GTSM 地殼應變儀分析技術與應用

研習計畫：井下應變儀與水位計聯合觀測(Ⅲ)
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目錄

一、 前言

地殼應變儀有極精密之解析能力(可感測 10^{-9}~10^{-12} 之微細應變)，頻寬涵蓋 DC~200Hz，恰可填補地震儀與 CGPS 觀測之死角。若能將其埋入地下深處，既可有效降低干擾雜訊，又可緊密接觸地下厚實且未經風化之堅硬岩盤，確實為進行地震前兆觀測之理想工具。井下型應變儀可分為「體應變儀(volumetric strainmeter 或 dilatometer)」及「三分量應變儀(three components 或 tensor strainmeter)」。後者藉由互相間隔 120 度之三具感測元件，除了可感測相當於體應變之面應變（areal strain）外，尚可感測到地殼剪應變。由美國加州長期之地震觀測資料顯示，有些斷層蠕動(creeping)不會觸發體應變儀及水壓計（piezometer）反應，卻會在三分量應變儀留下明確訊號（Gwyther et al., 1996）。再者因為剪應變具有方向性，將有助於判斷此應變異常較有可能是因哪一條斷層之活動所引起的。

地震與地殼應變關係密不可分。地殼應變已知分布於板塊邊界及其附近，故 PBO-T 計畫之核心即是以慎密規劃的 GPS 觀測網搭配井下應變儀觀測網及原已佈建完整之地震網來觀測板塊邊界之變形。地質調查所繼九十二年十一月分別於曾文水庫管理園區(曾文水庫南站, RST-)、烏埔山區(曾文水庫北站, RNT-)、及甲仙 (十八灣站, ECT-)完成三處 GTSM 三分量井下應變儀觀測站設置之後，又於九十四年六月上旬完成竹東地區大坪國小站 (DPMT)、梅花國小站（PFMT）及瑞峰國小站（LMMT）等三處 GTSM 觀測站。由儀器記錄之資料明顯可見地潮及膨脹性水泥熱應力訊號，表示新建三站之應變儀也已正常運作。應變儀一般於安裝成功開始運轉後需時三年才能達穩定狀態。第一年前半年觀測資料會明顯呈現指數衰減之水泥漿固熱應變訊號。此外，地層因鑽井擾動的應力狀態亦須要兩、三年才能恢復。

由於地震儀及 GPS 技術均已成熟且已商業化，相對擁有較多之研究人員與研究資源。但井下型應變儀製造與分析技術現今仍侷限在美國、澳洲及日本少數幾個研究單位內，研究人員與研究資源均不易獲得。故積極引進資料處理與分析之完整技術能力應是本計畫之最重要目標。再者，自 2004 至 2008 年，北美板塊邊界觀測計畫(PBO)預計安裝 174 具 GTSM 三分量井下應變儀，其對觀測地殼應變週期、採樣頻率、檔案結構、檔案保存、資料存取等皆有完整的規劃，足供吾人參考。最後，2004 年 9 月 28 日比預期晚了 12 年規模達 6.0 的地震，終於現身美國加州 Parkfield 小鎮。參與此項有史以來全世界規劃最完備、地點最恰當、研究資源最豐沛之地震預測實驗計畫的學者專家，已承認無論是地震預測或是可靠的地震前兆，以目前的地震理論尚難有突破性的成果。他山之石，可以攻錯。美國爾後地震研究之方向可能會有何種調整，值得吾人持續觀察與借鏡。

二、訪問目的

本參訪之目的有以下三點：

(1) 引進三分量井下型應變儀觀測資料處理、分析、解釋之技術與能力。

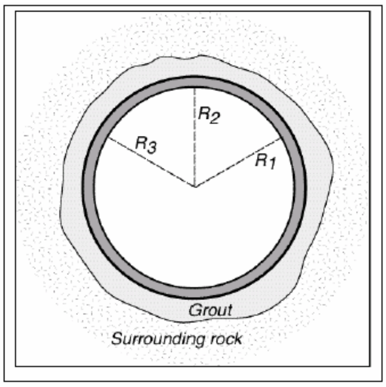
(2) 釐清 PBO 有關 GTSM 資料採樣頻率、檔案結構、檔案保存、資料

存取之方式。

(3) 探討 Parkfield 地震預測實驗失敗之後，地殼應變觀測研究之方向。

三、資料處理分析

GTSM(Gladwin Tensor Strain Meter)經由垂直疊置的三個應變感測元件，感測軸 R1，R2 及 R3 分別旋轉相隔 120 度(或 60 度)如圖一。



圖一：井下型應變儀三個感測元件以互相旋轉 120°疊置

在地表或接近地表，垂直應力可視為零，故可用 plane stress 來描述水平面上發生的 strain。在直角座標系，令 u 為 x 方向上之位移，v 為 y 方向上之位移，則應變張量由 6 個元素減少為 3 個，即

$$\varepsilon_{xx} = \frac{\partial_u}{\partial_x}; \quad \varepsilon_{yy} = \frac{\partial_v}{\partial_y}; \quad \varepsilon_{xy} = \varepsilon_{yx} = \frac{1}{2}\left(\frac{\partial_u}{\partial_x} + \frac{\partial_v}{\partial_y}\right) \qquad \cdots\cdots(1)$$

依慣例，應變收縮（contraction）為負號，伸張（extension）為正號。

在一固體內以 x 方向反時針旋轉 θ 角度上之伸長量(elongation)，e，

$$e(\theta) = \varepsilon_{xx}\cos^2\theta + \varepsilon_{yy}\sin^2\theta + 2\varepsilon_{xy}\cos\theta\sin\theta$$

或

$$e(\theta) = \frac{1}{2}(\varepsilon_{xx} + \varepsilon_{yy}) + \frac{1}{2}(\varepsilon_{xx} - \varepsilon_{yy})\cos 2\theta + \varepsilon_{xy}\sin 2\theta \qquad \cdots\cdots(2)$$

即吾人可以 ε_{xx}，ε_{yy}及 ε_{xy}線性組合成任意 θ 角度之伸張量。此即 GTSM 可利用平面上 θ 量得之任意三個互相獨立的伸張量，即可決定該點之應變張量。若應變張量已知，則與 x 軸交角為 θ (反時針)之任意垂直面上之剪應變為

$$\gamma(\theta) = (\varepsilon_{yy} - \varepsilon_{xx})\sin 2\theta + 2\varepsilon_{xy}\cos 2\theta \qquad \cdots\cdots(3)$$

工程分析上習慣定義下列三量：

$$\varepsilon_a = \varepsilon_{xx} + \varepsilon_{yy}$$
$$\gamma_1 = \varepsilon_{xx} - \varepsilon_{yy} \qquad \cdots\cdots(4)$$
$$\gamma_2 = 2\varepsilon_{xy}$$

式（2）可改寫成：

$$e(\theta) = \frac{1}{2}\varepsilon_a + \frac{1}{2}\gamma_1\cos 2\theta + \frac{1}{2}\gamma_2\sin 2\theta \qquad \cdots\cdots(5)$$

或以矩陣方式表示為：

$$\begin{bmatrix} e_1 \\ e_2 \\ e_3 \end{bmatrix} = \begin{bmatrix} \frac{1}{2} & \frac{1}{2}\cos 2\theta_1 & \frac{1}{2}\sin 2\theta_1 \\ \frac{1}{2} & \frac{1}{2}\cos 2\theta_2 & \frac{1}{2}\sin 2\theta_2 \\ \frac{1}{2} & \frac{1}{2}\cos 2\theta_3 & \frac{1}{2}\sin 2\theta_3 \end{bmatrix} \begin{bmatrix} \varepsilon_a \\ \gamma_1 \\ \gamma_2 \end{bmatrix} \qquad \cdots\cdots\cdots\cdots (6)$$

上式說明了應變儀內某一個特定方向之變形量可由 ε_a，γ_1 及 γ_2 線性組合而成。反之，吾人只要將上式逆推，即可由應變儀三個互成 60°之感測軸應變量求得 ε_a，γ_1 及 γ_2。

若要 u_1，u_2 及 u_3 分別為應變儀三個感測器量得的位移量，則下式為完整的關係式，其中包括各項必須之修正量：

$$\begin{bmatrix} u_1 \\ u_2 \\ u_3 \end{bmatrix} = \begin{bmatrix} 1/g_1 & 0 & 0 \\ 0 & 1/g_2 & 0 \\ 0 & 0 & 1/g_3 \end{bmatrix} \begin{bmatrix} \frac{1}{2} & \frac{1}{2}\cos 2\theta_1 & \frac{1}{2}\sin 2\theta_1 \\ \frac{1}{2} & \frac{1}{2}\cos 2\theta_2 & \frac{1}{2}\sin 2\theta_2 \\ \frac{1}{2} & \frac{1}{2}\cos 2\theta_3 & \frac{1}{2}\sin 2\theta_3 \end{bmatrix} \begin{bmatrix} c & 0 & 0 \\ 0 & d & 0 \\ 0 & 0 & d \end{bmatrix} \begin{bmatrix} t_{11} & t_{12} & t_{13} \\ t_{21} & t_{22} & t_{23} \\ t_{31} & t_{32} & t_{33} \end{bmatrix} \begin{bmatrix} \varepsilon_a \\ \gamma_1 \\ \gamma_2 \end{bmatrix}$$

$$\cdots\cdots\cdots\cdots (7a)$$

或表示為 U = M × G × H × T × S ……………………………………(7b)

其中，U 為應變儀變形向量，

M 為三個感應器之機械差異性矩陣，

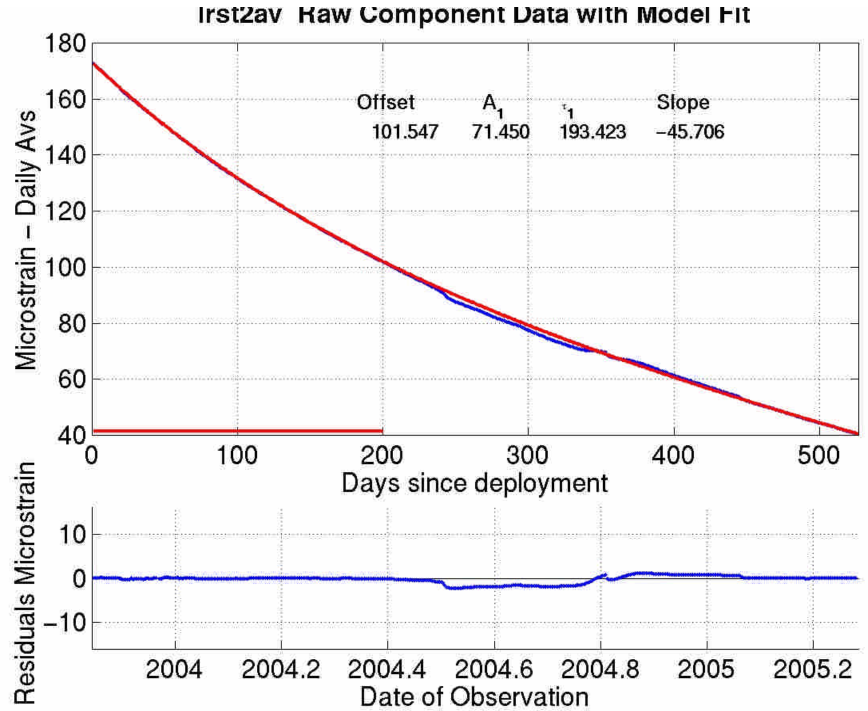
G 為三個感應器安置之方向性矩陣，

H 為面應變與剪應變藕合因子矩陣，

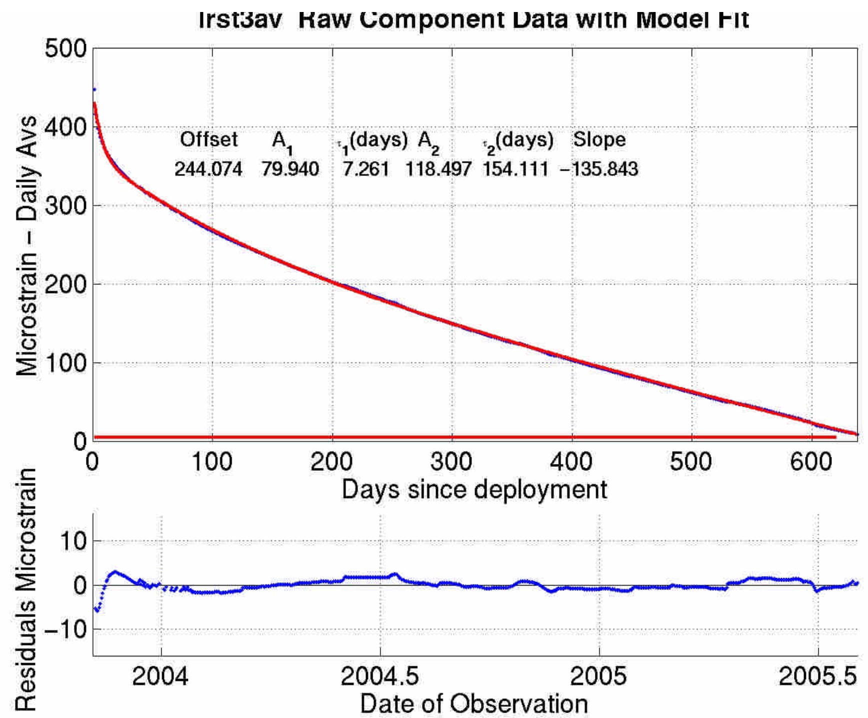
T 為地形與地質影響矩陣，

S 為觀測井所在位置之應變狀態，正是吾人觀測之主要目標。

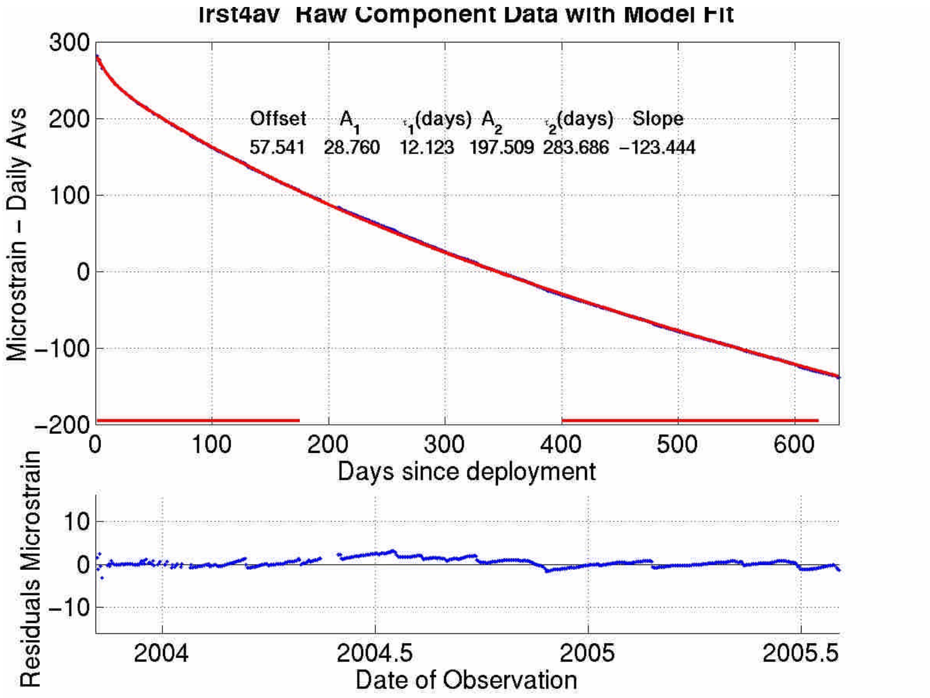
至九十四年七月曾文水庫地區三站之連續觀測資料已進行編輯處理與分析，顯示每站四個應變感應器皆能依其擺置方位正確記錄應變橢圓之伸縮變形。大多數感應器觀測資料顯示影響趨勢有兩個指數函數及一個線性函數，少數則僅受一個指數函數及一個線性函數之影響(圖二~四)。



圖二 ： 曾文水庫南站(RST)channel_2 應變紀錄,紅色為模式。



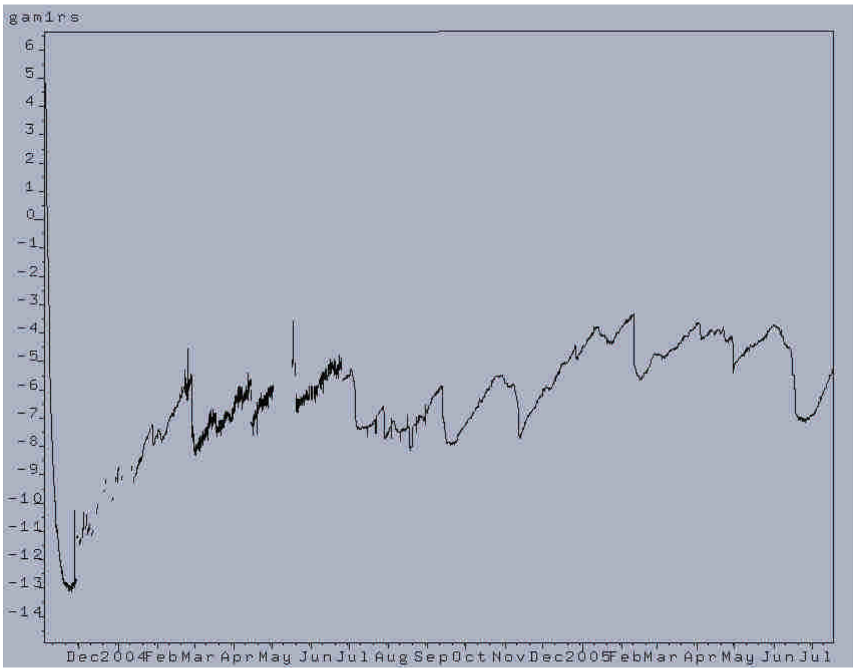
圖三 ： 曾文水庫南站(RST)channel_3 應變紀錄,紅色為模式。



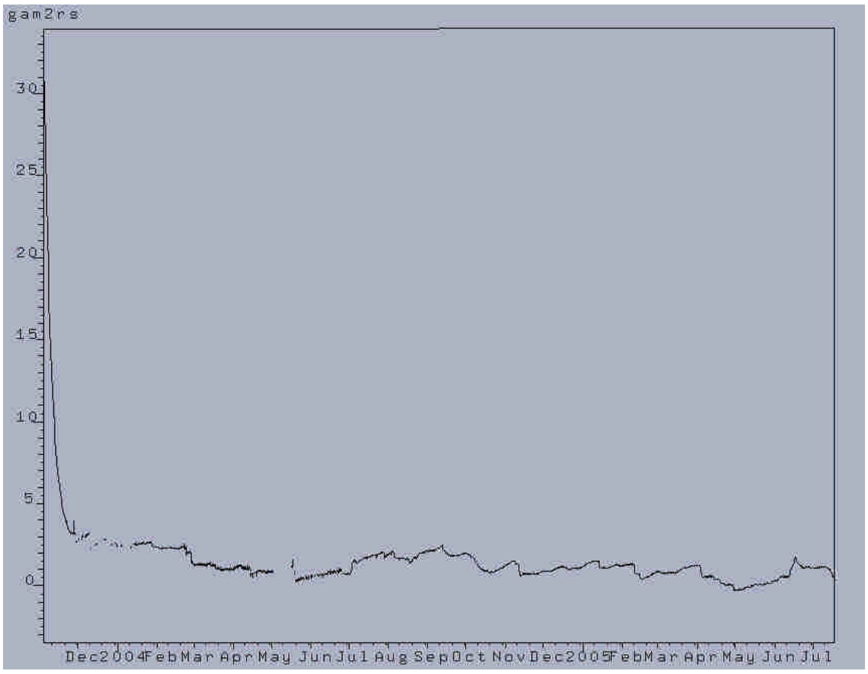
圖四 ： 曾文水庫南站(RST)channel_4 應變紀錄,紅色為模式。

本研究將原始資料與長期趨勢預測模式相減即得殘餘值，並據此合成面應變與兩個剪應變(圖五~七)。然而在資料完全穩定之前，無論是趨勢預測或是應變張量計算皆可能出現相當誤差，必須謹慎比對。

圖五 ： 曾文水庫南站(RST)合成之面應變(areal strain)。



圖六 ： 曾文水庫南站(RST)合成之剪應變(shear strain, gamma_1)。



圖七 ： 曾文水庫南站(RST)合成之剪應變(shear strain, gamma_2)。

由於井下應變儀觀測會受地潮、氣壓及雨量等影響。若觀測站非深處內陸則又必須考慮海潮之影響。BAYTAP-G 是進行觀測資料分析的一種常用軟體，它可將觀測資料分解成地潮分量、氣壓分量、趨勢項及不規則雜訊。雨量因為屬非線性影響，必須單獨分析。GOTIC2 則是另一項分析軟體，它可處理海潮之影響，但必須搭配有觀測站地區之海底地形與陸上地形資料。

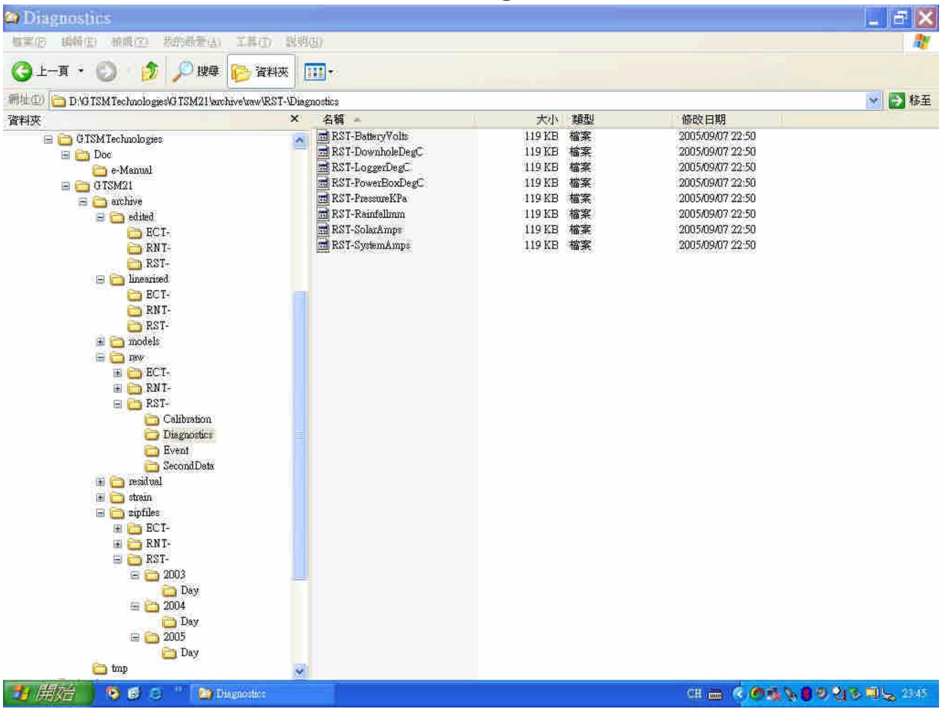
應變儀觀測資料預計需時三年才能達穩定狀態。第一年前半年觀測資料會明顯有呈指數衰減之水泥漿固放熱之熱應變訊號。此外，地層因鑽井擾動

的應力狀態亦須要兩、三年才能恢復。設若觀測資料訊雜比(S/N)足夠高，則前述兩項效應皆可除去。之後，利用地潮響應(earth tide response)來校正儀器，以獲得藕合因子及機械差異性因子。再將僅考慮此兩項修正量的觀測資料利用 BAYTAP-G 及 GOTIC2 分析以萃取出來自地體構造運動引起的應變訊號。當然，地形與地質、地下水位變動、及非線性降雨量等效應修正，均是影響地殼應變儀觀測斷層活動性成果品質之重要因素。

目前 GTSM 應變儀資料處理與分析之完整程式必須於 SUN Solaries 環境下執行。此外，GTSM Technologies 公司又發展了一套用於 Wintel(Windows + Intel) 環境之套裝軟體 Winxqp，但功能尚未完備，其一般性介紹見附錄一。

四、採樣頻率、檔案結構、檔案保存與資料存取

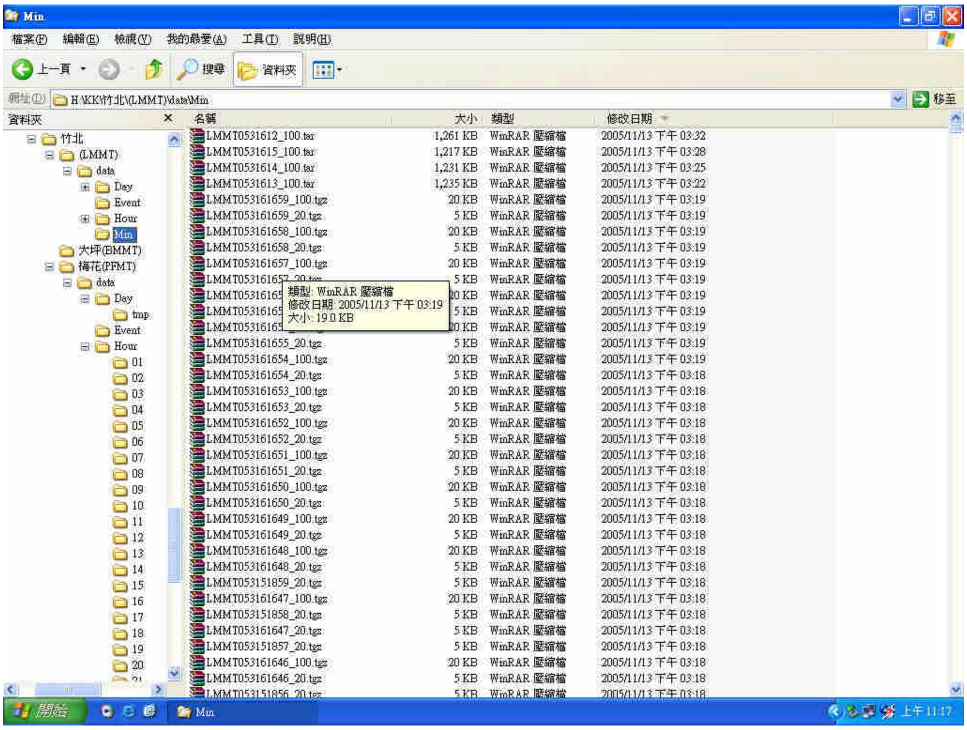
曾文水庫地區三站 GTSM 應變儀於 2003 年 10 月安裝後，即以每秒一筆（1Hz）之方式紀錄現地觀測資料，各頻道每一小時將所有資料打成一包存於資料記錄儀之/Hour/dd/hh 目錄下（dd=01~30 或 31；hh=00~23），每站共有 4 個頻道，故一天即有 96 個 1Hz 之應變觀測資料檔。隔日中午 12:00 整又將前一日 1Hz 資料轉換成 10 分鐘一筆之資料，另存一檔置於/Day 目錄下。若有地震發生則自動啓動高頻紀錄(100Hz)置於/Event 目錄下。此外，尚有一些環境監測資料如雨量、氣壓、觀測小屋(FRP)內溫度、井底溫度、蓄電池供電能力等及自我偵測與校正紀錄，則分別置於/Calibration 及/Diagnostics 目錄（圖八）。



圖八：GTSM 應變儀觀測資料檔案架構

2004 年 GTSM Technologies 公司爲配合美國 PBO 計畫要求，將高頻資料（20Hz 及 100Hz）由事件啓動改爲連續紀錄，這會增加許多儲存空間，故 100Hz 資料僅於現地保存兩小時，若不能即時下載，兩小時後即自動刪除；20Hz 資料則於現地保存兩週才刪除。兩種高頻資料均以小時爲單位存成一檔置於/Min 目錄下。檔案命名原則分別爲 xxxxyydddhhmm_20.tgz 及 xxxxyydddhhmm_100.tgz，其中 xxxx 爲 4 字元觀測站代號（如瑞峰站爲 LMMT）；yy 爲西元年份後兩位數

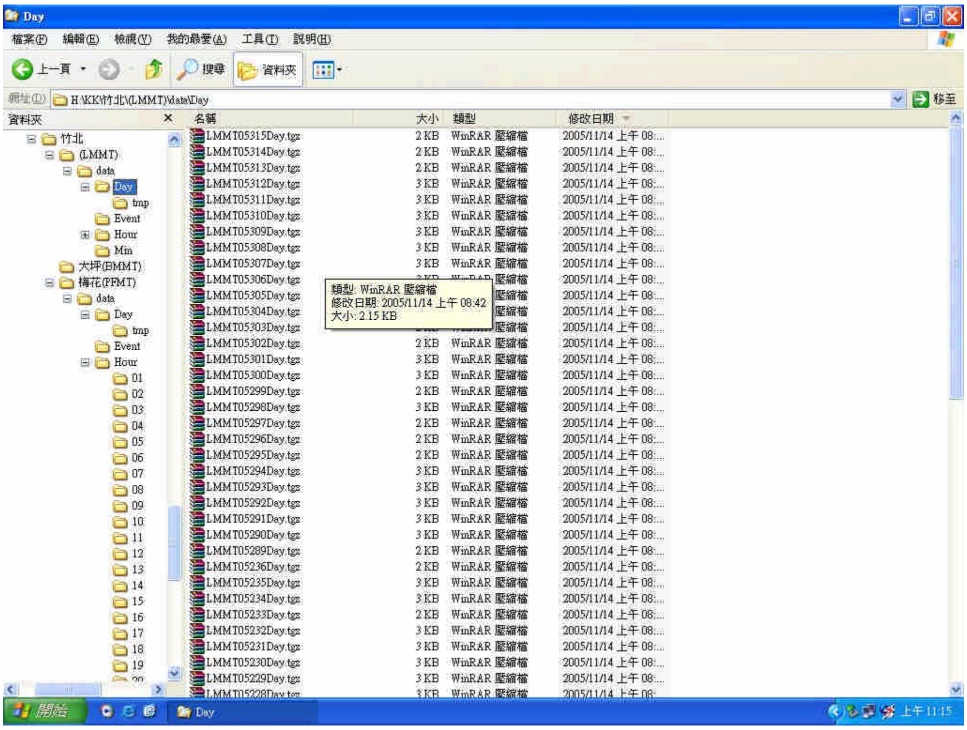
（如 2005 年爲 05）；ddd 爲儒略日（Julian day，如 2005 年 11 月 12 日爲當年度第 316 日）；hhmm 爲當時之時間（圖九）。



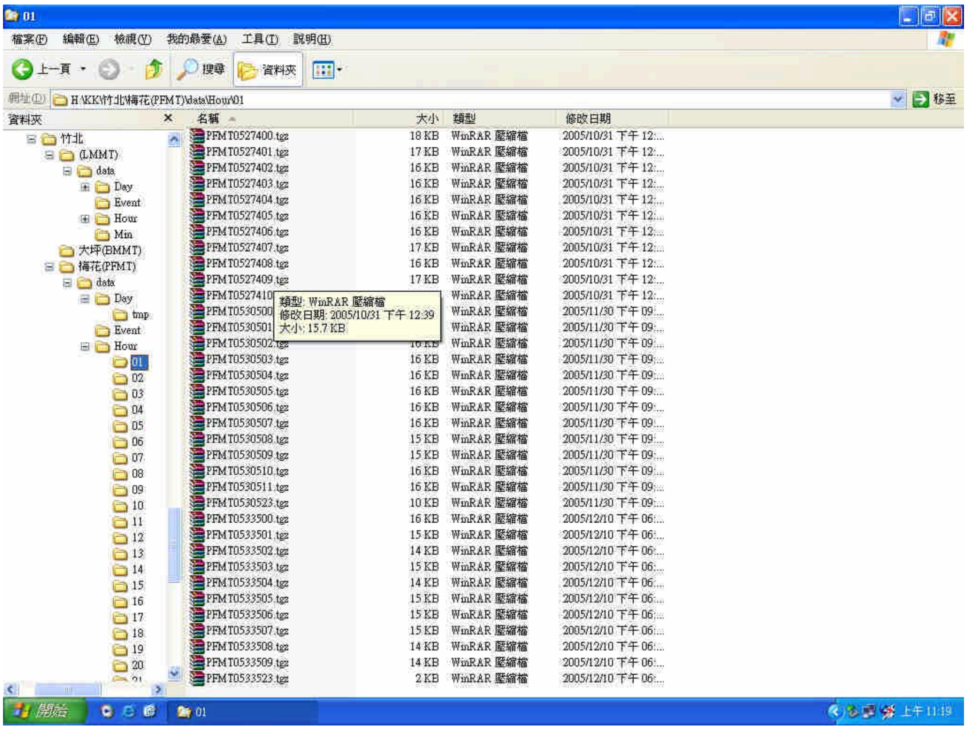
圖九：GTSM 應變儀觀測資料檔案架構

至於 1Hz 及 10 分鐘一筆之資料檔儲存架構則大致未改變。檔案命名原則 10 分鐘資料爲 xxxxyydddDay，一天之資料全部壓縮成一個檔（圖十）；1Hz 資料爲 xxxxyydddhh，一天共有 24 個檔置於/Hour/dd（dd：01~30 或 31，如 11 月 01 日與 12 月 01 日都會存在/Hour/01 目錄下）（圖十一）。

現地資料經由 Winxqp 以 ADSL 或電話撥接方式下載回地調所。一般地殼應變分析僅以 10 分鐘資料爲素材；1Hz 及更高頻之資料基本上用於地震事件研究。將下載之十分鐘資料檔（檔名爲 xxxxyydddDay.tgz）置於/GTSM21/tmp 目錄內，Winxqp 可將其解壓縮並依站名、頻道、及時間精準併合在已下載資料流之後，再儲存於/GTSM21/archive/raw/xxxx/（圖八），而原下載之現地檔則保存在/GTSM21/archive/zipflies/xxxx/yyyy/Day/。已解壓縮之原始資料經過編輯（以去除確定之雜訊）後則存於/GTSM21/archive/edited/xxxx。



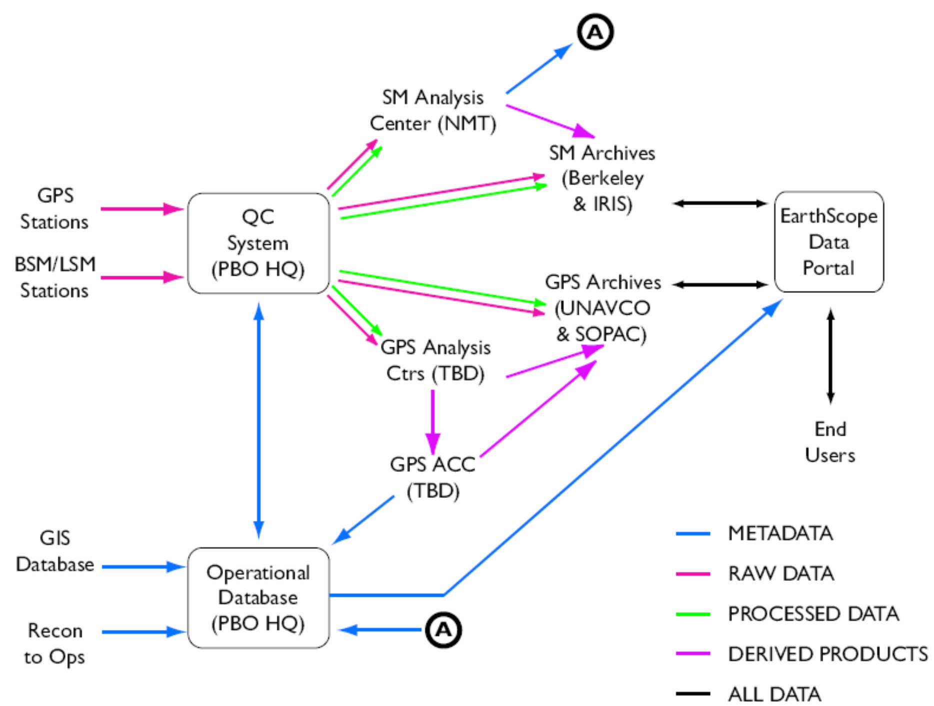
圖十：GTSM 應變儀觀測資料檔案架構



圖十一：GTSM 應變儀觀測資料檔案架構

利用已經過編輯之好資料求此時間序列受到環境影響之趨勢（model）， 如水泥固化熱應變、鑽井擾動之地殼應變恢復等，模式一般包含一個線性函數及一至二個指數函數。將已編輯之資料減去模式資料即可得殘值（residual），再由殘值即可合成一個面應變及兩個剪應變。這些不同分析階段之資料檔即分別儲存於/GTSM21/archive/models/xxxx/、 /GTSM21/archives/residual/xxxx/ 及/GTSM21 /archive/strain/xxxx/各子目錄下。

美國板塊邊界觀測計畫（PBO）預計於 2004 ~2008 期間安裝 875 具 CGPS，174 具井下型三分量應變儀（BSM）及 5 具長基線鐳射應變儀（LSM），以高密度、高精度方式連續觀測北美西部板塊邊界的地殼變形。由於計畫經費都來自公部門，故計畫所產生的所有資料皆採開放方式（Open Data Policy）提供給終端使用者（圖十二）。



圖十二：PBO 應變儀資料處理、分析、與存檔分工圖

現地觀測資料(Level 0)經由各種遙傳（telecommunications）方式傳回 PBO 計畫總部位於科羅拉多州博德市之 UNAVCO 進行快速品質檢驗(QC) 。

經過 QC 的 Level 0 資料立刻傳送給兩處資料分析中心 (SM Analysis Center) ，必須於資料到達後 24 小時內產生 Level 1 資料，其中包括已自動編輯並去除錯誤的原始位移時間序列 $u_1 \sim u_4$ (參見式 7a) ，及其他輔助分析資料檔。

Level 2 資料再分兩階段：第一階段為在兩星期內將 Level 1 資料再經人為仔細除錯並合成出一個面應變及兩個剪應變。第二階段則在三至六個月內提供最終成果。

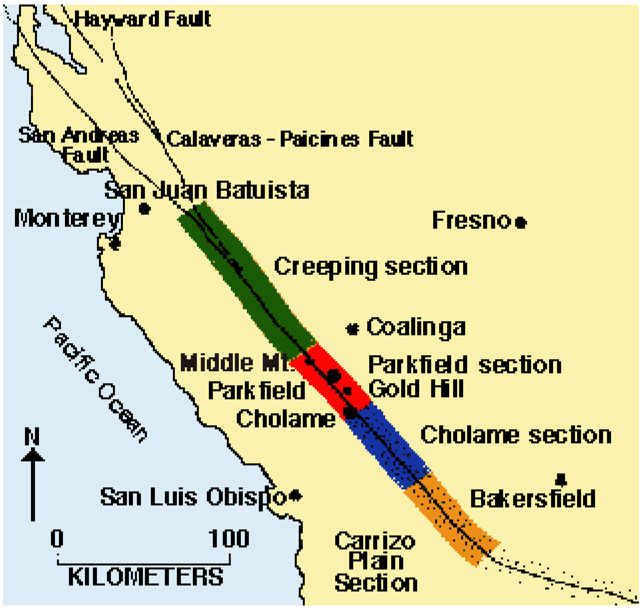
所有階段之資料將由另外兩處檔案中心 (SM Archives Center)存檔並提供資料給終端使用者。有關 PBO 資料管理計畫之詳細內容請參見附錄二。

五、美國加州 Parkfield 地震預測實驗之省思

地震災害至今仍是吾人無法確實預測並防止其造成重大危害之最重要天然災害。自從 1975 年中國大陸成功地對規模達 7.3 級的海城地震提出先期預警，並因而大幅減低居民生命及財產之損失，地震預測研究的可行性即受到地震學者的重視(Deng et al., 1981)。不僅在前蘇聯及中國大陸持續進行廣泛的研究，並因而促使日本(Oki 和 Hiraga, 1988)及美國(Bakun 和 Lindh, 1985)開始有計畫地於特定地區進行地震預測研究。其中堪稱史上最有系統、最多樣儀器佈設、也最密集觀測

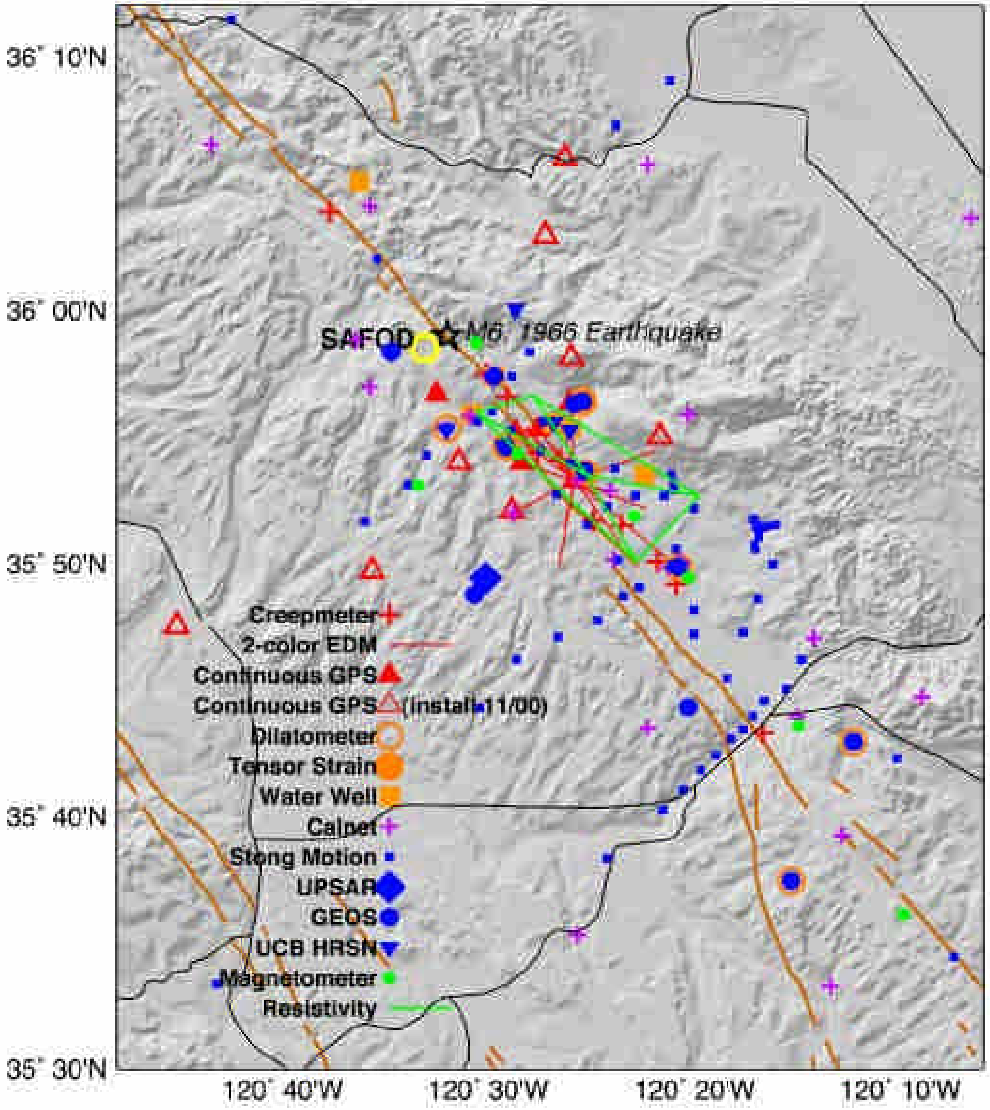
的爲美國加州 Parkfield 地震預測研究計畫。

Parkfield 位於 San Andreas 斷層上，大約介於舊金山與洛杉磯兩城市連線之中點位置(圖十三) 。自 1857 年以來，即相當規律地於 1857、1881、1901、1922、



圖十三：Parkfield 位於 Middle Mt. 及 Gold Hill 這一段(紅色)是以蠕滑(creep)爲主的西北段(綠色)及長時間鎖住(locked)的東南段之過渡帶。1857 發生於東南段 Mw = 7.9 之 Fort Tejon 地震即由 Parkfield 地震所觸發。雖然 2004 事件與 1922、1934、及 1966 三次事件皆符合特徵地震(即重複發生在同一段斷層且規模相近)，但前者震央位於 Gold Hill 往西北方破裂；而後三者震央則位於 Middle Mt. 往東南方破裂。

1934 及 1966 年各發生一次規模達 6 級之地震，故其回復周期（recurrence interval）爲 22 ±3 年。Bakun 和 Lindh 即據此推斷下一個相同規模的地震，將有 95%之可信度會於 1993 年以前發生。美國「國家地震預測評估委員會（National Earthquake Prediction Evaluation Council, NEPEC）」，與「加州地震預測評估委員會（California Earthquake Prediction Evaluation Council, CEPEC）」根據前項結論於 1985 年開展了此項大型地震預測實驗計畫。觀測項目涵蓋了地震、地殼變形、地球化學、地下水位、電磁幅射等 21 項（Roeloffs 和 Langbein，1994）(圖十四&表一)。計畫目標則是要將地震發生過程之各種訊號記錄下來，並且在可能的情況下（即有多項關鍵指標均超過警戒值時），對此期待中規模達 6 級的地震於發生前三天發出預警。



圖十四：Parkfield 地震預測實驗儀器佈設網。

至 1992 年底此預期中的地震並未發生，反倒是在加州 Loma Prieta 及 Landers 各發生一次規模爲 7.1（1989）及 7.4（1992）的大地震。1994 年又於加州 North Ridge 發生規模爲 6.8 之地震。NEPEC 及 CEPEC 兩個委員會已於 1992 年 12 月 31 日宣佈停止於 Parkfield 之地震預測實驗，但是所有的儀器觀測則繼續進行。同樣的挫折也發生於日本。1995 年因野島斷層活動而發生的兵庫縣南部大地震，規模達

表一：Parkfield 地震預測實驗儀器佈設網及其觀測頻率與精度。

TABLE 1a. Prediction Monitoring Networks at Parkfield With Defined Alert/Status Levels as of November 1992

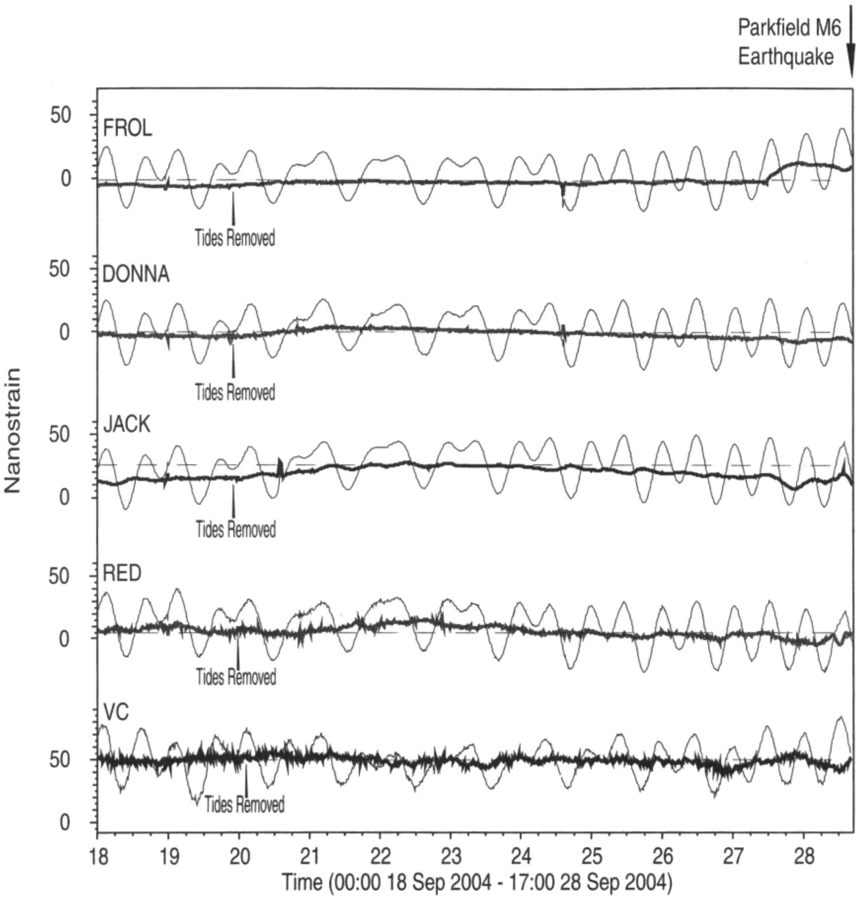
Network	*Number of Sites*	*Sensitivity/ Threshold*	*Measurement Interval*	*References*
Seismicity (USGS Calnet)	40	Magnitude 1.0	continuous	*Nishioka and Michael* [1990]
Continuous strain*	6	10^{-9}	10 min	*Myren and Johnston* [1989]
Magnetic field	7	0.25 nT	10 min	*Mueller et al.* [1994]
Creep meters (Invar wire-LVDT†)	13	0.01 mm	10 min	*Schulz* [1989]
Groundwater level*	10	1 mm	15 min	*Roeloffs et al.* [1989]
Two-color laser geodimeter	18 lines	1 mm	3 times/week	*Langbein et al.* [1990]
Borehole tensor strain;*† University of Queensland, Australia	2	10^{-9}	10 min	*Gladwin et al.* [1987]
Tilt;*† USGS	5	1 μrad	10 min	*Mortensen et al.* [1978]
Groundwater radon;² USGS	2	1 pCi/L	10 min	*Noguchi and Wakita* [1977]
Soil hydrogen;² USGS, Reston	7	10 ppm	10 min	*Sato et al.* [1986]
Borehole microtemperature; USGS	1	10^{-4} °C	12 min	C. Williams (oral communication, 1992)
Resistivity; UC, Riverside	6 dipoles	1%	daily average	*Park* [1991]
80-kHz magnetic field; University of Alaska	1	0.5 μV	6 s	E. Wescott (oral communication, 1992)
0.01- to 10-Hz magnetic field; Stanford University	2	1 pT	30 min, average	*McGill et al.* [1993], *Bernardi et al.* [1991]
Trilateration (4 to 33 km lines); USGS	113 lines	3 mm + 0.2 mm/km	yearly	*King et al.* [1987]
Small-aperture nets (3 to 4 km lines); USGS	4	3–4 mm	yearly	*King et al.* [1987]
GPS; USGS, SIO	4	<1 cm north, east; 1–2 cm vertical	4 times per year	*Prescott et al.* [1989]
Rapid static GPS; JPL, USGS	107	2 mm	yearly	*Hurst et al.* [1992]
Continuous GPS; SIO, JPL, USGS	1	1 cm	continuous	K. Hudnut (oral communication, 1992)
Highway 46 GPS array; USGS, SIO	16	1 cm	2 times per year	K. Hudnut (oral communication, 1992)
Leveling; UC, Santa Barbara	7 lines	1 mm/km	yearly	*Sylvester* [1991]
Creep meters (Invar rod-digital caliper); CIRES	3	0.2 mm	1 min	J. Behr and R. Bilham (oral communication, 1992)
Acoustic emission (30, 60, 170 kHz); IBM, USGS	1	1 μbar	continuous	*Armstrong and Valdes* [1991]
Borehole seismometers; Duke University, LBL, UCB	10	magnitude 0	continuous	*Michelini et al.* [1991]
Vibroseis waveform; LBL, UCB	80 paths, 9 components	5 ms	4–5 times per year	*Karageorgi et al.* [1992]
Vertical seismic array; LBL, UCB, Duke University	1	32 three-component to 1000 m	continuous	*Daley et al.* [1990]
GPS; SIO	2 lines	<1 cm north, east; 1 cm vertical	1–2 times per year	Y. Bock (oral communication, 1992)

TABLE 1c. Instrumentation Designed to Record Rupture Propagation and/or Strong Ground Motion for Engineering Applications

Network and Operator	*Number of Sites or Instruments*	*References*
Dense seismic array; USGS	14 geophones, 14 accelerometers in a 1 km² area	*Fletcher et al.* [1992]
Liquefaction array; EPRI, USGS	5 accelerometers, 7 piezometers, vertical benchmarks	*Holzer et al.* [1988]
EPRI dense accelerograph array; EPRI, CDMG	21 three-component FBA (13 surface, 8 subsurface) within a 120-m radius	*Schneider et al.* [1990]
CDMG strong motion array; CDMG	48 three-component SMA	*McJunkin and Shakal* [1983]
GEOS digital recording (acceleration, velocity, volumetric strain); USGS	13 three-component FBA, 7 geophones, 6 borehole strain meters	*Borcherdt et al.* [1985, 1988]
Fault rupture video camera; USGS	2 cameras	
Coseismic slip meter; CalTech	1	K. Hudnut (oral communication, 1992)
Pipeline experiment; Weidlinger Associates	2 strain-gaged pipeline segments, 8 ductile iron pipes	*Isenberg et al.* [1989, 1991]
Turkey flat strong-motion array; CDMG	six three-component FBA (four surface, two downhole), 2-km linear array	*Real and Tucker* [1988]

7.2，並造成神戶地區 5500 人死亡及超過 2000 億美金之損失。雖然地震發生後有研究証實震央地區地下水中 Cl^-及 SO_4^{-2}兩樣離子濃度於地震發生前 5 個月開始明顯上升（Tsunogai and Wakita, 1995），但是地震還是悄然發生了。於是國際地震研究學者普遍認爲地震是不可預測的(Geller, 1997)，應當將研究經費轉至其它更值得研究之領域。但是也有學者如 Sykes 等（1999），認爲地震發生過程是很複雜的，其中有可預測的、可能可預測的，及不可預測的部分。我們在做預測研究時必須於時間及空間上先將其劃分出來。例如臨震預報（數分鐘）及短期預報（數小時～數星期）因牽涉有太多非線性因子，故基本上是不可能達到的。但是對於調查非常清楚且非常活躍的斷層段(segment)，則中期（數月～10 年）及長期預報（10 年～30 年）是可行的。

Scholz(1997)認爲預測地震之步驟爲第一步：佈署前兆監測儀器在可能發生地震的地區。第二步：偵測和認識這些前兆。第三步：召集所有的同事去同意，然後通過贊同的管道，公開的預測地震。依此原則，Bakun 等推動並執行的 Parkfield 地震預測實驗已確定符合第一步，因爲全世界有史以來僅有此處已發現有一連串特徵地震近乎規則地重複出現在同一段斷層。期待中的地震終於在 2004 年 9 月 28 日現身，然而，除了應變儀有偵測到可能爲前兆的非常微小($< 10^{-8}$)應變異常，



圖十五：Parkfield 地震前 24 小時出現之可疑應變前兆(Langbein et al.,2005)

其他各種觀測儀器皆無反應(Bakun et al., 2005; Langbein et al., 2005)。以地震預測四要素(地點、規模、時間、及機率)而言，Bakun 等僅答對了前兩項。而以預測地震之第二步：偵測和認識這些前兆而言，Bakun 等宣布此項實驗是失敗的，但

認爲也累積了極多寶貴的科學資料有助於吾人更了解地震發生機制，並建議爾後研究應加強對地震震度分布之預測。

本次參訪對象 Prof. Michael Gladwin 認爲地震預測本質上就是非常困難的，一來是地震發生機制仍然幽微而難明；二來是地震前兆可能量級都很小，故有必要將儀器做的更精細、更耐用、安裝更深入地殼。最重要的是，我們必須對活動性大的斷層進行觀測，以更進一步瞭解地震發生之過程及機制。就像當初大陸漂移及板塊運動之理論確定也是在足夠支持它存在的資料長期累積之後才完成的。所以，吾人也不能排除在地震發生之物理及化學機制充份瞭解後，至少某些型式的地震是有可能可以預測的。

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附錄一 ：**WINXQP**

A direct access plotting and data selection tool for PBO

GTSM has an in house GUI based tool developed for front end presentation and visual evaluation of field data. It takes as input the raw field data structures which are reported in the full UNAVCO archive and give reasonable access to raw and process data.
The tool incorporates the bottle structures of the raw field data and is suitable for accumulation of full or partial data bases.

Main features of interest are:

- Direct presentation and comparison of up to four different GTSM data sets
  - o raw sensor data at a site at any sampled frequencies,
  - o intercomparison of sites across the array
  - o station diagnostics,
  - o derivation of strain using default calibrations or user defined sensor calibrations if available.
- Full time scale zoom and pan capabilities with all sensors displayed to the same timescale and to appropriate scales.
- Direct presentation of actual data values
- Removal of predetermined exponential borehole models so that residuals of interest can be directly compared over long or short time scales
- A Merge tool which allows concatenation of new raw data sets onto old data archives
- Print screen capabilities either direct or via jpg file outputs
- Export of screen selected data sets into csv files for independent analysis

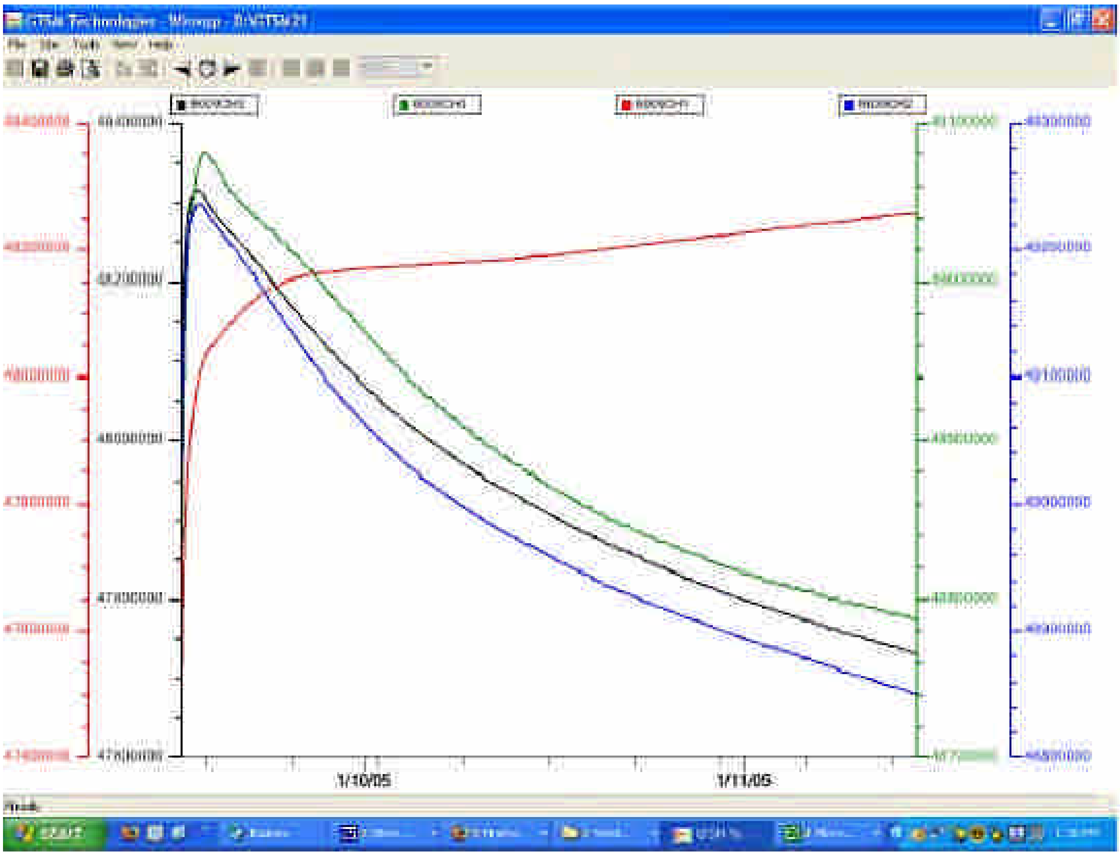
Expressions of interest for us to provide this tool for more general use would be appreciated. It is a very valuable complementary tool for access to the PBO data archive.

The major functions within the program can be seen from the normal view toolbar are consistent with intuitive windows applications. The tool bar adjusts to the task in hand. Icons control file open functions, save, print (direct or to jpg) , merging, pan window time interval, derivation of models, production of residuals from predetermined exponential coefficients stored in an xml style control file, and production of strains for any time interval. Stations are selected from a drop down menu.

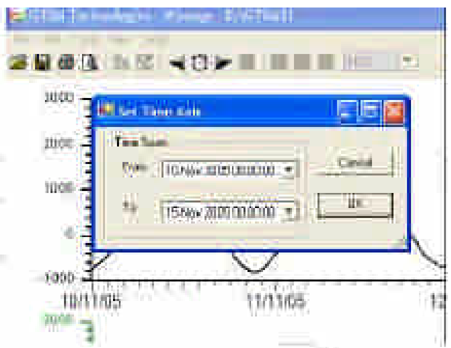
Example of Outputs

A typical point of entry to the data sets for a site is a full plot of the raw data files for each of the four raw sensors. The base screen is shown below. Each of the channels is automatically assigned a screen color and the file names and color code s of the data are presented in a live legend.

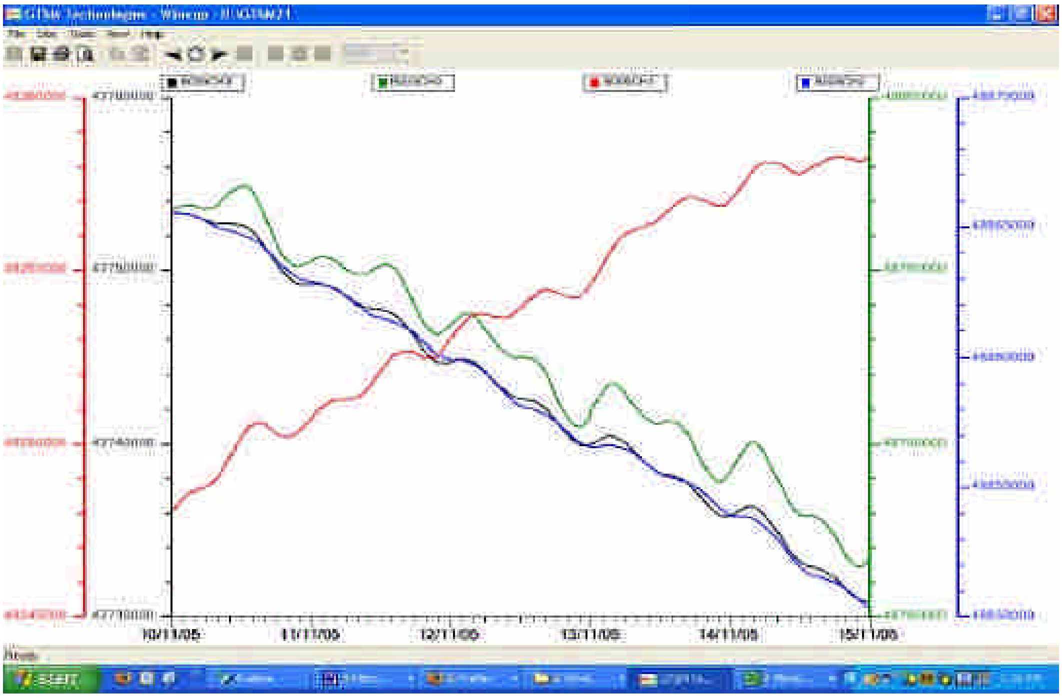
The y scales are initially optimized for visibility, but can be "normalized" to give equal scale ranges for all associated variables. This particular example shows a five month interval following installation with the grout cure and borehole recovery exponentials.



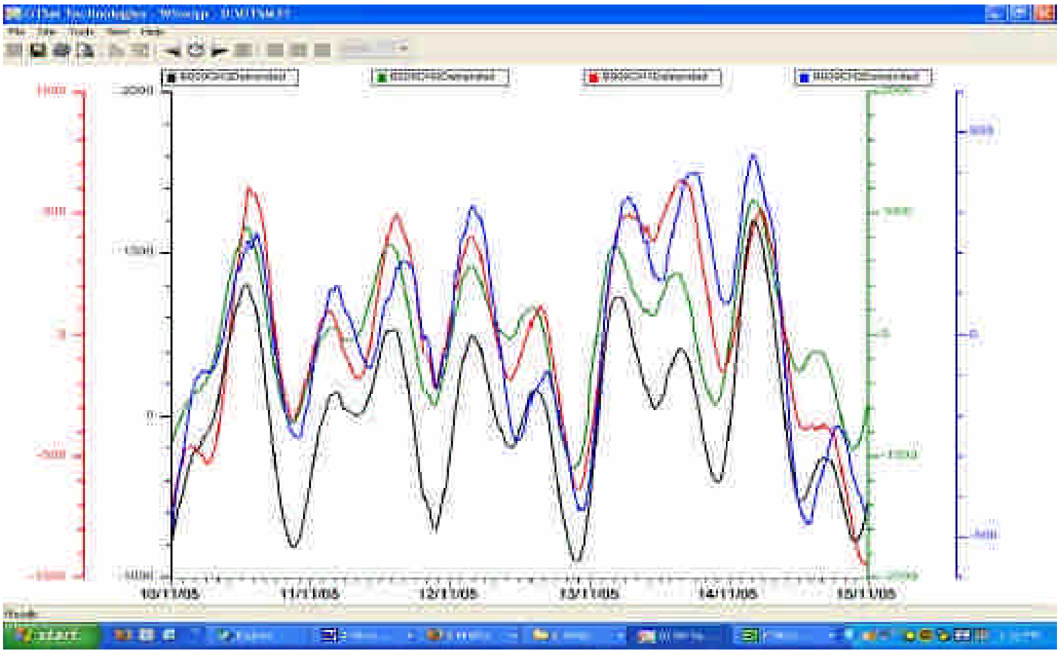
Raw data may be zoomed to any particular time interval to provide smaller time window views



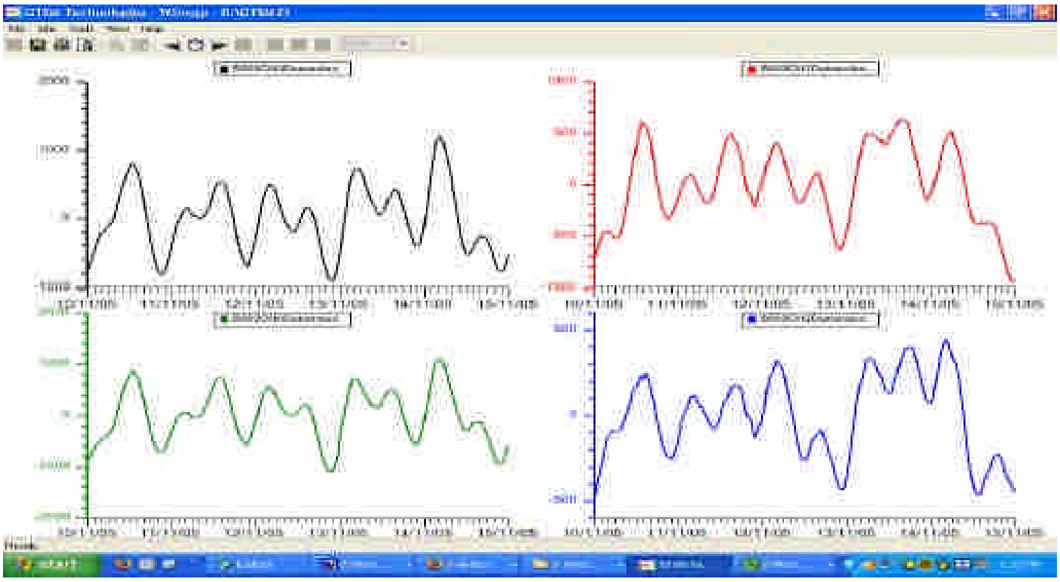
witch can then be displayed.



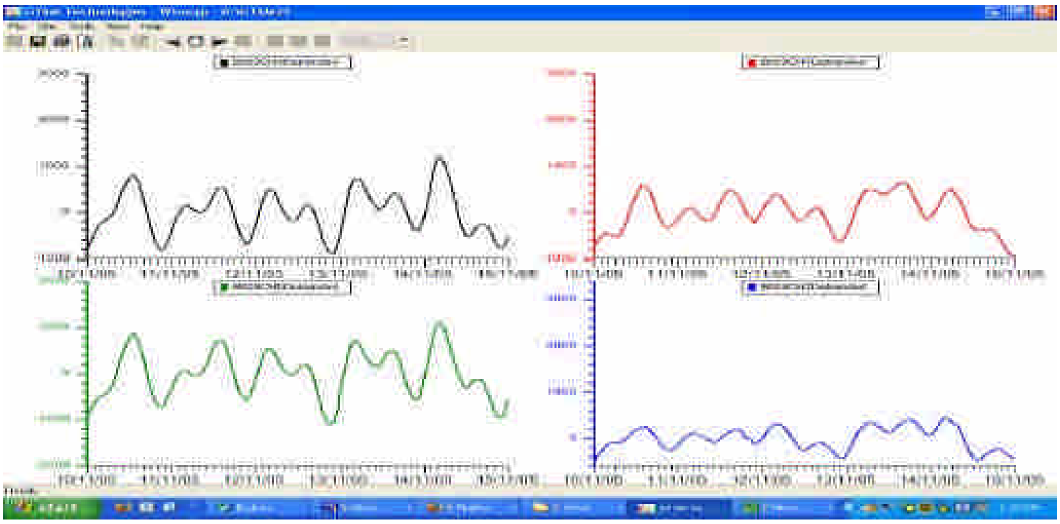
These raw data are contaminated by the borehole recovery effects, and the data can be better examined if the local linear trend is removed. The linear detrend tool allows removal of a linear trend across an arbitrary interval to produce images like the following. Full and proper removal of multiple long term exponential/linear trends is also supported.



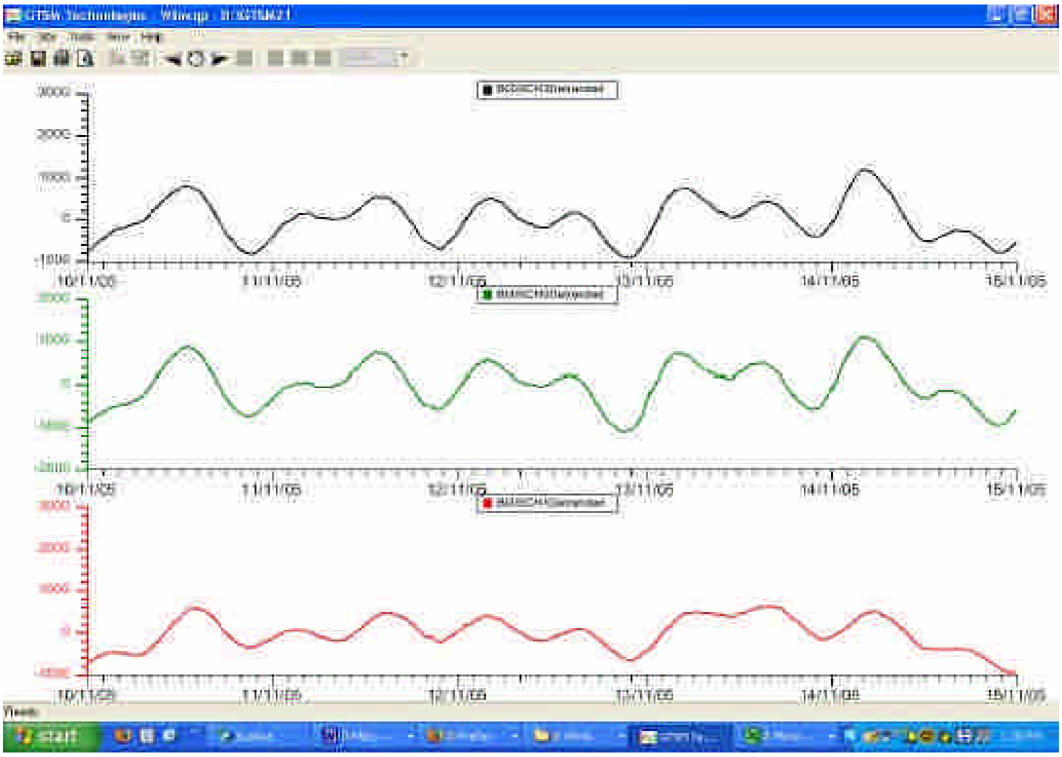
The data sets can be presented in two ways, as over-plotted for timing comparisons or as "tiles" for clear view of individual bottles.



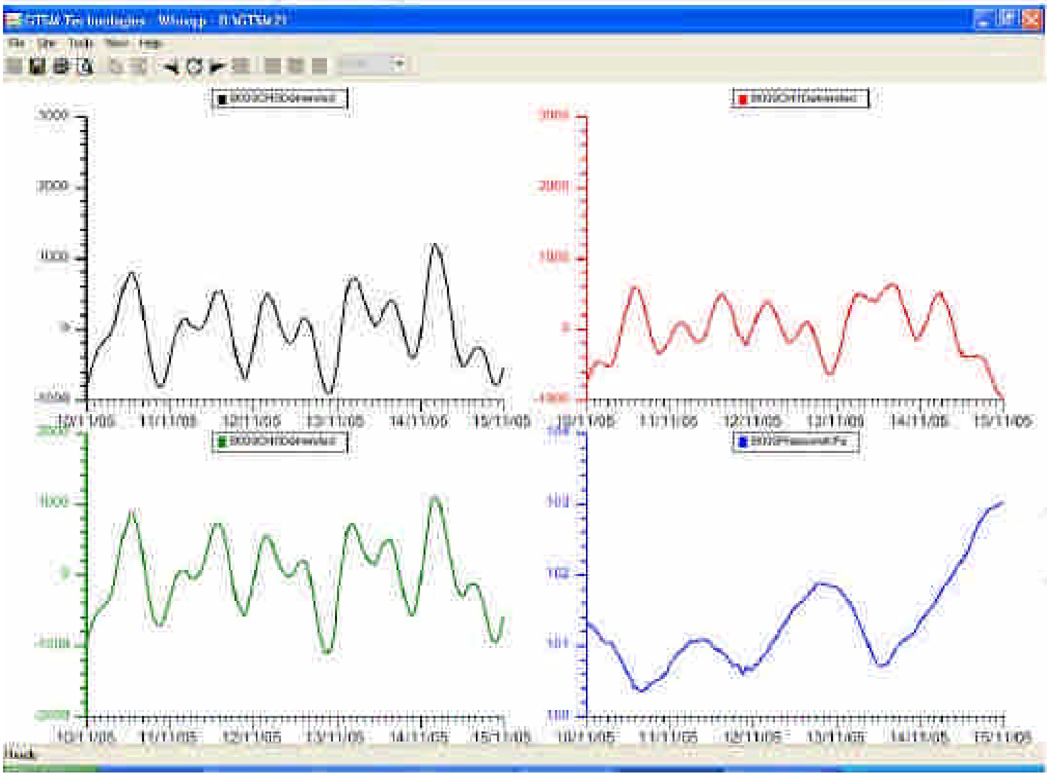
Data can be normalized to provide the same scale range on any plot view as shown below :



This normalized tiled view can be set to any number of traces less than four (three is often used to identify characteristics in the strain record as shown on the following image.

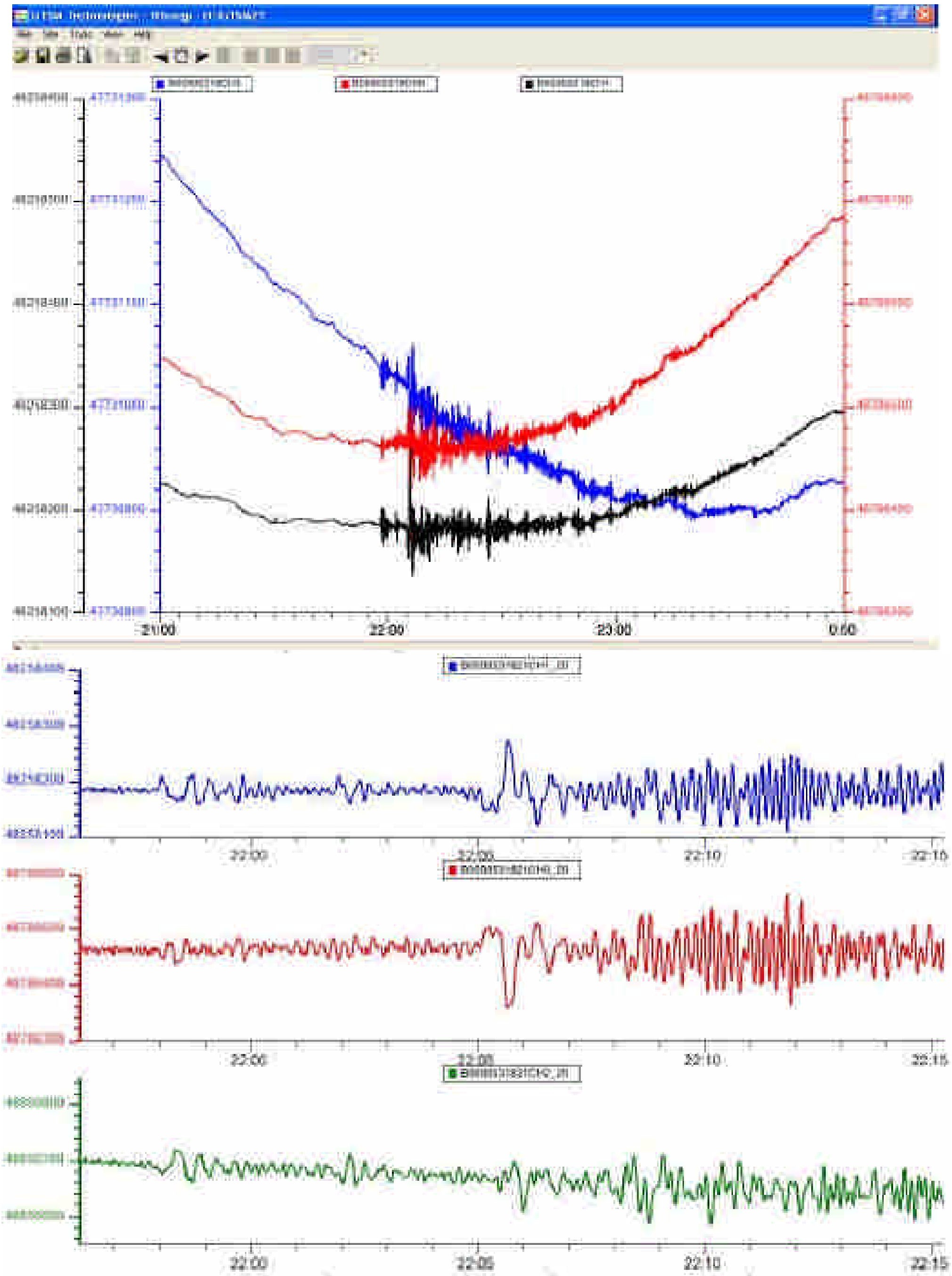


In any window, diagnostics or data from other sites can be incorporated in the correct time position. In the image below the atmospheric pressure has been added to the three normalized plots.



Any associated data set (no matter what the sampling regime) at any time scale can be displayed in these ways with currently up to four channels on screen

An example of zoomed 20 Hz data taken during the Honshu earthquake is shown below. The earthquake data are shown raw and superimposed on the tidal signal in the top image, and at higher zoom in the lower image where the tidal signal is less evide nt.



November 20, 2005

附錄二

Plate Boundary Observatory Data Management Plan

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UNAVCO, Inc.

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June 9, 2004

Policies

2.1 Document Scope

This is the primary document defining PBO data management policies, strategies, and PBO data products. Where this document summarizes any matters (e.g., station installations, monumentation, etc.) that are officially and fully documented in another primary PBO document, such as the Project Execution Plan, other management plans, or a contract statement of work, that other document takes precedence.

2.2 PBO Data Policy

The following policy will govern all PBO data and data products, which are defined as any data and/or data product generated with PBO funding:

Data from all PBO stations will be available on-line as soon as they can be moved from the site to the PBO Archives.

All raw data and metadata from PBO continuously-operating stations and survey-mode observations made by PBO personnel or with core EarthScope funding, and Level 1 and 2 data products derived from those data, will be made freely available through the PBO Data Portal as rapidly as possible, except where release of such data could harm PBO operations; examples of data that will not be released include receiver/data logger IP addresses, lockbox key numbers, and landowner name and contact information.

Raw data collected with independent PI-driven research funding but using PBO survey-mode GPS equipment, and metadata related to those data, will be archived in the PBO GPS Archives and PBO Operational Database as rapidly as possible after the end of a given survey, and within six months of data collection at the latest. Level 1 data products will be derived from such data by the PBO GPS Analysis Centers. The raw data, metadata, and higher-level derived products will be made available exclusively to the principal investigator of the given survey for a period of two years from the time of data collection; these products will be made available to other groups during that two-year window only with written permission of the given principal investigator. Two years after data collection, theraw data, metadata, and derived products will be made publicly accessible through the EarthScope Data Portal.

All software developed by PBO or with PBO funding will be governed by the PBO Software License, which will be based on existing open-source licenses such as the Gnu General Public License. The primary features of the license are that all source code will be freely available to the United States academic and non-profit communities, and that no PBO software may be used for commercial purposes by any entity (person, group, organization, or institution) receiving PBO funding.

Any PBO-funded entity that modifies software licensed from any other entity must submit the modified source code to the license holder for further distribution to the community under the external entity's license.

No entity that receives funding to generate, archive, or analyze PBO data, metadata, derived data products, or software may derive commercial profit from his/her/their/its PBO-funded work.

Users of PBO data must acknowledge EarthScope and the NSF as the source of those data. We request users include text similar to the following in reports, papers, and other products using PBO data: "We acknowledge EarthScope and its sponsor, the National Science Foundation, for providing data[or derived data products, as appropriate] used in this study."

2.3 Oversight

2.3.1 Data Products Advisory Working Group

The PBO Data Products Advisory Working Group(DPAWG) is charged with helping the PBO Data Products Manager(DPM) and PBO Direct or in defining high-level requirements for collection, archiving, analysis of data from the PBO GPS and strainmeter installations, and derived data products. DPAWG members represent the EarthScope science user community and are appointed at the sole discretion of the PBO Director. The DPAWG will meet at least annually to evaluate PBO data and data products and to review, and if necessary suggest revisions to, the PBO data management plan. After each meeting, the DPAWG Chair will submit a written evaluation report to the PBO DPM and Director, which they will use in evaluating progress and initiating necessary changes to PBO data management systems. The current DPAWG members, as of June 9, 2004, are:

Jeff Freymueller (Chair),University of Alaska, Fairbanks
Duncan Agnew, University of California, San Diego
Rick Bennett, Harvard-Smithsonian Center for Astrophysics
Elizabeth Hearn, University of British Columbia
Nancy King, United States Geological Survey, Pasadena
John Langbein, United States Geological Survey, Menlo Park

In addition, there will be two non-voting ex-officio members of the DPAWG: (1) the Analysis Center Coordinator (ACC), and (2) a representative of the PBO Archives, appointed by the PBO Director. A current list of the DPAWG membership will be maintained on the PBO web site.

2.3.2 Data Analysis Strategies Working Group

The PBO DPM is ultimately responsible for the analysis of PBO data, through supervision of the PBO Analysis Center Coordinator and the Analysis Centers. PBO will convene a Data Analysis Strategies Working Group (DASWG) to give the DPM detailed advice on GPS and strainmeter data analysis strategies and standards; members of the DASWG will include the ACC, representatives of the ACs, the Strainmeter Data Analyst, and experts on GPS and strainmeter data analysis drawn from the EarthScope community. The DASWG will help develop a detailed PBO data analysis strategy based on the outlines given in the DMP, and will also review that strategy at least annually, making recommendations for changes as needed. A current list of the DASWG membership will be maintained on the PBO web site.

2.3.3 Standing Committee

The PBO Standing Committee (PBOSC) is charged with the role of advising the UNAVCO, Inc. Board of Directors in overseeing all functions and all aspects of PBO management. The members of the PBOSC are appointed by, and report to, the UNAVCO Board. The PBOSC represents the PBO scientific data user community to ensure that the scientific goals of the PBO are met, to the extent possible within fiscal and other practical limits. The PBOSC meets at least three times per year to review, in detail, the progress on all aspects of PBO operations, facilities, and contracts. In particular, the PBOSC will review this data management plan and the RFPs for the Analysis Centers and Analysis Center Coordinator. The PBOSC will identify issues of concern and recommend actions to the UNAVCO Board, which will in turn advise the UNAVCO, Inc. President and PBO Director. The current PBOSC members, as of June 9, 2004, are:

Paul Segall (Chair), Stanford University
John Beavan, Institute of Geological and Nuclear Sciences
Greg Beroza, Stanford University
Brad Hager, Massachusetts Institute of Technology
William Holt, State University of New York, Stony Brook
Susan Owen, University of Southern California
Evelyn Roeloffs, United States Geological Survey, Vancouver
Mark Simons, California Institute of Technology

A current list of the PBOSC membership will be maintained on the PBO web site.

2.4 Conflicts of Interest Policy

PBO will impose the following main restrictions on the PBO Archives, Analysis Centers, Analysis Center Coordinator, and advisory group membership:

1. No PBO GPS Analysis Center may include any member who receives, is supervised by someone who receives, or supervises someone who receives, funding to act as a PBO GPS Archive or the PBO Analysis Center Coordinator. Similarly, no PBO GPS Archive may include any member who receives, is supervised by someone who receives, or supervises someone who receives, funding to act as a PBO GPS Analysis Center or the PBO Analysis Center Coordinator.

2. Entities (individuals, groups, organizations, or institutions) that receive funding to act as PBOGPS Archives may bid for a position as a PBO GPS Analysis Center or the Analysis Center Coordinator. However, if such an entity's bid is successful, the entity will be required to give up its role and all funding as a PBO GPS Archive when the entity takes on its new role as a PBO GPS Analysis Center or the Analysis Center Coordinator.

3. No individual that receives, is supervised by someone who receives, or supervises someone who receives, funding to act as a PBO GPS Archive or PBO GPS Analysis Center may receive funding to act as the PBO Analysis Center Coordinator. Any individual may bid to become the PBO Analysis Center Coordinator; however, if the successful bidder falls into any category listed in the previous sentence, he or she will be required to resign from any and all Archiving or Analysis Center activities and forfeit all Archiving or Analysis Center funding when they begin their new role as PBO Analysis Center Coordinator.

4. No PBO Strainmeter Analysis Center may include any member who receives, is supervised by someone who receives, or supervises someone who receives, funding to act as a PBO Strainmeter Archive. Similarly, no PBO Strainmeter Archive may include any member who receives, is supervised by someone who receives, or supervises someone who receives, funding to act as a PBO Strainmeter Analysis Center.

5. No individual who receives, or is supervised by anyone who receives, or supervises any individual who receives funding to act as a PBO Archive, Analysis Center, or the Analysis Center Coordinator may serve in a voting capacity on the PBO advisory working group overseeing that aspect of PBO.

6. Any member of any PBO advisory working group who wishes to submit a proposal in response to any PBO RFP or RFQ must declare his or her intention to do so in writing to the PBO Director, and will be required to resign his or her voting position if he or she is the successful bidder.

7. Prior to reviewing PBO RFPs, RFQs, and Statements of Work, members of the UNAVCO Board of Directors and PBOSC will be required to sign a non-disclosure agreement(NDA) governing the particular document. Those Board or PBOSC members who may be interested in bidding on a given RFP or RFQ will not have to sign the NDA and will be excluded from any

discussion of that RFP or RFQ. Board or PBOSC members who do sign an NDA and participate in the review of the given RFP or RFQ will be prohibited from discussing any aspect of that RFP/RFQ with any member who has not signed the NDA, and will be prohibited from bidding on the finalRFP/RFQ.

8.Exceptionstothispolicy may be granted by the PBO Director, with concurrence of the UNAVCO President and Board of Directors, when necessary to meet PBO science, budget, schedule, and/or reporting requirements.

PBO will impose these restrictions in order to

1 spread responsibility for PBO functions across the community, thus increasing community involvement;
2 separate facility roles(archiving) from scientific roles(analysis);
3 increase accountability to PBO management and its sponsors;
4 improve the transparency of the EarthScope project for its community;
5 simplify the PBO management structure;
6 help prevent any PBO AC from developing dependence on any particular PBO Archive; and
7 ensure that decisions governing PBO data, data products, and software will not be made by those receiving funding to generate those data, data products, or software.

2.5 Site/Data Naming Conventions

4-character station/site IDs have been widely used in the community in the past, but 4-character IDs have several problems that make them inadequate for PBO needs: they are non-unique, there is no obvious way to connect station IDs to the geodetic coordinates of the station, and their brevity is overly limiting. Therefore, PBO has developed its own proposed naming conventions, outlined below, which will be used in all PBO data and derived data products. Appendix D gives much more detail on these new conventions.

The first main change in the PBO naming conventions is a specific terminology describing a hierarchy from sites to data channels. Currently, “site” and “station” are used interchangeably, which is ambiguous. PBO’s naming hierarchy is meant to address that ambiguity, as follows:

- Site
  The property on which one or more stations are installed, delineated by the legal definition in each site’s permit.

- Station
  A collection of sensors and a reference point. For example, a PBO GPS station consists of the GPS monument and antenna, and optional met sensors, and the reference point for a PBO CGPS station is the tip of the center-support screw on the D3 adaptor atop the GPS monument. A given site may have more than one station installed.

- Sensor
  A particular instrument, such as a GPS antenna, each component of a borehole seismometer, or a fiber anchor for a laser strainmeter. A given station may contain multiple sensors.

- Channel
  A channel is a specific data stream from a specific sensor, recorded at a specific sample rate; a given sensor may have more than one channel. For example, a GPS station may have channels at 15-sec, 1-sps, and 5-sps, or a borehole strainmeter’s north-south sensor could have channels sampled at 20-sps, 10-sps, 1-sps, and so on.

The other main change is that PBO stations will not have a primary 4-characterID,butinstead will have two longer main identifiers: a 12-character geocode based on the station's precise position, and a 16-character short name based on a common geographic reference:

- Station Location Geocode

  The primary station identifier for PBO will be a geocode that converts the position of the station's reference point, when installed, into a compact representation that is suitable for filenames and the like. We will use the GHAM geocodes proposed by Duncan Agnew (pers. comm.), which can specify locations to arbitrary accuracy and are structured such that stations located near each other will appear near each other in a lexicographically-sorted list of geocodes (see Appendix C for more details on how the GHAM system works). PBO Station Location Geocodes are 12 characters long; an example geocode for a site at 32.867772° N, -117.252331° E would be E4I8U3W2V7I3.

- Station Short Name

  The secondary station identifier for PBO will be a 16-character name, based on some nearby landmark as is current practice. The short name will have the format ccccccccccrryyyy, where cccccccccc is a 10 alphanumeric character station name string, yyyy is the 4-digit year in which the station was installed, and rr is a 2-character region code. An example is Marshall__CO2004 for the station installed at Marshall Field, in Boulder, Colorado in 2004. The short name will be used as a secondary identifier for filenames, on maps, and in informal communications.

Files containing PBO data and derived data products will be named using the Station Location Geocode, as described in Appendix D. These files will also be accessible via the station short name, for ease of searching.

PBO Analysis Centers, Archives, and the Analysis Center Coordinator will use the new PBO conventions for their work, but in order to make PBO data and data products widely usable, we will make PBO products as backward compatible as possible. PBO will store the new PBO station identifiers as comments in current standard formats such as RINEX files and make the 4-character PBO Dot Number(described in Appendix D) available as an additional station identifier. PBO will also support GPS processing software development necessary to allow the use of a longer station identifier without loss of functionality. Finally, PBO will work with the community to develop updated formats that can be used for both PBO data and data products and those from other groups as well.

We recognize that these are non-trivial changes that will cause some degree of controversy in the community. However, we strongly believe that the long-term benefits for the community that will result from using longer, location-based station IDs outweigh the temporary disruption caused by changing to such a structure.

PBO Data and Data Products

3.1 Metadata

Meta data about PBO sites, stations, sensors, data, and derived data products will be collected and stored in the PBO Operational Database(POD).POD development is being led by the PBO Database/Web Software Engineer(DWSE) along with a group of external developers, and managed by the PBO DPM. The POD will be maintained by the PBO DWSE and operated from PBO Headquarters in Boulder. Metadata contained in the POD will include such classes as:

Standard station information: location, point of contact, etc.

Site equipment information: equipment type, UNAVCO ID, serial number, telecommunications paths, etc.

Reconnaissance, siting, and permitting: pictures, pointers to paper field reconnaissance logs and site permits, scanned images of site permits, etc.

Installation and construction data: Dates installed, who by, geology type, materials used, etc.

Network state of health: history of data received, battery voltages, temperature, etc.

Derived parameters from data products: long-term GPS station velocity; noise parameters; seasonal signals; offsets and outliers; BSM and LSM tidal admittance and scale factors; etc.

Table 3.1 gives some more details on the types of metadata planned for the POD.

Metadata related to reconnaissance, siting, permitting, and installation will be submitted manually using the PBO Site Reconnaissance Report(SRR) and Site Installation Report(SIR), a set of tools based on the SCIGN Site Evaluation and Construction Reports and the current UNAVCO Facility Permanent Station Database interface. Metadata related to network state of health will be gathered automatically to a holding area, where they will be vetted and uploaded to the POD by PBO staff. PBO Analysis Centers will also upload various metadata derived from data analysis and product generation using a similar system.

Table 3.1 Sample Metadata Classes

Metadata Type	Examples	Source	Update frequency
Station	Station Name	SIR[2]	Never
	Station Location Geocode	SIR	Never
	Point of Contact	SIR	As needed
	Descriptive Location	SIR	As needed
	ITRF Location	Data Processing	Monthly
	Installation date	SIR	Never
	Geology type	SRR[3]/SIR	As needed
Equipment	Receiver/antenna type	SIR	As needed
	Rcvr/antenna serial #	SIR	As needed
	Date installed	SIR	As needed
	Antenna height	SIR	As needed
	Station IP address	SIR	As needed
	Telecommunication path	SIR	As needed
Recon,	Recon log index pointer	PBO staff	Never
Siting,	Site permit pointer	PBO staff	Never

Permitting	Scanned recon logs	PBO staff	Never
	Scanned site permits	PBO staff	Never
	Site pictures	PBO staff	As needed
Network SOH	History of data rec'd	QCS	Daily
	Battery voltages	PBO staff	Daily
Parameters from Data Processing	GPS station velocity	Data Processing	Monthly
	Tidal admittance	Data Processing	Monthly
	Time series noise	Data Processing	Monthly
	Seasonal signals	Data Processing	Monthly
	Offsets and outliers	Data Processing	Monthly
	BSM/LSM scale factors	Data Processing	As needed

1.This is not an exhaustive list, but merely intended to give examples of the kinds of metadata to be collected in the POD.
2.PBO Site Installation Report, derived from the SCIGN Site Construction Report.
3.PBO Site Recon Report, derived from the SCIGN Site Evaluation Report.

In order to facilitate metadata queries and help prevent metadata loss, the PBO Archives will act as backup repositories for public metadata from PBO. The POD will contain the master copy of PBO metadata, and each of the PBO Archives will have asecondary copy derived from, and kept in sync with, the master copy. We will work with the PBO Archives to develop and implement appropriate methods for distribution, synchronization, and storage of PBO metadata.

It is important to note that not all metadata related to PBO sites will be made public, and that only publicly available PBO metadata will be kept in the secondary metadata repositories. Those metadata, including receiver IP addresses and lockbox key numbers, that are critical to PBO operational security will be strictly limited to PBO staff only. As there is no need for anyone outside PBO operational staff to have access to these metadata, this restriction should have no impact on PBO end users. Also, some public metadata may not be stored online; for example, original paper copies of permits or site log sheets may not be scanned into the POD, depending on budgetary and staff constraints. However, any such metadata will be made available on request.

EarthScope community members will access public PBO metadata using a read-only interface to the POD, which will ultimately be part of the EarthScope Data Portal. This interface will also allow users to sign up for automated e-mail notification of changes to metadata stored in the POD. Also, PBO Archives may make public metadata available on a read-only basis through their own access methods, provided the Archives prominently identify the metadata as generated by PBO.

3.3 PBO Strainmeter Stations and Data

3.3.1 BSM Station Configuration

Each of the 174 PBO borehole strainmeter installations will consist of:

- one three-component tensor strainmeter, sampled at 20-sps for the Gladwin and 40-sps for the SES-3 instruments, with 24-bit digital recording

- one three-component seismometer, sampled at 100-sps, with 24-bit digital recording
- one biaxial tiltmeter, sampled once every 300 seconds, with 16-bit digital recording
- one pore-fluid pressure sensor, sampled once per second, with 16-bit digital recording
- one surface barometer, sampled once per second, with 16-bit digital recording
- one surface thermometer and rainfall gauge, each sampled once every 300 seconds, with 16-bit digital recording

There are also a number of auxiliary channels sampled at 300-sec sampling, including battery voltages; further details are dependent on the final choice of sensors and data logger. Higher sample rates for the strain data cannot be supported for the Gladwin tensor strainmeter without significant development costs and time.

3.3.3 Strainmeter Data Flow

BSM data will be buffered on-site and downloaded in near real time to PBOHQ over direct Internet connections (DSL, cable modem, etc.), cellular modem connections, radio modem-to-Internet connections, or radio modem-to-cellular modem connections. BSM data will be transferred using a secure data transport system, likely based on the Antelope (http://www.brtt.com) or Earthworm software, to a central machine at PBO Head quarters(HQ) in Boulder; there will also be a redundant backup system, fully capable of rapid fail-over in case of emergency in Boulder, at an appropriate off-site location.

BSM data will be quality-checked at PBOHQ in Boulder before being passed on to the Strainmeter Archives and Strainmeter Data Analyst. Metadata in the BSM data files will be compared with the most up-to-date station metadata in the PBO Operational Database. If the POD and raw data headers are in conflict, the file in question will be flagged and removed from the forward stream, and the data will be examined to determine the proper course of action, including updating the POD to reflect new metadata correctly defined in the data file. Beyond metadata checking, the BSM data will be checked for the time of last data returned, the completeness of data over some time period, the ability of the strainmeters to track tidal signals, and data outliers; further criteria will be determined by the PBO DPM in consultation with the PBOSWG.BSM seismic data quality standards will be set in consultation with the PBO DASWG and USArray personnel.

Once the data have been vetted and digitally signed, they will be distributed via Antelope, Earthworm, or similar software directly and simultaneously to the Strainmeter Archives and Data Analyst. In addition, the seismic data may be made available to regional seismic network operators, subject to negotiation of memoranda of understanding governing their access and use.

PBO LSM data will be buffered on-site and downloaded in near real time to PBOHQ via a secure data transport system running over direct Internet connections (DSL, cable modem, etc.), cellular modem connections, radio modem-to-Internet connections, radio modem-to-cellular modem connections, or satellite communications. From PBOHQ, LSM data will be sent simultaneously to Scripps Institution of Oceanography, where SIO staff under the supervision of Duncan Agnew and Frank Wyatt will perform initial quality checks, and the PBO Strainmeter

Archives for storage. The LSM metadata in the POD will be updated through a system still to be determined.

Figures 3.3 and 3.4 outline the BSM and LSM data flows, respectively.

3.3.4 BSM Data Analysis and Products

Level 0 BSM data products include raw, uncorrected gauge data from the strainmeters, raw data from the seismometer and other sensors, and metadata describing all of these data and the station. Gladwin tensor strainmeter data will be sampled at 20-sps and SES-3 data at 40-sps, while seismometer data will be sampled at 100-sps, and the other sensors at 1-sps and 300-sec. The strain and seismic data will be stored in SEED format, while the other data will be stored in a PBO XML-SM format derived from the USGS Low-Frequency Data XML format(http://quake.usgs.gov/research/deformation/ monitoring/info/xml.html).

The Level 0 BSM data will be delivered to the Strainmeter Data Analyst via Antelope, Earthworm, or similar software; the SDA will then use these data to generate theLevel1 and2BSMdataproducts. Level 1BSMdataproducts will include time series of straingauge, tiltmeter (for those holes with tiltmeters installed), and environmental data that have preliminary corrections for such effects as telemetry spikes or power glitches done automatically, using software developed by the Strainmeter Data Analyst. These time series will be scaled to natural units and will be stored in SEED format. No changes in sampling rate will be made at this stage.

Level 2 BSM data products will include strain gauge, tiltmeter, and environmental data, scaled and corrected for offsets with human input, and derived dilatational and shear(γ_1 and γ_2)strain time series without tides removed. The SDA will also create an earth tide model to allow the end user to remove the effect of tides before data analysis; this tide model will be another Level 2 BSM product. All corrections made to any BSM data will be stored in an XML-SM format file to allow the end user to remove those corrections he or she deems unnecessary. All Level 2 series will be decimated down to 300-sec sampling and stored in the XML-SM format mentioned above.

Level 0 BSM products will be made available as rapidly as they can be moved from the site to the archives, and Level 1 products will be nearly as rapid; the additional delay will only be that necessary for the automated processing. Level 2 BSM products will have three latency levels: (2a) a preliminary analysis performed daily upon the end of the24-hourday;(2b) a rapid product generated, with obvious blunders and other glitches corrected,within2 weeks; and(2c) a final version, with all know nproblems corrected, which will be available within 3–6 months of data collection. The SDA will deliver the Level 1 and 2 products to the Strainmeter Archives by placing them into a specified location for automated

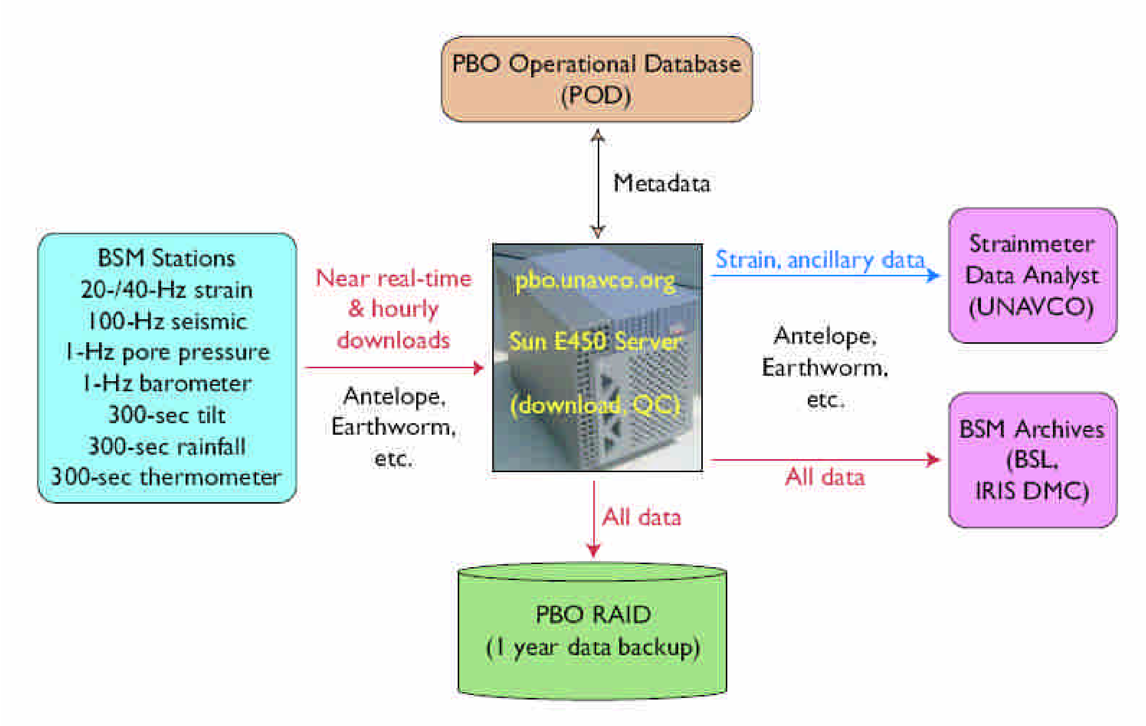

Figure3.3:Boreholestrainmeterdata flow. BSM stations will collect3 strainmeter channels(20-spsfor Gladwin,40-spsforSES-3instruments),3 seismic channels(100-sps), one channel each of pore-fluid and atmospheric pressure recorded at 1 sample/sec, and two channels of tilt and one channel each of rainfall and temperature recorded at one sample every 300 seconds. Data will be sent at least hourly to PBOHQ via Antelope, Earthworm, or similar software, where they will undergo QC. All channels, except seismic data, will go to the Strainmeter Data Analyst for processing into higher level products. All data goes to the BSM Archives at the Berkeley Seismological Laboratory and the IRIS DMC for archiving and distribution to end users.

There will be no Level 1 or 2 data products from PBO seismometers; PBO will generate raw waveform data only, not such higher-level products as phase picks, amplitudes, earthquake catalogs, etc. PBO waveforms may be integrated into other data products, such as those from USArray, and PBO seismic data maybe used in conjunction with PBO strainmeters for calibration or other purposes, but higher-level products will not be generated by PBO directly.

Table 3.4 gives a summary of the BSM data products.

3.3.6 Strainmeter Data Product Archiving and Delivery

PBO BSM and LSM data will be archived at the Berkeley Seismological Laboratory and the IRIS Data Management Center. These archives will mirror each other’s data using a system based on the current BSL and IRIS DMC data distribution system, which will be built in consultation with USArray and Berkeley personnel. PBO will support development of software necessary to meet PBO needs in BSM/LSM archiving and distribution. The Archives will archive PBO raw data, public metadata, and derived data products, and distribute these to the user community through the EarthScope Data Portal, as with the PBO CGPS data.

Table 3.4: PBO Strainmeter Data Products

Level	Station Type	Data Product	Format	Generation Frequency
0	BSM	20-sps or 40-sps 3-comp. gauge data	SEED	Hourly
		100-sps 3-component seismic data	SEED	Hourly
		1-sps pore & barometric pressure	XML-SM[1]	Hourly
		300-sec rainfall, surface temp., and biaxial tilt	XML-SM	Daily
	LSM	12 channels of 1-sps LSM fringe count, environmental, and instrument state of health data	XML-SM	Real-time
	Both	Station metadata	POD/XML-MD[2]	Daily
1	BSM	20-or 40-sps auto-corrected and -scaled gauge data	SEED	Daily
	LSM	1-sps auto-corrected and -scaled laser fringe data	XML-SM	Daily
	Both	Auto-corrected and -scaled environmental data	XML-SM	Daily
2a	Both BSM	File listing all corrections made 300-sec human-correctedand -scaledgauge data and dilatational and shear strain	XML-SM XML-SM	Daily Daily[3]
	LSM Both	Same, but for linear strain Same, but for environmental data File listing all corrections made Earth tide model	XML-SM XML-SM XML-SM XML-SM	Daily[3] Daily[3] Daily[3] Daily[3]
2b	BSM	300-sec human-correctedand -scaledgauge data and dilatationaland shear strain with all obvious blunders and other glitches re moved	XML-SM	2-week delay[3]
	LSM	Same, but for linear strain	XML-SM	2-week delay
	Both	Same, but for environmental data	XML-SM	2-week delay
2c	Both BSM	File listing all corrections made 300-sec human-correctedand -scaledgauge data with all known problems corrected	XML-SM XML-SM	2 week delay 3–6 month delay[3]
	LSM	Same, but for linear and 3-comp. tensor strain	XML-SM	3–6 month delay
	Both	File listing all corrections made	XML-SM	3–6 month delay

[1] XML-SM: Strainmeter XML data format based on USGS low-frequency data format

[2] XML-MD: Metadata XML format, to be defined.

[3] Daily estimates will be made automatically and within 24 hours of data receipt at the strainmeter analysis centers. Preliminary corrected versions of strain data with human intervention will be available within about two weeks. “Final” corrected versions of strain data with human intervention and all known problems corrected will be available within about 3–6 months. Note that the first Level 2a and 2b composite strain data products (shear and dilatational strain) willbedelayedby2–3 months after station installation, due to the need for enough data to properly estimate the gauge scale factors.

Naming Convention Details

This appendix gives more details on the new PBO naming conventions, including details of the site, station, sensor, and channel identifiers, how files will be named, and how these conventions will be used.

D.1 Naming Hierarchy

PBO's naming hierarchy explicitly distinguishes between "sites" and "stations", unlike current usage. In the PBO lexicon, a site is a parcel of land on which PBO holds a permit to install one or more stations, and is defined by the permit for that site, while a station is a collection of one or more sensors and a common reference point. There may be multiple stations at a given site, and therefore we want to distinguish between stations and sites. Sites have a single identifier: a descriptive name, usually based on some nearby geographic feature; Table D.1 describes this identifier in more detail.

PBO CGP Sstations consist of the GPS monument and antenna, and optional met sensors; the receiver is not a sensor per se, but instead a datalogger. The reference point for a PBO CGPS station is the tip of the center-support screw on the D3 adaptor atop the GPS monument. The reference point for a PBO SGPS station would be the center punch on the disk, or a similar point on other types of marks. For BSM stations, the reference point would be the center of the top of the wellhead. Each station has multiple identifiers, as described in Table D.1.

Agiven station may have multiple sensors, such as in the case of a BSM station, where there are three individual borehole strainmeter sensors(one for each component),three borehole seismometer sensors, a pore pressure sensor, and so on. Each of these sensors may record data at multiple sample rates; for example, a GPS station may have channels at 15-sec, 1-sps, and 5-sps, or a borehole strainmeter's north-south sensor could have channels sampled at 20-sps, 10-sps, 1-sps, and so on. Sensors and channels have multiple identifiers, described in Table D.1.

Table D.1: Site/Station/Sensor/Channel Identifiers

Site Identifiers

Site Descriptive Name		
	Format	45 alphanumeric characters and underscores Responsible
	Source	PBO Regional Engineer Appears in POD and as a
	Usage	comment in raw data files
	Example	Carson_Sink_Nevada

Station Identifiers

Station Long Name	Format	60 alphanumeric characters and underscores
	Source	Based on Site Descriptive Name, with additional space to separate stations at a single site, and including installation dates to handle resets
	Usage	Appears in POD and as a comment in raw data files and derived data products
	Example	Carson_Sink_Nevada_2005_CGPS
Station Short Name	Format	16 alphanumeric characters: ccccccccccrryyyy cccccccccc: 10 alphanumeric character name string rr: 2-character region code yyyy: 4-digit station installation year
	Source	Responsible PBO Regional Engineer
	Usage	Secondary station name in filenames, and appears in POD, on PBO maps, in e-mail and other informal communications
	Example	CARSONSNK_NV2004
Station Location Geocode	Format	12 alphanumeric characters: CNCNCNCNCNCN C: uppercase English letter N: single digit from 0–9
	Source	12-character Level 6 GHAM geocode (see Appendix B), computed from station precise latitude and longitude
	Usage	Primary station identifier, used in naming data files, in the POD, and in all PBO raw data files and derived data products
	Example	E4I8U3W2V7I3, corresponding to 32.86772°N, -117.252331° E
Station Type code	Format	4 alphanumeric characters
	Source	Responsible PBO Regional Engineer
	Usage	Distinguishes co-located stations (such as a BSM station with a GPS monument installed on the wellhead). Will appear in the POD and as comments in PBO raw data files and derived data products
	Example	CGPS: continuous GPS, BSM_: borehole strainmeter

Station Change Number	Format	4 digits, starting at 0001, incremented any time there is a station visit, changes in equipment, or another significant event
	Source	POD
	Usage	Allows PBO data users to determine which data have been affected by changes at a given station. Will appear in the POD and as a comment in PBO raw data files and derived data products
	Example	See Appendix D for examples of how the sequence number changes
IERS DOMES Number	Format	9 alphanumeric characters, AAANNMPPP AAA: 3-character "area code" NN: 2-digit station number, unique inside a given area M: indicates the PBO station reference point is a "ground mark" PPP: 3-digit sequential point number that allows for resets and the like
	Source	Assigned by IERS based on station location
	Usage	Only applicable for PBO GPS stations. Will appear in the POD, as a comment in PBO BINEX data files, and in the MARKER NUMBER field in PBO RINEX data files
	Example	40479M001, DOMES number for the SCIGN station BLYT
PBO Dot Number	Format	4 alphanumeric characters
	Source	PBO proposal
	Usage	Backward compatibility with current standards. Will appear in POD, PBO BINEX data files, and in the MARKER NAME field in PBO RINEX data files. Tertiary filename identifier.
	Example	P041 for the station at Marshall Field, Colorado (which has the Short Name Marshall__CO2004 and the Geocode E5O7A7N2D4W4)

Sensor Identifiers

Sensor Type code	Format	24 alphanumeric characters and underscores
	Source	PBO
	Usage	Will appear in POD and as comment in PBO raw data files and derived data products.
	Example	Gladwin_TSM_1_component_, for the 1-component of a Glad-win Tensor Strainmeter

Sensor Change number	Format	4 digits, starting at 0001, incremented any time there is a station visit, changes in a particular sensor, or another significant event
	Source	POD
	Usage	Allows PBO data users to determine which data have been affected by changes at a given sensor. Will appear in the POD and as a comment in PBO raw data files and derived data products
	Example	See Appendix D for examples of how the sensor sequence num ber changes

Channel Identifiers

Channel code	Format	sssssssssssssssssssssss+rrrrrrrr sssssssssssssssssssssss: Sensor Type Code described above, same for all channels from a particular sensor rrrrrrrr: 8-digit channel sample rate, specified in samples per 86400 seconds.
	Source	PBO
	Usage	Will appear in the POD and as a comment in PBO raw data files and derived data products.
	Example	Gladwin_TSM_1_component_+01728000, for the 1-component of a Gladwin Tensor Strainmeter, sampled at 20-sps.
SEED Code	Format	3-character codes in SEED-standard format.
	Source	SEED conventions
	Usage	Will appear in the POD and will be used in creating SEED-format files from data from PBO strainmeter stations.
	Example	BSN for a 20-sps channel from a borehole strainmeter's north-south sensor

D.3 Naming: BSM-Only Example

Assume the following:

Station installed at 33.609249 ° N, -116.458801 ° E
Station is the 48th installed overall

- Station has the following sensors:
  - Gladwin 3-component tensor strainmeter, recording at sample rates of 20-sps, 1-sps, 60-sec, and 600-sec
  - L22-3C 3-component borehole seismometer, recording at 100-sps, 40-sps, and 1-sps
  - Biaxial tiltmeter, recording at 600-sec
  - Pore-fluid pressure sensor, recording at 1-sps, 60-sec, and 600-sec
  - Paroscientific surface barometer, recording at 1-sps, 60-sec, and 600-sec
  - Surface thermometer, recording at 600-sec
  - Rainfall gauge, recording at 600-sec

Assume the following events happen in the lifetime of the station:

19-Sep-2004: Borehole drilled, tensor strainmeter, pore-pressure sensor, tiltmeter, and seismometer installed
20-Sep-2004: Barometer, thermometer, and rain gauge installed; station completed
11-Oct-2004: Tensor strainmeter reset
18-Dec-2004: Tensor strainmeter reset
23-Feb-2005: Significant earthquake
01-May-2005: Tiltmeter re-leveling
19-Oct-2006: Barometer fails
23-Oct-2006: Barometer replaced
18-Nov-2006: Rain gauge reset
21-Apr-2009: Significant earthquake
05-Aug-2011: Significant unexplained pore-pressure change
10-Jun-2014: Tiltmeter fails
11-Feb-2015: 3 component of seismometer fails, others fine
12-Sep-2018: 2 component of tensor strainmeter fails, others fine

Table D.3 shows the history of changes to the identifiers associated with this site.

Table D.3: BSM-Only Naming History

19-Sep-2004: Borehole completed, tensor strainmeter, pore-pressure sensor, tiltmeter, and seismometer installed

Site descriptive name Pinyon_Flat_NCMN_California_2004 Station long name Pinyon_Flat_NCMN_California_2004_BSM_ Station short name PINYNFLAT_CA2004 Station location geocode E4J1E4Y5S7N2 Station type code BSM_ Station change number 0001 Strainmeter sensor type codes Gladwin_TSM_component_1_+0001 Gladwin_TSM_component_2_+0001

Gladwin_TSM_component_3_+0001

Strainmeter sensor change numbers 0001, 0001, 0001

Seismometer sensor type codes Borehole_L223C_1________

Borehole_L223C_2________

Borehole_L223C_3________

Seismometer sensor change numbers 0001, 0001, 0001

Tiltmeter sensor type codes Borehole_tiltmeter_1____

Borehole_tiltmeter_2____ Tiltmeter sensor change numbers 0001, 0001 Pore-pressure sensor type code Downhole_pore_pressure__ Pore-pressure sensor code 0001 20-sps strainmeter channel codes Gladwin_TSM_component_1_+01728000 Gladwin_TSM_component_2_+01728000 Gladwin_TSM_component_3_+01728000 1-sps strainmeter channel codes Gladwin_TSM_component_1_+00086400 Gladwin_TSM_component_2_+00086400 Gladwin_TSM_component_3_+00086400 60-sec strainmeter channel codes Gladwin_TSM_component_1_+00001440 Gladwin_TSM_component_2_+00001440 Gladwin_TSM_component_3_+00001440 600-sec strainmeter channel codes Gladwin_TSM_component_1_+00000144 Gladwin_TSM_component_2_+00000144 Gladwin_TSM_component_3_+00000144 100-sps seismometer channel codes Borehole_L223C_1________+08640000 Borehole_L223C_2________+08640000 Borehole_L223C_3________+08640000 40-sps seismometer channel codes Borehole_L223C_1________+03456000 Borehole_L223C_2________+03456000 Borehole_L223C_3________+03456000 1-sps seismometer channel codes Borehole_L223C_1________+00086400 Borehole_L223C_2________+00086400 Borehole_L223C_3________+00086400 Tiltmeter channel codes Borehole_tiltmeter_1____+00000144 Borehole_tiltmeter_2____+00000144

Pore-pressure channel codes Downhole_pore_pressure__+00086400 Downhole_pore_pressure__+00001440 Downhole_pore_pressure__+00000144

20-sps strainmeter SEED codes BS1, BS2, BS3
1-sps strainmeter SEED codes LS1, LS2, LS3
60-sec strainmeter SEED codes US1, US2, US3
600-sec strainmeter SEED codes RS1, RS2, RS3
100-sps seismometer SEED codes EP1, EP2, EP3
40-sps seismometer SEED codes SP1, SP2, SP3
1-sps seismometer SEED codes LP1, LP2, LP3
Tiltmeter SEED codes RA1, RA2
1-sps pore-pressure SEED codes LDD
60-sec pore-pressure SEED codes UDD
600-sec pore-pressure SEED codes RDD

20-Sep-2004: Barometer, thermometer, and rain gauge installed; station completed

Station change number 0002 Barometer sensor type code Parosci_surf_barometer__ Barometer sensor change number 0001 Thermometer sensor type code Surface_thermometer_____ Thermometer sensor change number 0001 Rainfall gauge sensor type code Rainfall_gauge__________ Rainfall gauge sensor change number 0001 1-sps barometer channel code Parosci_surf_barometer__+00086400 60-sec barometer channel code Parosci_surf_barometer__+00001440 600-sec barometer channel code Parosci_surf_barometer__+00000144 Thermometer channel code Surface_thermometer_____+00000144 Rainfall gauge channel code Rainfall_gauge__________+00000144 1-sps barometer SEED code LDO 60-sec barometer SEED code UDO 600-sec barometer SEED code RDO Thermometer SEED code RKO Rainfall Gauge SEED code RR1

11-Oct-2004: Tensor strainmeter reset

Station change number 0003
Strainmeter sensor change numbers 0002, 0002, 0002

18-Dec-2004: Tensor strainmeter reset

Station change number 0004
Strainmeter sensor change numbers 0003, 0003, 0003

23-Feb-2005: Significant earthquake

Station change number 0005

01-May-2005: Tiltmeter re-leveling
Station change number 0006
Tiltmeter sensor change numbers 0002, 0002

19-Oct-2006: Barometer fails
Station change number 0007
Barometer sensor change number 0002

23-Oct-2006: Barometer replaced Station change number 0008 Barometer sensor type code New_surface_barometer__ Barometer sensor change number 0001

18-Nov-2006: Rain gauge reset
Station change number 0009
Rainfall gauge sensor change number 0002

21-Apr-2009: Significant earthquake
Station change number 0010

05-Aug-2011: Significant unexplained pore-pressure change
Station change number 0011
Pore-pressure sensor change number 0002

10-Jun-2014: Tiltmeter fails
Station change number 0012
Tiltmeter sensor change numbers 0003, 0003

11-Feb-2015: 3-component of seismometer fails, others fine Station change number 0013
Seismometer 3-comp sensor change num-0002 ber
12-Sep-2018: 2-component of tensor strainmeter fails, others fine Station change number 0014
Strainmeter 2-comp sensor change num-0004

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