AIP Applied Physics Letters

Towards direct realisation of the SI unit of sound pressure in the audible hearing range based on optical free-field acoustic particle measurements

Triantafillos Koukoulas and Ben Piper

Citation: Applied Physics Letters **106**, 164101 (2015); doi: 10.1063/1.4918786
View online: http://dx.doi.org/10.1063/1.4918786
View Table of Contents: http://scitation.aip.org/content/aip/journal/apl/106/16?ver=pdfcov
Published by the AIP Publishing

APPLIED PHYSICS LETTERS **106**, 164101 (2015)

Towards direct realisation of the SI unit of sound pressure in the audible hearing range based on optical free-field acoustic particle measurements

Triantafillos Koukoulas[a)] and Ben Piper
Acoustics Group, National Physical Laboratory, Hampton Road, Teddington, Middlesex TW11 0LW, United Kingdom

(Received 17 March 2015; accepted 10 April 2015; published online 20 April 2015)

Since the introduction of the International System of Units (the SI system) in 1960, weights, measures, standardised approaches, procedures, and protocols have been introduced, adapted, and extensively used. A major international effort and activity concentrate on the definition and traceability of the seven base SI units in terms of fundamental constants, and consequently those units that are derived from the base units. In airborne acoustical metrology and for the audible range of frequencies up to 20 kHz, the SI unit of sound pressure, the pascal, is realised *indirectly* and without any knowledge or measurement of the sound field. Though the principle of reciprocity was originally formulated by Lord Rayleigh nearly two centuries ago, it was devised in the 1940s and eventually became a calibration standard in the 1960s; however, it can only accommodate a limited number of acoustic sensors of specific types and dimensions. International standards determine the device sensitivity either through coupler or through free-field reciprocity but rely on the continuous availability of specific acoustical artefacts. Here, we show an optical method based on gated photon correlation spectroscopy that can measure sound pressures directly and absolutely in fully anechoic conditions, remotely, and without disturbing the propagating sound field. It neither relies on the availability or performance of any measurement artefact nor makes any assumptions of the device geometry and sound field characteristics. Most importantly, the required units of sound pressure and microphone sensitivity may now be experimentally realised, thus providing *direct* traceability to SI base units. [http://dx.doi.org/10.1063/1.4918786]

Rayleigh's Theory of Sound[1] is widely acclaimed to be one of the most significant scientific pieces of work in physics, published nearly 150 years ago. Of particular significance are the mathematical foundations of the reciprocity principle; in acoustical metrology, this principle has provided the means for the most accurate calibration method for condenser microphones and thus represents the cornerstone in this particular branch of metrology.[2,3] The main objective of a microphone calibration is to obtain its sensitivity over a certain frequency range. However, for reciprocity to be realised, a set of three transducers are required rather than just the device under investigation and also it is applicable only to specific dimensional types of microphones, which also need to be condenser based to satisfy the reciprocity requirement. Most crucially, the third drawback relates to the unit of the sensitivity itself which is V Pa^{-1}. During a typical calibration, the volt is realised and experimentally traced by the measured electrical response of the device under test; the pascal, however, is realised indirectly through the calculation of the acoustical transfer impedance and from characteristics such as temperature, humidity, speed of sound, dimensions of coupler, and front volumes, thus calculating the pressure present. In other words, throughout the history of airborne acoustical metrology, the Systeme International (SI) unit of sound pressure has yet to be experimentally realised in an absolute and direct manner.

Yeh and Cummins pioneering work[5] on the measurement of particle velocities in flows based on the Doppler effect in the 1960s opened up exciting possibilities and laid down the foundations of the scientific field of optical measurements in fluid dynamics. Nearly 10 years later, Taylor[6] realised that this is perhaps the way of directly and absolutely measuring particle velocities and hence pressures for the ranges and environmental conditions applicable to airborne acoustics. However, the two major drawbacks were the fact that measurements took place inside a standing wave tube and also seeding particles had to be introduced into the air flow in order to increase the photon scatter. The benefits of using a standing wave tube were that the optical system could probe and measure the acoustic particle velocity at a specific point in space (i.e., velocity anti-node of the excited air column) and that the mean flow would be sufficiently smaller than the acoustic oscillation. However, this arrangement (i.e., a small enclosed space in the shape of a tube) in conjunction with the need for a substantial number of seeding particles produced significant challenges as to how to realise the acoustic pressure in unseeded (or similar particle densities to) air and subsequently calibrate an acoustic device.

In the ensuing 10 yr after Taylor's work, research concentrated on homodyne photon correlation spectroscopy[7,8] in parallel to heterodyne Doppler based techniques and analysis. In this case, rather than measuring the particle velocity through the Doppler shift, captured photon sequences were auto-correlated and subsequent mathematical analysis[9] yielded the particle velocity directly. The benefit of this approach was that the signal could be gated and locked at the maximum acoustic amplitude which in turn gave the possibility to remove the need of the standing wave tube and hence performs the measurements in open conditions. However, the major drawback was the necessity of keeping

a)triantafillos.koukoulas@npl.co.uk

all the optical and acoustical components at very close proximity with each other in order to avoid the need of artificial seeding and to increase the efficiency of the photon capturing collection optical part. In this arrangement though, significant acoustic reflections due to all the experimental components present would mean that the measured pressures would not be representative of anechoic (i.e., free-field) conditions. In addition to photon correlation spectroscopy,[10–12] other techniques such as particle image velocimetry,[13–15] laser Doppler anemometry,[16–18] and laser Doppler velocimetry[19–21] were also investigated. In addition to various techniques investigated, research also concentrated on the decoupling of the mean (also called streaming) and acoustic particle velocities.[22–24] During the course of time and despite all the research, the main obstacles remained the need for standing wave tubes and significant artificial airborne seeding, the very limited frequency range of operation and the decoupling of acoustic particle velocity from the mean flow in order to move to fully anechoic conditions. Subsequent calibrations of micromachined[25] and standard microphones[12,26] were reported reliably increasing the frequency limit up to 4 kHz in acoustic tubes. Research also focused on the optimisation of the optical configuration sensitivity to accommodate very low levels of seeding particles[27] and this resulted in artificial particle concentrations very similar to those found in ambient conditions.

Since Taylor's original work back in the 70s in the optical measurement of pressure and the work of researchers over the course of the ensuing four decades to realise the pascal directly, the authors last year reported[28] an optical system based on photon correlation that could measure particle velocities and therefore sound pressures at a point inside a fully anechoic chamber remotely and without disturbing the propagating sound field for a limited frequency range up to 4 kHz. However, the extension of the frequency range from 4 kHz to 20 kHz provided a significant amount of challenges in terms of optical system stability and resolution capabilities, phase instrumentation errors, required pressure levels to be delivered by the sound source, and measurement repeatability and accuracy of the technique, in short, important parameters for the establishment of an optically based primary standard.

In this case, the measurement configuration of the setup includes a fully custom designed optical system placed in a standard laboratory which can remotely measure acoustic particle velocities (and hence pressures) due to airborne sound propagating in free-field conditions inside an adjacent

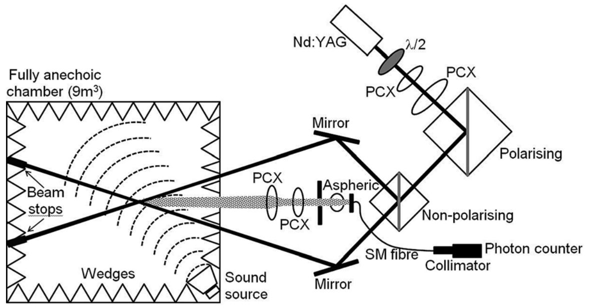

FIG. 1. The optical system and acoustic chamber arrangement (not to scale).

fully anechoic acoustical chamber (Fig. 1). The optical delivery system consists of an Nd:YAG frequency doubled laser source (532 nm wavelength). The first half-plate ($\lambda/2$) and large polarising cube beam splitter act as the power control for the beam that is suitably adjusted between alignment and measurement processes; most crucially and regardless of the optical power delivered, it ensures that any minute horizontal polarisation contributions in the beam are removed as only the vertically polarised component is re-directed to the subsequent optical section. The next smaller non-polarising cube is splitting the beam into two identically polarised (vertical) beams. The following two aluminium mirrors direct the beams, through two small openings on the wall of the anechoic chamber, inside the acoustic room where they cross to form an ellipsoid volume with interference fringes. Due to the fact that the total optical path length from the laser source to the point of beams intersection is over 3 m, the natural divergence of the beams would cause large waists at the ellipsoid volume. One approach would be to couple the main laser source onto two separate single mode fibres that can then collimate and focus the individual beams inside the chamber. However, this would result in optical power loss due to the fibre coupling. To overcome this issue, a beam expender based on two convex lenses was used after the laser source which was manually adjusted to focus the beams inside the chamber. This approach resulted in focal waists of 1 mm at the cross-over laser region inside the chamber.

As sound propagates from the sound source inside the chamber, airborne particles oscillate (due to the passage of the sound wave); within the interference ellipsoid volume, the particles will periodically cross the fringes and by doing so, photons will be scattered. The collection optical system (also placed outside the acoustical chamber) was based on a Keplerian architecture that sharply images this optical region through a small opening to the acoustic chamber using a pair of convex lenses in back-scattered mode. Immediately after the eyepiece of the telescope, a short focal length aspheric lens is used to focus the formed image onto a single mode optical fibre that is matched to the wavelength of the optical source. At the other end of the fibre, a collimator directs the captured optical wavefront onto a single photon device. The output of the photon counter is essentially a transistor-transistor logic (TTL) pulse sequence, with each digital pulse corresponding to a single photon event (i.e., single photon capture). The choice of the fibre proved to be quite crucial; the fibre was placed at the focal point of the aspheric lens that was placed after the telescope; as such, it was the resulting Fourier plane of the formed image resulting from the photon interference region from inside the chamber that was to be coupled into the fibre. Using a single rather than a multimode fibre ensured that only the lower spatial frequencies of the optical image were coupled into the photon counter, thus significantly improving the signal-to-noise ratio. Minimal levels of airborne seeding (polyol solution in demineralised water) were also introduced into the acoustical chamber in order to increase the level of photon scattering. A minimum of 2 h after the introduction of the seeding was allowed before any optical measurements were attempted to ensure that only the smaller of the introduced particles in the air remained airborne and also to reduce any resulting thermal gradients. Measurements using particle counters revealed that the introduced population resulted in 4–6 artificial particles per natural occurring airborne particle, which changes the speed of sound by less than 0.1%.

In order to extract any periodicity due to the propagating sound resulting from the scattered photon events captured by the collection optical system, it was necessary to auto-correlate the resulting photon sequences from the optical counter. It has been mathematically derived[10] that this auto-correlation function (ACF) relies on the expectation operator of the captured auto-correlated sequences and relies on a number of parameters such as Gaussian profile of the laser beams, optical detection sensitivity, average number of airborne particles, and particle velocity amongst others. After a very detailed mathematical analysis,[9,10] it is shown that the particle velocity is directly proportional to the wavelength of the laser source and inversely proportional to the half angle of the beams intersection and the time it takes for the ACF to reach its first minimum.

Unlike standing wave tubes where sound appears to be stationary in terms of velocity distributions, the particle velocity in an anechoic chamber will fluctuate with time due to the free-field propagation. It is therefore necessary to gate the TTL photon sequences from the optical counter in order to extract any resulting periodicity. To achieve this, the function generator driving the acoustic source was used to provide a trigger signal at the beginning of each acoustic cycle; this trigger was directed to a second function generator that provided a pulse with frequency equal to the acoustic frequency but duration equal to quarter of the acoustic signal duration. On first thought, it may be considered sufficient to introduce a phase delay on the gating pulse to align with the maximum amplitude section of the acoustic cycle. However, there will be an additional phase introduced due to the response of the measurement channel instruments and so it was necessary at each frequency step to manually trace the maximum particle velocity resulting from the propagating sound.

The measured signals are influenced by the ambient mean flow within the chamber, and it was equally necessary to decouple this steady flow from the acoustic particle measurements; keeping in mind that during the first half of the acoustic cycle, the mean and acoustic particle velocities will be in the same direction while during the second half of the acoustic cycle they will be in opposite directions. By doubling the frequency of the gating signal (and also by introducing the required phase delay), it was possible to simultaneously capture and analyse the particle velocity without the influence of the mean flow velocity because the mean flow component would be averaged out of the measurements.

Optical measurements at the centre frequency of 17 standard 1/3 octave bands in the range of 501 Hz–19.95 kHz were performed. In each case, the gated photon sequences were auto-correlated using a custom designed digital correlator board (Figure 2). In order to avoid over or underestimation of the first ACF minimum due to quantisation error introduced by the number of delay points in the auto-correlation calculation, a spline interpolation fit on each of the experimental functions was applied to identify the true time value of each first minimum. At each frequency step,

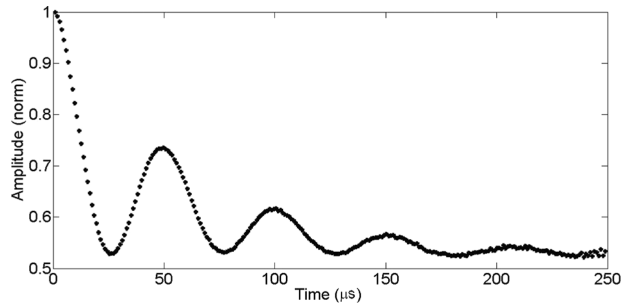

FIG. 2. Gated auto-correlated function at 1 kHz.

the uncertainty of the optical measurement was calculated as the square root of the sum of squares between the Type A (random) measurement uncertainty (four repeats per frequency) and the uncertainty of the interpolation algorithm.

Once all the acoustical pressures were calculated through the optical particle velocity measurements, the acoustical device was then placed with the centre of its diaphragm on the laser intersection region. In order to ensure that the same acoustical conditions were achieved during the optical and microphone measurements, a $\frac{1}{4}''$ monitoring microphone inside the chamber was used to verify the sound pressure repeatability that was better than 1%. In order to align the device with the acoustic axis of propagation and the optical region, 6 laser beams were utilised that allowed its accurate positioning in the chamber measurement area. Measuring the electrical response of the device at each frequency step and combining it with knowledge of the pressure measured optically allowed the determination of the sensitivity with *direct* experimental traceability to both voltage and length standards.

The investigated acoustical device was then calibrated using the existing international standard of coupler reciprocity; at each frequency step, the sensitivity was corrected to include the required free-field correction values.[4] The uncertainty was the square root of the sum of squares of the Type A measurement uncertainty, the uncertainty given by the reciprocity calibration, and the uncertainty stated by the free-field corrections. Table I shows the comparison between the sensitivities derived indirectly by the existing standard and the direct measurement by the photon correlation technique.

The existing reciprocity standard is implemented in coupler conditions with specified geometries and assumptions about the sound field through knowledge of parameters such as temperature humidity, adiabatic conditions, coupler, and acoustical device dimensions. The applied free-field corrections to the reciprocity based sensitivity values are based upon diffraction of sound due to a well-defined obstacle in free-field conditions and the discrepancy between what is measured and the actual value can be up to 9 dB at the highest frequency. Also, these applied corrections assume a specific geometry that may not be representative of the particular arrangement, is rather generalised and assumes that they can be applied in most (or in fact, all) applications. In addition, they are based on acoustic measurements with one of the triad devices (at any one time) providing the acoustic excitation at low pressure levels, typically much

TABLE I. Comparison between reciprocity (R) and optical (O) calibration in terms of sensitivities.

Frequency (Hz)	Sensitivity (R) (mV/Pa)	Unc. 95% (%)	Sensitivity (O) (mV/Pa)	Unc. 95% (%)	Difference (%)
501	10.11	1.05	9.56	0.87	5.79
631	10.12	1.07	10.18	0.64	−0.57
794	10.14	1.10	10.05	1.60	0.91
1000	10.16	1.23	9.90	2.05	2.62
1259	10.22	1.13	10.18	0.65	0.40
1585	10.30	1.30	10.19	0.32	1.08
1995	10.44	1.51	9.51	0.75	9.81
2510	10.65	1.65	10.35	0.79	2.87
3160	10.97	1.75	9.90	0.55	10.85
3980	11.54	1.73	10.92	1.33	5.67
5010	12.39	1.62	12.04	0.75	2.88
6310	13.81	1.76	13.46	1.43	2.60
7940	16.23	2.24	15.41	0.67	5.28
10 000	19.65	3.35	19.31	0.84	1.77
12 590	24.55	4.06	25.71	2.22	−4.51
15 850	28.74	2.94	31.52	1.22	−8.80
19 950	27.19	2.19	27.71	3.13	−1.87

lower than 0.5 Pa, throughout the frequency range and subsequently assuming that the device response can linearly scale up with increasing pressures.

The optical measurement of pressures, on the other hand, was achieved remotely with the acoustic chamber being completely empty of the obstacles that are necessary to be present for the reciprocity method (e.g., mounts and stands) and therefore represents the first true free-field realisation. It subsequently requires only the acoustic device under test to be present. It provides a consistent assessment (based on the uncertainty values) of the propagating sound but most importantly it provides the required sensitivity values directly, in conditions and levels that are more typical to real applications.

By comparing the uncertainties (Table I) between the existing method and the proposed one, it appears that even though they both seem to be of the same order (in both cases up to 4%), the difference in the given sensitivities sometimes exceeds the combined errors. The discussion above outlined a number of potential sources responsible for the discrepancies. It needs to be emphasised that none of the reasons strictly suggests that there are invalid assumptions in either of the methods in an absolute sense; however, in a relative sense, both methods take place under very different conditions, from a theoretical, experimental, and measurement perspective. Further work will focus on thoroughly investigating those reasons and their random and systematic nature.

The results can thus provide the basis of an optically based primary standard for the free-field calibration of any airborne acoustical device of standard and non-standard dimensions, the characterisation of sound in hemi, and fully anechoic situations within the audible frequency range and also offer the possibility to extend the work into airborne infra and ultrasound assessment. Such a standard would require an extensive theoretical and experimental study of random and systematic sources of uncertainty and this is currently underway. To fully eliminate the current need for very low levels of seeding, the laser will be replaced with a higher power version (∼1 W). This will also require work on the inertial and momentum transfer properties of ambient air particles with increasing optical powers. The method allows the realisation of the pascal through direct optical particle velocity measurements without any assumptions on the propagation characteristics of sound or geometrical characteristics of the device under investigation. It allows a direct approach to characterise any acoustical device and most crucially it allows an absolute basis in acoustical metrology without the reliance on the availability and performance of specific artefacts, specific configurations and does so with direct experimental traceability through the volt and the metre.

The authors gratefully acknowledge financial support from the National Measurement Office of the UK Department of Business Innovation and Skills. Queen's Printer and Controller of HMSO, 2015.

[1]Lord Rayleigh, *The Theory of Sound*, 1 ed. (Macmillan, 1877), Vol. 1; 1 ed. (Macmillan, 1878), Vol. 2; 2 ed. (Macmillan, 1894), Vol. 1; 2 ed. (Macmillan, 1896), Vol. 2.
[2]IEC 61094-2, Measurement microphones - Part 2: Primary method for pressure calibration of laboratory standard microphones by the reciprocity technique, 2009.
[3]IEC 61094-3, Measurement microphones - Part 3: Primary method for free-field calibration of laboratory standard microphones by the reciprocity technique, 1995.
[4]IEC 61094-7, Measurement microphones: Values for the difference between free-field and pressure sensitivity levels of laboratory standard microphones, 2006.
[5]Y. Yeh and H. Z. Cummins, "Localised fluid flow measurements with an He-Ne laser spectrometer," Appl. Phys. Lett. **4**(10), 176 (1964).
[6]K. J. Taylor, "Absolute measurement of acoustic particle velocity," J. Acoust. Soc. Am. **59**(3), 691–694 (1976).
[7]F. H. Barnes, Q. I. Daudpota, C. A. Greated, and I. Grant, "Application of photon correlation techniques to the measurement of flow with a sinusoidal perturbation," Phys. Fluids. **20**(2), 211–215 (1977).
[8]C. A. Greated, "Measurement of acoustic velocity fields," Strain **22**(1), 21–24 (1986).
[9]T. S. Durrani and C. A. Greated, *Laser Systems in Flow Measurement* (Plenum Press, 1977).
[10]J. P. Sharpe and C. A. Greated, "A stochastic model for photon correlation measurements in sound fields," J. Phys. D: Appl. Phys. **22**, 1429–1433 (1989).
[11]D. Hann and C. A. Greated, "Acoustic measurements in flows using photon correlation spectroscopy," Meas. Sci. Technol. **4**, 157–164 (1993).
[12]T. MacGillivray, D. Campbell, C. Greated, and R. G. Barham, "The development of a microphone calibration technique using photon correlation spectroscopy," Acta Acust. Acust. **89**, 369–376 (2003).
[13]J. P. Sharpe, C. A. Greated, C. Gray, and D. M. Campbell, "The measurement of acoustic streaming using particle image velocimetry," Acustica **68**, 168–172 (1989).
[14]M. P. Arroyo and C. A. Greated, "Stereoscopic particle image velocimetry," Meas. Sci. Technol. **2**, 1181–1186 (1991).
[15]M. Campbell, J. A. Cosgrove, C. A. Greated, S. Jack, and D. Rockliff, "Review of LDA and PIV applied to the measurement of sound and acoustic streaming," Opt. Laser Technol. **32**, 629–639 (2000).
[16]T. Loizeau and Y. Gervais, "Measurement of the acoustic velocity by laser Doppler anemometry," Acta Acust. Acust. **83**, 945–954 (1997).
[17]J. S. Cullen, C. A. Greated, and D. M. Campbell, "LDA measurement of sound: Amplitude modulation of laser Doppler signals," Meas. Sci. Technol. **10**, 812–823 (1999).
[18]H. Bailliet, P. Lotton, M. Bruneau, V. Gusev, J. C. Valière, and B. Gazengel, "Acoustic power flow measurement in a thermoacoustic resonator by means of laser Doppler anemometry and microphonic measurement," Appl. Acoust. **60**, 1–11 (2000).
[19]J. C. Valiere, P. Herzog, V. Valeau, and G. Tournois, "Acoustic velocity measurements in the air by means of laser Doppler velocimetry: Dynamic and frequency range limitations and signal processing improvements," J. Sound Vib. **229**(3), 607–626 (2000).

[20]B. Gazengel, S. Poggi, and J. C. Valiere, "Evaluation of the performance of two acquisition and signal processing systems for measuring acoustic particle velocities in air by means of laser Doppler velocimetry," Meas. Sci. Technol. **14**, 2047–2064 (2003).

[21]C. Mellet, J. C. Valiere, and V. Valeau, "Use of frequency trackers in laser Doppler velocimetry for sound field measurement: Comparative study of two estimators," Mech. Syst. Sign. Process. **17**(2), 329–344 (2003).

[22]D. B. Hann and C. Greated, "The measurement of flow velocity and acoustic particle velocity using particle-image velocimetry," Meas. Sci. Technol. **8**, 1517–1522 (1997).

[23]M. W. Thompson and A. A. Atchley, "Simultaneous measurement of acoustic and streaming velocities in a standing wave using laser Doppler anemometry," J. Acoust. Soc. Am. **117**, 1828–1838 (2005).

[24]L. Simon, O. Richoux, A. Degroot, and L. Lionet, "Laser Doppler velocimetry for joint measurements of acoustic and mean flow velocities: LMS-based algorithm and CRB calculation," IEEE Trans. Instrum. Meas. **57**(7), 1455–1464 (2008).

[25]R. Raangs, T. Schlicke, and B. Barham, "The calibration of a micromachined particle velocity microphone in a standing wave tube using an LDA photon-correlation technique," Meas. Sci. Technol. **16**, 1099–1108 (2005).

[26]T. J. MacGillivray, D. Campbell, C. Greated, and R. Barham, "The development of a microphone calibration technique using laser Doppler anemometry," Acta. Acust. Acust. **88**, 135–141 (2002).

[27]T. Koukoulas, P. Theobald, T. Schlicke, and R. G. Barham, "Towards a future primary method for microphone calibrations: Optical measurement of acoustic velocity in low seeding conditions," Opt. Laser Eng. **46**, 791–796 (2008).

[28]T. Koukoulas, B. Piper, and P. Theobald, "Gated photon correlation spectroscopy for acoustical particle velocity measurements in free-field conditions," J. Acoust. Soc. Am. **133**(3), 156–161 (2013).