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Metrological traceability of a digital 3-axis MEMS accelerometers sensor network

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1       **Towards the metrological traceability of a sensor network and the**  
2       **trustworthiness of data provided: a case study on 25 digital**  
3       **MEMS accelerometers**

4  
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7  
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12  
13       Abbreviated title: Metrological traceability of a sensor network

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32     **Abstract**

33     Digital MEMS sensor networks are nowadays widely applied in environmental and manufacturing appli-  
34     cations. However, fundamental metrological requirements, such as traceability and trustworthiness of data, are  
35     often disregarded by manufacturers and end-users. In this work, traceability of a sensor network prototype,  
36     composed of 25 digital 3-axis MEMS accelerometers, conceived for structural monitoring at low-frequencies,  
37     is investigated. Main and transverse sensitivities are provided for each axis at three low-frequencies by two  
38     laboratories with recently-developed independent vibration calibration systems using inclined planes. Com-  
39     parison of the 225 main sensitivities shows compatible results. Given the large amount of data to be managed  
40     by end-users, the possibility of decreasing its number is then investigated by managing sensitivity and uncer-  
41     tainty data according to different combinations of three examined factors, i.e. MEMS, frequency and axis.  
42     Thus, the number of data is reduced at the expense of higher uncertainties but preserving the traceability and  
43     the trustworthiness of sensors data.

44  
45     **Keywords:** Vibration calibration, Digital Sensors, Network sensitivity, MEMS, Trustworthiness, Traceability.

66 **1. Introduction**

67 Nowadays systems for survey, monitoring and control based on digital MEMS sensor networks has become  
68 a widely established practice in many application and engineering fields. The ease of use, flexibility, low-cost  
69 and low-power consuming of MEMS sensors, together with the enhanced big data flows managing and the  
70 digitalization, have made these “technological sensing infrastructures” very attracting tools to detect a great  
71 variety of physical quantities, processes and phenomena, from the small-scale up to the large-scale (until the  
72 Earth-scale). Besides, the development of new technologies based on independent devices and communica-  
73 tions, such as IoT in each different implementation, from healthcare to smart industries, from domotics to  
74 autonomous driving, is based on the deployment of very complex wide distributed grids of sensors.

75 However, by referring to the terminology defined in VIM [1] and in [2], some typical metrological attributes  
76 of measuring instruments, such as traceability, accuracy and the trustworthiness of data provided, are often  
77 disregarded for MEMS sensors, applied in the nodes of networks. «Trustworthiness of measurements» repre-  
78 sents in a comprehensive and very communicative way the measurement quality level, under several technical  
79 points of view [3, 4].

80 Sometimes, end-users implement custom calibration techniques (or more properly, custom adjustments) or  
81 rely on the calibration data provided by the manufacturers, without traceable methods. Depending on the ap-  
82 plications (more or less sensitive), it may be necessary to actually have traceable and accurate data, or at least  
83 data-sets expressed within well-defined confidence levels. It follows that a traceable network of sensors is  
84 certainly more trustworthy (and much more competitive) than ordinary networks, since data supplied can be  
85 considered effectively representative of measured phenomena, beyond to be compatible and reproducible.

86 In order to amend this lack, some applicative protocols begin to be published, e.g., by IEEE Standard As-  
87 sociation [5] providing common framework for sensor performance specification terminology, units, condi-  
88 tions, and limits. Indeed, the large deployment of sensors with digital output and network systems needs to be  
89 underpinned by new metrological approaches (such as remote self-calibration, data aggregation in network  
90 systems and uncertainty analysis) allowing to support trustworthy and safe operation, linked to traceability  
91 chains, to guarantee higher quality management requirements.

92 The relevance of these emerging needs in the field of metrology, has recently oriented the strategy plan of  
93 BIPM [6], in order to «identify and deliver the highest impact opportunities to support National Metrology  
94 Institutes (NMIs) priorities in, for example, the areas of “big data” and digital transformation», as well as  
95 several consultative committees within it [7-10], with the aim to provide suitable calibration procedures for  
96 these systems, against national primary standards, and to provide the traceability chain to the national labora-  
97 tories and to the manufacturers, at present not yet available.

98 In Fig. 1 the metrological traceability chain and the path of the International System of Units propagation,  
99 through subsequent calibrations, from primary standard to end-users, is schematically represented.

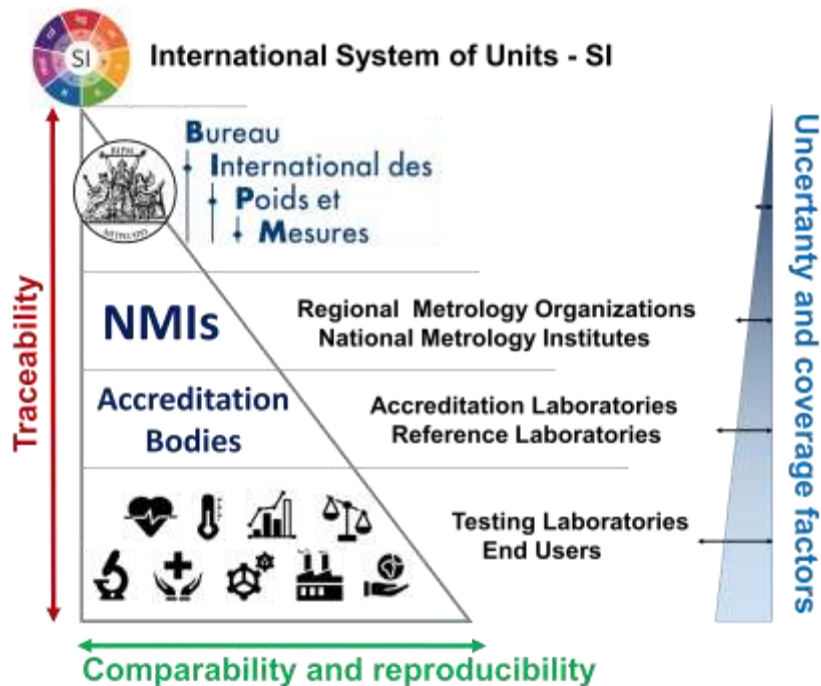


Fig. 1. The metrological traceability chain and the propagation of the SI.

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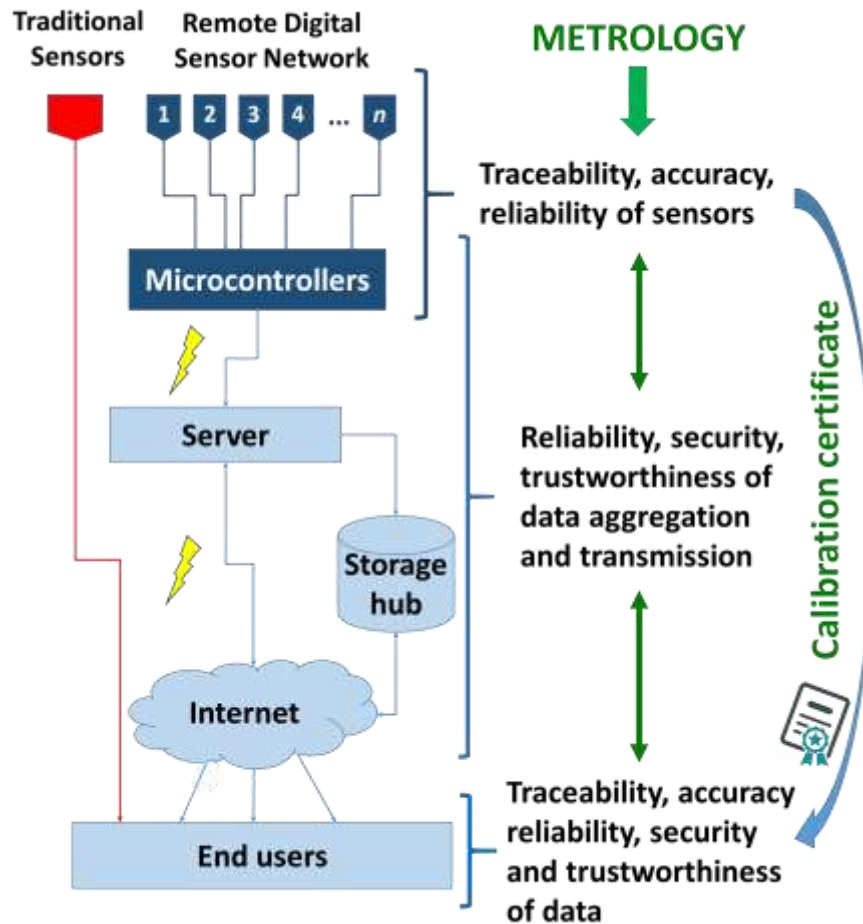
As a consequence, there are not still technical standards for the calibration of sensors with digital output and digital interface, thus end-users will usually get neither a calibration certificate nor a traceability statement from the manufacturer, although the sensitivity is adjusted during the production process. As it is known, in some applications there are several legal or insurance reasons for which it is preferable to use sensors calibrated in accredited and certified laboratories, according to the ISO 17025 standard [11].

In the frame of the Strategy 2019 to 2029 of the Consultative Committee for Acoustics, Ultrasound, and Vibration at BIPM, the vision is strongly oriented to the issue of digitalization and to the traceability of sensors with digital interfaces, since markets are generating the basic components to enable to development of low-cost robust sensor systems capable of wireless, autonomous and intelligent operation, possibly combining multi-parameter sensing within a single device or network of devices. Indeed, the metrology applied to sensor networks, under several points of view, is particularly stimulated from both industrial needs and sensors manufacturers, and several NMIs worldwide are planning their activities along these perspectives. From a general survey beyond specific applications, in USA at NIST, security, trust and trustworthiness of sensors applied in networks and in distributed system for Internet of Things (IoT) and Network of Things (NoT), are investigated [12]; in Germany at PTB, the role of metrology for the digitalization of the economy and society in the digital age is studied [13]; in Italy at INRIM, within an integrated industrial partnership network [14], the processes of knowledge transfer, supporting the traceability chain to sensors with digital outputs, are applied for environment, industry and smart manufacturing [15-20].

Within the framework of the European Association of National Metrology Institutes (EURAMET), this topic is widely debated and several proposals are developed within joint research projects, such as “Metrology

123 for the Factory of the Future” (Met4FoF) [21], “Metrology for the next-generation digital substation instru-  
 124 mentation” (FutureGrid II) [22] or “Communication and validation of smart data in IoT-networks” (Smart-  
 125 Com) [23], among others.

126 The metrological research devoted to the sensor networks, intended as the whole infrastructure – i.e., from  
 127 the acquisition systems (sensing elements, nodes), to the systems for transferring, processing and distributing  
 128 signals (microcontrollers), to the transmission and connectivity protocols, to the collecting hubs, up to the end-  
 129 user – is a wide field of investigation, aimed to provide trustworthy and traceable data, within suitable coverage  
 130 factors and uncertainties budgets, tailored to the actual needs of specific applications and employments, and a  
 131 multidisciplinary effort of different competences has to be harmonized, steps by steps. In Fig. 2 the description  
 132 of a simplified sensor network infrastructure and the related metrological needs are depicted.  
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134  
 135 **Fig. 2.** The sensor network infrastructure and the metrological needs.  
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137 The first fundamental step, from a metrological perspective towards the traceability of a sensor network as  
 138 a whole, is founded on the trustworthiness of data provided by the single sensors employed, once properly  
 139 calibrated, thus on the ability to provide measurement uncertainty and/or quality information together with the

140 measurement data. Nevertheless, since «these technologies have different mounting requirements, use differ-  
141 ent testing and calibration protocols, and use digital interfaces for data and communications» [7], it is not  
142 always possible to completely fulfill the current standard requirements for the calibration; on the other hand,  
143 some different analyses and limitations need to be applied, in order to identify and quantify the actual sensi-  
144 tivity values of digital sensors. In addition, standard calibration methods are not feasible in terms of timings  
145 and costs, compatibly with the low-cost of the sensors.

146 In the case of digital MEMS accelerometers, the sensitivity is generally provided by the manufacturer with-  
147 out traceable methods and sometimes it is estimated in static conditions. Dynamic response, as a function of  
148 frequency, is often unknown. On the other hand, traceable calibration methods for digital sensors, including  
149 sensitivity parameter and uncertainty analysis are necessary, in order to consider digital MEMS accelerometers  
150 as actual measurement devices in the frequency domain [24-27]. For these reasons, two independent calibration  
151 systems using tilted plates suitable for MEMS accelerometers have been developed by INRIM (National In-  
152 stitute of Metrological Research) [28-29] and UNIVAQ (University of L'Aquila) [30-33].

## 153 **2. Material and methods**

154 In this work, as a case-study, the traceability and the reproducibility of sensors to be employed in a network,  
155 composed of 25 digital 3-axis MEMS accelerometers, nominally identical, are investigated. Each sensor is  
156 calibrated by comparison to INRIM secondary standard (previously calibrated against INRIM primary stand-  
157 ard), to establish the first link to the metrological traceability chain. In this way, the traceability is assured, and  
158 the robustness of compatibility and reproducibility is verified on the basis of a bilateral comparison between  
159 INRIM and UNIVAQ. It is worth noting that in relevant standards, calibration of rectilinear vibration trans-  
160 ducers is mainly intended for the evaluation of magnitude sensitivity and optionally for phase shift sensitivity.  
161 Therefore, in the following, calibration measurements are related to the first case. Traceability of the sensors,  
162 to be applied within the network, is provided through calibration methods by comparison to a calibrated refer-  
163 ence transducer: the actual main sensitivity, in frequency domain, of each axis for each single MEMS accel-  
164 erometer, and the transverse sensitivities, due to the mutual interactions among axes, are accurately quantified.  
165 Experimental results, obtained from the two independent dynamic calibration systems and procedures in terms  
166 of “digitized sensitivities”, are then verified and finally compared to each other and with the nominal sensitivity  
167 provided by the manufacturer [34]. The analyzed MEMS accelerometers are a part of the same production  
168 batch, provided by manufacturer (STMicroelectronics). Calibration results of the 25 MEMS accelerometers  
169 are then compared and experimental expanded uncertainties are used to evaluate the sensitivity ranges of the  
170 MEMS accelerometers, with suitable coverage factors, in order to estimate the trustworthiness of data provided  
171 by the sensors within the network, employed by end-users. The sensors under investigation are the sensing  
172 elements of a network-prototype, conceived for structural and infrastructures health monitoring and for seismic  
173 safety networks at urban/building scale, suitable for low-frequency range vibration measurements [35-39].

174

175 2.1 Sensitivity and sensors

176 2.1.1 «Digitized» Sensitivity

177 First of all, it is necessary to define a proper sensitivity parameter for digital outputs. According to the IEEE  
178 Standard for digital accelerometer [5], the sensitivity is defined in terms of Least Significant Bit (LSB) referred  
179 to g, i.e., g/LSB. The change in acceleration input corresponding to 1 LSB change in output. This definition is  
180 widely used in digital sensors datasheets. Nevertheless, in our opinion, the use of term LSB is partially con-  
181 fusing for digital outputs for two main reasons. First, the actual digital output value is a n bit 0/1 binary se-  
182 quence, converted into a decimal number (Decimal<sub>n-bit</sub>). Second, although 1 LSB corresponds to  $20=1$  Deci-  
183 mal<sub>n-bit</sub> in most of the cases, according to IEEE Standard, it is not always true, since 1 LSB could correspond  
184 to other bit positions, i.e.  $21=2$  Decimal<sub>n-bit</sub>,  $22=4$  Decimal<sub>n-bit</sub>, or more. Therefore, in the following, the «dig-  
185 itized sensitivity» of a digital MEMS accelerometer is expressed, in linear units, as  $\text{Decimal}_{n\text{-bit}}/(\text{m s}^{-2})$  (or  
186 simply  $D_{n\text{-bit}}/(\text{m s}^{-2})$ ), by analogy to typical sensitivity of analog accelerometers, expressed in linear units, in  
187 terms of  $\text{V}/(\text{m s}^{-2})$ . The n-bit subscript indicates the number of bits to which the Decimal refers to, i.e. 12-bit,  
188 16-bit, depending on the standard used by the device.

189

190 2.1.2 Sensor network sensitivity

191 The definition of sensor network sensitivity could be misleading when compared to the traditional concept  
192 of sensitivity. In fact, traditionally, the sensitivity, together with the associated uncertainty, is provided to each  
193 individual sensor by varying the main parameters of influence (e.g., frequencies and axes, in the case of accel-  
194 erometers), with the result that several quantities are related to a single transducer. However, in the case of  
195 sensor networks, that may consist of tens, hundreds, if not thousands of transducers, attributing sensitivity to  
196 each transducer and for each parameter of influence might be difficult to manage in numerical, computational  
197 and consuming terms by end-users in actual applications [40–43], particularly at present time in which manu-  
198 facturers usually do not provide traceable sensitivities [27]. By way of example, in the case of triaxial accel-  
199 erometer transducers, the sensitivity is usually provided for each single axis of sensitivity for different fre-  
200 quencies, at a specific oscillation amplitude. Therefore, as a lower estimate, from 9 (3 frequencies  $\times$  3 main  
201 axes) to 36 (12 frequencies  $\times$  3 main axes) sensitivity values are attributed to each sensor (neglecting the  
202 possible variability with amplitude and the evaluation of the transverse sensitivities). Projecting this count to  
203 a small network of 25 sensors, as in this case, an amount of sensitivity data ranging from 225 to 900 is obtained.  
204 Despite the small size of this MEMS accelerometers network, however, such number of data might be difficult  
205 to manage by the end-user, with the risk of compromising the trustworthiness of data provided by the network  
206 if the end-user, in order to reduce the number of sensitivities to manage, has no experience in handling these  
207 data with a metrological approach, in terms of mean sensitivity values and propagation of the associated un-  
208 certainties. Therefore, before drafting a traceability protocol, it is important to consider this aspect in order to  
209 evaluate what kind of and how many sensitivity data should be provided to the end-users, commensurate with  
210 the size and final application of the sensor network, that ensure its optimal trustworthiness.



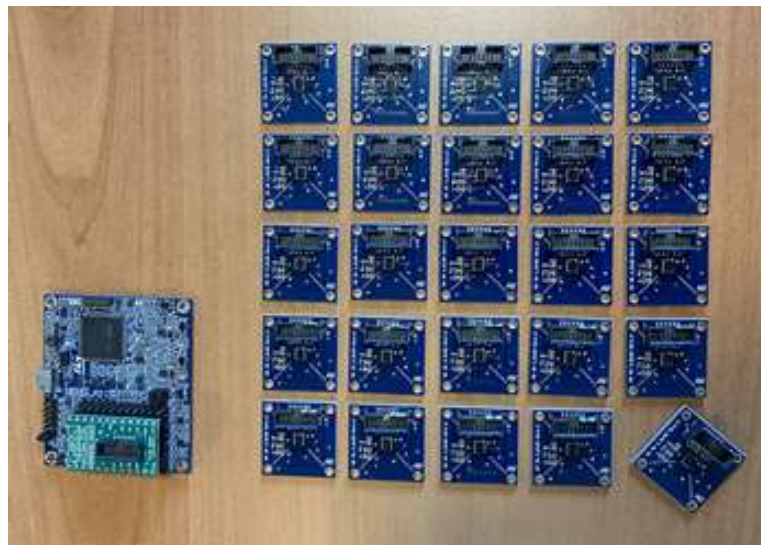
211 In this case study, therefore, beside evaluating the sensitivity of all 25 MEMS in terms of main (and trans-  
212 verse) sensitivities for each single axis and for each tested frequency (225 main sensitivity values in total), the  
213 possibility to provide a lower number of sensitivity values with associated uncertainties, from the case of axis-  
214 and frequency-independent sensitivity for each MEMS (25 sensitivity values) to the limit case of a single  
215 sensitivity value independent from MEMS, axis and frequency, is investigated, as it will be shown in Section  
216 IV.

217

### 218 2.1.3 The digital 3-axis MEMS accelerometer

219 The 25 digital 3-axis MEMS accelerometers investigated in this work (Fig. 3) are commercial low-power  
220 digital MEMS accelerometers (ST, model LSM6DSR [34]). The device is composed of an accelerometer sen-  
221 sor, a charge amplifier, and an analog-to-digital converter. The digital MEMS accelerometers are connected  
222 by a serial cable to a separated external microcontroller, in which other electronic components are integrated.  
223 In this comparison the same external microcontroller (ST, model 32F769IDISCOVERY [44]), to acquire the  
224 digital samples and to provide the required power supply to the MEMS accelerometer, is used.

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227

**Fig. 3.** The set of 25 digital 3-axis MEMS accelerometers and the microcontroller.

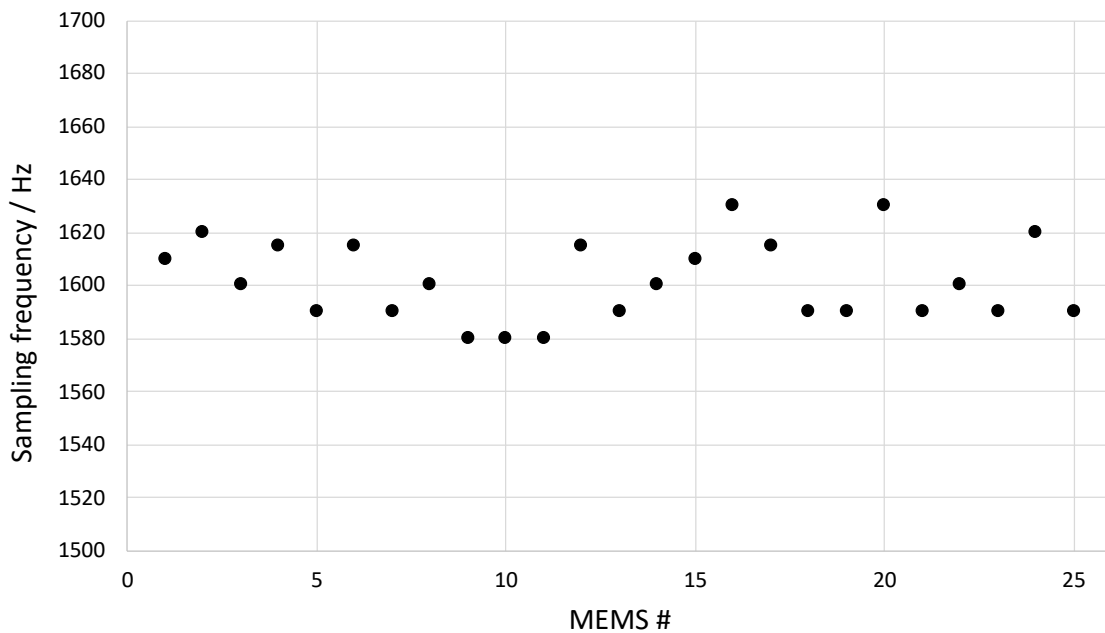
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229 The microcontroller has from 3 to 5 Serial Peripheral Interfaces (SPIs) available, and, to each one, it is  
230 possible to connect up to 8/10 sensors. Therefore, it is technically possible to connect from 20 to 40 sensors  
231 for each microcontroller, without introducing complications (such as other electronic components) [45]. How-  
232 ever, in real cases, as for the present case of structural and infrastructures health monitoring at urban/building  
233 scale, different microcontrollers should be used. As a matter of fact, the maximum MEMS-microcontroller  
234 distance depends on the interface and data speed. With an SPI interface and considering only one sensor, a 2  
235 m cable, suitable for building scales, can be used. By increasing the number of sensors on the same channel,  
236 the transfer speed has to be increased, thus the length of the cable has to be reduced. Therefore, at building

237 scale, it would only be practical for such MEMS sensors to have a dedicated microcontroller and network the  
 238 microcontrollers. However, since, as a first step, the aim is to provide traceability to single sensors inde-  
 239 pendently of the adopted microcontrollers, calibration is performed by connecting the microcontroller to a  
 240 single MEMS.

241 The signal is acquired by means of a SPI, which is a synchronous serial communication interface used for  
 242 connecting digital sensors together. The 1-bit signal from the  $\Sigma\Delta$ -ADC is then converted through a decimation  
 243 process and a low pass filter into a standard 16-bit-signed PCM (Pulse Code Modulation) signal with a nominal  
 244 sampling frequency rate of 1660 Hz. According to the manufacturer [45], however, sampling frequencies up  
 245 to -6% of the target, i.e. up to 1560 Hz, can be expected. For this reason, the actual sampling frequency of  
 246 every MEMS, as shown in Fig. 4, is previously evaluated by counting the number of points of the known  
 247 generated sinusoidal signals, in order to perform accurate calibration measurements. Sampling frequencies  
 248 range from around 1580 Hz to 1630 Hz.

249



250

**Fig. 4.** The actual sampling frequency of the 25 digital 3-axis MEMS accelerometers.

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252

253 The amplitude values range between  $-2^{16-1} = -32768$  D<sub>16-bit-signed</sub> and  $+(2^{16-1}-1) = +32767$  D<sub>16-bit-signed</sub>, where the  
 254 digit unit is a signed 16-bit sequence converted into a decimal number.

255 The linear acceleration sensitivity of a digital MEMS accelerometer, expressed by manufacturer in terms  
 256 of mg/LSB, depends on the “full scale” used in testing condition, and it is conventionally attributed to every  
 257 sensitive axis of the sensor, for static and dynamic measurements, independently from frequency, without any  
 258 indication about the associated uncertainty, and is not evaluated through traceable calibration methods. In this  
 259 work, by using a “full scale” of  $\pm 2$  g, the sensitivity declared is 0.061 mg/LSB.

260 In decimal units, it corresponds to  $0.061 \text{ mg}/D_{16\text{-bit-signed}}$ , i.e.  $0.598 \times 10^{-3} \text{ (m s}^{-2}\text{)}/D_{16\text{-bit-signed}}$ . As commonly  
 261 used in analogue transducers, the sensitivity is expressed as a function of the reference quantity, thus it properly  
 262 corresponds to  $1671 D_{16\text{-bit-signed}} / (\text{m s}^{-2})$ .

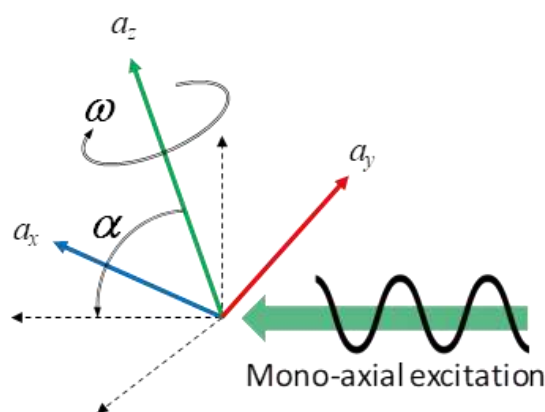
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## 264 2.2 Calibration procedure

265 The calibration procedure and the related metrological characterization of the set of 25 sensors is aimed at  
 266 verifying the actual amplitude response in dynamics, as a function of frequency, on the basis of the bilateral  
 267 comparison between laboratories. The procedure is based on a calibration by comparison, with a reference  
 268 accelerometer (in analogy to ISO Standard 16063-21 [46]), in order to provide the first “connection” to the  
 269 primary standard and to verify its transferability, through the secondary standards, to the sensors under inves-  
 270 tigation. In order to avoid further sources of uncertainty, the calibration of the 25 MEMS is performed by using  
 271 the same external microcontroller, in both laboratories, although the influence of the microcontrollers in terms  
 272 of systematic errors and uncertainty contribution, is negligible [45].

273 Calibration is carried out in a low frequency range, namely 3 Hz, 6 Hz and 10 Hz, by comparison to a  
 274 reference transducer. A sinusoidal mechanical dynamic excitation is generated along a single-axis, by means  
 275 of linear vibrating tables (according to the laboratory equipment), at nearly constant peak amplitude of  $1 \text{ m s}^{-2}$ .  
 276 The reference acceleration  $a_{\text{ref}}$  is measured by a reference accelerometer, previously calibrated against IN-  
 277 RiM primary standard. In order to simultaneously calibrate the three sensitive axes of the sensors, measure-  
 278 ments are performed on inclined planes which allow to generate the projection of the single-axis excitation  
 279 acceleration, along three sensitive axes ( $a_x, a_y, a_z$ ) simultaneously, as schematically shown in Fig. 5, according  
 280 to the laboratory setups and specific procedures.

281



282

283 **Fig. 5.** The schematic principle of the simultaneous 3-axis calibration, with respect to a single-axis of ex-  
 284 citation.

285

286 In time domain, 100 cycles of oscillation, for each frequency of calibration, are taken into account for the  
 287 determination of output data. The 3-axis digital MEMS accelerometer under investigation is fixed to the center

288 of the vibrating table at known angles of rotation  $\omega$  and at different tilt angles  $\alpha$ , with respect to the direction  
 289 of the single-axis excitation.

290 The detailed uncertainty budget is evaluated by both laboratories according to GUM [47], taking into ac-  
 291 count to the sensitivity equations and the related uncertainty contributions peculiar of each calibration system.

292

293 *2.3 The experimental method and uncertainty assessment*

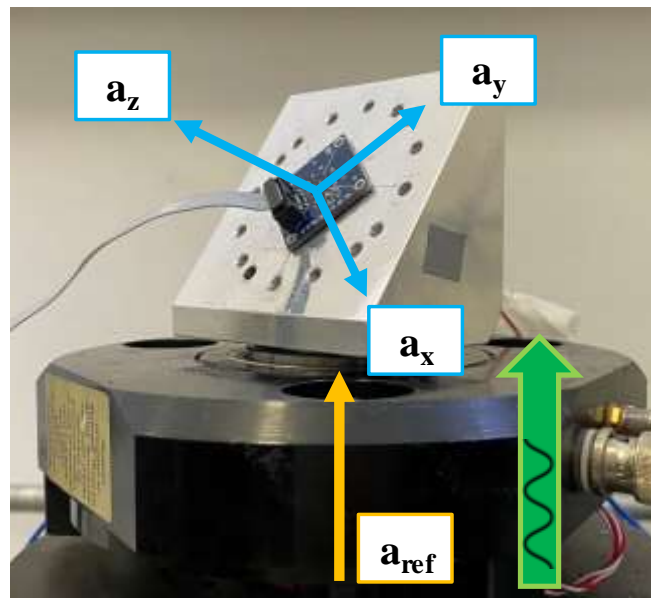
294 The calibration aims at quantifying, as a function of frequency, the average main sensitivities  $S_{ii}$ , as well as  
 295 the related dispersion of the 25 MEMS accelerometers within opportune coverage factors, and the occurring  
 296 transversal sensitivities  $S_{ij}$ , due to the possible mutual interaction among axes. As a matter of facts, in particular  
 297 for low-cost sensors, the outputs interact with each other and transverse sensitivities might play a crucial role,  
 298 unlike in traditional high-quality accelerometers. The three sensitivity axes of the MEMS accelerometer are  
 299 located with a certain tilt angle  $\alpha$ , and a certain rotation angle  $\omega$ , with respect to the direction of the excitation.  
 300 The experimental calibration systems are designed and independently realized in each laboratory, as described  
 301 in detail in [28-33].

302

303 *2.3.1 INRIM*

304 The calibration setup realised at INRIM consists of a single-axis vibrating table, on which aluminium in-  
 305 clined planes are screwed (Fig. 6). More details can be found in [28].

306



307

308

309

**Fig. 6.** Calibration setup used at INRIM laboratory.

310 The digital MEMS accelerometer is fixed to the inclined plane, along the axis of excitation, allowing to  
 311 generate a projection of the excitation acceleration along the three axes of the MEMS simultaneously. The  
 312 reference acceleration  $a_{ref}$ , corresponding to the sinusoidal excitation acceleration, is measured by a single axis

313 transducer (PCB model 080A199/482A23, calibrated against INRIM primary standard), integrated in the  
 314 stroke of the vertical shaker (PCB Precision Air Bearing Calibration Shaker), for the calibration at 6 Hz and  
 315 10 Hz. For the calibration at 3 Hz, a single axis horizontal linear slide (APS ELECTRO-SEIS shaker) is used  
 316 and the reference acceleration is measured by means of laser-Doppler velocimetry (Polytec OFV 505). The  
 317 reference acceleration is acquired by an acquisition board NI 4431 (sampling rate of 50 kHz) integrated in the  
 318 PC and processed through LabVIEW® software to provide the Root Mean Square (RMS) reference value in  
 319  $\text{m s}^{-2}$ . In this way, the reference accelerations along the MEMS axes can be found according to:

320

$$a_x = |a_{ref} \sin \alpha \cos \omega| \quad (1)$$

$$a_y = |a_{ref} \sin \alpha \sin \omega| \quad (2)$$

$$a_z = |a_{ref} \cos \alpha| \quad (3)$$

321

322 where,  $\alpha$  is the tilt angle,  $\omega$  is the angle of rotation,  $a_{ref}$  is the RMS reference acceleration along the vertical  
 323 axis  $z'$  of the excitation system, and  $a_x, a_y, a_z$  are the RMS reference accelerations spread along  $x$ -,  $y$ - and  $z$ -  
 324 axis of the MEMS accelerometer. Measurements are performed in four configurations at different angles of  
 325 rotation  $\omega$  and tilt  $\alpha$  ( $\alpha=0^\circ$  and  $\omega=270^\circ$ ;  $\alpha=15^\circ$  and  $\omega=90^\circ$ ;  $\alpha=75^\circ$  and  $\omega=0^\circ$ ;  $\alpha=75^\circ$  and  $\omega=90^\circ$ ). These  
 326 configurations are chosen since calibration results are compatible with those obtained from 48 configurations  
 327 as detailed in [48]. Systematic effects, due to spurious components acting on the perpendicular plane with  
 328 respect to the excitation axis caused by vibrational modes of the inclined aluminum plates and due to horizontal  
 329 motions of the shaker, are quantified in terms of amplitude and phase, by means of Laser-Doppler velocimetry  
 330 (Polytec OFV 505), and corrected for each inclined plane and for all frequencies, as described in detail in [28].

331 The digital MEMS output is acquired by the external microcontroller and saved as binary files. These files  
 332 are then processed with MATLAB® software: the digital value for each specific frequency  $f$  is obtained by  
 333 applying a first-order Butterworth band-pass filter, centred at the frequency of interest with a fractional band-  
 334 width of 10%, to the temporal signals and, subsequently, by computing the Root Mean Square (RMS), in order  
 335 to remove the off-set due to gravity and the influence of background vibrations.

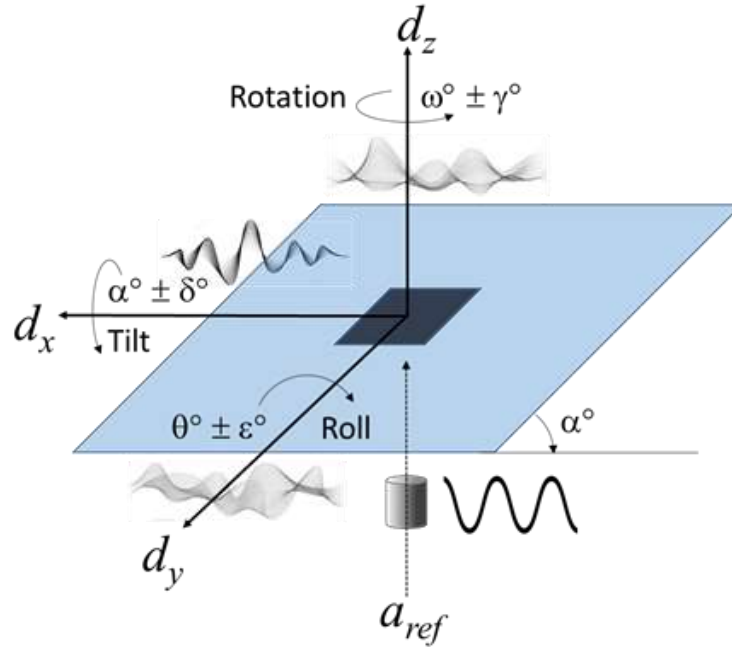
336 The 3-axis digital MEMS accelerometer outputs  $d_i$  (expressed in  $D_{16\text{bit-signed}}$ ), are calculated in matrix form,  
 337 as a linear combination of the acceleration component in  $\text{m s}^{-2}$ , as shown in (4), where the main sensitivities  
 338  $S_{ii}$  and transverse sensitivities  $S_{ij}$  are directly obtained from the elements of the sensitivity matrix  $\mathbf{S}$ :

339

$$[d_x \quad d_y \quad d_z] = [a_x \quad a_y \quad a_z] \cdot \begin{bmatrix} S_{xx} & S_{xy} & S_{xz} \\ S_{yx} & S_{yy} & S_{yz} \\ S_{zx} & S_{zy} & S_{zz} \end{bmatrix} \quad (4)$$

340

341 For each MEMS, sensitivity uncertainty matrix  $\mathbf{U}(\mathbf{S})$  (at a confidence level of 95%) is obtained from the  
 342 covariance matrix of the independent variables by applying the general rule of random error propagation in  
 343 matrix form [28]. Independent variables, are schematically shown in Fig.7.  
 344



345  
 346 **Fig. 7.** Schematic representation of uncertainties in INRIM calibration setup.  
 347

348 Independent variables are represented by the reference acceleration  $a_{ref}$ , tilt angle  $\alpha$ , rotation angle  $\omega$ , roll  
 349 angle  $\theta$ , and by the systematic terms  $a_{x',syst}$ ,  $a_{y',syst}$ ,  $a_{z',syst}$  and  $\varphi_{x',syst}$ ,  $\varphi_{y',syst}$ ,  $\varphi_{z',syst}$  which are the amplitudes and  
 350 the phase differences, with respect to the reference signal  $a_{ref}$ , of the spurious components affecting the accu-  
 351 racy of the MEMS output  $d_x$ ,  $d_y$  and  $d_z$ . Uncertainty contribution  $\varepsilon$  due to the roll angle  $\theta$ , nominally  $0^\circ$ , is  
 352 considered negligible.

353 Standard uncertainty  $u(a_{ref})$  associated to the reference acceleration along the  $z'$ -axis of the excitation sys-  
 354 tem derives from the Calibration and Measurement Capabilities (CMC) declared by INRIM [49], which is  
 355 0.8% in terms of relative expanded uncertainty from 5 Hz to 1 kHz. At 3 Hz, it is increased to 1%. Standard  
 356 uncertainties associated to tilt angle  $u(\alpha)$ , rotation angle  $u(\omega)$ , considered as type B uncertainty contributions  
 357 with half-widths  $\delta=0.1^\circ$ ,  $\gamma=1^\circ$ , respectively, and spurious components,  $u(a_{x',syst})$ ,  $u(a_{y',syst})$ ,  $u(a_{z',syst})$ ,  $u(\varphi_{x',syst})$ ,  
 358  $u(\varphi_{y',syst})$ ,  $u(\varphi_{z',syst})$ , are evaluated according to [28].

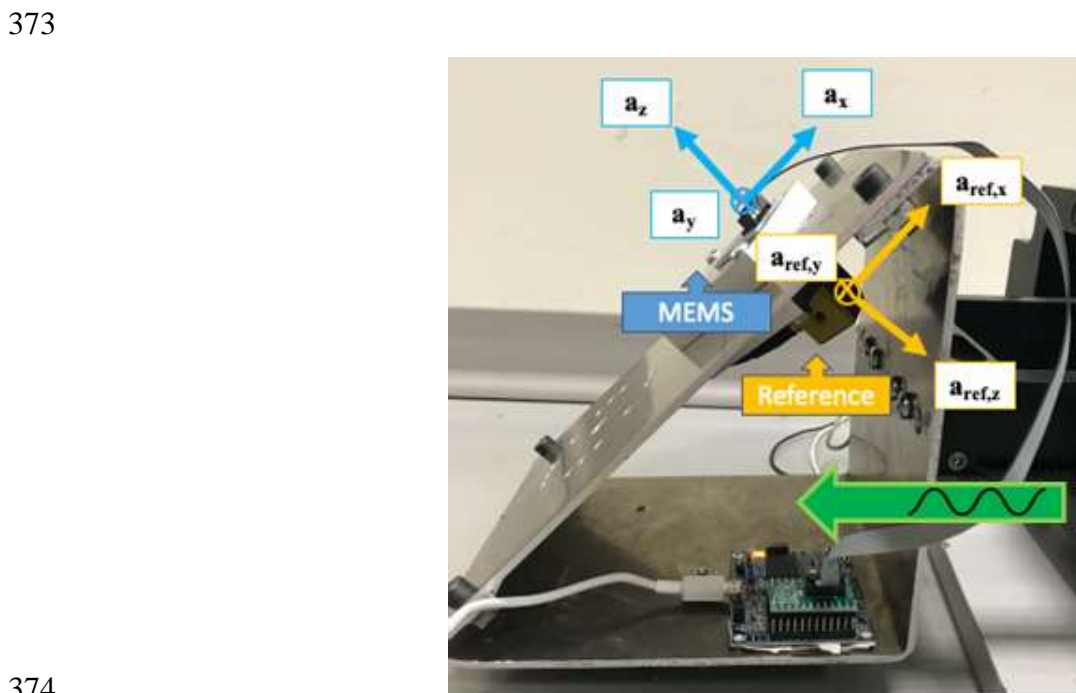
359 By way of example, the detailed uncertainty budget for the  $a_x$  reference acceleration at an inclination of  
 360  $75^\circ$ , a rotation of  $90^\circ$  and a frequency of 6 Hz, is shown in Table I.  
 361  
 362  
 363

364 **Table 1**  
 365 Uncertainty table of reference acceleration along x-axis at an inclination of 75°, a rotation of 0° and a  
 366 frequency of 6 Hz.

Variable $x_k$				$u^2(x_k)$	$c_k$	$u_k^2(a_x)$
Symb.	Value	Unit	Note			
$a_{ref}$	0.707	$\text{ms}^{-2}$	Cmc	8,1E-06	9,7E-01	7,6E-06
$\alpha$	75	°	Acc.	3,3E-03	3,6E-03	4,3E-08
$\omega$	0	°	Acc.	3,3E-01	3,1E-05	3,1E-10
$a_{x',syst}$	0.011	$\text{ms}^{-2}$	Rep.	1,9E-06	-2,6E-01	1,3E-07
$a_{y',syst}$	0.002	$\text{ms}^{-2}$	Rep.	1,9E-06	0,0E+00	0,0E+00
$a_{z',syst}$	0.048	$\text{m s}^{-2}$	Rep.	1,9E-06	9,7E-01	1,8E-06
$\varphi_{x',syst}$	173.04	°	Rep.	4,0E+00	-6,2E-06	1,5E-10
$\varphi_{y',syst}$	-0.77	°	Rep.	4,0E+00	0,0E+00	0,0E+00
$\varphi_{z',syst}$	0.01	°	Rep.	4,0E+00	4,1E-07	6,7E-13
$a_x$	0.727	$\text{m s}^{-2}$	Variance, $u^2(a_x)$		9,5E-06	

367  
 368 **2.3.1 UNIVAQ**

369 The calibration set-up realised at University of L'Aquila, consisting of a single-axis horizontal vibrating  
 370 table on which an aluminium hollow inclined plane with a tilt angle of 45° is screwed, generates a projection  
 371 of the horizontal slide acceleration along three MEMS axes simultaneously (Fig. 8). More details can be found  
 372 in [33].

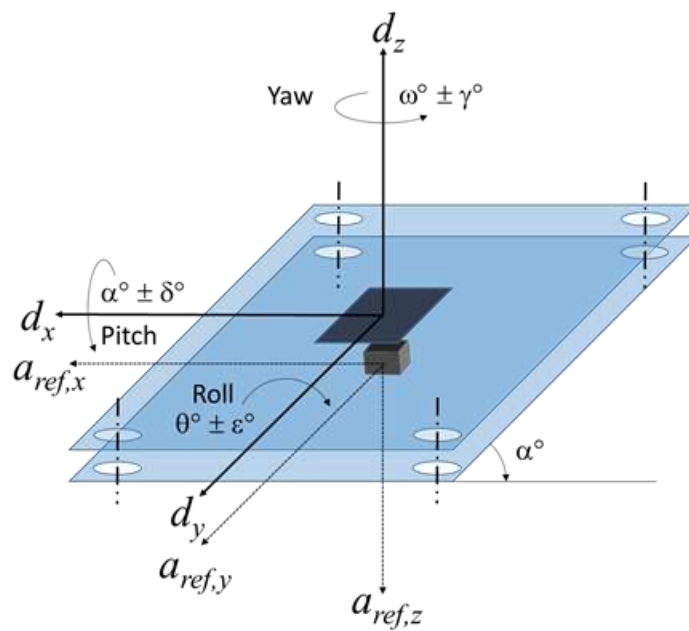


374  
 375 **Fig. 8.** Calibration setup used at UNIVAQ laboratory

376 The reference acceleration  $a_{ref}$ , provided by a tri-axial piezoelectric accelerometer (PCB model  
 377 TLD356B18), and the MEMS accelerometer under test are coaxially installed on the two opposite sides of the  
 378 45° inclined plane surface, so that their axes are aligned. Measurements are performed in three configurations  
 379 by placing the MEMS and the reference accelerometer at three angles of rotation  $\omega$  (0°, 30° and 330°). Single  
 380 sinusoidal signals are generated by a horizontal linear slide (APS 113 ELECTRO-SEIS shaker). Reference  
 381 accelerometer signal is acquired by CompactRio 9040 by National Instruments. MEMS output is acquired by  
 382 the external microcontroller and saved in binary file. Both MEMS and reference acceleration signals are pro-  
 383 cessed by performing an FFT analysis. The amplitudes of the spectrum in the range, centred at the oscillation  
 384 frequency with a width of  $\pm 10\%$ , are added up, in order to prevent eventual variability of sampling frequency  
 385 of the MEMS. Since the axes of the reference tri-axial accelerometer are nominally coaxial with those of the  
 386 MEMS accelerometer under investigation (i.e.,  $a_i = |a_{ref,i}|$ ), the main sensitivities  $S_{ii}$  are obtained by dividing  
 387 the MEMS digital output  $d_i$  values and the measured reference accelerations  $a_{ref,i}$ , as follows:  
 388

$$\begin{cases} S_{xx} = |d_x/a_{ref,x}| \\ S_{yy} = |d_y/a_{ref,y}| \\ S_{zz} = |d_z/a_{ref,z}| \end{cases} \quad (5)$$

389  
 390 By analogy, the values of transverse sensitivities  $S_{ij}$  are calculated as  $S_{ij} = d_i/|a_{ref,j}|$  by generating sinus-  
 391 oidal accelerations along each sensitivity axis and measuring the MEMS response along the other two orthog-  
 392 onal axes, simultaneously. In Fig. 9 a schematic representation of uncertainty due to the independent variables,  
 393 is shown.  
 394



395  
 396 **Fig. 8.** Schematic representation of uncertainties in UNIVAQ calibration setup



397 For each MEMS under investigation, the evaluation of the sensitivity expanded uncertainties  $U(S_{ij})$  (at a  
 398 confidence level of 95%) is carried out by considering the reproducibility standard deviations of the three  
 399 configurations at three different angles of rotation and the uncertainty of the reference accelerometer; the un-  
 400 certainty of the coaxiality, between MEMS axes and reference accelerometer axes, is estimated with a yaw  
 401 angle  $\gamma^\circ = \pm 1^\circ$  on the rotation angle  $\omega$  and a pitch angle  $\delta^\circ = \pm 1^\circ$  on the tilt angle  $\alpha$ , while the uncertainty due to  
 402 the roll angle  $\theta$ , nominally  $0^\circ$ , can be considered negligible. Standard uncertainty  $u(a_{ref})$  of the reference ac-  
 403 celerations, in terms of relative expanded uncertainty, is 2% at 3 Hz and 6 Hz, and 1.5% at 10 Hz according to  
 404 the calibration certificate. By way of example, the detailed uncertainty budget of sensitivity along y-axis of  
 405 MEMS #22 at a rotation angle of  $30^\circ$  and at a frequency of 3 Hz, is shown in Table II

407 **Table 2**

408 Uncertainty table of MEMS #22 sensitivity along Y-axis at a rotation angle of  $30^\circ$  and at a fre-  
 409 quency of 3 Hz.

Variable $x_k$				$u^2(x_k)$	$c_k$	$u_k^2(S_y)$
Symb.	Value	Unit	Note			
$a_{ref,y}$	0,50	ms <sup>-2</sup>	Cert.	2,5E-03	-3,3E+02	2,8E+02
$\omega$	45	°	Acc.	3,3E-01	-5,0E+01	8,4E+02
$\alpha$	30	°	Acc.	3,3E-01	-2,9E+01	2,8E+02
Repr.				2,1E+03	1,0E+00	2,1E+03
$S_{yy}$	1657	$D_{16bit}/(m/s^2)$	Variance, $u^2(S_y)$			3,5E+03

410

411 **3. Experimental results**

412 Experimental results of the 25 MEMS accelerometers from the two laboratories, at 3 Hz, 6 Hz and 10 Hz,  
 413 in terms of main sensitivities values along x-, y- and z-axis, and related expanded uncertainties (at a confidence  
 414 level of 95%), expressed in  $D_{16-bit-signed}/(m/s^2)$ , are collected in Tables 3 and 4 (with mean values  $m$ , standard  
 415 deviation  $s$ , and maximum value  $M$ ) and summarized in Figs. 10 and 11.

416 In general, from a first qualitative point of view, both laboratories show quite uniform main sensitivity  
 417 values among the 25 MEMS at the different frequencies under investigation, and are close to manufacturer  
 418 sensitivity of  $1671 D_{16-bit-signed}/(m/s^2)$ , which is nominally referred to all sensitivity axes and for all frequencies  
 419 without the associated uncertainty. Expanded uncertainties at INRiM are in the order of 2% -4%, while at and  
 420 UNIVAQ are in the order of 2% -6% with  $S_{yy}$  showing higher uncertainty values due to higher reproducibility  
 421 standard deviations among the configurations. In both laboratories, uncertainties associated to  $S_{zz}$  are lower  
 422 than the opposite axes due to the lower number of independent variables involved. It is also worth noting that

423 standard deviations between the 25 MEMS sensitivity values (as average, around 13  $D_{16\text{-bit-signed}}/(\text{m s}^{-2})$ ) are  
 424 lower than the calibration standard uncertainties (as average, around 35  $D_{16\text{-bit-signed}}/(\text{m s}^{-2})$ ).

425

426 **Table 3**

427 Main sensitivities with expanded uncertainties ( $k=2$ ) of the 25 MEMS at INRIM. Values are ex-  
 428 pressed in  $D_{16\text{-bit-signed}}/(\text{m s}^{-2})$ .

#	3 Hz			6 Hz			10 Hz		
	$S_{xx}$	$S_{yy}$	$S_{zz}$	$S_{xx}$	$S_{yy}$	$S_{zz}$	$S_{xx}$	$S_{yy}$	$S_{zz}$
1	1658±56	1667±59	1691±37	1649±57	1657±59	1665±36	1653±57	1649±58	1678±37
2	1666±58	1653±57	1666±36	1650±58	1628±57	1650±36	1643±58	1628±57	1644±36
3	1691±59	1651±59	1687±37	1635±57	1653±59	1650±36	1663±57	1641±58	1660±36
4	1691±59	1693±59	1683±37	1630±57	1639±57	1648±36	1637±57	1642±57	1668±36
5	1672±58	1668±58	1680±37	1665±58	1628±57	1653±36	1664±58	1649±59	1658±36
6	1673±59	1700±61	1675±36	1647±58	1653±59	1643±36	1637±58	1641±59	1654±36
7	1660±58	1666±60	1669±36	1628±57	1647±59	1651±36	1639±57	1654±59	1661±36
8	1645±56	1683±60	1675±36	1625±57	1634±59	1652±36	1650±58	1653±59	1655±36
9	1665±58	1670±59	1693±37	1616±57	1639±58	1680±37	1647±58	1625±59	1666±36
10	1688±59	1667±59	1693±37	1626±57	1653±59	1675±36	1645±57	1644±59	1674±36
11	1685±58	1663±59	1672±36	1661±58	1634±58	1655±36	1639±57	1622±57	1647±36
12	1681±59	1670±59	1679±37	1656±59	1616±58	1669±36	1656±58	1634±59	1663±36
13	1672±58	1659±59	1694±37	1644±58	1630±58	1674±36	1633±57	1633±59	1670±36
14	1692±60	1697±60	1698±37	1670±59	1664±59	1648±36	1675±59	1637±59	1668±36
15	1685±59	1685±60	1682±37	1647±58	1652±59	1667±36	1636±57	1636±59	1655±36
16	1695±60	1680±60	1691±37	1661±59	1644±58	1660±36	1656±58	1635±59	1656±36
17	1686±59	1659±56	1685±37	1659±58	1640±56	1638±36	1642±57	1630±55	1651±36
18	1669±58	1669±59	1687±37	1635±58	1664±59	1677±37	1644±58	1647±59	1672±36
19	1678±58	1676±60	1708±37	1676±58	1657±59	1678±37	1650±57	1655±59	1674±37
20	1672±59	1666±59	1689±37	1666±59	1621±58	1669±36	1654±58	1640±59	1672±36
21	1666±59	1667±59	1695±37	1661±59	1667±59	1640±36	1659±59	1651±59	1656±36
22	1679±60	1673±60	1683±37	1622±58	1626±58	1640±36	1653±58	1649±59	1657±36
23	1680±59	1692±60	1699±37	1654±58	1632±58	1667±36	1658±58	1660±59	1677±37
24	1690±59	1670±59	1680±37	1648±58	1666±59	1635±36	1642±57	1641±59	1657±36
25	1657±57	1680±58	1684±37	1652±58	1641±57	1649±36	1617±56	1633±56	1670±36
<i>m</i>	1676	1673	1686	1647	1643	1657	1648	1641	1663
<i>s</i>	13	13	10	16	15	14	12	10	9
<i>M</i>	60	61	37	59	59	37	59	59	37

429

430

**Table 4**

431

Main sensitivities with expanded uncertainties ( $k=2$ ) of the 25 MEMS at UNIVAQ. Values are

432

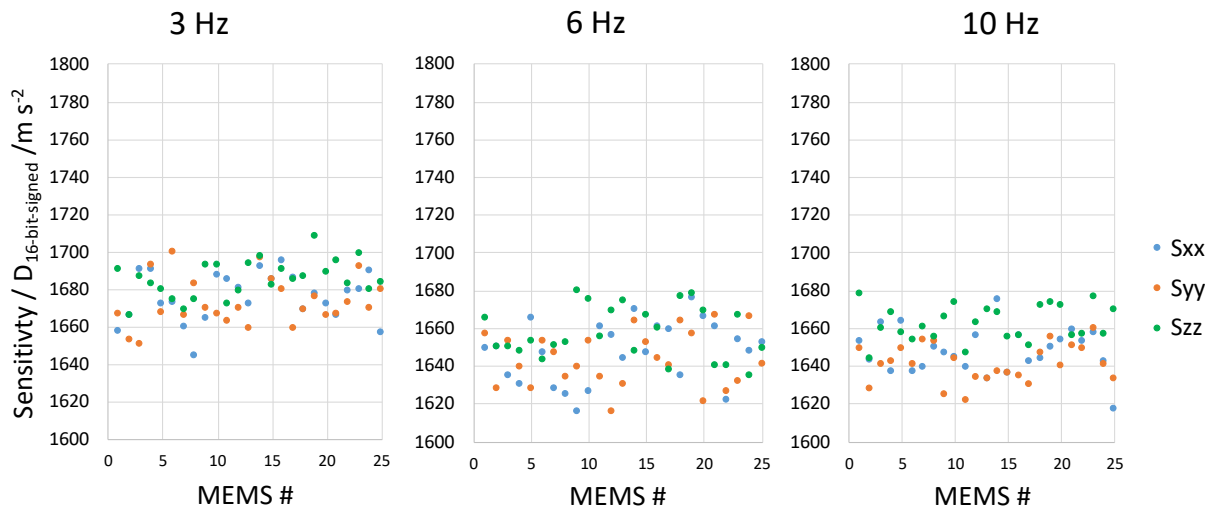
expressed in  $D_{16\text{-bit-signed}}/(m s^{-2})$ .

#	3 Hz			6 Hz			10 Hz		
	$S_{xx}$	$S_{yy}$	$S_{zz}$	$S_{xx}$	$S_{yy}$	$S_{zz}$	$S_{xx}$	$S_{yy}$	$S_{zz}$
1	1693±65	1701±80	1732±45	1668±65	1681±79	1708±44	1646±62	1660±76	1692±37
2	1692±50	1715±102	1697±44	1675±50	1700±102	1681±43	1680±45	1706±100	1690±37
3	1698±49	1711±74	1703±44	1671±49	1685±72	1680±43	1661±45	1677±69	1671±37
4	1692±50	1721±77	1713±44	1678±48	1705±76	1700±44	1659±43	1683±72	1683±37
5	1711±47	1724±67	1712±45	1679±48	1695±66	1682±43	1672±44	1689±62	1677±37
6	1694±49	1710±89	1705±43	1681±51	1701±90	1692±43	1676±45	1695±88	1691±36
7	1694±60	1724±126	1715±46	1679±58	1709±126	1702±44	1673±54	1702±126	1698±38
8	1698±52	1728±101	1712±44	1670±51	1702±99	1687±43	1654±45	1686±97	1673±37
9	1691±52	1704±101	1709±44	1677±52	1692±102	1697±44	1671±47	1683±100	1694±37
10	1692±51	1708±101	1717±44	1666±51	1681±98	1694±44	1654±45	1667±96	1684±37
11	1692±51	1705±87	1706±44	1664±50	1681±88	1680±43	1655±46	1672±85	1673±37
12	1688±52	1713±76	1698±44	1674±49	1702±76	1688±43	1673±46	1698±73	1690±37
13	1688±50	1719±103	1730±45	1661±50	1693±101	1704±44	1647±47	1679±97	1692±38
14	1690±58	1752±120	1704±44	1679±54	1741±122	1694±44	1668±51	1727±115	1686±37
15	1686±51	1729±112	1705±44	1663±51	1709±110	1685±43	1671±48	1717±108	1695±37
16	1717±51	1692±82	1707±45	1693±51	1670±81	1686±44	1688±47	1668±80	1682±37
17	1708±53	1720±101	1715±44	1681±52	1697±97	1689±43	1671±47	1686±95	1685±37
18	1710±53	1717±101	1717±45	1676±52	1688±97	1686±43	1669±47	1684±94	1682±37
19	1704±51	1728±97	1721±46	1689±50	1714±97	1707±42	1684±45	1710±94	1705±38
20	1705±49	1713±73	1713±44	1688±47	1699±74	1699±44	1672±42	1683±69	1685±37
21	1703±51	1739±98	1710±44	1688±49	1724±99	1697±44	1669±44	1704±98	1680±38
22	1687±49	1726±98	1707±45	1662±50	1704±98	1685±43	1667±44	1708±96	1692±37
23	1717±48	1648±86	1710±45	1694±49	1739±90	1679±43	1688±45	1735±87	1677±37
24	1697±47	1761±94	1691±45	1677±48	1737±94	1671±45	1680±44	1735±97	1676±39
25	1696±55	1712±114	1714±45	1676±54	1694±114	1696±44	1676±48	1693±115	1698±38
<i>m</i>	1698	1717	1711	1676	1702	1691	1669	1694	1686
<i>s</i>	9	21	9	9	18	10	11	20	9
<i>M</i>	65	126	46	65	126	45	62	126	39

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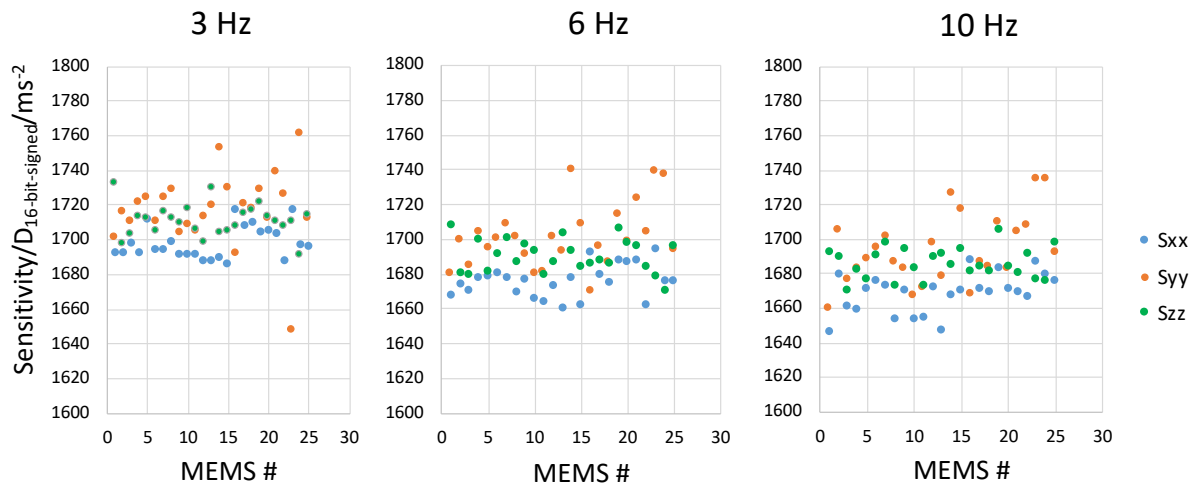


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**Fig. 10.** Main sensitivities of the 25 MEMS at 3 Hz, 6 Hz and 10 Hz evaluated at INRIM.



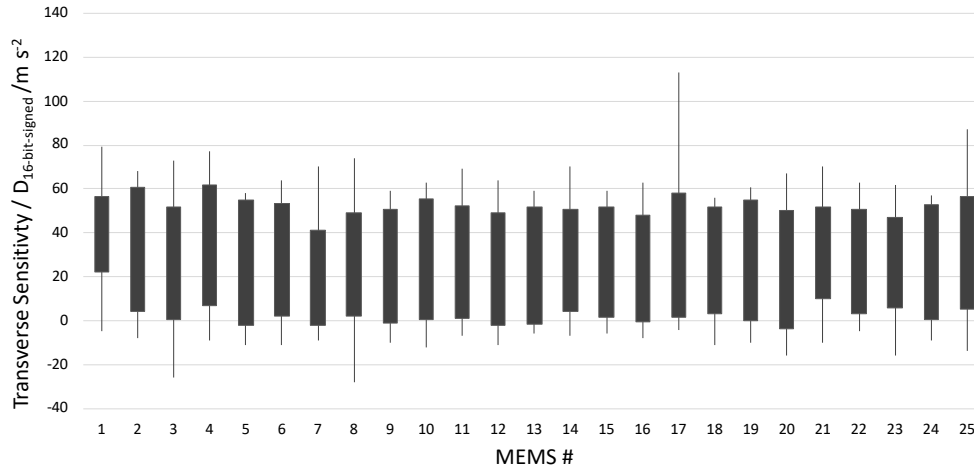
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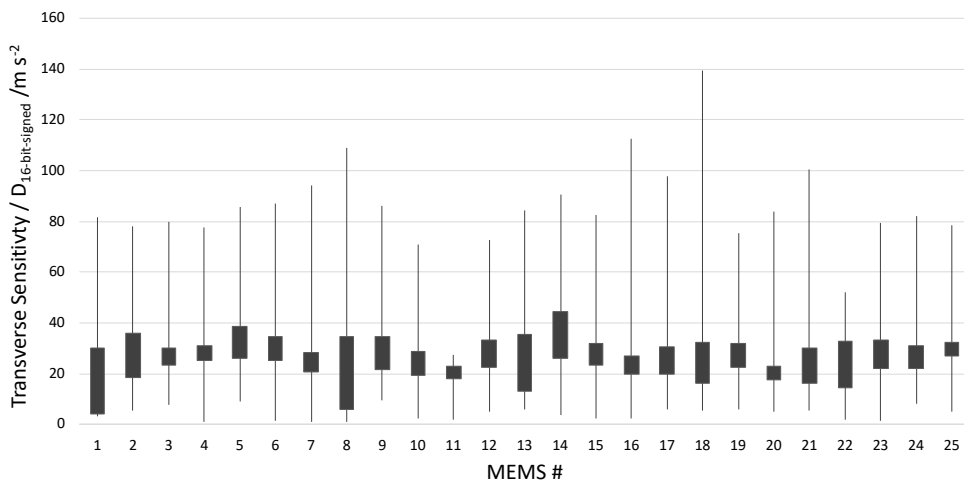
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**Fig. 11.** Main sensitivities of the 25 MEMS at 3 Hz, 6 Hz and 10 Hz evaluated at UNIVAQ.

442 Transverse sensitivities of the 25 MEMS evaluated by the two laboratories are in the order of 1% -3% and  
 443 are depicted in Figs. 12 and 13 as boxplots. It is worth noting that transverse sensitivities evaluated by INRIM  
 444 in matrix form, also defined as cross-sensitivities, are part of the sensitivity of the sensor as they are used in  
 445 the exploitation equations [28], therefore values can be positive or negative.



**Fig. 12.** Transverse sensitivity ranges of the 25 MEMS at 3 Hz, 6 Hz and 10 Hz evaluated at INRiM.



**Fig. 13.** Transverse sensitivity ranges of the 25 MEMS at 3 Hz, 6 Hz and 10 Hz evaluated at UNIVAQ.

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An analysis based on the estimation of the normalized error ( $E_n$ ), according to ISO/IEC 17043:2010 [51], is performed in order to assess the compatibility of the 25 MEMS sensitivity values, obtained from the two laboratories, for each axis and frequency under investigation. The data can be considered compatible when  $E_n \leq 1$ . Results, reported in Table 5, are compatible, although different mechanical excitation systems are used and different data analysis are adopted for the simultaneous determination of the sensitivities along the three axes. This result confirms the compatibility and the reproducibility of the two independent calibration systems for MEMS accelerometers within the metrological traceability chain.

464

**Table 5**

465

Normalized errors between INRIM and UNIVAQ

#	3 Hz			6 Hz			10 Hz		
	$E_n(S_{xx})$	$E_n(S_{yy})$	$E_n(S_{zz})$	$E_n(S_{xx})$	$E_n(S_{yy})$	$E_n(S_{zz})$	$E_n(S_{xx})$	$E_n(S_{yy})$	$E_n(S_{zz})$
1	0.40	0.34	0.71	0.22	0.24	0.76	0.08	0.12	0.28
2	0.34	0.53	0.55	0.33	0.62	0.56	0.50	0.67	0.90
3	0.09	0.63	0.27	0.48	0.35	0.53	0.03	0.40	0.21
4	0.02	0.29	0.52	0.65	0.69	0.92	0.31	0.45	0.29
5	0.53	0.63	0.55	0.18	0.77	0.52	0.11	0.47	0.37
6	0.28	0.09	0.53	0.44	0.45	0.88	0.53	0.52	0.72
7	0.41	0.42	0.79	0.62	0.44	0.89	0.44	0.35	0.72
8	0.70	0.39	0.65	0.59	0.59	0.63	0.05	0.29	0.35
9	0.33	0.29	0.28	0.80	0.45	0.30	0.32	0.50	0.55
10	0.05	0.35	0.42	0.52	0.24	0.34	0.13	0.21	0.19
11	0.09	0.40	0.59	0.04	0.45	0.44	0.22	0.49	0.51
12	0.09	0.44	0.33	0.24	0.90	0.33	0.23	0.68	0.52
13	0.21	0.51	0.62	0.22	0.54	0.54	0.19	0.40	0.42
14	0.03	0.41	0.11	0.11	0.57	0.81	0.10	0.70	0.34
15	0.01	0.35	0.40	0.21	0.46	0.32	0.46	0.66	0.78
16	0.28	0.12	0.28	0.41	0.26	0.46	0.43	0.34	0.50
17	0.28	0.53	0.52	0.28	0.51	0.91	0.40	0.51	0.66
18	0.52	0.41	0.51	0.52	0.21	0.16	0.34	0.34	0.20
19	0.34	0.46	0.22	0.16	0.51	0.52	0.46	0.50	0.59
20	0.43	0.50	0.41	0.29	0.83	0.52	0.25	0.48	0.25
21	0.48	0.63	0.26	0.36	0.49	1.00	0.14	0.47	0.47
22	0.11	0.46	0.41	0.53	0.69	0.80	0.19	0.53	0.68
23	0.49	0.42	0.19	0.53	1.00	0.21	0.40	0.71	0.00
24	0.09	0.82	0.18	0.38	0.64	0.63	0.53	0.83	0.35
25	0.49	0.25	0.52	0.31	0.42	0.83	0.80	0.47	0.54

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467 **4. Discussion**

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As stated in Section II, even a small sensor network implies a large number of sensitivity data to be managed by end-users. By way of example, in this case, the sensitivity related to the sensor network, consisting of these 25 MEMS, entails a number of data from 225 (25 MEMS  $\times$  3 frequencies  $\times$  3 main sensitivity axes) up to 675 (if transverse sensitivities are also considered). Therefore, considering INRIM data as reference (Table 3), the

472 possibility of decreasing the number of sensitivities related to the sensor network is investigated. The idea is  
 473 to perform different types of averages from the 225 main sensitivity data, in order to provide a lower number  
 474 of sensor network sensitivities. Averages are performed in order that sensitivities are independent of MEMS,  
 475 frequency or axis, or combination of these factors, up to the limit case of a single sensitivity value attributed  
 476 to the whole sensor network independent from the three examined factors, the so-called ensemble sensitivity.  
 477 In this way, the number of data to be managed is reduced, at the expense of an introduction of larger uncer-  
 478 tainties and a loss of information about the influence of the investigated factors, but that can be accepted in  
 479 several practical conditions and in this particular case of structural and infrastructures health monitoring and  
 480 seismic safety networks at urban/building scale [52-54].

481 Mean sensitivities associated to the different combinations of these factors can be summarized in the fol-  
 482 lowing paragraphs. It is worth reminding that the sensitivity value declared by the manufacturer is 1671 D<sub>16-bit</sub>-  
 483 signed /m s<sup>-2</sup> and is reported in the following figures, as a continuous black line, for comparisons. For each case,  
 484 uncertainties, in terms of expanded uncertainties *U* at a confidence level of 95%, are evaluated by performing  
 485 the root sum squared of the maximum calibration uncertainty among the averaged data and the standard devi-  
 486 ation of the averaged data. As a consequence, in this case, relative expanded uncertainties increase at increasing  
 487 number of averaged data. However, in general, the data-set of sensitivity values, averaged as a function of  
 488 MEMS, frequency or axes, show good compatibility, both in terms of mean values and associated expanded  
 489 uncertainties, beyond to be consistent with the nominal sensitivity provided by the manufacturer.

490 However, preliminarily, an analysis of variance of the three factors (MEMS, axis and frequency) is per-  
 491 formed in order to identify the main influencing effects on sensitivity. As a matter of fact, depending on the  
 492 application, it can be useful to have a better resolution of vibration measurements as a function of frequency  
 493 or direction of propagation. Results of analysis of variance, with sum of squares (SS), degree of freedom (DF)  
 494 and Fisher's-Test *F* value, are reported in Table 6.

496 **Table 6**  
 497 Analysis of variance of sensitivity data

<i>Factor</i>	<i>SS</i>	<i>DF</i>	<i>F</i>	
MEMS	23771.01	24	0.8	
Freq.	119480.19	2	49.7	*
Axis	30480.99	2	12.7	*
MEMS × Freq.	17267.15	48	0.3	
MEMS × Axis	32680.35	48	0.6	
Freq. × Axis	1715.73	4	0.4	
MEMS × Freq. × Axis	30472.93	96	0.3	

498  
 499 Significant values at 95% confidence level are marked with \* symbol. It is found that frequency and axis  
 500 have a statistically significant effect on the sensitivity, whereas no influence due to the different MEMS sensors  
 501 or due to interactions among the three factors is found. This is confirmed by the fact that, as average, standard

502 deviations of frequency and axis dependent sensitivities among all 25 MEMS are lower than MEMS dependent  
 503 sensitivities, as shown as follows.

504

505 *4.1 Ensemble sensor network sensitivity*

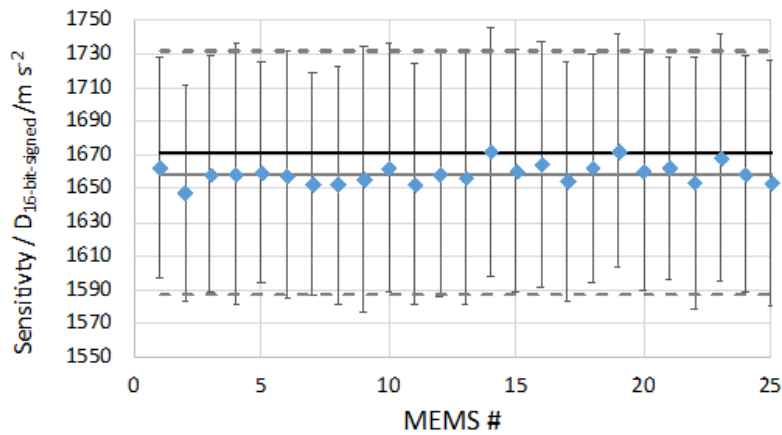
506 The limit case of this approach is the evaluation of one single sensitivity to be attributed to the whole sensor  
 507 network by calculating the mean value between sensitivity values of all MEMS axes and frequencies. In this  
 508 way, an «ensemble» sensitivity of  $1659 \pm 72 \text{ D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  is obtained and is reported in the following fig-  
 509 ures as grey lines (continuous line represents the mean value. dotted lines represent lower and upper limits). It  
 510 should be noted that  $72 \text{ D}_{16\text{-bit-signed}} = 4.3 \cdot 10^{-2} \text{ m s}^{-2}$ , in the MEMS configuration used in the investigation. It  
 511 follows that, by using the ensemble sensitivity, the associated expanded uncertainty is around 4.5%.

512

513 *4.2 MEMS dependent sensor network sensitivity*

514 By averaging sensitivities of each single MEMS for all axes and frequencies, values reported in Fig. 14 are  
 515 obtained. Given the similar sensitivity, due to the observed good compatibility among the 25 MEMS, mean  
 516 values are close to the ensemble sensitivity of all 25 MEMS and it can be reasonably attributed to each single  
 517 MEMS independently if specific frequency and axis information is not necessary. Associated relative ex-  
 518 panded uncertainties are around 4.3%.

519



520

521 **Fig. 14.** Sensitivities of the 25 MEMS averaged for all frequencies and axes. Black line corresponds to  
 522 the sensitivity declared by the manufacturer. Grey lines correspond to the ensemble sensitivity with lower  
 523 and upper limits.

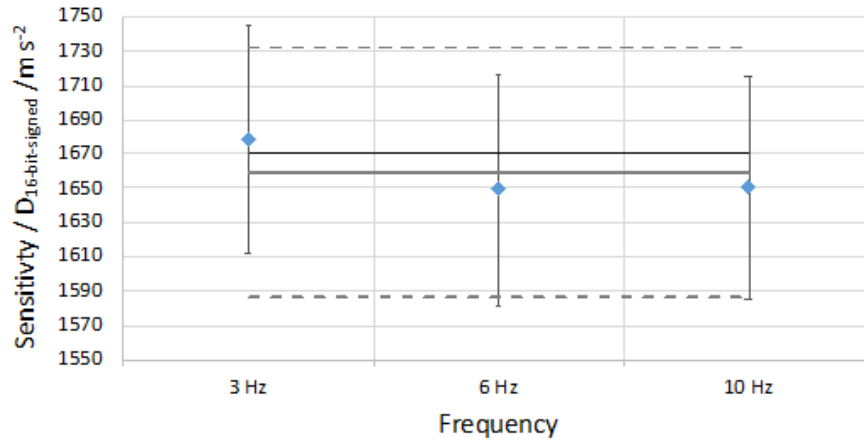
524

525 *4.3 Frequency dependent sensor network sensitivity*

526 By averaging the sensitivity values of the 25 MEMS as a function of frequency, the related sensitivity of  
 527 the network is more trustworthy and accurate for frequency analysis of occurring vibration phenomena. In this  
 528 case study the sensitivity is  $1678 \pm 66 \text{ D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  at 3 Hz,  $1649 \pm 67 \text{ D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  at 6 Hz and  $1650 \pm 65$   
 529  $\text{D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  at 10 Hz, and relative expanded uncertainties are around 4%.



530 In the graph of Fig. 15, the values of frequency dependent sensitivities are shown, with respect to the nom-  
 531 inal sensitivity and within the ensemble sensitivity lower and upper limits.  
 532

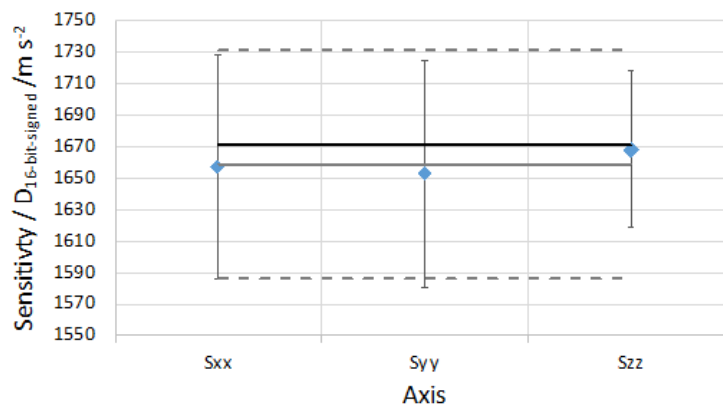


533  
 534 **Fig. 15.** Frequency dependent network sensitivity. Black line corresponds to the sensitivity declared by  
 535 the manufacturer. Grey lines correspond to the ensemble sensitivity with lower and upper limits.  
 536

537 *4.4 Axis dependent sensor network sensitivity*

538 By averaging the sensitivity values of the 25 MEMS as a function of axis, the sensitivity of the network  
 539 allows to define the direction of vibration propagation with a better resolution, with respect to frequency.

540 In this case study the sensitivity is  $1657 \pm 71 \text{ D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  for  $x$ -axis.  $1653 \pm 72 \text{ D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  for  $y$ -  
 541 axis and  $1668 \pm 50 \text{ D}_{16\text{-bit-signed}}/(\text{m/s}^2)$  for  $z$ -axis. Relative expanded uncertainties are around 3% -4%. In the graph  
 542 of Fig. 16, the values of axis dependent sensitivities are shown, with respect to the nominal sensitivity and  
 543 within the ensemble sensitivity lower and upper limits.  
 544

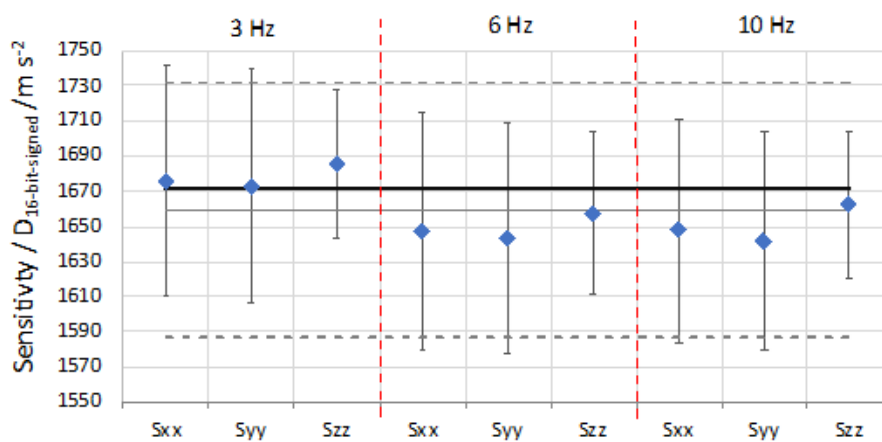


545  
 546 **Fig. 16.** Axis dependent network sensitivity. Black line corresponds to the sensitivity declared by the  
 547 manufacturer. Grey lines correspond to the ensemble sensitivity with lower and upper limits.  
 548  
 549

## 550 4.5 Frequency and axis dependent sensor network sensitivity

551 An optimized compromise, in order to evaluate with a suitable trustworthiness both frequency response and  
 552 direction of propagation of the vibration phenomena at the same time, by managing only 9 values of sensitivity  
 553 data. can be achieved by defining the network sensitivity as a function of averaged frequency sensitivities and  
 554 averaged axes sensitivities, as shown in the graph of Fig. 17. In this case study, the sensitivities in  $D_{16\text{-bit-}}$   
 555  $\text{signed}/(\text{m/s}^2)$  at 3 Hz, along  $x$ -,  $y$ - and  $z$ -axis, are, respectively,  $1676\pm65$ ,  $1673\pm66$  and  $1686\pm42$ ; at 6 Hz, are  
 556  $1647\pm67$ ,  $1643\pm66$  and  $1657\pm46$ ; and, at 10 Hz, are  $1648\pm64$ ,  $1641\pm62$  and  $1663\pm42$ . Relative expanded un-  
 557 certainties are between 2% and 4%.

558



559

560 **Fig. 17.** Sensitivities of the 25 MEMS averaged for all frequencies and axes. Black line corresponds to  
 561 the sensitivity declared by the manufacturer. Grey lines correspond to the ensemble sensitivity with lower  
 562 and upper limits.

563

## 564 5. Conclusions

565 The increasingly widespread use of digital sensor networks. in many applications, including very sensitive  
 566 ones (such as structural health monitoring), raises some important questions about the actual trustworthiness  
 567 and accuracy of the data collected, in particular if neither standard calibration procedures nor traceable proto-  
 568 cols are available for these sensors and for the interconnected network as a whole. In the field of metrology  
 569 and measurement science, this fundamental topic begins to be investigated, with the aim of including these  
 570 sensing infrastructures within the traceability chain, in analogy to traditional measuring instruments, therefore  
 571 identifying their accuracy and trustworthiness, from adequate calibration systems and procedures, and sup-  
 572 porting their compatibility and reproducibility, based on comparisons. In addition, the new developed proce-  
 573 dures will have also to take into account both the low cost of the sensors and the huge quantity of MEMS  
 574 produced, and they will have therefore to be adequately proportioned in such context.

575 In this work, the possibility of providing traceability, in terms of magnitude sensitivity, to digital MEMS  
576 accelerometers is investigated, on the basis of a rigorous metrological approach. The main purpose is to identify  
577 the problems inherent in calibration and to provide the relative possible solutions. Experimental data of  
578 the calibration of 25 MEMS accelerometers at 3 Hz, 6 Hz and 10 Hz, at nearly constant amplitude of  $1 \text{ m}\cdot\text{s}^{-2}$ ,  
579 from two laboratories (NMI and University) are shown and compared. The resulting comparison gives useful  
580 information with reference to a possible procedure for calibration of MEMS tri-axis accelerometers. Different  
581 calibration methods are used, in terms of test benches, data processing techniques and reference standards,  
582 allowing to identify pros and cons of the specific approach. An analysis based on the estimation of the normalized  
583 error ( $E_n$ ), according to ISO/IEC 17043:2010 shows compatible results at uncertainty levels between 2% -  
584 6%. This comparison allows to point out the aspects to be optimized into the procedure, concerning the management  
585 of the geometrical parameters of the devices used for calibration and the dynamic effects of test  
586 benches at low frequencies, to improve, in the future, calibration accuracy and further decrease the associated  
587 uncertainties.

588 Once the traceability of digital MEMS accelerometers is provided and the proper sensitivity (within the  
589 related uncertainty budget) is identified, a procedure to provide a suitable sensitivity to the sensor network as  
590 a whole is proposed, in order to decrease the number of sensitivity values to be managed by end-users. Different  
591 types of averages from the 225 main sensitivity data, in order that sensitivities are independent of MEMS,  
592 frequency or axis, or combination of these factors, up to the limit case of a single sensitivity value attributed  
593 to the whole sensor network, are proposed.

594 It is shown that, if a single value of sensitivity is used, independently on MEMS, axis and frequency of  
595 vibration, the associated uncertainty to this ensemble sensitivity is within 4.5%. Furthermore, the nominal  
596 value of sensitivity provided by the manufacturer is consistent with the obtained results, if this level of uncertainty  
597 is considered. Similar sensitivities appear among all the MEMS, if the same axes and frequencies are  
598 considered, while an increasing effect is acknowledged depending on the axis of vibration and on the vibration  
599 frequency, having the most relevant effects. An optimized compromise, in order to evaluate with a suitable  
600 trustworthiness both frequency response and direction of propagation of the vibration phenomena at the same  
601 time, by managing only 9 values of sensitivity data, instead of 225 single sensitivity values, can be achieved  
602 by defining the network sensitivity as a function of averaged frequency sensitivities and averaged axes sensitivities.  
603

604 As a final remark, this work demonstrates the need of evaluating performances of MEMS as a single sensor  
605 or as a network, by a calibration procedure which takes into account carefully the main interfering aspects, in  
606 order to provide trustworthy and traceable data, within suitable coverage factors and uncertainties budgets,  
607 tailored to the actual needs of specific applications and employments.

608 Future work will be aimed at realizing a suitable calibration procedure for networks of digital MEMS accelerometers  
609 in terms of phase shift sensitivity, at evaluating the effects related to the different sampling rates

610 among MEMS sensors for dynamic applications, and finally at validating this MEMS accelerometers network  
611 in *in-field* applications.

612

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