Noise Characteristics of Short-duration, High Frequency GPS-records

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KEY WORDS: GPS, collocated instruments, coloured noise, white nose, time-series analysis

ABSTRACT:

Measurements of bridge oscillations by collocated GPS receivers, at the limit of the instrument range of operation, revealed important differences in the instrument output, and this result led us to investigate this problem on the basis of systematic experiments. 10Hz measurements from various types of collocated stationary GPS receivers were analyzed. The analysis was focused on short-duration measurements (10 to 10^4sec) usually corresponding to signals of earthquakes and of oscillations of various structures. The output of these experiments was to confirm the existence of differences between identical, collocated instruments, even an absence of correlation between their recordings, which was not, however, due to phase shifts. Spectral analysis revealed that differences between short duration GPS records are mainly due to their low frequency (below ~0.2Hz) components which are dominated by colored noise, while their high-frequency components (above ~2.5Hz) contain only white noise. The limit between colored and white noise seems to be a function of the duration of observations, and for this reason, long-term observations are practically contaminated by white noise only and hence permit mm-level accuracy. This result puts some constraints in the use of GPS for short-duration recordings, for instance efficiency in identification of dynamic movements, but not of small amplitude, semi-static movements.

1. INTRODUCTION

A question arising from different fields of the Measurement Science is whether the output of identical, well-calibrated instruments measuring the same physical process (or quantity) at the same time/place under identical conditions will be similar, or better, whether the difference of their output will be within the range of random noise.

For *static* (long-duration, low-sampling rate) measurements, i.e. measurements repeated several times over a time interval much longer than that of the duration of the measurements, from which an average value is obtained, the answer is most likely yes. For *dynamic* (short duration, high sampling rate) measurements on the other hand, i.e. measurements which cannot be repeated and averaged, the answer is most probably no, as evidence from preliminary experiments revealed. These experiments were based on GPS instruments used for monitoring of structural dynamic displacements (Figs. 1,2).

A further assessment of this result was obtained on the basis of experiments with GPS. The reason is that GPS is an instrument with numerous metrological applications, and is not confined to measurement of coordinates (or of other physical parameters deriving from coordinates such as distances or spectra, see Fig. 2), but is used also for measurement of the time in a global scale and of frequency, and hence is used as a global calibration device (Lombardi, 2008).

2. EXPERIMENTS

The aim of our experiments was to model the noise of two collocated rover receivers in fixed positions, i.e. of two receivers one next to the other, approaching as much as possible the hypothesis of two instruments simultaneously recording the same physical process under the same conditions.

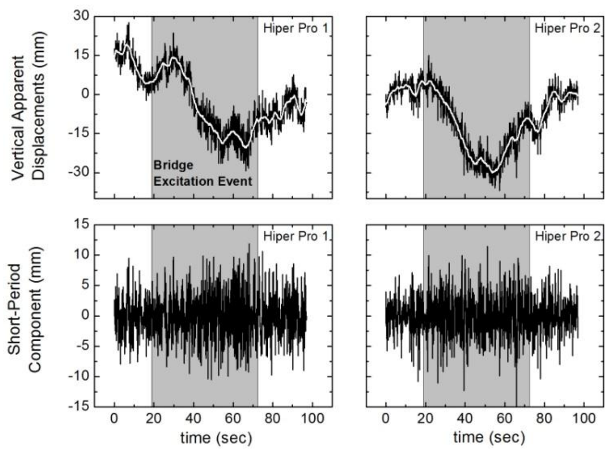

Figure 1 Apparent vertical displacements of the mid span of a 40m-long steel truss bridge during a forced excitation (upper row) and their short period component (lower row) deduced from two identical nearly adjacent GPS instruments. The gray-shaded area corresponds to the bridge excitation interval defined by an accelerometer. The white line in the upper raw is the long-period component of the apparent displacement. The residual short-period component is shown in the lower row. Unexpectedly, the long-period signal is very different between the two collocated GPS instruments (after Moschas and Stiros, 2011).

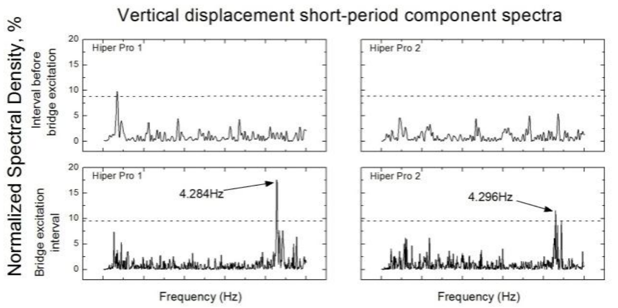

Figure 2 Upper row: Spectra of the short-period component of the vertical apparent displacements of the two collocated instruments of Fig 1 for the interval before the bridge excitation, reflecting noise. Lower row: Spectra of the short-period component of the apparent displacement during the bridge excitation interval. Results are accurate, for both instruments showing similar dominant frequencies during the excitation and white noise before it. A dashed line indicates the 95% peak significance level (after Moschas and Stiros, 2011).

Because the two rover receivers were in stationary positions, their apparent movements reflected measurements noise.

We made numerous experiments with duration of around 1 minute, compatible to that of usual dynamic effect such as wind gusts, vehicles passing from a bridge, earthquakes (Soyoz and Feng, 2009), and also experiments with a gradually longer duration, up to 3.5 hours, in order to examine whether and how the noise characteristics change with the duration of the observations.

We used two identical, rover receivers, stationary side by side, and a third base receiver at a small distance, usually up to a few tens of meters, so that the satellite signals to the three receivers was affected by the same processes from its source to its destination. All receivers were recording with a 10Hz sampling rate

These experiments were made with similar and different types of GPS instruments (Topcon Hiper Pro compact receivers, Topcon GB-1000 receivers with PG-A1 antennas, Javad Legacy E receivers with Javad Legacy H antennas, Trimble R7 receivers with Trimble Zephyr Antennas), in different environments and different conditions, in order to avoid site-specific etc. results, not representative of results of broader significance.

3. PRELIMINARY DATA ANALYSIS

The output of each experiment was analyzed with the appropriate software, occasionally different software (Topcon Pinnacle, Leica Geo Office) to avoid software-dependent events, and the 3-D time series of the instantaneous coordinates of each rover receiver were computed. Then, the time series of the apparent displacements relative to the mean value of each coordinate were computed (Fig. 3).

In addition, these apparent displacements were decomposed into high and low-frequency components using simple filtering techniques (Moschas and Stiros, 2011) (in the results of Figure 3 a moving average filter with step 0.1 seconds and overlap 8 seconds).

4. DATA ANALYSIS AND EVALUATION

The first output of this study was that the long-period components of the measurements are significantly different in the two collocated receivers, while their short-period component is not (Fig. 3). This was also confirmed by spectral analysis results presented further below.

The next step was to examine whether the observed differences were due to possible phase differences between time-series of the collocated instruments. Cross Correlation results (typical correlograms are presented in Figure 4) did not reveal any systematic phase shifts between the two instruments.

At a next step, the spectral characteristics of the time series were examined. In the present study the spectral analysis method used instead of the FFT was the Lomb periodogram which is based on the Least squares method and has the advantage of estimating the statistical significance level of the computed spectral peaks. Spectral Analysis for the present study was conducted using the "Normperiod" code (Pytharouli and Stiros, 2008). Typical spectral analysis results are presented in Figure 5.

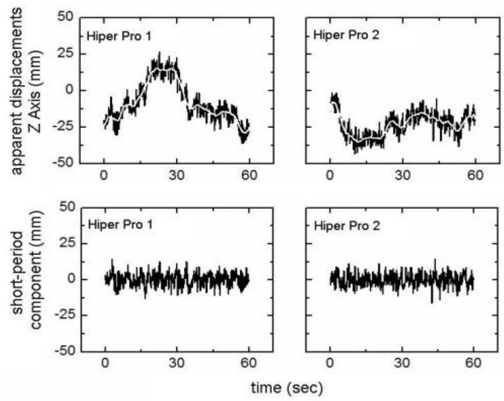

Figure 3. Apparent displacement time-series (upper row) from two collocated, simultaneously recording GPS instruments (noted as Hiper Pro 1 and Hiper Pro 2). The thick, white line represents the long-period component of the time series. In the bottom row the short –period component, resulting after subtracting the long-period component, is presented. It is obvious that each instrument presents a significantly different long-period component waveform.

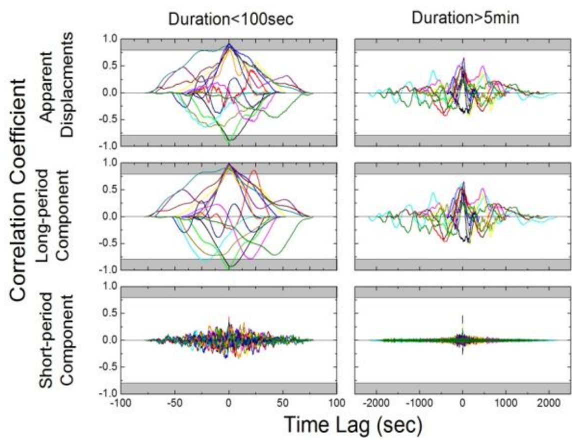

Figure 4. Typical cross correlation curves for two collocated Hiper Pro rover instruments. The gray-shaded area marks results with correlation coefficient > 0.8. No systematic evidence of a time lag between the two receivers exists. Results correspond with the vertical – Up Axis, while similar results were obtained for the horizontal Axes.

Spectra were examined in logarithmic scale permitting the identification of the noise type characterizing the time-series. From Figure 5 it is evident that the noise spectra of the two collocated instruments consist of a mixture of:

● colored noise (inclined line) up to a critical ("transition") frequency **fo**

● white noise (flat spectrum) above critical frequency $\mathbf{f_o}$

The results of the spectral analysis indicate that noise affecting GPS time series is not simply random (white), because a significant part of the noise spectrum corresponds to colored noise. Parameters **α** (spectral index) and **fo** (transition frequency) for each instrument are summarized in Figure 6. Different **α** and **fo** parameters for each instrument (low correlation coefficients between instruments) indicate slightly different noise pattern for each one of the two identical instruments. From Figure 6 it is obvious that the transition frequency **fo** decreases for longer time-series indicating that longer time-series are mostly affected by white noise. Spectral index α falling between -1 and -2 indicates a combination of colored noise plus white noise, a result compatible with results of previous studies (Genrich and Bock, 2006).

At a second step we focused on the statistically significant peaks of the spectra and examined them with regard to the duration of the studied time-series. Typiacl histograms of significant noise frequencies are presented in Figure 7 As obvious from the histograms no characteristic noise frequencies can be identified while for both instruments significant noise frequencies are found below 0.2 Hz.

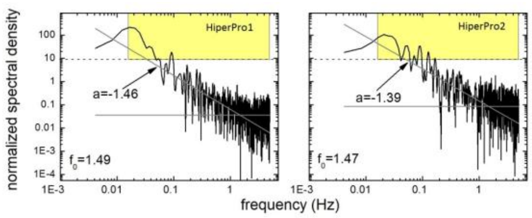

Figure 5 Spectra of the apparent displacement time-series presented in Figure 3 corresponding with two collocated GPS instruments. The yellow area indicates the statistically significant part of the spectra. Noise spectra consist of an inclined (colored noise) part with inclination **α**, which becomes flat (indicative of white noise) after the critical frequency $\mathbf{f_0}$. Values of **α** and $\mathbf{f_0}$ differ between the four instruments indicating slightly different noise processes.

5. SUMMARY OF THE NOISE DISTRIBUTION IN GPS

From the analysis presented in Paragraph 5, it was shown that 10Hz GPS time-series are affected by colored noise the significance of which decreases for high frequencies and after a certain transition frequency only white noise is present Significant differences found between recordings of collocated GPS instruments are mainly due to statistically significant colored noise affecting low (<0.2Hz) frequencies.

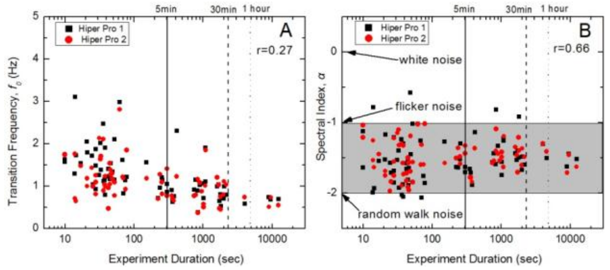

Figure 6 Transition frequency $\mathbf{f_0}$ (transition between colored and white noise) (left) and inclination **α (**right**)** of the inclined part of the noise spectra for 75 time-series of various durations for two collocated GPS receivers. Obviously parameters **f0** and **α** are different between instruments, while the colored noise part corresponds with colored noise processed (flicker noise-random walk noise).

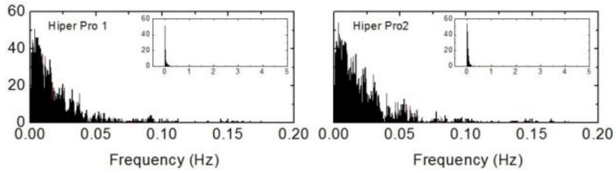

Figure 7 Histograms of the statistically significant spectral peaks for 34 long-duration (5min-3.5hours) apparent displacement time-series from two collocated identical GPS instruments (vertical -Up Axis). Insets show same data but for the whole frequency interval 0-5Hz. Results indicate absence of significant spectral peaks at frequencies >0.2Hz while significant frequencies concentrate towards low frequencies(below 0.08Hz) where also the majority of different frequencies are observed. Histograms were computed for bins (intervals) of 0.0004Hz.

Summarizing the above results, we can assume that GPS measurements are affected by instrument-specific colored noise not characterized by specific frequencies but covering the low frequency (<0.2 Hz) part of the GPS noise spectrum. Colored noise dominates short-duration dynamic measurements while it is less important for long-duration static measurements. The spectral characteristics of noise affecting 10Hz GPS time series are summarized in Equation 1.

$$f_t = \begin{cases} 0.0-0.2Hz \rightarrow \text{statistically significant colored noise+white noise} \\ 0.2-0.4Hz \rightarrow \text{colored noise+white noise} \\ 0.4-2.5Hz \rightarrow \text{transition zone between colored and white noise} \\ \qquad \text{(limit decreases with increase in time series length)} \\ 2.5-5.0Hz \rightarrow \text{only white noise} \end{cases} \tag{1}$$

6. IMPLICATIONS FOR GPS DYNAMIC MEASUREMENTS

As low frequency instrument-specific noise seems to be important for low frequency/short duration measurements (for instance semi-static movements (Nakamura, 2000; Psimoulis and Stiros 2007), there is a possibility of different results from each instrument for such types of displacements.

By high-pass filtering of the apparent displacement time-series instrument-specific colored noise can be significantly reduced leaving only white noise (if the time-series are high-passed above the transition frequency $\mathbf{f_0}$). As a result, after filtering, no significant differences are expected for high frequency dynamic displacements between collocated instruments

A typical example of the above procedure is presented in Figures 1 and 2. The oscillations of a steel footbridge where measured by two collocated GPS instruments. As obvious, apparent displacement time series are significantly different due to low-frequency colored noise. On the other hand, small differences are obvious in the high-frequency component of the time-series. The above is confirmed by spectral analysis, as the same oscillation frequency is identified in the spectra of the high-frequency components from both examined instruments.

7. CONCLUSION

In the present study, the noise characteristics from multiple collocated GPS instruments were examined. It was found that a significant part of the noise affecting high rate (10Hz) GPS measurements is instrument-dependent and presents different characteristics even for identical instruments. This effect presents a big challenge for metrology since GPS is widely used as standard for the measurement of frequency (Lombardi, 2008) and of time, while differences have been observed in various types of electronic instruments measuring physical processes such as acceleration (Wang et al, 2003), rain drop (Tokay et al., 2008) etc., or even instruments used for various industrial measurements (Fisher, 1998).

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