# Final Report of APMP.AUV.V-K3.1: Key comparison in the field of Acceleration on the complex voltage sensitivity

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# 1. Introduction

This report presents the results of the APMP comparison in the area of 'vibration', which here refers to the calibration of the accelerometer standards set in compliance with method 1 or method 3 as recommended in the international standard ISO 16063-11:1999.

The participants have reached a consensus and considered the most appropriate method, then referred to CCAUV.V-K3 report [1], the weighted mean and the degrees of equivalence were evaluated for this particular comparison. The calculation of the key weighted mean was in accordance with the Guidelines for CIPM key comparisons [2].

The "linking" procedure was applied to establish the relationship between the results of the participants and those of the CIPM comparison in the field of vibration, which was CCAUV.V-K3. Only one pilot laboratory, NIM, acted as the linking laboratory. The linking factors were defined as the ratio and difference for magnitude and phase shift respectively through the NIM results in CCAUV.V-K3 and APMP.AUV.V-K3.1. Using the linking factors, this RMO results of six participants were directly compared with the results of CCAUV.V-K3.

The Technical Protocol presented in Annex A, shows the aim and the task, the conditions for the measurements, the transfer standard used, the measurement instructions and the time schedule of this comparison.

# 2. Participants

Six national metrology institutes (NMIs) from Asia Pacific Metrology Programme (APMP), and Intra-Africa Metrology System (AFRIMETS) participated in the comparison. They are listed in the chronological order of measurement in Table 2.1.

# 3. Task and purpose of the comparison

According to the rules set up by the CIPM MRA, the consultative committees of the CIPM have the responsibility to establish degrees of equivalence between the different measurement standards operated by the NMIs. This was done by conducting key comparisons (KC) on different levels of the international metrological infrastructure. The previous key comparisons CCAUV.V-K1, CCAUV.V-K2, and CCAUV.V-K3, in the frequency range 40 Hz to 5 kHz, 10 Hz to 10 kHz and 0.1 Hz to 40 Hz were completed in the year 2001, 2014 and 2016, respectively.

Recently, the APMP NMIs had improved the calibration capabilities and extended their low-frequency vibration limit down to 0.1 Hz. Thus, the decision was taken to launch the preparation of comparison during the meeting of APMP TCAUV in 2017. The task of the comparison was to compare measurements of linear vibration calibration within the frequency range 0.1 Hz to 40 Hz.

The results of this APMP comparison will, after approval by CCAUV, serve as supporting evidence for "calibration and measurement capabilities" (CMCs) at low vibration frequency.

Table 2.1 List of participants and schedule of APMP AUV.V-K3.1

| No. | Participant Laboratory | Acronym | Economy | Calibration period (Y/M/D) | Remark |
|---|---|---|---|---|---|
| 1 | Center for Measurement Standards - Industrial Technology Research Institute | CMS-ITRI | Chinese Taipei | 2018/05/21 to 2018/05/27 | Pilot institute |
| 2 | National Institute of Metrology, China | NIM | China | 2018/06/05 to 2018/07/08 | Coordinating institute |
| 3 | National Institute of Metrology (Thailand) | NIMT | Thailand | 2018/07/16 to 2018/07/29 | |
| 4 | Korea Research Institute of Standards and Science | KRISS | Republic of Korea | 2018/08/06 to 2018/08/19 | |
| 5 | National Metrology Institute of South Africa | NMISA | South Africa | 2018/08/27 to 2018/09/09 | |
| 6 | CSIR - National Physical Laboratory of India | CSIR-NPLI | India | 2018/09/17 to 2018/09/28 | |

The results of this comparison are expected to provide direct support to CMCs related to the primary calibration of complex voltage sensitivity of both acceleration measuring chains and accelerometers at low frequencies. This support could be extended to a wider scope of measurements, including primary calibration of complex voltage sensitivity and current sensitivity of accelerometers.

For the calibration of the accelerometer standard set, method 3 of the international standard ISO 16063-11:1999 had to be applied for the entire frequency range. Specifically, the magnitude of the complex voltage sensitivity had to be given in millivolts per meter per second squared (mV/(m/s$^2$)) and phase shift in degrees (°) for the different measurement conditions specified in the Annex A. The reported complex voltage sensitivities and associated uncertainties were used for the calculation of the degrees of equivalence between the participating NMI and to the KCRV computed for CCAUV.V-K3.

## 4. Transfer standard used as artifact

For the purpose of the comparison, the pilot laboratory selected one accelerometer for which the monitoring data during the interval of ten months were available and not included in any published international cooperation work.

- One transfer standard accelerometer (single-ended), type SA704, S/N 1054 (manufacturer: NIM).
- One signal conditioner, type MSA-I, S/N 131211 (manufacturer: NIM).

The artifact set was monitored by the pilot laboratory at least once a month before and after the circulation. The monitoring results show the artifact was in controlled condition based on the collected data.

## 5. Circulation of the artifact

The transducer set was circulated between the participating laboratories considering a measurement period of two weeks provided for each participating laboratory and one week for the pilot laboratory. Any careless drop could change its sensitivity or even damage it; therefore, the artifact set was hand-carried during transportation between participants with great caution.

## 6. Results of the monitoring measurements

Starting with calibration data in July 2017, the accelerometer standard set was measured by the pilot laboratory before and after the circulation of the artifact. As a representative of the overall variation during the monitored period, the measurements at several sample frequencies are shown in Figure 6.1 and Figure 6.2

The stability of the artifact was monitored through a series of monitoring measurements. The measurement results are summarized by the statistical properties and are shown in Tables 6.1 and 6.2. This analysis indicates that the stability of the artifacts was acceptable considering the standard uncertainty claimed. It is worth noting that the option of gain 100 was selected on the conditioner for frequencies from 0.1 Hz to 0.4 Hz. To allow direct comparison with the magnitude of sensitivity results for the frequencies higher than 0.4 Hz, the normalization of 1/100 was used to describe the monitoring results.

Table 6.1 Mean and its relative standard deviation of voltage sensitivity of the artifacts calculated from the monitoring measurements.

| Frequency (Hz) | Long term mean (mV/(m/s$^2$)) | rel. std. dev. (%) | rel. std. unc. (%) |
|---|---|---|---|
| 0.1 | 131.08 | 0.02 | 0.15 |
| 0.5 | 131.03 | 0.02 | 0.15 |
| 1 | 130.98 | 0.03 | 0.15 |
| 1.6 | 130.96 | 0.03 | 0.15 |
| 6.3 | 130.97 | 0.02 | 0.15 |
| 10. | 130.97 | 0.02 | 0.15 |
| 16 | 130.98 | 0.02 | 0.15 |
| 40 | 131.68 | 0.02 | 0.15 |

Table 6.2 Mean and its standard deviation of phase shift of the artifacts calculated from the monitoring measurements

| Frequency (Hz) | Long term mean ( ° ) | abs. std. dev. ( ° ) | abs. std. unc. ( ° ) |
|---|---|---|---|
| 0.1 | -0.37 | 0.01 | 0.15 |
| 0.5 | -0.02 | 0.01 | 0.15 |
| 1 | -0.07 | 0.01 | 0.15 |
| 1.6 | -0.09 | 0.01 | 0.15 |
| 6.3 | -0.24 | 0.01 | 0.15 |
| 10 | -0.41 | 0.02 | 0.15 |
| 16 | -0.66 | 0.02 | 0.15 |
| 40 | -1.90 | 0.02 | 0.15 |

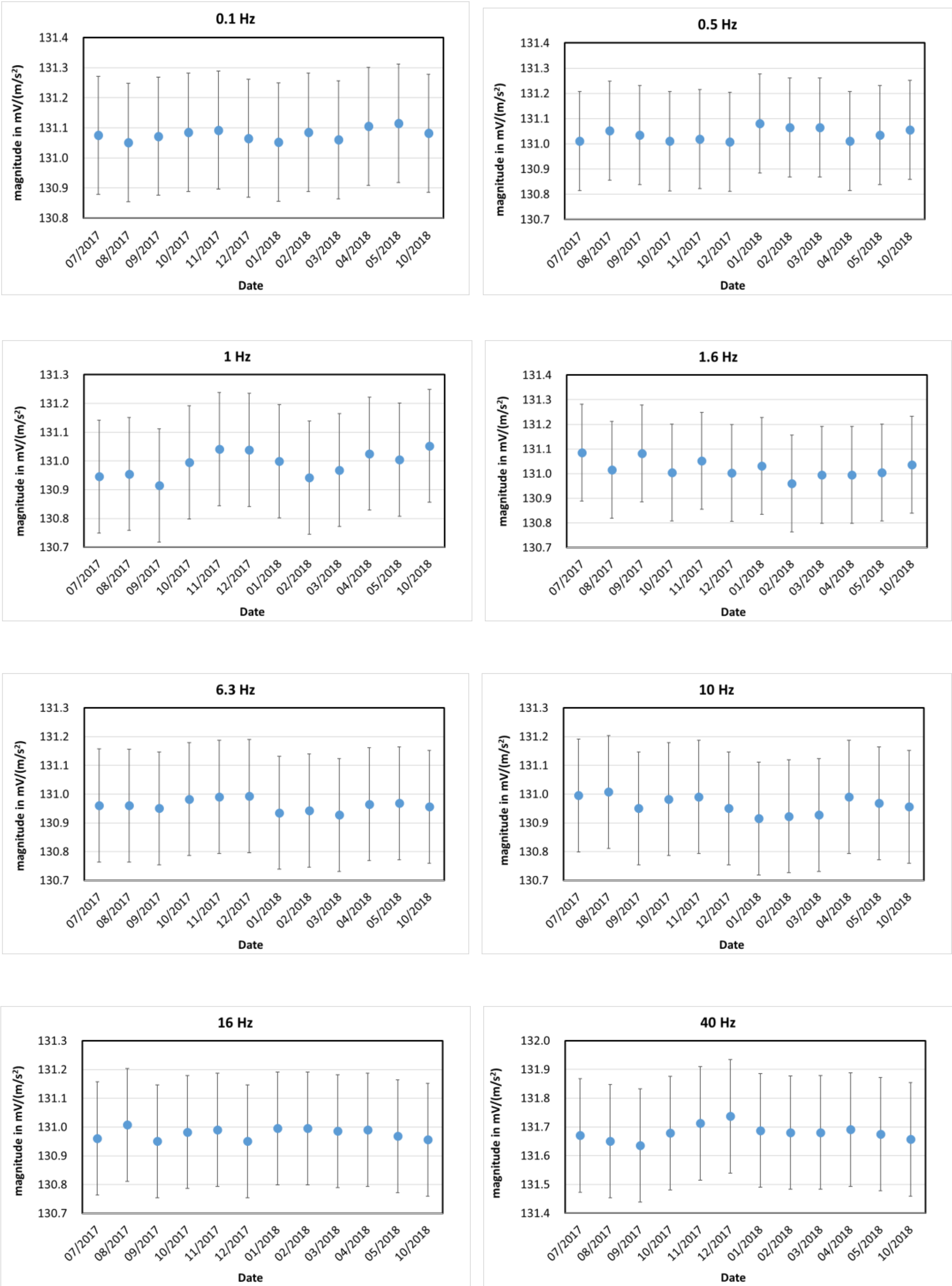



Figure 6.1 Monitoring of the voltage sensitivity over the comparison period.

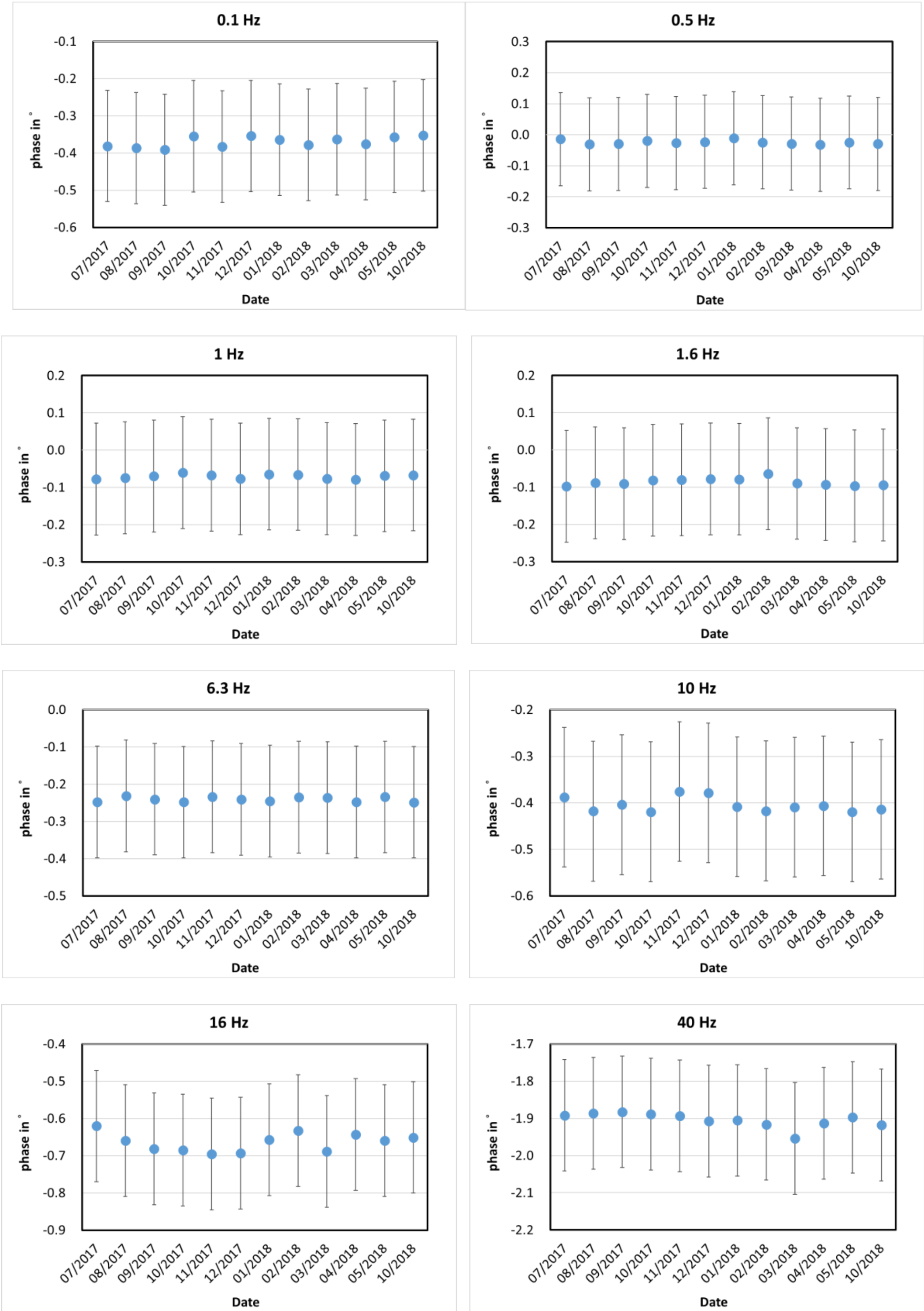



Figure 6.2 Monitoring of the phase shift over the comparison period

# 7. Results of the participants

The following sections are presenting the results from the participants submitted to the pilot laboratory using the mandatory report spreadsheet. The results presented are in mV/(m/s²) and degree (°) for the magnitude and phase shift, respectively. The vibration excitation was horizontal for CMS-ITRI, NIM, KRISS, NMISA and CSIR-NPLI, and vertical for NIM and NIMT. Whether the calibration was performed in vertical or horizontal direction at or below 0.4 Hz, the bias from earth gravitational acceleration was compensated to zero by adding offset with the signal conditioner in actual measurement by participants. Normalization of 1/100 was applied to compensate for the gain setting of 100 on the conditioner for frequencies from 0.1 Hz to 0.4 Hz. That means in this frequency range, the reported magnitude of sensitivity was divided by 100 for each participant.

## 7.1 Results for the magnitude of the complex voltage sensitivity

Results for the horizontal and the vertical excitation and for frequency range from 0.1 Hz to 40 Hz are shown in Tables 7.1.1 and 7.1.2, respectively.

Table 7.1.1 Reported participants' results for the magnitude of the accelerometer sensitivity with relative expanded uncertainties ($k$ = 2) for horizontal excitation.

| Horizontal | CMS-ITRI | | NIM | | KRISS | | NMISA | | CSIR-NPLI | |
|---|---|---|---|---|---|---|---|---|---|---|
| actual frequency (Hz) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) |
| 0.1 | 131.07 | 0.3 | 131.19 | 0.3 | 132.40 | 1.3 | 131.27 | 0.8 | 131.24 | 1.0 |
| 0.125 | 131.01 | 0.3 | 131.19 | 0.3 | 131.91 | 1.0 | 131.28 | 0.8 | 131.21 | 1.0 |
| 0.16 | 131.02 | 0.3 | 131.19 | 0.3 | 131.67 | 0.8 | 131.35 | 0.8 | 131.19 | 1.0 |
| 0.2 | 130.99 | 0.3 | 131.19 | 0.3 | 131.51 | 0.5 | 131.29 | 0.8 | 131.22 | 1.0 |
| 0.25 | 130.97 | 0.3 | 131.18 | 0.3 | 131.42 | 0.5 | 131.26 | 0.5 | 131.18 | 1.0 |
| 0.315 | 130.95 | 0.3 | 131.17 | 0.3 | 131.32 | 0.3 | 131.25 | 0.5 | 131.16 | 1.0 |
| 0.4 | 130.96 | 0.3 | 131.16 | 0.2 | 131.22 | 0.3 | 131.21 | 0.5 | 131.14 | 1.0 |
| 0.5 | 131.01 | 0.3 | 131.02 | 0.2 | 131.08 | 0.4 | 130.98 | 0.5 | 131.14 | 0.7 |
| 0.63 | 131.00 | 0.3 | 131.08 | 0.2 | 131.07 | 0.4 | 130.99 | 0.5 | 131.15 | 0.7 |
| 0.8 | 130.97 | 0.3 | 131.01 | 0.2 | 131.11 | 0.4 | 130.99 | 0.5 | 131.15 | 0.7 |
| 1 | 130.94 | 0.3 | 131.00 | 0.2 | 131.13 | 0.4 | 130.98 | 0.3 | 131.06 | 0.7 |
| 1.25 | 130.93 | 0.3 | 130.99 | 0.2 | 131.13 | 0.4 | 131.00 | 0.3 | 131.14 | 0.7 |
| 1.6 | 130.94 | 0.3 | 130.98 | 0.2 | 131.09 | 0.3 | 131.01 | 0.3 | 131.14 | 0.7 |
| 2 | 130.94 | 0.3 | 130.99 | 0.2 | 130.98 | 0.3 | 131.01 | 0.3 | 131.09 | 0.7 |
| 2.5 | 130.94 | 0.3 | 131.00 | 0.2 | 130.97 | 0.3 | 131.01 | 0.3 | 131.14 | 0.7 |
| 3.15 | 130.93 | 0.3 | 131.02 | 0.2 | 130.98 | 0.3 | 131.01 | 0.3 | 131.15 | 0.7 |
| 4 | 130.95 | 0.3 | 130.99 | 0.2 | 130.95 | 0.3 | 131.01 | 0.3 | 131.10 | 0.7 |
| 5 | 130.94 | 0.3 | 130.99 | 0.2 | 130.96 | 0.3 | 131.03 | 0.3 | 131.10 | 0.7 |
| 6.3 | 130.96 | 0.3 | 131.00 | 0.2 | 131.01 | 0.3 | 131.01 | 0.3 | 131.17 | 0.7 |
| 8 | 130.97 | 0.3 | 131.01 | 0.2 | 131.02 | 0.3 | 130.98 | 0.3 | 131.10 | 0.7 |
| 10 | 130.97 | 0.3 | 131.02 | 0.2 | 131.03 | 0.3 | 130.98 | 0.3 | 131.10 | 0.7 |
| 12.5 | 131.00 | 0.3 | 131.04 | 0.2 | 131.05 | 0.3 | 130.98 | 0.3 | 131.19 | 0.7 |
| 16 | 131.04 | 0.3 | 131.07 | 0.2 | 131.13 | 0.3 | 130.99 | 0.3 | 131.20 | 0.7 |
| 20 | 131.06 | 0.3 | 131.12 | 0.2 | 131.17 | 0.3 | 130.96 | 0.3 | 131.23 | 0.8 |
| 25 | 131.11 | 0.3 | 131.20 | 0.2 | 131.23 | 0.3 | 130.95 | 0.3 | 131.25 | 0.8 |
| 31.5 | 131.27 | 0.3 | 131.35 | 0.2 | 131.36 | 0.3 | 131.03 | 0.3 | 131.42 | 0.9 |
| 40 | 131.68 | 0.3 | 131.70 | 0.2 | 131.53 | 0.3 | 131.23 | 0.3 | 131.59 | 0.9 |

Table 7.1.2 Reported participants' results for the magnitude of the accelerometer sensitivity with relative expanded uncertainties ($k$ = 2) for vertical excitation

| Vertical | NIM | | NIMT | |
|---|---|---|---|---|
| actual frequency (Hz) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) | magnitude of voltage sensitivity (mV/(m/s$^2$)) | rel.exp. Unc. (%) |
| 0.1 | 131.09 | 0.3 | 131.14 | 0.60 |
| 0.125 | 131.10 | 0.3 | 131.19 | 0.60 |
| 0.16 | 131.11 | 0.3 | 131.10 | 0.60 |
| 0.2 | 131.15 | 0.3 | 131.16 | 0.60 |
| 0.25 | 131.14 | 0.3 | 131.16 | 0.60 |
| 0.315 | 131.15 | 0.3 | 131.14 | 0.60 |
| 0.4 | 131.16 | 0.2 | 131.13 | 0.60 |
| 0.5 | 131.15 | 0.2 | 130.95 | 0.60 |
| 0.63 | 131.07 | 0.2 | 130.97 | 0.60 |
| 0.8 | 131.03 | 0.2 | 130.94 | 0.60 |
| 1 | 131.02 | 0.2 | 130.96 | 0.51 |
| 1.25 | 131.01 | 0.2 | 130.96 | 0.51 |
| 1.6 | 131.00 | 0.2 | 130.93 | 0.51 |
| 2 | 131.00 | 0.2 | 130.93 | 0.48 |
| 2.5 | 130.99 | 0.2 | 130.91 | 0.48 |
| 3.15 | 130.98 | 0.2 | 130.95 | 0.48 |
| 4 | 130.99 | 0.2 | 130.93 | 0.48 |
| 5 | 130.98 | 0.2 | 130.93 | 0.45 |
| 6.3 | 130.99 | 0.2 | 130.93 | 0.41 |
| 8 | 130.99 | 0.2 | 131.00 | 0.41 |
| 10 | 131.01 | 0.2 | 131.00 | 0.38 |
| 12.5 | 131.03 | 0.2 | 131.01 | 0.38 |
| 16 | 131.07 | 0.2 | 131.05 | 0.38 |
| 20 | 131.10 | 0.2 | 131.10 | 0.38 |
| 25 | 131.15 | 0.2 | 131.18 | 0.38 |
| 31.5 | 131.28 | 0.2 | 131.32 | 0.38 |
| 40 | 131.50 | 0.2 | 131.52 | 0.38 |

## 7.2 Results for the phase shift of the complex voltage sensitivity

Table 7.2.1 Reported participants' results for the phase shift of the accelerometer sensitivity with expanded uncertainties ($k$ = 2) for horizontal excitation

| Horizontal | CMS-ITRI | | NIM | | KRISS | | NMISA | | CSIR-NPLI | |
|---|---|---|---|---|---|---|---|---|---|---|
| actual frequency (Hz) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) |
| 0.1 | -0.35 | 0.3 | -0.34 | 0.2 | -0.34 | 0.2 | -0.36 | 0.2 | -0.37 | 1.0 |
| 0.125 | -0.42 | 0.3 | -0.42 | 0.2 | -0.42 | 0.2 | -0.43 | 0.2 | -0.44 | 1.0 |
| 0.16 | -0.55 | 0.3 | -0.54 | 0.2 | -0.53 | 0.2 | -0.54 | 0.2 | -0.53 | 1.0 |
| 0.2 | -0.68 | 0.3 | -0.68 | 0.2 | -0.67 | 0.2 | -0.68 | 0.2 | -0.64 | 1.0 |
| 0.25 | -0.85 | 0.3 | -0.85 | 0.2 | -0.83 | 0.2 | -0.85 | 0.2 | -0.83 | 1.0 |
| 0.315 | -1.07 | 0.3 | -1.07 | 0.2 | -1.04 | 0.2 | -1.07 | 0.2 | -1.10 | 1.0 |
| 0.4 | -1.35 | 0.3 | -1.36 | 0.2 | -1.33 | 0.2 | -1.35 | 0.2 | -1.33 | 1.0 |
| 0.5 | -0.02 | 0.3 | -0.02 | 0.2 | -0.01 | 0.2 | -0.01 | 0.2 | -0.32 | 0.7 |
| 0.63 | -0.02 | 0.3 | -0.02 | 0.2 | -0.01 | 0.2 | -0.01 | 0.2 | -0.27 | 0.7 |
| 0.8 | -0.03 | 0.3 | -0.04 | 0.2 | -0.01 | 0.2 | -0.02 | 0.2 | -0.24 | 0.7 |
| 1 | -0.04 | 0.3 | -0.05 | 0.2 | -0.02 | 0.2 | -0.02 | 0.2 | -0.20 | 0.7 |
| 1.25 | -0.05 | 0.3 | -0.06 | 0.2 | -0.03 | 0.2 | -0.02 | 0.2 | -0.18 | 0.7 |
| 1.6 | -0.06 | 0.3 | -0.07 | 0.2 | -0.05 | 0.2 | -0.03 | 0.2 | -0.17 | 0.7 |
| 2 | -0.07 | 0.3 | -0.09 | 0.2 | -0.06 | 0.2 | -0.04 | 0.2 | -0.19 | 0.7 |
| 2.5 | -0.09 | 0.3 | -0.12 | 0.2 | -0.09 | 0.2 | -0.04 | 0.2 | -0.20 | 0.7 |
| 3.15 | -0.12 | 0.3 | -0.13 | 0.2 | -0.12 | 0.2 | -0.05 | 0.2 | -0.22 | 0.7 |
| 4 | -0.15 | 0.3 | -0.18 | 0.2 | -0.16 | 0.2 | -0.07 | 0.2 | -0.23 | 0.7 |
| 5 | -0.22 | 0.3 | -0.22 | 0.2 | -0.21 | 0.2 | -0.09 | 0.2 | -0.27 | 0.7 |
| 6.3 | -0.25 | 0.3 | -0.28 | 0.2 | -0.27 | 0.2 | -0.14 | 0.2 | -0.43 | 0.7 |
| 8 | -0.33 | 0.3 | -0.36 | 0.2 | -0.34 | 0.2 | -0.15 | 0.2 | -0.40 | 0.7 |
| 10 | -0.38 | 0.3 | -0.45 | 0.2 | -0.43 | 0.2 | -0.17 | 0.2 | -0.48 | 0.7 |
| 12.5 | -0.53 | 0.3 | -0.56 | 0.2 | -0.54 | 0.2 | -0.22 | 0.2 | -0.58 | 0.7 |
| 16 | -0.69 | 0.3 | -0.72 | 0.2 | -0.69 | 0.2 | -0.28 | 0.2 | -0.76 | 0.7 |
| 20 | -0.85 | 0.3 | -0.90 | 0.2 | -0.88 | 0.2 | -0.35 | 0.2 | -1.03 | 0.8 |
| 25 | -1.02 | 0.3 | -1.14 | 0.2 | -1.11 | 0.2 | -0.42 | 0.2 | -1.37 | 0.8 |
| 31.5 | -1.35 | 0.3 | -1.47 | 0.2 | -1.42 | 0.2 | -0.51 | 0.2 | -1.84 | 0.9 |
| 40 | -2.05 | 0.3 | -2.07 | 0.2 | -1.83 | 0.2 | -0.70 | 0.2 | -1.99 | 0.9 |

Table 7.2.2 Reported participants' results for the phase shift of the accelerometer sensitivity with expanded uncertainties ($k$ = 2) for vertical excitation

| Vertical | NIM | | NIMT | |
|---|---|---|---|---|
| actual frequency (Hz) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) | phase of voltage sensitivity (˚) | abs.exp. Unc. (˚) |
| 0.1 | -0.30 | 0.2 | -0.34 | 0.83 |
| 0.125 | -0.41 | 0.2 | -0.46 | 0.83 |
| 0.16 | -0.54 | 0.2 | -0.55 | 0.83 |
| 0.2 | -0.67 | 0.2 | -0.70 | 0.83 |
| 0.25 | -0.84 | 0.2 | -0.86 | 0.83 |
| 0.315 | -1.07 | 0.2 | -1.09 | 0.83 |
| 0.4 | -1.35 | 0.2 | -1.38 | 0.83 |
| 0.5 | -0.01 | 0.2 | -0.03 | 0.83 |
| 0.63 | -0.02 | 0.2 | -0.04 | 0.83 |
| 0.8 | -0.02 | 0.2 | -0.04 | 0.83 |
| 1 | -0.04 | 0.2 | -0.04 | 0.61 |
| 1.25 | -0.06 | 0.2 | -0.06 | 0.61 |
| 1.6 | -0.07 | 0.2 | -0.07 | 0.61 |
| 2 | -0.09 | 0.2 | -0.08 | 0.54 |
| 2.5 | -0.11 | 0.2 | -0.10 | 0.54 |
| 3.15 | -0.14 | 0.2 | -0.13 | 0.54 |
| 4 | -0.18 | 0.2 | -0.16 | 0.54 |
| 5 | -0.23 | 0.2 | -0.20 | 0.47 |
| 6.3 | -0.29 | 0.2 | -0.26 | 0.47 |
| 8 | -0.37 | 0.2 | -0.34 | 0.47 |
| 10 | -0.46 | 0.2 | -0.43 | 0.45 |
| 12.5 | -0.58 | 0.2 | -0.55 | 0.45 |
| 16 | -0.74 | 0.2 | -0.71 | 0.45 |
| 20 | -0.93 | 0.2 | -0.90 | 0.45 |
| 25 | -1.16 | 0.2 | -1.13 | 0.45 |
| 31.5 | -1.43 | 0.2 | -1.45 | 0.45 |
| 40 | -1.89 | 0.2 | -1.87 | 0.45 |

# 8. Degrees of equivalence with respect to the RMO weighted mean value

The evaluation of the results was performed using a weighted mean computed with the following equations [3]:

$$x_{\mathrm{WM}}(f) = \sum \frac{x_i(f)}{u_i^2(f)} \cdot \left(\sum \frac{1}{u_i^2(f)}\right)^{-1} \quad (1)$$

$$u_{\mathrm{WM}}(f) = \left(\sum \frac{1}{u_i^2(f)}\right)^{-1/2} \quad (2)$$

where

$x_i(f)$ result of participant $i$ at frequency $f$

$u_i(f)$ absolute standard uncertainty of participant $i$ at frequency $f$

$x_{\mathrm{WM}}(f)$ best estimate of the weighted mean sensitivity at frequency $f$ $u_{\mathrm{WM}}(f)$ estimated absolute standard uncertainty for the weighted mean at frequency $f$

Consistency checks were performed for magnitude and phase shift of the complex voltage sensitivity. The test defined by Cox [4, 5] was applied to determine the participants that were members of the **Largest Consistent Subset** (LCS). The weighted mean was finally determined through the participants in the members of the consistent subset. Tables 8, are the consistency test results for both magnitude and phase shift respectively. Cells are highlighted in yellow and with an asterisk (*) when $\chi^2_{\mathrm{obs}} > \chi^2(\nu)$. Cells in Table 8(a) highlighted in yellow and marked with an asterisk (*) were considered as not within the LCS and were excluded from the calculation of the weighted mean. It should be noted that, NMISA's results from 16 Hz to 40 Hz did not contribute to the calculation of the weighted mean for phase shift. Tables 8(a) and 8(b) present the results of the consistency test applied to the horizontal and vertical excitation results reported by the LCS for magnitude (left) and phase shift (right), respectively.

Table 8 Results of the consistency test applied to all the horizontal excitation results reported by the participants respectively for magnitude (left) and phase shift (right)

| Frequency (Hz) | Number of Participants | Number of Degrees of Freedom | $\chi^2_{obs}$ | $\chi^2_{(\nu)}$ with p<0.05 |
|---|---|---|---|---|
| 0.1 | 5 | 4 | 2.31 | 9.49 |
| 0.125 | 5 | 4 | 1.93 | 9.49 |
| 0.16 | 5 | 4 | 1.56 | 9.49 |
| 0.2 | 5 | 4 | 1.94 | 9.49 |
| 0.25 | 5 | 4 | 1.62 | 9.49 |
| 0.315 | 5 | 4 | 1.82 | 9.49 |
| 0.4 | 5 | 4 | 1.03 | 9.49 |
| 0.5 | 5 | 4 | 0.13 | 9.49 |
| 0.63 | 5 | 4 | 0.20 | 9.49 |
| 0.8 | 5 | 4 | 0.26 | 9.49 |
| 1 | 5 | 4 | 0.35 | 9.49 |
| 1.25 | 5 | 4 | 0.45 | 9.49 |
| 1.6 | 5 | 4 | 0.40 | 9.49 |
| 2 | 5 | 4 | 0.12 | 9.49 |
| 2.5 | 5 | 4 | 0.20 | 9.49 |
| 3.15 | 5 | 4 | 0.26 | 9.49 |
| 4 | 5 | 4 | 0.15 | 9.49 |
| 5 | 5 | 4 | 0.19 | 9.49 |
| 6.3 | 5 | 4 | 0.19 | 9.49 |
| 8 | 5 | 4 | 0.10 | 9.49 |
| 10 | 5 | 4 | 0.11 | 9.49 |
| 12.5 | 5 | 4 | 0.21 | 9.49 |
| 16 | 5 | 4 | 0.35 | 9.49 |
| 20 | 5 | 4 | 0.72 | 9.49 |
| 25 | 5 | 4 | 1.34 | 9.49 |
| 31.5 | 5 | 4 | 2.05 | 9.49 |
| 40 | 5 | 4 | 4.07 | 9.49 |

| Frequency (Hz) | Number of Participants | Number of Degrees of Freedom | $\chi^2_{obs}$ | $\chi^2_{(\nu)}$ with p<0.05 |
|---|---|---|---|---|
| 0.1 | 5 | 4 | 0.02 | 9.49 |
| 0.125 | 5 | 4 | 0.01 | 9.49 |
| 0.16 | 5 | 4 | 0.02 | 9.49 |
| 0.2 | 5 | 4 | 0.01 | 9.49 |
| 0.25 | 5 | 4 | 0.03 | 9.49 |
| 0.315 | 5 | 4 | 0.06 | 9.49 |
| 0.4 | 5 | 4 | 0.04 | 9.49 |
| 0.5 | 5 | 4 | 0.76 | 9.49 |
| 0.63 | 5 | 4 | 0.54 | 9.49 |
| 0.8 | 5 | 4 | 0.43 | 9.49 |
| 1 | 5 | 4 | 0.28 | 9.49 |
| 1.25 | 5 | 4 | 0.23 | 9.49 |
| 1.6 | 5 | 4 | 0.21 | 9.49 |
| 2 | 5 | 4 | 0.27 | 9.49 |
| 2.5 | 5 | 4 | 0.42 | 9.49 |
| 3.15 | 5 | 4 | 0.50 | 9.49 |
| 4 | 5 | 4 | 0.79 | 9.49 |
| 5 | 5 | 4 | 1.21 | 9.49 |
| 6.3 | 5 | 4 | 1.64 | 9.49 |
| 8 | 5 | 4 | 2.93 | 9.49 |
| 10 | 5 | 4 | 4.90 | 9.49 |
| 12.5 | 5 | 4 | 7.83 | 9.49 |
| 16 | 5 | 4 | 13.16* | 9.49 |
| 20 | 5 | 4 | 20.71* | 9.49 |
| 25 | 5 | 4 | 35.28* | 9.49 |
| 31.5 | 5 | 4 | 62.09* | 9.49 |
| 40 | 5 | 4 | 117.00* | 9.49 |

Note: Cells were highlighted in yellow and with an asterisk (*) when $\chi^2_{obs} > \chi^2(\nu)$

Table 8(a) Results of the consistency test applied to all the horizontal excitation results reported by the largest consistent subset respectively for magnitude (left) and phase shift (right)

| Frequency (Hz) | Number of Participants | Number of Degrees of Freedom | $\chi^2_{obs}$ | $\chi^2_{(\nu)}$ with p<0.05 |
|---|---|---|---|---|
| 0.1 | 5 | 4 | 2.31 | 9.49 |
| 0.125 | 5 | 4 | 1.93 | 9.49 |
| 0.16 | 5 | 4 | 1.56 | 9.49 |
| 0.2 | 5 | 4 | 1.94 | 9.49 |
| 0.25 | 5 | 4 | 1.62 | 9.49 |
| 0.315 | 5 | 4 | 1.82 | 9.49 |
| 0.4 | 5 | 4 | 1.03 | 9.49 |
| 0.5 | 5 | 4 | 0.13 | 9.49 |
| 0.63 | 5 | 4 | 0.20 | 9.49 |
| 0.8 | 5 | 4 | 0.26 | 9.49 |
| 1 | 5 | 4 | 0.35 | 9.49 |
| 1.25 | 5 | 4 | 0.45 | 9.49 |
| 1.6 | 5 | 4 | 0.40 | 9.49 |
| 2 | 5 | 4 | 0.12 | 9.49 |
| 2.5 | 5 | 4 | 0.20 | 9.49 |
| 3.15 | 5 | 4 | 0.26 | 9.49 |
| 4 | 5 | 4 | 0.15 | 9.49 |
| 5 | 5 | 4 | 0.19 | 9.49 |
| 6.3 | 5 | 4 | 0.19 | 9.49 |
| 8 | 5 | 4 | 0.10 | 9.49 |
| 10 | 5 | 4 | 0.11 | 9.49 |
| 12.5 | 5 | 4 | 0.21 | 9.49 |
| 16 | 5 | 4 | 0.35 | 9.49 |
| 20 | 5 | 4 | 0.72 | 9.49 |
| 25 | 5 | 4 | 1.34 | 9.49 |
| 31.5 | 5 | 4 | 2.05 | 9.49 |
| 40 | 5 | 4 | 4.07 | 9.49 |

| Frequency (Hz) | Number of Participants | Number of Degrees of Freedom | $\chi^2_{obs}$ | $\chi^2_{(\nu)}$ with p<0.05 |
|---|---|---|---|---|
| 0.1 | 5 | 4 | 0.02 | 9.49 |
| 0.125 | 5 | 4 | 0.01 | 9.49 |
| 0.16 | 5 | 4 | 0.02 | 9.49 |
| 0.2 | 5 | 4 | 0.01 | 9.49 |
| 0.25 | 5 | 4 | 0.03 | 9.49 |
| 0.315 | 5 | 4 | 0.06 | 9.49 |
| 0.4 | 5 | 4 | 0.04 | 9.49 |
| 0.5 | 5 | 4 | 0.76 | 9.49 |
| 0.63 | 5 | 4 | 0.54 | 9.49 |
| 0.8 | 5 | 4 | 0.43 | 9.49 |
| 1 | 5 | 4 | 0.28 | 9.49 |
| 1.25 | 5 | 4 | 0.23 | 9.49 |
| 1.6 | 5 | 4 | 0.21 | 9.49 |
| 2 | 5 | 4 | 0.27 | 9.49 |
| 2.5 | 5 | 4 | 0.42 | 9.49 |
| 3.15 | 5 | 4 | 0.50 | 9.49 |
| 4 | 5 | 4 | 0.79 | 9.49 |
| 5 | 5 | 4 | 1.21 | 9.49 |
| 6.3 | 5 | 4 | 1.64 | 9.49 |
| 8 | 5 | 4 | 2.93 | 9.49 |
| 10 | 5 | 4 | 4.90 | 9.49 |
| 12.5 | 5 | 4 | 7.83 | 9.49 |
| 16 | 4 | 3 | 0.08 | 7.81 |
| 20 | 4 | 3 | 0.21 | 7.81 |
| 25 | 4 | 3 | 0.82 | 7.81 |
| 31.5 | 4 | 3 | 1.25 | 7.81 |
| 40 | 4 | 3 | 3.17 | 7.81 |

Table 8(b) Results of the consistency test applied to all the vertical excitation results reported by the participants respectively for magnitude (left) and phase shift (right)

| Frequency (Hz) | Number of Participants | Number of Degrees of Freedom | $\chi^2_{obs}$ | $\chi^2_{(\upsilon)}$ with p<0.05 |
|---|---|---|---|---|
| 0.1 | 2 | 1 | 0.02 | 3.84 |
| 0.125 | 2 | 1 | 0.04 | 3.84 |
| 0.16 | 2 | 1 | 0.00 | 3.84 |
| 0.2 | 2 | 1 | 0.00 | 3.84 |
| 0.25 | 2 | 1 | 0.00 | 3.84 |
| 0.315 | 2 | 1 | 0.00 | 3.84 |
| 0.4 | 2 | 1 | 0.00 | 3.84 |
| 0.5 | 2 | 1 | 0.22 | 3.84 |
| 0.63 | 2 | 1 | 0.05 | 3.84 |
| 0.8 | 2 | 1 | 0.05 | 3.84 |
| 1 | 2 | 1 | 0.03 | 3.84 |
| 1.25 | 2 | 1 | 0.01 | 3.84 |
| 1.6 | 2 | 1 | 0.04 | 3.84 |
| 2 | 2 | 1 | 0.04 | 3.84 |
| 2.5 | 2 | 1 | 0.06 | 3.84 |
| 3.15 | 2 | 1 | 0.01 | 3.84 |
| 4 | 2 | 1 | 0.03 | 3.84 |
| 5 | 2 | 1 | 0.03 | 3.84 |
| 6.3 | 2 | 1 | 0.03 | 3.84 |
| 8 | 2 | 1 | 0.00 | 3.84 |
| 10 | 2 | 1 | 0.00 | 3.84 |
| 12.5 | 2 | 1 | 0.00 | 3.84 |
| 16 | 2 | 1 | 0.00 | 3.84 |
| 20 | 2 | 1 | 0.00 | 3.84 |
| 25 | 2 | 1 | 0.01 | 3.84 |
| 31.5 | 2 | 1 | 0.01 | 3.84 |
| 40 | 2 | 1 | 0.01 | 3.84 |

| Frequency (Hz) | Number of Participants | Number of Degrees of Freedom | $\chi^2_{obs}$ | $\chi^2_{(\upsilon)}$ with p<0.05 |
|---|---|---|---|---|
| 0.1 | 2 | 1 | 0.01 | 3.84 |
| 0.125 | 2 | 1 | 0.01 | 3.84 |
| 0.16 | 2 | 1 | 0.00 | 3.84 |
| 0.2 | 2 | 1 | 0.00 | 3.84 |
| 0.25 | 2 | 1 | 0.00 | 3.84 |
| 0.315 | 2 | 1 | 0.00 | 3.84 |
| 0.4 | 2 | 1 | 0.00 | 3.84 |
| 0.5 | 2 | 1 | 0.00 | 3.84 |
| 0.63 | 2 | 1 | 0.00 | 3.84 |
| 0.8 | 2 | 1 | 0.00 | 3.84 |
| 1 | 2 | 1 | 0.00 | 3.84 |
| 1.25 | 2 | 1 | 0.00 | 3.84 |
| 1.6 | 2 | 1 | 0.00 | 3.84 |
| 2 | 2 | 1 | 0.00 | 3.84 |
| 2.5 | 2 | 1 | 0.00 | 3.84 |
| 3.15 | 2 | 1 | 0.00 | 3.84 |
| 4 | 2 | 1 | 0.00 | 3.84 |
| 5 | 2 | 1 | 0.01 | 3.84 |
| 6.3 | 2 | 1 | 0.01 | 3.84 |
| 8 | 2 | 1 | 0.01 | 3.84 |
| 10 | 2 | 1 | 0.01 | 3.84 |
| 12.5 | 2 | 1 | 0.01 | 3.84 |
| 16 | 2 | 1 | 0.02 | 3.84 |
| 20 | 2 | 1 | 0.01 | 3.84 |
| 25 | 2 | 1 | 0.01 | 3.84 |
| 31.5 | 2 | 1 | 0.00 | 3.84 |
| 40 | 2 | 1 | 0.00 | 3.84 |

## 8.1 Results for the magnitude of the complex voltage sensitivity

For the further evaluation of the comparison, the unilateral degrees of equivalence with respect to the weighted mean were calculated according to:

$$d_{i,\mathrm{WM}}(f) = x_i(f) - x_{\mathrm{WM}}(f) \tag{3}$$

$$u_{i,\mathrm{WM}}^2(f) = \begin{cases} u_i^2(f) - u_{\mathrm{WM}}^2(f) & \text{for results within the LCS} \\ u_i^2(f) + u_{\mathrm{WM}}^2(f) & \text{for results not within the LCS} \end{cases} \tag{4}$$

These formulas were applied for both magnitude and phase shift results. Unilateral degrees of equivalence obtained from results which were excluded from the LCS and which therefore did not contribute to the calculation of the weighted mean.

Table 8.1.1 Unilateral degrees of equivalence for the magnitude (horizontal) of sensitivity with absolute expanded uncertainties ($k$ = 2)

| Horizontal | Weighted Mean | | CMS-ITRI | | NIM | | KRISS | | NMISA | | CSIR-NPLI | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency | $X_{WM}$ | $U_{WM}$ | $d_{i,WM}$ | $U_{i,WM}$ | $d_{i,WM}$ | $U_{i,WM}$ | $d_{i,WM}$ | $U_{i,WM}$ | $d_{i,WM}$ | $U_{i,WM}$ | $d_{i,WM}$ | $U_{i,WM}$ |
| (Hz) | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | |
| 0.1 | 131.17 | 0.27 | -0.10 | 0.31 | 0.02 | 0.31 | 1.23 | 1.8 | 0.10 | 1.1 | 0.07 | 1.3 |
| 0.125 | 131.15 | 0.27 | -0.14 | 0.31 | 0.04 | 0.31 | 0.76 | 1.3 | 0.14 | 1.1 | 0.06 | 1.3 |
| 0.16 | 131.16 | 0.26 | -0.14 | 0.31 | 0.03 | 0.31 | 0.51 | 1.1 | 0.19 | 1.1 | 0.04 | 1.3 |
| 0.2 | 131.16 | 0.25 | -0.17 | 0.32 | 0.02 | 0.32 | 0.35 | 0.62 | 0.13 | 1.1 | 0.06 | 1.3 |
| 0.25 | 131.15 | 0.24 | -0.18 | 0.33 | 0.03 | 0.33 | 0.27 | 0.62 | 0.11 | 0.62 | 0.03 | 1.3 |
| 0.315 | 131.16 | 0.22 | -0.21 | 0.34 | 0.02 | 0.34 | 0.16 | 0.34 | 0.09 | 0.63 | 0.00 | 1.4 |
| 0.4 | 131.13 | 0.19 | -0.17 | 0.36 | 0.03 | 0.21 | 0.09 | 0.36 | 0.07 | 0.64 | 0.01 | 1.4 |
| 0.5 | 131.03 | 0.20 | -0.02 | 0.35 | -0.01 | 0.20 | 0.05 | 0.51 | -0.05 | 0.64 | 0.11 | 0.90 |
| 0.63 | 131.06 | 0.20 | -0.06 | 0.35 | 0.03 | 0.20 | 0.01 | 0.51 | -0.07 | 0.64 | 0.09 | 0.90 |
| 0.8 | 131.02 | 0.20 | -0.05 | 0.35 | -0.01 | 0.20 | 0.09 | 0.51 | -0.03 | 0.64 | 0.13 | 0.90 |
| 1 | 131.00 | 0.19 | -0.06 | 0.36 | 0.00 | 0.22 | 0.13 | 0.51 | -0.02 | 0.36 | 0.06 | 0.91 |
| 1.25 | 131.00 | 0.19 | -0.07 | 0.36 | -0.01 | 0.22 | 0.13 | 0.51 | -0.01 | 0.36 | 0.14 | 0.91 |
| 1.6 | 131.01 | 0.18 | -0.07 | 0.36 | -0.02 | 0.22 | 0.08 | 0.36 | 0.00 | 0.36 | 0.14 | 0.91 |
| 2 | 130.98 | 0.18 | -0.04 | 0.36 | 0.00 | 0.22 | 0.00 | 0.36 | 0.02 | 0.36 | 0.11 | 0.91 |
| 2.5 | 130.99 | 0.18 | -0.05 | 0.36 | 0.01 | 0.22 | -0.02 | 0.36 | 0.02 | 0.36 | 0.16 | 0.91 |
| 3.15 | 131.00 | 0.18 | -0.07 | 0.36 | 0.02 | 0.22 | -0.02 | 0.36 | 0.01 | 0.36 | 0.15 | 0.91 |
| 4 | 130.98 | 0.18 | -0.03 | 0.36 | 0.01 | 0.22 | -0.03 | 0.36 | 0.03 | 0.36 | 0.11 | 0.91 |
| 5 | 130.99 | 0.18 | -0.05 | 0.36 | 0.01 | 0.22 | -0.03 | 0.36 | 0.04 | 0.36 | 0.11 | 0.91 |
| 6.3 | 131.00 | 0.18 | -0.04 | 0.36 | 0.00 | 0.22 | 0.01 | 0.36 | 0.01 | 0.36 | 0.17 | 0.91 |
| 8 | 131.00 | 0.18 | -0.03 | 0.36 | 0.01 | 0.22 | 0.02 | 0.36 | -0.02 | 0.36 | 0.10 | 0.91 |
| 10 | 131.01 | 0.18 | -0.04 | 0.36 | 0.01 | 0.22 | 0.02 | 0.36 | -0.03 | 0.36 | 0.09 | 0.91 |
| 12.5 | 131.03 | 0.18 | -0.03 | 0.36 | 0.01 | 0.22 | 0.02 | 0.36 | -0.05 | 0.36 | 0.16 | 0.91 |
| 16 | 131.07 | 0.18 | -0.03 | 0.36 | 0.00 | 0.22 | 0.06 | 0.36 | -0.08 | 0.36 | 0.14 | 0.91 |
| 20 | 131.09 | 0.18 | -0.03 | 0.36 | 0.03 | 0.22 | 0.08 | 0.36 | -0.13 | 0.36 | 0.14 | 1.1 |
| 25 | 131.14 | 0.18 | -0.03 | 0.36 | 0.06 | 0.22 | 0.09 | 0.36 | -0.19 | 0.36 | 0.11 | 1.1 |
| 31.5 | 131.27 | 0.18 | 0.00 | 0.36 | 0.07 | 0.22 | 0.09 | 0.36 | -0.25 | 0.36 | 0.15 | 1.2 |
| 40 | 131.57 | 0.18 | 0.11 | 0.36 | 0.13 | 0.22 | -0.04 | 0.36 | -0.34 | 0.36 | 0.02 | 1.2 |

Table 8.1.2: Unilateral degrees of equivalence for the magnitude (vertical) of sensitivity with absolute expanded uncertainties ($k$ = 2)

| Vertical | Weighted Mean | | NIM | | NIMT | |
|---|---|---|---|---|---|---|
| Frequency | $X_{WM}$ | $U_{WM}$ | $d_{i,WM}$ | $U_{i,WM}$ | $d_{i,WM}$ | $U_{i,WM}$ |
| (Hz) | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | | (mV/(m/s$^2$)) | |
| 0.1 | 131.10 | 0.36 | -0.01 | 0.18 | 0.04 | 0.72 |
| 0.125 | 131.12 | 0.36 | -0.02 | 0.18 | 0.07 | 0.72 |
| 0.16 | 131.11 | 0.36 | 0.00 | 0.18 | -0.01 | 0.72 |
| 0.2 | 131.16 | 0.36 | 0.00 | 0.18 | 0.01 | 0.72 |
| 0.25 | 131.14 | 0.36 | 0.00 | 0.18 | 0.02 | 0.72 |
| 0.315 | 131.15 | 0.36 | 0.00 | 0.18 | -0.01 | 0.72 |
| 0.4 | 131.16 | 0.27 | 0.00 | 0.10 | -0.03 | 0.76 |
| 0.5 | 131.13 | 0.27 | 0.02 | 0.10 | -0.18 | 0.76 |
| 0.63 | 131.06 | 0.27 | 0.01 | 0.10 | -0.09 | 0.76 |
| 0.8 | 131.02 | 0.27 | 0.01 | 0.10 | -0.09 | 0.76 |
| 1 | 131.01 | 0.26 | 0.01 | 0.11 | -0.05 | 0.63 |
| 1.25 | 131.00 | 0.26 | 0.01 | 0.11 | -0.04 | 0.63 |
| 1.6 | 130.99 | 0.26 | 0.01 | 0.11 | -0.06 | 0.63 |
| 2 | 130.99 | 0.26 | 0.01 | 0.12 | -0.06 | 0.59 |
| 2.5 | 130.98 | 0.26 | 0.01 | 0.12 | -0.07 | 0.59 |
| 3.15 | 130.98 | 0.26 | 0.01 | 0.12 | -0.03 | 0.59 |
| 4 | 130.98 | 0.26 | 0.01 | 0.12 | -0.05 | 0.59 |
| 5 | 130.97 | 0.26 | 0.01 | 0.12 | -0.05 | 0.55 |
| 6.3 | 130.98 | 0.25 | 0.01 | 0.13 | -0.04 | 0.48 |
| 8 | 130.99 | 0.25 | 0.00 | 0.13 | 0.00 | 0.48 |
| 10 | 131.01 | 0.25 | 0.00 | 0.14 | -0.01 | 0.44 |
| 12.5 | 131.03 | 0.25 | 0.00 | 0.14 | -0.01 | 0.44 |
| 16 | 131.06 | 0.25 | 0.00 | 0.14 | -0.01 | 0.44 |
| 20 | 131.10 | 0.25 | 0.00 | 0.14 | 0.01 | 0.46 |
| 25 | 131.16 | 0.25 | -0.01 | 0.14 | 0.02 | 0.46 |
| 31.5 | 131.29 | 0.25 | -0.01 | 0.14 | 0.03 | 0.46 |
| 40 | 131.50 | 0.25 | -0.01 | 0.14 | 0.02 | 0.46 |

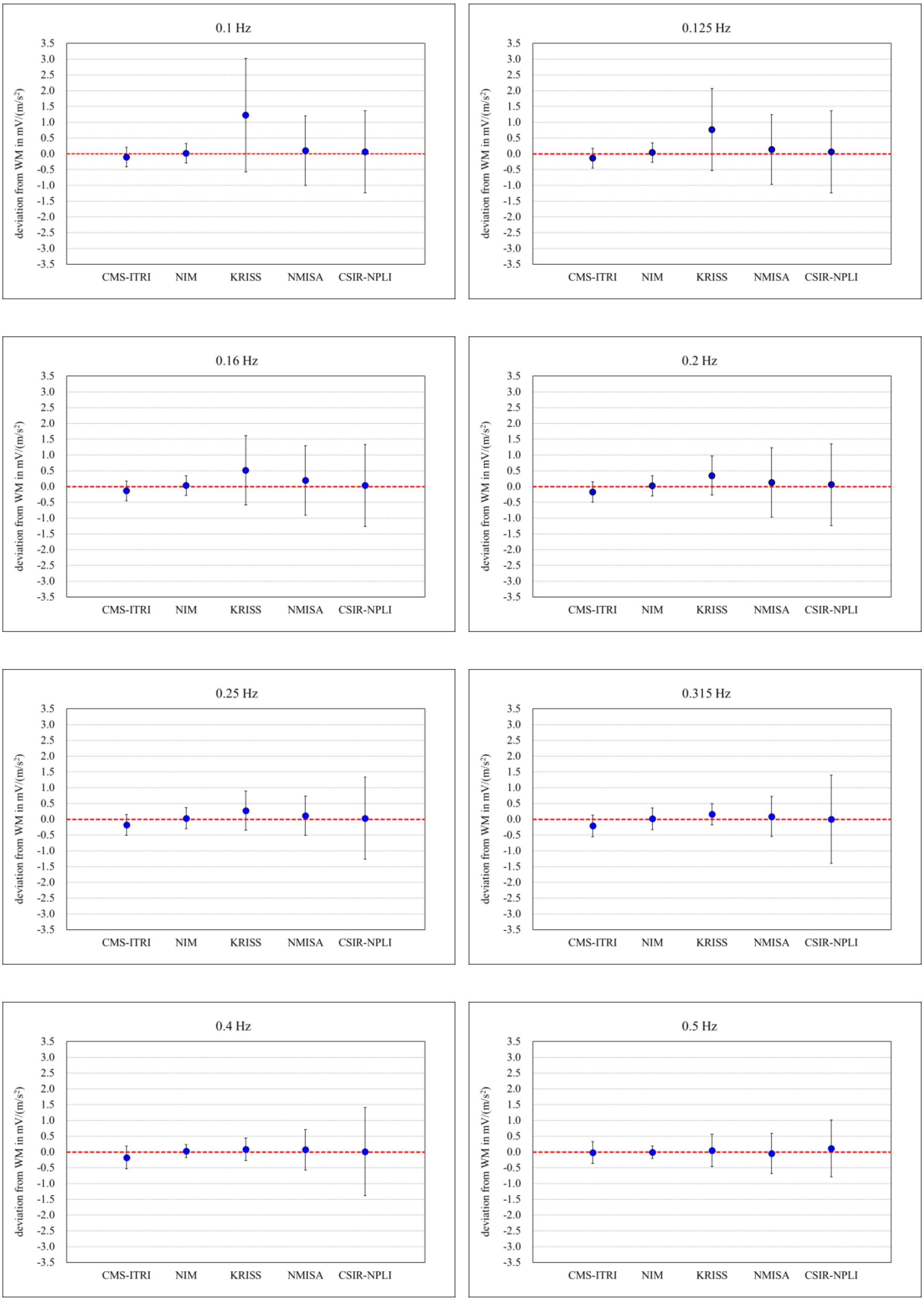



Figure 8.1.1 Deviation of the magnitude (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2).

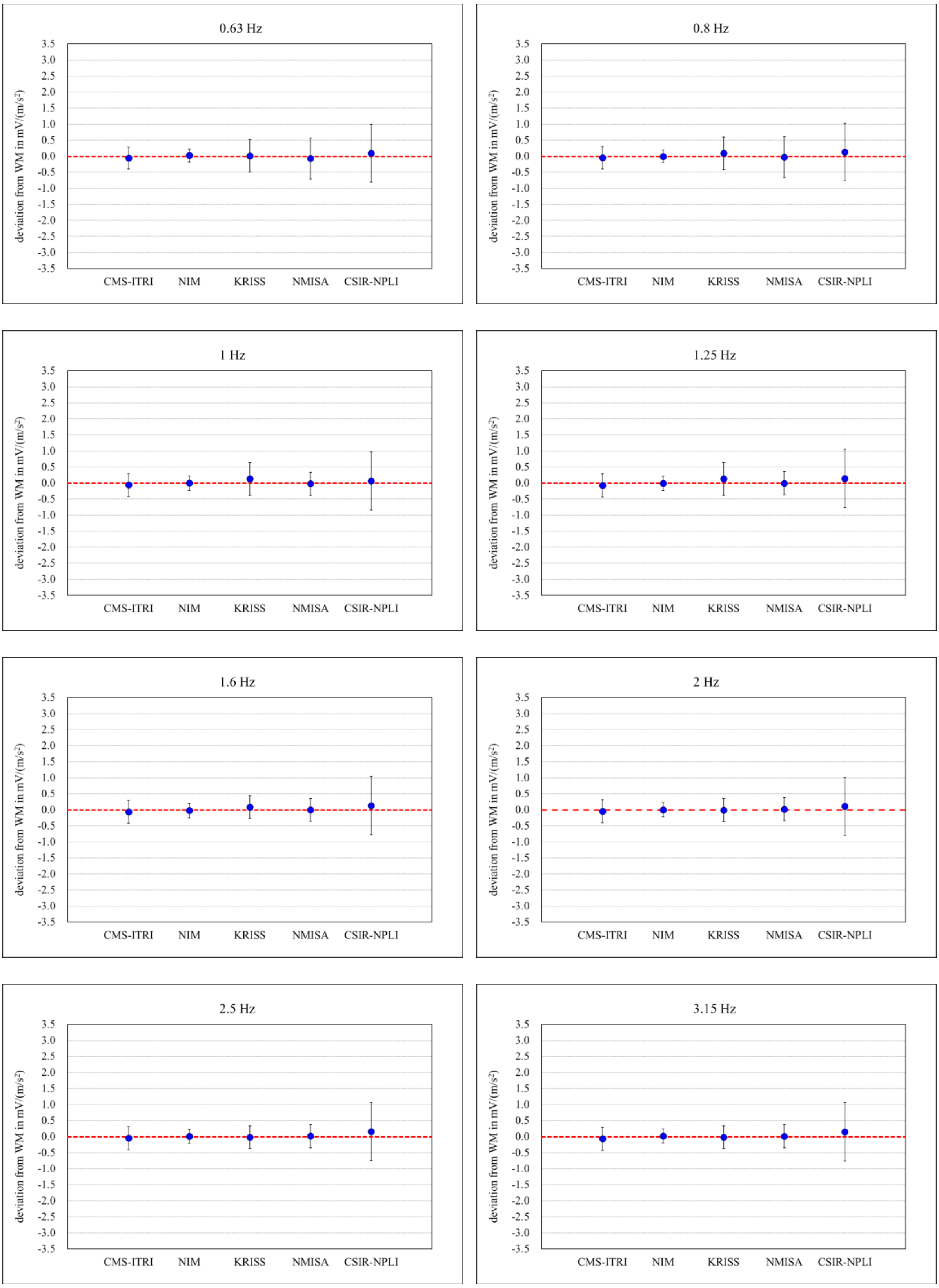



Figure 8.1.1 Deviation of the magnitude (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2). (Cont.)

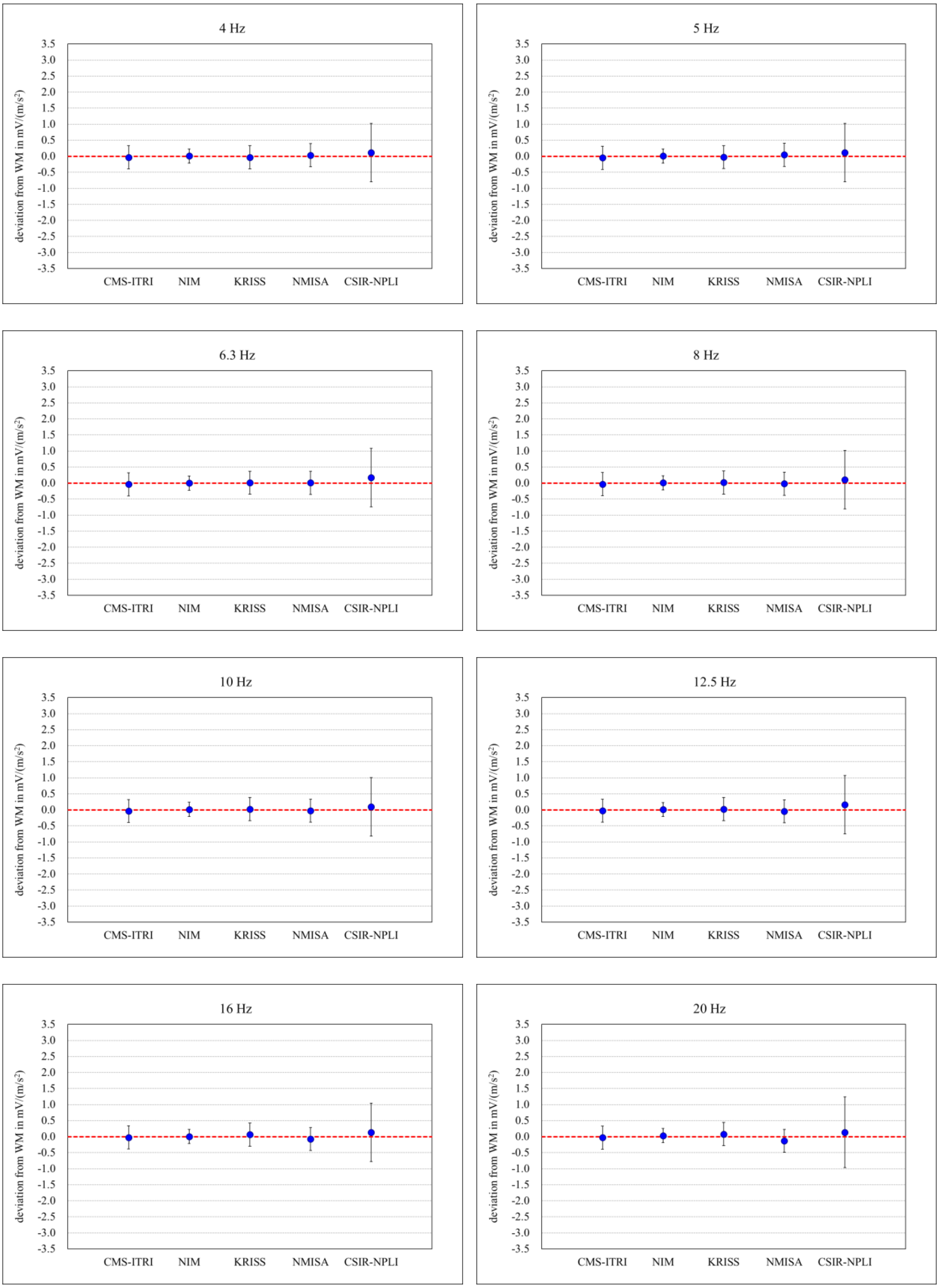



Figure 8.1.1 Deviation of the magnitude (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2). (Cont.)

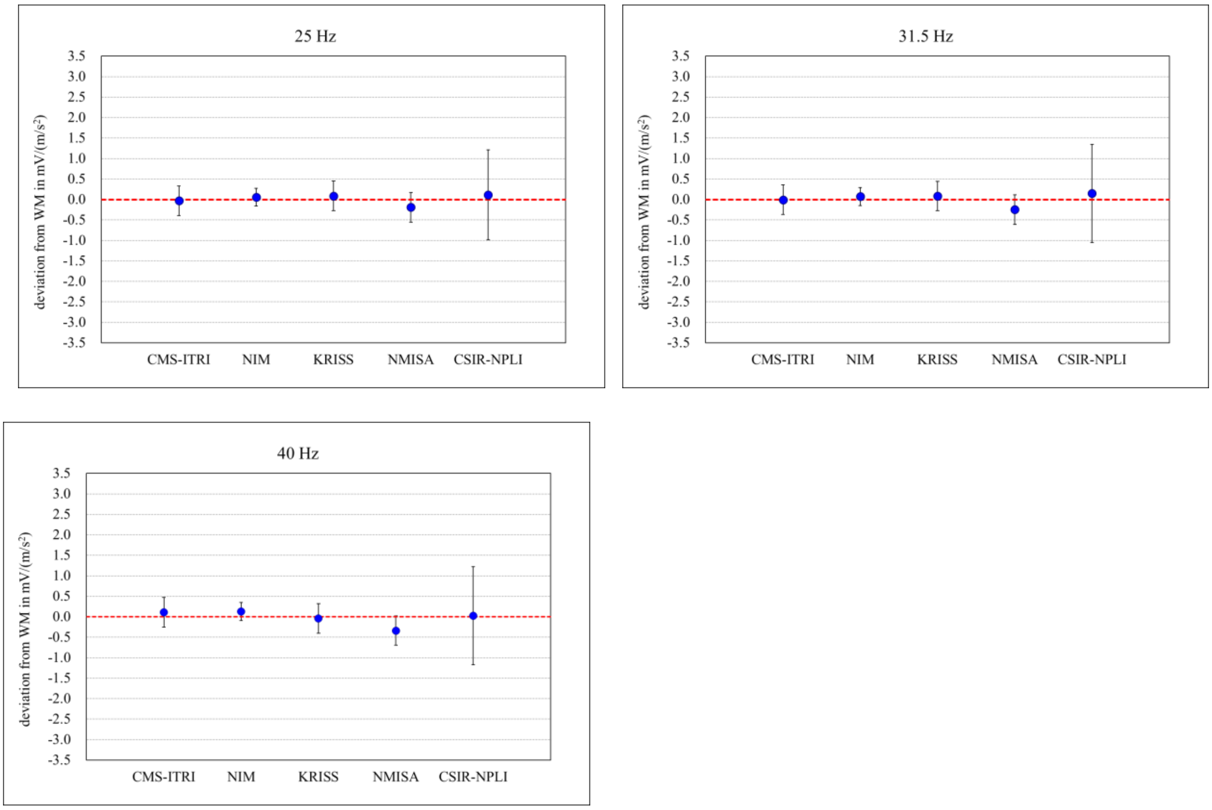



Figure 8.1.1 Deviation of the magnitude (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2). (Cont.)

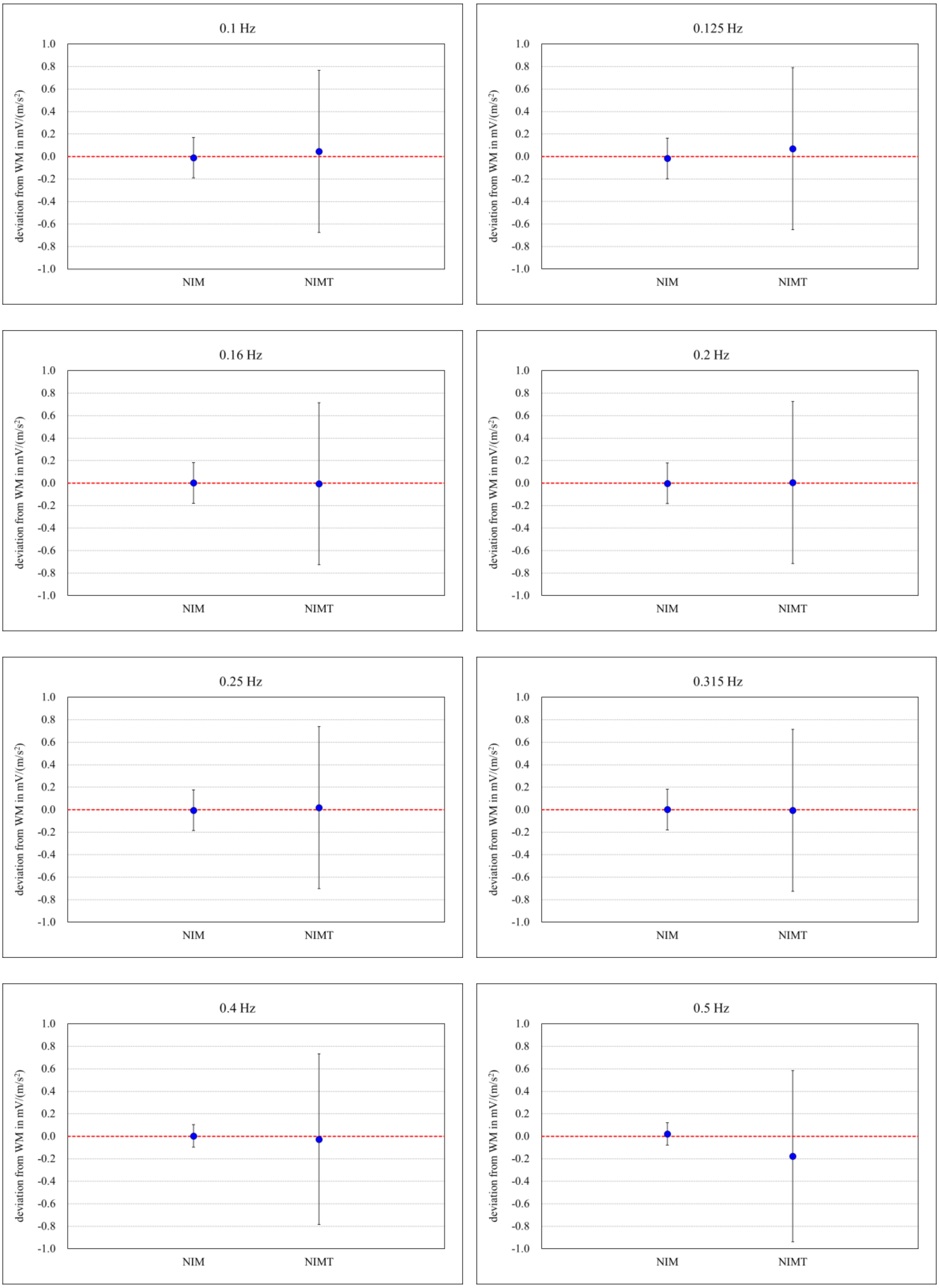



Figure 8.1.2 Deviation of the magnitude (vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2).

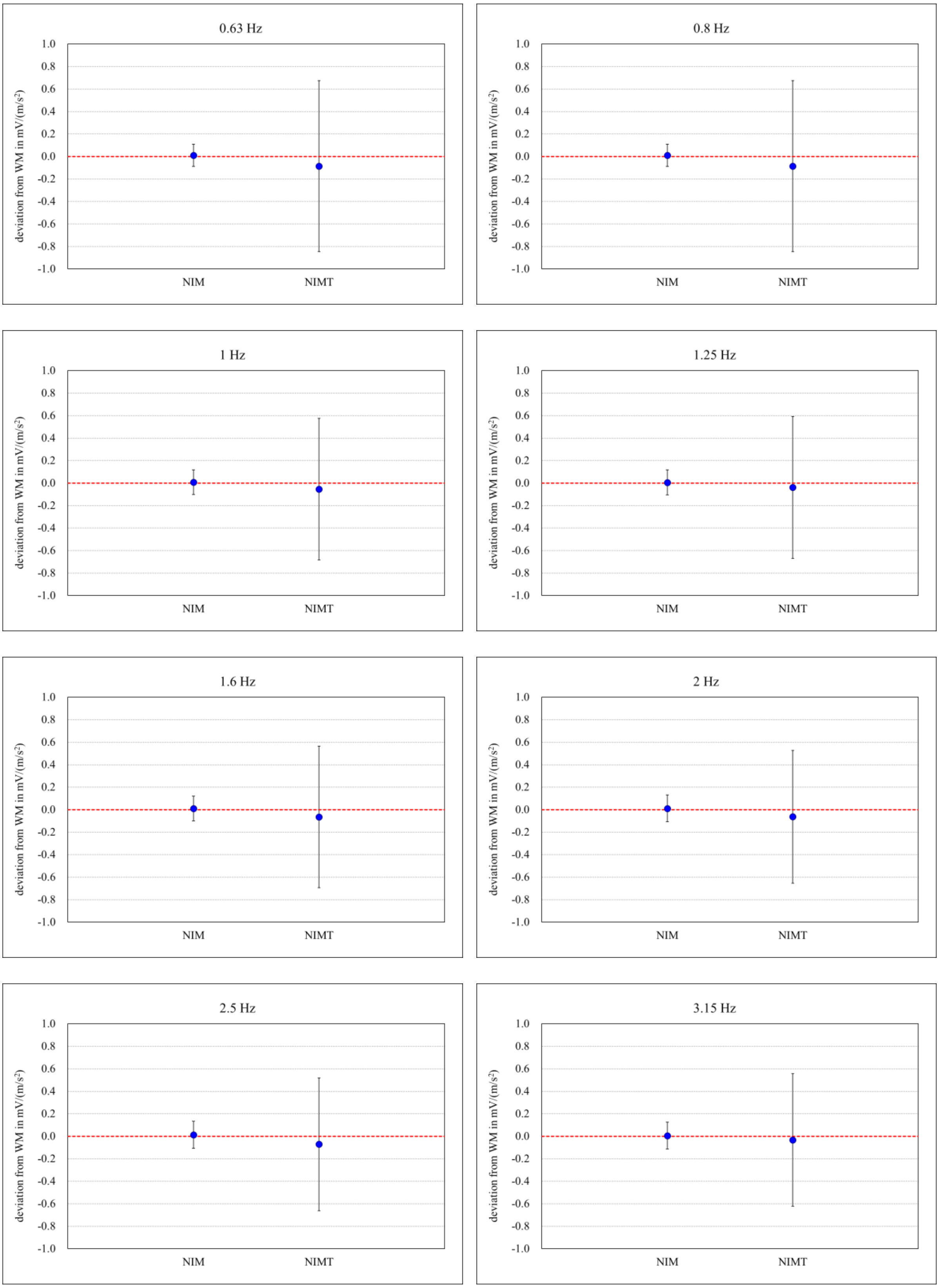



Figure 8.1.2 Deviation of the magnitude (vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2). (Cont.)

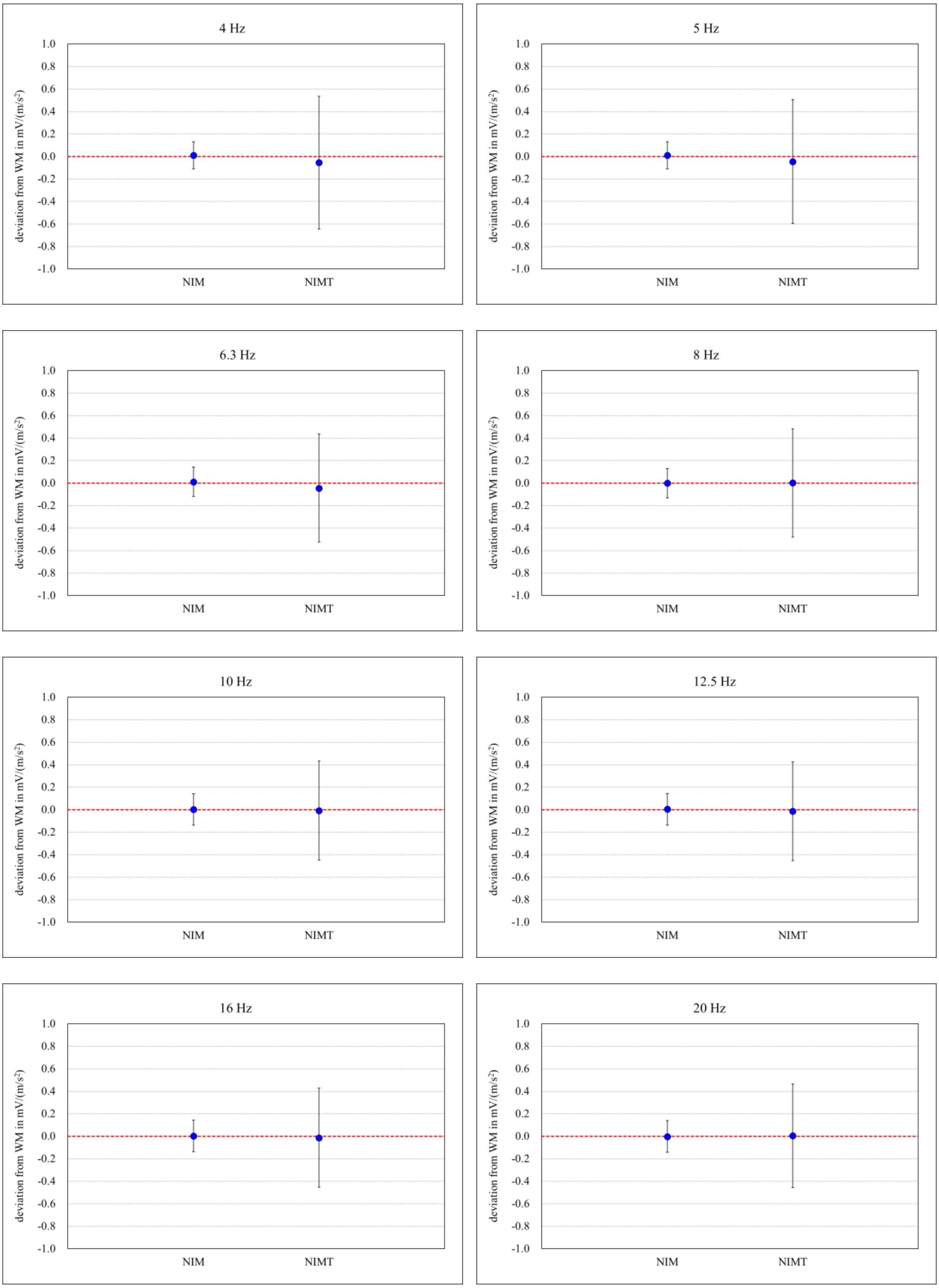



Figure 8.1.2 Deviation of the magnitude (vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2). (Cont.)

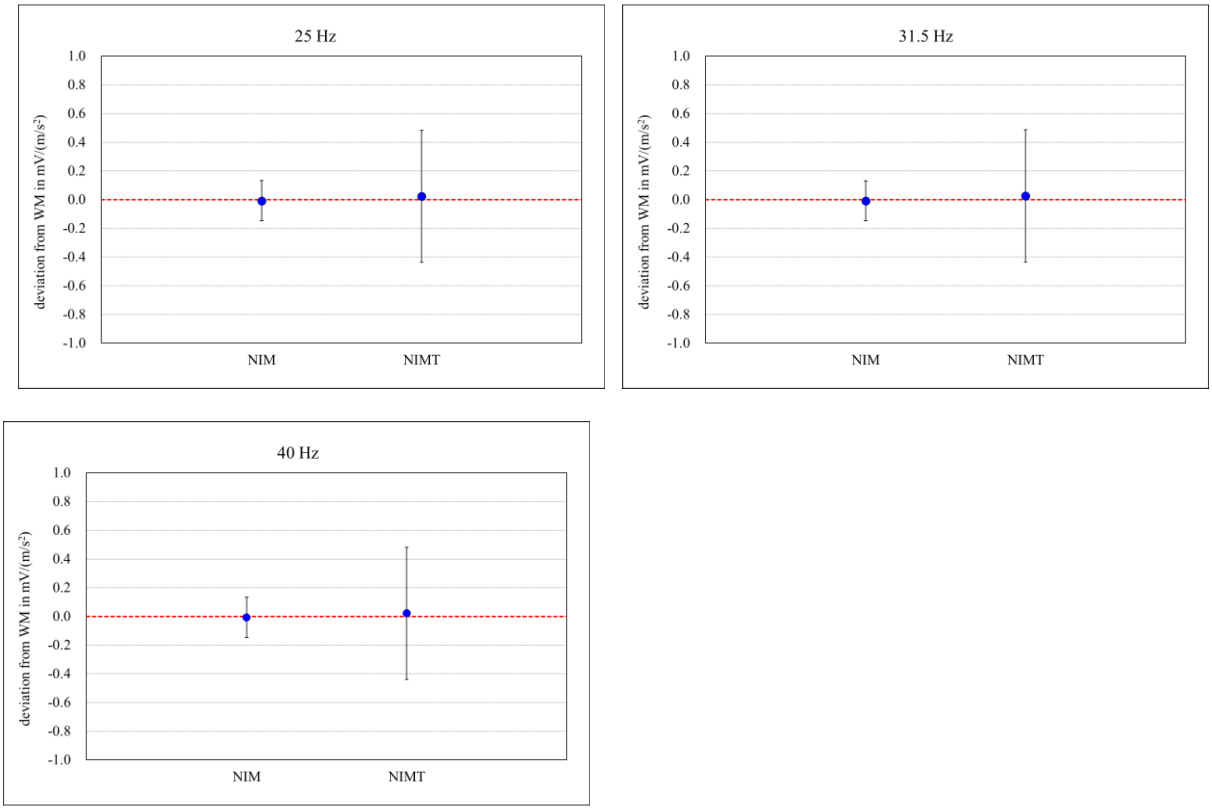



Figure 8.1.2 Deviation of the magnitude (vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2). (Cont.)

## 8.2 Results for the phase shift of the complex voltage sensitivity

Table 8.2.1 Unilateral degrees of equivalence for the phase shift (horizontal) of sensitivity with absolute expanded uncertainties (*k* = 2)

| Horizontal | Weighted Mean | | CMS-ITRI | | NIM | | KRISS | | NMISA | | CSIR-NPLI | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| Frequency (Hz) | $X_{WM}$ ( ° ) | $U_{WM}$ ( ° ) | $d_{i,WM}$ ( ° ) | $U_{i,WM}$ ( ° ) | $d_{i,WM}$ ( ° ) | $U_{i,WM}$ ( ° ) | $d_{i,WM}$ ( ° ) | $U_{i,WM}$ ( ° ) | $d_{i,WM}$ ( ° ) | $U_{i,WM}$ ( ° ) | $d_{i,WM}$ ( ° ) | $U_{i,WM}$ ( ° ) |
| 0.1 | -0.35 | 0.11 | 0.00 | 0.29 | 0.006 | 0.17 | 0.01 | 0.17 | -0.01 | 0.17 | -0.02 | 1.0 |
| 0.125 | -0.42 | 0.11 | 0.00 | 0.29 | 0.000 | 0.17 | 0.00 | 0.17 | -0.01 | 0.17 | -0.02 | 1.0 |
| 0.16 | -0.54 | 0.11 | -0.01 | 0.29 | -0.004 | 0.17 | 0.01 | 0.17 | 0.00 | 0.17 | 0.01 | 1.0 |
| 0.2 | -0.68 | 0.11 | 0.00 | 0.29 | -0.002 | 0.17 | 0.01 | 0.17 | 0.00 | 0.17 | 0.04 | 1.0 |
| 0.25 | -0.84 | 0.11 | -0.01 | 0.29 | -0.006 | 0.17 | 0.01 | 0.17 | -0.01 | 0.17 | 0.01 | 1.0 |
| 0.315 | -1.06 | 0.11 | -0.01 | 0.29 | -0.009 | 0.17 | 0.02 | 0.17 | -0.01 | 0.17 | -0.04 | 1.0 |
| 0.4 | -1.35 | 0.11 | 0.00 | 0.29 | -0.013 | 0.17 | 0.02 | 0.17 | 0.00 | 0.17 | 0.02 | 1.0 |
| 0.5 | -0.02 | 0.11 | 0.00 | 0.29 | -0.003 | 0.17 | 0.01 | 0.17 | 0.01 | 0.17 | -0.30 | 0.7 |
| 0.63 | -0.02 | 0.11 | 0.00 | 0.29 | 0.000 | 0.17 | 0.01 | 0.17 | 0.01 | 0.17 | -0.25 | 0.7 |
| 0.8 | -0.03 | 0.11 | 0.00 | 0.29 | -0.012 | 0.17 | 0.02 | 0.17 | 0.01 | 0.17 | -0.21 | 0.7 |
| 1 | -0.03 | 0.11 | -0.01 | 0.29 | -0.012 | 0.17 | 0.01 | 0.17 | 0.01 | 0.17 | -0.17 | 0.7 |
| 1.25 | -0.04 | 0.11 | -0.01 | 0.29 | -0.015 | 0.17 | 0.01 | 0.17 | 0.02 | 0.17 | -0.14 | 0.7 |
| 1.6 | -0.05 | 0.11 | -0.01 | 0.29 | -0.017 | 0.17 | 0.00 | 0.17 | 0.03 | 0.17 | -0.12 | 0.7 |
| 2 | -0.07 | 0.11 | 0.00 | 0.29 | -0.023 | 0.17 | 0.01 | 0.17 | 0.03 | 0.17 | -0.12 | 0.7 |
| 2.5 | -0.09 | 0.11 | 0.00 | 0.31 | -0.032 | 0.17 | 0.00 | 0.17 | 0.05 | 0.17 | -0.11 | 0.7 |
| 3.15 | -0.11 | 0.11 | -0.01 | 0.31 | -0.025 | 0.17 | -0.01 | 0.17 | 0.06 | 0.17 | -0.11 | 0.7 |
| 4 | -0.14 | 0.11 | -0.01 | 0.31 | -0.041 | 0.17 | -0.02 | 0.17 | 0.07 | 0.17 | -0.09 | 0.7 |
| 5 | -0.18 | 0.11 | -0.04 | 0.31 | -0.041 | 0.17 | -0.03 | 0.17 | 0.09 | 0.17 | -0.09 | 0.7 |
| 6.3 | -0.24 | 0.11 | -0.01 | 0.31 | -0.045 | 0.17 | -0.03 | 0.17 | 0.10 | 0.17 | -0.19 | 0.7 |
| 8 | -0.29 | 0.11 | -0.04 | 0.31 | -0.068 | 0.17 | -0.05 | 0.17 | 0.14 | 0.17 | -0.11 | 0.7 |
| 10 | -0.36 | 0.11 | -0.02 | 0.31 | -0.092 | 0.17 | -0.07 | 0.17 | 0.18 | 0.17 | -0.12 | 0.7 |
| 12.5 | -0.45 | 0.11 | -0.08 | 0.31 | -0.108 | 0.17 | -0.09 | 0.17 | 0.24 | 0.17 | -0.13 | 0.7 |
| 16 | -0.70 | 0.13 | 0.01 | 0.30 | -0.016 | 0.16 | 0.01 | 0.16 | 0.43 | 0.24 | -0.06 | 0.7 |
| 20 | -0.89 | 0.13 | 0.04 | 0.30 | -0.015 | 0.16 | 0.01 | 0.16 | 0.54 | 0.24 | -0.14 | 0.8 |
| 25 | -1.11 | 0.13 | 0.09 | 0.30 | -0.025 | 0.16 | 0.00 | 0.16 | 0.70 | 0.24 | -0.26 | 0.8 |
| 31.5 | -1.44 | 0.13 | 0.09 | 0.30 | -0.033 | 0.16 | 0.02 | 0.16 | 0.93 | 0.24 | -0.40 | 0.9 |
| 40 | -1.97 | 0.13 | -0.08 | 0.30 | -0.102 | 0.16 | 0.14 | 0.16 | 1.27 | 0.24 | -0.02 | 0.9 |

Table 8.2.2 Unilateral degrees of equivalence for the phase shift (vertical) of sensitivity with absolute expanded uncertainties ($k$ = 2)

| Vertical | Weighted Mean | | NIM | | NIMT | |
|---|---|---|---|---|---|---|
| Frequency (Hz) | $X_{WM}$ (°) | $U_{WM}$ (°) | $d_{i,WM}$ (°) | $U_{i,WM}$ (°) | $d_{i,WM}$ (°) | $U_{i,WM}$ (°) |
| 0.1 | -0.30 | 0.20 | 0.00 | 0.05 | -0.04 | 0.82 |
| 0.125 | -0.41 | 0.20 | 0.00 | 0.05 | -0.04 | 0.82 |
| 0.16 | -0.54 | 0.20 | 0.00 | 0.05 | -0.01 | 0.82 |
| 0.2 | -0.67 | 0.20 | 0.00 | 0.05 | -0.03 | 0.82 |
| 0.25 | -0.84 | 0.20 | 0.00 | 0.05 | -0.02 | 0.82 |
| 0.315 | -1.07 | 0.20 | 0.00 | 0.05 | -0.02 | 0.82 |
| 0.4 | -1.35 | 0.20 | 0.00 | 0.05 | -0.02 | 0.82 |
| 0.5 | -0.01 | 0.20 | 0.00 | 0.05 | -0.02 | 0.82 |
| 0.63 | -0.02 | 0.20 | 0.00 | 0.05 | -0.02 | 0.82 |
| 0.8 | -0.03 | 0.20 | 0.00 | 0.05 | -0.01 | 0.82 |
| 1 | -0.04 | 0.20 | 0.00 | 0.07 | 0.00 | 0.60 |
| 1.25 | -0.06 | 0.20 | 0.00 | 0.07 | 0.00 | 0.60 |
| 1.6 | -0.07 | 0.20 | 0.00 | 0.07 | 0.00 | 0.60 |
| 2 | -0.09 | 0.19 | 0.00 | 0.07 | 0.01 | 0.51 |
| 2.5 | -0.11 | 0.19 | 0.00 | 0.07 | 0.01 | 0.51 |
| 3.15 | -0.14 | 0.19 | 0.00 | 0.07 | 0.01 | 0.51 |
| 4 | -0.18 | 0.19 | 0.00 | 0.07 | 0.02 | 0.51 |
| 5 | -0.22 | 0.19 | 0.00 | 0.08 | 0.02 | 0.45 |
| 6.3 | -0.28 | 0.19 | 0.00 | 0.08 | 0.02 | 0.45 |
| 8 | -0.36 | 0.19 | 0.00 | 0.08 | 0.02 | 0.45 |
| 10 | -0.46 | 0.19 | 0.00 | 0.08 | 0.02 | 0.43 |
| 12.5 | -0.57 | 0.19 | 0.00 | 0.08 | 0.03 | 0.43 |
| 16 | -0.74 | 0.19 | -0.01 | 0.08 | 0.03 | 0.43 |
| 20 | -0.92 | 0.19 | 0.00 | 0.08 | 0.03 | 0.43 |
| 25 | -1.16 | 0.19 | 0.00 | 0.08 | 0.03 | 0.43 |
| 31.5 | -1.43 | 0.19 | 0.00 | 0.08 | -0.01 | 0.43 |
| 40 | -1.89 | 0.19 | 0.00 | 0.08 | 0.01 | 0.43 |

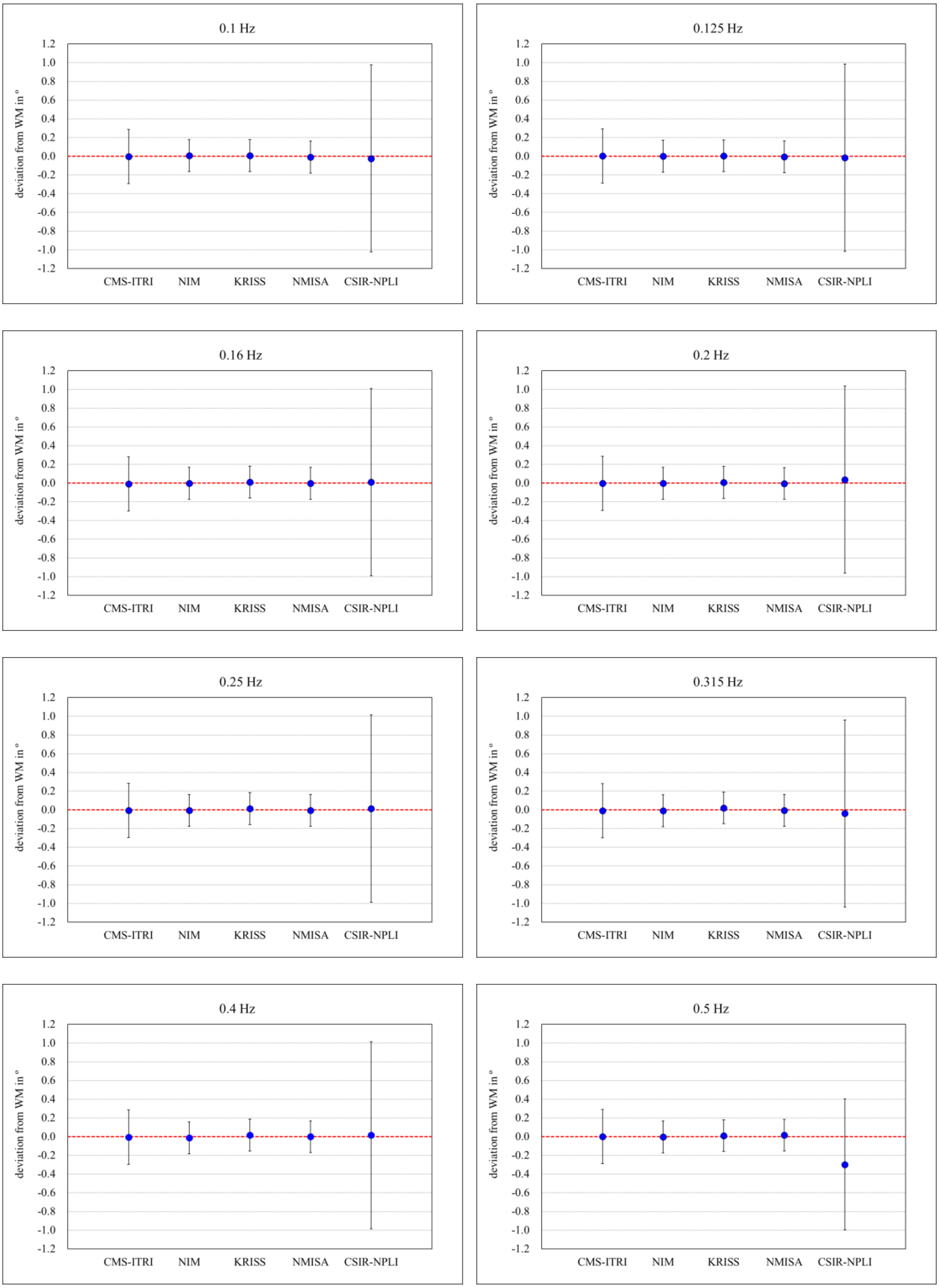



Figure 8.2.1 Deviation of the phase shift (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2)

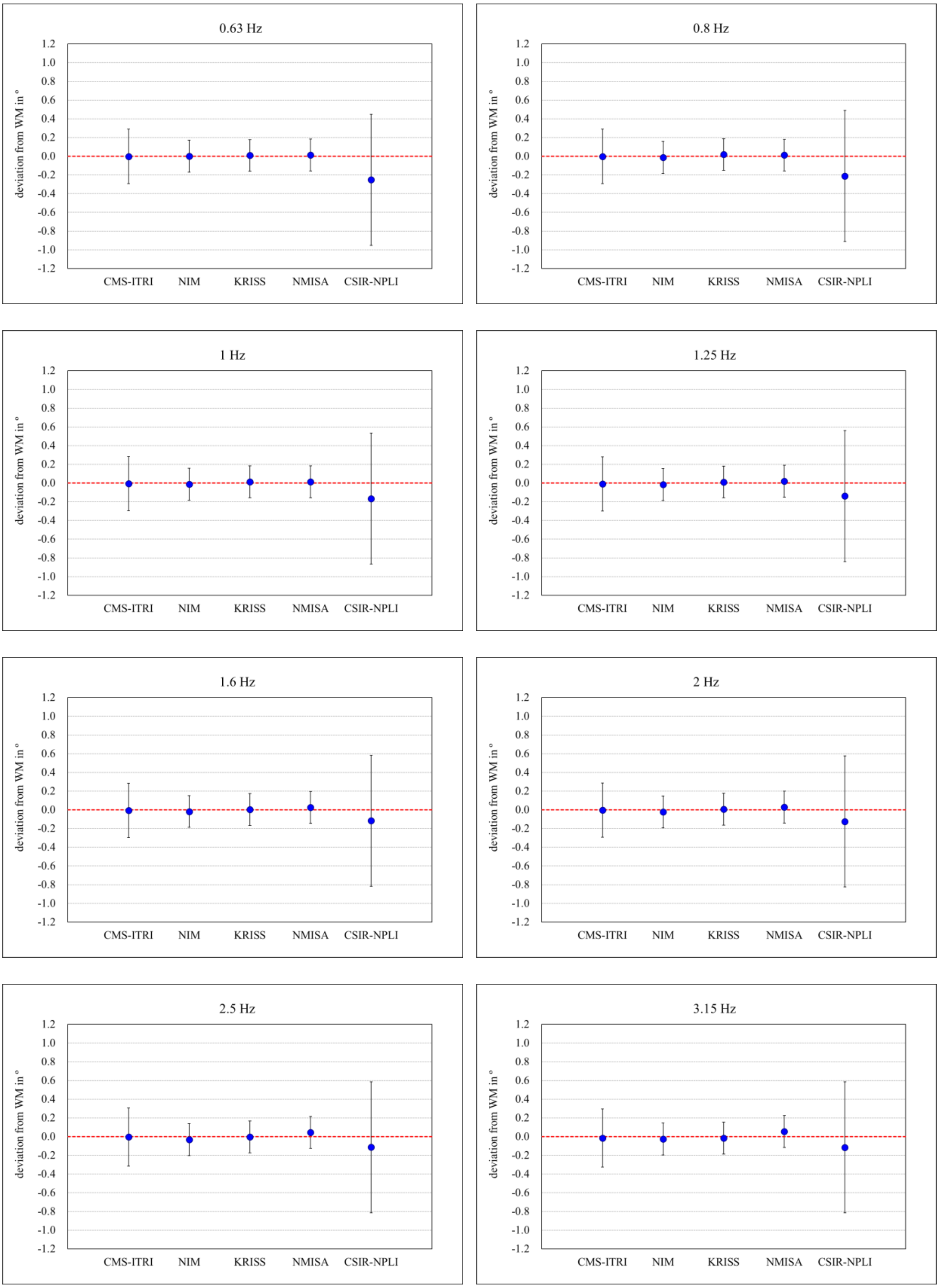



Figure 8.2.1 Deviation of the phase shift (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2) (Cont.)

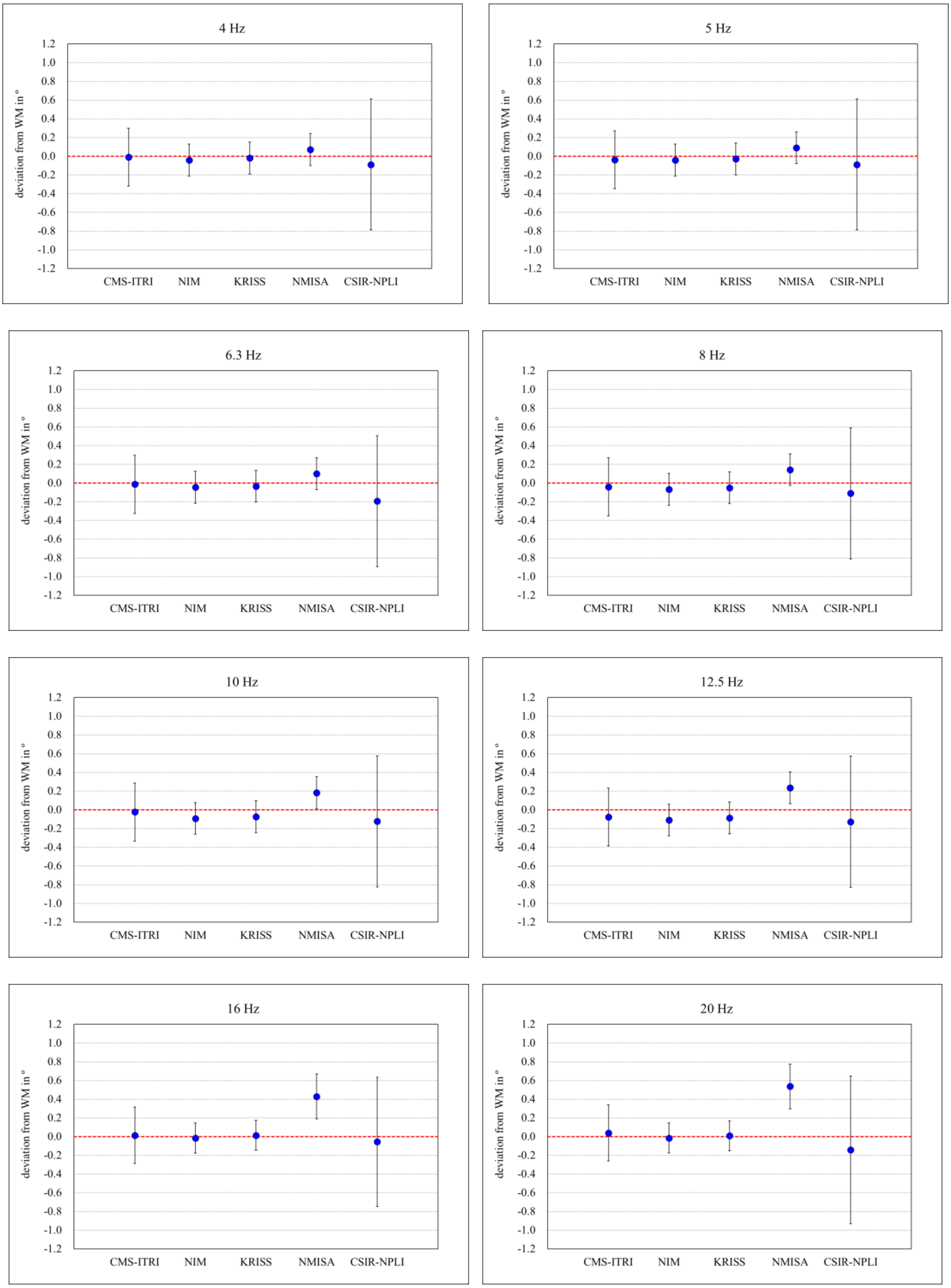
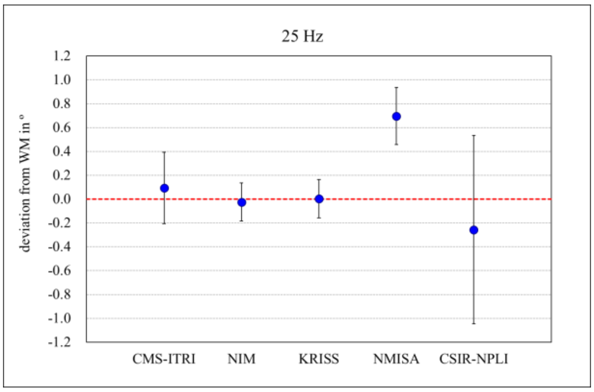
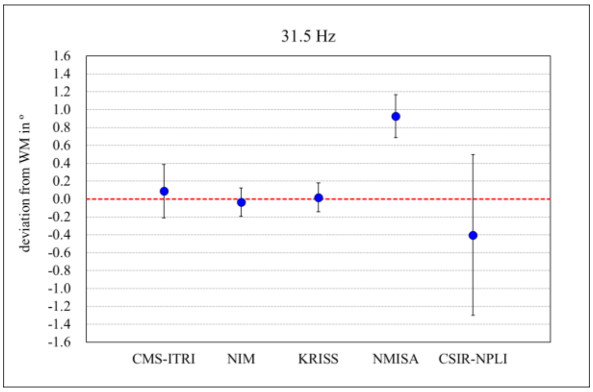



Figure 8.2.1 Deviation of the phase shift (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2) (Cont.)



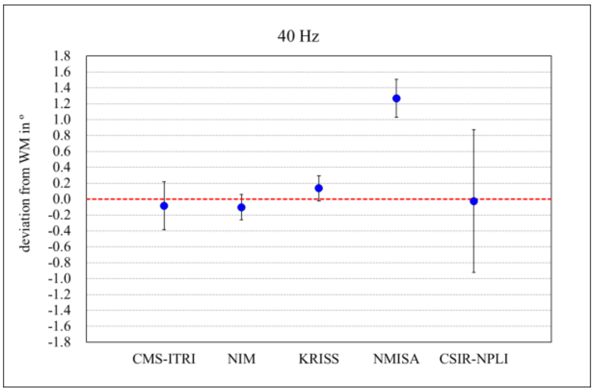




Figure 8.2.1 Deviation of the phase shift (horizontal) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2) (Cont.)

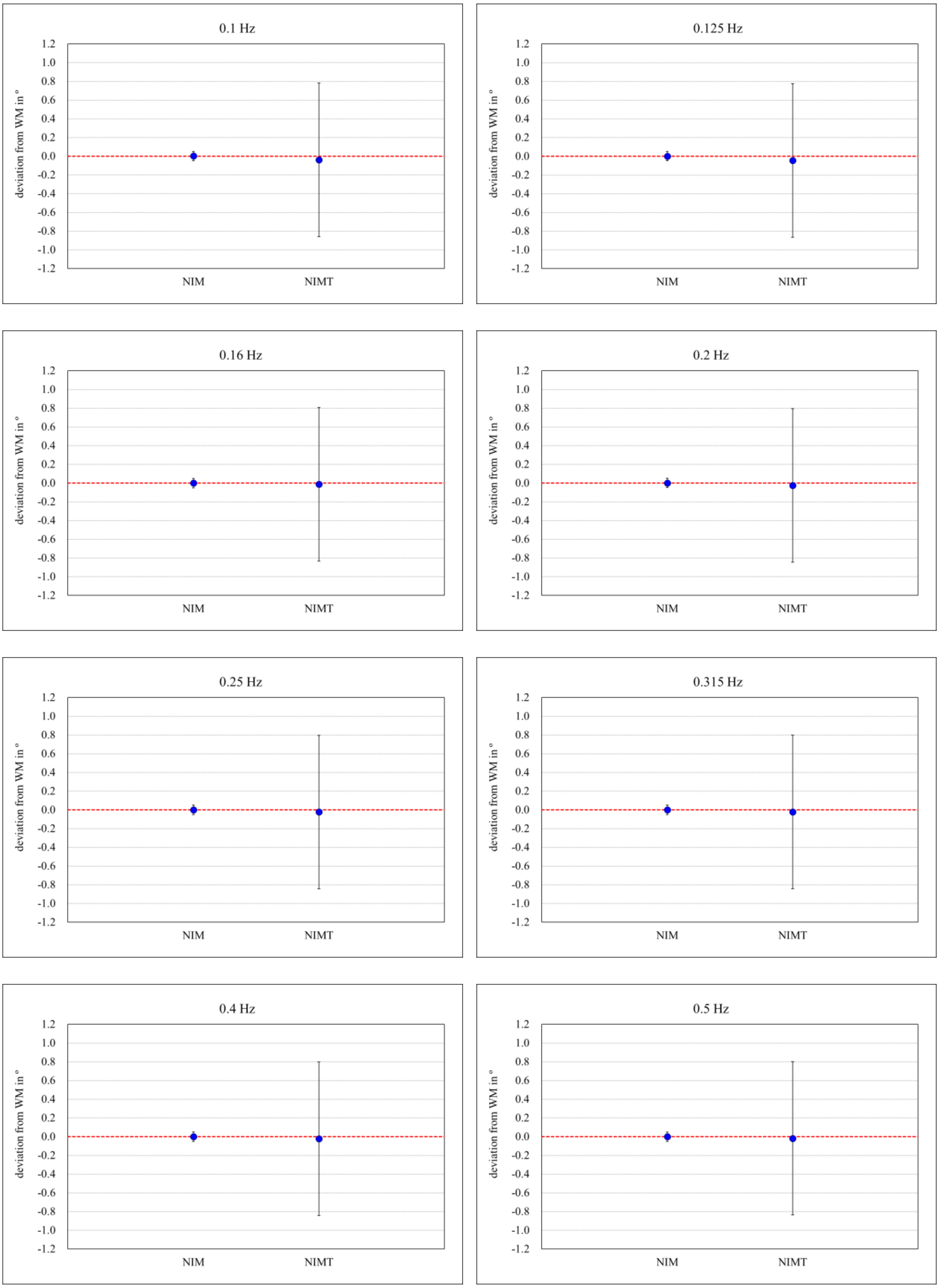



Figure 8.2.2 Deviation of the phase shift (Vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2)

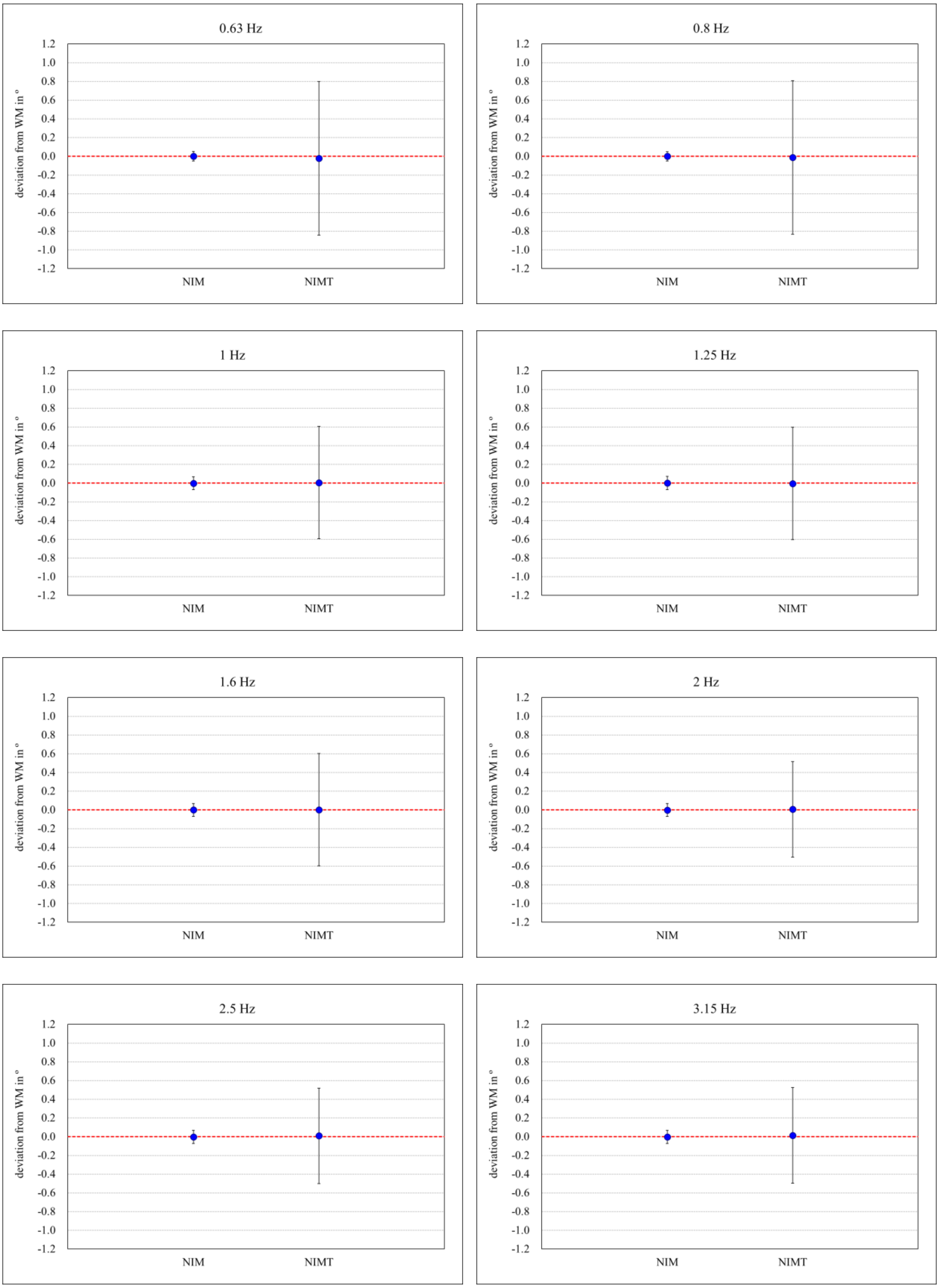



Figure 8.2.2 Deviation of the phase shift (Vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2) (Cont.)

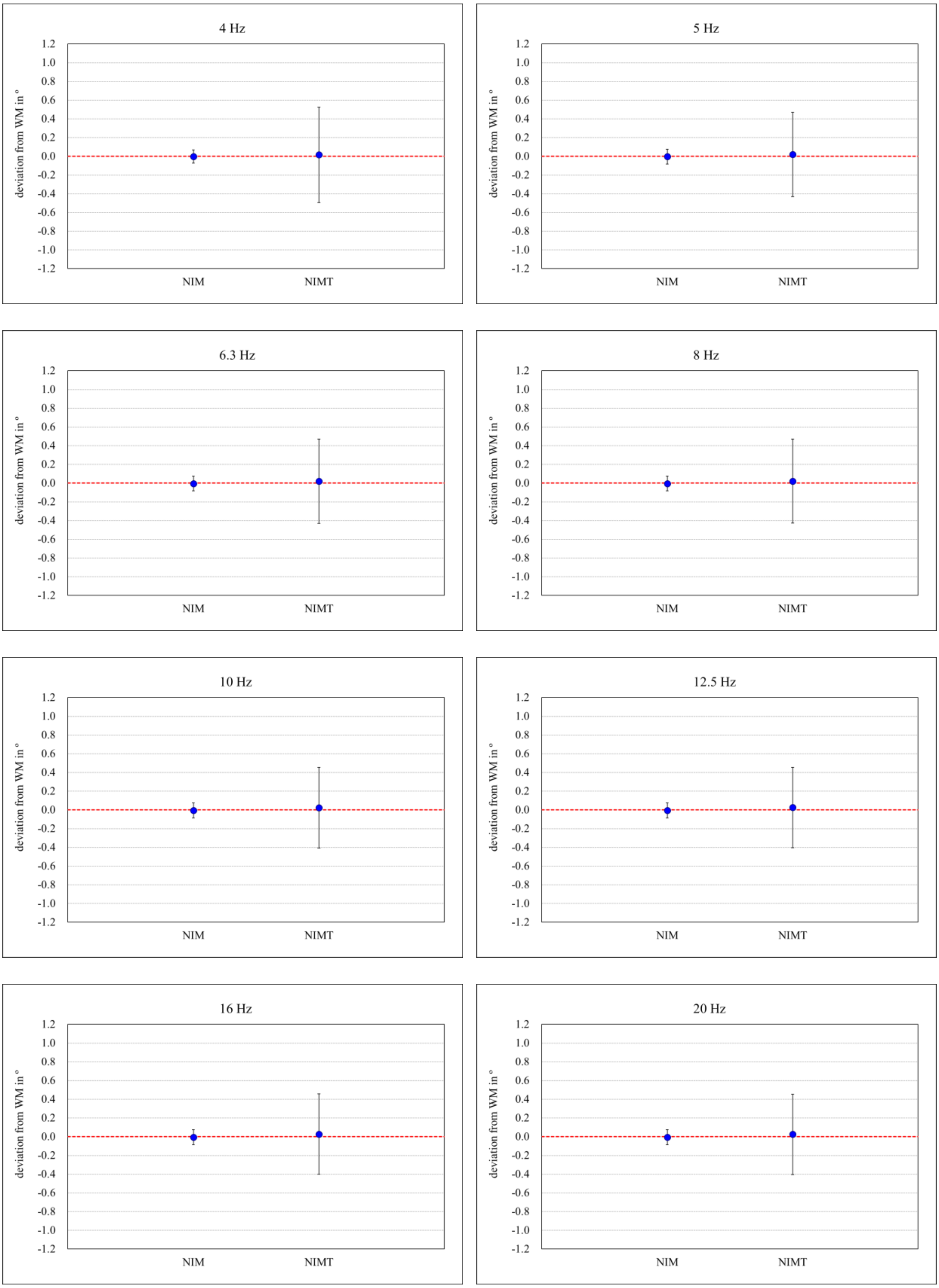
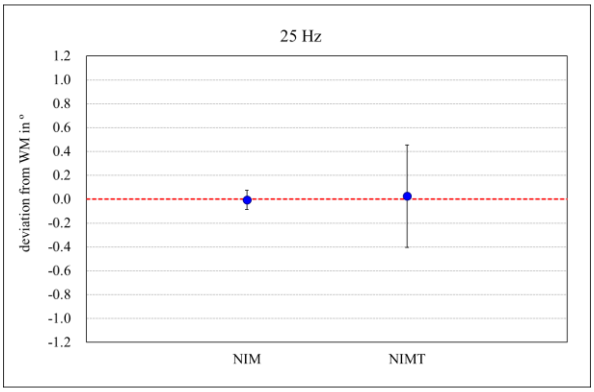
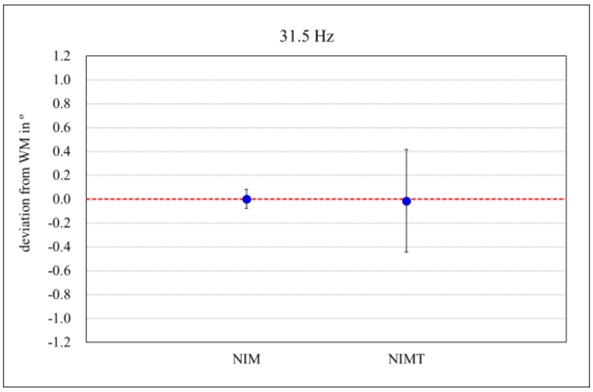



Figure 8.2.2 Deviation of the phase shift (Vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2) (Cont.)



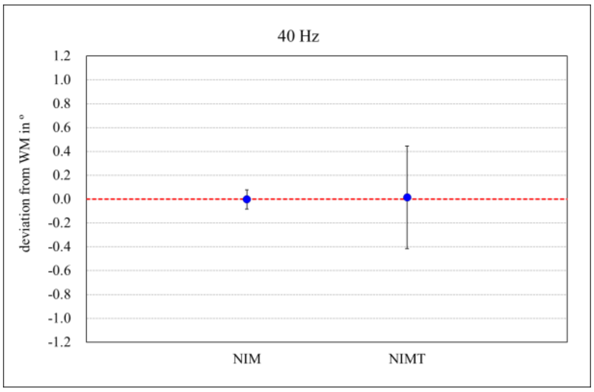




Figure 8.2.2 Deviation of the phase shift (Vertical) from the weighted mean for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{WM}}$ ($k$ = 2) (Cont.)

# 9. Linking procedure and degrees of equivalence with the KCRV

The linking procedure to the relevant CC comparison and calculation of the KCRV are described in this chapter. It was recommended to consider the influence of correlation of the results of the linking laboratory(ies) based on the procedure described in the previous publication by Clemens Elster et al [6]. The linking transforms the results ($y_i$, $u(y_i)$) of the participants of this comparison to scaled values $z_i$ and their respective uncertainties $u(z_i)$, which are directly comparable to the relevant CC comparison results of CCAUV.V-K3. The scaling was done with the so-called linking factor $r$. Then, $r$ is defined by two complex voltage sensitivities ($x_{\mathrm{NIM}}$ and $y_{\mathrm{NIM}}$) in the CIPM and RMO comparisons of NIM（linking laboratory) as follows.

## 9.1 Degrees of equivalence for the magnitude of the complex voltage sensitivity

The linking factor for magnitude between CIPM and RMO comparisons was defined as following.

$$r_m = \frac{x_{NIM_m}}{y_{NIM_m}} \tag{5}$$

where the uncertainty associated was described as

$$u^2(r_m) = \left(\frac{\partial r_m}{\partial x_{NIM_m}}\right)^2 u^2(x_{NIM_m}) + \left(\frac{\partial r_m}{\partial y_{NIM_m}}\right)^2 u^2(y_{NIM_m}) + 2\left(\frac{\partial r_m}{\partial x_{NIM_m}}\right)\left(\frac{\partial r_m}{\partial y_{NIM_m}}\right) u(x_{NIM_m}) u(y_{NIM_m}) r(x_{NIM_m}, y_{NIM_m}) \tag{6}$$

Considering the correlation coefficient of uncertainty in two comparisons $r(x_{NIM_m}, y_{NIM_m})$ was equal to 1, equation (6) can be written as equation (7).

$$u^2(r_m) = \left(\frac{1}{y_{NIM_m}}\right)^2 u^2(x_{NIM_m}) + \left(-\frac{x_{NIM_m}}{y_{NIM_m}^2}\right)^2 u^2(y_{NIM_m}) - 2\left(\frac{x_{NIM_m}}{y_{NIM_m}^3}\right) u(x_{NIM_m}) u(y_{NIM_m}) \tag{7}$$

Then APMP.AUV.V-K3.1 result can be transformed to the scaled value $z_{i_m}$ of CCAUV.V-K3 employing $r_m$ as follows

$$z_{i_m} = r_m y_{i_m} = \frac{x_{NIM_m}}{y_{NIM_m}} y_{i_m} \tag{8}$$

Thus, the degrees of equivalence are given as the differences between the scaled complex voltage sensitivities in the APMP.AUV.V-K3.1 and the KCRV of the CCAUV.V.K3.

$$d_{i,KCRV_\mathrm{m}} = z_{i_m} - x_{KCRV_\mathrm{m}} = \frac{x_{NIM_m}}{y_{NIM_m}} y_{i_m} - x_{KCRV_\mathrm{m}} \tag{9}$$

Here $y_{im}$ is independent of other variables, and the squared standard uncertainties associated with these differences are described as follows

$$u^2(d_{i,KCRV_\mathrm{m}}) = \left(\frac{y_{i_m}}{y_{NIM_m}}\right)^2 u^2(x_{NIM_m}) + \left(-\frac{x_{NIM_m} y_{i_m}}{y^2{}_{NIM_m}}\right)^2 u^2(y_{NIM_m}) + \left(\frac{x_{NIM_m}}{y_{NIM_m}}\right)^2 u^2(y_{i_m}) + (-1)^2 u^2(x_{KCRV_\mathrm{m}}) + 2\left(\frac{y_{i_m}}{y_{NIM_m}}\right)\left(-\frac{x_{NIM_m} y_{i_m}}{y^2{}_{NIM_m}}\right) u(x_{NIM_m}, y_{NIM_m}) + 2\left(\frac{y_{i_m}}{y_{NIM_m}}\right)(-1) u(x_{NIM_m}, x_{KCRV_\mathrm{m}}) + 2\left(-\frac{x_{NIM_m} y_{i_m}}{y^2{}_{NIM_m}}\right)(-1) u(y_{NIM_m}, x_{KCRV_\mathrm{m}}) \quad (10)$$

## 9.2 Degrees of equivalence for the phase shift of the complex voltage sensitivity

The linking factor for phase shift between CIPM and RMO comparisons was defined as following.

$$r_p = x_{NIM_p} - y_{NIM_p} \quad (11)$$

where the uncertainty associated was described as

$$u^2(r_p) = \left(\frac{\partial r_p}{\partial x_{NIM_p}}\right)^2 u^2\left(x_{NIM_p}\right) + \left(\frac{\partial r_p}{\partial y_{NIM_p}}\right)^2 u^2\left(y_{NIM_p}\right) + 2\left(\frac{\partial r_p}{\partial x_{NIM_p}}\right)\left(\frac{\partial r_p}{\partial y_{NIM_p}}\right) u\left(x_{NIM_p}\right) u\left(y_{NIM_p}\right) r\left(x_{NIM_p}, y_{NIM_p}\right) \quad (12)$$

Considering the correlation coefficient of uncertainty in two comparisons $r(x_{NIM}, y_{NIM})$ was equal to 1, equation (12) can be written as equation (13).

$$u^2(r_p) = (1)^2 u^2\left(x_{NIM_p}\right) + (-1)^2 u^2\left(y_{NIM_p}\right) - 2u\left(x_{NIM_p}\right) u\left(y_{NIM_p}\right) \quad (13)$$

APMP.AUV.V-K3.1 comparison participant result can be transformed to the scaled value $z_{i_p}$ of CCAUV.V.K3 comparison employing $r$ as follows

$$z_{i_p} = y_{i_p} + r_p = y_{i_p} + (x_{NIM_p} - y_{NIM_p}) \quad (14)$$

Thus, the degrees of equivalence are given as the differences between the scaled complex voltage sensitivities in the APMP.AUV.V-K3.1 comparison and the KCRV of the CCAUV.V.K3 CIPM comparison.

$$d_{i,\mathrm{KCRV_p}} = z_{i_p} - x_{KCRV_\mathrm{p}} = y_{i_p} + (x_{NIM_p} - y_{NIM_p}) - x_{KCRV_\mathrm{p}} \quad (15)$$

Here $y_{ip}$ is independent of other variables, and the squared standard uncertainties associated with these differences are described as follows

$$u^2\left(d_{i,KCRV_\mathrm{p}}\right) = u^2\left(y_{i_p}\right) + u^2\left(x_{NIM_p}\right) + (-1)^2 u^2\left(y_{NIM_p}\right) + (-1)^2 u^2\left(x_{KCRV_\mathrm{p}}\right) +$$

$$2(-1)u\left(x_{NIM_p}, y_{NIM_p}\right) + 2(-1)u\left(x_{NIM_p}, x_{KCRV_\mathrm{p}}\right) + 2u\left(y_{NIM_p}, x_{KCRV_\mathrm{p}}\right) \quad (16)$$

## 9.3 Result

Both in equation (10) and (16), the same processes were performed as below. Because $r(x_{NIM}, y_{NIM})$ is equal to 1, the item $u(x_{NIM}, y_{NIM})$ is equal to $u(x_{NIM})u(y_{NIM})$.
The item $r(x_{NIM}, x_{KCRV})$ was carried out as follows.

$$r(x_{NIM}, x_{KCRV}) = \frac{\frac{\partial x_{NIM} \partial x_{KCRV}}{\partial x_{NIM}\ \partial x_{NIM}} u^2(x_{NIM})}{u(x_{NIM})u(x_{KCRV})} = \frac{1 \cdot \frac{1/u^2(x_{NIM})}{1/u^2(x_{KCRV})} u^2(x_{NIM})}{u(x_{NIM})u(x_{KCRV})} = \frac{u(x_{KCRV})}{u(x_{NIM})} \quad (17)$$

The transformation of $u(x_{NIM}, x_{KCRV}) = u(x_{NIM})u(x_{KCRV})r(x_{NIM}, x_{KCRV})$ was rewritten as follows.

$$u(x_{NIM}, x_{KCRV}) = u(x_{KCRV})u(x_{KCRV}) = u^2(x_{KCRV}) \quad (18)$$

Also, the transformation of $u(y_{NIM}, x_{\mathrm{KCRV}}) = u(y_{NIM})u(x_{\mathrm{KCRV}})r(y_{NIM}, x_{\mathrm{KCRV}})$ can be given as equation (19) same as equation (17 ) because $r(x_{NIM}, y_{NIM}) = 1$.

$$r(y_{NIM}, x_{KCRV}) = \frac{\frac{1/u^2(x_{NIM})}{1/u^2(x_{KCRV})} u(x_{NIM}, y_{NIM})}{u(y_{NIM})u(x_{KCRV})} = \frac{u(x_{KCRV})}{u(y_{NIM})u^2(x_{NIM})} u(x_{NIM}, y_{NIM}) =$$

$$r(x_{NIM}, y_{NIM}) \frac{u(x_{KCRV})}{u(x_{NIM})} = r(x_{NIM}, x_{KCRV}) r(x_{NIM}, y_{NIM}) = r(x_{NIM}, x_{KCRV}) \quad (19)$$

Finally, the transformation can be rewritten as

$$u(y_{NIM}, x_{KCRV}) = u(x_{KCRV})u(x_{KCRV})u(y_{NIM})/u(x_{NIM})$$

$$= u^2(x_{KCRV})u(y_{NIM})/u(x_{NIM}) \quad (20)$$

The value of equation (18) at each frequency is shown in Table 9.3.1.

Table 9.3.1 Correlation coefficients of combined standard uncertainty between CCAUV.V-K3 and APMP.AUV.V-K3.1 international comparison for magnitude (left) and phase shift (right)

| Frequency (Hz) | $u(x_{KCRV})$ (mV/(m/s$^2$)) | $u(x_{NIM})$ (mV/(m/s$^2$)) | $r(x_{NIM}, x_{KCRV})$ | Frequency (Hz) | $u(x_{KCRV})$ ( ° ) | $u(x_{NIM})$ ( ° ) | $r(x_{NIM}, x_{KCRV})$ |
|---|---|---|---|---|---|---|---|
| 0.1 | 0.08 | 0.35 | 0.23 | 0.1 | 0.02 | 0.10 | 0.20 |
| 0.125 | 0.08 | 0.35 | 0.23 | 0.125 | 0.02 | 0.10 | 0.20 |
| 0.16 | 0.08 | 0.35 | 0.23 | 0.16 | 0.02 | 0.10 | 0.20 |
| 0.2 | 0.06 | 0.35 | 0.17 | 0.2 | 0.02 | 0.10 | 0.20 |
| 0.25 | 0.06 | 0.35 | 0.17 | 0.25 | 0.02 | 0.10 | 0.20 |
| 0.315 | 0.06 | 0.35 | 0.17 | 0.315 | 0.02 | 0.10 | 0.20 |
| 0.4 | 0.05 | 0.14 | 0.36 | 0.4 | 0.02 | 0.10 | 0.20 |
| 0.5 | 0.04 | 0.14 | 0.29 | 0.5 | 0.02 | 0.10 | 0.20 |
| 0.63 | 0.04 | 0.14 | 0.29 | 0.63 | 0.02 | 0.10 | 0.20 |
| 0.8 | 0.04 | 0.14 | 0.29 | 0.8 | 0.02 | 0.10 | 0.20 |
| 1 | 0.04 | 0.14 | 0.29 | 1 | 0.02 | 0.10 | 0.20 |
| 1.25 | 0.04 | 0.14 | 0.29 | 1.25 | 0.02 | 0.10 | 0.20 |
| 1.6 | 0.04 | 0.14 | 0.29 | 1.6 | 0.02 | 0.10 | 0.20 |
| 2 | 0.04 | 0.14 | 0.29 | 2 | 0.02 | 0.10 | 0.20 |
| 2.5 | 0.04 | 0.14 | 0.29 | 2.5 | 0.02 | 0.10 | 0.20 |
| 3.15 | 0.04 | 0.14 | 0.29 | 3.15 | 0.02 | 0.10 | 0.20 |
| 4 | 0.04 | 0.14 | 0.29 | 4 | 0.02 | 0.10 | 0.20 |
| 5 | 0.04 | 0.14 | 0.29 | 5 | 0.02 | 0.10 | 0.20 |
| 6.3 | 0.04 | 0.14 | 0.29 | 6.3 | 0.04 | 0.10 | 0.40 |
| 8 | 0.04 | 0.14 | 0.29 | 8 | 0.04 | 0.10 | 0.40 |
| 10 | 0.04 | 0.14 | 0.29 | 10 | 0.04 | 0.10 | 0.40 |
| 12.5 | 0.04 | 0.14 | 0.29 | 12.5 | 0.04 | 0.10 | 0.40 |
| 16 | 0.04 | 0.14 | 0.29 | 16 | 0.04 | 0.10 | 0.40 |
| 20 | 0.04 | 0.14 | 0.29 | 20 | 0.04 | 0.10 | 0.40 |
| 25 | 0.04 | 0.14 | 0.29 | 25 | 0.04 | 0.10 | 0.40 |
| 31.5 | 0.04 | 0.14 | 0.29 | 31.5 | 0.04 | 0.10 | 0.40 |
| 40 | 0.04 | 0.14 | 0.29 | 40 | 0.04 | 0.10 | 0.40 |

These degrees of equivalence of the Acceleration are each a pair of values of the difference $d_{i,\mathrm{KCRV}}$ between the respective corresponding participants $i$ and KCRV with the expanded uncertainty $U_{i,\mathrm{KCRV}}$ of this difference. (See Tables 9.3.2, 9.3.3 and Figure 9.3.1, 9.3.2) These values were calculated with a coverage factor of $k$ = 2 for each frequency according to:

$$d_{i,KCRV} = z_i - x_{KCRV} \tag{21}$$

$$U_{i,KCRV} = k \cdot \sqrt{u^2(d_{i,KCRV})} \tag{22}$$

Table 9.3.2 Degrees of equivalence to the KCRV of CCAUV.V-K3 for the magnitude of sensitivity with absolute expanded uncertainties ($k$ = 2)

| Horizontal Frequency (Hz) | CMS-ITRI | | KRISS | | NMISA | | CSIR-NPLI | |
|---|---|---|---|---|---|---|---|---|
| | $d_{i,\mathrm{KCRV}}$ | $U_{i,\mathrm{KCRV}}$ | $d_{i,\mathrm{KCRV}}$ | $U_{i,\mathrm{KCRV}}$ | $d_{i,\mathrm{KCRV}}$ | $U_{i,\mathrm{KCRV}}$ | $d_{i,\mathrm{KCRV}}$ | $U_{i,\mathrm{KCRV}}$ |
| | mV/(m/s$^2$) | | mV/(m/s$^2$) | | mV/(m/s$^2$) | | mV/(m/s$^2$) | |
| 0.1 | -0.74 | 0.51 | 0.64 | 1.9 | -0.53 | 1.2 | -0.57 | 1.5 |
| 0.125 | -0.60 | 0.51 | 0.34 | 1.5 | -0.31 | 1.2 | -0.39 | 1.5 |
| 0.16 | -0.45 | 0.51 | 0.23 | 1.2 | -0.10 | 1.2 | -0.27 | 1.5 |
| 0.2 | -0.44 | 0.51 | 0.10 | 0.75 | -0.12 | 1.2 | -0.20 | 1.5 |
| 0.25 | -0.37 | 0.51 | 0.10 | 0.75 | -0.06 | 0.75 | -0.15 | 1.5 |
| 0.315 | -0.34 | 0.51 | 0.05 | 0.51 | -0.03 | 0.75 | -0.12 | 1.5 |
| 0.4 | -0.28 | 0.43 | -0.01 | 0.43 | -0.02 | 0.70 | -0.09 | 1.4 |
| 0.5 | 0.04 | 0.43 | 0.11 | 0.57 | 0.01 | 0.70 | 0.18 | 1.0 |
| 0.63 | 0.00 | 0.43 | 0.07 | 0.57 | -0.02 | 0.70 | 0.15 | 1.0 |
| 0.8 | 0.00 | 0.43 | 0.14 | 0.57 | 0.02 | 0.70 | 0.18 | 1.0 |
| 1 | -0.01 | 0.43 | 0.19 | 0.57 | 0.03 | 0.43 | 0.12 | 1.0 |
| 1.25 | -0.03 | 0.43 | 0.18 | 0.57 | 0.04 | 0.43 | 0.19 | 1.0 |
| 1.6 | -0.02 | 0.43 | 0.13 | 0.43 | 0.05 | 0.43 | 0.19 | 1.0 |
| 2 | -0.07 | 0.43 | -0.03 | 0.43 | 0.00 | 0.43 | 0.09 | 1.0 |
| 2.5 | -0.04 | 0.43 | -0.01 | 0.43 | 0.03 | 0.43 | 0.17 | 1.0 |
| 3.15 | -0.06 | 0.43 | -0.01 | 0.43 | 0.02 | 0.43 | 0.17 | 1.0 |
| 4 | -0.03 | 0.43 | -0.03 | 0.43 | 0.04 | 0.43 | 0.12 | 1.0 |
| 5 | -0.08 | 0.43 | -0.06 | 0.43 | 0.01 | 0.43 | 0.09 | 1.0 |
| 6.3 | -0.06 | 0.43 | -0.01 | 0.43 | -0.01 | 0.43 | 0.16 | 1.0 |
| 8 | -0.02 | 0.43 | 0.03 | 0.43 | -0.01 | 0.43 | 0.12 | 1.0 |
| 10 | 0.01 | 0.43 | 0.07 | 0.43 | 0.02 | 0.43 | 0.14 | 1.0 |
| 12.5 | 0.03 | 0.43 | 0.08 | 0.43 | 0.01 | 0.43 | 0.23 | 1.0 |
| 16 | 0.13 | 0.43 | 0.22 | 0.43 | 0.08 | 0.43 | 0.30 | 1.0 |
| 20 | -0.21 | 0.43 | -0.10 | 0.43 | -0.32 | 0.43 | -0.04 | 1.2 |
| 25 | -0.19 | 0.43 | -0.07 | 0.43 | -0.36 | 0.43 | -0.05 | 1.2 |
| 31.5 | -0.03 | 0.43 | 0.06 | 0.43 | -0.29 | 0.43 | 0.13 | 1.3 |
| 40 | 0.07 | 0.43 | -0.09 | 0.43 | -0.40 | 0.43 | -0.02 | 1.3 |

Table 9.3.3 Degrees of equivalence to the KCRV of CCAUV.V-K3 for the phase shift of sensitivity with absolute expanded uncertainties ($k$ = 2)

| Horizontal Frequency (Hz) | CMS-ITRI | | KRISS | | NMISA | | CSIR-NPLI | |
|---|---|---|---|---|---|---|---|---|
| | $d_{i,KCRV}$ (°) | $U_{i,KCRV}$ (°) | $d_{i,KCRV}$ (°) | $U_{i,KCRV}$ (°) | $d_{i,KCRV}$ (°) | $U_{i,KCRV}$ (°) | $d_{i,KCRV}$ (°) | $U_{i,KCRV}$ (°) |
| 0.1 | -0.02 | 0.31 | -0.01 | 0.21 | -0.03 | 0.21 | -0.04 | 1.01 |
| 0.125 | -0.01 | 0.31 | -0.01 | 0.21 | -0.02 | 0.21 | -0.03 | 1.01 |
| 0.16 | -0.02 | 0.31 | 0.00 | 0.21 | -0.01 | 0.21 | 0.00 | 1.01 |
| 0.2 | -0.01 | 0.31 | 0.00 | 0.21 | -0.01 | 0.21 | 0.03 | 1.01 |
| 0.25 | 0.00 | 0.31 | 0.02 | 0.21 | 0.00 | 0.21 | 0.02 | 1.01 |
| 0.315 | 0.00 | 0.31 | 0.03 | 0.21 | 0.00 | 0.21 | -0.03 | 1.01 |
| 0.4 | 0.01 | 0.31 | 0.03 | 0.21 | 0.01 | 0.21 | 0.03 | 1.01 |
| 0.5 | 0.02 | 0.31 | 0.03 | 0.21 | 0.03 | 0.21 | -0.28 | 0.71 |
| 0.63 | -0.01 | 0.31 | 0.00 | 0.21 | 0.00 | 0.21 | -0.26 | 0.71 |
| 0.8 | 0.06 | 0.31 | 0.08 | 0.21 | 0.07 | 0.21 | -0.15 | 0.71 |
| 1 | 0.03 | 0.31 | 0.05 | 0.21 | 0.05 | 0.21 | -0.13 | 0.71 |
| 1.25 | 0.03 | 0.31 | 0.05 | 0.21 | 0.06 | 0.21 | -0.10 | 0.71 |
| 1.6 | 0.03 | 0.31 | 0.04 | 0.21 | 0.06 | 0.21 | -0.08 | 0.71 |
| 2 | 0.03 | 0.31 | 0.04 | 0.21 | 0.06 | 0.21 | -0.09 | 0.71 |
| 2.5 | 0.05 | 0.33 | 0.05 | 0.21 | 0.10 | 0.21 | -0.06 | 0.71 |
| 3.15 | 0.04 | 0.33 | 0.04 | 0.21 | 0.11 | 0.21 | -0.06 | 0.71 |
| 4 | 0.06 | 0.33 | 0.05 | 0.21 | 0.14 | 0.21 | -0.02 | 0.71 |
| 5 | 0.03 | 0.33 | 0.04 | 0.21 | 0.16 | 0.21 | -0.02 | 0.71 |
| 6.3 | 0.05 | 0.33 | 0.03 | 0.22 | 0.16 | 0.22 | -0.13 | 0.71 |
| 8 | 0.03 | 0.33 | 0.02 | 0.22 | 0.21 | 0.22 | -0.04 | 0.71 |
| 10 | 0.08 | 0.33 | 0.03 | 0.22 | 0.29 | 0.22 | -0.02 | 0.71 |
| 12.5 | 0.04 | 0.33 | 0.03 | 0.22 | 0.35 | 0.22 | -0.01 | 0.71 |
| 16 | 0.04 | 0.33 | 0.04 | 0.22 | 0.45 | 0.22 | -0.03 | 0.71 |
| 20 | 0.09 | 0.33 | 0.06 | 0.22 | 0.59 | 0.22 | -0.09 | 0.81 |
| 25 | 0.19 | 0.33 | 0.10 | 0.22 | 0.79 | 0.22 | -0.16 | 0.81 |
| 31.5 | 0.21 | 0.33 | 0.14 | 0.22 | 1.05 | 0.22 | -0.28 | 0.91 |
| 40 | 0.05 | 0.33 | 0.27 | 0.22 | 1.40 | 0.22 | 0.11 | 0.91 |

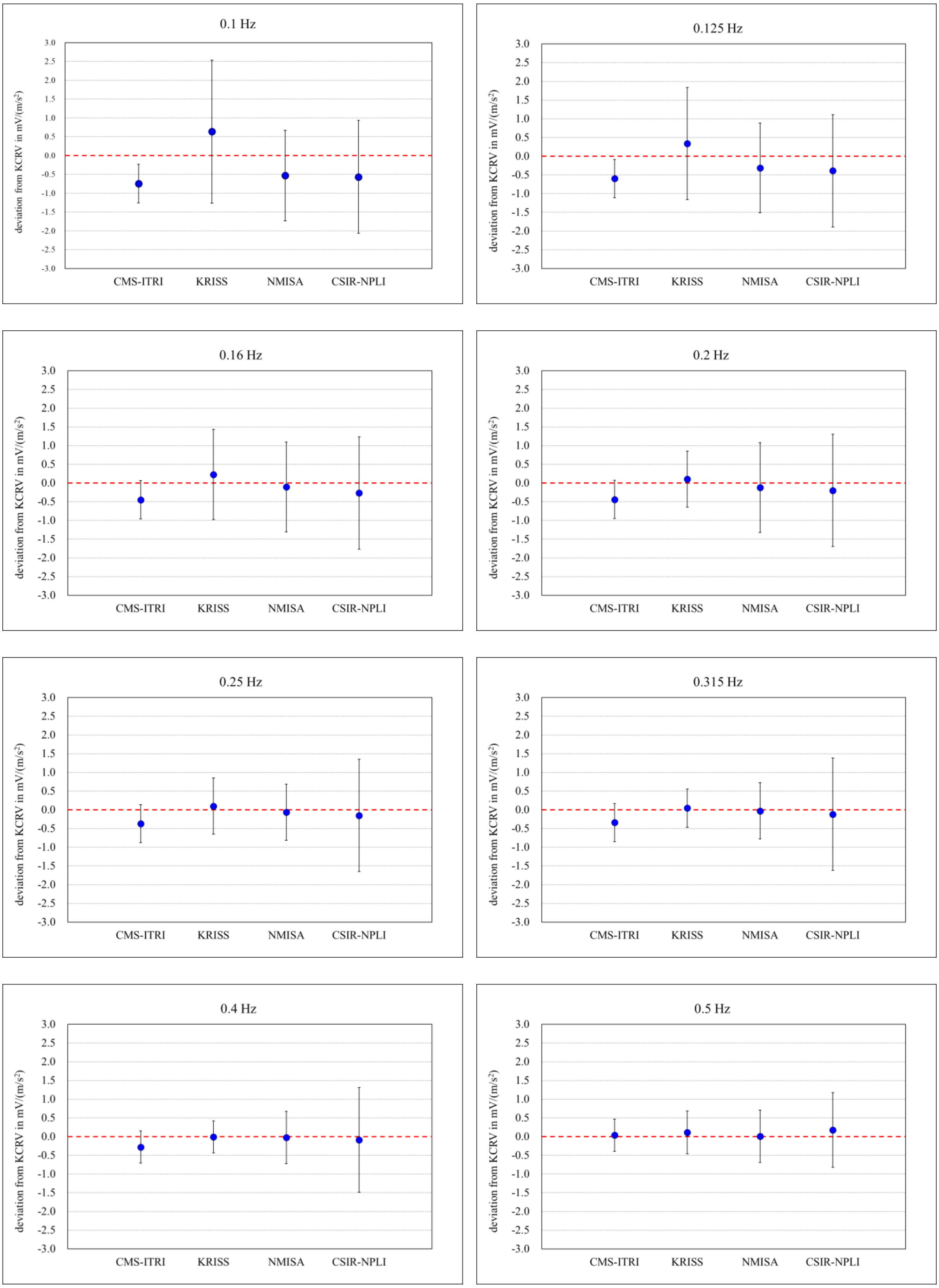



Figure 9.3.1 Deviation of the magnitude from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2)

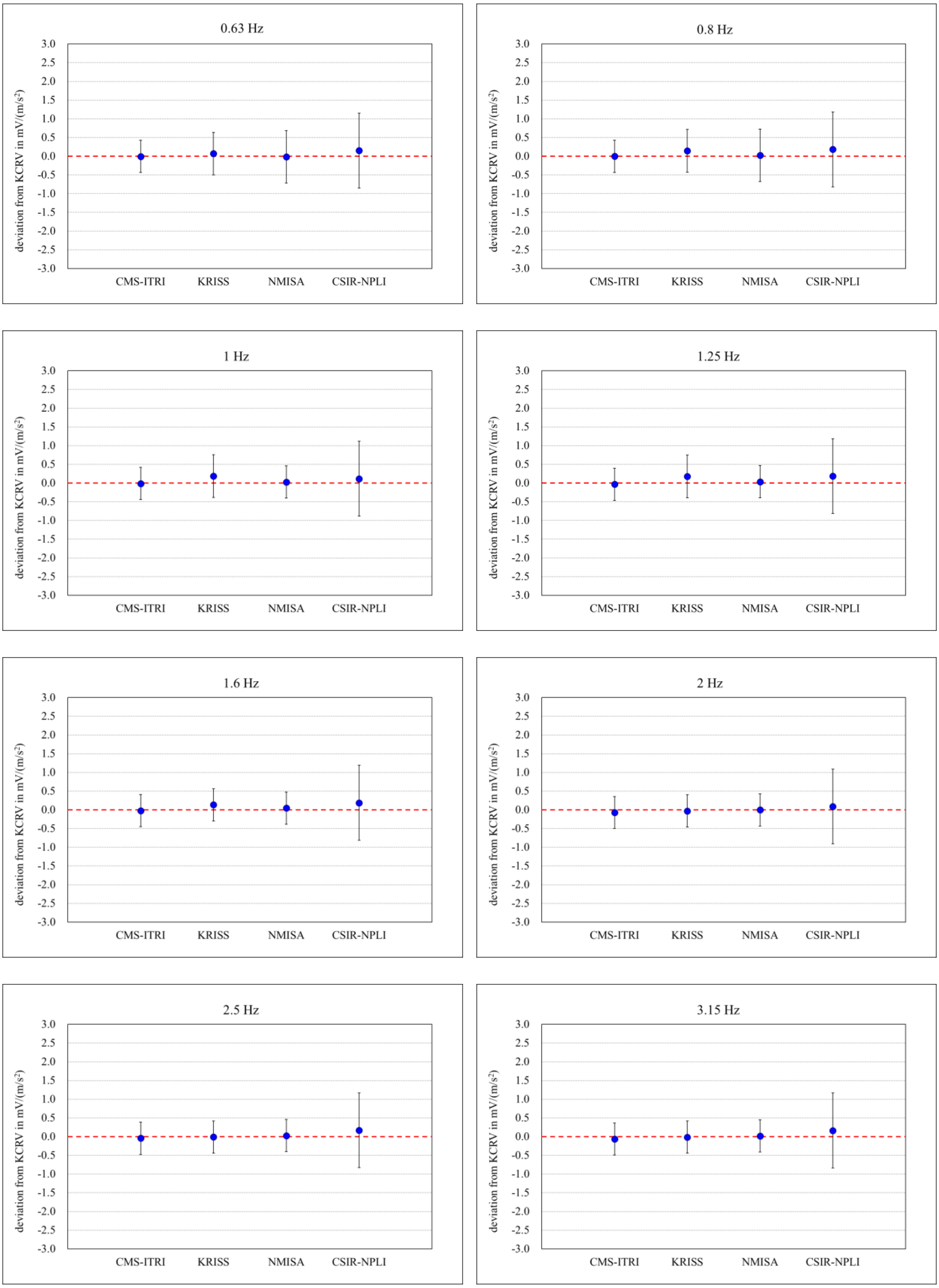



Figure 9.3.1 Deviation of the magnitude from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2) (Cont.)

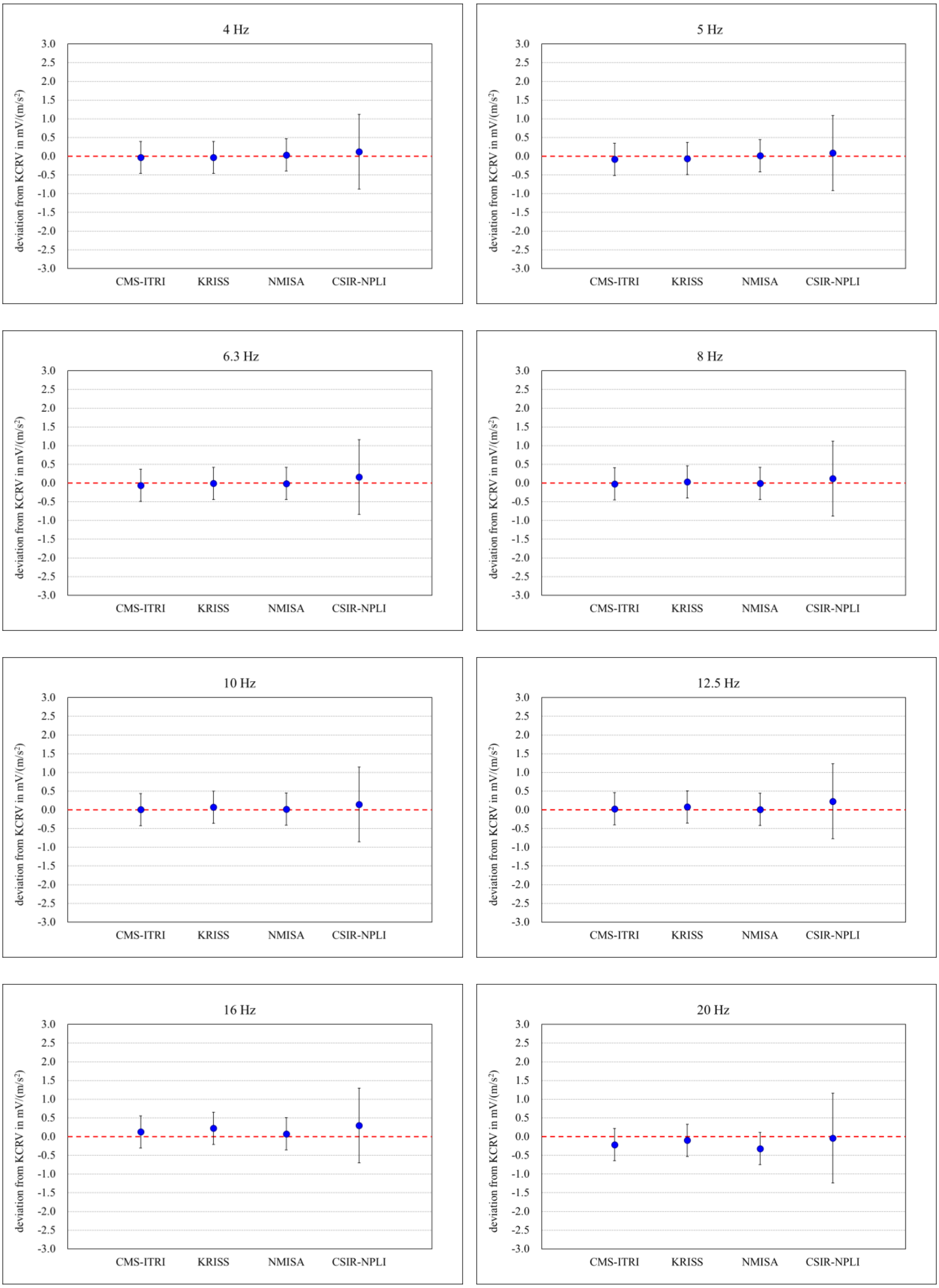



Figure 9.3.1 Deviation of the magnitude from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2) (Cont.)

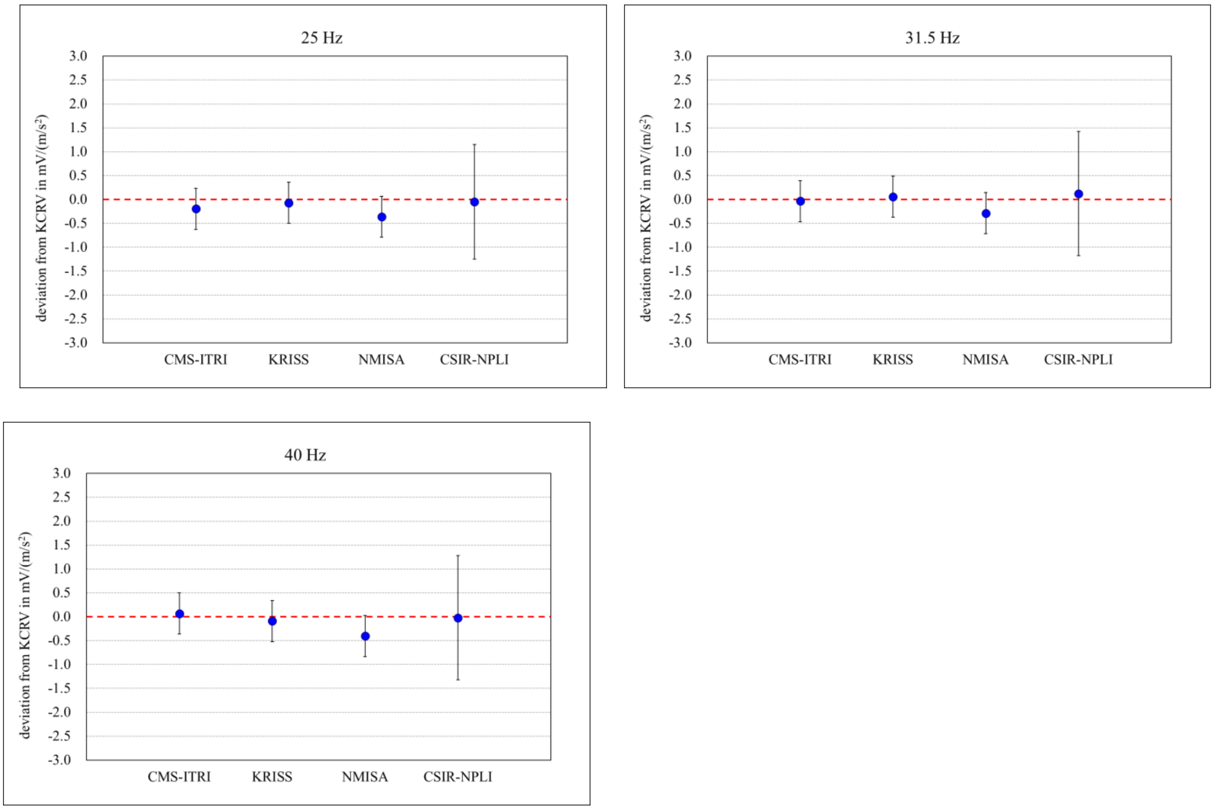



Figure 9.3.1 Deviation of the magnitude from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2) (Cont.)

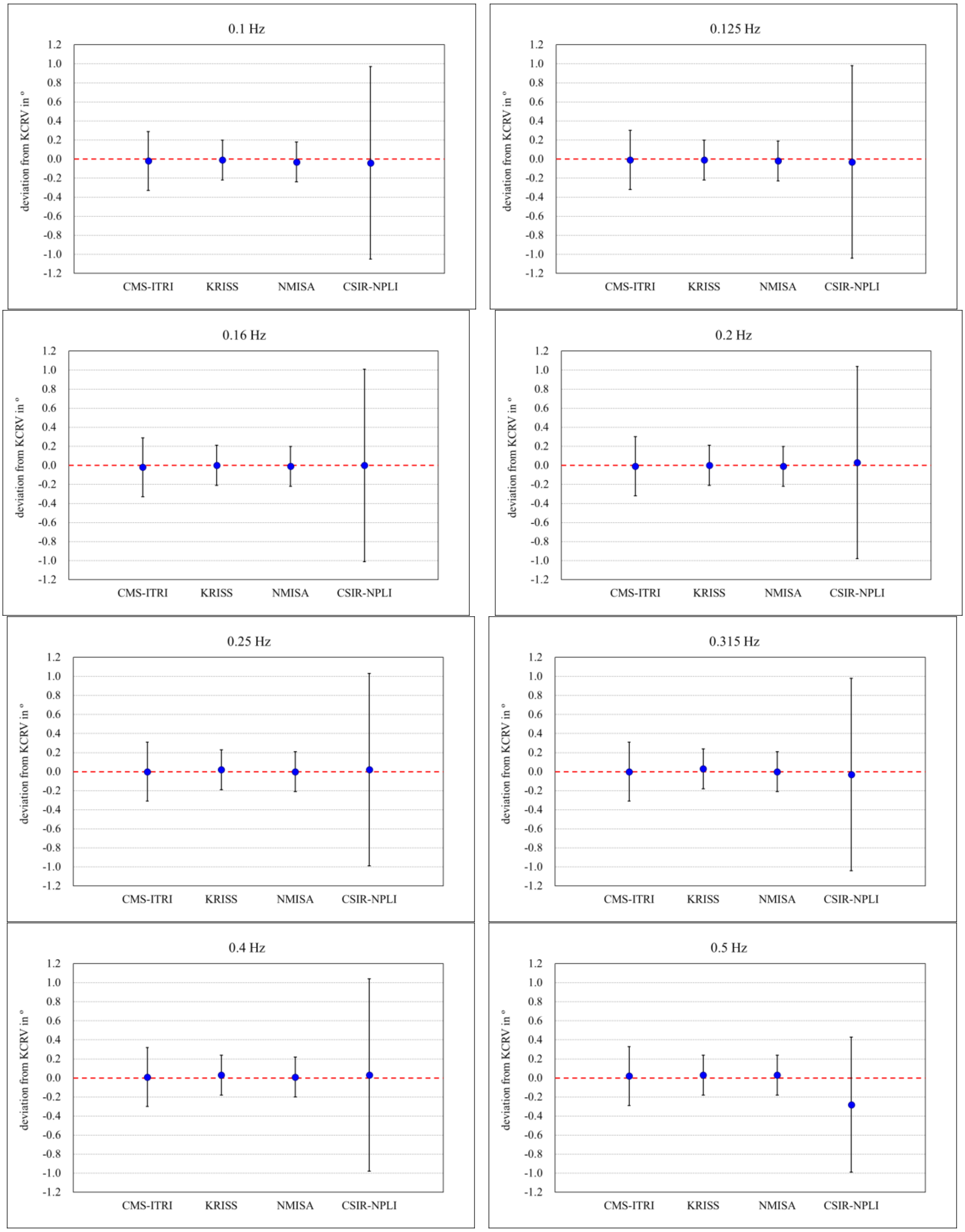



Figure 9.3.2 Deviation of the phase shift from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2)

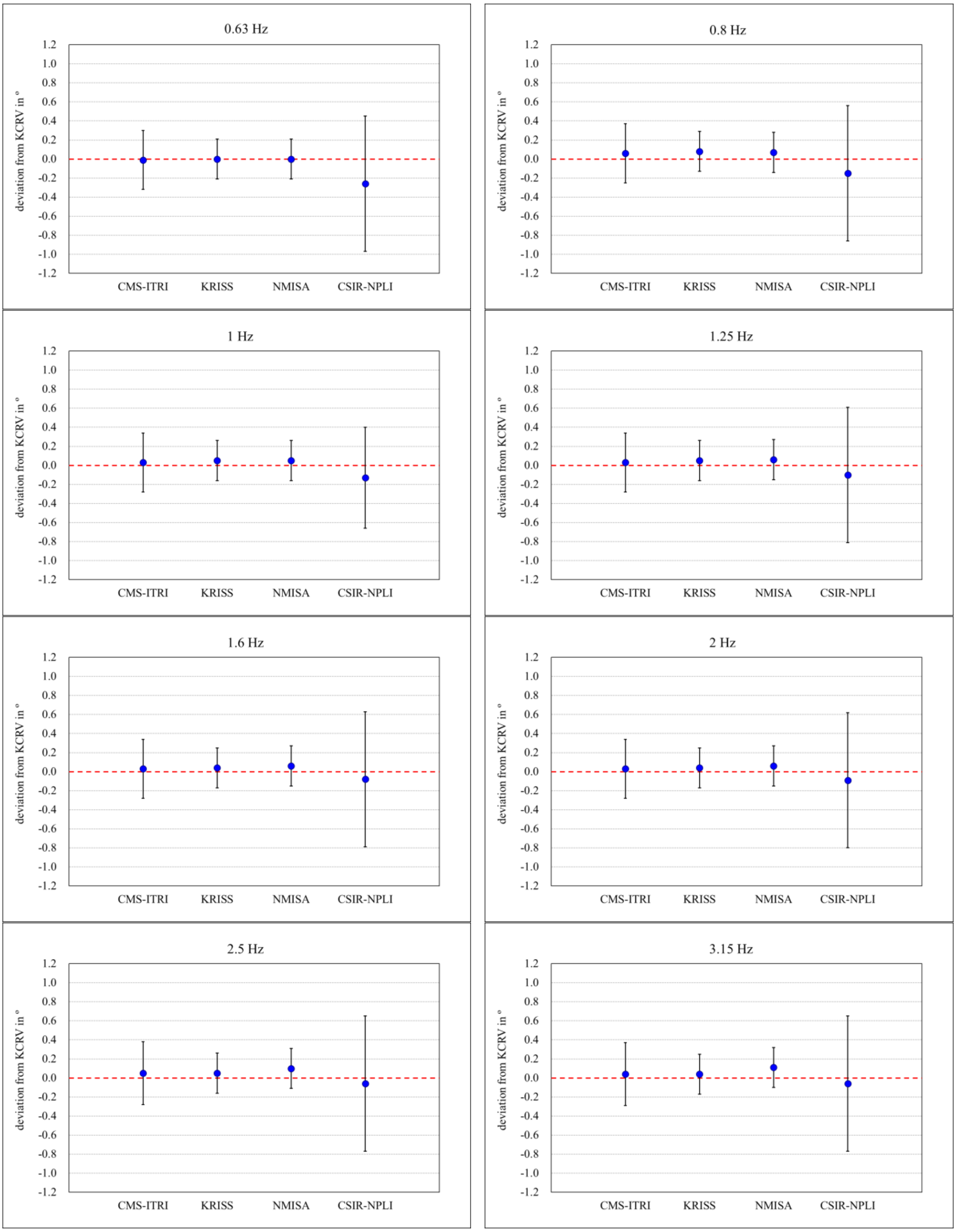



Figure 9.3.2 Deviation of the phase shift from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2) (Cont.)

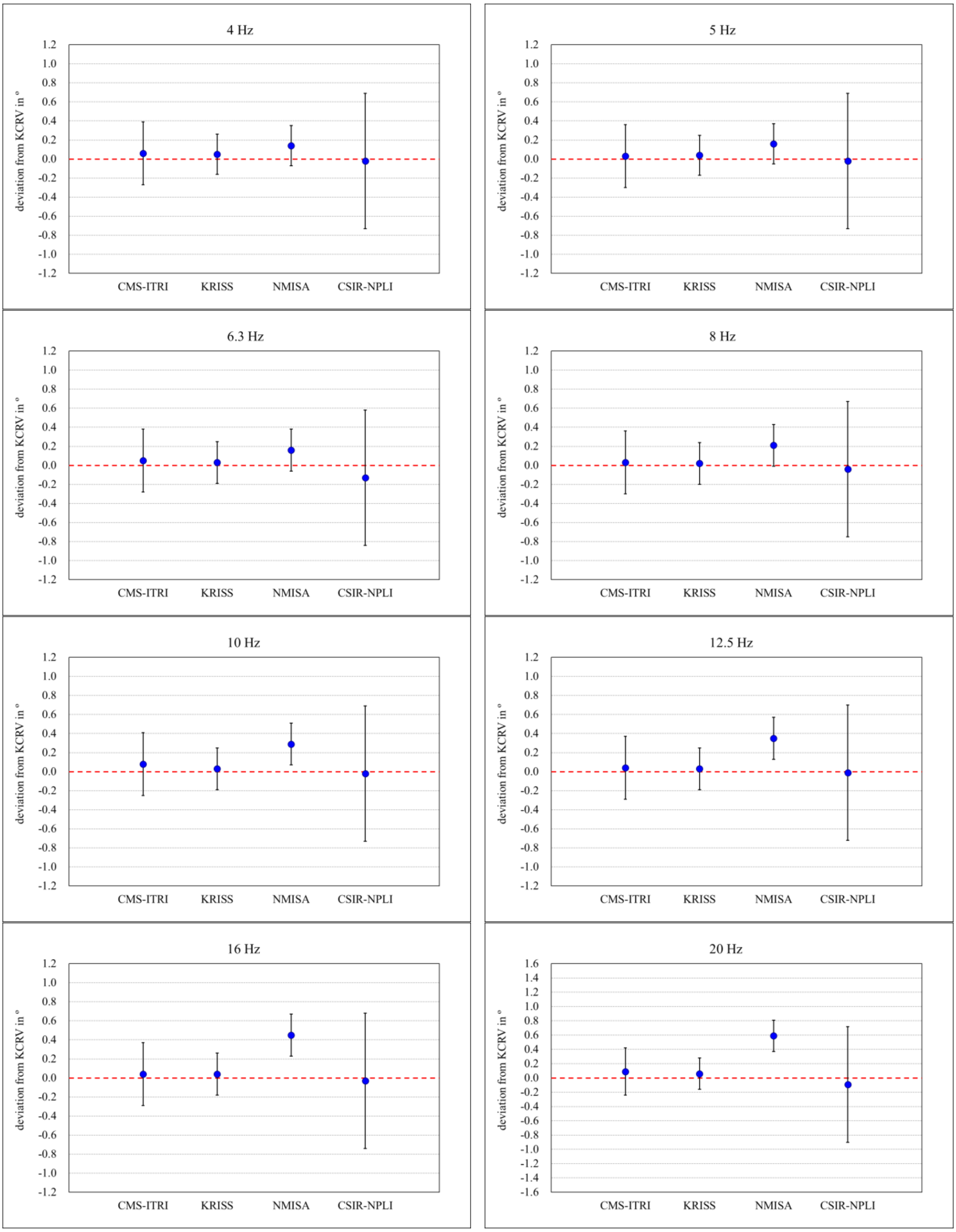



Figure 9.3.2 Deviation of the phase shift from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2) (Cont.)

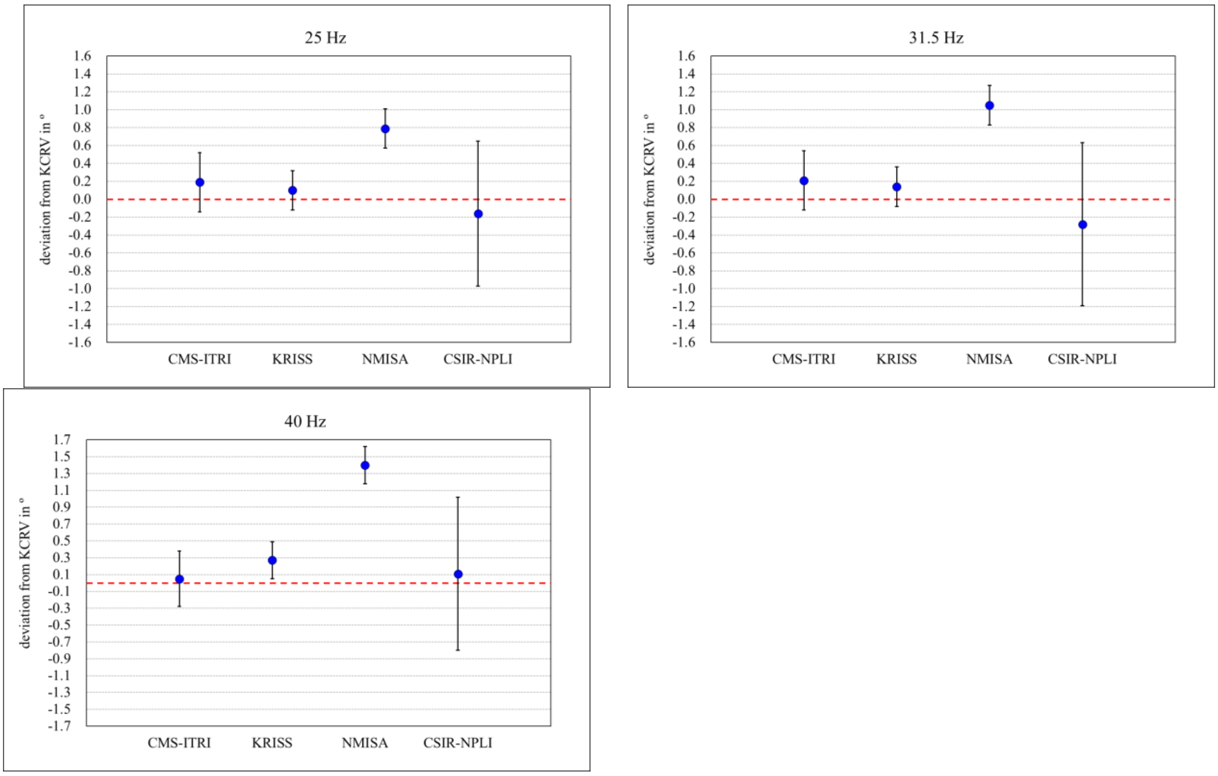



Figure 9.3.2 Deviation of the phase shift from the KCRV for all frequencies of the comparison with expanded uncertainties $U_{i,\mathrm{KCRV}}$ ($k$ = 2) (Cont.)

# 10. Conclusion

The key comparison APMP AUV.V-K3.1 in vibration revealed the current calibration capabilities of the six participants from APMP and AFRIMETS. All of the participating laboratories provided their calibration results, which were mostly consistent with each other within their declared expanded uncertainties for magnitude and phase results. For the phase shift, only one participant failed to contribute to the weighted mean values calculated for five frequencies out of a total of twenty-seven comparison frequencies.

The RMO key comparison in vibration APMP.AUV.V-K3.1 had been successfully finished. All participating laboratories had their results linked to the KCRV of the relevant CIPM level key comparison, namely CCAUV.V-K3, via linking laboratory NIM. The degrees of equivalence of the participants to the KCRV can be used to support their calibration and measurement capabilities.

# 11. Acknowledgment

The authors gratefully acknowledge all the participating institutes for their cooperation and support. In addition, the authors would like to express their thanks and best wishes to Dr Mahavir Singh who superannuated in October, 2021 for his kind effort and the help from Huang Yeu-Jong, WANG Sheng-Han, Huang Yen-Chun of CMS/ITRI.

# 12. Bibliography

[1] https://www.bipm.org/utils/common/pdf/final_reports/AUV/V-K3/CCAUV.V-K3.pdf.

[2] Guidelines for CIPM key comparisons (Appendix F to the “Mutual recognition of national measurements standards and of measurement certificates issued by national metrology institutes” (MRA)). March 1, 1999.

[3] Von Martens, H.-J. et al., Final report on key comparison CCAUV.V-K1, 2003, Metrologia, 40, Tech. Suppl. 09001.

[4] M.G. Cox, The evaluation of key comparison data, Metrologia, 2002, volume 39, p.589-595.

[5] M.G. Cox, The evaluation of key comparison data: determining a largest consistent subset, Metrologia, 2007, 44, 187-200.

[6] Clemens Elster et al., Proposal for linking the results CIPM and RMO key comparisons, Metrologia 40, 189-194, 2003.

**Annex A : Technical protocol**

# Technical Protocol of the APMP Key Comparison

# APMP.AUV.V-K3.1

## Task and Purpose of the Comparison

Since recent improvements at the APMP NMIs have extended the low-frequency vibration limit of calibration capabilities down to 0.1 Hz, the decision was taken to make a preparation of comparison during the meeting of APMP TCAUV in 2017. The task of the comparison is to compare measurements of linear vibration calibration within the frequency range from 0.1 Hz to 40 Hz. The results of this APMP comparison will, after approval by CCAUV, serve as evidence at low vibration frequency for the registration of ‘calibration and measurement capabilities’ (CMC) for NMIs in the framework of the CIPM MRA.

It is the task of the comparison to measure the complex voltage sensitivity of one standard acceleration measuring chain or simply calling an accelerometer standard set (including a quartz-flexure servo-accelerometer of single-ended type and a signal conditioner) at different frequencies with acceleration amplitudes as specified in section 3. The voltage sensitivity is to be calculated as the ratio of the amplitude of the output voltage of the accelerometer standard set to the acceleration at its reference surface. The magnitude of the complex voltage sensitivity shall be given in millivolt per metres per second squared (mV/(m/s$^2$)) and the phase shift in degrees.

For the calibration of the accelerometer standard set, laser interferometry in compliance with method 1 or method 3 of the international standard ISO 16063-11:1999 has to be applied, in order to cover the entire frequency range.

The reported complex voltage sensitivities and associated uncertainties will be used for the calculation of the degrees of equivalence between the participating NMI and to the weighted mean link to CCAUV.V-K3.

## Pilot Laboratory

Pilot laboratory for this regional key comparison is

Precision and Dynamic Engineering Metrology Laboratory
Measurement Standards and Technology Division
Center for Measurement Standards (CMS), Industrial Technology Research Institute (ITRI)
Building 16, No. 321, Section 2, Kuang Fu Road, Hsinchu, 30011, Taiwan

This is the address for delivery of the circulating artifact and the written and signed reports.
Contact Persons are

| TU Tsung-Hsien | WANG Sheng-Han |
|---|---|
| Tel.:+886 3 574 3791 | Tel.: +886 3 574 3719 |
| e-mail:thtu@itri.org.tw | shwango@itri.org.tw |
| Fax:+886 572 6445 | |

Co-Pilot laboratory for this regional key comparison is

Vibration and Gravity Laboratory
Mechanics and Acoustics Metrology Division
National Institute of Metrology, P.R. China
BeiSanHuanDongLu 18, ChaoYang District, 100013 Beijing, P.R. China

Contact Person is

| YANG Lifeng |
|---|
| Tel:+86 10 64524606 |
| e-mail: yanglf@nim.ac.cn |
| Fax:+86 10 10 64218628 |

## Device under Test and Measurement Conditions

For the calibration task of this key comparison, one quartz-flexure accelerometer set will be circulated between participating laboratories. The set includes a 'single-ended' (SE) servo accelerometer, namely a SA 704 (SN: to be decided), with a signal conditioner, namely MSA-I (SN: to be decided) and a power supply for the conditioner.

The complex voltage sensitivity of the accelerometer set shall be calibrated according to those procedures and conditions implemented by the laboratory in conformance with ISO 16063-11. The complex voltage sensitivities reported shall be for the complete accelerometer set (or acceleration measuring chain), including all effects from the signal conditioner. The frequency range of the measurements is from 0.1 Hz to 40 Hz. Specifically, the laboratories are supposed to measure at the following frequencies (all values in Hz):

0.1, 0.125, 0.16, 0.2, 0.25, 0.315, 0.4, 0.5, 0.63, 0.8, 1, 1.25, 1.6, 2, 2.5, 3.15, 4, 5, 6.3, 8, 10, 12.5, 16, 20, 25, 31.5, 40.

Depending on the stroke limitation of the shaker used in the NMI, some frequencies can be considered optional as listed below.

| 0.1 to 0.4 | 0.5 to 20 | 25 to 40 |
|---|---|---|
| optional | mandatory | optional |

The measurement conditions should be kept according to the laboratory's standard conditions for calibration of customers' accelerometers for claiming their calibration capabilities or CMC where applicable. This presumes that these conditions comply with those defined by the applicable ISO documentary standards [1, 2, 3], simultaneously.

Specific conditions for the measurements of this KC are:

- Acceleration amplitudes: a range of 0.05 m/s$^2$ to 30 m/s$^2$ is recommended.
- Ambient temperature and accelerometer temperature during the calibration:
- (23 ± 2) ℃ (actual values to be stated within tolerances of ± 0.3 ℃).
- Relative humidity: max. 75 %RH.
- The input line voltage of the power supply for the signal conditioner is 220 V.

## Circulation Type, Schedule and Transportation

The transducer set will be circulated between the participating laboratories considering a measurement period of two weeks provided for each participating laboratory and one week for the pilot laboratory.

At the beginning and the end of the circulation as well as between certain subsequent measurements of participating laboratories, the transducer set is measured by the pilot laboratory in order to check reference values and to monitor the stability of the transducer set.

The schedule is planned as follows:

| Participant | Measurement | Transportation to next Participant |
|---|---|---|
| CMS-ITRI | 2018/05/21 - 2018/05/27 | 2018/05/28 - 2018/06/04 |
| NIM | 2018/06/05 - 2018/07/08 | 2018/07/09 - 2018/07/15 |
| NIMT | 2018/07/16 - 2018/07/29 | 2018/07/30 - 2018/08/05 |
| KRISS | 2018/08/06 - 2018/08/19 | 2018/08/20 - 2018/08/26 |
| NMISA | 2018/08/27 - 2018/09/09 | 2018/09/10 - 2018/09/16 |
| CSIR-NPLI | 2018/09/17 - 2018/09/28 | 2018/09/29 - 2018/10/07 |
| CMS-ITRI | 2018/10/08 - 2018/10/12 | |

The cost of transportation to the next participating laboratory shall be covered by the participating laboratory. The transducer set has to be hand-carried with great caution. In case the transducer set gets damaged or lost during transportation, the participating laboratory responsible for the delivery should pay 6,000 € to the pilot laboratory.

## Measurement and Analysis Instructions

The participating laboratories have to observe the following instructions:

- The motion of the quartz-flexure accelerometer shall be measured on the moving part of the horizontal vibration exciter, close to the accelerometer's mounting surface, since the mounting (reference) surface is usually not directly accessible.
- The mounting surface of the accelerometer and the moving part of the exciter must be slightly lubricated before mounting.
- The cable between accelerometer and signal conditioner should be taken from the set delivered to the laboratory.

- It is advised that the measurement results should be compiled from complete measurement series carried out at different days under nominally the same conditions, except that the accelerometer is remounted and the cable re-attached. The standard deviation of the subsequent measurements should be included in the report.

- Participants should not perform any experiments other than comparison measurements stipulated in this protocol with the artifact.

## Communication of the Results to Pilot Laboratory

Each participating laboratory shall submit one printed and signed calibration report for the accelerometer set to the pilot laboratory, including the following:

- A description of the calibration systems used for the comparison and the detailed information about the mounting of the accelerometer

- A description of the calibration methods used

- Documented record of the ambient conditions during measurements

- The calibration results, including the relative expanded measurement uncertainty, and the applied coverage factor for each value.

- A detailed uncertainty budget for the system covering all components of measurement uncertainty (calculated according to GUM [4, 5]). Including, among others, information on the type of uncertainty evaluation (A or B), assumed probability distribution and repeatability component.

In addition, the use of the electronic spreadsheets that will be provided by the pilot laboratory for reporting is mandatory. The consistency between the results in electronic form and in the printed and signed calibration report is responsibility of the participating laboratory. The data submitted in the electronic spreadsheet shall be deemed the official results submitted for the comparison.

The results have to be submitted to the pilot laboratory within six weeks after the measurements have been completed.

The pilot laboratory will submit its set of results to the executive secretary of CCAUV in advance to start the circulation for measurements by the other participating laboratories.

## Remarks on post processing

Presuming consistency of the results, the degrees of equivalence will be calculated according to the established methods agreed upon already for CCAUV.V-K1. This regional key comparison is to be linked to the CIPM key comparison CCAUV.V-K3. The degrees of equivalence will be determined in reference to the key comparison reference value (KCRV) calculated for CCAUV.V-K3.

## References

[1] ISO 16063-1:1998 ‘Methods for the calibration of vibration and shock transducers - Part 1: Basic concepts.

[2] ISO 16063-11:1999 ‘Methods for the calibration of vibration and shock transducers - Part 11: Primary vibration calibration by laser interferometry’.

[3] ISO/IEC 17025:2017 ‘General requirements for the competence of testing and calibration laboratories’.

[4] ISO/IEC Guide 98-3:2008 ‘Uncertainty of measurement -- Part 3: Guide to the expression of uncertainty in measurement (GUM:1995).

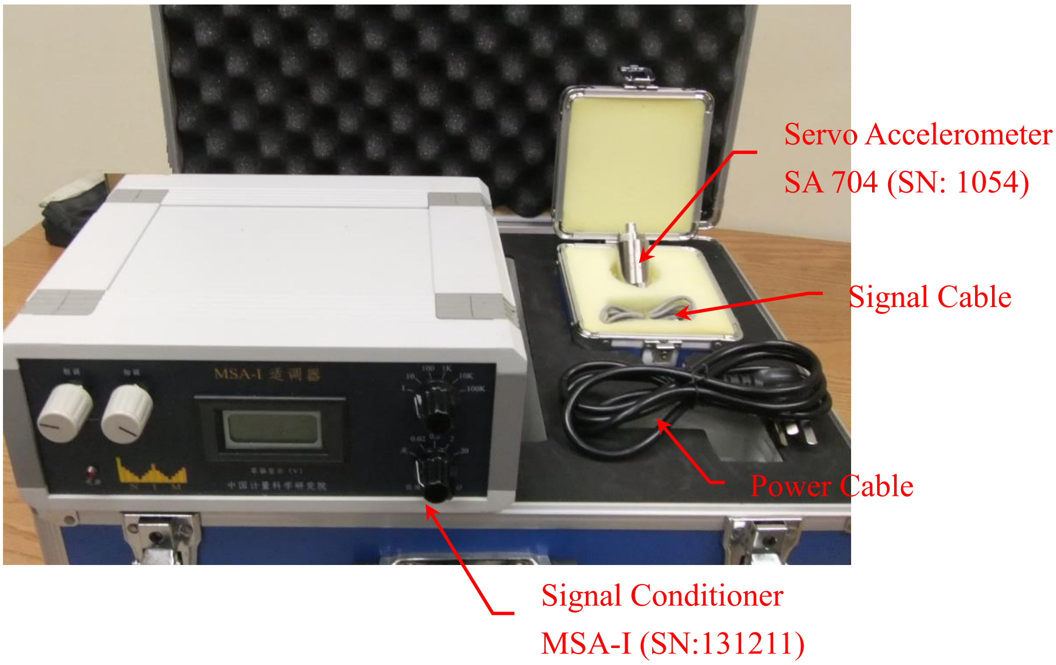
[5] ISO/IEC Guide 98-3:2008/Supplement 1:2008 ‘Propagation of distributions using a Monte Carlo method’.

# Annex A：

## I. Items List and Settings of Conditioning Amplifier

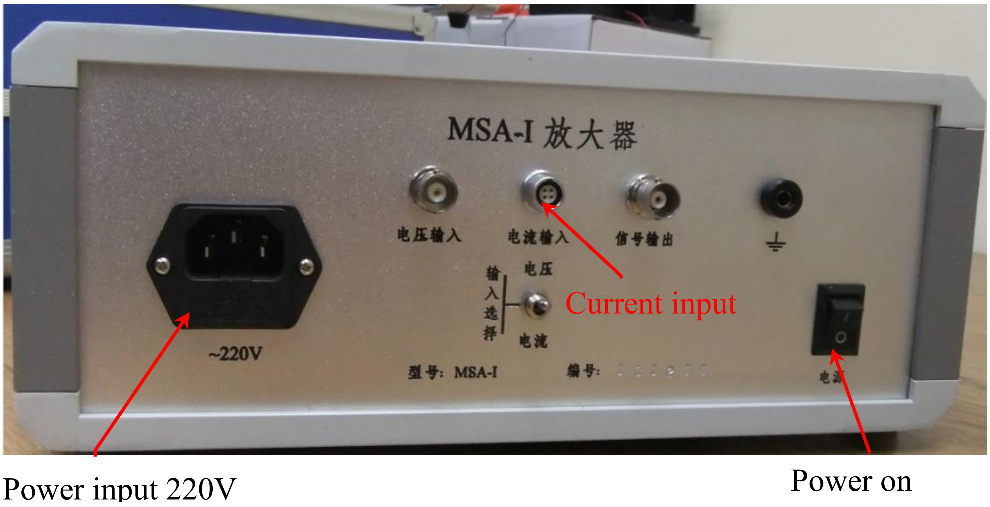
The set includes a 'single-ended' (SE) servo accelerometer, namely a SA 704 (SN: 1054), with a signal conditioner, namely MSA-I (SN:131211) and a power supply for the conditioner.

| NO. | Item | Quantity |
|---|---|---|
| 1 | Servo accelerometer | 1 |
| 2 | Signal conditioner | 1 |
| 3 | Signal cable | 1 |
| 4 | Power cord | 1 |
| 5 | Technical protocol | 1 |




Front side


Rear side




**Procedure of zero setting of conditioning amplifier:**

1. Using the knob of ‘Coarse’ to adjust to zero first;
2. Using the knob of ‘Fine’ to adjust to zero precisely;
3. Setting the gain to 100 and repeat steps 1 and 2, to get more precise value of zero if necessary.
4. "Input selection" switch on the MSA-I conditioning amplifier should be on "Current input".

**Other settings:**

| Frequency Hz | Filter Setup Hz | Gain |
|---|---|---|
| 0.100 | 20 | 100 |
| 0.125 | 20 | 100 |
| 0.160 | 20 | 100 |
| 0.200 | 20 | 100 |
| 0.250 | 20 | 100 |
| 0.315 | 20 | 100 |
| 0.400 | 20 | 100 |
| 0.500 | off | 1 |
| 0.630 | off | 1 |
| 0.800 | off | 1 |
| 1.000 | off | 1 |
| 1.250 | off | 1 |
| 1.600 | off | 1 |
| 2.000 | off | 1 |
| 2.500 | off | 1 |
| 3.150 | off | 1 |
| 4.000 | off | 1 |
| 5.000 | off | 1 |
| 6.300 | off | 1 |
| 8.000 | off | 1 |
| 10.000 | off | 1 |
| 12.500 | off | 1 |
| 16.000 | off | 1 |
| 20.000 | off | 1 |
| 25.000 | off | 1 |
| 31.500 | off | 1 |
| 40.000 | off | 1 |

## II. Reports Information

1. Calibration method.
2. Frequency range
3. Installation of equipment.
4. Environmental conditions, ambient temperature.
5. Uncertainty budget.

Example:

| Laboratory / Information | CMS-ITRI |
|---|---|
| 1. | Sine Approximation Method |
| 2. | Frequency range from 0.1 Hz to 40 Hz |
| 3. | Horizontal / APS 500 |
| 4. | (23 ± 2) ℃ / 55 % RH |
| 5. | |

| i | Standard Uncertainty contribution u(xi) | ISO -SAM- Urel(S) | Uncertainty contribution ui(y) |
|---|---|---|---|
| 1 | $u(\hat{u}_V)$ | accelerometer output voltage measurement(waveform recorder; e.g. ADC-resolution) | $u_1(S)$ |
| 2 | $u(\hat{u}_F)$ | voltage filtering effect on accelerometer output amplitude measurement(frequency band limitation) | $u_2(S)$ |
| 3 | $u(\hat{u}_D)$ | effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise) | $u_3(S)$ |
| 4 | $u(\hat{u}_T)$ | effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity) | $u_4(S)$ |
| 5 | $u(\varphi_{M,Q})$ | effect of interferometer quadrature output signal disturbance on phase amplitude measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(S)$ |
| 6 | $u(\varphi_{M,F})$ | interferometer signal filtering effect on phase amplitude measurement (frequency band limitation) | $u_6(S)$ |
| 7 | $u(\varphi_{M,VD})$ | effect of voltage disturbance on phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(S)$ |
| 8 | $u(\varphi_{M,MD})$ | effect of motion disturbance on phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(S)$ |
| 9 | $u(\varphi_{M,PD})$ | effect of phase disturbance on phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(S)$ |
| 10 | $u(\varphi_{M,RE})$ | residual interferometric effects on phase amplitude measurement(interferometer function) | $u_{10}(S)$ |
| 11 | $u(f_{FG})$ | vibration frequency measurement (frequency generator and indicator) | $u_{11}(S)$ |
| 12 | $u(S_{RE})$ | residual effects on sensitivity measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{12}(S)$ |

| i | Standard Uncertainty contribution u(xi) | ISO -SAM - U(Δ φ) | Uncertainty contribution ui(y) |
|---|---|---|---|
| 1 | $u(\varphi_{u,V})$ | accelerometer output phase measurement(waveform recorder; e.g. ADC-resolution) | $u_1(\Delta\varphi)$ |
| 2 | $u(\varphi_{u,F})$ | voltage filtering effect on accelerometer output phase measurement(frequency band limitation) | $u_2(\Delta\varphi)$ |
| 3 | $u(\varphi_{u,D})$ | effect of voltage disturbance on accelerometer output phase measurement (e.g. hum and noise) | $u_3(\Delta\varphi)$ |
| 4 | $u(\varphi_{u,T})$ | effect of transverse, rocking, and bending acceleration on accelerometer output phase measurement (transverse sensitivity) | $u_4(\Delta\varphi)$ |
| 5 | $u(\varphi_{s,Q})$ | effect of interferometer quadrature output signal disturbance on displacement phase measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(\Delta\varphi)$ |
| 6 | $u(\varphi_{s,F})$ | interferometer signal filtering effect on displacement phase amplitude measurement (frequency band limitation) | $u_6(\Delta\varphi)$ |
| 7 | $u(\varphi_{s,VD})$ | effect of voltage disturbance on displacement phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(\Delta\varphi)$ |
| 8 | $u(\varphi_{s,MD})$ | effect of motion disturbance on displacement phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(\Delta\varphi)$ |
| 9 | $u(\varphi_{s,PD})$ | effect of phase disturbance on displacement phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(\Delta\varphi)$ |
| 10 | $u(\varphi_{s,RE})$ | residual interferometric effects on displacement phase amplitude measurement(interferometer function) | $u_{10}(\Delta\varphi)$ |
| 11 | $u(\Delta\varphi_{RE})$ | residual effects on phase shift measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{11}(\Delta\varphi)$ |

Note: The report file should be provided as word file with the scanning of signing pages.

# Annex B : Measurement Uncertainty Budget (MUB)

## I. CMS-ITRI

### Magnitude sensitivity

| D. Voltage Sensitivity uncertainty budget - CMS-ITRI | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| i | Standard Uncertainty contribution u(xi) | ISO -SAM- Urel(S) | Uncertainty contribution ui(y) | Estimated Uncertainty(%) | | Probability Distribution | Divisor factor | Standard Uncertainty contribution Ui(y) | |
| | | | | 0.1 Hz to 0.4 Hz | 0.5 Hz to 40 Hz | | | 0.1 Hz to 0.4 Hz | 0.5 Hz to 40 Hz |
| 1 | $u(\hat{u}_V)$ | accelerometer output voltage measurement(Type A repeat stability) | $u_1(S)$ | 0.23 | 0.18 | normal | 2 | 0.115 | 0.090 |
| 2 | $u(\hat{u}_F)$ | voltage filtering effect on accelerometer output amplitude measurement(frequency band limitation) | $u_2(S)$ | 0.08 | 0.03 | Rectangular | 1.732 | 0.046 | 0.017 |
| 3 | $u(\hat{u}_D)$ | effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise) | $u_3(S)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 4 | $u(\hat{u}_T)$ | effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity) | $u_4(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 5 | $u(\varphi_{M,Q})$ | effect of interferometer quadrature output signal disturbance on phase amplitude measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(S)$ | 0.11 | 0.11 | Rectangular | 1.732 | 0.064 | 0.064 |
| 6 | $u(\varphi_{M,F})$ | interferometer signal filtering effect on phase amplitude measurement (frequency band limitation) | $u_6(S)$ | 0.03 | 0.03 | Rectangular | 1.732 | 0.017 | 0.017 |
| 7 | $u(\varphi_{M,VD})$ | effect of voltage disturbance on phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(S)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 8 | $u(\varphi_{M,MD})$ | effect of motion disturbance on phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(S)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 9 | $u(\varphi_{M,PD})$ | effect of phase disturbance on phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(S)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 10 | $u(\varphi_{M,RE})$ | residual interferometric effects on phase amplitude measurement(interferometer function) | $u_{10}(S)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 11 | $u(f_{FG})$ | vibration frequency measurement (frequency generator and indicator) | $u_{11}(S)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 12 | $u(S_{RE})$ | residual effects on sensitivity measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{12}(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| Combined Uncertainty of amplitude measurement (in %) | | | | | | | | 0.148 | 0.122 |
| Expanded Uncertainty of amplitude measurement (in %) (Coverage factor $k$ = 2) | | | | | | | | 0.30 | 0.30 |

## Phase shift

| E. Phasee Sensitivity uncertainty budget - CMS-ITRI | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| i | Standard Uncertainty contribution u(xi) | ISO -SAM - U(Δφ) | Uncertainty contribution ui(y) | Estimated Uncertainty(°) | | Probability Distribution | Divisor factor | Standard Uncertainty contribution Ui(y) | |
| | | | | 0.1 Hz to 0.4 Hz | 0.5 Hz to 40 Hz | | | 0.1 Hz to 0.4 Hz | 0.5 Hz to 40 Hz |
| 1 | $u(\varphi_{u,V})$ | accelerometer output phase measurement(Type A repeat stability) | $u_1(\Delta\varphi)$ | 0.19 | 0.13 | normal | 2 | 0.095 | 0.065 |
| 2 | $u(\varphi_{u,F})$ | voltage filtering effect on accelerometer output phase measurement(frequency band limitation) | $u_2(\Delta\varphi)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 3 | $u(\varphi_{u,D})$ | effect of voltage disturbance on accelerometer output phase measurement (e.g. hum and noise) | $u_3(\Delta\varphi)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 4 | $u(\varphi_{u,T})$ | effect of transverse, rocking, and bending acceleration on accelerometer output phase measurement (transverse sensitivity) | $u_4(\Delta\varphi)$ | 0.1 | 0.1 | Rectangular | 1.732 | 0.058 | 0.058 |
| 5 | $u(\varphi_{s,Q})$ | effect of interferometer quadrature output signal disturbance on displacement phase measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(\Delta\varphi)$ | 0.1 | 0.1 | Rectangular | 1.732 | 0.058 | 0.058 |
| 6 | $u(\varphi_{s,F})$ | interferometer signal filtering effect on displacement phase amplitude measurement (frequency band limitation) | $u_6(\Delta\varphi)$ | 0.03 | 0.03 | Rectangular | 1.732 | 0.017 | 0.017 |
| 7 | $u(\varphi_{s,VD})$ | effect of voltage disturbance on displacement phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 8 | $u(\varphi_{s,MD})$ | effect of motion disturbance on displacement phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 9 | $u(\varphi_{s,PD})$ | effect of phase disturbance on displacement phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 10 | $u(\varphi_{s,RE})$ | residual interferometric effects on displacement phase amplitude measurement(interferometer function) | $u_{10}(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 11 | $u(\Delta\varphi_{RE})$ | residual effects on phase shift measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{11}(\Delta\varphi)$ | 0.06 | 0.06 | Rectangular | 1.732 | 0.035 | 0.035 |
| **Combined Uncertainty of amplitude measurement (in °)** | | | | | | | | **0.144** | **0.126** |
| **Expanded Uncertainty of amplitude measurement (in °) (Coverage factor k = 2)** | | | | | | | | **0.30** | **0.30** |

# II. NIM

## Magnitude sensitivity

| D. Voltage Sensitivity uncertainty budget - NIM | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| i | Standard Uncertainty contribution u(xi) | ISO -SAM- Urel(S) | Uncertainty contribution ui(y) | Estimated Uncertainty(%) | | Probability Distribution | Divisor factor | Standard Uncertainty contribution Ui(y) | |
| | | | | 0.1 Hz to < 0.4 Hz | 0.4 Hz to 40 Hz | | | 0.1 Hz to < 0.4 Hz | 0.4 Hz to 40 Hz |
| 1 | $u(\hat{u}_V)$ | accelerometer output voltage measurement(waveform recorder; e.g. ADC-resolution) | $u_1(S)$ | 0.006 | 0.006 | Rectangular | 1.732 | 0.003 | 0.003 |
| 2 | $u(\hat{u}_F)$ | voltage filtering effect on accelerometer output amplitude measurement(frequency band limitation) | $u_2(S)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 3 | $u(\hat{u}_D)$ | effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise) | $u_3(S)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 4 | $u(\hat{u}_T)$ | effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity) | $u_4(S)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 5 | $u(\varphi_{M,Q})$ | effect of interferometer quadrature output signal disturbance on phase amplitude measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(S)$ | 0.1 | 0.1 | Rectangular | 1.732 | 0.058 | 0.058 |
| 6 | $u(\varphi_{M,F})$ | interferometer signal filtering effect on phase amplitude measurement (frequency band limitation) | $u_6(S)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 7 | $u(\varphi_{M,VD})$ | effect of voltage disturbance on phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 8 | $u(\varphi_{M,MD})$ | effect of motion disturbance on phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 9 | $u(\varphi_{M,PD})$ | effect of phase disturbance on phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 10 | $u(\varphi_{M,RE})$ | residual interferometric effects on phase amplitude measurement(interferometer function) | $u_{10}(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 11 | $u(f_{FG})$ | vibration frequency measurement (frequency generator and indicator) | $u_{11}(S)$ | 0 | 0 | Rectangular | 1.732 | 0.000 | 0.000 |
| 12 | $u(S_{RE})$ | residual effects on sensitivity measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{12}(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 13 | u(Sv) | Vibration set acceleration sensitivity amplitude and phase shift stability | $u_{13}(S)$ | 0.2 | 0.1 | normal | 3 | 0.067 | 0.033 |
| 14 | u(Su) | effect of other effects on accelerometer output voltage measurements | $u_{14}(S)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| Combined Uncertainty of amplitude measurement (%) | | | | | | | | 0.115 | 0.099 |
| Expanded Uncertainty of amplitude measurement (%)($k$=2) | | | | | | | | 0.30 | 0.20 |

## Phase shift

| E. Phasee Sensitivity uncertainty budget - NIM | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| i | Standard Uncertainty contribution u(xi) | ISO -SAM - U(Δφ) | Uncertainty contribution ui(y) | Estimated Uncertainty(°) | | Probability Distribution | Divisor factor | Standard Uncertainty contribution Ui(y) | |
| | | | | 0.1 Hz to < 0.4 Hz | 0.4 Hz to 40 Hz | | | 0.1 Hz to < 0.4 Hz | 0.4 Hz to 40 Hz |
| 1 | $u(\varphi_{u,V})$ | accelerometer output phase measurement(waveform recorder; e.g. ADC-resolution) | $u_1(\Delta\varphi)$ | 0.015 | 0.01 | Rectangular | 1.732 | 0.009 | 0.006 |
| 2 | $u(\varphi_{u,F})$ | voltage filtering effect on accelerometer output phase measurement(frequency band limitation) | $u_2(\Delta\varphi)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 3 | $u(\varphi_{u,D})$ | effect of voltage disturbance on accelerometer output phase measurement (e.g. hum and noise) | $u_3(\Delta\varphi)$ | 0.02 | 0.02 | Rectangular | 1.732 | 0.012 | 0.012 |
| 4 | $u(\varphi_{u,T})$ | effect of transverse, rocking, and bending acceleration on accelerometer output phase measurement (transverse sensitivity) | $u_4(\Delta\varphi)$ | 0.04 | 0.04 | Rectangular | 1.732 | 0.023 | 0.023 |
| 5 | $u(\varphi_{s,Q})$ | effect of interferometer quadrature output signal disturbance on displacement phase measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(\Delta\varphi)$ | 0.1 | 0.1 | Rectangular | 1.732 | 0.058 | 0.058 |
| 6 | $u(\varphi_{s,F})$ | interferometer signal filtering effect on displacement phase amplitude measurement (frequency band limitation) | $u_6(\Delta\varphi)$ | 0.01 | 0.01 | Rectangular | 1.732 | 0.006 | 0.006 |
| 7 | $u(\varphi_{s,VD})$ | effect of voltage disturbance on displacement phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 8 | $u(\varphi_{s,MD})$ | effect of motion disturbance on displacement phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 9 | $u(\varphi_{s,PD})$ | effect of phase disturbance on displacement phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 10 | $u(\varphi_{s,RE})$ | residual interferometric effects on displacement phase amplitude measurement(interferometer function) | $u_{10}(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| 11 | $u(\Delta\varphi_{RE})$ | residual effects on phase shift measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{11}(\Delta\varphi)$ | 0.002 | 0.002 | Rectangular | 1.732 | 0.001 | 0.001 |
| 12 | u(φv) | Vibration set acceleration sensitivity amplitude and phase shift stability | $u_{12}(\Delta\varphi)$ | 0.2 | 0.1 | normal | 3 | 0.067 | 0.033 |
| 13 | u(φu) | effect of other effects on accelerometer output voltage measurements | $u_{13}(\Delta\varphi)$ | 0.05 | 0.05 | Rectangular | 1.732 | 0.029 | 0.029 |
| **Combined Uncertainty of amplitude measurement ( °)** | | | | | | | | **0.113** | **0.097** |
| **Expanded Uncertainty of amplitude measurement ( °)(*k* =2)** | | | | | | | | **0.30** | **0.20** |

## III. NIMT

### Magnitude sensitivity

| i | Standard Uncertainty contribution u(xi) | ISO -SAM- Urel(S) | Uncertainty contribution ui(y) | Probability Distribution | Divisor | .1 to 0.8 Hz | 0.8 to 1.6 H | >1.6 to 4 Hz | >4 to 5 Hz | >5 to 8 Hz | >8 to 40 Hz |
|---|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $u(\hat{u}_V)$ | Vibration velocity (Uncertainty of tracing back) | $u_1(S)$ | Normal | 2 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 | 0.10 |
| 2 | $u(\hat{u}_x)$ | Voltage Ux | $u_2(S)$ | Normal | 2 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 | 0.03 |
| 3 | $u(\hat{u}_w)$ | Angular frequency of v signal | $u_3(S)$ | Square | 1.732 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 4 | $u(\hat{u}_{Gr})$ | Amplifier gain | $u_4(S)$ | Normal | 2 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 | 0.02 |
| 5 | $u(\hat{u}_{Kf})$ | Frequency response | $u_5(S)$ | Normal | 2 | 0.1 | 0.1 | 0.1 | 0.1 | 0.05 | 0.05 |
| 6 | $u(\hat{u}_{Kq})$ | Transverse motion | $u_6(S)$ | Square | 1.732 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 | 0.007 |
| 7 | $u(\hat{u}_{Ko})$ | Harmonics | $u_7(S)$ | Square | 1.732 | 0.001 | 0.00 | 0.001 | 0.001 | 0.001 | 0.001 |
| 8 | $u(\hat{u}_{Kbr})$ | Hum | $u_8(S)$ | Normal | 2 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 | 0.01 |
| 9 | $u(\hat{u}_{Kr})$ | Noise | $u_9(S)$ | Normal | 2 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 10 | $u(\hat{u}_{Kgmo})$ | Effect of geometric location | $u_{10}(S)$ | Square | 1.732 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 11 | $u(\hat{u}_{Kmk})$ | Sensor attachment | $u_{11}(S)$ | Square | 1.732 | 0 | 0 | 0 | 0 | 0 | 0 |
| 12 | $u(\hat{u}_{Krel})$ | Cable routing and fixing | $u_{12}(S)$ | Square | 1.732 | 0.25 | 0.2 | 0.18 | 0.16 | 0.16 | 0.14 |
| 13 | $u(\hat{u}_{Ktk})$ | Relative motion | $u_{13}(S)$ | Square | 1.732 | 0.05 | 0.02 | 0.01 | 0.01 | 0.01 | 0.001 |
| 14 | $u(\hat{u}_{Kl})$ | Temperature change | $u_{14}(S)$ | Square | 1.732 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 | 0.0015 |
| 15 | $u(\hat{u}_{Ki})$ | Linearity | $u_{15}(S)$ | Square | 1.732 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 16 | $u(\hat{u}_{Kres})$ | Temporal instability of v signal | $u_{16}(S)$ | Square | 1.732 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 | 0.001 |
| 17 | $u(\hat{u}_{Kgmo})$ | Residual effects | $u_{17}(S)$ | Square | 1.732 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 | 0.05 |
| 18 | $u(\hat{u}_{rep})$ | Repeatability | $u_{18}(S)$ | Normal | 1 | 0.0094 | 0.0071 | 0.0044 | 0.0051 | 0.0081 | 0.0033 |
| | | Combined Uncertainty | | | | **0.298** | **0.254** | **0.238** | **0.223** | **0.205** | **0.190** |
| | | Expanded Uncertainty | | | | **0.60** | **0.51** | **0.48** | **0.45** | **0.41** | **0.38** |

## Phase shift

| i | Standard Uncertainty contribution u(xi) | ISO -SAM - U(Δφ) | Uncertainty contribution ui(y) | Probability Distribution | Divisor | 0.1 to 0.8 Hz | >0.8 to 1.6 Hz | >1.6 to 4 Hz | >4 to 8 Hz | >8 to 40 Hz |
|---|---|---|---|---|---|---|---|---|---|---|
| 1 | $u(\varphi_{u,V})$ | Vibration velocity (Uncertatinty of tracing back) | $u_1(\Delta\varphi)$ | Normal | 2 | 0.050 | 0.050 | 0.050 | 0.050 | 0.050 |
| 2 | $u(\varphi_{u,x})$ | Voltage Ux | $u_2(\Delta\varphi)$ | Normal | 2 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| 3 | $u(\varphi_{w})$ | Angular frequency of v signal | $u_3(\Delta\varphi)$ | Square | 1.732 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 4 | $u(\varphi_{u,G})$ | Amplifier gain | $u_4(\Delta\varphi)$ | Normal | 2 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| 5 | $u(\varphi_{Kf})$ | Feqneucy response | $u_5(\Delta\varphi)$ | Normal | 2 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| 6 | $u(\varphi_{Kq})$ | Transverse motion | $u_6(\Delta\varphi)$ | Square | 1.732 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 7 | $u(\varphi_{Ko})$ | Harmonics | $u_7(\Delta\varphi)$ | Square | 1.732 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 8 | $u(\varphi_{Kbr})$ | Hum | $u_8(\Delta\varphi)$ | Normal | 2 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| 9 | $u(\varphi_{Kr})$ | Noise | $u_9(\Delta\varphi)$ | Normal | 2 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| 10 | $u(\varphi_{Kbd})$ | Effect of geometric location | $u_{10}(\Delta\varphi)$ | Square | 1.732 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| 11 | $u(\Delta\varphi_{Kma})$ | Sensor attanchment | $u_{11}(\Delta\varphi)$ | Square | 1.732 | 0.000 | 0.000 | 0.000 | 0.000 | 0.000 |
| 12 | $u(\Delta\varphi_{Kmk})$ | Cable routing and fixing | $u_{12}(\Delta\varphi)$ | Square | 1.732 | 0.300 | 0.200 | 0.140 | 0.100 | 0.070 |
| 13 | $u(\Delta\varphi_{Krel})$ | Relative motion | $u_{13}(\Delta\varphi)$ | Square | 1.732 | 0.200 | 0.100 | 0.100 | 0.050 | 0.050 |
| 14 | $u(\Delta\varphi_{Ktk})$ | Temperature chage | $u_{14}(\Delta\varphi)$ | Square | 1.732 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| 15 | $u(\Delta\varphi_{KL})$ | Linearity | $u_{15}(\Delta\varphi)$ | Square | 1.732 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| 16 | $u(\Delta\varphi_{KI})$ | Temporal instability of v signal | $u_{16}(\Delta\varphi)$ | Square | 1.732 | 0.010 | 0.010 | 0.010 | 0.010 | 0.010 |
| 17 | $u(\Delta\varphi Kre_s)$ | Residual effects | $u_{17}(\Delta\varphi)$ | Square | 1.732 | 0.100 | 0.100 | 0.100 | 0.100 | 0.100 |
| 18 | $u(\Delta\varphi Kre_s)$ | Repeatability | $u_{18}(\Delta\varphi)$ | Normal | 1 | 0.0025 | 0.0016 | 0.0008 | 0.0004 | 0.0008 |
| | | Combined Uncertainty | | | | **0.416** | **0.305** | **0.270** | **0.236** | **0.225** |
| | | Expanded Uncertainty | | | | **0.83** | **0.61** | **0.54** | **0.47** | **0.45** |

# IV. KRISS

## Magnitude sensitivity

**D. Voltage Sensitivity uncertainty budget - KRISS**

| Uncertainty component | Comment | Symbol | Type | Distribution | Factor | Uncertainty contribution | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | 0.1 Hz | 0.125 Hz | 0.16 Hz | 0.2 Hz to 0.25 Hz | 0.315 Hz to 0.4 Hz | < 0.4 Hz to 1.25 Hz | < 1.25 Hz to 40 Hz |
| accelerometer output voltage measurement | DAQ resolution and calibration | u1 | B | rectangular | 0.577 | 4.5E-02 | 4.5E-02 | 4.5E-02 | 4.5E-02 | 4.5E-02 | 1.9E-01 | 1.2E-01 |
| effect of laser wavelength | recommendation value | u2 | B | normal | 1 | 1.5E-04 | 1.5E-04 | 1.5E-04 | 1.5E-04 | 1.5E-04 | 1.5E-04 | 1.5E-04 |
| voltage disturbance | hum on accelerometer output voltage measurement | u3 | B | rectangular | 0.577 | 8.4E-06 | 8.4E-06 | 8.4E-06 | 8.4E-06 | 8.4E-06 | 5.1E-04 | 4.6E-05 |
| effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity) | transverse acceleration on accelerometer output voltage measurement | u4 | B | U-type | 1.41 | 7.1E-06 | 7.1E-06 | 7.1E-06 | 7.1E-06 | 7.1E-06 | 7.1E-06 | 7.1E-06 |
| effect of cosine error | interferometer misalignment | u5 | B | rectangular | 0.577 | 7.2E-04 | 7.2E-04 | 7.2E-04 | 7.2E-04 | 7.2E-04 | 7.2E-04 | 7.2E-04 |
| harmonics on accelerometer output voltage measurment | total distortion on accelerometer output voltage measurment | u6 | A | rectangular | 0.577 | 5.8E-06 | 5.8E-06 | 5.8E-06 | 5.8E-06 | 5.8E-06 | 8.0E-07 | 6.8E-07 |
| effect of voltage disturbance on phase amplitude measurement | random noise in the photoelectric measuring chains on phase amplitude measurement | u7 | B | rectangular | 0.577 | 1.1E-02 | 1.1E-02 | 1.1E-02 | 1.1E-02 | 1.1E-02 | 1.1E-02 | 1.1E-02 |
| effect of motion disturbance on phase amplitude measurement | relative motion between the accelerometer reference surface and the spot sensed by the interferometer on phase amplitude measurement | u8 | B | normal | 1 | 3.3E-02 | 3.3E-02 | 3.3E-02 | 3.3E-02 | 3.3E-02 | 3.3E-02 | 3.3E-02 |
| vibration frequency measurement | deviation of sample clock from generator clock | u9 | B | rectangular | 0.577 | 5.8E-03 | 5.8E-03 | 5.8E-03 | 5.8E-03 | 5.8E-03 | 5.8E-03 | 5.8E-03 |
| residual effects on sensitivity measurement | repeat measurements; experimental standard devitation of arithmetic mean | u10 | A | normal | 1 | 5.0E-01 | 4.5E-01 | 3.0E-01 | 2.0E-01 | 2.2E-02 | 2.3E-02 | 2.2E-02 |
| **Relative combined standard uncertainty** | | | | | **in %** | **5.0E-01** | **4.5E-01** | **3.1E-01** | **2.1E-01** | **0.061** | **0.196** | **0.123** |
| **Relative expanded uncertainty (k=2)** | | | | | **in %** | **1.0E+00** | **9.1E-01** | **6.1E-01** | **4.2E-01** | **0.122** | **0.392** | **0.246** |
| **Stated relative expanded uncertainty** | | | | | **in %** | **1.3** | **1** | **0.8** | **0.5** | **0.3** | **0.4** | **0.3** |

## Phase shift

**E. Phasee Sensitivity uncertainty budget - KRISS**

| Uncertainty coponent | Comment | | Type | Distribution | Factor | Uncertainty contribution 0.1 Hz to 40 Hz |
|---|---|---|---|---|---|---|
| accelerometer output phase measuremen | ADC-resolution | u1 | B | rectangular | 0.577 | 3.6E-05 |
| voltage disturbance on accelerometer output phase measurement | hum and noise | u2 | B | rectangular | 0.577 | 4.7E-02 |
| transverse, rocking, and bending acceleration on accelerometer output phase measurement | transverse acceleration on accelerometer output phase measurement | u3 | B | U-type | 1 | 7.0E-04 |
| voltage disturbance on displacement phase amplitude measurement | random noise in the photoelectric measuring chains | u4 | B | rectangular | 0.577 | 5.0E-06 |
| motion disturbance on displacement phase amplitude measurement | drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer | u5 | B | rectangular | 0.577 | 1.2E-02 |
| phase disturbance on displacement phase amplitude measurement | phase noise of the interferometer signals | u6 | B | rectangular | 0.577 | 2.9E-04 |
| delay of laser interferometer | delay of laser interferometer | u7 | B | rectangular | 0.577 | 4.2E-06 |
| residual effects on phase shift measurement | random effect in repeat measurements; experimental standard devitation of arithmetic mean | u8 | A | normal | 1 | 1.7E-02 |
| **combined standard uncertainty** | | | | | **in °** | **0.051** |
| **expanded uncertainty (k=2)** | | | | | **in °** | **0.103** |
| **stated expanded uncertainty** | | | | | **in °** | **0.2** |

# V. NMISA

## Magnitude sensitivity

| UNCERTAINTY BUDGET MATRIX (UBM) | | | | | | | | | | Certificate No | | AV\VS-3709 |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| | | | | | | | | | | Procedure No | | AV\VS-0001 |
| Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9) | | | | | | | | | | | | |
| Description: | Sensitivty calibration (modulus) as per ISO 16063-11 method 3 | Make & model: | | Brüel & Kjær Endevco | | Range: | 0,1 Hz to 20 kHz | | | | | Metrologist |
| | | Serial number: | | | | | | | | | | Ian Veldman |
| | Mathematical Model: | $S=\hat{u}/\hat{a}=\hat{u}/(2\pi f)^2 d$ | | | | | | | | | | |
| Symbol | Input Quantity (Source of Uncertainty) | Standard Uncertainty Contribution $U_i(y)$ | | | | | | | | Reliability | Degrees of Freedom | Remarks |
| | | 0,1 Hz 0,2 Hz | > 0,2 Hz < 1 Hz | 1 Hz to 1 kHz | > 1 kHz < 5 kHz | 5 kHz to 7 kHz | > 7 kHz to 12 kHz | > 12 kHz to 15 kHz | >15 kHz to 20 kHz | | infinite | |
| $u$ | ▼ Standards and Reference Equipment (Uncorrelated) ▼ | % | % | % | % | % | % | % | % | % | $v$ | |
| $\varphi_Q$ | Interferometer output signal disturbance on phase amplitude | 0,006 | 0,006 | 0,006 | 0,058 | 0,115 | 0,115 | 0,173 | 0,289 | 100 | infinite | e.g. offsets, voltage amplitude deviations, <> 90° Corrected with Heydemant procedure |
| $\varphi_{VD}$ | Effect of voltage disturbance on phase amplitude measurement | 0,000 | 0,000 | 0,000 | 0,000 | 0,001 | 0,001 | 0,001 | 0,002 | 100 | infinite | Additive uncorrelated noise is reduced by 1/√n. Where n=number of samples pes vibration cycle. Worse case =10%/1000 |
| $\varphi_{MD}$ | Effect of motion disturbance on phase amplitude measurement | 0,012 | 0,006 | 0,009 | 0,115 | 0,231 | 0,404 | 0,462 | 0,462 | 100 | infinite | Relative motion between sensing spot, exiter and accelerometer. Worse case calculated for 16mm double ended accelerometer. |
| $\varphi_{PD}$ | Effect of phase disturbance on phase amplitude measurement | 0,006 | 0,006 | 0,006 | 0,029 | 0,058 | 0,058 | 0,115 | 0,289 | 100 | infinite | Corrected for using Heydemann correction procedure |
| $\varphi_{RE}$ | Residual interferometric effects on phase amplitude measurement | 0,012 | 0,012 | 0,006 | 0,006 | 0,058 | 0,029 | 0,058 | 0,115 | 100 | infinite | Not aware of any |
| $f_{FG}$ | Vibration frequency measurement accuracy | 0,006 | 0,006 | 0,029 | 0,040 | 0,087 | 0,115 | 0,144 | 0,173 | 100 | infinite | ISO 16063-11 requirement: ≤ 0,05 % of reading |
| $\lambda_U$ | Uncertainty on laser wavelength measurement | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 0,000 | 100 | infinite | Uncertainty quoted on certificate |
| $\hat{u}_V$ | Accelerometer output voltage measurement (ADC resolution/accuracy) | 0,087 | 0,035 | 0,058 | 0,035 | 0,035 | 0,035 | 0,035 | 0,035 | 100 | infinite | Manufacturer's specification worse case on 1 V range |
| $S_F$ | Filtering effect on sensitivity measurement | 0,046 | 0,046 | 0,058 | 0,058 | 0,115 | 0,115 | 0,115 | 0,231 | 100 | infinite | $e=(f/f_{Hp})^2$ |
| $G_{CA}$ | Charge amplifier gain accuracy | 0,100 | 0,100 | 0,050 | 0,100 | 0,100 | 0,100 | 0,100 | 0,100 | 100 | infinite | Conditiong amplifier uncertainty |
| | | | | | | | | | | | | |
| | | | | | | | | | | | | |
| | ▼ Unit Under Test / Calibration (Uncorrelated) ▼ | | | | | | | | | | | |
| $\hat{u}_D$ | Effect of voltage disturbance on accelerometer output voltage measurement | 0,035 | 0,025 | 0,015 | 0,030 | 0,025 | 0,025 | 0,100 | 0,150 | 100 | infinite | $U_{THD}$ = ½(d/100)²; Maximum allowed by ISO 16063 |
| $\hat{u}_T$ | Effect of transverse motion on accelerometer output voltage measurement | 0,025 | 0,015 | 0,025 | 0,025 | 0,040 | 0,050 | 0,125 | 0,125 | 100 | infinite | Transeverse error for a transverse sensitivity of 1% |
| $\hat{u}_{RES}$ | Residual effects on accelerometer output voltage measurement | 0,025 | 0,025 | 0,025 | 0,035 | 0,025 | 0,050 | 0,050 | 0,050 | 100 | infinite | Tribo-electric effect |
| | | | | | | | | | | | | |
| $\hat{u}_\sigma$ | Standard deviation on accelerometer output voltage measurement | 0,300 | 0,200 | 0,100 | 0,150 | 0,200 | 0,350 | 0,450 | 0,500 | | 7 | ESDM for sensitivity calulation using 4 points |
| About UBM | TOTAL COMBINED UNCERTAINTY | | | | | | | | | | | |
| Best Measurement Capability (Excluding UUT contribution) | Combined Uncertainty (Normal) ▼Confidence Level▼ | 0,14 | 0,117 | 0,101 | 0,184 | 0,325 | 0,468 | 0,553 | 0,698 | $V_{eff}$ | infinite | Checked and Approved By: |
| | Expanded Uncertainty $k$ = 2 95,45 % | 0,28 | 0,23 | 0,20 | 0,37 | 0,65 | 0,94 | 1,11 | 1,40 | $k$ = | 2,00 | |
| Uncertainty of Measurement (Including UUT contribution) | Combined Uncertainty (Normal) ▼Confidence Level▼ | 0,34 | 0,235 | 0,147 | 0,243 | 0,385 | 0,589 | 0,732 | 0,882 | $V_{eff}$ | infinite | |
| | Expanded Uncertainty $k$ = 2 95,45 % | 0,8 | 0,5 | 0,3 | 0,5 | 0,8 | 1,2 | 1,5 | 1,8 | $k$ = | 2,00 | |

## Phase shift

| | | | | | | | | | | |
|---|---|---|---|---|---|---|---|---|---|---|
| **UNCERTAINTY BUDGET MATRIX (UBM)** | | | | | | | | Certificate No | | AV\VS-3709 |
| | | | | | | | | Procedure No | | AV\VS-0001 |
| Reference: Guide to the Expression of Uncertainty in Measurement, issued by BIPM, IEC, IFCC, ISO, IUPAC, IUPAP, OIML - ISO 1995 (ISBN 92-67-10188-9) | | | | | | | | | | |
| **Description:** | Complex Sensitivity Calibration (Phase) as per ISO 16063-11 method 3 | **Make & model:** | | Brüel & Kjær Endevco | | **Range:** | 0,1 Hz to 20 kHz | | | **Metrologist** |
| | | **Serial number:** | | 123 | | | | | | Ian Veldman |
| **Mathematical Model:** | | $S_{phase} = UUT_{Phase} - Ref_{Phase} - Ref_{Delay} - AtoD_{Phase} - DSP_{Delay}$ | | | | | | | | |
| **Symbol** | **Input Quantity (Source of Uncertainty)** | **Standard Uncertainty Contribution *Ui*(y)** | | | | | | **Reliability** | **Degrees of Freedom** | **Remarks** |
| | | **0,1 Hz to 100 Hz** | **> 100 Hz to 1 kHz** | **> 1 kHz < 5 kHz** | **5 kHz to 12 kHz** | **> 12 kHz to 15 kHz** | **> 15 kHz to 20 kHz** | | infinite | |
| ***u*** | **▼ Standards and Reference Equipment (Uncorrelated) ▼** | (°) | (°) | (°) | (°) | (°) | (°) | % | *v* | |
| $\varphi_{s,Q}$ | Interferometer output signal disturbance on displacement phase measurement | 0,035 | 0,046 | 0,075 | 0,115 | 0,231 | 0,202 | 100 | infinite | e.g. offsets, voltage amplitude deviations, <> 90°<br>Corrected with Heydemant procedure |
| $\varphi_{s,VD}$ | Effect of voltage disturbance on displacement phase measurement | 0,029 | 0,040 | 0,058 | 0,069 | 0,144 | 0,202 | 100 | infinite | Additive uncorrelated noise is reduced by 1/√n.<br>Where n=number of samples pes vibration cycle. Worse case =10%/1000 |
| $\varphi_{s,MD}$ | Effect of motion disturbance on displacement phase measurement | 0,029 | 0,029 | 0,058 | 0,069 | 0,115 | 0,231 | 100 | infinite | Relative motion between sensing spot, exiter and accelerometer.<br>Worse case calculated for 16mm double ended accelerometer. |
| $\varphi_{s,PD}$ | Effect of phase disturbance on displacement phase measurement | 0,040 | 0,040 | 0,115 | 0,087 | 0,144 | 0,173 | 100 | infinite | Corrected for using Heydemann correction procedure |
| $\varphi_{s,RE}$ | Residual interferometric effects on displacement phase measurement | 0,012 | 0,012 | 0,046 | 0,058 | 0,173 | 0,173 | 100 | infinite | Not aware of any |
| $\Delta_{\varphi E}$ | Environmental effects on phase shift measurement | 0,017 | 0,017 | 0,029 | 0,058 | 0,115 | 0,087 | 100 | infinite | ISO 16063-11 requirement: ≤ 0,05 % of reading |
| $\varphi_{u,V}$ | Accelerometer output phase measurement (ADC resolution/accuracy) | 0,025 | 0,025 | 0,100 | 0,150 | 0,200 | 0,175 | 100 | infinite | SAM phase calculation accuracy |
| $\varphi_{u,F}$ | Filtering effect on accelerometer output phase measurement | 0,029 | 0,029 | 0,087 | 0,231 | 0,289 | 0,289 | 100 | infinite | e=(f/fHp)2 |
| $\varphi_{C,A}$ | Charge amplifier phase accuracy | 0,035 | 0,040 | 0,050 | 0,127 | 0,127 | 0,127 | 100 | infinite | Certified value |
| | | | | | | | | | | |
| | **▼ Unit Under Test / Calibration (Uncorrelated) ▼** | | | | | | | | | |
| $\hat{u}_D$ | Effect of voltage disturbance on accelerometer output phase measurement | 0,012 | 0,023 | 0,069 | 0,144 | 0,231 | 0,289 | 100 | infinite | $U_{THD}$ = ½(d/100)2; Maximum allowed by ISO 16063 |
| $\hat{u}_T$ | Effect of transverse motion on accelerometer output phase measurement | 0,012 | 0,017 | 0,029 | 0,058 | 0,058 | 0,058 | 100 | infinite | Transeverse error for a transverse sensitivity of 1% |
| $\hat{u}_{RES}$ | Residual effects on accelerometer output voltage measurement | 0,005 | 0,010 | 0,025 | 0,025 | 0,025 | 0,058 | 100 | infinite | Tribo-electric effect |
| | | | | | | | | | | |
| $\hat{u}_{RES}$ | Standard deviation on accelerometer phase shift measurement | 0,050 | 0,090 | 0,100 | 0,150 | 0,250 | 0,550 | 100 | infinite | ESDM for sensitivity calulation using 5 cycles minimum |
| About UBM | **TOTAL COMBINED UNCERTAINTY** | | | | | | | | | |
| **Best Measurement Capability (Excluding UUT contribution)** | Combined Uncertainty (Normal) ▼Confidence Level▼ | 0,09 | 0,10 | 0,22 | 0,36 | 0,54 | 0,58 | $V_{eff}$ | infinite | Checked and Approved By: |
| | Expanded Uncertainty *k* = 2 95,45 % | 0,2 | 0,20 | 0,4 | 0,7 | 1,1 | 1,15 | *k* = | 2,00 | |
| **Uncertainty of Measurement (Including UUT contribution)** | Combined Uncertainty (Normal) ▼Confidence Level▼ | 0,10 | 0,13 | 0,24 | 0,39 | 0,60 | 0,80 | $V_{eff}$ | infinite | |
| | Expanded Uncertainty *k* = 2 95,45 % | 0,2 | 0,3 | 0,5 | 0,8 | 1,2 | 1,6 | *k* = | 2,00 | |

# VI. CSIR-NPLI

## Magnitude sensitivity

| D. Voltage Sensitivity uncertainty budget - CSIR-NPLI | | | | | | | |
|---|---|---|---|---|---|---|---|
| i | Standard Uncertainty contribution u(xi) | ISO -SAM- Urel(S) | Uncertainty contribution ui(y) | 0.1 Hz ≤ *f* < 0.5 Hz | 0.5 Hz ≤ *f* < 20 Hz | 20 Hz ≤ *f* < 31.5 Hz | 31.5 Hz ≤ *f* < 40 Hz |
| 1 | $u(\hat{u}_V)$ | accelerometer output voltage measurement(waveform recorder; e.g. ADC-resolution) | $u_1(S)$ | 0.139 | 0.115 | 0.115 | 0.115 |
| 2 | $u(\hat{u}_F)$ | voltage filtering effect on accelerometer output amplitude measurement(frequency band limitation) | $u_2(S)$ | 0.115 | 0.115 | 0.115 | 0.115 |
| 3 | $u(\hat{u}_D)$ | effect of voltage disturbance on accelerometer output voltage measurement (e.g. hum and noise) | $u_3(S)$ | 0.115 | 0.115 | 0.115 | 0.115 |
| 4 | $u(\hat{u}_T)$ | effect of transverse, rocking, and bending acceleration on accelerometer output voltage measurement (transverse sensitivity) | $u_4(S)$ | 0.115 | 0.06 | 0.06 | 0.09 |
| 5 | $u(\varphi_{M,Q})$ | effect of interferometer quadrature output signal disturbance on phase amplitude measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(S)$ | 0.115 | 0.06 | 0.09 | 0.09 |
| 6 | $u(\varphi_{M,F})$ | interferometer signal filtering effect on phase amplitude measurement (frequency band limitation) | $u_6(S)$ | 0.115 | 0.06 | 0.06 | 0.09 |
| 7 | $u(\varphi_{M,VD})$ | effect of voltage disturbance on phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(S)$ | 0.115 | 0.06 | 0.09 | 0.115 |
| 8 | $u(\varphi_{M,MD})$ | effect of motion disturbance on phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(S)$ | 0.1731 | 0.11 | 0.11 | 0.115 |
| 9 | $u(\varphi_{M,PD})$ | effect of phase disturbance on phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(S)$ | 0.115 | 0.11 | 0.11 | 0.115 |
| 10 | $u(\varphi_{M,RE})$ | residual interferometric effects on phase amplitude measurement(interferometer function) | $u_{10}(S)$ | 0.115 | 0.115 | 0.115 | 0.115 |
| 11 | $u(f_{FG})$ | vibration frequency measurement (frequency generator and indicator) | $u_{11}(S)$ | 0.001 | 0.001 | 0.001 | 0.001 |
| 12 | $u(S_{RE})$ | residual effects on sensitivity measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{12}(S)$ | 0.289 | 0.173 | 0.242 | 0.289 |
| **Combined Uncertainty (in %)** | | | | **0.50** | **0.35** | **0.40** | **0.45** |
| **Expanded Uncertainty (*k*=2) in %** | | | | **1.00** | **0.70** | **0.80** | **0.90** |

## Phase shift

| E. Phasee Sensitivity uncertainty budget - CSIR-NPLI | | | | | | | |
|---|---|---|---|---|---|---|---|
| i | Standard Uncertainty contribution u(xi) | ISO -SAM - U(Δφ) | Uncertainty contribution ui(y) | 0.1 Hz ≤ *f* < 0.5 Hz | 0.5 Hz ≤ *f* < 20 Hz | 20 Hz ≤ *f* < 31.5 Hz | 31.5 Hz ≤ *f* < 40 Hz |
| 1 | $u(\varphi_{u,V})$ | accelerometer output phase measurement(waveform recorder; e.g. ADC-resolution) | $u_1(\Delta\varphi)$ | 0.173 | 0.144 | 0.144 | 0.144 |
| 2 | $u(\varphi_{u,F})$ | voltage filtering effect on accelerometer output phase measurement(frequency band limitation) | $u_2(\Delta\varphi)$ | 0.173 | 0.11 | 0.133 | 0.133 |
| 3 | $u(\varphi_{u,D})$ | effect of voltage disturbance on accelerometer output phase measurement (e.g. hum and noise) | $u_3(\Delta\varphi)$ | 0.173 | 0.11 | 0.115 | 0.115 |
| 4 | $u(\varphi_{u,T})$ | effect of transverse, rocking, and bending acceleration on accelerometer output phase measurement (transverse sensitivity) | $u_4(\Delta\varphi)$ | 0.173 | 0.11 | 0.115 | 0.115 |
| 5 | $u(\varphi_{s,Q})$ | effect of interferometer quadrature output signal disturbance on displacement phase measurement(e.g. offsets, voltage amplitude deviation, deviation from $90^0$ nominal angle difference) | $u_5(\Delta\varphi)$ | 0.029 | 0.029 | 0.029 | 0.029 |
| 6 | $u(\varphi_{s,F})$ | interferometer signal filtering effect on displacement phase amplitude measurement (frequency band limitation) | $u_6(\Delta\varphi)$ | 0.029 | 0.029 | 0.029 | 0.029 |
| 7 | $u(\varphi_{s,VD})$ | effect of voltage disturbance on displacement phase amplitude measurement(e.g. random noise in the photoelectric measuring chains) | $u_7(\Delta\varphi)$ | 0.029 | 0.029 | 0.029 | 0.029 |
| 8 | $u(\varphi_{s,MD})$ | effect of motion disturbance on displacement phase amplitude measurement(e.g. drift; relative motion between the accelerometer reference surface and the spot sensed by the interferometer) | $u_8(\Delta\varphi)$ | 0.029 | 0.029 | 0.029 | 0.029 |
| 9 | $u(\varphi_{s,PD})$ | effect of phase disturbance on displacement phase amplitude measurement(e.g. phase noise of the interferometer signals) | $u_9(\Delta\varphi)$ | 0.115 | 0.11 | 0.115 | 0.115 |
| 10 | $u(\varphi_{s,RE})$ | residual interferometric effects on displacement phase amplitude measurement(interferometer function) | $u_{10}(\Delta\varphi)$ | 0.173 | 0.144 | 0.144 | 0.173 |
| 11 | $u(\Delta\varphi_{RE})$ | residual effects on phase shift measurement(e.g. random effect in repeat measurements; experimental standard devitation of arithmetic mean) | $u_{11}(\Delta\varphi)$ | 0.289 | 0.173 | 0.242 | 0.289 |
| Combined Uncertainty (in °) | | | | 0.50 | 0.35 | 0.40 | 0.45 |
| Expanded Uncertainty (*k*=2) in ° | | | | 1.00 | 0.70 | 0.80 | 0.90 |