FILTERING TECHNIQUES APPLIED ON RAW CARRIER PHASE FOR GPS DETECTING SMALL DYNAMIC DISPLACEMENTS[1]

Técnicas de filtragem aplicada na fase portadora bruta para o uso de GPS na detecção de pequenos deslocamentos dinâmicos

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RESUMO

Este trabalho faz parte de uma pesquisa em desenvolvimento desde 2000, que tem por objetivo principal medir pequenos deslocamentos dinâmicos utilizando receptores GPS, L1. Um caminho muito sensível para detectar deslocamentos milimétricos periódicos é baseado no Método dos Resíduos de Fase (MRF). Este método consiste na análise de domínio de freqüências dos resíduos do processamento estáticos da dupla diferença de fase da portadora L1 entre dois satélites com ângulo de elevação quase ortogonal. Neste trabalho se propõe obter os resíduos de fase diretamente dos resíduos brutos coletados em linhas de base curtas, durante um intervalo de tempo limite; ao invés da utilização dos arquivos de dados de resíduos gerados por programas de processamento, que nem sempre permitem a escolha dos satélites de interesse. Com o objetivo de melhorar a habilidade de detectar oscilações milimétricas, duas técnicas de filtragem de dados foram introduzidas. Uma é a autocorrelação que reduz o ruído da fase que apresenta comportamento temporal aleatório. A outra é a média corrida que permite separar as fases das freqüências altas das freqüências baixas. Dois testes foram realizados para verificar o método proposto e as técnicas de filtragem. Um deles simula um

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deslocamento vertical da antena de 2.5 mm e o segundo utiliza dados GPS coletados durante um teste de carga numa ponte. Os resultados mostram notável consistência na detecção de oscilações milimétricas.

Palavras-chave: Monitoramento de Estruturas; Pontes; Fase da Portadora; GPS; Técnicas de Filtragens.

ABSTRACT

This work is part of a research under construction since 2000, in which the main objective is to measure small dynamic displacements by using L1 GPS receivers. A very sensible way to detect millimetric periodic displacements is based on the Phase Residual Method (PRM). This method is based on the frequency domain analysis of the phase residuals resulted from the L1 double difference static data processing of two satellites in almost orthogonal elevation angle. In this article, it is proposed to obtain the phase residuals directly from the raw phase observable collected in a short baseline during a limited time span, in lieu of obtaining the residual data file from regular GPS processing programs which not always allow the choice of the aimed satellites. In order to improve the ability to detect millimetric oscillations, two filtering techniques are introduced. One is auto-correlation which reduces the phase noise with random time behavior. The other is the running mean to separate low frequency from the high frequency phase sources. Two trials have been carried out to verify the proposed method and filtering techniques. One simulates a 2.5 millimeter vertical antenna displacement and the second uses the GPS data collected during a bridge load test. The results have shown a good consistency to detect millimetric oscillations.

Keywords: Monitoring of Structures; Bridges; Carrier Phase; GPS; Filtering Techniques.

1. ENHANCEMNT OF THE PRM

The PRM (Schaal, et al., 2002) has been extensively applied on the healthy structure monitoring. It is based on the analysis of the L1 double difference phase residuals (DDPR) of regular static observation over a short baseline and short time span. Most scenarios of displacement monitoring include a reference point in the neighborhood up to 1 Km, allowing the use of single frequency receivers. In most of cases, the vibration modes frequencies of the structures are excited in short time span under moving loads. The turbulent wind pressure, however, would have varied randomly with time (Irvine, 2001).

The DDPR is composed by atmosphere scintillation, satellite and receiver electronics noise, multipath, antennas phase center pattern, satellites orbital dynamics and any antenna movement ranging from millimeters to some centimeters. Fortunately, in this particular case, the double differenced time variations of each one of these effects are quite distinguishable, presenting a different frequency spectrum. The electronics and atmosphere presents a rapid random behavior as a function of the equivalent phase detector noise bandwidth; multipath in most scenarios is a slow time varying function; antennas phase center pattern and satellites dynamics can be neglected for a short time observations and, finally, the antenna movement contribution will depend on inner vector product between the movement direction and the unit vector to the satellite direction. The large structures vibrations are mostly a periodic time function. Converting the residual data to the frequency domain using the Fast Fourier Transform (FFT), the different disturbing sources can be separated (Brigham, 1988).

The dynamic behavior of structure can be described by periodical vertical, lateral and torsional oscillation. To detect a vertical oscillation for example, a reference satellite must be close to the horizon and the measuring satellite close to zenith. Ten degrees of tolerance will not compromise the results because angular corrections can be done mathematically.

2. DIRECT PHASE RESIDUAL METHOD (DPRM)

The first task for obtaining the phase residuals from the raw data is to verify the data quality looking for phase jumps and missing epochs. This can be done looking the data continuity of the chosen satellites. The loose of some sporadic epoch and any small phase jump that stays within the noise level will not compromise the results. In case of a large phase jump the data must be disregarded and a proper window must be selected, as no phase jump correction is performed.

The L1 double difference phase observable is given by Leick (2004):

$$\begin{aligned}\varphi^{pq}_{km,1}(t) = \frac{f}{c}\rho^{pq}_{km}\left(\hat{t}^{\,p}\right) + N^{pq}_{km}(1) + I^{\mathrm{pq}}_{\mathrm{km,1},\varphi}(t) + \\ \frac{f}{c}T^{pq}_{km}(t) + d^{pq}_{km,1,\varphi}(t) + \varepsilon^{pq}_{km,1,\varphi}\end{aligned} \tag{1}$$

Multiplying both side of Expression (1) by L1 wavelength λ_1:

$$\begin{aligned}\lambda_1\varphi^{pq}_{km,1}(t) = \rho^{pq}_{km}\left(\hat{t}^{\,p}\right) + \lambda_1 N^{pq}_{km}(1) + \\ \lambda_1 I^{\mathrm{pq}}_{\mathrm{km,1},\varphi}(t) + T^{pq}_{km}(t) + \lambda_1 d^{pq}_{km,1,\varphi}(t) + \lambda_1\varepsilon^{pq}_{km,1,\varphi}\end{aligned} \tag{2}$$

The first term of the right side of Expression (2) is the double difference of topocentric distances between ***p, q*** satellites and ***k, m*** receivers. The second term is the first epoch ambiguity and it has not time dependence. The time dependence of third and fourth terms, respectively related to the Ionosphere and Troposphere, can be separated in two behaviors. For a short baseline, one is almost a steady state and the second will depend on the lack of correlation among the Ionosphere and Troposphere phase scintillation, with a random time behavior. The fifth term is any time dependent phase disturbance. Finally, the last term is related to receivers phase noise with a random behavior.

Rearranging the Expression (2) joining terms with similar time behavior:

$$\lambda_1 \varphi_{km,1}^{pq}(t) = \rho_{km}^{pq}\left(\hat{t}^{\,p}\right) + S + \lambda_1 d_{km,1,\varphi}^{pq}(t) + N \tag{3}$$

The term S comprises the steady state components, involving the ambiguity, and part of the Ionosphere and Troposphere contributions. The term N involves Ionosphere and Troposphere phase scintillation and receiver random phase noise. The topocentric distance, as a function of time, between satellite p and receiver k is given by the expression:

$$\rho_k^p\left(\hat{t}^{\,p}\right) = \sqrt{\begin{matrix}\left(x^p\left(\hat{t}^{\,p}\right) - x_k\right)^2 + \left(y^p\left(\hat{t}^{\,p}\right) - y_k\right)^2 + \\ \left(z^p\left(\hat{t}^{\,p}\right) - z_k\right)^2\end{matrix}} \tag{4}$$

Same expressions are for the other three distances. The double difference among the four topocentric distances in a short baseline - up to 20 Km - as a function of time can be substituted by *n* order polynomial.

$$\rho_{km}^{pq}\left(\hat{t}^{\,p}\right) = a_n\left(\hat{t}^{\,p}\right)^n + a_{n-1}\left(\hat{t}^{\,p}\right)^{n-1} + \ldots a_0 \tag{5}$$

Substituting (5) in (3):

$$\begin{aligned}&\lambda_1 \varphi_{km,1}^{pq}(t) = a_n\left(\hat{t}^{\,p}\right)^n + a_{n-1}\left(\hat{t}^{\,p}\right)^{n-1} + \ldots a_0 + \\ &S + \lambda_1 d_{km,1,\varphi}^{pq}(t) + N(t)\end{aligned} \tag{6}$$

In the expression (6) the coefficient a_0 can be added to the steady sate components S and, the time behavior of observed double difference can be fitted to the polynomial function which residuals contain the time dependent phase disturbances and random phase noise. Expression 7 gives the phase residuals, *R(t),* in meters:

$$\begin{aligned}&R(t) = \lambda_1 d_{km,1,\varphi}^{pq}(t) + N(t) = \\ &\lambda_1 \varphi_{km,1}^{pq}(t) - \left[a_n\left(\hat{t}^{\,p}\right)^n + a_{n-1}\left(\hat{t}^{\,p}\right)^{n-1} + \ldots a_0 + S\right]\end{aligned} \tag{7}$$

The polynomial fit can be done by parametric minimum least square method (Leick, 2004).With this approximation it is possible to obtain directly the phase residual from the raw data, independent of a regular data processing program, to be analyzed in the frequency domain by the FFT.

Millimeter or unstable periodic oscillations caused by movements of a large structure are difficult to separate from the random noise, degrading the precision of the measurement. One way to improve the signal to noise ratio is the auto-correlation technique. Auto-correlation enhances periodic functions and lessens random values. In the auto-correlation a data of n samples is converted to a half time sample because the delay can only be shifted half the original sample. Expression 8 presents the applied auto-correlation function with the delay (t) ranging from 0 to n/2.

$$R(\tau) = \sum_{t=0}^{n/2} \mathrm{R}(t) \cdot R(t+\tau) \tag{8}$$

3. METHOD AND RESULTS

In order to test the proposed method a simulation trial was conducted under a controlled condition.

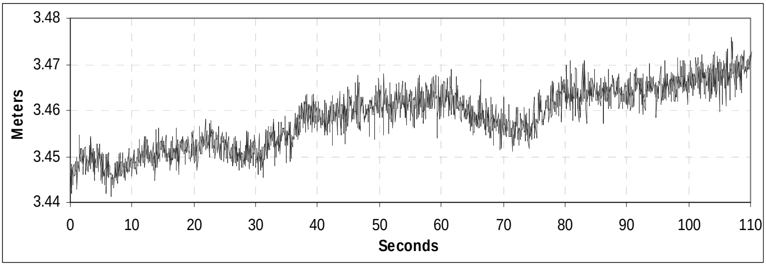
The trial was carried out 24th of August, 2005 at the Department of Transportation of the São Carlos Engineering School (EESC) of the University of São Paulo (USP) using a pair of Leica GX1230 receivers collecting 20 Hz data connected to Leica AX1202 geodetic antenna. To ensure a known phase periodic source on the data, a forced vertical sine-wave movement was applied to the rover antenna installed over an electro-mechanical oscillator (EMO) as shown in Figure 1. The baseline is approximately 2 meters and an observing time session of 8 minutes. A sinusoidal oscillation with 2.5 millimeters amplitude span was applied on the rover antenna and frequency close to 1 Hz. The EMO frequency is dependent of voltage applied to a DC driver motor which is not stabilized, but can be considered constant during the trial.

The period of observation session was selected to ensure a high elevation satellite, which phase data would be directly affected by the antenna movement (G30 at 85 degrees of elevation). As phase reference satellite, any other low elevation satellite can be chosen because its phase data will almost not affected by the movement (G25 at 8 degrees of elevation) synchronization and avoid phase jumps.

Figure 1 - The antennas at the EESC – USP Campus and the rover antenna is mounted over the EMO.

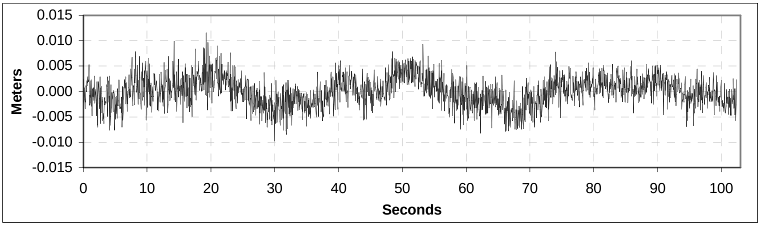
Figure 2 presents the double difference, in meters.

Figure 2 – Raw Phase Double Difference between G30 (elevation 85°) and G25 (elevation 08°). 2 meter baseline.



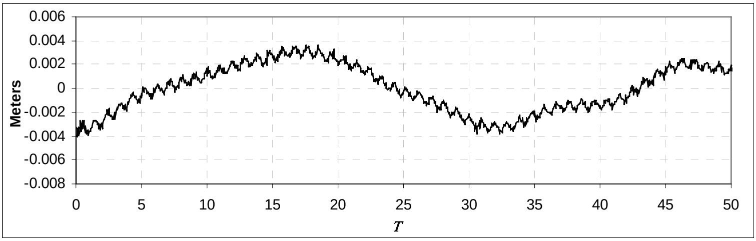
In order to obtain the phase residuals, a 3rd degree polynomial was adjusted to period of 2048 epochs, of the Raw Phase Double Difference which is about 100 seconds of observation. This time is short enough to disregard higher order terms. The resulting residuals are shown in Figure 3.

Figure 3 – L1 Phase residuals obtained from a 3rd order polynomial.



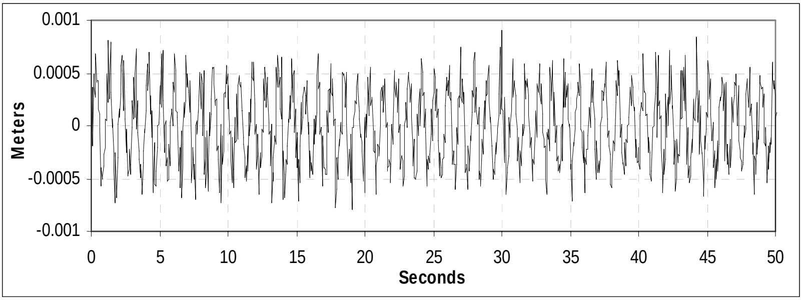
The amplitude of the random noise is in the order of 10 millimeters, masking the 2.5 millimeter imposed to the antenna. Figure 4 presents the residuals after applying auto-correlation filtering.

Figure 4 – Auto-correlation of the phase residuals.



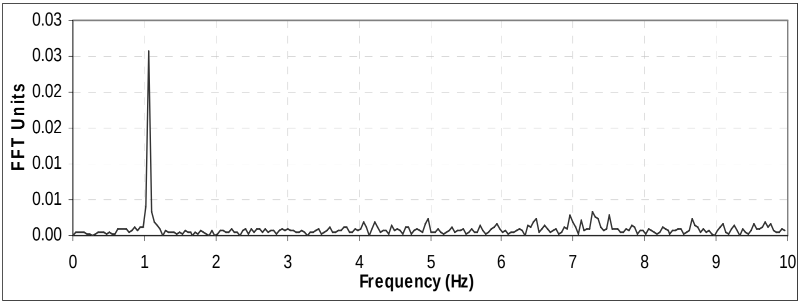
The relation between the periodic signal and the noise remarkable increased presenting a clear detection of the antenna oscillation. Auto-correlation enhances all other frequencies present in the residuals, mostly generates by the multipath. One method to separate these low frequencies from the higher frequencies in the time domain is to subtract a running mean computed with number of samples larger than the number of epochs that define the period of the higher frequency. In this trial, period of the EMO takes about 20 epochs, so a 30 samples mean was chosen. Figure 5 shows the resulted difference.

Figure 5 – Difference values from auto-correlation and running mean.



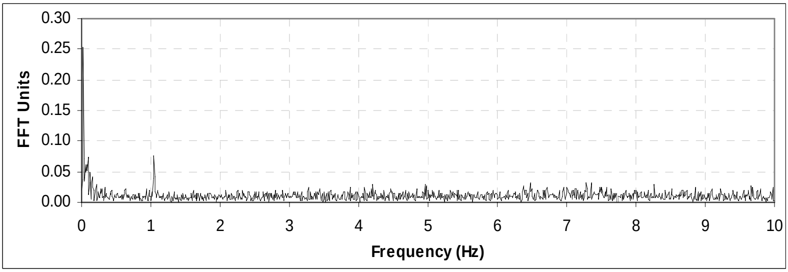
As the third step, the FFT was applied on values from the difference between auto-correlation and running mean for identifying the peak due to the frequency of EMO what was done with successful as shows the Figure 6.

Figure 6 - Frequency spectrum of the values from the difference between auto-correlation and running mean.



To show how the filtering technique improves the detection of the higher frequencies oscillation, the FFT was computed directly on the residuals as shown in the Figure 7.

Figure 7**:** Frequency spectrum of the original phase residuals.



The spectrum below 0.2 Hz is generated by the low frequency phase sources, which are not under analyses in this article.

As this technique allowed so promising results it was decided to apply on previous trial conducted on the 30th of October, 2003 at the Hawkshaw Cable-stayed Bridge, in Nackwic, New Brunswick, Canada (Larocca, 2004, Larocca et al., 2005 and Schaal & Larocca, 2009). Its deck is composed by one north span of 54.44 m; one south span of 29.44 m and the center span with 217.32 m of length. Two towers with 36 m of height support the deck by a harp-type arrangement with six steel cables (Figure 8).

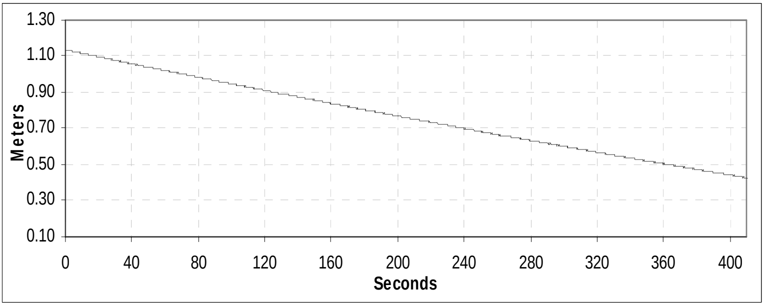
During this trial the rover antenna at the bridge was also installed on the same EMO device with 12 mm displacement, to provide a phase reference to all bridge vertical measurements.

The data analyzed and presented were collected with a pair of TRIMBLE 5700 receivers with one Trimble Zephyr™ Geodetic antenna (on reference station) and one Trimble StealthTM Ground Plane (as a rover antenna on the middle of the deck) under 10 Hz data rate. During the selected observation period, the highest satellite (G25) was at 80^o degrees of elevation and the lowest (G13) at 09^o degrees of elevation, providing a good geometry to measure vertical displacements. The baseline is 284 meters and data two observing time sub-session of 8 minutes were analyzed.

Figure 8 - Hawkshaw Cable-stayed Bridge in New Brunswick, Canada.

The computed raw phase Double Difference from the RINEX observation data is presented in Figure 9.

Figure 9 – Raw phase Double Difference between G25 at 80° of elevation and G13 at 09° in a 284 meters baseline.



After that it was computed the phase residuals from the Double Difference adjusted by the 3rd order polynomial fit as shown in Figure 10.

Figure 10 – Hawkshaw Bridge L1 phase residuals obtained by the 3rd order polynomial.

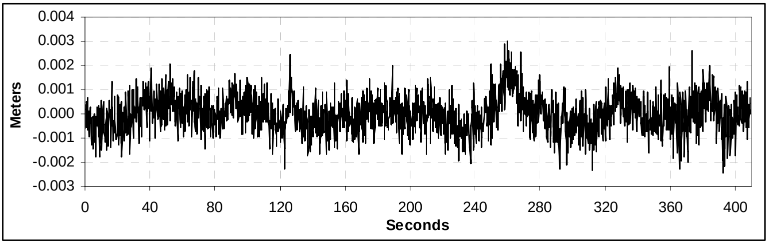
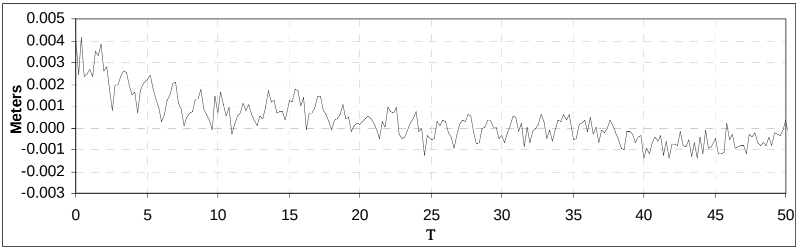


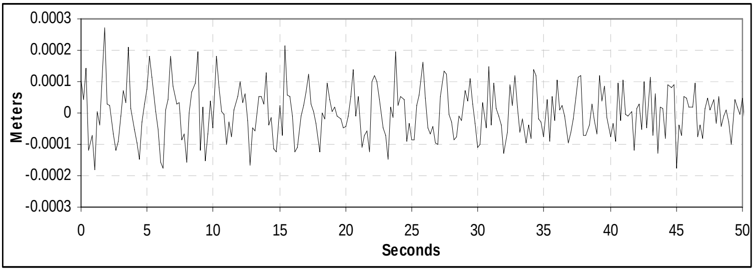
Figure 11 presents the residuals after applying auto-correlation. It is possible to observe well defined periodical during the initial 40 seconds. This is related due to design trucks that were crossing the deck and their position on it (Larocca, 2004; Larocca et al., 2005).

Figure 11 – Hawkshaw Bridge auto-correlated residuals.



After that it was computed the difference values between the auto-correlation values minus the running mean of 40 samples as shown for the first 50 seconds in Figure 12.

Figure 12 - Auto-correlation of the phase residuals.



The FFT was applied on values from the difference between auto-correlation and running mean for identify the peak due to the frequency expected caused by the moving load composed by four different trucks. The theoretical vertical frequency value expected was 0.57 Hz (Hirsch and Bachmann, 1991).

Figure 13 presents the spectrum obtained from the FFT where the moving load 0.57 Hz oscillation, the 1.0 Hz EMO is clearly and a 2.15 Hz oscillation with no well known source that is under study.

Figure 13 – Hawkshaw Bridge frequency spectrum of the values from the difference between auto-correlation and running mean.

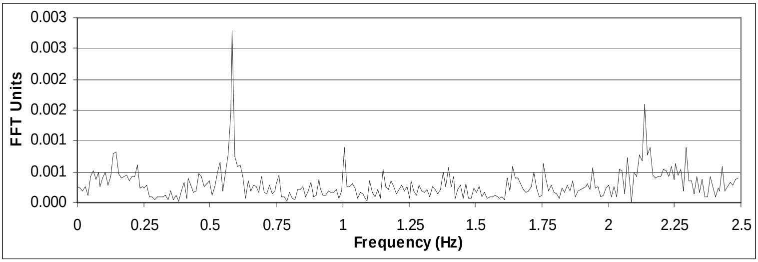
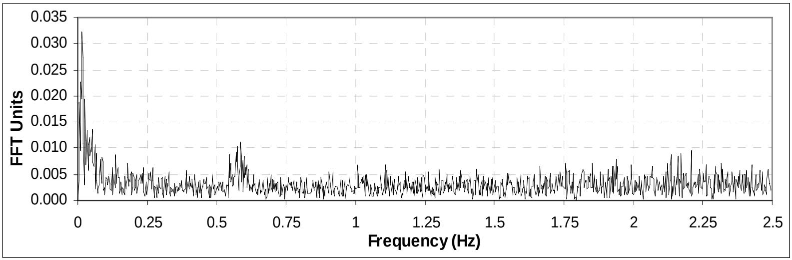


Figure 14 presents the spectrum of the phase residuals without applying auto-correlation and any other filtering technique. The l oscillation caused by the moving load spreads around the nominal value. The EOM oscillation is masked by the noise and the unknown source oscillation is not clear.

Figure 14 – Hawkshaw Bridge frequency spectrum of the phase residual values.



4. CONCLUSIONS

The proposed method to detect higher frequencies directly from raw phase data is very straightforward in monitoring large structures - the simulation and bridge trials had presented consistent results. Frequency domain and spectral analysis through Fast Fourier Transform is a fundamental tool for engineering development. Short baseline and short time session dispense the use of fancy position processing programs. The autocorrelation is very handful to enhance the oscillations and the running mean is useful to clean up undesired lower frequencies. Multipath influence will be closed investigated during future tests using 100 Hz data rate receivers. The use of an electromechanical device to calibrate the vertical displacement spectrum was already established in other works (Schaal et al., 2002; Larocca 2004; Larocca et al., 2005).

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