Experimental assessment of the accuracy of a Ground-Based Radar Interferometer in a fully controlled laboratory environment

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ABSTRACT

Ground Based Radar Interferometry (GBRI) counts almost twenty years of maturity. Ever since its infancy, GBRI has been extensively used in structural health monitoring, thanks to its high sampling rate (up to 200 Hz) and remote, ultra-high displacement observation accuracy (claimed to be of the order of ± 0.01 mm in lab. conditions) at multi-point locations on a structure. Nevertheless, despite the fact that GBRI has already been extensively used for bridge monitoring projects, the published results of the comparisons derived between GBRI and other technologies (*e.g.*, accelerometers, seismometers and Laser Doppler Vibrometers) are usually limited to real structures cases at operational conditions; and therefore, an exhaustive assessment of the inherent quality measures of GBRI observables is still missing. This paper presents the results obtained from an exhaustive investigation of the performance capabilities of a GBRI sensor (IBIS-S sensor, IDS Radar®), in terms of precision (repeatability) and accuracy (trueness) at fully controlled, lab conditions. Dynamic displacements of a sinusoidal form were produced using an automatically operated portable shake table and on-purpose built software. Testing scenarios cover a frequency range corresponding to structural modal frequencies (up to 20 Hz) and an amplitude range of 10^{-5} to 10^{-2} m. The measurements of a Laser Tracker sensor serve as a benchmark against which the results of the GBRI unit are assessed, in terms of displacement accuracy and frequency estimation correctness.

I. INTRODUCTION

Systematic recording of oscillations in large-scale structures provides critical information regarding their dynamic behavior, and ultimately, the assessment of their structural integrity. This process is performed in the context of structural integrity monitoring (Structural Health Monitoring, SHM) (Farrar and Worden, 2013). Also, monitoring the actual dynamic response of structures contributes to an improvement of their design parameters for future use (Calvi *et al.*, 2008), as well as to the improvement of preventive maintenance strategies (Staszewski *et al.*, 2004). The study of dynamic response of structures is based on physical quantities such as displacement, velocity, acceleration, tension, inclination and strain. Among them, measures of displacement surpass other parameters in structural integrity monitoring studies, as structural modal frequencies do not usually exceed 20 Hertz (Hz). For the extraction of the dynamic characteristics of structures (modal frequencies, modal shapes, damping coefficient, etc.) methodologies such as Operational Modal Analysis (OMA) (Zhang and Brincker, 2005) are used. They rely on vibrations referred only to environmental and operational excitation such as wind, temperature variation and road traffic. Contrarily, Experimental Modal Analysis (EMA) (Cunha *et al.*, 2006) entail structural oscillation measurements resulting from controlled excitations. A key challenge of OMA techniques relates to the fact that the dynamic response of structures under functional / environmental excitations is extremely low, with an oscillation amplitude ranging from a few centimeters, for more flexible structures (Rodelspelger *et al.,* 2010) down to and below a millimeter, for the most rigid ones (Gikas *et al.,* 2019). This feature dictates using extremely high performance displacement sensors (in terms of sensitivity, accuracy, precision, sampling rate, etc.) to depict the actual structure kinematics and their frequency content. In addition, the same quality characteristics necessitate for detecting structural defects (Farrar and Worden, 2013) through tracking local variations in the dynamic response, associated to minor changes in the pattern of oscillations (Rezvani *et al.,* 2018). However, despite the substantial advantages, measuring dynamic displacements in SHM applications is still a cumbersome and specialized task (Dong *et al.,* 2019). Many technologies allow the direct measurement of displacements at individual points of a structure with high accuracy (of the order of a few millimeters or better), but none of them has been established in practice, as a benchmark for monitoring the structural integrity of structures. These technologies include: digital levels (Owerko *et al.,* 2012), extensometers (Ziaei *et al.,* 2017), robotic total stations (Psimoulis and Stiros, 2007), differential methods of GNSS (Moschas, 2014), accelerometers (Bartoli *et al.,* 2008), Linear Variable

Differential Transformers (LVDTs) (Song *et al.,* 2007), Digital Image Correlation (DIC) (Piniotis *et al.,* 2016) and Laser Doppler Vibrometers (Gocal *et al.,* 2013). Ground Based Radar Interferometry (GBRI) is a non-destructive technology for monitoring vibrations of structures, such as bridges, buildings, high structures, etc. GBRI provides remote displacement measurements with high sampling rate (up to 200 Hz) and extremely high accuracy (better than ± 0.1 mm), which is claimed to be of the order of ± 0.01mm in laboratory conditions. In the past, several studies have examined the performance of GBRI technology against alternative technologies in applications of structural response monitoring. However, the published studies to the best of the authors knowledge, are limited to comparisons of displacement time series in project-scale structural measurement scenarios. These studies do not account for critical parameters in data collection such as sensor installation strategies, data sampling or synchronization issues with other sensors and do not consider for methodological issues concerned with data processing and analysis. The objectives of this work are: (i) the experimental testing and performance assessment of a real aperture ground based radar interferometer (IBIS-S radar; Ingeneria Dei Systemi, IDS) in dynamic monitoring (oscillations) in controlled laboratory conditions, and by extension, (ii) to demonstrate the potential (capabilities and limitations) of the GBRI technology.

A. *GBRI technology in dynamic monitoring of structures*

Monitoring structural behavior and condition of structures aims at evaluating their performance against operating loads, detecting potential damages, and overly assessing their structural integrity (Technical Chamber of North Greece, 2009; Farrar and Worden, 2013). Benefits include the improvement of their safe operational level, through early warnings in case of damage or failure, the reduction of maintenance costs, through preventive interventions, and the increase of structural efficiency, as a result of reducing downtime for maintenance work.

In this context, GBRI technology has been used in monitoring buildings (Luzi *et al.,* 2017), bridges (Bartoli *et al.,* 2008; Gentile, 2010; Piniotis *et al.,* 2016), masonry towers (Pieraccini *et al.*, 2013), industrial chimneys (Rodelspelger *et al.*, 2010; Piniotis *et al.*, 2013), suspension cables of cable-stayed bridges (Piniotis *et al.*, 2016), wind turbines (Pieraccini, 2013), cable masts (Gentile and Ubertini, 2012) and lighting pylons (Kuras *et al.*, al. 2009).

B. *Previous related work*

Evaluation of IBIS-S radar performance in structural monitoring applications has been previously performed against accelerometer sensors (Bartoli *et al.*, 2008), velocity sensors (Gentile, 2010), seismometers (Negulescu *et al.*, 2013), inductive gauge (Beben, 2011) thermal camera (Stabile *et al.*, 2012), video recording system (Kohut *et al.*, 2012), laser interferometer and Laser Doppler Vibrometer (Gocal *et al.*, 2013). In the latter, the static-semi-static performance of GBRI technology was studied, through thoroughly designed experimental tests demonstrating an accuracy of ± 0.1 mm. Gocal *et al*. (2013) also compared the dynamic displacement measurements of the IBIS-S radar with the corresponding measurements of a Laser Doppler Vibrometer, in real conditions of monitoring a tram crossing bridge, confirming an accuracy better than ± 0.1mm. A thorough examination of the relevant literature reveals that, in most studies, the evaluation of the IBIS-S radar system is performed in real structures through comparative presentation of measured displacement, velocity or acceleration time series against other sensors' data, and in some cases frequency domain diagrams, providing no further quantitative or qualitative investigation.

II. INSTRUMENTATION AND EXPERIMENTAL SCENARIOS

A. *Experimental design requirements*

This research aims to evaluate the GBRI displacement measurements in terms of precision (repeatability) and reliability (correctness) in laboratory conditions, under controlled dynamic oscillation scenarios, with oscillation characteristics corresponding to the dynamic characteristics of large-scale structures. More specifically, evaluation of the sensor under examination (IBIS-S, IDS) relies on comparisons between the radar measured displacements against those of a Laser Tracker sensor, while producing oscillations via a portable shake table of one degree of freedom.

In order to ensure that the research goals were achieved, the following prerequisites should be met:

- Conducting of the experiments in a suitable laboratory space, that can drastically reduce the presence of unwanted signals (electromagnetic interference, reflected signals, etc.) and additionally ensure the operational stability of the measurement systems and the absence of external environmental conditions (*e.g*. wind).
- Design of observation scenarios with emphasis on the oscillation characteristics of large-scale structures, in which, the oscillation amplitude decreases as the oscillation frequency increases. More specifically, oscillation amplitudes from μm (response proportional to rigid structures) to a few cm (response proportional to flexible structures) were selected. The range of the oscillation frequencies is representative of the modal frequencies that most structures demonstrate (up to 20 Hz).
- Adequate sampling frequency of measurement systems for the correct representation of displacement time series. According to ISO 4866:

2010 (Kuras, 2015), the sampling frequency in oscillation measurements must be at least five times higher than the highest oscillation frequency value, in order to reliably represent the motion event.

- Satisfy specific, preselected dynamic oscillation characteristics (amplitude and frequency) for each experimental scenario.
- Ensure sufficient amount of measurements to ensure the necessary analysis in determining the response frequency.
- Strict alignment of the IBIS-S radar line of sight (LOS) with the motion axis of the shake table so that the observables of both systems are directly comparable.
- Accurate synchronization of recording systems, required for the automation of data processing.

B. *Test site and instrumentation*

Data collection took place in the anechoic chamber of the Laboratory of Wireless and Long Distance Communications of the School of Electrical and Computer Engineering, NTUA (Figure 1). The chamber is used for laboratory testing of electromagnetic radiation equipment, as it effectively neutralizes or reduces reflected waves (Chronopoulos, 2017). It is a specially designed cage, insulated from external radiation sources and lined up with suitable tiles for the absorption of unwanted electromagnetic signals.

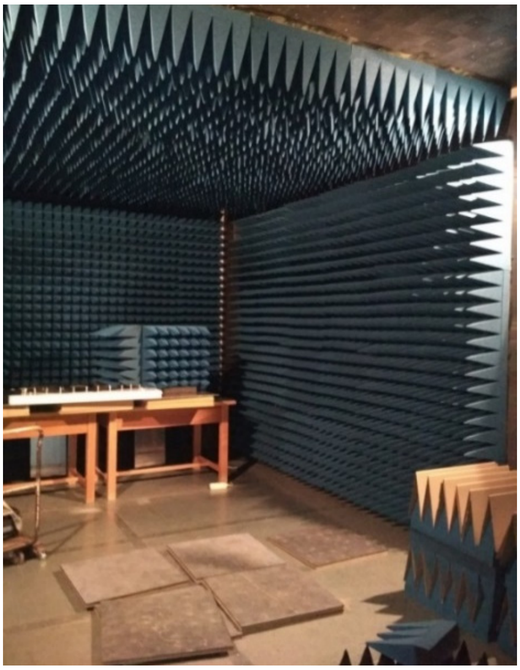


Figure 1. The anechoic chamber of the Laboratory of Wireless and Long Distance Communications, of the School of Electrical and Computer Engineering, NTUA.

The device used for oscillation generation consists of two parts, the electrodynamic power generator (shake table) ELECTRO-SEIS® Shaker 400 by APS Dynamics and the amplifier APS EP-124. The shake table allows for a maximum oscillation amplitude of ± 8 cm and a frequency range from 0.01 Hz to 200 Hz (APS 400 Data sheet & manual). The APS EP-124 unit amplifies the incoming electrical signal and supplies the shake table with the appropriate electrical power. The amplitude of the shake table oscillation is altered by controlling its power supply through the amplifier. During the experimental process, the shake table was set to sinusoidal oscillation at pre-determined values of oscillation amplitude and frequency for each observation scenario. To control the oscillation frequencies and monitor the corresponding amplitude, an on purpose built PC software was developed in Labview programming language. The 6211-USB (National Instruments®) digitizer was used to connect and "drive" the shake table from a PC.

In order to cross check the shake table motion performance, a velocity measuring sensor, namely a Laser Doppler Vibrometer/LDV (VibroMet 500V) was used. The LDV sensor was set to measure the velocity of a metallic target that was fixed suitably on the moving shake table platform.

Since the motion of the shake table was set to be sinusoidal at a specific, unique frequency (f) for every scenario, the conversion of velocity data to displacements was straightforward, through their division by the term (2 × π × f). This was accomplished by the in house built Labview software routine, in real time, after having collected and digitized the raw velocity data. With this process, the peak to peak amplitude of the shake table's oscillation was displayed in real time on the PC screen, enabling the adjustment of the default nominal oscillation amplitude for each experimental scenario, by the appropriate tuning of the shake table's power supply through the amplifier.

The evaluation of the performance of the IBIS-S radar was performed by comparing its results with those of the Faro® Laser Tracker Vantage sensor. The Laser Tracker system is a portable device capable of computing the 3D coordinates of the system's target (Spherical Mount Reflector, SMR), through extremely accurate measurements of the zenith angle, the horizontal angle and the radial distance to the target. It uses the Absolute Distance Meter (ADM) phase shift technology to measure distances, while it utilizes a built-in meteorological station for their correction. The accuracy of the instrument, according to standard ASME B89.4.19-2006, is expressed in the form of the maximum permissible error (Maximum Permissible Error, MPE), which is ± 16 μm + 0.8 μm / m for distances and ± 20 μm + 5 μm / m for angle measurements (FARO Laser Tracker Vantage Manual). According to Faro®, the standard performance of the sensor corresponds to accuracy that is half the value of the aforementioned Maximum Permissible Errors (MPE). The system has an effective range of 0 m - 80 m and is used for static as well as dynamic measurements, due to its high sampling frequency (1000 Hz).

C. *Instrumentation setup*

The experiment regards measuring the harmonic oscillations performed by the shake table at specific pair values of nominal frequency and amplitude. For this purpose, a passive GBRI system target (metallic cone), a Laser Tracker system SMR target and an LDV metallic target were properly fixed on the moving surface of the shake table (Figure 2).

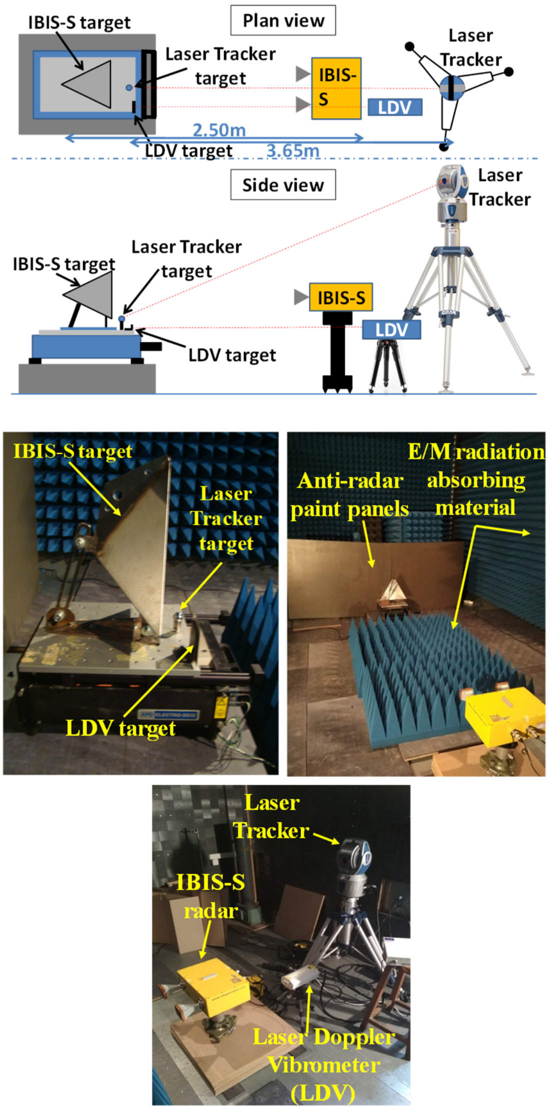


Figure 2. Instrumentation setup.

Then, the measuring systems were placed so that their lines of sight were parallel to the motion axis of the shake table. To ensure adequate accuracy in the alignment, the Laser Tracker was used in the setting out process.

This setup allowed for a direct comparison of the shake table's oscillation amplitude as resulted from the two observation systems (*i.e.*, the radar IBIS-S and the Laser Tracker).

Prior to experimental testing, in order to determine the noise level of the radar sensor in the anechoic chamber, a series of measurements were performed with the shake table being stationary.

The scope of this investigation was to determine the signal amplitude attributed to noise due to various sources of error; for instance, signal interference, signal reflections and building microtremors, or other unusual patterns, suggesting problems in observational conditions. As shown in Figure 3, the estimated noise level is extremely low, as the apparent displacement is of the order of 3 μm maximum (standard deviation of ± 0.8 μm).

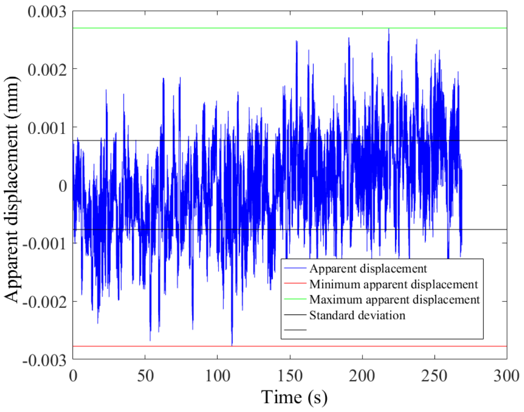


Figure 3. Apparent displacement with stationary shake table.

In addition, the results of the measurement series of the stationary radar target are presented in a Box & Whisker plot (Figure 4). All observation scenarios exhibit a mean noise value of less than 10 μm (maximum mean value: 8 μm) and maximum standard deviation ± 2.6 μm. This value is considered negligible, confirming the ideal experimental conditions and emphasizing the high precision (repeatability) of the IBIS-S radar, which proves to be better than ± 0.01 mm in laboratory conditions.

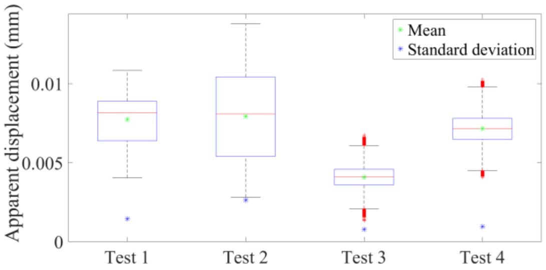


Figure 4. Apparent displacements' Box & Whisker plot.

D. *Experimental scenarios*

The sampling frequency for both recording systems was set at 200 Hz (ten times the maximum oscillation frequency of the shake table) to ensure dense representation of the vibration events. Scenarios of low oscillation frequencies (1 Hz – 5 Hz) paired with oscillation amplitudes ranging from 0.5 mm to 20 mm, whilst scenarios at higher frequencies (10 Hz - 20 Hz) paired with signal amplitudes spanning from 0.05 mm to 0.75 mm. In total, 25 experimental scenarios were performed, summarized in Table 1.

Table 1. Experimental scenarios. F= frequency; A= Amplitude

f (Hz) @ A (mm)
1 @ (5, 10, 15, 20)
2 @ (1, 5, 10, 15)
5 @ (0.5, 1, 5)
10 @ (0.05, 0.1, 0.5, 0.75)
15 @ (0.05, 0.1, 0.25, 0.3)
20 @ (0.05, 0.075, 0.1, 0.1, 0.1, 0.2)

Since data synchronization was not possible via an absolute (*e.g.* GNSS) or relative (*e.g.* triggering) time source, synchronization was accomplished via two excitation events using the cross-correlation method. Both events were realized through appropriate modifications in the shake table's Labview "driving" software, to perform instant "start" and "stop" operation.

III. DATA PROCESSING AND RESULTS' ANALYSIS

Considering raw data processing, custom software was developed in Matlab® programming language to implement the following tasks:

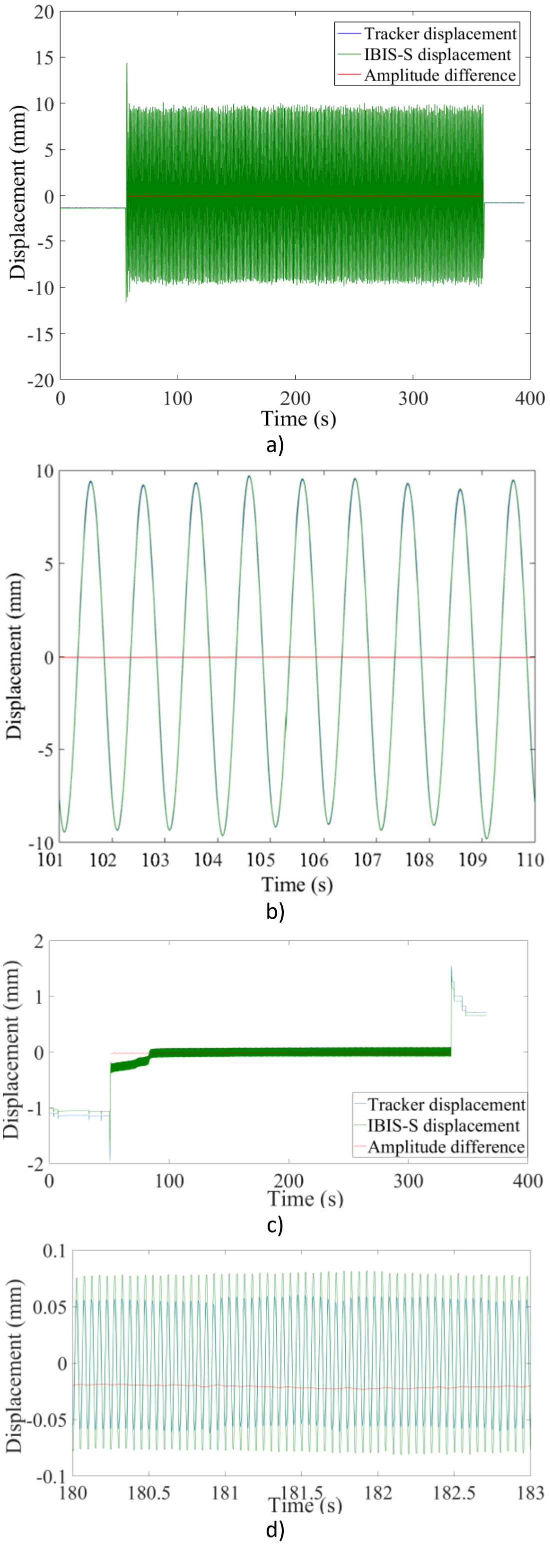
- Compute the time difference between the signals of the two measurement systems through cross-correlation.
- Visualize the synchronization outcome of the cross-correlation event via plotting the time series of the synchronized signals.
- Generate the Power Spectral Density (PSD) diagrams for each dataset and derive the oscillation frequency value.
- Compute the oscillation amplitude for both systems' signals via calculating half of the difference between the local maximum and local minimum, for each oscillation period and store the matrix of oscillation amplitudes.
- Compute the differences in the oscillation amplitude for both measurement systems.
- Create the histogram of the oscillation amplitude differences for each experimental scenario.

A. *Time domain analysis*

Detailed examination of the synchronized time series data of the two systems (Laser Tracker and GBRI) confirmed the ultra-high degree of coincidence of the results.

Figure 5 shows the oscillation time series obtained for both systems for two representative trials – *i.e.*, a low (f=1 Hz, A=10 mm) and a high frequency (f=20 Hz, A = 0.1 mm).

Statistical analysis of the oscillation amplitude differences (not shown here), reveal a strong normal distribution pattern. However, the most prominent findings result from the analysis of the Empirical Cumulative Distribution Function (ECDF) diagrams organized according to their nominal frequency.



a)

b)

c)

d)

Figure 5. a) and b) Oscillation time series and zoomed in instances obtained from both systems, for low frequency (f=1 Hz, A=10 mm); c) and d) high frequency (f=20 Hz, A = 0.1 mm).

Analysis of the ECDF diagrams (Figure 6) suggests that the trueness (deviation from nominal value) of IBIS-S system is substantially better than ± 0.1 mm, in laboratory conditions. Except from two test scenarios all values of amplitude differences range from -0.10 mm to 0.02 mm. The ECDF curves demonstrate a highly steep slope, suggesting that the vast majority of observed amplitudes follow closely their nominal values.

In addition, it is apparent that as the oscillation amplitude increases, for scenarios performed at the same nominal oscillation frequency, the slope of the ECDF curve decreases, indicating an increase in variability.

This phenomenon probably reflects a small error in the alignment between the line of sight of IBIS-S radar and the actual direction of oscillation, also affected by the small difference in the targets' location that becomes clear for largest oscillation widths (see Box and Whisker plot in Figure 7).

B. *Frequency domain analysis*

For the evaluation of the IBIS-S system in the frequency domain, power spectral density diagrams were built on a linear scale for the two sensors. For each sensor and experimental scenario, the nominal oscillation frequency of the shaker is dominant, *i.e*. the resulting frequency values for each observation scenario coincide with each other and with the corresponding nominal frequency of the shake table. This demonstrates the excellent performance of the IBIS-S system in determining frequencies. Also, the power spectral density diagrams were examined on a logarithmic scale. In this form, in addition to the dominant motion frequency, low value frequencies and harmonics of the nominal frequency are also evident, as a result of the imperfect sinusoidal motion of the shake table. In particular, since the shake table was not operated in a closed loop (no feedback sensor was used), and thus, its electrical control power was not corrected in real time, its motion was not perfectly sinusoidal. However, for the needs of the present work, the creation of a "perfect" sinusoidal motion is not required, as the research goal is to compare the measured signals from two measuring systems while monitoring the same phenomenon, *i.e*. the shake table movement.

IV. CONCLUDING REMARKS

This paper offers a systematic attempt to evaluate the accuracy (precision and trueness) and potential of a Ground Based Radar Interferometer/GBRI (IBIS-S, IDS) in laboratory conditions. The experimental process utilizes a shake table to generate oscillations of known characteristics in a controlled laboratory environment and a Laser Tracker system as a means of evaluating the GBRI system. As the interest of this study is focused on monitoring the dynamic behavior of large-scale structures, the oscillation characteristics (frequency and amplitude) are selected to represent corresponding modal frequencies and amplitudes.

Statistical analysis of the experimental results shows that the precision (repeatability) of the system is ± 0.01 mm or better and its accuracy (reliability) better than ± 0.1 mm. Additionally, the extremely high sensitivity of the system in the determination of oscillation frequencies up to 20 Hz and amplitudes of less than 1 mm is proven.

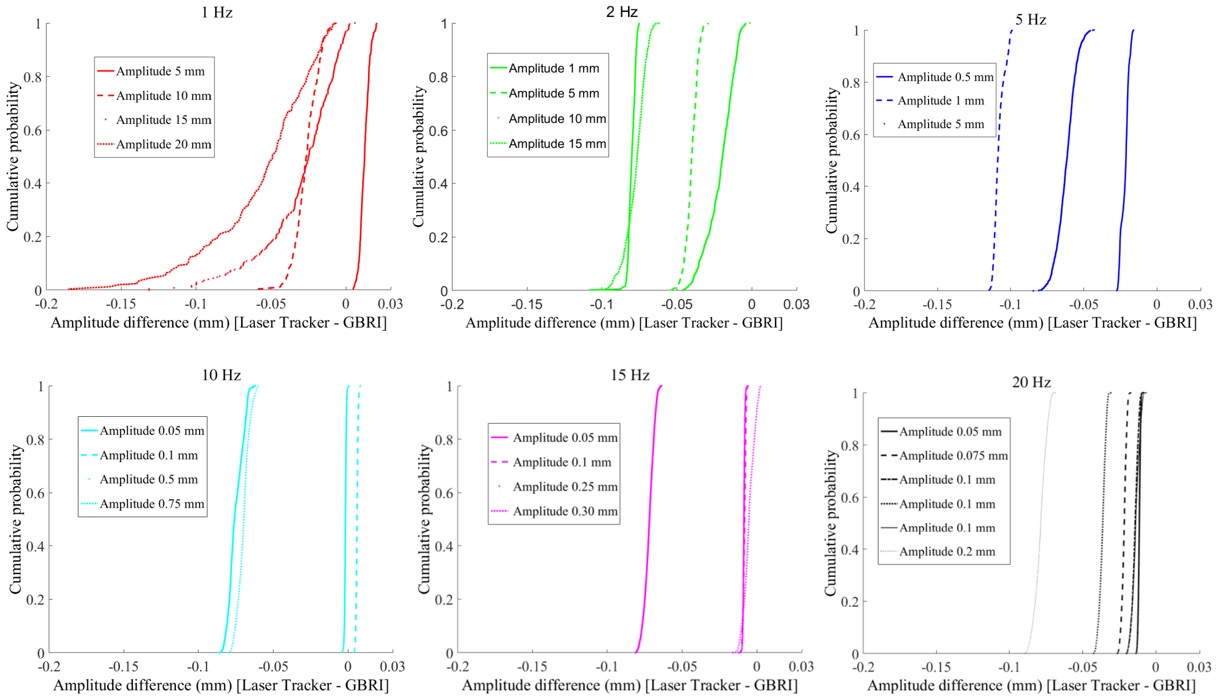


Figure 6. Empirical Cumulative Distribution Function (ECDF) diagrams, organized according to nominal frequency.

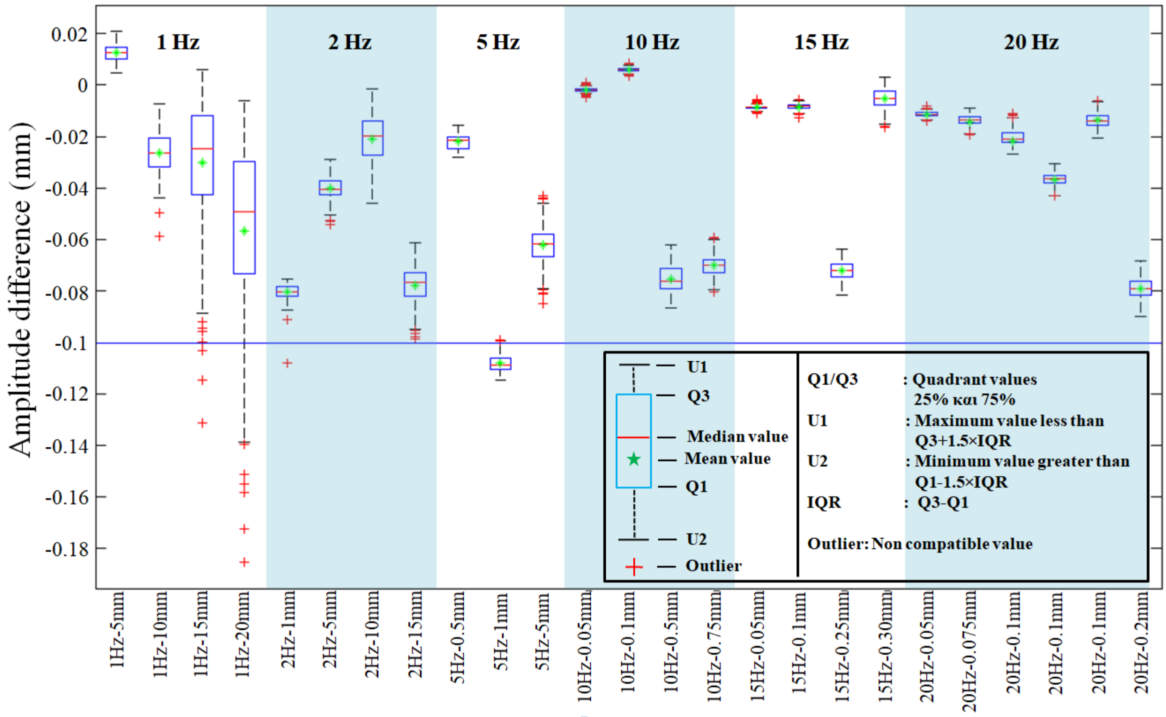


Figure 7. Box and Whisker plot of all experimental scenarios.

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