperature variations along the pipe may be encountered.

In Geometry A, because an equipotential surface exists along the entire pipe, the fluid is everywhere in equilibrium and the fluid responds locally to temperature effects. In a filled tube (Geometry B), in contrast, small temperature fluctuations in the water pipe may cause a local expansion, which drives fluid along the pipe, concentrating these effects as motions of the free surface at the ends of the pipe. In all three geometries the air pipe is an essential requirement, in order to maintain identical pressure at each end. Because of the low kinematic viscosity of the air, the cross-section of the air path must be much larger than the cross-section of the water path. Geometries A and B have widespread applications, but geometry C has not, largely because the central differential pressure transducer has potential mechanical drift that is avoided in the other two types of tiltmeter.

The diameter of the water pipe in Geometry A can be as small as 10 cm if it rests on a horizontal concrete or rock

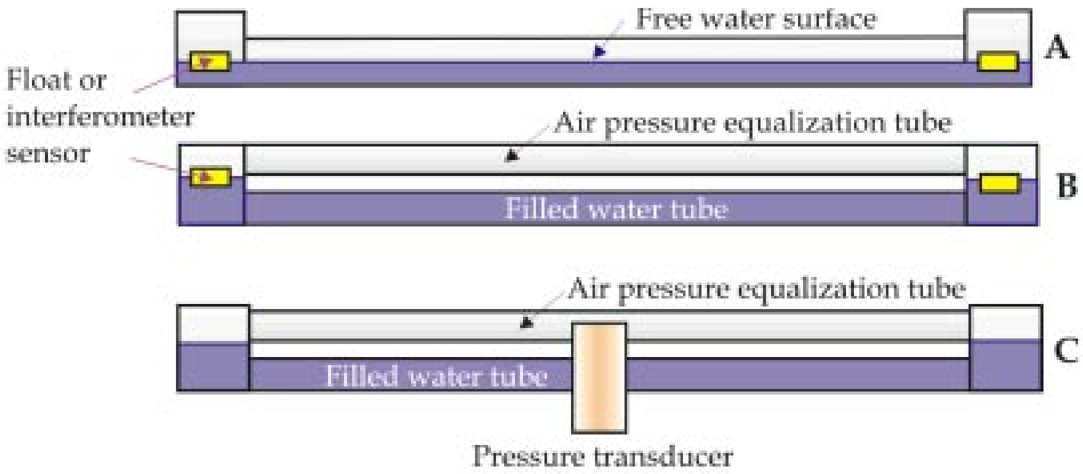


Fig. 3. Tiltmeter geometries used in long-baseline tiltmeters. A shows a half-filled pipe tiltmeter. In B and C the fluid pipe is filled.

surface (e.g. a basement of a building or a tunnel). In soils it is essential to use the pipe of a diameter that does not result in constriction of the air-path, or a severance of the water-path, should the pipe settle during the years following installation. A 20 cm diameter thin-walled plastic (PVC or polyethylene) water pipe is an effective choice. The pipe is either glued, or a bell-ended gasket O-ring connection for standard thin-walled sewer PVC pipe is used. Small leaks in the water path are less important than in the air path. Water leaks cause the water level to sink identically at each end, whereas air leaks introduce high frequency noise into the measurements. The pipe should be collocated at the bottom of the 1-1.5 m depth trench and accurately leveled.

A buried, half-filled, horizontal, water pipe (LBT) acts like an underground pond. Pressure and temperature variations in the pipe occur slowly at depths of 1-2 m so that no currents occur in the air above the water or in the water. Under these conditions the surface of the water assumes that of an equipotential surface. If the Earth's surface tilts, or if changes in mass distribution near the tiltmeter occur, water will flow so as to maintain an equipotential surface in the pipe. If surface tilts are slow compared to the time taken for the water to flow to equilibrium it is merely necessary to measure the reduction of water height at one end of the tiltmeter, and its rise at the other, to determine the tilt of the Earth's surface.

Dynamic response of water pipe tiltmeters to tilt and acceleration

Tilt of the water pipe results in fluid flow. In a filled pipe (Figure 3B) an exact solution for the resonant period is $T = 2\pi\sqrt{L/g}$, yielding a resonant period of roughly 60 seconds for a 1 km tiltmeter. By suitable choice of pipe diameter this resonant condition can be critically damped. No exact analytic solution is available for the half-filled tube although the resonant period is observed to be similar. A wave or "mini-tsunami" traveling along the pipe has been empirically determined to have a velocity $V = \sqrt{hg}$, where h is the mean depth of the water. This results in a ~30-minute two-way travel time for a half-filled 20 cm diameter pipe, 1 km long. In a 400 m half-filled pipe this mode has been observed to be underdamped with a 1/e decay period of 20 minutes. In locations where the wave-sloshing mode might be stimulated (e.g., by moderate earthquakes near a volcano) it may be desirable to increase the viscosity of the water (by adding glycol), or by using baffles in the pipe to damp the flow (e.g., submerged fiberglass mat).

Transducers in water pipe tiltmeters

A tilt signal of 1 µrad applied to a 1 km long tiltmeter will cause water level changes up to 1 mm. Whereas the range of a transducer suitable for volcano monitoring needs to be from 500 nm to 10 cm, a subduction zone instrument expects to experience a signal with an amplitude of up to 5 µrad/year (5 mm range transducer), and perhaps as small as 0.5 µrad/year (0.5 mm/km). Although interferometers have been used to measure such signals and ranges (Wyatt *et al.* 1984), these sensors are capricious and not suited to remote low-power operation.

In contrast, floats have the advantage that their position can be measured using various displacement transducers, which consume little power, and are relatively trouble free. A disadvantage is that surface tension effects can introduce jumps of tens of µm unless care is taken to suppress their effects on float position. Typical strategies are: to slope the edge of the float so that the water surface is horizontal where it meets the float; to make the reservoir much larger than the float, or to wet the inner surface of the reservoir using a porous surface. Strategies to overcome surface and adhesive tension, and thermal effects in the transducer are well established and it is possible to obtain 1 μm resolution over a range of 8 mm relatively inexpensively.

Deep referencing

The long baseline water pipe should be installed at a depth of 1-1.5 m in soil. While temperature variations are mostly suppressed at these depths, tilt noise levels usually remain unacceptably high, unless rock is encountered. The attachment of the transducer to a point at the level of the buried pipe is adequate if the subsurface is close to rock. However, if the subsurface material is soil it is essential to link the transducer to a stable reference point at depth.

The simplest solution, adopted in Guerrero, is to drive a stiff steel rod to a depth of 5-6 m where it encountered rock. The preferred solution is to drill a water well to 10-20 m depth and fix an invar, glass-fiber or stainless steel rod to the base of the hole. The transducer is mounted on the top of this rod, and maintained in tension by special supporting arms (Figure 4). The main feature of this float sensor system is that although the core of the LVDT (Linear Variable Differential Transformer) is attached to the float and immersed in water, the body of the LVDT remains outside the water pipe and can be directly linked mechanically to the base of the borehole.

The design shown in Figure 4 should effectively measure tilt between two points that are 10 m deep and 0.5-1 km apart. Thermoelastic and rainfall-induced noise levels are typically of the order of 1-10 μm at these depths, yielding a theoretical noise level of 0.01 μrad/year.

Two tilt axes are needed to specify the tilt vector in the general case. Both installations can usually share a common mid-point. The overall design of the tiltmeter thus consists of two long pipes at right angles buried at a depth of roughly 1 m. Three vaults are installed at the ends of the L-shaped instrument, each with a 10 m borehole. Three transducers measure the tilt. If a flat site is unavailable the two axes of the tiltmeter must follow contours. This usually means that four transducers are needed, one for each axis.

LBT INSTALLATION IN MEXICO

The deployment of LBT on the Pacific coast of Mexico required resolving a number of problems. The most essential of them are: determining an appropriate site for the installation; getting permission for the construction; power supply; waterproofing, safety, etc. We decided to make the first experimental installation on the LBT on the Costa Chica, southeast from Acapulco, where a ~30 km leveling line was installed and reoccupied several times since 1995 (Figure 1). There were many factors considered in favor of this location including an easy and quick access to the site by highway.

Determining and selection of the site

The location of an LBT site depends on the main objective of the installation. Seismotectonic studies at the Mexican subduction zone require a monitoring of highest attainable tilt (of the order of 1 μrad/year) at the locations where important changes in the tilt values are expected. Whatever the physics of the eventual failure process, the rupture (earthquake) of the locked seismogenic patch will nucleate from a point on the locked zone that is progressively stressed towards instability. This is most likely to occur in the transition zone between aseismic loading and stick-slip behavior, at the base of the seismogenic zone.

We wish to determine the precise location and the effective width of the transition from creep to locked segments of the plate boundary. For the Guerrero area an episodic transient slip could be an important failure mode in the transition zone (Lowry *et al.,* 2001). Aseismic slip events seem to be rather common in subduction zones. Recent accurate GPS monitoring techniques have detected slow events of this type with different amplitude and duration, for instance in Japan (Ozawa *et al.,* 2001) and Cascadia (Dragert *et al.,* 2001). It is probable that seismic rupture occurs as a consequence of monotonic, incremental loading of the lower edge of the seismogenic (coupled) zone, and may be preceded by slow transient slip on this edge or on the transition deeper part of the plate interface.

Unfortunately the details of episodic slip cannot be observed by geodetic surveys of the Mexican convergence zone because they do not obtain continuous data. Strain and tilt instrumentation or continuous GPS, gravity or tide gage observations are needed to reveal the duration and spatial development of episodic creep processes. LBT is similar in cost to GPS receivers but is more sensitive by up to a factor of 1000. When used with GPS, LBT data can provide unique constraints on dislocation parameters.

To determine the optimum location for the LBT deployment some preliminary tilt modeling is necessary. The geometry of the interface between the oceanic and continental plates in Guerrero was determined from local seismicity studies and gravity modeling (Suárez *et al.,* 1990; Pardo and Suárez, 1995; Kostoglodov *et al.,* 1996; Peláez, 1999). Rupture parameters of two 1962 Mw 7.1, 7.0 events

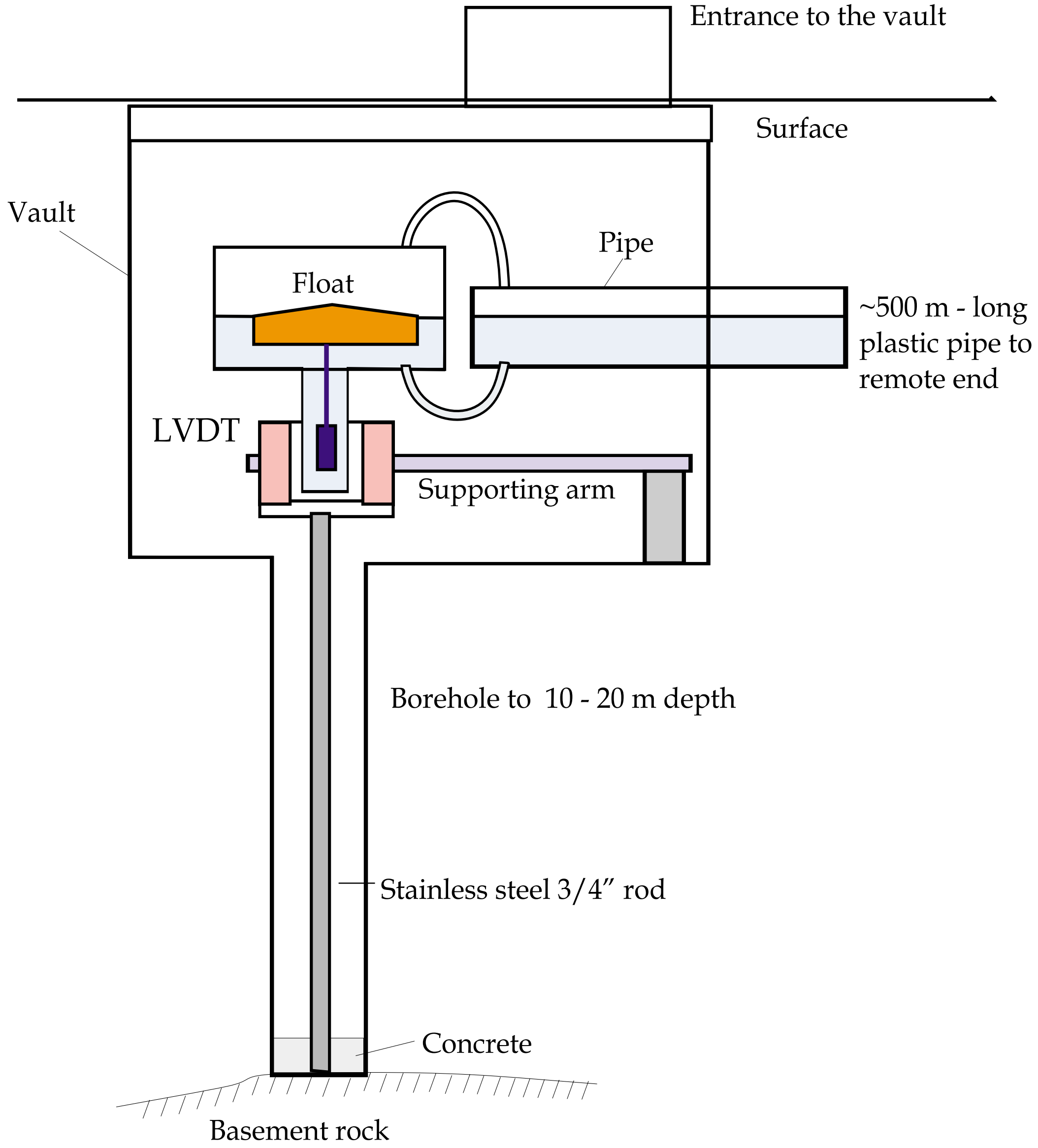


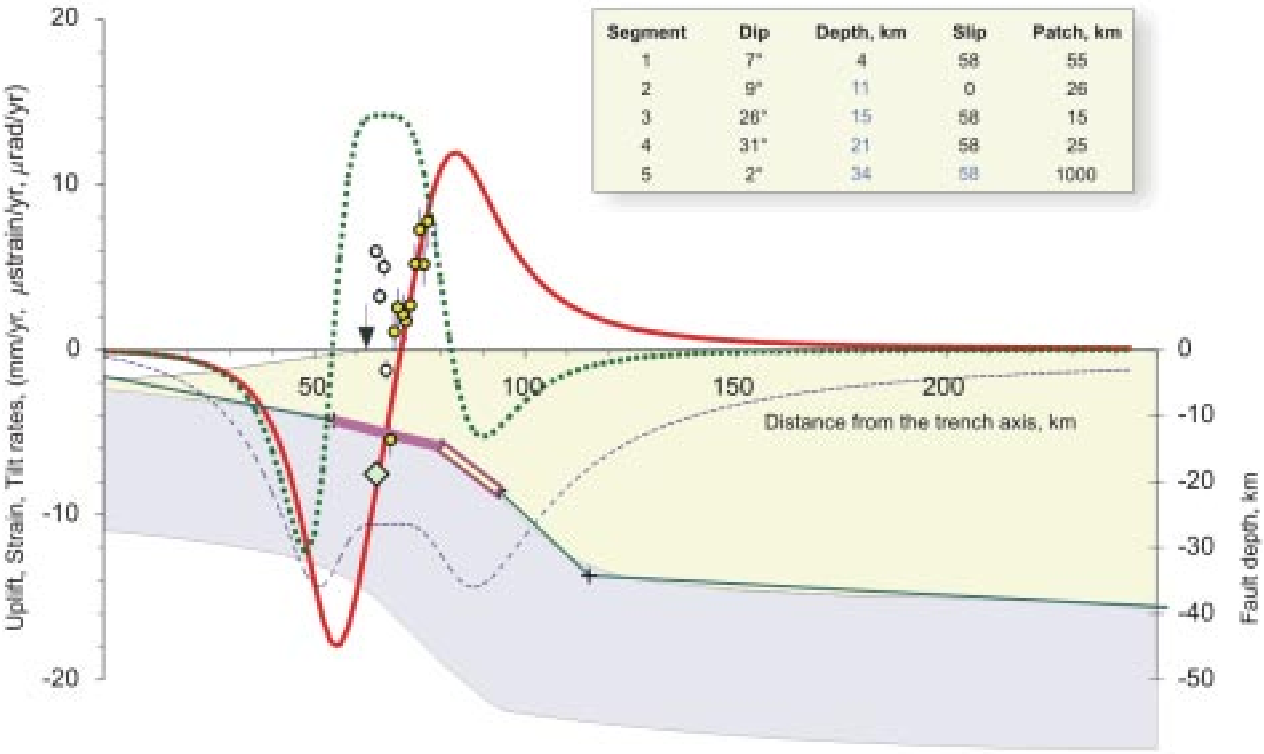
Fig. 4. Schematic of deep-referenced float transducer. A direct measurement is made between the water surface and a point buried 10-20 m below the Earth's surface. A stainless steel (invar, glass-fiber) rod is cemented to the base of a 1" to 4" diameter borehole (a water well hole is adequate). The water pipe is sealed, and all parts in the water are either plastic or stainless steel. The transducer is accessible outside from the pipe system for easy maintenance and calibration. LVDT sensor - Linear Variable Differential Transformer.

(Ortiz *et al.,* 2001), which occurred right below Acapulco (Figure 1), and recent high precision leveling measurements (Kostoglodov *et al.,* 2001) were used to model a location of the coupled segment on the plate interface, corresponding surface crustal deformations and tilt.

A simple 2-D half-space elastic dislocation model (Savage, 1983) applied to fit the crustal uplift rates data from repeated leveling surveys on the Acapulco line (Figure 1) assessed the uplift and strain rates as well as the tilt rate distribution (Figure 5).

A maximum of the modeled tilt rate of ~14 μrad/year extends from the coast up to a ~8-10 km inland from the coast. This tilt is high enough to be accurately monitored with the LBT. The variation of tilt signal depends on the geometry and location of the locked-seismogenic and partially coupled segments of the plate interface (Kostoglodov *et al.,* 2001). According to the model (Figure 5) the optimal site for the LBT installation is at a distance of ~8-9 km along the leveling profile where the most variation of the tilt can be expected as a result of relatively small changes in the plate coupling.

Horizontal easily accessible installation locations are difficult to find in the mountains and the coastal plane of Guerrero. The site for LBT was chosen on the "Costa Chica", SW from Acapulco city, at the distance of 8.5-9 km from the



Segment	Dip	Depth, km	Slip	Patch, km
1	7°	4	58	55
2	9°	11	0	26
3	28°	15	58	15
4	31°	21	58	25
5	2°	34	58	1000

Fig. 5. Modeling of the vertical uplift rate (solid line), strain rate (dashed line), and tilt rate (dotted line) for the Acapulco leveling profile (Elastic dislocation model, Savage, 1983). Shaded areas represent the configuration of the subducting Cocos plate and the interplate contact according to Kostoglodov *et al*. (1996). The geometric parameters of the fault segments and the slip rate are given in the inset. Locked (shallower) and slipping or partially locked (deeper) segments are shown as elongated filled, and open rectangles below the coast correspondingly. Circles with vertical bars represent uplift rate and cumulative errors estimates from repeated leveling. Diamond indicates a long-term subsidence rate estimated from continuous GPS and tide gauge records at Acapulco (Kostoglodov *et al.,* 2000).

coast along the "Diamante" highway (Figures 1, 6A,B). Only one component LBT was possible to install on the federal land, close to the highway "Diamante" (a variety of troubles arose related with the permission for the construction on the private lands). This site is not optimal for LBT construction: it has a shallow water table and the slope is ~0.23° (less than 0.06° is recommended). The advantages of the site are that the bedrock is only 6-7 m deep, and it is close to a highway tollbooth with an AC electric connection. Also the site is fairly secure.

This LBT site is designed to detect minor changes in coupling, and changes in the configuration of locked seismogenic or partially coupled patches. Models similar to that presented in Figure 5 show, for example, that shortening of the locked segment from 28 to 22 km would result in a decrease of the tilt rate of ~0.25 µrad/yr (Figure 7). Other changes in configuration and slip of the interface zone segments (e.g., partial locking of segment X3 in Figures 5, 7) can cause the tilt to vary more than 0.5 µrad.

Repeated high precision leveling surveys on the Acapulco profile (Kostoglodov *et al.,* 2001; Figure 6) show some apparent changes in the tilt rate at the LBT site (Figure 8). The changes may be attributed to the variation in the dimensions or coupling of the seismogenic zone. The influence of an apparent shallow crustal fault zone, which is seen as a local minimum at a distance of ~4 km on the profiles, is negligible at the LBT location.

The coordinates (WGS-84) of the end points of the water pipe measured with GPS are Southern vault end, lat = 16° 51" 13.95247' N, long = 99° 45" 16.67670' W; Northern vault end, lat = 16° 50" 57.64729' N, long = 99° 45" 21.59394' W. The ends of the pipe are leveled within 1-2 mm. Ellipsoid height is *h* ~21 m. The total length (ellipsoid distance) of the water pipe is 518 m, and the geodetic azimuth is θ ~ 16°. The LBT pipe is not exactly perpendicular to the strike of the subduction trench axis (Figure 6B).

LBT construction and features

The construction of the LBT starts with leveling the line where the water pipe is to be buried, indicating the relative elevation from the highest point of the profile. This will

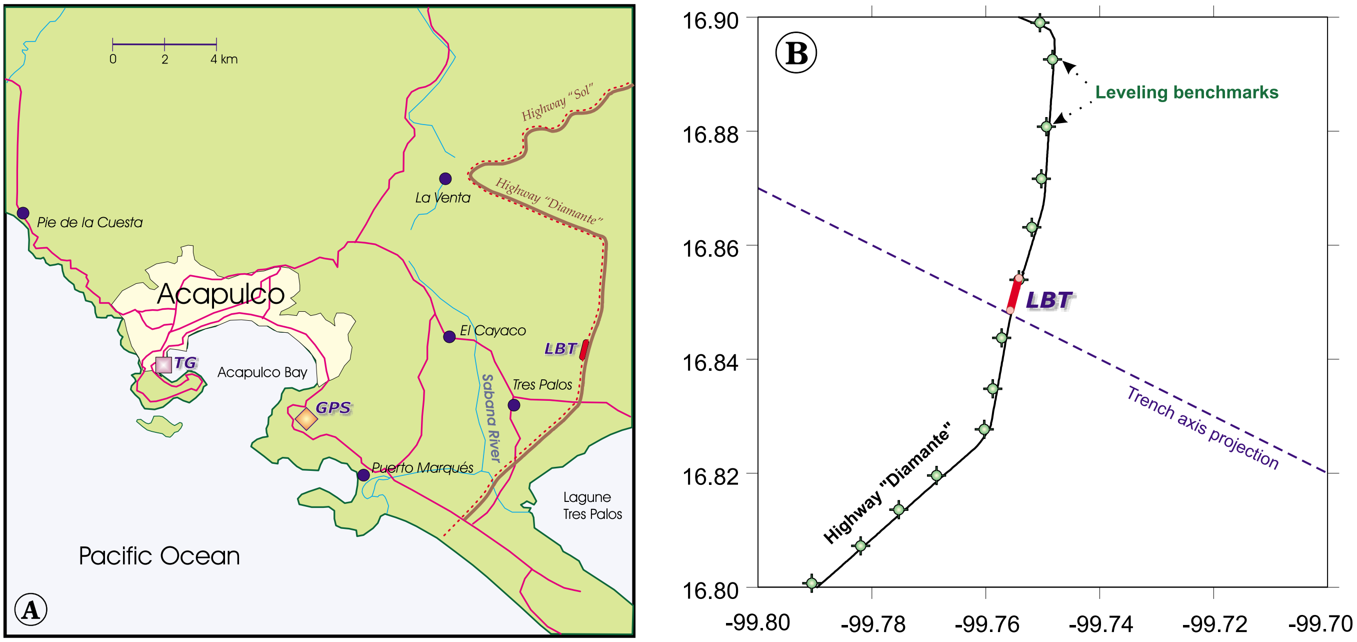
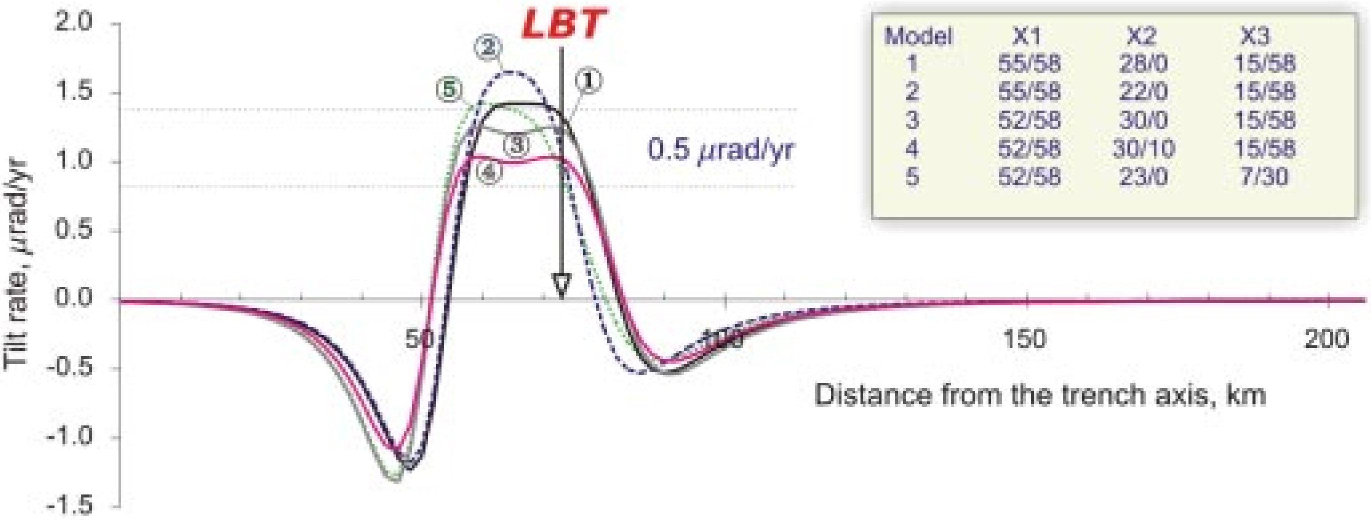


Fig. 6. A - Map of the Acapulco area and location of the LBT site. GPS and TG are GPS and tide gauges continuous stations. Dotted line along the highways shows the Acapulco leveling profile. B – Detailed map of the LBT location. Circles are the leveling benchmarks. The trench axis projection is drawn to specify the orientation of the LBT axis with respect to the trench.



Model	X1	X2	X3
1	55/58	28/0	15/58
2	55/58	22/0	15/58
3	52/58	30/0	15/58
4	52/58	30/10	15/58
5	52/58	23/0	7/30

Fig. 7. Different models of the tilt rate, when dimensions and location of seismogenic segment, degree of coupling or slipping on the plate interface are varied. Solid line (1) is a tilt rate distribution for the initial model (Figure 5). Length(km)/slip(mm/yr) of the first three shallower segments (X1, X2, X3) of the interplate zone are presented in the inset. Arrow indicates the location of the LBT. Up to 0.5 μrad/yr may be expected at the LBT site due to changes in the locked zone geometry and coupling.

help to excavate the trench down to desired depth along the line. It is preferable to choose a surface with a slope of less than 0.06° (1 m per 1 km), but the path does not have to be straight. The bottom of the trench is flattened out horizontally and leveled within ~5 cm along the entire line before putting the pipe in place. In our case the LBT site has the slope of 0.2°, which is less convenient for the installation and needs more work and expenses.

Digging the trench starts at one end and should be continuously controlled for the correct depth. In our situation the control depth referred to the elevation of the highest point

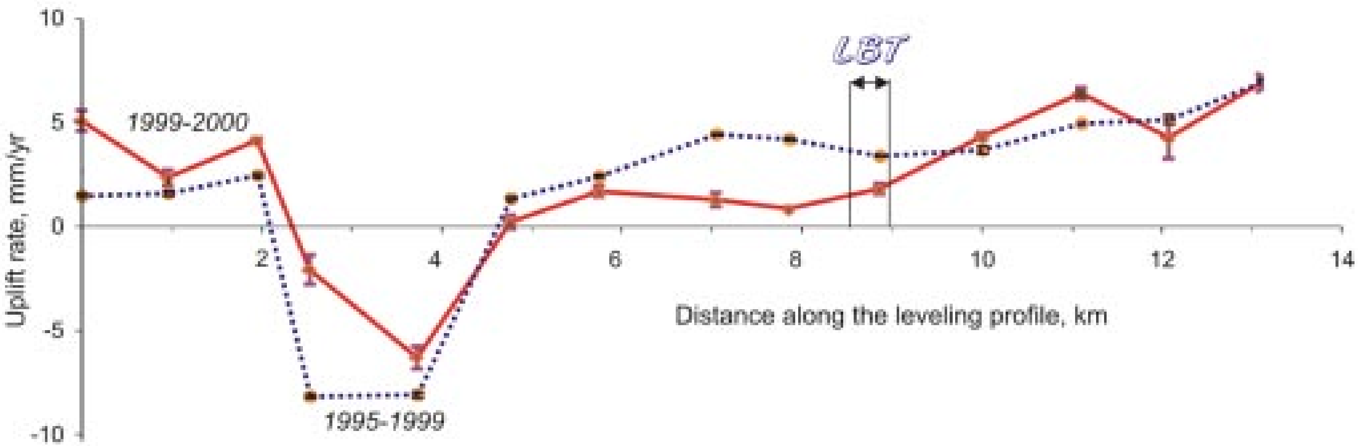


Fig. 8. Uplift rates on the Acapulco leveling line estimated for the periods: 1999-2000 and 1995-2000. At the LBT site, 8.5-9 km along the leveling line, some change in the tilt rate can be noticed. Error bars are 1σ.

of the profile was ~2m. Care should be taken not to overexcavate, particularly when machinery is used. After every ~50 m the pipe segments are placed in position and joined together. The ends of the pipe are protected with caps to prevent dirt from getting in. The top of the pipe is leveled within 2-5 mm. The pipe is left unburied until it is entirely installed, after when it is leveled before burial (Figure 9). A skilled backhoe operator can excavate the trench to the control depth very fast. After that, the depth adjustment and installation of the pipe are easier to do, particularly if the PVC pipe with bell-ended joints is used. If polyethylene pipe is used the welding of the joints requires more effort and time. Polyethylene pipe is more durable (comparing with PVC pipe) but it possesses a large thermal expansion (about 10 cm per 100 m), which complicates the leveling and installation of the pipe.

Before the trench is filled, the power and signal cables should be deployed on the bottom between the vaults. The cables may be slotted in a plastic tube for water protection.

The construction of the vaults depends on the design and material to be used, but in any case it starts with the excavation to the depth of 2-2.5 m. After that a ∅4" boreholes should be drilled at the bottom of vaults down to the depth of the basement rock. For our LBT site this depth is only 6-7 m from the surface, but if there is no shallow rock the borehole should be drilled deeper (10-30 m). A steel or PVC ∅4" pipe should be installed in the borehole. Before the vault construction a ∅3/4" stainless steel, invar or fiberglass rod is positioned inside the borehole pipe and cemented at the bottom of the borehole. The rod should not touch the walls of the borehole and should extent up to the level of the water pipe. The anchoring is very important to eliminate surface noise. If the water table is close to the surface special precautions should be taken to make the borehole waterproof, otherwise the vault will be flooded during the rainy season.

The vaults construction is easier to make from local materials, for example, concrete blocks or bricks. A concrete base of at least 15 cm should be built with a borehole pipe (containing a deep-referenced rod) through it. The vaults may be circular or square with a wall of 2 x 2 m to a height of ~2 m. The seals of the vaults have ~70 cm height entrance pit with a steel lid on top. Figures 9 and 10 show LBT construction and final state. The water pipe needs to protrude ~30 cm into the vaults and has the end caps fixed to it. It was very important on the Pacific coast of Mexico to make the vaults waterproof, and to install automatic water pumps in the vaults for flood emergencies. Figure 11 shows the transducer installation inside the vaults.

The water pipe needs about 8000 liters of water to half fill it. The water must be at half level of the diameter of the pipe. A standard T-shape polyethylene joint installed in the mid-point of the 518 m pipe is used to pour the water and to control the level.

The floats are designed to shed water droplets and air bubbles (Figure 4). They are made of glass and gold-plated stainless steel, with stainless-steel flexure pivots to maintain their axial position. The water contains "Iodine" to inhibit bacterial growth (most biological activity is small because the pipes are completely sealed and dark), and "Photo flo" to reduce surface tension.

A schematic of electronic equipment used for the LBT is shown in Figure 12. The transducers are LVDT (Linear

Fig. 9. Installation of the LBT. A – Polyethylene ∅8” pipe and the southern vault. B – Trench near the midpoint. The trench was accurately excavated and its bottom flattened using leveling control before pipe installation. C – Northern vault.

Fig. 10. LBT after installation. Left, southern vault. Right, northern vault with a benchmark in foreground and the highway tollbooth in the background. The vaults and the pipe are covered with at least 1 m topsoil to reduce temperature variation.

Variable Differential Transformer, electronic device that produces an electrical output proportional to the displacement of a separate, moveable magnetic core), series XS-A 253 from Schaevitz™ Sensors (http://www.schaevitz.com/). ATA 2001 signal amplifier is of the same company. Individual calibration of each LVDT and amplifier was accomplished before the installation. The calibration is ~1 mm/v in the linear part of the LVDT response.

Analog signals from the LVDTs, atmospheric pressure sensor, and termistors are digitized using DGH (Dutile, Glines and Higgins Corporation, http://www.dghcorp.com/) D1000

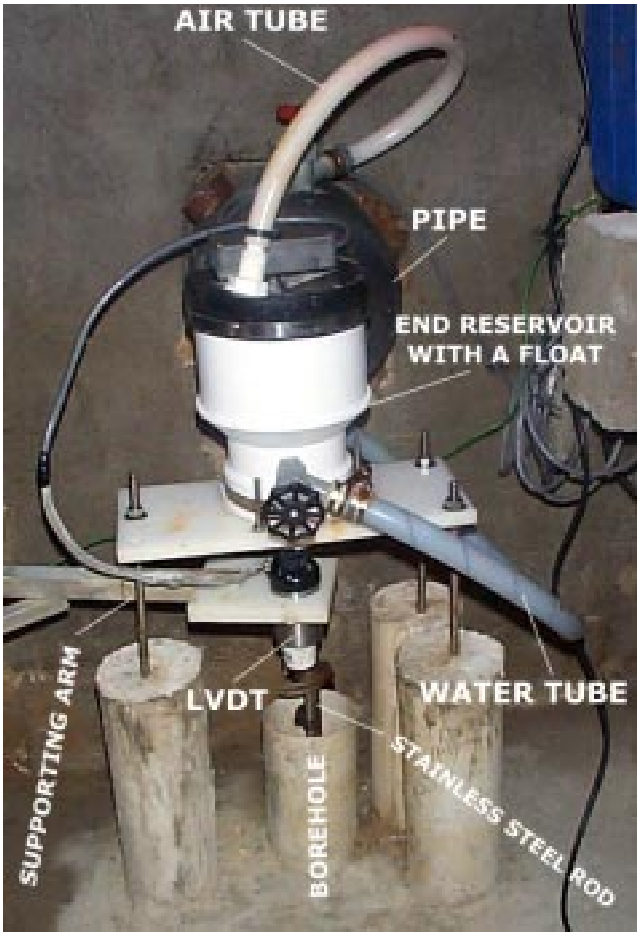


Fig. 11. View inside the southern vault and sensor. See Figure 4 for the reference. The water surface is measured relative to the base of a borehole through the stainless steel rod.

series, 16 bit A-D converters: D1132 series for LVDT and pressure sensors, and D1450 series for temperature sensors (termistors). DGH A1000-115, RS-232/RS-485 Converter/Repeater are appropriate to convert RS-232 communication signal levels to the correct electrical signals required by RS-485. The RS-485 communications standard is recommended when many DGH modules, or other addressable devices, must be connected to a host computer over long distances. The A1000 converter allows communications bus lengths of up to ~1300 m and baud rates up to 115K baud.

A PC installed in the southern vault performs all data acquisition and storage. Tilt, pressure and temperature are recorded once per min. The time is controlled by internal PC clock but in future it will be automatically synchronized by GPS.

DATA PROCESSING AND PRELIMINARY RESULTS

An important property of long-baseline tiltmeters is that the two end sensors record equal and opposite signals only in the presence of pure tilt, rotation of the Earth's surface about a horizontal axis (Bilham *et al.*, 1982). Flexure of the surface causes asymmetry in the signal amplitude. This property can be used to discriminate between locally generated tilt noise and true tilt by analyzing the coherence between signals from each end of the water pipe.

The resulting tilt time series is an absolute sum of records from the two end LBT sensors divided by the dis-

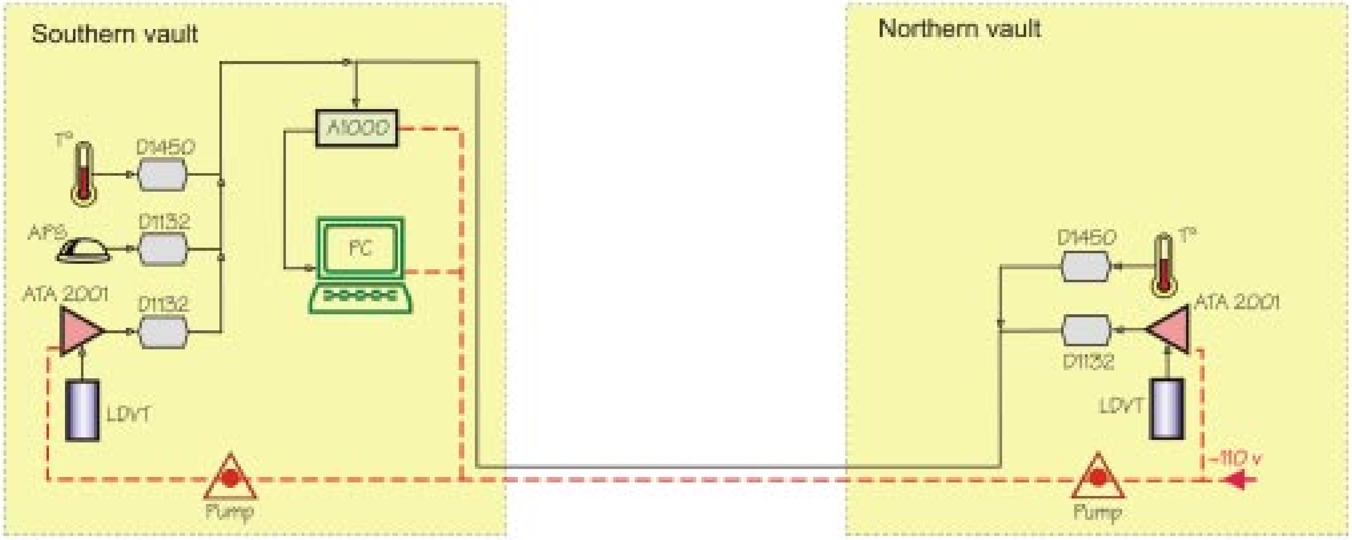


Fig. 12. Schematic of LBT electronic equipment. T° – termistors, APS – atmospheric pressure sensor, LDVT – transducers, PC – computer. Daisy-chained scheme is used to connect all sensors in line to the single communication port of the host PC. See text for other notations.

tance between the two water-depth transducers. The tilt signal contains a small thermal component introduced by temperature variations in and near the water-depth transducers. The tilt record can be corrected for this thermal signal using measured temperature variations. Figure 13A shows the raw tilt calculated as a sum of two end-sensor absolute records divided by the length of the water pipe. The record duration is about 90 days. Short period peaks correspond to the solid Earth tide and ocean tide load tilt effects. The record also contains relatively large and long period tilt variations of up to 2 μrad. Comparing the raw tilt record with the atmospheric pressure record (Figure 13B) one can notice an apparent coherence between these two signals. The coherence is clearer comparing the low pass filtered pressure and tilt records (Figure 13 C and E), or the detided tilt record (Figure 13D) obtained by fitting a simplified tidal model (using TSOFT program of the Royal Observatory of Belgium: http://www.astro.oma.be/SEISMO/TSOFT/ tsoft.html).

A strong correlation between the atmospheric pressure and tilt records is observed with a phase shift of 14.4 hours. The effect of atmospheric pressure loading on the surface crustal displacement is not well determined in geodetic studies. The vertical motion is the largest component of the surface displacement associated with pressure loading. It can cause radial displacement of the Earth's surface of up to 10-25 mm with a temporal variation dominated by periods of approximately 2 weeks (VanDam *et al.,* 1994). These variations of the atmospheric pressure are related with the migration of synoptic scale (of 1000-2000 km) pressure systems. The pressure loading signal is clearly observed on records A-D in Figure 13 during the period of ~2 weeks, approximately from 30-10-00 to 12-11-00. The shorter period (less than 1 week) correlated variations can be noticed too between the pressure and tilt signals. To remove the effect of pressure loading we calculated the admittance (TSOFT program) between the filtered tilt and pressure signals (records D, E accordingly in Figure 13) and applied this admittance function to the pressure signal to estimate the correlated part of the tilt signal. Subtracting this predicted pressure correlated tilt from the tilt signal D (Figure 13) should result in a tilt partially filtered from the atmospheric pressure load effect. Figure 13F shows that the filtering procedures reduce significantly the variations in the tilt signal associated with the tide and pressure effects. The residual tilt signal still contains noticeable variations correlated with the pressure loading but at periods shorter than one week. The LBT data accumulated for the longer period of time should permit us to obtain a more accurate estimate of admittance and to achieve better filtering results.

It is difficult to estimate the tectonic tilt change from the filtered record on Figure 13F. The expected long period tilt variation related with subduction of the Cocos plate is of the order of 1 μrad/yr at the LBT location. The trend value determined from the curve on Figure 13F is smaller than 1 μrad/yr but is not statistically reliable for this length of record.

In future we expect to suppress the tilt-tide signal using predictive filtering with the solid Earth tide and the Acapulco tide-gauge data as input. We anticipate a semidiurnal load tide with mean amplitude of 100 nrad in Acapulco, and non-periodic secular load signal that will vary from 10 to 200 nrad as a result of coastal ocean loading. The latter should present a significant noise source unless it is suppressed using an appropriate admittance function between the tide gauge data and the tiltmeter data.

Ultimately we hope to telemeter LBT, Acapulco GPS and tide gauge data to realize a near real time tilt data processing and to publish the results for further research purposes and public access on a web site.

CONCLUSIONS

The first experimental installation of the LBT in Mexico provides a range of possibile applications to seismotectonic studies in subduction zones. Resolving a lot of technical problems that arose during the deployment of the LBT improved our know-how for future LBT installations in the Pacific coast of Mexico. The results of preliminary LBT data processing show that application of additional filtering procedures using information from the Acapulco tide gauge and from continuous GPS may refine the final tilt estimates to better than ~100 nrad accuracy for long period observations. To study short period (~10-60 min) tilt signals associated with local seismic events it is essential to develop high precision solid tide and ocean tide loading models. Technical upgrading of the LBT should allow real time telemetric acquisition and preliminary data processing with the future endeavor in seismotectonic monitoring.

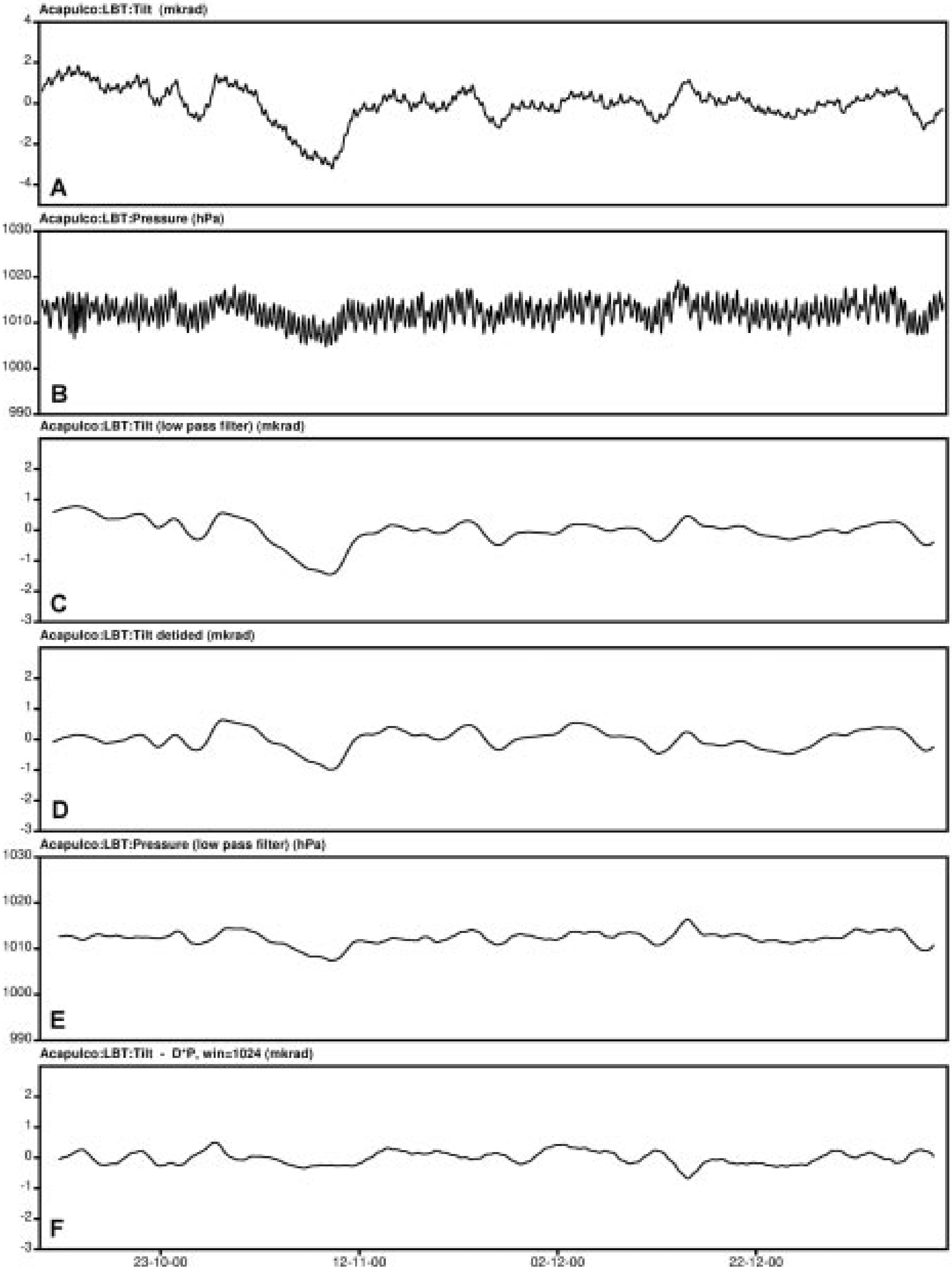


Fig. 13. LBT records and some preliminary data processing results. A–total raw tilt calculated as a sum of two end-sensor absolute records divided by the length of the water pipe. B – raw record of the atmospheric pressure gauge. C–low pass filtered record A. D–detided low pass filtered record A. E–low pass filtered pressure record B. F–residual tide signal calculated by subtracting the pressure tidal load effect from D.

APPENDIX

Technical characteristics of the LBT (Acapulco, Costa Chica, Mexico)

Length	518 m
Pipe	∅8” black polyethylene pipe
Fluid	water (~8000 l)
End Reservoirs	∅30 cm PVC
Floats	∅20 cm glass (light bulb)
Float sensors	Schaevitz large bore ±8 mm range, 0.4 µm resolution
Calibration	1 % nominal
Linearity	1%
Mechanical over-range	80 mm (limited by pipe diameter)
Voltage out	±4 Volts low impedance
Power supply	12 V at 20 mA
Tilt sensitivity	~1 nrad per 500 m
Tilt range	±20 µrad before mechanical reset with zero adjustment ±200 µrad
Telemetry (not installed)	16 bit serial A-D optional for RS232. 30 -300 s filter optional. radio line of sight link optional to 100 km
Above surface access	subsurface power and signal cables (solar panel and telemetry mast can be used).Manhole to enter transducer vault at each end.
Vault construction	2.5 m deep masonry, cement culvert. Manhole access lid 60X60 cm. Top of vault graded above land level to shed rain.
Pipe installation	1-2.5 m deep trench. Excavated by machine being careful not to excavate below horizontal pipe grade. High precision leveling along the pipe (±1-2 mm at the ends).
Borehole installation	PVC lined ∅10 cm hole (water well). Concrete plug into base.

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