HIGH ACCURACY REAL-TIME DAM MONITORING USING LOW COST GPS EQUIPMENT

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Presentation Layout

- GPS in Engineering Monitoring.
- GPS Carrier Phase Multipath Error
- Multipath Sidereal-day Correction Technique
- Proposed Technique for using Low-Cost GPS in EM
- Initial Tests of this Proposed Technique
- Dam Monitoring with GPS
- Conclusions and Suggestions for Further Works

GPS Versus Conventional methods

Conventional methods

- Advantages
  - High accuracy can be obtained
  - High redundancy of observations
  - Gives absolute displacements of selected points
- Drawbacks
  - Need inter-visibility between stations
  - Bad weather conditions limit observations
  - Are labour intensive and required skilful observers
  - Not all methods suitable for real time

GPS

- Advantages
  - Inter-visibility not necessary
  - Automated operation- with high observation rate
  - All weather condition- in real time
- Drawbacks
  - High Cost !!!
  - Low accuracy in real time applications !!!

GPS Carrier Phase Multipath Error(1/4)

$s_d = V\cos\theta$

$s_r = \alpha V\cos(\phi+\theta) \quad 0\le\alpha\le 1$

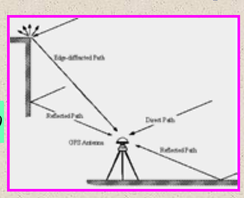
$s = s_d + s_r$

$s = \beta V\cos(\phi+\psi)$

$\beta = \sqrt{1+2\alpha\cos(\theta)+\alpha^2}$

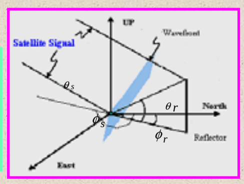
$\psi = \tan^{-1}\left(\frac{\alpha\sin(\theta)}{1.0+\alpha\cos(\theta)}\right)$

Path delay due to MP $= \frac{2*\pi}{\lambda} * \psi$



Geometric Aspects of Carrier Phase Multipath

$$\psi = d_r\left[\frac{1}{\cos\theta_r} - \tan\theta_r\sin\theta_s - \cos\theta_s\cos(\phi_s-\phi_r)\right]$$



GPS Phase Multipath Error (2/4)

Characteristics of GPS Phase Multipath

- Highly dependant on Site location (Not reduced through differential processing)
- It can reach magnitudes of 0.25 of wave length (nearly 5 cm of L1 carrier)
- Its value and shape depends on many factors such as:
  - Antenna Reflector distance
  - Antenna Reflector geometry
  - Satellite Elevation Angle and Azimuth
  - Signal Wave length
  - Reflection Coefficient

GPS Phase Multipath Error (3/4)

Characteristics of GPS Phase Multipath

- It has nearly zero mean so it may be cancelled by averaging the residuals
- It has little effect on final accuracy of positioning for a long period of observation , but it causes a disaster for GPS real time applications such as GPS Engineering Monitoring
- It repeats itself every Sidereal day (Mean Sidereal day = 23h 56m 4s of mean solar day)

GPS Carrier Phase Multipath Error (4/4)

Extraction of GPS Phase Multipath

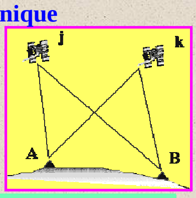
- **GPS Carrier Phase observation equation**

$$\phi_r^s = R_r^s + C(dt_r - dt^s) + T_r^s - I_r^s + \lambda N_r^s + M_r^s + Noise$$

$$R_r^s = \sqrt{(X_r - X^s)^2 + (Y_r - Y^s)^2 + (Z_r - Z^s)^2}$$

- **GPS phase Double Differencing Technique**

$$\phi_{AB}^{JK} = (\phi_A^J - \phi_B^J) - (\phi_A^K - \phi_B^K)$$

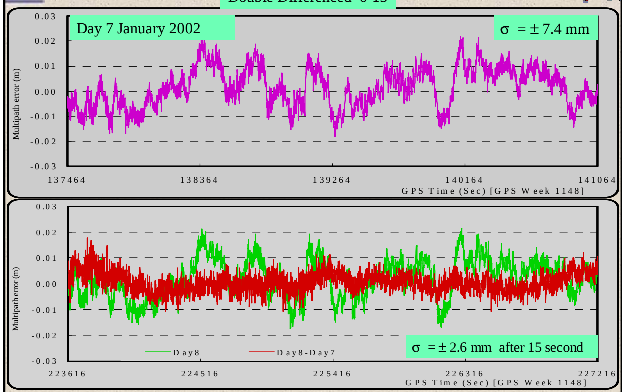


$$\phi_{AB}^{JK} = R_{AB}^{JK} + C(dt_{AB} - dt^{JK}) + T_{AB}^{JK} - I_{AB}^{JK} + \lambda N_{AB}^{JK} + M_{AB}^{JK} + Noise$$

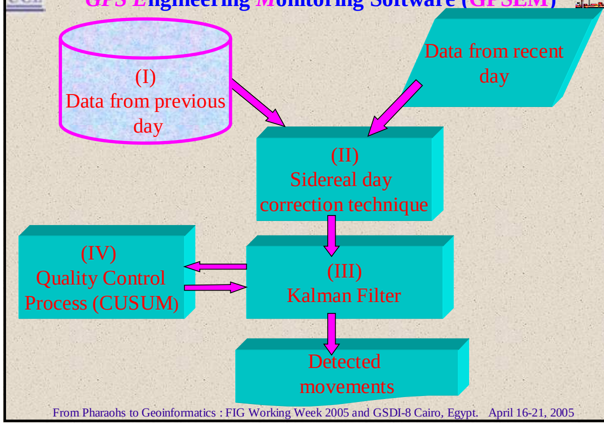
$$\phi_{AB}^{jk} = \frac{f}{c}R_{AB}^{jk} + \frac{f}{c}\left[\dot{\rho}_A^j dt_A - \dot{\rho}_B^j dt_B\right] - \frac{f}{c}\left[\dot{\rho}_A^k dt_A - \dot{\rho}_B^k dt_B\right] + \lambda N_{AB}^{jk} + M_{AB_{\phi mult}}^{jk} + \varepsilon_{AB_{\phi rec}}$$

GPS Carrier Phase Multipath Repeatability (1/2)

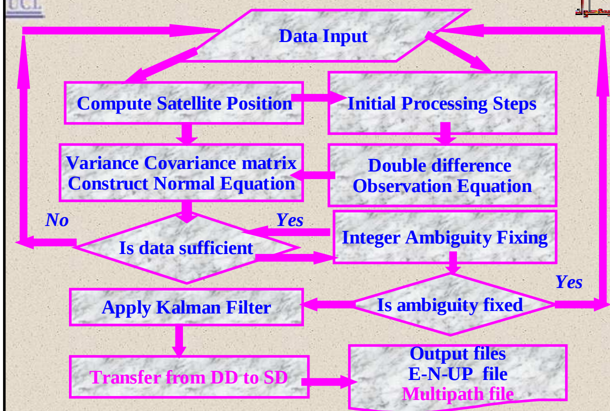
Double Differenced 6-15



Block Diagram of the Suggested Technique for *GPS E*ngineering *M*onitoring Software (GPSEM)



I- Data From Previous Day (1/2)



I- Data From Previous Day (2/2)

Format of Multipath file

- **Approximate Coordinates of Rover Station**
- **The Stored Data for Each Epoch :**
  - **Time of observation and number of used satellites**
  - **For every satellite, data are stored in one single line:**
    - Satellite identifiers number (PRN)
    - Satellite position coordinate in X-direction in WGS84
    - Satellite position coordinate in Y-direction in WGS84
    - Satellite position coordinate in Z-direction in WGS84
    - Residual of single difference L1 phase observations with respect to approximate coordinates of rover station.
    - Number used in the stochastic model indicates the strength of signal

II- Sidereal day Correction Technique (1/3)

Estimation of Sidereal day time shift between two days (T)

- **Revolution Period of slave satellite is computed using Kepler's third law of planetary motion (t)**

$$t = \left[2\pi\sqrt{\frac{r^3}{GM}}\right]$$

G is the universal gravitational constant
M is the mass of the Earth
r is the radius from the center of the Earth to the center of the satellite.

- **Every GPS satellite makes two revolutions per one day so**

T = 2* t

- **Search through previous day data in certain searching volume centered by T, to find the time of epoch which gives the smallest distances between location of this satellite between the two days**
- **If this satellite does not exist in the stored file, this satellite will not be used for any further calculations**

II- Sidereal day Correction Technique (2/3)
Computing the Rover station positions for two days

- Formation DD observation equations using data from previous day
- Formation Weight matrix of DD Phase observations

$$C_{DD} = \frac{1}{\sigma_0^2}\begin{bmatrix} \sigma^2_{DD(r,1)} & \sigma^2_{SD(r)} & \cdots & \sigma^2_{SD(r)} \\ \sigma^2_{SD(r)} & \sigma^2_{DD(r,2)} & \cdots & \vdots \\ \vdots & \vdots & \ddots & \vdots \\ \sigma^2_{SD(r)} & \cdots & \cdots & \sigma^2_{DD(r,N-1)} \end{bmatrix} \longleftarrow \sigma^2_{DD(ri)} = \sigma^2_{SD(r)} + \sigma^2_{SD(i)}$$

- one-way path between satellite and antenna σ_i^2 may be computed as the product of 3 functions such as:

$$\sigma_i^2 = F_1 * F_2 * F_3 \qquad F3 = e^{(|d|/D)}$$

- Formation of Normal matrix and solve for position associated with their covariance matrix using LS Technique
- Subtracting positions of two days → movements and noise

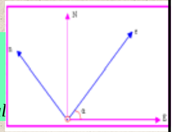
II- Sidereal day Correction Technique (3/3)
Necessary Coordinate Transformations

- Transformation from WGS84 to Local Coordinate System (E-N-UP)

$$\begin{bmatrix} E \\ N \\ UP \end{bmatrix} = \begin{bmatrix} -\sin(\lambda) & Cos(\lambda) & 0 \\ -Cos(\lambda)\sin(\varphi) & -Sin(\lambda)\,Sin(\varphi) & Cos(\varphi) \\ Cos(\lambda)\,Cos(\varphi) & Sin(\lambda)\,Cos(\varphi) & Sin(\varphi) \end{bmatrix} \begin{bmatrix} X-X_o \\ Y-Y_o \\ Z-Z_o \end{bmatrix}$$

- Transformation from Local Coordinate System (E-N-UP) to Engineering Object Coordinate System (EOS)

$$\begin{bmatrix} \text{Along deformation axis } e \\ \text{Perpendicular axis } n \\ \text{UP direction } up \end{bmatrix}_{EOS} = \begin{bmatrix} \cos\alpha & \sin\alpha & 0 \\ -\sin\alpha & \cos\alpha & 0 \\ 0 & 0 & 1 \end{bmatrix} \begin{bmatrix} E \\ N \\ UP \end{bmatrix}_{Local}$$



- Transforming the difference between position and their covariance matrix from WGS84 to Engineering Object coordinate System (EOS)

$$\Delta_{EOS} = \{R\}\Delta_{WGS84} \qquad Q_{EOS} = \{R\} Q_{WGS84} \{R^T\}$$

III- Kalman Filter Technique (1/2)
Equations

Time Update

1- Predict State Vector

$$\hat{X}_i(-) = \phi_{i-1}\hat{X}_{i-1}(+)$$

2- Compute Covariance matrix of prediction

$$C_{\hat{X}_i(-)} = \phi_{i-1} C_{\hat{X}_{i-1}} \phi^T_{i-1} + C_{y_{i-1}}$$

Measurement Update

3- Compute predicted residuals

$$\hat{v}_i(-) = b_i - H_i \hat{X}_i(-)$$

4- Compute gain matrix

$$G_i = C_{\hat{X}_{i(-)}} H_i^T \left[C_{l_i} + H_i C_{\hat{X}_{i(-)}} H_i^T\right]^{-1}$$

5- Update state vector

$$\hat{X}_i(+) = \hat{X}_i(-) + G_i \hat{v}_i(-)$$

6- Update state covariance matrix

$$C_{\hat{X}_{i(+)}} = [I - G_i H_i] C_{\hat{X}_{i(-)}}$$

III- Kalman Filter Technique (2/2)
Constant Velocity Model

- State Vector

$$x^T = [E \;\; N \;\; UP \;\; v_E \;\; v_N \;\; v_{UP}]^T$$

- Corresponding transition matrix

$$M = \begin{bmatrix} I & \vdots & S \\ \cdots & \cdots & \cdots \\ 0 & \vdots & T \end{bmatrix}$$

$$S = diag\{s\} = diag\{\alpha^{-1}(1-t)\} \qquad T = diag\{t\} = diag\{e^{-\alpha\Delta t}\}$$

- Covariance of dynamic model noise

$$C_y(\omega) = \begin{bmatrix} Q_1\Delta t + s_{22}Q_2 & \vdots & s_{23}Q_2 \\ \cdots & \cdots & \cdots \\ s_{23}Q_2 & \vdots & s_{33}Q_2 \end{bmatrix}$$

$$s_{22} = diag\{s_{22}\} = (-3 + 2\alpha\Delta t + 4e^{-\alpha\Delta t} - e^{-2\alpha\Delta t})/2\alpha^3$$

$$s_{23} = s_{32} = diag\{s_{32}\} = (1 - 2e^{-\alpha\Delta t} + e^{-2\alpha\Delta t})/2\alpha^2$$

$$s_{33} = diag\{s_{33}\} = (1 - e^{-2\alpha\Delta t})/2\alpha$$

If α is very small due to long correlation length

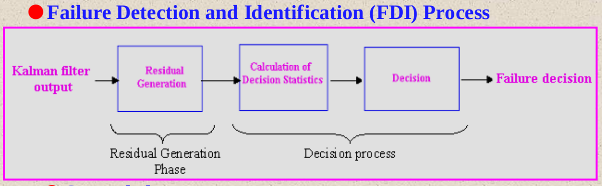
$$C_y(\omega) = \begin{bmatrix} Q_1\Delta t + \frac{1}{3}Q_2\Delta t^3 & \vdots & \frac{1}{2}Q_2\Delta t^2 \\ \cdots & \cdots & \cdots \\ \frac{1}{2}Q_2\Delta t^2 & \vdots & Q_2\Delta t \end{bmatrix}$$

If α is very large due to short correlation length

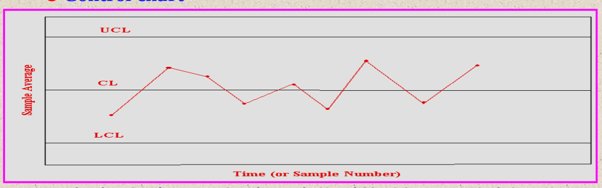
$$C_y(\omega) = \begin{bmatrix} Q_E & 0 & 0 \\ 0 & Q_N & 0 \\ 0 & 0 & Q_{UP} \end{bmatrix}$$

IV- Quality Control Process
Control chart

- Failure Detection and Identification (FDI) Process



- Control chart



IV- Quality Control Process (2)
CUmulative SUM Control chart (CUSUM)

- CUSUM First proposed by Page [1954]

$$C_n = C_{n-1} + (X_n - \mu) \qquad C_0 = 0$$

$$S_n = S_{n-1} + (X_n - \mu)/\sigma \qquad S_0 = 0$$

- CUSUM Statistical Control Limits

$$S_i^+ = max[0 \;,\; y_i - K + S_{i-1}^+] \qquad y_i = \frac{x_i - \mu_0}{\sigma}$$

$$S_i^- = max[0 \;,\; -y_i - K + S_{i-1}^-]$$

- Chosen reference or allowance value (K), decision interval (H) and Average Run Length (ARL)

K = 0.5 for ARL = 500 → H = 4.389.

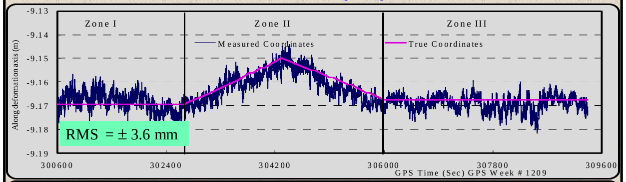
Decrease the false alarm rate by pushing the in-control ARL out to1000 readings, then the required H would become 5.071

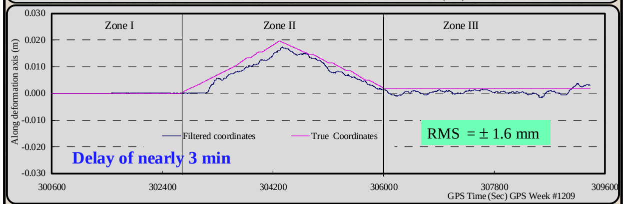
Initial Test of the system(1/2)

- **Location:** UCL main library roof
- **Equipment:** UCL main library roof
  Two GPS Leica 500 - AT502
  Base line length 81.7 m
- **Period of observations:**
  Days 69, 70, and 71, of 2003
  Nearly three hours /day
- **Observation rate**
  1 Hz, mask angle 7.5 degree
- **Data Collection scenario :**
  Days 69 and 70 no movement
  Day 71 movement had been introduced with certain pattern

Initial Test of the system(2/2)

Time Series of Day71





Monitoring Pacoima Dam with GPS (1/2)

PACOIMA DAM

Location : California - USA

Uses : Flood Control- water conservations

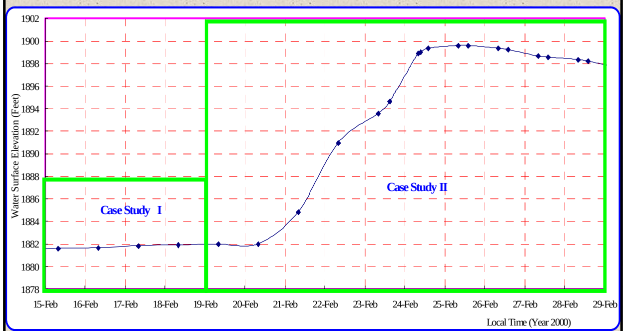
GPS Operator : SCIGN

Baseline Length =103.7 m

Receiver Ashtech Z-XII3 and Choke ring antenna

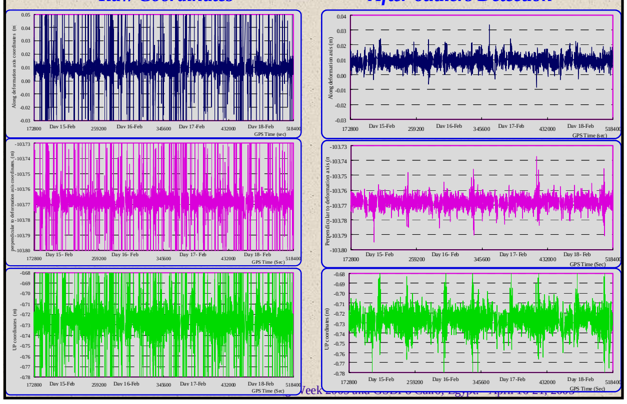
Monitoring Pacoima Dam with GPS(1 /2)

Water Level and Studying Cases



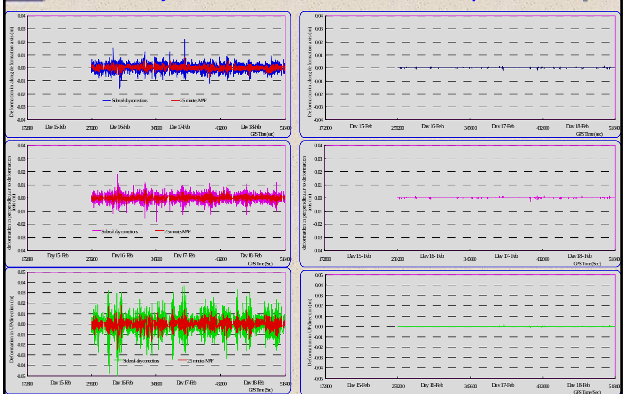
Analyses on the First Case Study (1 / 5)

Raw Coordinates | *After outliers Detection*



Analyses on the First Case Study (2 / 5)

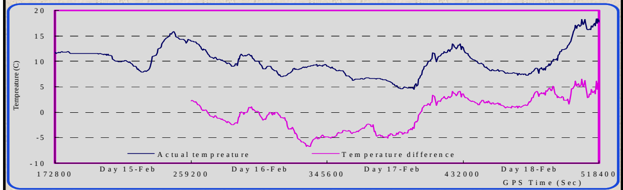
Sidereal day correction | *Kalman filter*



Analyses on the First Case Study (3 / 5)

- To assess the precision of the system, we look at the behaviour of the system from day to day, and also the factors that cause these movements between the two days..
- The system is said to be precise if it reacts in the same way under similar conditions.
- The two possible factors that can cause dam deformation are: an increase in water level in the dam reservoir or change in temperature.
- The difference in water levels between two successive days is in order of 0.1 feet (i.e. ≈ 3.4 cm). This has no impact on the dam deformation.

Analyses on the First Case Study (4 / 5)



- The average of the differences in temperatures between two successive days are in order of 2° C. The effect is negligible .
- There is no cause for any movements to occur between any two successive days.
- The question now is: does the output from the system reflect this reality?

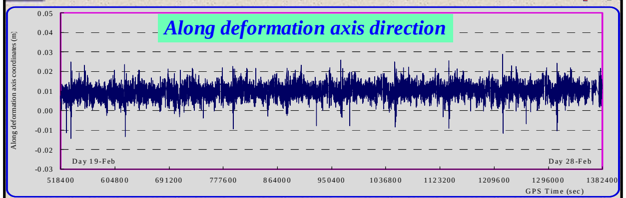
Analyses on the First Case Study (5/ 5)

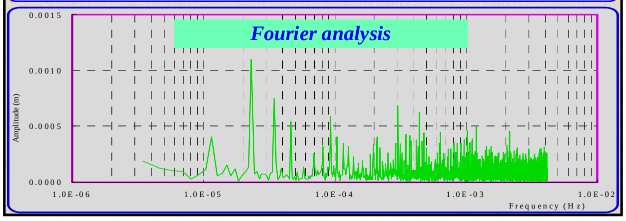
Type of time series and analysis	Maximum μ (mm)	Maximum σ (mm)
Raw Coordinates	0.6	± 13.75
Sidereal-day corrections + Kalman filter (real-time)	0.0	± 0.1

- The results show no deformation is detected with high precision in real-time. The standard deviations of the time series are in order of ±0.1 mm
- The behaviour of the dam from day to day is consistent with the Geo-technical measurements within ±0.04 mm.
- Thus, high precision can be obtained by applying the proposed system in such deformation monitoring applications.

Analyses on the Second Case Study (1 / 5)

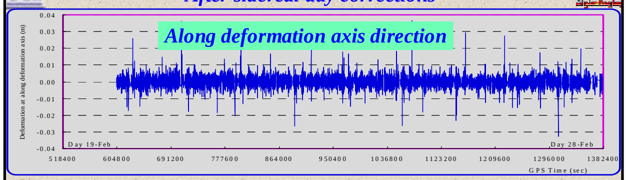
Raw data from 10 days





Analyses on the Second Case Study (2 / 5)

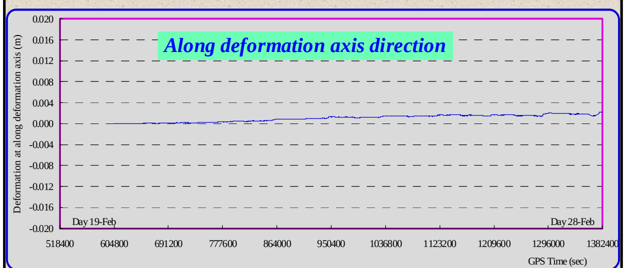
After sidereal day corrections



- *If the data shown is filtered, the result will only be the deformation that occurred between the two successive days.*
- *To overcome this:*
  - *The deformations are considered to be zero on the first day*
  - *For any recent epoch, the computed deformation values are added to those in the file. The process is carried out for the next epoch, and so on till the end.*
- *In other words, the output will be an accumulated time series of the filtered deformation.*

Analyses on the Second Case Study (3 / 5)

After Kalman Filter



Analyses on the Second Case Study (4 / 5)

Deformation Consistency with the Water Surface Elevation

- **Deformation consistency with water level**

There is a strong correlation (≈ 98%) between the deformation occurred along principle deformation axis and the water surface level in the reservoir

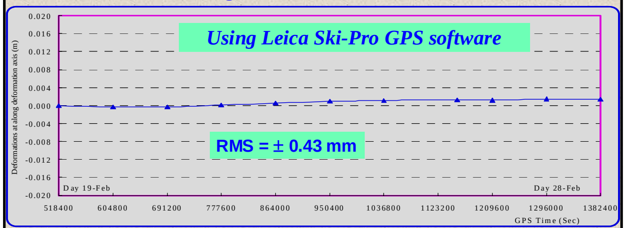
Analyses on the Second Case Study (5 / 5)

Validation of the System

- **Validation of GPSEM**

LEICA SKI-Pro GPS software is used to process the data for whole 24-hour to overcome the problem of multipath error.

The output is the three coordinates in WGS84. These coordinates are transformed to bring these coordinates in the same frame



Conclusions (1 / 3)

- **GPS overcomes all conventional methods drawbacks, but it has its own. These drawbacks are low accuracy in real-time and high cost of the equipment**
- **The phase Multipath error is the dominant error that limits the implementation of GPS in real-time EM applications**
- **The GPS phase Multipath error is highly dependent on antenna reflectors, satellite relative geometry, and almost repeats itself every sidereal day**
- **A methodology for GPS Engineering Monitoring using GPS (GPSEM) has been developed and implemented**

Conclusions (2 / 3)

- **It detects the movements occurring in engineering objects by applying the sidereal-day correction technique for phase GPS multipath errors, a Kalman filter and a Cumulative SUM (CUSUM) control chart.**
- **Based on the results obtained from the investigations carried out on Pacoima Dam, The system shows high precision for detecting deformation of a real continuous monitoring GPS project.**

Conclusions (3 /3)

- **There is a strong correlation (≈ 98%) between the deformation that occurred along the principle deformation axis computed from GPSEM and changes in the water level in the reservoir.**
- **The dam's deformations computed from GPSEM in real time are consistent with those computed from commercial software (i.e. SKI-Pro) using 24-hour solutions. The RMS of the differences between the two solutions in the direction of deformation is ± 0.43 mm.**

Recommendations and Suggestions for Further Work

- **The system and software are needed to be tested under operation circumstance on real engineering object (like high dam on Aswan).**
- **More investigations are needed to study the behaviour of the technique under high amplitude and frequency deformation that may occur in long-span bridges for example.**

THANK YOU