COMPARATIVE TESTING AND ANALYSIS OF RTS VERSUS GPS FOR STRUCTURAL MONITORING USING CALIBRATION MEASUREMENTS UPON SINUSOIDAL EXCITATION

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Abstract: In the past, conventional and satellite surveying methods have been used to monitor the dynamic behavior of oscillating engineering structures. However, only very recently, a thorough examination of their capabilities and limitations in terms of positioning quality measures has been attempted.

This paper presents an experimentally based approach to the study and cross-examination of the modal characteristics of GPS and Robotic Total Stations (RTS) used for structural monitoring applications. Dynamic deformations of a fully controlled sinusoidal form were produced using an oscillating source, on which an on purpose built metallic brace adapter attached to hold the reflector and the GPS antenna. The GPS and RTS were set to record data at sampling rates up to 20 Hz and 6 Hz respectively. A total of 100 sets of experiments were performed to simulate the harmonic motions of known amplitude and frequency values ranging from ±1 cm to ±5 cm and from 0.1 Hz to 2 Hz respectively, which cover the dominant frequency spectrum of most major flexible structures.

Data spectral analysis techniques were employed to compute the parameters (frequency, amplitude) of motion of the oscillating prism and the GPS antenna using the recorded positions. Data analysis was based on two processing methodologies. Under the first scenario, the nominal signal is considered unknown, and therefore, the residuals between the observed signal and its least squares estimates reflect the precision of the measuring sensors. The second scenario simulates a natural system with known motion parameters. In this case, is assessed the ability of the sensors to reproduce the nominal (original) signal.

1. INTRODUCTION AND RESEARCH SPECIFIC OBJECTIVES

In dynamic analysis of high-rise / slender structures the natural vibration properties (frequency, period of oscillation) are of great interest as they refer to and specify their dynamic behavior. Depending on the type and complexity of a structure these properties can be estimated using exact or numerical methods that presuppose knowledge of the loading conditions and of the physical parameters of the system; such as the mass, the mass distribution and the stiffness of the structure (Chopra, 2007). Likewise, based on a totally different approach and methodology, the natural vibration parameters of a structure can be also estimated using deformation monitoring data. The results of deformation monitoring studies combined with the findings of structural dynamic analyses can be used to qualify the integrity and durability of structures as well as for the design verification and justification of associated maintenance costs.

In the past, various types of geodetic sensors have been used to collect and analyze monitoring data of dynamic deformations of structures. GPS and accelerometers were extensively used for structural health monitoring of high-rise buildings / slender structures (Lovse et al, 1995; Ogaja, 2000; Kijewski, 2003) and of cable supported bridges (Nakamura, 2000; Roberts et al, 2004; Guo et al, 2005). Although to a lesser degree, RTS and laser interferometer systems were also used in similar applications (Lovse et al, 1995; Cosser et al, 2003; Palazzo et al, 2006). However, despite the extensive use of these systems in real applications their quality measures (precision, accuracy) in recording harmonic movements have not fully studied and validated. In fact, only few recent studies of the tolerance of individual sensors are known (Gikas and Daskalakis, 2006; Kopacik et al, 2005; Nickitopoulou et al, 2006; Psimoulis and Stiros, 2007).

This paper studies the tolerance of GPS and RTS for dynamic structural monitoring. For this purpose, a single-degree of freedom seismic table of was used to produce oscillations of a fully controlled sinusoidal form. A large number of experiments were conducted to simulate the harmonic vibrations (natural frequency and amplitude values) of various types of actual structures. The specific objectives of this study are to assess separately the performance of GPS and RTS in dynamic structural monitoring in two ways; firstly, in terms of precision (i.e. to study the dispersion of observed displacements in relation to their least squares estimates - the “best fitted” harmonic function) and secondly, in terms of accuracy (i.e. to check for the ability of the systems to reproduce the original (nominal) signal). Furthermore, within the scope of this paper is to perform a comparative analysis and assessment of GPS versus RTS and to conclude (in the form of parametric diagrams) which method deems to be more appropriate for certain applications depending on their natural vibrations properties.

2. INSTRUMENTATION AND EXPERIMENT PROCEDURE

The experimental setup consists of four basic segments:

- the seismic table used to generate controlled oscillations of a sinusoidal type,
- a pair of dual-frequency GPS receivers. The new Leica GX1230 GG (L1/L2) receivers were used because of their ability to record data at high sampling rates (up to 20 Hz),
- a robotic theodolite with accompanying cyclic prism. The Leica TCA 1800 system was used with in-house developed tracking software (Gikas and Daskalakis, 2005)

capable to record raw data with a sampling rate up to 6 Hz and time resolution 10^{-3} sec,
- a PC to control the motion parameters in the oscillator and a laptop to record the RTS data.

In order to enable quantitative comparisons between GPS and RTS data, the GPS antenna and the RTS reflector were placed one after another (i.e. on the same vertical) using an on purpose built metallic brace adapter suitably fixed on the oscillating table. In contrast with observation setups used in the past and in order the experiments to better simulate actual application scenarios, the RTS was set up at a distance nearly 300 m away from the oscillating reflector – a somewhat threefold value to the distance adopted in Gikas and Daskalakis (2005). Furthermore, in order to avoid the interference of the wind on the oscillating sensors, a dead calm day was chosen in order to curry out the experiments.

As already stated, the key objective of this research is to examine the performance of GPS and RTS at the same frequency and amplitude spectra that exhibit actual structures. Therefore, taking into account that most high-rise / slender structures exhibit fundamental natural vibration periods in the range of 0.5 sec - 10 sec (0.1 Hz < f < 2 Hz) and amplitudes between ±0.01m to ±0.05 m, the experiment was scheduled in the following manner. Five groups of tests were performed in which the table was set to oscillate at nominal frequencies 0.1, 0.2, 0.5, 1 and 2 Hz. Each group of experiments comprises four individual tests performed at different amplitude values; i.e. ±0.01, ±0.02, ±0.03 and ±0.05 m, resulting in a total of twenty individual tests.

However, though this set of experiments is assumed adequate for studying the GPS case in a comprehensive manner, further tests were curried out to deliberate the RTS situation. The necessity for extra experiments springs from the fact that RTS behavior depends on the angle (called twist angle thereinafter) that forms the sighting direction of the instrument to the reflector with respect to the direction of the moving reflector. As detailed in Gikas et al (2005), this phenomenon relates to the technical characteristics of the servo motors of the RTS and other factors. Hence, in order to accommodate for this need, every individual experiment was repeated for twist angles 0, 30, 45, 60 and 90 deg. Each individual test was scheduled to collect about 500 observations, which equals approximately 90 sec of data recording.

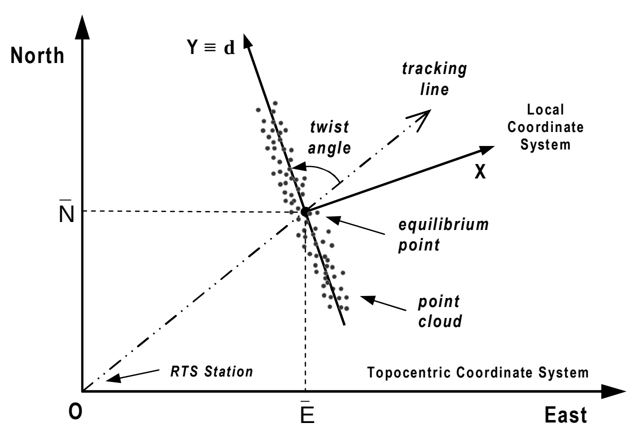

Figure 1: - Coordinate systems

3. PROCESSING TECHNIQUES AND PRELIMINARY RESULTS

For every individual set of observations data processing is performed in two steps, i.e. coordinate computations / coordinate system transformations and computation of the parameters of motion using frequency analysis techniques.

Coordinate computation of the RTS raw data provides the location of the reflector (x, y) directly in the horizontal plane, in a local coordinate system. In contrast, the GPS antenna coordinates are originally derived in their geocentric (X,Y,Z) components, which are then transformed into local, topocentric coordinate system (East, North). Finally, both RTS and GPS local coordinates are rotated about the equilibrium point of the oscillation so that the motion is described in a single direction. Hence, the recorded positions are finally expressed in the form of a time-series (displacement versus time - (d, t)), which is suitable for further analysis (Figure 1). The coordinates of the point of equilibrium are computed statistically as the average value of all clean coordinates recorded in the experiment.

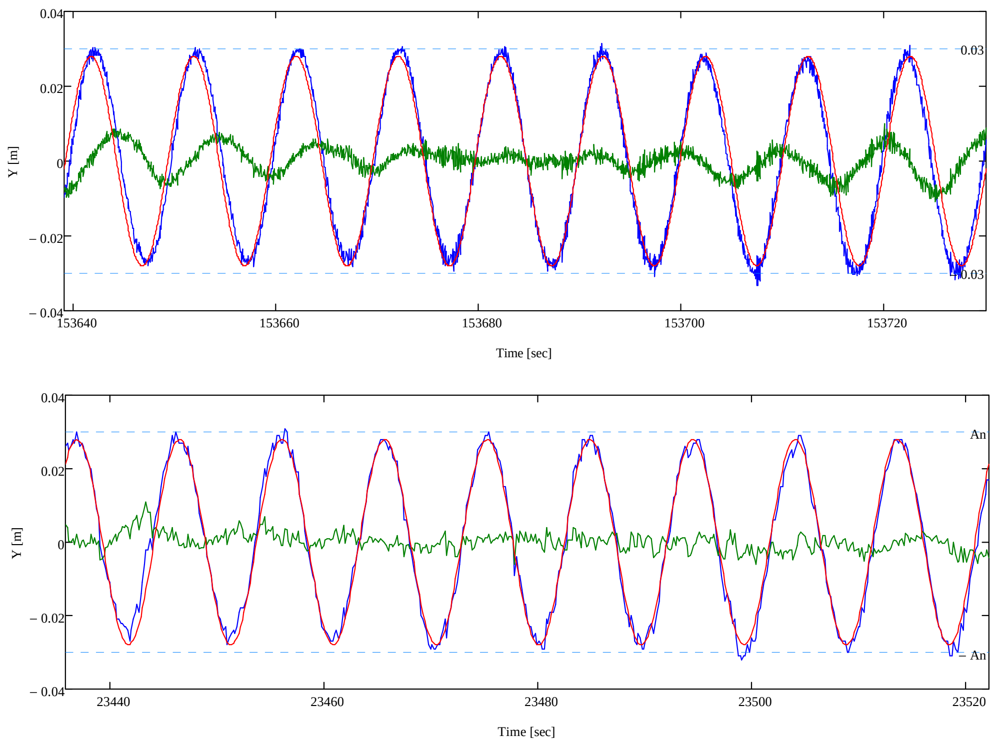

Figure 2 - Observed displacements (bleu), computed displacements (red) and residual values (green) for an amplitude ±0.03 m, frequency 0.1 Hz and twist angle 45 deg for the GPS (up) and RTS (bottom) case

The next stage of data processing involves computation of the vibration motion parameters (frequency, amplitude) of the GPS antenna and the RTS reflector using the time-series of observed displacements, i.e. the (d, t) records. For this purpose standard spectral analysis algorithms were used for the GPS data. For the RTS case, however, because the recorded data are not equidistant more specialized spectral analysis techniques were applied based on the Lomb periodogram (Lomb, 1976). Figure 2 shows a typical example of the computed (modeled) displacements (shown in red) of a measured time-series (shown in bleu) for the GPS and RTS cases. For reasons of completeness, Figure 3 shows the periodogram obtained from the spectral analysis for the RTS data discussed in Figure 2. Similar processing was undertaken for all data sets acquired in the experiment.

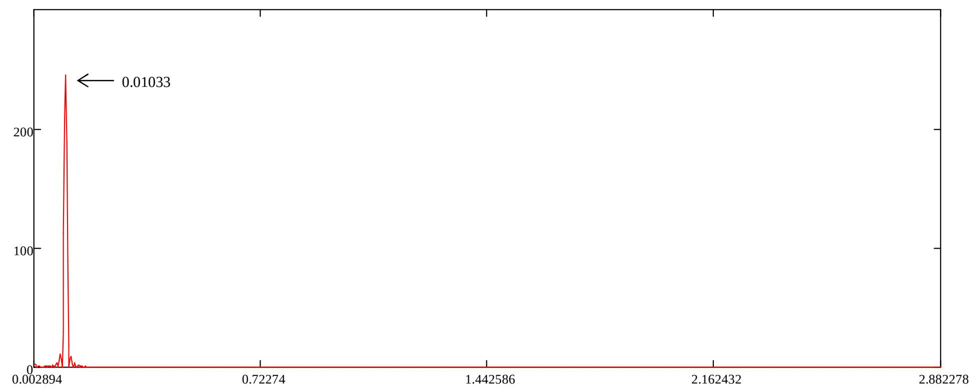

Figure 3: - Periodogram computed for RTS data presented in Figure 2

4. DATA ANALYSIS AND DISCUSSION

4.1. Analysis with Motion Parameters Unknown

The first part of the analysis assumes that the nominal parameters of the motion are unknown, and thus a precision analysis is performed. It involves a thorough examination of the goodness of fit of the computed (modeled) displacements against the measured ones. In essence, for every individual set of measurements a residual analysis is performed. Two statistics were adopted in the analysis, i.e. the mean difference (Mean_Diff) and the root-mean-square difference (RMS_Diff). The mathematical formulation of Mean_Diff is given by:

$$\text{Mean\_Diff} = \frac{\sum_{i=0}^{N-1} \left| residual_i \right|}{N} \tag{1}$$

whereas, the RMS_Diff is computed by:

$$\text{RMS\_Diff} = \sqrt{\frac{\sum_{i=0}^{N-1} residual_i^{\,2}}{N}} \tag{2}$$

where, *residual* denotes the difference between the computed and measured displacement (shown in green in Figure 2) and N indicates the number of measurements collected at an individual test.

Analysis proved that both error estimates produced comparable results; albeit, Mean_Diff, on average produced smaller values. However, in the present study, subsequent analysis is based solely on the RMS_Diff as it is the most well known error statistic and produces minimum variance estimates. Notwithstanding, it is realized that further analysis is required to the study of the nature of the residual values itself (in terms of systematic errors, probability distribution, etc.) that will eventually lead to the selection of the most appropriate error statistic.

Figure 4 and 5 summarize the precision analysis results for the GPS and RTS respectively in the form of parametric diagrams. They present the quality of fit (RMS_Diff) as a function of the oscillation frequency for each system respectively. More specifically, each diagram comprises five curves - one for each of the four amplitude values adopted in the experiment and a curve representing the variation in the average RMS_Diff values.

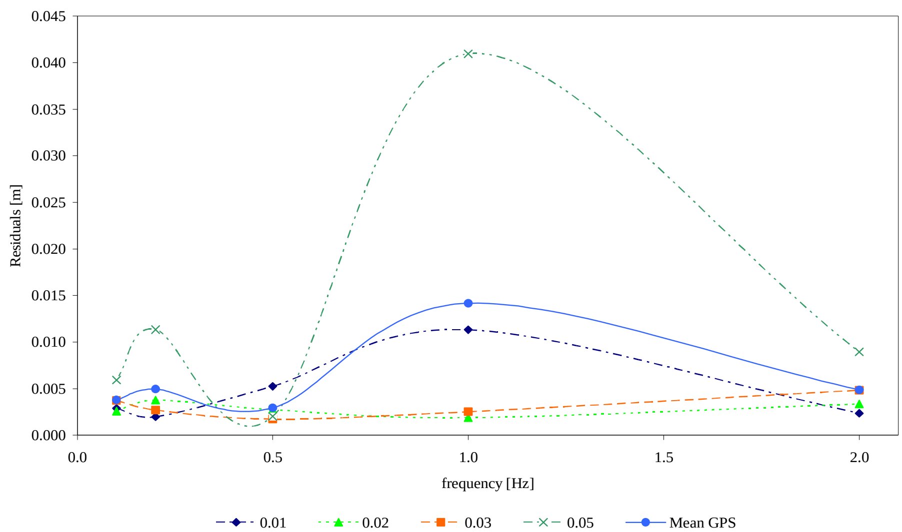

Figure 4: - RMS_Diff versus frequency computed for GPS

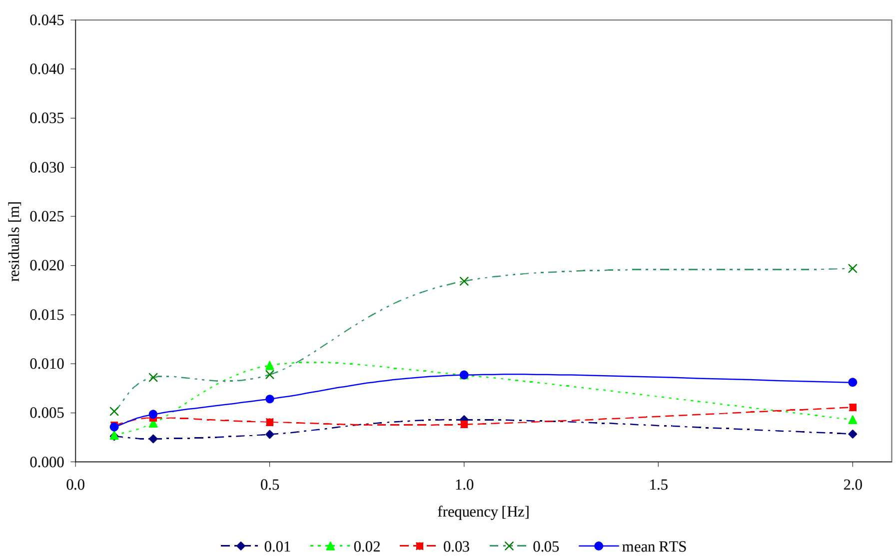

Figure 5: - RMS_Diff versus frequency computed for RTS

The main conclusion to draw from Figure 4 is that GPS can best record oscillations with amplitudes ranging from ±0.02 m to ±0.03 m as the expected residuals are of the order of 0.005 m for all frequency values adopted in the experiment, i.e. 0.1 Hz - 2 Hz. However, when the oscillator was set to operate in amplitudes of 0.01 m and 0.05 m, the analysis results in rather unstable residual values. Fail to record successfully oscillations of particularly small (0.01 m) amplitudes indicates the limitations of GPS system. In contrast, the source of high residual values obtained when the oscillator performs at large amplitudes (0.05 m) is hard to explain and it might relate to external sources of errors such as multipath or abrupt changes in the satellite geometry. Analysis of the RTS data, with only the exemption of large amplitude (0.05 m) and frequency (> 1 Hz) oscillations, exhibits consistent results. More specifically, as shown in Figure 5, all residual values vary between 0.005 m to 0.01 m.

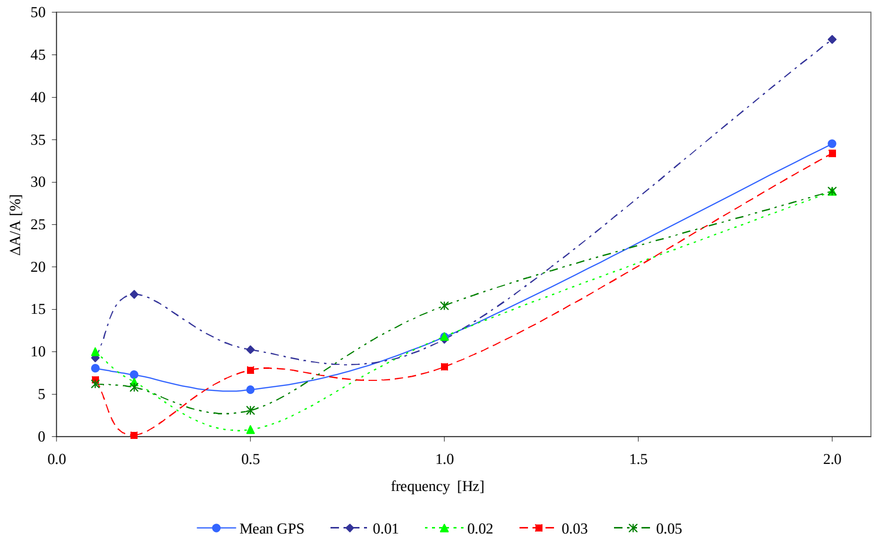

Figure 6 - Percentage difference of computed minus nominal amplitude vs frequency for GPS

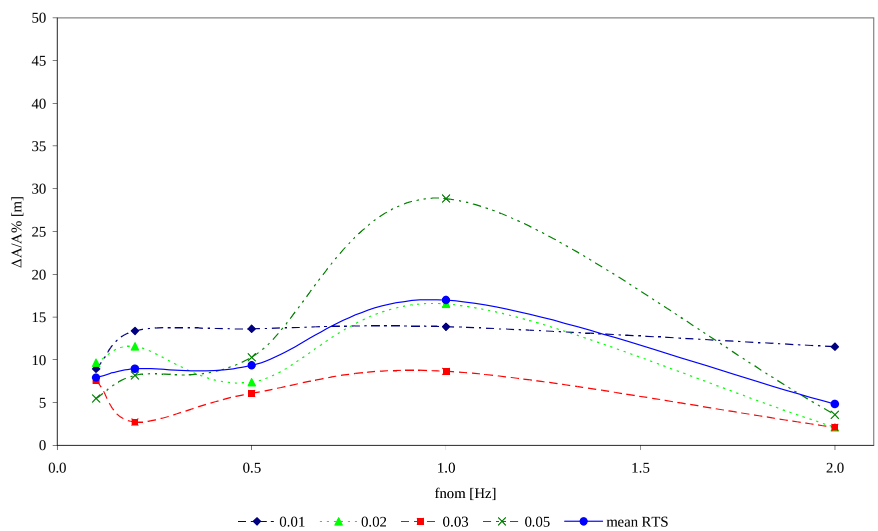

Figure 7: - Percentage difference of computed minus nominal amplitude vs frequency for RTS

4.2. Analysis with Motion Parameters Known

In this study, analysis with known the motion parameters is referred to as accuracy analysis. It aims to investigate the ability of GPS and RTS to reproduce the actual signals, and thus it provides a measure of the reliability of the systems. Accuracy analysis involves the computation of the differences between the computed (modeled) frequency / amplitude estimates and their corresponding nominal (actual) values. These differences are denoted as Δf ($f_{computed} - f_{nominal}$) and ΔA ($A_{computed} - A_{nominal}$), and they are more meaningful if presented in the form of percentage differences with respect to their nominal value, i.e. $\Delta f/f(\%)$ and $\Delta A/A(\%)$. Therefore, in order to be able to assess the performance of an instrument for certain conditions related to an expected vibration, it is useful to produce diagrams of $\Delta f/f(\%)$ and $\Delta A/A(\%)$ as a function either of amplitude or frequency. It should be noted, however, the latter are more useable as for an actual structure it is more likely to be known its natural vibration frequency than its amplitude spectrum.

Figures 6 and 7 show the variation in $\Delta A/A(\%)$ versus frequency for the GPS and RTS respectively. Figure 6 indicates that when GPS is used the error induced in the observed amplitude is of the order of 5% - 15% for frequencies up to 1 Hz; which translates to particularly small error values ($\Delta A_{max} = \pm 0.0015$ m for amplitude ± 0.01 m, and $\Delta A_{max} = \pm 0.007$ m for amplitude ± 0.05 m). However, ignoring amplitude, $\Delta A/A(\%)$ increases substantially (30% - 40%) for frequencies > 1.5 Hz. Also, analysis of the RTS data exhibits some interesting results. From Figure 7 it can be concluded that, ignoring amplitude, $\Delta A/A(\%)$ hardly exceeds 15%. It is important to note that small error values are also derived for high frequencies (1 Hz - 2 Hz), suggesting that the RTS can cope better in higher frequencies compared to GPS. Furthermore, for reasons of completeness, it is pointed out that higher (> 15%) $\Delta A/A(\%)$ values are attributed to the twist angle that the RTS operates and are not further elaborated in this study.

Finally, Figure 8 shows the variation in the average $\Delta f/f(\%)$ error values (i.e. the mean Δf for all frequencies examined in the experiment) as a function of amplitude. In essence, it presents the expected error in the estimation of the vibration frequency of an structure using GPS or RTS. Two points are directly evident from this diagram. Firstly, the error $\Delta f/f(\%)$ is independent of the amplitude and, secondly it is one order of magnitude smaller for GPS (~ 0.4%) compared to RTS (~ 4%). This observation relates to the sampling rate of GPS and RTS; however, in any case both values are still small.

5. SUMMARY AND CONCLUSIONS

This paper studies the performance characteristics of GPS and RTS systems for monitoring the dynamic deformations of oscillating engineering structures. Testing methodology is based on experimental data collection using an oscillating source capable to reproduce the fundamental natural vibration properties of actual structures. Data analysis is based on specialized spectral processing techniques and statistical examination of the results. The results are organised in the form of parametric diagrams; hence, certain conclusions are drawn for the use (suitability, viability) of GPS and RTS in various applications depending on the specific vibration parameters they exhibit.

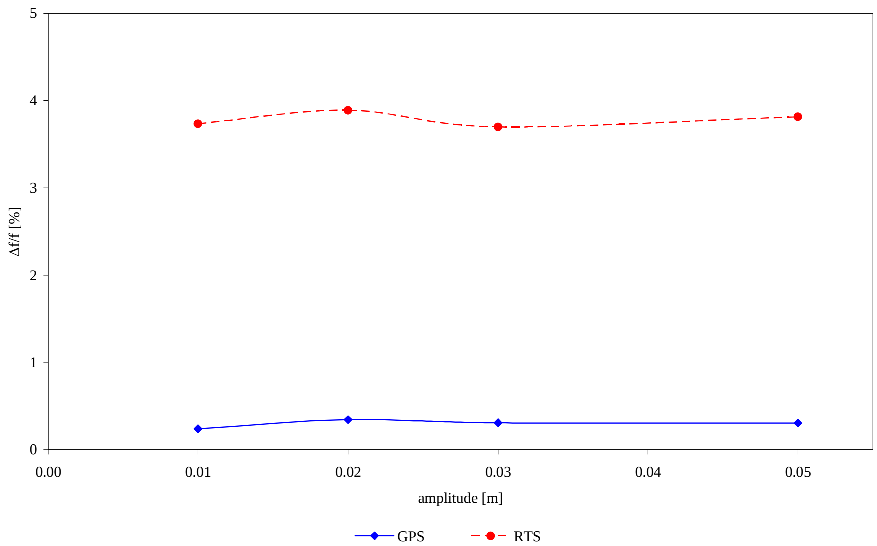

Figure 8: - Percentage difference of computed minus nominal frequency vs amplitude for GPS and RTS

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