Chapter 8
Physico-Mechanical Metrology

Part III: Thermal, Optical Radiation and Acoustic Metrology

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Abstract This chapter describes the three physico-mechanical metrology streams; temperature and humidity, optical radiation and acoustic and vibration metrology. Among the seven base SI units, temperature and optical radiation encompasses the two SI units while acoustic comprises only derived parameters. Temperature metrology includes realization and dissemination of temperature and humidity

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parameters, optical radiation metrology includes parameters like illuminance, illuminance responsivity, luminous flux, luminance, colour temperature, colour coordinates and spectral irradiances. Acoustic metrology includes sound pressure, vibration amplitude, sound transmission and absorption coefficients. All the parameters are inter-connected to fulfil the human needs and endeavours and have immense importance in the socio-economic growth of the country. The contribution, insinuation, impact, significance and relevance of these PMPs in different sectors like health, process and manufacturing, lighting industry, building acoustics, SODAR system and noise mapping are described along with established measurement standards and facilities, CMCs, participation in key comparisons, gap analysis and futuristic requirements and suggestions. All these endeavours are carried for the inclusive industrial growth of the nation.

> Refining is inevitable in science when you have made measurements of phenomenon for a long period of time.
>
> – Charles Richter (1900-1985)

8.1 Temperature and Humidity Metrology

This section describes the comprehensive information on the importance and status of temperature and humidity metrology, brief history about origin of temperature scale, its development, various techniques and principles associated with them, methods to realize these parameters at laboratory level, dissemination, applications in various sectors, potential services and future prospects, etc.

8.1.1 Introduction and Historical Aspects

Temperature and humidity are critical and essential parameters that need to be monitored and controlled in various fields such as in science, technology, medical, agriculture, pharmaceutical, industries and environmental applications. Industries and organizations need to have complete confidence in the performance of their measurements, over a wide range of temperatures and in extreme conditions. Therefore, it is important for the metrological communities to provide the accurate, precise and reproducible measurement of the temperature and humidity to face the globalization of industrial production and harmonization in doing trade.

Temperature, in general, is considered to be the degree of hotness or coldness. More specifically, it is the property required to describe the macroscopic state of a system which is in thermal equilibrium. Thermodynamic temperature is a fundamental physical quantity and is defined as one of the seven base quantities in the SI. To

the most surprise, even being in SI unit, there was no proper definition of temperature until eighteenth century. Even today, only few people who are directly associated with thermometry, have an intuitive understanding of what is being measured. In 1869, Maxwell–Boltzmann gave a relation between the velocity or energy distribution of particles in a system at thermal equilibrium, given as $E = kT/2$. For a molecule of mass 'm' and velocity 'v', the average of the square of the velocity is then given by $v = \sqrt{(3kT/m)}$. Boltzmann constant k thus provides the link between the mechanical quantity (quantum or classical) and thermal parameter.

Temperature is an intensive quantity which means it is non-additive. This tells that temperature scale is non-uniform and has to be measured in the whole temperature regime with maximum possible points. The measurement of temperature is termed as thermometry. The ability to precisely measure temperature strongly depends on the measuring sensor and method. The history of thermometry, since the first device which can measure the degree of hotness and coldness relative to ambient temperature was invented between 1592 and 1603 AD based on a glass bulb connected to a long tube immersed in the liquid. At the start of the seventeenth century, a need was realized to standardize these thermometers by temperature fixed points. In the 1724, D G Fahrenheit developed mercury-in-glass thermometers standardized using three fixed points: a mixture of ice, water and ammonium chloride, a mixture of ice and water and the human body and the corresponding temperatures were taken as 0 °F, 32 °F and 96 °F, respectively. Concurrently, the French scientist Amontons developed the gas thermometer by using air medium and found the ratio of greatest summer heat to greatest winter in Paris to be approximately five or six. Later, he concluded that the expansion coefficient of all gases is approximately the same and hence temperature is simply proportional to the pressure of a gas, and thus, only one fixed point is required to define the scale. Still Gas thermometry for a long time relied upon two fixed points using the equation:

$$p(T) = p(0) \cdot (1 + \alpha T), \tag{8.1}$$

where $p(0)$ is the reference fixed point.

In 1742, Anders Celsius developed mercury-in-glass thermometer and scaled by using freezing point (0 °C) and boiling point (100 °C) of water at standard atmospheric pressure (101.325 kPa). He divided this temperature scale into 100 equal parts, and the unit of the temperature was defined as degree Celsius (°C). At the start of eighteenth century, two approaches given by Fahrenheit and Amontons were followed for the further development of thermometry. In the beginning, the practical temperature scale was defined by ice point (0 °C) and steam point (100 °C). In 1854, William Thomson (Lord Kelvin) had proposed the new temperature scale by developing an idea of absolute zero temperature, where all the microscopic motions of constituent particles of matter completely cease, along with one additional fixed-point. Eventually, in 1948 at 9th CGPM, the triple point of water (TPW) was proposed as the primary reference point to define thermodynamic temperature. The TPW provides better accuracy than ice and boiling point of water, which were found to depend on atmospheric pressures. The thermodynamic temperature of the TPW is

estimated by Gay-Lussac's gas law and calculated to be 273.16 K (0.01 °C). Thus the Eq. (8.1) remained valid until the unit of thermodynamic temperature was redefined by assigning a numerical value to just one fixed point, i.e. TPW. In 1954, 10th CGPM officially accepted the definition of SI unit of thermodynamic temperature, kelvin (K) based on TPW state, as the fraction 1/273.16 of the thermodynamic temperature of the TPW.

8.1.1.1 Primary Thermometry Methods

Thermodynamic temperature is the physical property which is intensive in nature and absolute measurement of temperature. The fundamental methods to determine the thermodynamic temperature is known as the primary thermometry methods. Primary thermometers are based on the well-understood physical system where the equation of state can be written explicitly without need of introducing unknown, temperature-dependent, constants [1, 2]. For instance, ideal gas law and Planck's law are the equations which satisfy this condition and are primary thermometry methods. When two objects having different temperatures come into contact, the only thing they share is the energy per degree of freedom. The thermodynamic temperature is a measure of energy per degree of freedom, but we can't express it in terms of Joule per degree of freedom because the temperature is expressed in kelvin. Moreover, Boltzmann constant is the fundamental constant, which appears as a constant in the thermal energy (kT). Therefore, the kelvin was proposed to be defined through thermal energy by fixing the value of Boltzmann constant. CGPM approved the new definition of thermodynamic temperature based on Boltzmann constant at its 26th meeting on 16th November 2018, and it was implemented from world metrology day, on 20th May 2019 [3]. Therefore, primary thermometric methods are playing a major role in the determination of Boltzmann constant with low uncertainty and dissemination of thermodynamic temperature (T). Also, the metrology community is making measurements of T-T$_{90}$, to come-up with the future practical thermometry scale (ITS-202X).

Primary thermometry methods for the determination of Boltzmann constant (k) and measurement of thermodynamic temperature are based on the fact that a macroscopic property is measured which can be related to the temperature at a known pressure e.g. density in Constant volume gas thermometry [1], dielectric constant in Dielectric constant gas thermometry [4], speed of sound in Acoustic gas thermometry [5, 6]. Johnson noise thermometry [7] and Doppler broadening thermometry [1, 8] are statistics and quantization methods. The Johnson noise thermometry is based on the relationship between thermodynamic temperature and generated fluctuating noise voltage or current in a resistor due to thermal motion of electron while the Doppler broadening thermometry is based upon the principle that Doppler broadening and the width of absorption line of the gas particles or atoms at thermodynamic equilibrium is proportional to the thermal motion of gas molecules. Total radiation thermometry is another primary method based on the Stefan-Boltzmann law of thermal radiation.

The fundamental equations for CVGT, AGT and DCGT are shown in Table 8.1.

Table 8.1 Fundamental equations for CVGT, AGT and DCGT

CVGT	AGT	DCGT
$pV = nRT$	$c = (\gamma RT/M)^{1/2}$	$p = kT(\varepsilon \text{-} \varepsilon_o)/\alpha_o$

Although these primary methods give very accurate way to measure the Thermodynamic temperature, but because of the complicated, time consuming and expensive measuring setup of this thermometry, it remained limited to the laboratory only and it demands a unifying method to realize temperature in a practical manner and to disseminate kelvin. Furthermore, these thermometers are not as reproducible as the platinum resistance thermometer in the most of temperature range.

CSIR-NPL has taken initiatives on development of Acoustic Gas Thermometry for the realization of Boltzmann constant based New Kelvin. This is one of the innovative projects, CSIR-NPL is carrying out towards the international efforts on re-definition of base units based upon fundamental constants. Under 12th Five-year plan project on Measurement Innovations in Science and Technology (MIST), the project was initiated. In the primary thermometry methods (equation of state-based methods) and in the laws of physics, the thermodynamic energy is proportional to the product kT, therefore if the value of 'k' is fixed, the thermodynamic temperature can be directly measured by measuring the energy (J/K). Among the primary methods discussed above, the best estimation of Boltzmann constant with the lowest uncertainty was attained by using the AGT. The AGT is one of the primary thermometry methods where velocity of sound is measured in the monoatomic gas in a temperature-stabilized acoustic resonator, where the resonating frequency is proportional to the dimension of resonator. In AGT, in terms of macroscopic measurable properties, the relation be (5, 6):

$$k = Mu_0^2/N_A\gamma_0 T_{\text{TPW}} \tag{8.2}$$

where k is Boltzmann constant N_A is the Avogadro constant, γ_0 is the ratio of the principal heat capacities of the gas in the limit of low pressure, u_0 is speed of sound at low pressure limit M is the molar mass of the gas and T_{TPW} is the thermodynamic temperature at TPW. Nowadays, the speed of sound is measured in argon or helium gas medium by using quasispherical resonator.

The equation can be rewritten in terms of acoustic and microwave resonance frequencies as:

$$k = \left\langle \frac{3}{5} \frac{mc_0^2}{T_{TPW}} \left(\frac{Z_{nl}^{EM}}{Z_{nl}^A} \right)^2 \lim_{p \to 0} \left(\frac{\langle f_{nl}^A + \Delta f_{nl}^A \rangle}{\langle f_{nl}^{EM} + \Delta f_{nl}^{EM} \rangle} \right)^2 \right\rangle \tag{8.3}$$

AGT method was first developed by NIST USA and then successfully achieved below 1 ppm by NPL UK and LNE France, and useful for the realization of k and then dissemination of thermodynamic temperatures in wide temperature ranges.

We are developing AGT set up at our laboratory with in-house efforts. With design-development and fabrication of copper quasi-spherical cavity acoustic-microwave resonator in India and by in-house collaborations of temperature, acoustic, microwave, pressure, dimension and gas metrology groups, it is possible to develop the desired primary standard at CSIR-NPL. Part of the development of critical components such as copper cavity resonator, large volume high stability bath, capsule SPRTs and resistance bridge for simultaneous temperature measurement of resonator, pressure and flow accessories are developed under the 12th FYP project. The remaining acoustic, microwave and gas purification equipment and accessories will be developed to determine k and will be integrated and experimental parameters will be optimized to get the accurate value of Boltzmann constant and Thermodynamic temperatures. Figures 8.1 and 8.2 show schematic of AGT at CSIR-NPL and design & fabrication of Copper quasi-sphere, pressure vessel and vacuum vessel respectively.

The first measurement of k will be carried out at TPW temperature. Thermodynamic temperature at other temperatures can be determined by measuring the acoustic and microwave resonances and based on the ratio method.

$$\frac{T}{T_{tpw}} = \lim_{p \to 0} \left[\frac{f_{0n}(T)}{f_{0n}(T_{tpw})} \frac{\langle f_{ln}^{\sigma}(T_{tpw}) \rangle}{\langle f_{ln}^{\sigma}(T) \rangle} \right]^2 \tag{8.4}$$
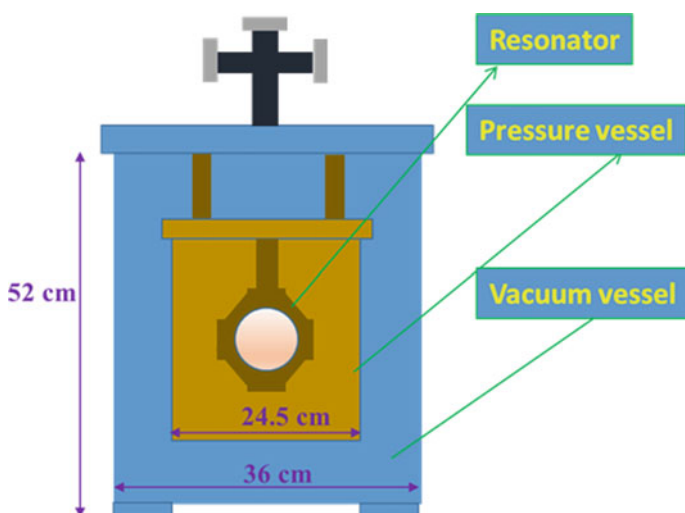

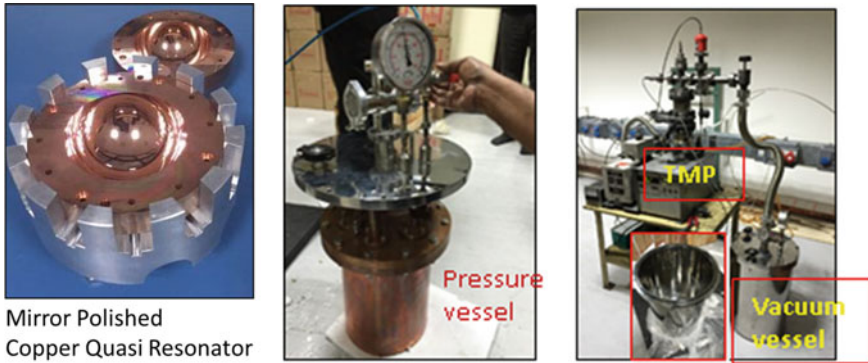
Fig. 8.1 Complete schematic of AGT at CSIR-NPL

Fig. 8.2 Design and fabrication of Copper cavity resonator, pressure vessel and vacuum vessel

8.1.1.2 Practical Temperature Scales

As an alternative to the primary thermometry, international temperature scales (ITS) have been formulated for both realization and dissemination of temperature. Practical temperature scales such as Fahrenheit, Celsius and Reaumur are the foundations of the development of new unified practical temperature scale based on fixed points. At present, temperature is defined in terms of Boltzmann constant and major research has been going on to develop primary thermometry methods for direct realization of thermodynamic temperature. However, practical scale is required as well because primary thermometers are still difficult to operate for the day to day temperature calibration and traceability. The advantage of International Temperature Scales and the reasons for their development are [9–11].

- Easy for realization and maintenance.
- Give temperature close approximation to thermodynamic temperature
- Reproducibility is better than thermodynamic temperature scale realization.
- The definition range can be improved according to the technological need of the time.
- Unified and accepted worldwide, and hence eases the world trade.

International Temperature Scale (ITS)

To unify the temperature scale worldwide, International Committee on Weights and Measures (CIPM) adopted an international temperature scale (ITS) in 1927 on the basis of generalizations made by the consulting committee on thermometry (CCT). The scale was based on three different parameters:

(i) Reproducible and robust fixed points called the thermal equilibrium states (freezing points, boiling points and melting points of highly pure substances) to which numerical values were assigned.

(ii)   Measuring instruments with highest degree of accuracy used as measurement standards (SPRT, Thermocouple, and pyrometer) in the different temperature ranges.

(iii) Mathematical relation is used to relate temperature with the measuring quantity of the instrument.

The platinum resistance thermometer, noble metal thermocouple (Platinum and 10% rhodium-platinum wires) and optical pyrometer were used for the low (-182.97 to 660 °C), medium (630 to 1064 °C) and high (1064 °C and above) temperature measurements, respectively.

Some changes were made in ITS-27 in 1948 in 9th CGPM and is termed as ITS-48. The ITS-48 was further amended as the IPTS-48 in 11th CGPM in 1960. The modification was formulated because in 1953 the TPW was designated as the unique fixed point which defines the unit of thermodynamic temperature. The ice point was replaced by TPW temperature (0.01 °C, 273.16 K) and FP of zinc (419.505 °C) was introduced as the fixed point in place of BP of Sulphur (444.6 °C). In 1968, 13th CGPM proposed the international practical temperature scale of 1968 (IPTS-68). Extensive changes in the IPTS-48 formulated the IPTS-68. It included new fixed points and changes in the assigned temperature of existing IPTS-48 defined fixed points to provide closer agreement with thermodynamic temperature. Further, the scale was amended in 1975 and 1976 provisional 0.5–30 K Temperature Scale (EPT-76).

The current scale of temperature is the International Temperature Scale of 1990 (ITS-90), which was adopted in 18th CGPM. The ITS-90 was made by choosing the set of highly reproducible states including melting, freezing, triple point and vapour pressure states of 17 very high pure substances from 0.65 to 1357 K, and is still open onwards. The Preston-Thomas et al. [12] describes the scale realization in ITS-90. The assigned temperatures to these defined fixed points are close to the thermodynamic temperatures.

ITS-90 provides one, unified and high precision temperature scale for the research and industrial users. The ITS-90 consists of many subranges, overlapping ranges and instruments which provides flexibility to user in scale realization to choose compatible instrument for accurate and reproducible measurement [12]. Fixed point defined in ITS-90 are listed in Table 8.2. The thermodynamic temperature to these phase transition fixed points were assigned by using the primary thermometric methods discussed. Apart from fixed points, the ITS-90 also defines instruments to be used for measurements between the defined fixed points as shown in Fig. 8.3.

NMI of each nation establishes the ITS-90 scale measurement facility. The defined protocols are applied to have the inter-comparisons amongst the NMIs to establish the equivalence of the measurements, and hence the worldwide physics research and industrial processes are made traceable to the unit definition of kelvin. In this way, the products and processes developed through these unbroken chains of calibrations are accepted worldwide.

Table 8.2   ITS-90 defined fixed points

| S. No.	Fixed point	State of matter	T_{90}/K	T_{90}/°C
1	He	Vapour pressure point (VP)	3–5	−270 to −268.15
2	e–H_2	Triple point	13.8033	−259.3467
3	e–H_2 (or He)	Vapour pressure point	17	−256.15
4	e–H_2 (or He)	Vapour pressure point	20.3	−252.85
5	Ne	Triple point (TP)	24.5561	−248.5939
6	O_2	Triple point	54.3584	−218.7916
7	Ar	Triple point	83.8058	−189.3442
8	Hg	Triple point	234.3156	−38.8344
9	H_2O	Triple point	273.16	0.01
10	Ga	Melting point (MP)	302.9146	29.7646
11	In	Freezing point (FP)	429.7485	156.5985
12	Sn	Freezing point	505.078	231.928
13	Zn	Freezing point	692.677	419.527
14	Al	Freezing point	933.473	660.323
15	Ag	Freezing point	1234.93	961.78
16	Au	Freezing point	1337.33	1064.18
17	Cu	Freezing point	1357.77	1084.62
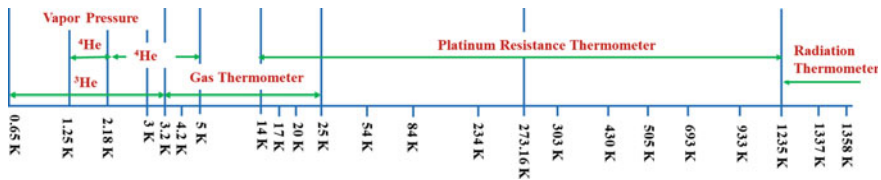
Fig. 8.3   ITS-90 defined ranges, subranges and interpolation instruments

ITS-90 Defined Measuring Instruments

Platinum Resistance Thermometry
In ITS-90, the Platinum resistance thermometer is defined primary interpolation device in the range from 13.8 to 1234.93 K. The resistance of platinum wire is used to define the temperature of a material. Qualities, such as, strong resistance to oxidation, chemically inertness in wide temperature range, high melting point, mouldable as fine wire in a high pure state make platinum appropriate for the resistance thermometry, which allows a unique resistance-temperature characteristics of platinum.

Temperature scales ITS-27, ITS-48 and ITS-68 were based on the relation between resistance and temperature of platinum resistance thermometer only. In ITS-90, the defining parameter is the normalized resistance obtained by taking ratios to the resistance at the TPW (273.16 K) and is given by:
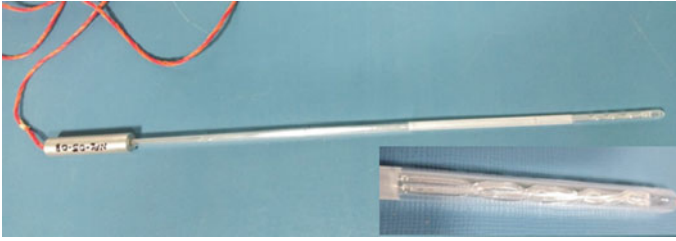
Fig. 8.4 Photograph of the long-stem SPRT fabricated at CSIR-NPL. Inset shows the expanded view of sensor part at the bottom

$$W(T_{90}) = \frac{R(T_{90})}{R(\text{TPW})} \tag{8.5}$$

where, $R(T_{90})$ and $R(\text{TPW})$ are resistances measured at T_{90} and TPW temperature, respectively. The measurement of resistance ratio $[W(T_{90})]$ eliminates the requirement for traceability to absolute resistance standards in the calibration of SPRT, and normalizes the drift effect induced due to thermal stress, mechanical shock, strain and contamination of platinum wire. The ITS-90 reference function and interpolation equation for platinum resistance thermometer is presented in the ITS-90 document. The criteria for SPRTs to be used as standard is given in ITS-90 and is based on the $W(T_{90})$ values at Ga (29.7645 °C) and Hg (−38.8344 °C) fixed Points [13, 14].

$$W(\text{Ga}) \geq 1.11807$$

$$W(\text{Hg}) \leq 0.844235$$

Three types of SPRTs are used for the temperature measurement based on the temperature range. Capsule SPRT (cSPRT) in temperature range from 13.8 K to 30 °C, which can be extended up to as high as 156 or 232 °C. Most commonly used long stem SPRTs are used between temperature range from T.P. of Argon (−189.3442 °C) to F.P. of Aluminum (660.323 °C) and the high-temperature SPRT (HTSPRT) designed to use temperature range from F.P. of Aluminum to F.P. of silver (961.78 °C). A typical schematic of SPRT is shown in Fig. 8.4.

Radiation Thermometry

Radiation thermometry provides a way to measure the temperature of a body in a non-contact manner. It is based on the Planck's law, according to which the spectral radiance of a blackbody cavity is the radiative power emitted per unit area per unit solid angle per unit wavelength, i.e.

$$L_{b,\lambda}(\lambda, T) = \frac{2hc^2}{n^2\lambda^5} \frac{1}{\exp\left(\frac{hc}{n\lambda kT}\right) - 1} \tag{8.6}$$

where the spectral radiation $L_{b,\lambda}(\lambda, T)$ is independent of the material and shape of the cavity wall, and function of the wavelength λ and temperature T. h stands for the Planck's constant, c is the speed of light, n for the refractive index of gas inside cavity and k is the Boltzmann constant. The unit of the spectral radiance is Wm^{-2} Sr^{-1} nm^{-1}.

In simplified form:

$$L_{b,\lambda}(\lambda, T) = \frac{c_1}{n^2\lambda^5} \frac{1}{\exp\left(\frac{c_2}{n\lambda T}\right) - 1} \tag{8.7}$$

where c_1 and c_2 are first and second radiation constants, respectively.

$$c_1 = 2hc^2 = 3.7417749 \ Wm^2$$

$$c_2 = hc/k = 0.014388 \ Km$$

The maximum spectral radiation wavelength shifted to shorter side as temperature increases [15].

Above silver fixed point (961.78 °C) the ITS-90 is defined by the radiation thermometry. In high temperature range, the T_{90} temperature is calculated by a spectral radiance ratio method relative to one of the ITS-90 defined primary blackbody fixed points (silver or gold or copper). Above copper fixed point (1084.62 °C) the uncertainty and temperature are calculated by using the extrapolation from these three fixed points. The unknown temperature ($T_{90,X}$) can be determined by the spectral radiance ratio:

$$\frac{L_\lambda\left(\lambda, T_{90,ref}\right)}{L_\lambda\left(\lambda, T_{90,X}\right)} = \frac{\exp\left(\frac{c_2}{\lambda T_{90,X}}\right) - 1}{\exp\left(\frac{c_2}{\lambda T_{90,ref}}\right) - 1} \tag{8.8}$$

where, c_2 is the second radiation constant and defined as 0.014388 Km. $T_{90,\ ref}$ stands for fixed-point temperature [Silver (961.78 °C), or Gold (1064.18 °C) or Copper (1084.62 °C)].

The spectral radiance ratio given in Eq. (8.8) by Planck's law is the idealized expression for the single wavelength. However, in practice, the radiation thermometer operates at monochromatic wavelength and has a finite bandwidth. Therefore, the expression for the practical implementation of ITS-90 is given by:

$$r = \frac{S(T_{90}(X))}{S(T_{90}(\text{ref}))} = \frac{\int_0^\infty \varepsilon(\lambda, T_{90}(X)).L_\lambda(T_{90}(X)).R(\lambda)d\lambda}{\int_0^\infty \varepsilon(\lambda, T_{90}(ref)).L_\lambda(T_{90}(\text{ref})).R(\lambda)d\lambda} \tag{8.9}$$

where r is the experimentally measured ratio of the detector signal, $S(T_{90}(X))$ and $S(T_{90}(\text{ref}))$ are detector signals (voltage or current) at unknown blackbody radiator
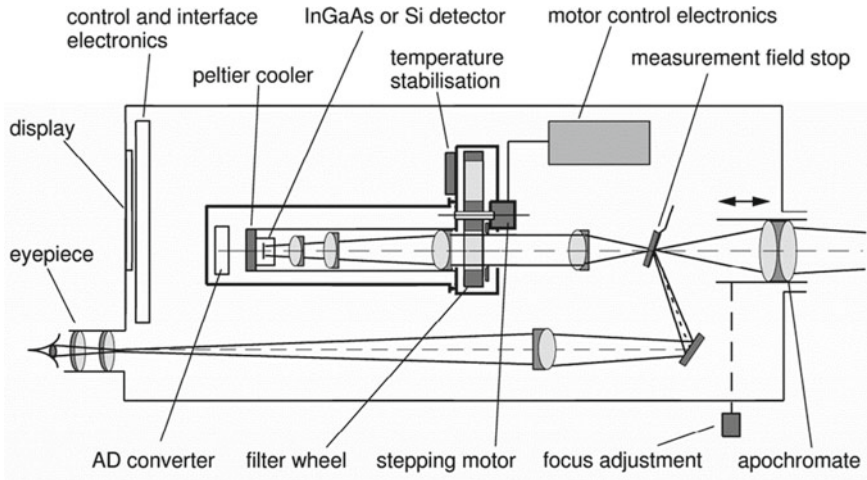
Fig. 8.5 Schematic of spectral linear pyrometer (LP4, KE Technologie GmbH) at CSIR-NPL

temperature and ITS-90 Fixed point (Ag, Au or Cu). $\varepsilon(\lambda, T_{90}(X))$ is the spectral emissivity of the unknown blackbody radiator at the temperature $T_{90}(X)$. $\varepsilon(\lambda, T_{90}(\text{Ref}))$ is the effective spectral emissivity of the ITS-90 fixed-point blackbody. $L_\lambda(T_{90}(X))$ is the spectral radiance concentration at a temperature $T_{90}(X)$, $R(\lambda)$ is the spectral responsivity of the radiation thermometer and λ is the wavelength of the radiation thermometer.

At CSIR-NPL, we are using spectral linear pyrometer (LP4) for the measurement and dissemination of T_{90} temperature and the schematic of LP4 is shown in Fig. 8.5. The measurement scheme to assign T_{90} to blackbody radiator using ITS-90 defined fixed point (Ag, Au or Cu) is shown in Fig. 8.6.

Thermocouple Thermometry: Secondary Interpolation Device

Thermocouples are based on the Seebeck effect, where two dissimilar metal or metal-alloy wires are joined at two junctions, one junction being at unknown temperature (T1) and another being at fixed reference such as ice point (T2). Due to the temperature gradient, there is flow of electrons from hotter junction to cooler junction. These thermally migrated electrons generates potential difference (emf or voltage) across the wires. A circuit for the thermocouple is shown in Fig. 8.7. The generated Seebeck voltage (dE_s) can be given by equation:

$$dE_s = s(T)dT \tag{8.10}$$

where, $s(T)$ is the Seebeck coefficient and dT is the temperature difference between two junctions.
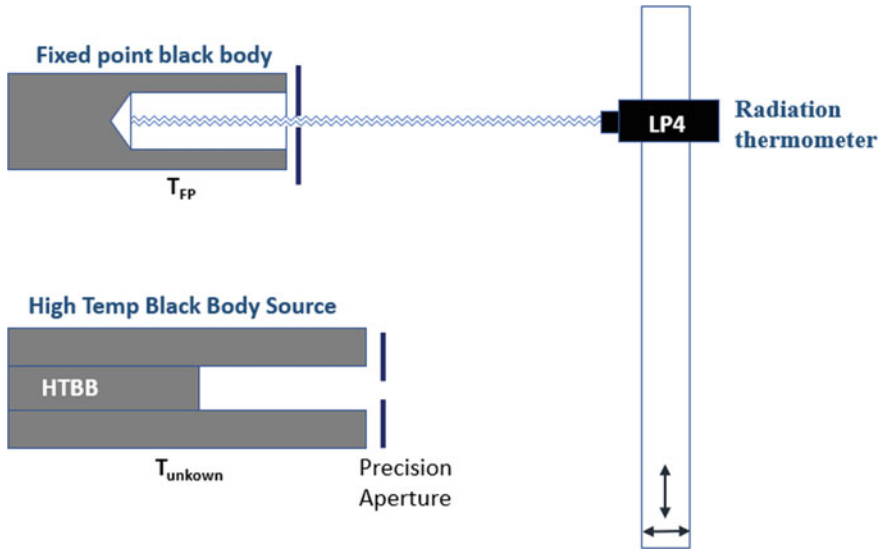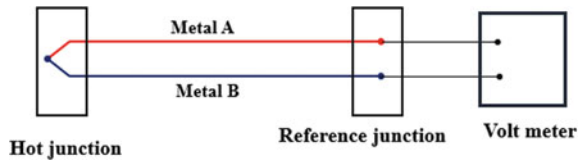
Fig. 8.6 Determination of unknown T_{90} temperature of blackbody source by a spectral radiance ratio measurement with respect to reference fixed point (Ag or Cu)

Fig. 8.7 Schematic of circuit for the thermocouple based on Seebeck effect

Thermocouples based on noble metal wires or its alloys such as Pt/Au, Pt/Pd, Pt/(Pt + 10%Rh)—Type-S, Pt/(Pt + 13%Rh)—Type-R, etc. are noble metal thermocouples and are used as reference thermocouples. Thermocouples made up of base metals are widely used in industries. These thermocouples are fabricated by many manufacturers with the standard reference tables [IEC (1977) (1982), CMEA (1978), GOST (1977), ASTM (1987b)]. The relative Seebeck effect was approved internationally for a number of different wire pairs. The type of standard thermocouple and their wire material are listed in Table 8.3.

Thermocouples are traceable to ITS-90 defined primary and secondary fixed points for different temperature ranges and subranges. Type-S and Type-R thermocouples are commonly used in laboratory to provide traceability to industries and other calibration labs. This provides a close approximation to T_{90} temperatures. Figure 8.8 shows the measurement scheme to realize fixed-point using thermocouple.

Thermocouples are calibrated by fixed-points primary and secondary fixed points as shown in Fig. 8.9. Ice point is used as the main reference point instead of TPW because thermocouples are not that accurate as platinum resistance thermometers and ice points provide accuracy about 1 mK which is sufficient for thermocouple

Table 8.3 Standard noble and base metal thermocouples

| S. No.	Type	Materials	Temperature range (°C)	Operating atmosphere
1	Type-B	Platinum 30% rhodium/platinum 6% rhodium	300–1800 °C	Oxidizing, inert, vacuum for short periods
2	Type-E	Nickel–chromium alloy/copper-nickel alloy	−200 to 870 °C	Oxidizing, inert
3	Type-J	Iron/copper-nickel alloy	−40 to 760 °C	Oxidizing, inert, reducing in partial vacuum
4	Type-K	Nickel–chromium alloy/nickel-aluminum alloy	−200 to 1200 °C	Oxidizing, inert
5	Type-N	Nickel–chromium-silicon alloy/nickel-silicon alloy	− 200 to 1200 °C	Oxidizing, inert
6	Type-R	Platinum 13% rhodium/platinum	−50 to 1600 °C	Oxidizing, inert
7	Type-S	Platinum 10% rhodium/platinum	−50 to 1600 °C	Oxidizing, inert
8	Type-T	Copper/a copper nickel alloy	−200 to 350 °C	Oxidizing, inert, reducing in partial vacuum
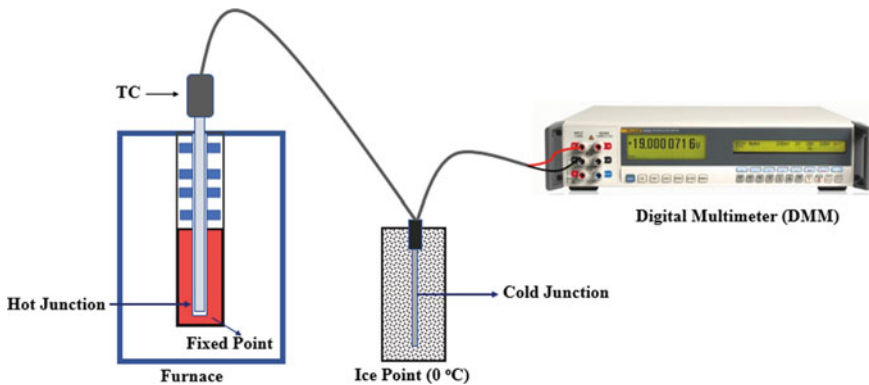
Fig. 8.8 Measurement scheme to calibrate thermocouple on ITS-90 defined fixed points

thermometer. Afterwards, thermocouples are calibrated on the ITS-90 defined fixed points up to Cu [1084.62 °C]. Above Cu point, Pd [1555 °C] and Pt [1768 °C] secondary fixed points are realized either by wire bridge method or miniature cells. We have developed Fe–C, Co–C and Ni–C eutectic fixed points for thermocouple calibrations above copper fixed point and improved our realization uncertainties.
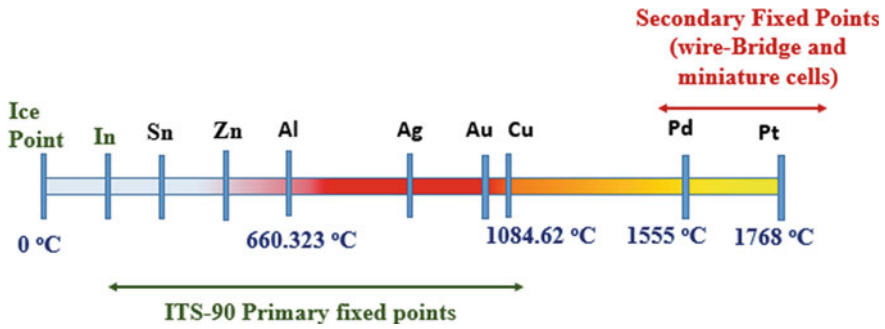
Fig. 8.9 Defined primary and secondary fixed points for thermocouple calibrations

Temperature Measurement by Liquid-In-Glass Thermometer (LIGT)

Liquid–in–glass thermometers (LIGT) are based on the linear expansion of material in a given temperature range. A typical glass thermometer is broadly composed of: a bulb (thin-walled cylinder that contains thermometric liquid like mercury or alcohol) and a stem (containing fine capillary where liquid expands or contracts). It is not possible to heat the liquid without heating the glass and the gas and these also respond to temperature changes. Mercury is the most widely used material in these devices over a wide range of temperature between its freezing point (−38.8 °C) and boiling point (357 °C). The range can be increased from −58 °C (by adding traces of thallium in the mercury) to as high as 500 °C by filling nitrogen gas in the upper portion of mercury column in the stem under pressure, thereby elevating the melting temperature. The main advantages of mercury-filled glass thermometer are cheap, handy to use and need no electric power to operate. However, because of its toxic nature WHO and Minamata convension on mercury has decided to phase-out the mercury use from the clinical applications by year 2020.

8.1.1.3   Development of Metal–Carbon Eutectic Fixed Points

CSIR-NPL has the facility for radiation thermometry up to temperature 3000 °C. The uncertainty of measurement at higher temperature is given by the extrapolation of Planck's Law from the Cu (1084 °C) to this temperature range. The extrapolation uncertainty largely contributes to the total uncertainty of pyrometers and thermal imager calibration, as high as ± 5 °C. To minimize these high uncertainty levels and to give direct traceability at high temperatures, International Thermometry community is researching on development of various metal–carbon eutectic fixed-point blackbodies from 1000 to 3000 °C. CSIR-NPL has indigenously developed the Fe–C [1153 °C] and Co–C [1324 °C] eutectic blackbody fixed points for the radiation thermometry applications, as well as for the thermocouple thermometry applications [16, 17]. The development process comprises design and fabrication of graphite crucible,
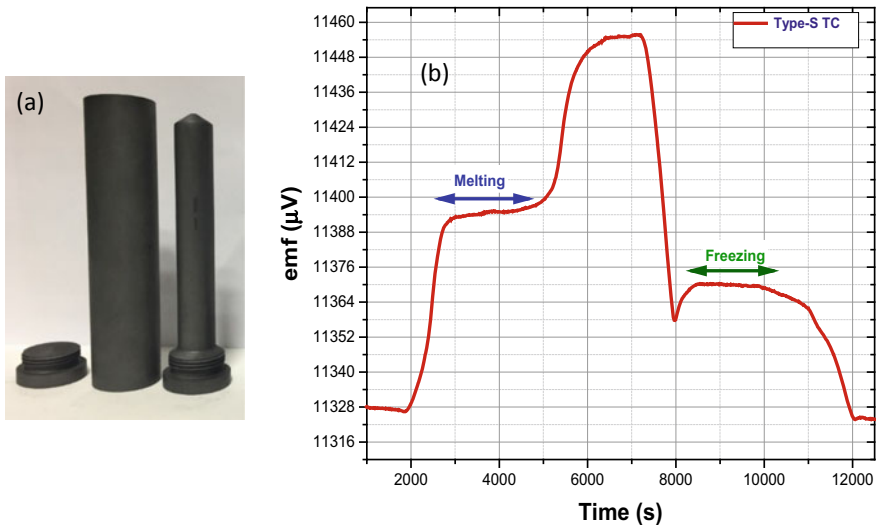
Fig. 8.10 **a** Blackbody designed at Temperature and Humidity Metrology, CSIR-NPL **b** typical melting and freezing cycle of Fe–C eutectic fixed-point measured by using Type S TC

optimization of eutectic composition of metal and carbon powder, assembly preparation, etc. The realization of blackbody fixed-point involves measurement of the melting plateau by using 650 nm spectral linear pyrometer (LP4). The LP4 gives the output in terms of photocurrent of the detector. The T_{90} temperature of the Fe–C cell was measured to be 1153.87 °C by LP4 as shown in Fig. 8.10. The repeatability and uncertainty parameters in realizing the cells are evaluated [16, 17]. CSIR-NPL is one of the few leading NMIs to achieve this metal–carbon eutectic technology.

8.1.1.4 Humidity Metrology

After having discussions about temperature metrology, we discuss about humidity metrology. Humidity plays an important role in our daily life. Relative humidity is defined as the amount of water vapour present in air expressed as a percentage of the amount needed for saturation at the same temperature. Humidity sensors are the devices that convert the amount of water vapour in some measurable parameters. Humidity sensors have wide range of applications in the industrial fields like pharmaceuticals, medical, chemical, agriculture, automobile, Grid transformers, etc. and their calibration is of utmost importance for the economy and the healthcare sector. There are various ways to generate humidity in a controlled manner. Some of these are:

- Saturated salt solution method
- Two-pressure, One-Temperature method

Fig. 8.11 Two pressure humidity generator (Thunder Scientific 2500) along with chilled mirror hygrometer (RH 370) established at CSIR-NPL

- 2 Pressure, 2 Temperature method
- Two-temperature method
- Mixed Flow method

CSIR-NPL has Thunder Scientific-2500 as Humidity generator based on "two-pressure, one temperature" principle. It is made traceable with CSIR NPL primary standard of temperature and pressure. It has a significant stability of better than 0.1% and capable of providing calibration in the range 10 to 95% RH with an uncertainty of 0.3% RH, and temperatures from 0 °C to 70 °C with the uncertainty of 0.02 °C. This system provides high precision humidity values for instrument calibration, and testing. Figure 8.11 shows the humidity generator facility at CSIR-NPL. The chilled mirror dew point hygrometer (RH 370) along with Thunder 2500 is used for the dew/frost measurements from −30 °C to 60 °C. This needs to be extended to −90 °C (Frost Point) to serve the low RH pharma and Transformer users in India.

8.1.1.5 Moisture Measurement

Moisture is a critical parameter for ascertaining the quality, storage and process conditions in agricultural, pharmaceuticals, polymers, food powders, and many others—during processing, storage and use. Moisture content above the permissible limit in the food grain and medicos result in rotting during the storage and has wider economic impacts. Moisture measurement in a bulk sample is a critical metrological task. The moisture content measurement in food grains is controlled under legal metrology in many countries. Moisture meters used under such transactions are under metrological scrutiny for traceable calibrations and verifications through a NMI.

At CSIR-NPL, we have developed two primary methods for the moisture measurements: Integrated Loss-on-Drying (LOD) method and Karl-Fischer Titrator method. CSIR-NPL has established and made extensive measurements of moisture content in food grains using the Loss-on-drying method traceable to primary standards of mass

and temperature. The measurement procedure used to determine the grain moisture content refers to ISO 712 recommendations.

LOD method is based on the thermogravimetric principle. In this method, a substance is heated until it loses all its weight corresponding to surface and bulk H_2O, and becomes constant when it is completely dry. Weight of the substance is measured at the beginning and once it is dried. The final weight loss is calculated, and represents as moisture content of the sample. In this context, moisture refers to all the vaporizable matter within a sample, and hence include not only water but volatile solvents, and alcohols also.

The other method, Karl Fischer Titration is based on the Bunsen reaction responsible for water quantification in terms of oxidation of sulfur dioxide with iodine. The reaction could be modified to give water content in a non-aqueous system. Two types of titration methods are available: Coulometric and Volumetric. At Temperature and Humidity laboratory of CSIR-NPL, we have volumetric titration method. The main components of this method are cathode, anode and an analyte. In volumetric method, anode solution itself is used as the titrant solution. The titrant consists of an alcohol (ROH), base (B), SO_2 and a known concentration of I_2.

These moisture measurement facilities are being used for the calibration of various moisture meters made for different commodities such as cotton, rice, wheat, etc. using respective standard samples, and also for the testing of moisture content in several solid and liquid samples.

8.1.2   Significance, Applications and Relevance in Different Sectors

A major of the manufacturing industry depends upon the temperature and humidity measurement. Few important sectors are listed here:

- In **Steel and metal, alloys Industries** In steel mills there are many areas where temperature measurements have to be made. Monitoring temperatures during the steel-making process assures the desired mechanical properties as required. Hence accurate temperature measurement is a must for assuring robustness and the mechanical properties of the material. Mishra Dhatu Nigam Limited, few Steel plants, CSIR-CIMFR Dhanbad, etc. are our users in this area.
- **Aircrafts** use thermometers and hygrometers to determine if atmospheric icing conditions exist along with their flight path.
- They are also applied in **meteorological and oceanographic applications** to weather forecast method, temperature, relative humidity, dew/frost, etc. IMD, NIOT, CPCB, etc. are our users in this field.
- **Healthcare sector** Body temperature is a critical measurement parameter in the human health diagnostics. A number of diseases are characterized by a change in body temperature. Even an error of ± 1 °C can lead to wrong medication and treatment plan. Different types of clinical thermometers are being used to measure

febrile temperature. Mercury-in-glass, electrical and IR Forehead/Ear thermometers are widely used thermometers to measure febrile temperature. Each type of thermometer has to be calibrated to get an accurate and reliable temperature value. Similarly, in medical incubator to measure surface temperature, body temperature and relative humidity required to be adequately maintained as per the prevalent conditions of patients.

- *Pharmaceutical sector* Maintaining relative humidity level is an essential parameter for the quality and safety of medications from reagent, making to packaging stages. High humidity causes products to absorb the excess moisture in the air. Therefore the need for accurate measurement of RH, Dew/frost are very vital for this field.
- *Agriculture sector* Whether the humidity is too high or too low, the loss of quality reduces the selling price of crops and increases production costs, both of which reduce profits. Crop may get spoiled if is stored in an environment above the prescribed limits. Hence temperature and humidity are important parameters to be controlled in agriculture sector.

8.1.3 Facilities and Global Status

8.1.3.1 Measurement Standards and Facilities

The apex level calibration services of Temperature and Humidity Metrology are provided from −200 to 3000 °C for SPRTs, RTDs, Thermocouples and Radiation Pyrometers, Thermal Imagers and Blackbody sources and 10–95% RH, −30 to 50 °C dew/frost measurements, moisture measurements and mercury-free (electrical and IR based) clinical thermometers. We have established the state-of-the-art Primary Standards of Temperature and Humidity, using the ITS-90 defined fixed points, and giving the traceability services to Indian and SAARC users. The detailed description of the various facilities, measurement range and the associated uncertainties are listed in Table 8.4.

8.1.3.2 Calibration and Measurement Capabilities

The CMCs of temperature and humidity parameters published in KCDB are given in Table 8.5.

8.1.3.3 Participation in International Key Comparisons

CSIR-NPL has participated in several international comparisons of temperature. The list is given in Table 8.6.

Table 8.4 Calibration facilities in the present scope of Laboratory

S. No.	Calibration items	Temperature range	Uncertainty ($k = 2$, 95% CL)
1	SPRT/HTSPRT/PRT/RTD by Fixed-point methods (Using ITS-90 fixed-point cells and Resistance Thermometry Bridge)	(i) −196 to 0.01 °C (BP LN2, TP Hg, TPW) (ii) 0.01 to 660 °C (TPW, FP Sn, Zn, Al) (iii) 0 to 962 °C ITS-90 Fixed Points (TPW, FP Sn, Zn, Al, Ag)	±2 ±0.17 m °C ±0.17 ±4.0 m °C ±0.17 ±6.0 m °C
2	SPRT/SSPRT/PRT/RTD/Thermistors by comparison method (Using ITS-90 calibrated SPRT and Liquid Bath/Furnace/Calibrator)	−196 to 0 °C 0 to 660 °C	±40 to ±4 m °C ±4 to ±60 m °C
3	SPRT/SSPRT/PRT/RTD/Thermistors by comparison method (Using ITS-90 calibrated SPRT and Liquid Bath/Furnace/Calibrator) with indicator (Ohm, °C, K)	−196 to 0 °C 0 to 660 °C	±40 to ±4 m°C ±4 to ±60 m °C With additional uncertainty due to Indicator
4	Liquid-in-Glass Thermometers and Digital thermometers (With ITS-90 calibrated SPRT and Liquid Bath)	−90 to 0 °C and 0 to 300 °C	±0.02 to ±0.04 °C or depending upon Least Count
5	Noble metal thermocouples (Type-S, Type-R & Type-B, Pt/Au, Pt/Pd) by fixed-point method	0 to 1200 °C (FP of In to FP of Cu) 0 to 1600 °C ITS-90 Fixed Points FP of In to MP of Pd)	±0.31 to ±0.6 °C and ±0.31 to±0.9 °C
6	Noble metal thermocouple (Type-S, Type-R & Type-B), Base Metal and Tungsten Thermocouples by comparison method, **with and without Indicators** (With ITS-90 calibrated Thermocouples and Three-zone high stability furnaces)	0 to 1200 °C and 0 to 1600 °C	±0.4 to ±1.2 °C and ±0.4 to ±1.6 °C
7	Standard tungsten strip lamp (With standard lamps and LP4 pyrometer)	800 to 1700 °C and 1600 to 2200 °C	±0.9 to ±1.3 °C and ±1.0 to ±2.5 °C

(continued)

Table 8.4 (continued)

S. No.	Calibration items	Temperature range	Uncertainty ($k = 2$, 95% CL)
8	Pyrometer (LP4) and Thermal Imagers Comparison calibration (Using LP4 calibrated on ITS-90 fixed points Ag, Cu, Fe–C and Co–C (±0.45 to ±2.5 °C @3000 °C) and Variable temperature blackbodies of emissivity greater than 0.997)	50 to 1300 °C and 600 to 3000 °C	±0.6 to ±1.2 °C and ±1.5 to ±4.0 °C
9	Blackbody Sources	50 to 1600 °C (beyond on case-by-case)	±1 to ±2.5 °C
10	Thermal Sources ([Dry Block Calibrator/Furnace/ Oven/Heating Chamber/Climatic Chamber)	−196 to 1600 °C	Depending on the combination of sensors and measurement units used
11	Relative Humidity Hygrometer	10 to 95% at temperature from −10 to 60 °C (Humidity only)	±0.3% RH
12	Air Temperature Sensor/Hygrometer and Surface temperature sensor	−10 to 60 °C at humidity @ fixed RH (Temperature only)	±0.02 °C
13	Dew Point/Frost Point Temperature	−30 to 60 °C	±0.07 °C
14	Moisture Meters (Integrated loss-on-drying method and Karl Fischer Titration method)	As per the samples standard or sample basis (solids and liquids)	0.3% MC
15	Moisture sample testing	As per the customer requirement	0.3% MC
16	Clinical/Medical Thermometer (Contact Type) (Source uncertainty = 0.03 °C, stability 0.01 °C) Calibration and Testing for Model Approval	35– 43 °C, (95–109.4 °F)	Laboratory accuracy ± 0.1 °C/LIGT; ± 0.2 °C/Electrical or As per the Standard Used

Table 8.4 (continued)

S. No.	Calibration items	Temperature range	Uncertainty ($k = 2$, 95% CL)
17	IR Ear/Fore Head (Non-contact type) (Source uncertainty = 0.06 °C, Stability 0.01 °C, source designed and developed as per International Standards) Calibration and Testing for Model Approval	35–43 °C, (95 to 109.4 °F)	Laboratory accuracy ±0.3 °C, as per the standard used
18	ITS-90 fixed-point cells- TPW, Other fixed-point cells for SPRT calibration- fixed-point cell with the user realization apparatus will be taken on case by case basis	−196 to 962 °C Simultaneous realization of NPL and DUC cell using NPL SPRT and Resistance Thermometry Bridge	±4 to ±0.3 m°C (TPW) to ± 80 m°C, depending upon the construction, impurity levels and plateau realizations

Table 8.5 CMCs of temperature and humidity parameters

Parameter	Instrument	Instrument type/Method	Range (°C)	Value
Temperature	Stem SPRT	Ga melting point cell	29.7646	1.36 mK
Temperature	LIGT, 0.05 °C	Comparison at water bath	5–95	0.02 °C
Temperature	LIGT, 0.05 °C	Comparison at oil bath	95–200	0.03 °C
Temperature	IPRTS	Comparison at oil bath & TPW cell	0.01–100	4–15 mK

8.1.3.4   Potential Services for Future Requirements

In ITS-90, the TPW cell is defined with the Vienna Standard Mean Ocean Water (VSMOW) with specific content of isotopes of Hydrogen and Oxygen. However, it is practically very difficult to maintain the purity level and isotope content in the water. Therefore, TPW becomes the material-dependent property or an artefact. The kelvin, earlier defined by the TPW, has been redefined in May 2019, by assigning an exact numerical value to the Boltzmann constant, as all the thermal energies are expressed as kT in the laws of physics. If k is fixed, the 'T-thermodynamic temperature" can be measured by computing the energy. This redefinition will ensure long-term stability and traceability of the unit for temperature by making it independent of any material substance.

CSIR-NPL is working in the direction of establishing facility to determine Boltzmann constant (k) and measurement of thermodynamic temperature by Acoustic Gas Thermometry. The combined acoustic-microwave copper spherical resonator has been fabricated to measure the velocity of sound to estimate the value of Boltzmann constant. The Boltzmann constant is the conversion factor between mechanical energy and temperature.

We have set up a calibration facility for IR clinical thermometers in India for the first time. This is a vital step for moving from the era of mercury thermometer to an era of mercury free thermometer to phase-out the mercury in healthcare applications. This standardization of mercury-free clinical thermometers is significant development in view of WHO and Minamata convention. Further, this is a major step in the present pandemic situation of COVID-19 where IR thermometers are playing a key role in screening the patients at the first level. These initiatives will help improve the quality of life and Society as a whole.

8.1.3.5   A Decade of Clients and Services

Calibration and Testing

CSIR-NPL provides the calibration service to several strategic sectors like DRDO, DAE-NPCIL (through other clients), ISRO (Bangalore, Ahmadabad, and Trivandrum), Air Force, Railway, BHEL, Oil–Gas and Petrochemicals,

Table 8.6 List of international comparisons participated by CSIR-NPL in temperature and humidity metrology

S. No.	Parameter	Range	Year	Name of Inter-comparison	Identification	Organized by
1	Temperature (Tungsten Strip Lamp No. 229A) Bilateral Comparison	1000–2000 °C	July–Aug. 1990	"Temperature unit standard inter-comparisons" of Bilateral Cooperation plan in the field of Temperature Metrology	Stage 3, Theme5.17	Bilateral Cooperation plan in Temperature Metrology between NPL, India and VNIIM Russia (USSR)
2	Temperature (Hg-in-Glass Thermometer) Among 7-Laboratories participated	0–50 °C	Dec. 2000	SADC-MET Regional Inter-laboratory Comparison. (SADC.T-P1)	SADC.T-P1	CSIR-NML, South Africa
3	Temperature (Type-R Thermocouple) 12-Laboratories participated	0–1100 °C	Sept–Dec. 2005	APMP Regional Comparison of Type-R Thermocouple	APMP-03	APMP Coordinated by NMIA, Australia
4	Pt/Pd Thermocouple on Co–C Eutectic fixed point	1324 °C	May 2016	APMP-T-S7 Supplementary Comparison, 7 NMIs	APMP-T-S7	APMP, Pilot-KRISS
5	Type-R Thermocouple on Cu, Co–C and Pd Fixed points	Up to 1554 °C	Nov 2017–2019 (Ongoing)	APMP-T-S16 Supplementary Comparison, 9 NMIs	APMP-T-S16	APMP, Pilot-NMIA
6	SPRT on Triple point of Mercury, Water, Gallium, Tin, Zinc (-38 oC to 420 oC)	−38.8344 to 419.527 °C	2000	Report available in App. C of KCDB of BIPM	APMP KC-3	Bilateral between VMI, Vietnam and NMI, South Africa

(continued)

Table 8.6 (continued)

S. No.	Parameter	Range	Year	Name of Inter-comparison	Identification	Organized by
7	SPRT on freezing point of Aluminum	660.323 °C	2004	Report available in App. C of KCDB of BIPM	APMP TK-4	APMP, Pilot-KRISS
8	SPRT on Freezing point of Silver	961.78 °C	2004	Report available in App. C of KCDB of BIPM	APMP TK-4	APMP, Pilot-KRISS
9	SPRT on Freezing Point of Zn to Triple Point of Ar	−189.344 °C −38.8344 °C 29.764 °C 156.598 °C 231.528 °C 419.527 °C	2018–2019	Ongoing	APMP TK-9	APMP, Pilot- NIM, China

STQC/ERTLs/ETDCs, IMD departments, Dairy, Ordinance Factory, private firms, intra and inter departments in CSIR-NPL and many more.

Consultancy and Technical Services

CSIR-NPL provides consultancy and technical service depending on the client's requirement. Several technical and consultancy service projects have been completed/undergoing. Out of them, one recent is sponsored by Legal Metrology Department to design, develop, fabricate and establish the testing and calibration facility for clinical thermometers (liquid-in-glass and electrical) with maximum device at 2 Regional Reference Standards Laboratories at Guwahati and Ranchi centers. This project will be completed by the mid 2021. Recently, a new technical service project is taken up by CSIR-NPL from DRDO-SASE for vetting of the items related to temperature, humidity and pyrometry services as part of this activity.

Training and Academic Services

Training program is conducted annually at CSIR-NPL to the officers of the different areas. We have given training to Legal Metrology officers, Air India officers, Indian Oil, ISRO, ARAI Pune at times which benefits them to understand various procedures adopted in the temperature and humidity metrology and help for accurate measurements. Various proficiency testing programs were organized by the Group in LIGTs and TCs in collaboration with NABL to disseminate the traceability of the laboratory to the NABL accredited laboratories and user industry as a part of metrology service to the nation.

Technology Development and Commercialization

Liquid temperature bath has been developed from −40 to 250 °C at CSIR-NPL and is transferred to M/s KV Scientific, Kirti Nagar, New Delhi.

8.1.3.6   Major Documentary Standards, Guides and SOPs

- Guide to the Realization of the ITS-90
- Fischer J, Battuello M, Sadli M, Ballico M, Park S N, Saunders P, Zundong Y, Johnson B C, van der Ham E, Li W, Sakuma F, Machin G, Fox N, Ugur S, Matveyev M (CCT-WG5 on radiation thermometry) (2003b) "Uncertainty budgets for realisation of scales by radiation thermometry" Working Document of BIPM Consultative Committee for Thermometry, 22nd Meeting, Document CCT/03–03.

8.1.4 Possible Gaps and Suggestions for Their Redressal

Realization of the Boltzmann constant based new kelvin at CSIR-NPL is essential to complete the traceability in temperature metrology at par [18]. We are also working to realize the new kelvin in radiation thermometry range by developing the new metal–carbon blackbodies, where ample opportunity is there to have in-house and improved traceability beneficial for thermometry and radiometry parameters. Besides this we lack behind the CMCs published in KCDB at present which has to be improved. We have to participate in international inter-comparisons and develop our facilities. There is yet no representation of India in TCT or APMP in Thermo-physical properties, such as thermal conductivity, thermal diffusivity, emissivity, etc. which need to be addressed, particularly for the new novel materials with the advancements in nano-sciences and nano-technology. This is an important area as most of the industries depend on this parameter for the quality check of their base materials. In radiation thermometry, emissivity measurement is a significant parameter and the accuracy of the temperature measurement hugely depend on this, however, we still need to develop facility for the emissivity measurement.

The group is also engaged in research and developmental activities for the creation of facility to realize Boltzmann constant based the new kelvin by developing the acoustic gas thermometry from about −80 to 100 °C, which can be enhanced later to about 1000 °C. Simultaneously, we are developing metal–carbon eutectic fixed points to realize the thermodynamic temperatures upto 3000 °C. With these two approaches, the CSIR-NPL possible traceability chart for the new kelvin is given in Fig. 8.12.
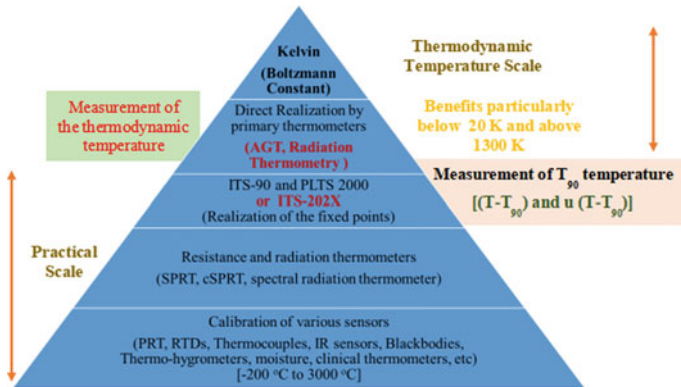

Fig. 8.12 Traceability chart

8.2 Optical Radiation Metrology

Radiation Metrology essentially covers metrology of all the electromagnetic waves or radiation fields which is studied under the branch of science called, 'Radiometry'. Therefore, radiometry is generally related to physical measurement of energy content and other properties of the electromagnetic radiation fields, including light or optical radiation, which is nothing but a very small visible spectral window of the electromagnetic spectrum. Radiations, on the other hand, obtained from radio nuclides, cosmogenesis and cosmic rays or artificially produced radiations, such as X-rays, gamma rays, etc. falls under 'Ionizing radiation', which have the tendency to ionize the medium present.

Photometry describes radiation effect of visible spectrum, perceived by the human eyes. It is science of measurement of physiological effects of electromagnetic radiation falling in visible spectral range, on the human eyes and can be defined in terms of photometric parameters, similar to those of radiometric parameters. The two fields of metrology namely, photometry and radiometry, and their parameters are closely linked and related through the current definition of the SI base unit, candela for luminous intensity [18]. The candela is the only SI base unit among the remaining six base units, related to a fundamental biological process 'human vision'.

The radiometric units (Q_e) can be converted to the photometric units (Q_v) using the following equation [19, 20]:

$$Q_v = K_m \int\limits_{380nm}^{780nm} Q_e(\lambda).V(\lambda)d\lambda \tag{8.11}$$

where $V(\lambda)$ is termed as the spectral luminous efficiency function, which describes the relative spectral responsivity of the average human eye for photopic vision (light adopted) and scotopic vision (dark adopted). K_m is a constant giving the number of photometric units corresponding to 1 radiometric unit at 555 nm, peak wavelength of $V(\lambda)$ curve and is termed as maximum luminous efficacy function and its value is 683 lm/W [19, 20]. Radiometric and photometric parameters and their measurements are extremely vital for number of industries and numerous applications, ranging from lighting, automotive and colour industries, aviation, space, signage, displays and imaging, optical communication, semiconductor, photovoltaic to climate change. Other emerging fields include appearance, terahertz applications, photonics, and quantum-based information.

Traditionally, metrology in both radiometry and photometry is based on primary radiation sources (blackbody radiators, electron synchrotrons) and on primary radiation detectors (cryogenic radiometers). Recent advancements in the controlled manipulation of radiant flux at the level of individual photons show great promise of production of radiant flux of precisely counted number of photons in very near future. The emerging trend towards solid-state lightings also requires the development of new calibration methodologies adapted to the properties of these light sources.

In the present day scenario of global warming and alarming pollution levels, including light pollution, the focus has shifted towards energy-efficient lighting. As the lighting technology evolves, the standardization techniques are also upgraded for meeting the industry requirements. Current Covid-19 pandemic situation has developed researchers' interest towards the effective and contactless sanitization based on ultraviolet germicidal effect of radiation.

8.2.1 Introduction and Historical Aspects

As the mandate of various NMIs is to establish, maintain and upgrade national standards, the unit *candela* is also established, realized and is upgraded accordingly. There are two well-known ways to realize various radiometric and photometric units, (i) source-based radiometry and (ii) detector based radiometry [21]. In the source-based radiometry, sources radiating well-defined radiations are used to realize various photometric and radiometric quantities. Realization of the units requires a primary standard, a physical entity which obeys the definition and the value of the measurand is obtained with minimum uncertainty.

Historical developments of luminous intensity scale are depicted in Fig. 8.13. Initially, before 1948, the photometric standards were light sources such as specified candle, oil lamps and group of carbon filament lamps. From 1948 to 1979, the radiation from a blackbody at the temperature of freezing platinum was used to define candela [21]. Realization of photometric and radiometric units using radiation sources especially blackbody falls in the purview of source-based radiometry and photometry. Blackbody, a well-known source of radiation, which follows the Planck Radiation Law, is also called the primary standard of optical radiation. Source-based radiometry directly follows the Planck Radiation Law [21, 22]. However, various factors namely, its high cost, small lifetime limit its scope in optical metrology. In addition, inter-comparison of an artefact in the form of an incandescent lamp calibrated against blackbody gives higher uncertainty in the measurements and also
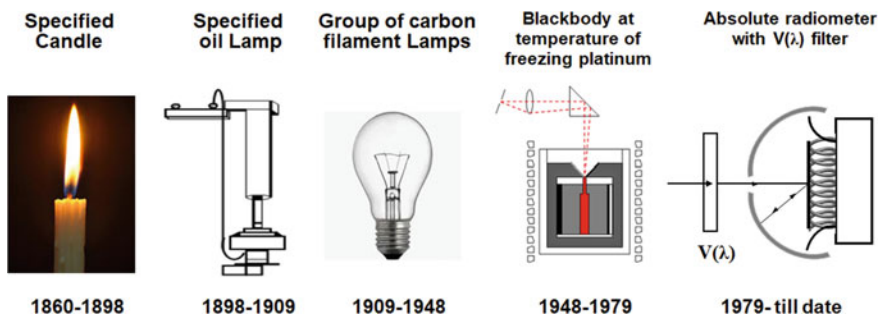

Fig. 8.13 Historical developments of luminous intensity standards

in the transfer of radiometric scales. In 1979, the 16th CGPM (1979) adopted a new definition of the candela following the difficulties in realizing a Planck radiator at high temperatures, and the new possibilities offered by radiometry, i.e. the measurement of optical radiation power, in which candela was expressed in terms of derived unit "Watt" [18–20].The present definition of the candela uses a fixed numerical value for the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, adopted in Resolution 1 of the 26th CGPM (2018).

Candela (cd), the SI base unit of luminous intensity, in a given direction, of a source that emits monochromatic radiation of frequency 540×10^{12} Hz and that has a radiant intensity in that direction of 1/683 W per steradian. It follows that the spectral luminous efficacy for monochromatic radiation of frequency of 540×10^{12} Hz is exactly 683 lumens per watt, $K_m = 683$ lm/W $= 683$ cd.sr/W. This definition is given in terms of monochromatic radiation (540×10^{12} Hz) rather than the broadband radiation emitted by a blackbody. This new definition provided a basis for establishing, on firm forting, a detector based radiometry [21, 23–28]. A detector, which is a self-calibrating device, can be used as primary standard of optical radiation. Therefore, electrically calibrated radiometers, which are also referred to as absolute radiometers, make the basis for detector-based radiometry. The detector based radiometry overcomes the shortcomings that were apparent in source-based radiometry.

8.2.2 Significance, Applications and Relevance in Different Sectors

Artificial Lighting is used not only for the purpose of general illumination but for a plethora of applications spanning various sectors including medical, defence, space, aviation and industrial manufacturing. Being used in such areas of strategic applications the standardization and accurate measurement of lighting speaks its importance. Not being different from other sectors, medical sector also depends heavily on lighting applications not only for examination and facilitating complex medical procedures but also for therapeutic applications.

Specialized lighting is used as illuminant on a dentist's chair, examination room, operation theater, and procedure rooms. Apart from these light finds application in the form of laser employed in various surgeries, from phototherapy in infants and adults to antimicrobial treatments. Optical diagnosis and imaging procedures like endoscopy, ophthalmic imaging, optical coherence tomography, etc. depend on application of light. Recently, light has also been used in path-breaking fields of drug-delivery in the form of light-activated nano-medicine, optogenic therapies implantable opto-electronic devices, etc. [29, 30]. All these applications require proper dosage of light and hence a standard and scientifically proven protocol for accurate measurement.

Germicidal illumination has gained importance in the present era of Covid-19 pandemic where for the germicidal action, radiation in the UV region is used [31]. To

eliminate inferior quality products from the market and provide standard products to the consumer, quality assessment of the UV illuminants is important. Recently, CSIR-NPL has augmented its spectral irradiance measuring capability for standardizing UV lights for catering the traceability services for germicidal applications.

In the area of defence, when technology plays a vital role in the modern warfare, the use of lighting has its own strategic importance. Right from using light for illumination along strategic areas and perimeter control, it is also used in weapon systems. Laser light is actively used in guided missile systems, satellite communication, range finders, jammers and communicators. Apart from these, Laser light itself is used as a potential weapon. Low light imaging and surveillance also remain an important defense application. Another important application is the night vision equipments involving light detection in the infrared region. In defense systems fiber-optic and laser gyros play an important role as inertial navigation sensors. Being of strategic importance in national defense, these systems require proper standardization to avoid on-field failures [29].

Lighting plays a very crucial role in the aviation sector as the modern-day aviation largely depends on it for critical activities. On an aircraft apart from the interior lighting, the exterior lighting plays crucial roles of position lighting, anti-collision lighting, navigation lights, landing lights and taxi lights. Another important aspect of lighting in the aviation sector is the runway lighting comprising runway edge lights, runway threshold lights, and runway end lights along with supplementary runway lightings. Testing and standardization of these lightings are of utmost importance for passenger and crew safety.

Space technology also depends on optical standardization. Vital components like satellite reflectors, laser gyros, and high-resolution satellite camera optics require apex level calibration. Upcoming space technologies like Laser satellite ranging and Light propelled spacecraft will be compelling for enhancement of the measurement capabilities.

Apart from the strategic applications discussed above, lighting plays an important role in the day-to-day activity of human society. Automobile lighting is one of them and requires proper testing and calibration of the illumination produced. Paint industry requires standardization in a respect other than illumination. Its requirement is limited for measurement of consistency with respect to colour. However, the general lighting industry remains concerned about both colour and different aspects of illumination.

In the past two decades the lighting, its various other applications and deployability with latest technological forms have evolved enormously which has propelled the requirement of upgradation of the photometric measurement protocols. With the growing importance of energy conservation leading to the increased manufacturing and usage of LED lightings, CSIR-NPL is in the process of establishing a facility, with funding from the Bureau of Energy Efficiency (BEE), Ministry of Power and Council of Scientific and Industrial Research (CSIR), to augment its state of the art photometry and radiometry facility for providing testing and calibration services to the entire nation and beyond the borders.

8.2.3 Facilities and Global Status

The quantification of photometric and radiometric parameters is of utmost importance in a wide range of industries including lighting, textiles, automotive and in health and medical industries. Few of the major existing facilities with Optical Radiation Metrology which are being used for catering services and to realize various parameters in the laboratory includes Blackbody, Cryogenic Radiometer, Goniophotometer, Integrating spheres, Fourier Transform IR Spectrometer, Double monochromator based spectral irradiance measurement setup, Spectrophotometers, Correlated photon metrology setup, Luminance measurement setup, Colour measurement setup, Near field Scanning Optical Microscope, various standard lamps, detectors, etc.

The CMCs on certain parameters and respective specific ranges are already published and available with their measurement uncertainties at BIPM-KCDB, also presented in detail in Sect. 8.2.3.2. To have an overall scenario and the global status of photometry and radiometry, selected facilities available across some NMIs are being presented based on their CMCs as published in the BIPM-KCDB.

National Institute of Standards and Technology (NIST) the NMI of USA [32], has a number of CMCs in the field of photometry and radiometry. To select a few, NIST has the capability of measuring Luminance (in the range 0.01–50,000 cd/m^2) using Integrating Sphere based source and has ability to provide Luminance responsivity of a Luminance Meter (in the range of 1–10,000 cd/m^2). Luminous intensity scale is provided for Tungsten lamps (in the range 0.01–10,000 cd) and for LED (in the range 0.01–1000 cd for white, red, green and blue LEDs) with uncertainties varying in different ranges. It has the capability of providing Illuminance Responsivity for Illuminance meters (over the range of 1 mlx–1 klx) using standard illuminant A. It can also provide scale for Illuminance over the range of 0.001–70,000 lx over a colour temperature of 2000–3200 K. NIST, USA has measurement capability of Luminous Flux for Tungsten Lamps (0.001–200,000 lm) and LED Lamps (0.001–10,000 lm for white LED) with uncertainties varying in different ranges. NIST also provides scale for colour coordinates (*x*, *y* and *u*, *v*) and Correlated Colour Temperature. Spectral Irradiance calibration is provided for Tungsten Lamps (250–2500 nm wavelength) and for Deuterium Lamp (200–400 nm) including UV, visible and IR ranges with uncertainties varying in different wavelength ranges. Spectral Radiance (225–2500 nm) and Spectral Radiant Flux (300–1100 nm) calibration services are also provided for Tungsten lamps. Calibration of detector responsivity is provided for various detectors.

The German NMI, Physikalisch-Technische Bundesanstalt (PTB) [33] also provides significant technical and scientific services in the field of photometry and radiometry. Calibration services for the parameter of Luminous Intensity is provided using a network of lamps and photometers over a range of 0.001–100,000 cd with one of the best uncertainty. It provides scale for Luminous Flux of Tungsten Lamps based on Goniophotometer measurements over a range of 0.001–100,000 lm with different range wise uncertainties. The capability of Illuminance measurement of Tungsten Lamp spans over a range of 0.001–100,000 lx. Services for calibration of averaged

Luminous Intensity for LED are also provided. It maintains the Spectral Irradiance Scale using the Deuterium Lamp and the Tungsten Lamp over respective wavelength ranges of 200–350 nm and 250–2500 nm with respective range wise measurement uncertainties. The spectral Radiance scale is maintained using the Deuterium Lamp (116–350 nm wavelength range) and the Tungsten Lamp (250–2500 nm wavelength range). However, the Spectral Radiant Intensity scale is maintained over the UV region of 116–350 nm through a Deuterium lamp. PTB, Germany also facilitates the calibration of detector responsivity for various detectors.

The National Physical Laboratory (NPL), UK [34] has Goniophotometer and Integrating Sphere based capability of measuring Luminous Flux of Tungsten Lamp over the range 1.0–20,000 lm. The Luminous Intensity measurement capability ranges over 1.0–10,000 cd for Tungsten Lamps having a CCT of 2000–3200 K. NPL, UK has the facility of measuring Illuminance over a range of 0.1–50,000 lx for Tungsten Source. The CMC for Luminance ranges over 1.0–20,000 cd/m^2. NPL, UK also has the measurement capability of Illuminance, Responsivity and Luminance Responsivity of respective meters. In the domain of colour measurements NPL, UK has the measuring capability of colour coordinates (*xy* and *u'v'*) and Correlated Colour Temperature. The Spectral Irradiance, Spectral Radiance and Spectral Radiant Intensity scales are maintained using the Tungsten Lamp over 250–2500 nm wavelength range. It has the facility of measuring responsivity of various detectors and spectroradiometers.

8.2.3.1 Measurement Standards and Facilities

Primary standard is a physical entity which obey the definition of a measurand along with its unit. The uncertainty in the measurement of the unit is, therefore, minimum. One can make a perfect blackbody at a well-defined temperature and hence have a source of known radiance [22]. Or else one can develop an absolute radiometer which can measure irradiance directly without requiring a calibrating source [24, 32, 33]. Hence, a blackbody and an absolute radiometer are the primary standards for optical radiation measurements.

Blackbody: Source-Based Primary Standard for Optical Radiation

Blackbody is a source of well-defined radiation following the Planck Radiation Law. According to the Planck Radiation Law, the spectral radiance at a given wavelength λ and at a particular absolute temperature T, defined as [21, 30, 31]:

$$L_\lambda(\lambda, T) = \varepsilon_\lambda c_{1L}/(n_\lambda^2 \lambda^5 (\exp[c_2/(n_\lambda \lambda T)] - 1))\text{W/cm}^3/\text{sr} \qquad (8.12)$$

where ε_λ is the spectral emissivity (1 for ideal blackbody), c_{1L} is the first radiation constant and its value is equal to 1.191043×10^{-12} Wcm^2, c_2 is the second radiation

Fig. 8.14 Schematic
diagram for spectral radiance
measurement with blackbody
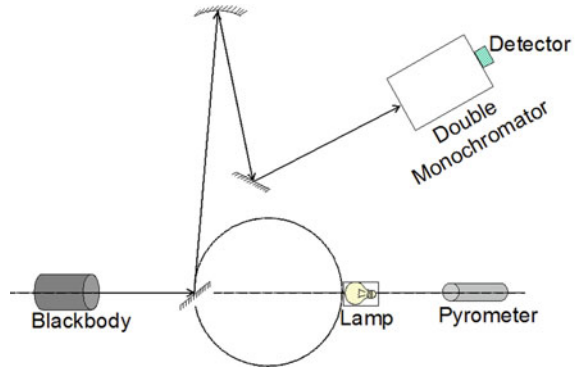
constant equal to 1.4388 cm K, n_λ is the refractive index of air at 15 °C and 1 atmospheric pressure.

Figure 8.14 depicts the measurement setup in schematic diagram for spectral radiance measurement setup. The temperature of the blackbody is measured by optical pyrometer to a minimum uncertainty and then it is used as a primary standard source whose spectral radiance is determined from Planck's blackbody equation. Further, the spectral radiance and irradiance scales are transferred to transfer standard sources, which are generally tungsten lamps [21, 22]. Primary standard of optical radiation in the form of a variable temperature (1800–3200 K) blackbody (Emissivity ~ 0.999) has been established at CSIR-NPL India. Blackbody is a thermal source emitting optical Planck's radiation in the ultraviolet, visible and near-infrared range, i.e. prominently in the wavelength range from 250 to 2500 nm. It features a radiator assembled of pyrographite rings with a cylindrical cavity heated by DC flowing directly through the radiator. The radiator with thermal insulation unit is mounted in a water-cooled chamber with an output window opened to the atmosphere and continually blown through with Ar gas. The chamber is also supplied with a system for preliminary air evacuation by means of vacuum pump. It also has a temperature stabilizing system based on optical feedback principle. In addition to 0.1% radiance uniformity, it also exhibits thermal stability in the range of ± 20 mK.

Initially, the blackbody is stabilized at certain temperature e.g. (2850 ± 0.02) K in the temperature stabilization mode with the help of optical feedback system and optical pyrometer. After stabilizing the blackbody at a particular temperature, the radiance values of the blackbody and the working standard lamp at various wavelengths in UV, visible and near-infrared region are measured using measurement system consisting of a double monochromator, photomultiplier tube (PMT), Si-photodiode and PbS-Te detectors. By comparing the spectral radiance of blackbody and working standard lamp, the spectral radiance scales are transferred for further calibrations.
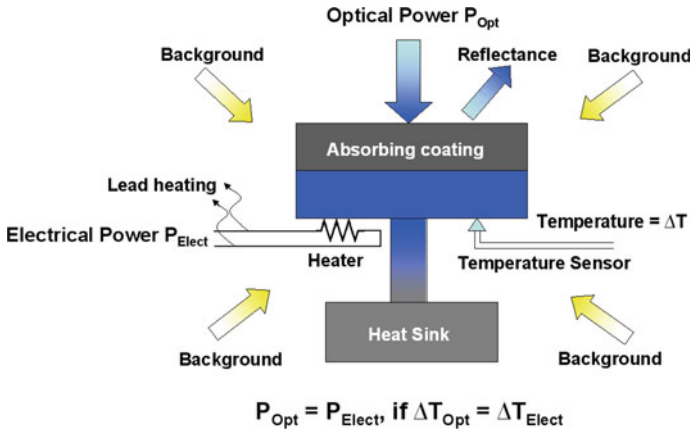
Fig.8.15 Schematics and principle of an ESR Radiometer

Cryogenic Radiometer: Detector Based Primary Standard for Optical Radiation

Absolute radiometers work on the principle of electrical substitution, in which optical power is linked with the electrical power [21, 25]. In the radiometers, absorbing cavity is used, which causes rise in temperature (ΔT) due to absorbed optical power, Fig. 8.15. Same rise in temperature is obtained by thermal heating with electrical power. When the two power inputs cause the same rise in temperature (ΔT) the optical (radiometric) and electrical powers are equivalent assuming negligible dissipation losses of energy. Hence, an electrically calibrated radiometer (ECR) uses the equivalence of radiant and electrical heating and therefore, the principle is also known as electrical substitution radiometry (ESR). An ECR has essentially 3 elements, (i) a radiation-absorbing element in which the absorbed power causes temperature rise; (ii) electrical heater with controllable and measurable electrical wattage; and (iii) a temperature sensor that is used to measure equality between radiant heating and electrical heating [25].

The measurement uncertainty in such ECRs can be reduced by keeping it at cryogenic temperature, which results in reduction in thermal noise upto a great extent as well as stability in measurements. Using cryogenic radiometers, the uncertainty can be reduced by factor > 50. Therefore, most of the NMIs prefers to realize SI base unit of luminous intensity, candela using cryogenic radiometer [27, 35]. CSIR-NPL India has also established the facility of cryogenic radiometer in 2014 for reducing the uncertainties in measurements, Fig. 8.16.

This cryogenic radiometer has a cavity absorbance 0.9998 at 632.8 nm wavelength and established to realize radiometric measurements in the visible region of spectrum. Cryogenic radiometer receiver cavity and heat sink replacement assembly has a receiver responsivity of (2 ± 0.25) K/mW, thermal response time < 5 s, and dynamic range 1.0 μW–1.0 mW. The noise, in this case, is as small as 2 nW and
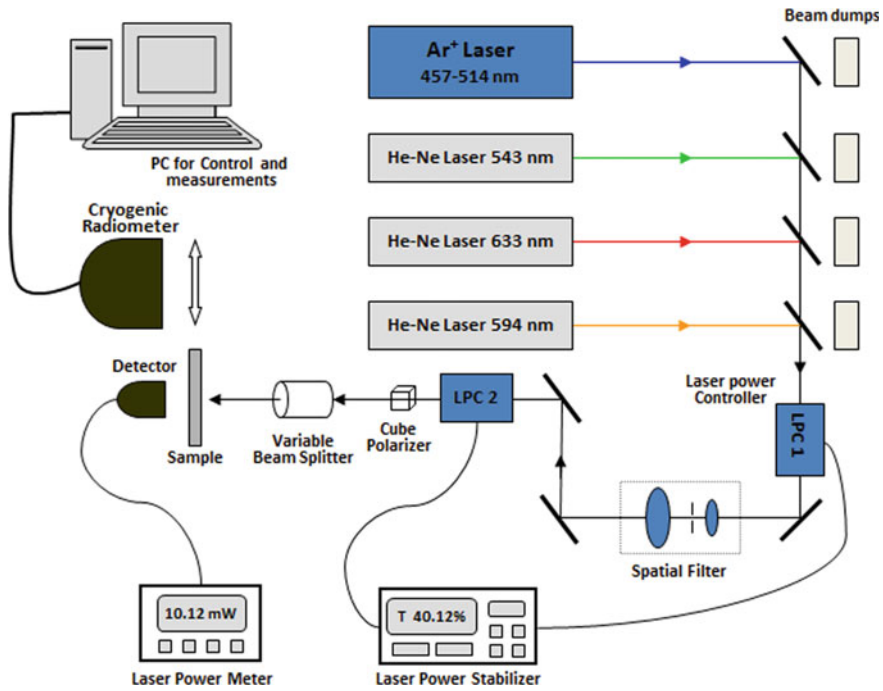
Fig. 8.16 Schematic diagram of the Cryogenic radiometer setup with laser alignments

absolute accuracy is of the order of 0.005%. The cavity is operated at the cryogenic temperature of 4.2 to 9 K, depending upon the optical power levels. The electronic control system exhibits two AC-Bridge thermometry circuits, two heater supply and measurement circuits for receiver and heat sink, multiple microprocessor controllers, temperature control circuit for the printed circuit boards, silicon diode thermometry readout for cryostat, calibration and system verification electronics. It also has a Brewster window assembly with transmission value of 99.96% at 632.8 nm, for laser measurements, kinematic window mount and liquid helium transfer line. Intensity stabilized Ar + ion along with other gas lasers, with frequency stability ± 1% or better, at various wavelengths is used for calibrating the radiometer at different wavelengths [27] in the visible spectral range. Turbomolecular pumping system provides oil-less operation for creation of ultra-high vacuum to reduce radiation and other losses inside the radiometer. High-quality trap detectors are used as transfer standards for transferring the scale of measurements [26, 28].

Radiometric and photometric measurements are of prime importance for a wide range of industries, including lighting, automotive, opto-electronics, telecommunications, space and health and safety. Precision measurements are required for quality control in industries and is key for new scientific findings. Optical radiation metrology at CSIR-NPL, encompasses traceable measurements in the spectral region of electromagnetic spectrum from 200 nm to 25 μm. The spectral region from

Table 8.7 Details of major calibration facilities with optical radiation metrology

Parameter	Range
Luminous intensity	$1-10^3$ cd
Luminous flux	$1-2 \times 10^4$ lm
Illuminance	$1-5 \times 10^3$ lx
Luminance	$1-10^4$ cd/m^2
Correlated colour temperature and chromaticity coordinates	2000–7000 K
Spectral irradiance (W/m^{-2} nm)	Wavelength range: 280–400 nm 400–800 nm 800–2500 nm
Spectroscopic measurements	
Spectral reflectance Diffuse Specular	380–780 nm
Spectral transmittance	380–780 nm

200 to 2500 nm is maximally used for measurement of photometric and radiometric parameters in many applications of interlinking disciplines. The core objective of the Optical Radiation Metrology at CSIR-NPL is to realize, establish, maintain, and upgrade the existing SI base unit of optical radiation, i.e. candela, and their derived units to provide apex level traceable calibration for various photometric parameters namely, luminous intensity, illuminance, luminous flux, luminance, detector responsivity, colour temperature and radiometric parameters namely, spectral transmittance, reflectance and spectral irradiance in the spectral range of 280–2500 nm. Table 8.7 shows the details of major calibration facilities with Optical Radiation Metrology.

8.2.3.2 Calibration and Measurement Capabilities

Currently, CSIR-NPL has 14 numbers of published CMCs for different photometric and radiometric parameters, namely luminous intensity, illuminance, illuminance responsivity, luminance, correlated colour temperature, luminous flux and spectral irradiance for their different respective ranges, which are available online at KCDB as listed in Table 8.8.

In addition, the measurement facilities for derived spectroscopic parameters namely spectral reflectance, spectral transmittance, absorbance, and polystyrene film calibration using FTIR technique are also available. Other calibration facilities of optical radiation metrology include calibration of thermo-vision camera, blackbody and NIR related measurements.

Table 8.8 List of calibration and measurement capabilities of CSIR-NPL India in the field of photometry and radiometry (PR)

Calibration or measurement service			Measurand level or range			Measurement conditions/independent variable		Expanded uncertainty			Level of confidence (%)	Is the expanded uncertainty a relative one?
Quantity	Instrument or artefact: measurand	Instrument type or method	Min. value	Max. value	Units	Parameter	Specifications	Value	Units	Coverage factor		
Luminous intensity	Tungsten lamp	Reference lamps and photometers	1	100	cd	Correlated colour temperature	2000–3000 K	1.6–1.4	%	2	95	Yes
Luminous intensity	Tungsten lamp	Reference lamps and photometers	100	1000	cd	Correlated colour temperature	2000–3000 K	1.4	%	2	95	Yes
Illuminance responsivity, tungsten lamp	Illuminance meter	Reference lamps and photometers			nA/lx	Correlated colour temperature	2000–3000 K	1.4	%	2	95	Yes
Luminous flux	Tungsten lamp	Integrating sphere, goniophotometer	1	100	lm	Correlated colour temperature	2000–3000 K	2.0 to 1.8	%	2	95	Yes
Luminous flux	Tungsten lamp	Integrating sphere, goniophotometer	100	20,000	lm	Correlated colour temperature	2000–3000 K	1.8–1.9	%	2	95	Yes
Illuminance	Tungsten lamp	Photometer	1	1000	Lx	Correlated colour temperature	2000–3000 K	1.6	%	2	95	Yes
Illuminance	Tungsten lamp	Photometer	1000	5000	lx	Correlated colour temperature	2000–3000 K	1.6–2.0	%	2	95	Yes
Luminance	Tungsten lamp	Calibrated integrating sphere d iff user and telephotometer	1	10	cd/m^2	Correlated colour temperature	2000–3000 K	2.0–1.8	%	2	95	Yes

(continued)

Table 8.8 (continued)

Calibration or measurement service			Measurand level or range			Measurement conditions/independent variable		Expanded uncertainty				
Quantity	Instrument or artefact: measurand	Instrument type or method	Min. value	Max. value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of confidence (%)	Is the expanded uncertainty a relative one?
								Expanded uncertainty				
Quantity	Instrument or artefact: measurand	Instrument type or method	Min. value	Max. value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of confidence (%)	Is the expanded uncertainty a relative one?
Luminance	Tungsten lamp	Calibrated integrating sphere diffuser and telephotometer	10	1000	cd/m²	Correlated colour temperature	2000–3000 K	1.8–1.6	%	2	95	Yes
Luminance	Tungsten lamp	Calibrated integrating sphere diffuser and telephotometer	1000	10,000	cd/m²	Correlated colour temperature	2000–3000 K	1.6–2.0	%	2	95	Yes
Spectral irradiance	Tungsten lamp	Spectral irradiance comparator	0.001	0.2	W/(m² nm)	Wavelength range	280–400 nm	6.0–1.9	%	2	95	Yes

(continued)

Table 8.8 (continued)

Calibration or measurement service			Measurand level or range			Measurement conditions/independent variable		Expanded uncertainty				
Quantity	Instrument or artefact: measurand	Instrument type or method	Min. value	Max. value	Units	Parameter	Specifications	Value	Units	Coverage factor	Level of confidence (%)	Is the expanded uncertainty a relative one?
						Bandwidth	10 nm					
Spectral irradiance	Tungsten lamp	Spectral irradiance comparator	0.001	0.2	W/(m² nm)	Wavelength range	400–800 nm	1.9	%	2	95	Yes
						Bandwidth	20 nm					
Spectral irradiance	Tungsten lamp	Spectral irradiance comparator	0.001	0.2	W/(m² nm)	Wavelength range	800–2500 nm	3.3–5.2	%	2	95	Yes
						Bandwidth	50 nm					
Correlated colour temperature	Tungsten lamp	Colorimeter	2000	3000	K			20	K	2	95	No

Table 8.9 List of various key comparisons performed by CSIR-NPL India in the area of Photometry and Radiometry (PR) and their current status

Comparison identifier	Metrology area	Sub-field	Description	Measurement period	Pilot institute	Status
APMP.PR-K3.a	Photometry and radiometry	Photometry	Luminous intensity	2012–2014	NMIJ AIST	Measurements in progress
APMP.PR-K4	Photometry and radiometry	Photometry	Luminous flux	2006– 2007	NIM	Approved for equivalence
APMP.PR-K3.b	Photometry and radiometry	Photometry	Luminous responsivity	1998–2000	NMIA	Approved for equivalence

8.2.3.3   Participation in International Key Comparisons

CSIR-NPL India, being a member of APMP, has been participating regularly in various key comparisons which are listed in Table 8.9.

Apart from this CSIR-NPL is also participating in the key comparison (APMP K1.a) for spectral irradiance within 250–2500 nm, to be piloted by the link laboratory NIM China, scheduled after the year 2020, as decided in the 33rd APMP General Assembly and Related Meetings, hosted by CSIR-NPL India during November 2017. Further, in order to establish new calibration and measurement capabilities (CMCs) in the area of LED metrology, CSIR-NPL India is also planning to participate in various other international inter-comparisons based on LED standards, post-installation of major measurement Systems under the LED testing and calibration facilities.

8.2.3.4   Potential Services for Future Requirements

As the challenges and threats towards safety of human life are ever-increasing, lighting technology is evolving and precision measurements and standardization techniques are being upgraded to meet such safety requirements from industries. In the current Covid-19 pandemic situation when the attention is again on radiation-based contactless ultraviolet germicidal lighting to contain the infection. Calibration and testing facility at CSIR-NPL India is being established for testing and standardization of such products to eliminate inferior quality products from the Indian market which may pose serious health hazard to the users. Because of energy efficiency, low power consumption, little heat, faster response, natural coupling for digital control and large lifetime (~50,000 h) Light emitting diode (LED) and LED-based lighting products are paving their ways in not only into lighting sector in a huge way but also into other spheres of general human life and other applications resulting in phasing out of the old energy-inefficient traditional lighting technology. Various countries, especially NMIs are putting their potential effort to explore its capability and bringing out more results relevant to exploit these energy-efficient sources in

terms of customizing its design, engineering and luminous performance. A number of luminaries manufacturing giants in India are shifting their business focus and production towards the LED-based lighting, attributed to its high efficacy and longer life time.

Since the heavy shift of consumers' and production units' interest towards the next generation energy-efficient, long-lived, solid-state lighting (SSL) sources many substandard products are being launched into the Indian market at cheap prices which not only have substandard luminous performance but also may contain harmful blue radiations higher than the level fixed as per the international guidelines. Since these products are not quality tested they may pose high radiation risk to the society if not stopped with calibration/testing mechanism well in place.

Being an apex level measurement laboratory, understanding its responsibility CSIR-NPL is in the process of establishing state of the art, National test and calibration facilities as per the National/International standards for such next generation energy-efficient light products. This facility will not only support the energy saving initiative of Government of India via promoting next-generation energy-efficient lamps on 'green technology', but also eliminate sub-standard products from the market and to cater the need of lighting industries which are in the manufacturing of such lightings. On the other hand, successful implementation and the establishment of such facility would make CSIR-NPL India visible in its R & D efforts towards LED metrology at par with other NMI's.

The SI base unit **candela** the unit of luminous intensity of optical radiation, in a given direction is defined by taking the fixed numerical value of the luminous efficacy of monochromatic radiation of frequency 540×10^{12} Hz, K_{cd}, to be 683 lm/W, which, for a monochromatic source to be 1 cd at frequency of 540 THz, straightway translates into emission of 4.09×10^{15} photons per second, in a given direction per unit solid angle.

The recent development in photon counting technology has revolutionized the areas of electronics, biotechnology, quantum information processing, medical physics, space and military applications, and meteorology. Utilizing the advantages of quantum optical technologies, optical radiation metrology capabilities can be improved [36]. Hence, R&D towards metrology of photons is necessary to take step to realize standard few photon sources for futuristic quantum optical technologies. Since no single photon source has been realized so far that can fulfill the requirements of futuristic photonic technologies. Various leading NMIs including NIST USA, NPL UK, PTB Germany, INRIM Italy, etc., independently and jointly are involved in realization and standardization of photon sources and detectors [37]. CSIR-NPL India has also taken initiative in terms of creating few basic facilities to perform R&D in photon physics, and can take step forward in terms of basic research, which would help to meet the global objectives in few photon metrology.

Fig. 8.17 Pie chart representation of sectorwise report generation over the spectrum of sectors in past one decade
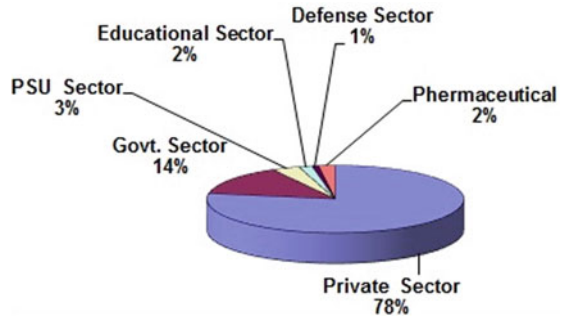
A Decade of Clients and Services

As an apex measurement institute of the country, CSIR-NPL India since last two decades, is catering for traceability requirement related to optical radiation metrology, of a broad spectrum of organizations/entities including various Industries, MSMEs, Research and Development Institutes, Educational Institutions, Testing and calibration laboratories etc. Apart from realization, and being custodian of national standards of optical radiation, CSIR-NPL provides traceability in terms of calibration and measurement service, rendered to various major sectors.

The main parameters for photometry, radiometry and colorimetry, which need precision measurements and calibration for their accurate value requirement in various in-situ measurement applications or have effect in the product development or service quality, are luminous intensity, luminous flux, illuminance, colour temperature, colour coordinates, illuminance, luminance, illuminance responsivity, spectral irradiance, spectral transmission, spectral absorption, wavelength calibration, etc.

Following are some glimpses of data of calibration services rendered to the customers, Fig. 8.17, that includes spectrum of organizations and industries playing significant role in the overall growth of the country and raising a quality infrastructure to complement the society with their quality products or services. Optical Radiation Metrology has contributed significantly in catering to its services through dissemination of traceability to its customer and by generating more than 3700 calibrations and testing reports in past one decade.

The customer base of Optical Radiation Metrology encompasses large variety of stakeholders of Government Sector including few of Ministries also, namely, *Ministry of Electronics and Information Technology, Ministry of Micro, Small and Medium Enterprises, Ministry of Textiles, Ministry of Civil Aviation, Ministry of Heavy Industries and Public Enterprises, Ministry of Railways, State Electricity Boards and various Autonomous bodies working under ministries.*

Table 8.10 List of major calibration parameters with optical radiation metrology

Photometric, radiometric and colorimetric measurements		
Parameter	Range	Measurement uncertainty at coverage factor $k = 2$
Luminous intensity	1–10^3 cd	$\pm$ 1.4–1.6%
Luminous flux	1–2×10^4 lm	$\pm$ 1.8–2.0%
Illuminance	1 lx to 5×10^3 lx	$\pm$ 1.6–2.0%
Luminance	1–10^4 cd/m^2	$\pm$ 1.6–2.0%
Correlated colour temperature and chromaticity coordinates	2000–7000 K	$\pm$ 20 K $\pm$ 0.002 unit
Spectral irradiance (W/m^{-2} nm)	Wavelength range: 280–400 nm 400–800 nm 800–2500 nm	$\pm$ 1.9–6.0% $\pm$ 1.9% $\pm$ 3.3–5.2%
Spectroscopic measurements		
Spectral reflectance Diffuse Specular	380–780 nm	$\pm$ 1.5%
Spectral transmittance	380–780 nm	$\pm$ 1.5%

Calibration and Testing

Optical radiation metrology at CSIR-NPL, generally, covers traceable measurements in the spectral region of electromagnetic spectrum from 200 nm to 25 µm. The spectral region from 200 to 2500 nm is maximally used for measurement of photometric and radiometric parameters in many applications of interlinking disciplines. Such precision and traceable measurements are used in a wide range of industries including General lamp and lighting, automotive, aviation, space, telecommunication, defence, medical and health industries, etc. and are prime requirements for quality control in industries and in scientific research to arrive at novel results. Apart from research in frontier areas of radiation metrology, the mandate of optical radiation metrology at CSIR-NPL is to realize, establish, maintain, and upgrade the existing SI base unit of optical radiation, i.e. candela and their derived units to provide apex level traceable calibration for various photometric parameters namely, luminous intensity, illuminance, luminous flux, luminance, detector responsivity, colour temperature and radiometric parameters namely, spectral transmittance, reflectance and spectral irradiance in the spectral range of 200–2500 nm as discussed in Table 8.10.

Consultancy and Technical Services

Currently, the Optical Radiation Metrology (ORM) is actively involved in consultancy services to strengthen the development of quality product in compliance to

standards guidelines, namely, the Section at present is involved in development of a UVC based sanitization application for MSME to help contain the Covid-19 pandemic infection, The ORM has also rendered its expert consultancy and technical services in past to various lighting industries and R&D organizations, through establishing critical measurement facilities at their sites.

Training and Academic Services

CSIR-NPL is also providing training and organize specialized short term courses on optical radiation metrology to personnel from industry or academic institutions. Such courses are organized, normally twice in each year, or as per need arises, covering hands-on training for optical radiation metrology, lectures and lecture notes on basics of metrology, knowledge of few relevant standards, exposure of hands-on measurement on real experimental set-ups and evaluation of uncertainty involved in measurements.

Since, metrology is a very specialized discipline of science which is why it finds place in curricula of degree courses of countable number of Universities/Institution. It is therefore imperative for CSIR-NPL to conduct specialized regular courses on precision metrology to create a bank of trained human resources to cater to the need of up-coming industry requirements in the field of metrology. Currently, CSIR-NPL is running a one-year Post Graduate Diploma on Precision Measurement and Quality Control (PMQC) under the umbrella of Academy of Scientific and Innovative Research (AcSIR) in the line of skill development of Government of India's programme. Optical Radiation Metrology is one of the key subject area of interest of students of this programme. More than two dozens of students have got their first breakthrough in Industries immediately after completing the course.

Apart from skill development program, guidance of students for their Post Graduate programme and PhD programme of AcSIR is also done.

Technology Development and Commercialization

Having fundamental knowledge and state-of-the-art facilities with Optical Radiation Metrology, CSIR-NPL is engaged in the upfront area of research and developing metrology of next-generation energy-efficient sources and other invisible sources. It is also active in solving societal problems and also working on new problems from industries that poses technological challenges during their commercialization or their reach to society.

8.2.3.5 Major Documentary Standards, Guides and SOPs

Optical Radiation Metrology parameter performs all of its calibration and testing activities according to the requirement of ISO/IEC 17025 and strictly adheres

with quality management system. Few major National and International Standards, pertaining to carry out measurement and calibration activities of Optical Radiation Metrology are listed below in Table 8.11.

Table 8.11 Standard operating procedures/ISO standards used in optical radiation metrology

Sl. No	Standard Operating Procedure/ISO Standards
1	ISO 80000–7: 2019 (EN) Quantities and units—Part 7: Light and radiation
2	CIE S 017/E: 2011 ILV: International Lighting Vocabulary
3	ISO 23539:2005/CIE S 010:2004 Photometry—The CIE System of Physical Photometry
4	ISO/CIE 19476:2014(EN): Characterization of the performance of illuminance meters and luminance meters
5	EN 13032–1: 2004 Light and lighting—Measurement and presentation of photometric data of lamps and luminaires—Part 1: Measurement and file format
6	CIE 202: 2011 Spectral Responsivity Measurement of Detectors, Radiometers and Photometers
7	CIE 015: 2018 Colorimetry (4th edition) & CIE 015: 2004 Colorimetry (3rd edition)
8	ISO 11664–1:2007/CIE S 014–2: 2006 Colorimetry—Part 2: CIE Standard Illuminants
9	CIE 114/4–1994 CIE Collection in Photometry and Colorimetry—Distribution Temperature and Ratio Temperature
10	IES LM-79–2008 Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products
11	CIE S 025/E:2015 Test Methods for LED Lamps LED Luminaires and LED Modules
12	ANSI/IES LM-79–19 Approved Method: Electrical and Photometric Measurements of Solid-State Lighting Products
13	IS 10322 (Part-5/Sec-1): 2012 Luminaire, Particular requirements
14	IS 13383 (Part-1): 1992: Method of photometric measurement of luminaires for use in interior lighting
15	IS 13383 (Part-2): 1992: Method of photometric measurement of luminaires for road & street lighting
16	IS 16106: 2012 Method of electrical and Photometric Measurements of Solid State Lighting (LED) Products
17	IS 16107 (Part-5/Sec-1): 2012 Luminaires Performance
18	IS 16103 (Part-2): 2012 LED Modules for general lighting: Performance requirements
19	Bureau International Des Poids Et Mesures (BIPM), Principal Governing Photometry (2nd Edition), Rapport BIPM-2019/05
20	CIE 198: 2011 Determination of Measurement Uncertainties in Photometry

8.2.4   Possible Gaps and Suggestions for Their Redressal

Since the area of photometry and radiometry has enormous opportunity of playing vital role in various scientific as well as industrial applications, which directly affects the outcome/results or safety and security aspect of human life. Though CSIR-NPL India holds limited number of CMCs depending upon the traceability requirement of industries and testing and calibration laboratories, however, due to rapid industrialization, demand for quality and safety products and rise of high-quality R&D Institutions in the country need for having more and more CMCs in various other derived parameters are now unfolding in exponential way. To cater the present need, it requires CSIR-NPL to expand its measurement and calibration facilities setting up new metrological grade measurement facilities in tune with the rapid growth and demands, with not only as per the national and international standards but also at par with the world's leading NMIs, to suffice the present growing requirements. CSIR-NPL has already taken its step on the way of establishing new measurement facilities understanding the present requirements from industries, especially lighting industries, water purification and sanitization industries and the overall global metrology scenario and setup a quality infrastructure in the country. The upcoming LED-based testing and calibration laboratory at CSIR-NPL is a gamut of state-of-the-art facility which would fill a big gap rendering apex level measurement and traceability to country for not only energy-efficient solid-state lighting (SSL) based products but also for other conventional lighting technologies.

With the advancement of technology and exponential rise of industries, MSMEs to fulfil the consumers' demand, dearth of skilled manpower in the country is always felt. CSIR-NPL as per its capacity, and without compromising in the quality, is conducting specialized regular course on precision metrology and quality control (PMQC) to fill in the big void of manpower in metrology.

8.3   Acoustics and Vibration Metrology

8.3.1   Introduction and Historical Aspects

The Acoustics and Vibration parameter of CSIR-NPL, since its inception, has played a key role in the industrial growth. In accordance with the well-laid out objectives of CSIR-NPL to strengthen and to carry out advance physics-oriented research, the acoustic and vibration parameter has immensely contributed to reducing the air and noise pollution in the country. The major activities involved are calibration of acoustical instruments, evaluation of industrial products, acoustical materials, performance characteristics of audio equipment, auditorium acoustics and noise and vibration measurements and control. The calibration and other facilities available in CSIR-NPL in the area of Acoustics and Vibration are comparable with facilities in other countries. It is equipped with advanced instrumentation for measurement

of sound and vibration and calibration of electro-acoustic equipment such as Sound Level Analyzer, Vibration Analyzer, Sound Intensity Probe and Impedance Tube system, specialized Reverberation and Anechoic Chambers for carrying out sound insulation and absorption studies of materials and diagnosing machinery noise. CSIR-NPL has been able to provide apex level calibration and testing services and technical advisory consultancy in architectural acoustics to the industries and institutions of the country.

This activity has not only provided calibration and testing services to the government bodies and industries but also provided consultancy and other technical services for reducing noise and vibration in machinery, transportation systems and ambient noise levels. The consultancy services provided to Delhi Metro, Bangalore Metro, Archaeological Survey of India, Delhi Development Authority, Central Pollution Control Board, etc. had been instrumental in tackling the noise and vibration issues associated with the transportation systems. The Acoustics and Vibration activity focuses on maintenance and up-gradation of two primary standards viz., the standard of sound pressure and standard of vibration amplitude. This activity is responsible to establish, maintain and upgrade continually the measurement standards of sound and vibration and for providing the apex level calibration services to the users across the country ensuring the measurement traceability in these parameters. The establishment of a self-reliant traceable sound and vibration systems and outstanding performance in recent key comparisons participated had been instrumental in strengthening the traceability chain. Till date, 34 Calibration and Measurement Capabilities (CMCs) in the field of sound and vibration has been included in the BIPM database. Efforts are targeted to increase the number of CMCs in the BIPM database to solve the problems and challenges faced by industries and other stakeholders.

To further strengthen research and developments in acoustics, in the early seventies, work in the area of atmospheric acoustics, the acoustic sounding of the lower atmosphere: SODAR (SOund Detection And Ranging) was initiated. It is one of the very promising and potential application-oriented activities of the laboratory.

8.3.2 Significance, Applications and Relevance in Different Sectors

The role of the Acoustics and Vibration parameter is multifaceted in various sectors such as automotive, avionics, heavy engineering industry, defence, space research and for environmental studies. The heavy engineering industry, avionics sector, automotive sector, and Public sector undertakings generally face the noise and vibration issues with machinery and products that require an engineering solution for meeting the international standards for ensuring the quality of products developed. The calibration, testing, and consultancy services provided in Acoustics and Vibration area had played a major role in helping all these sectors for solving their problems and challenges faced. The activity also contributed a lot in solving the environmental

noise issues and the development of standards. The activity is working in collaboration with the Central Pollution Control Board (CPCB) and other State Pollution Control boards for noise mapping studies for controlling noise pollution of various cities in the country. The low-frequency primary vibration standard is capable of calibrating the seismic sensors (mass up to 200 g). The primary standard of sound pressure in the frequency range of 31.5 Hz to 25 kHz is used to calibrate the reference standard microphones (LS1P and LS2P). The activity also caters to the calibration, testing, and consultancy needs of customers in sound and vibration parameters. The important applications of acoustics and vibration parameters are as follows:

(a) Maintenance of primary standards of sound pressure and vibration amplitude,
(b) Calibration and testing of electro-acoustical equipment,
(c) Noise and vibration measurements and control,
(d) Acoustics materials characteristics measurement for building industries,
(e) Technical advisory consultancy in building acoustics,
(f) Noise barrier design and development for highway, railway, metro, etc.,
(g) Environmental noise measurement and control,
(h) Air Quality management using SODAR, and
(i) Formulation of Standards for noise and vibration control.

8.3.3 Facilities and Global Status

The Acoustics and Vibration activity is realizing the primary and secondary standards of sound pressure and vibration amplitude to provide the traceability of the regional laboratories, government bodies, and the industrial sector in the country. The description of these facilities, research, and development works towards reducing the uncertainty in the measurements and global status of measurement facilities is described in detail in the next section.

8.3.3.1 Measurement Standards and Facilities

The Acoustics and Vibration activity is focused on the maintenance, realization, and up-gradation of primary and secondary standards of sound pressure and vibration amplitude. The primary standard of sound pressure is realized using the Reciprocity method for the calibration of laboratory standard microphones (LS1P and LS2P) in the coupler cavity in frequency range 31.5 Hz to 25 kHz with an expanded uncertainty of $\pm$ 0.05 dB to 0.17 dB [38]. The Reciprocity calibration apparatus of CSIR-NPL, India is the B&K type 9699 system. The primary standard of vibration amplitude is maintained using laser interferometry and sine approximation method as per ISO 16,063–11 [39, 40] in the frequency range of 0.1 Hz to 20 kHz with an expanded uncertainty of $\pm$ 0.30 to 1.80%. Figure 8.18a and b shows the pictorial view of the primary standard of sound pressure and Primary vibration calibration standard using
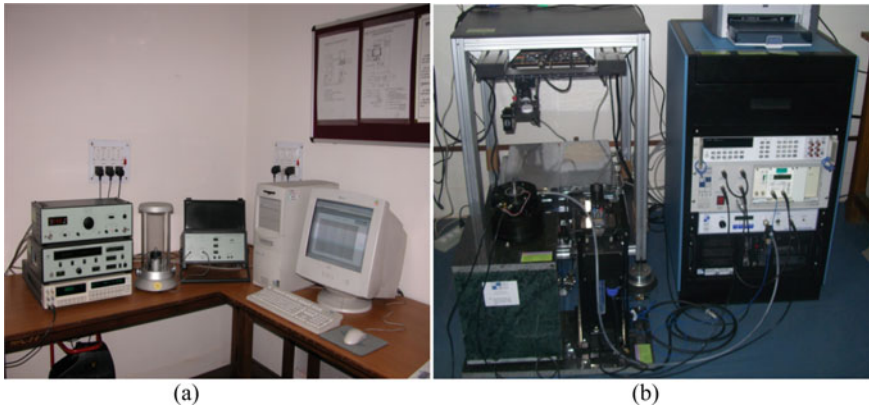
Fig. 8.18 **a** Primary microphone calibration standard using reciprocity method. **b** Primary vibration calibration method using a laser interferometer

a laser interferometer approach (TMS 9155D system) in the frequency range 0.1 Hz to 20 kHz.

The reciprocity method is usually employed by many NMIs in the world. The sensitivity of the microphone is obtained from measurements of the electrical transfer impedance and acoustical transfer impedance between the microphones in compliance with IEC 61094–2. The long coupler and short coupler are used to measure the sensitivity in the frequency range 31.5 Hz to 2 kHz and to record the sensitivity deviations. The measurement data is analyzed using computer software *MP.EXE* developed by Brüel & Kjær (B&K), Denmark as shown in Fig. 8.19 and sensitivity fitting exercise is performed for obtaining the final sensitivity [38].
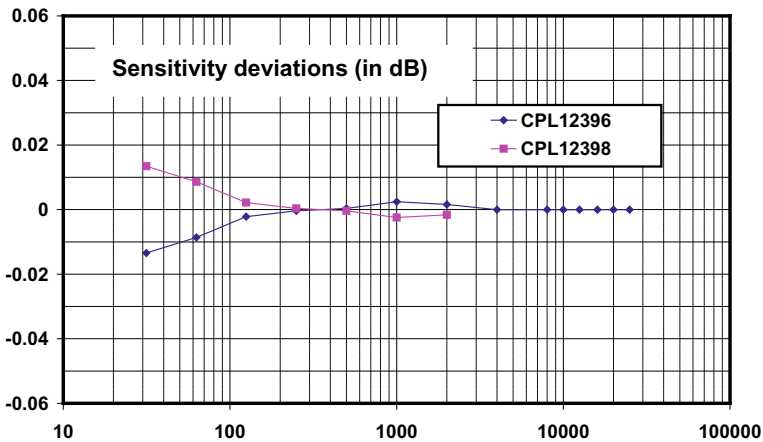

Fig. 8.19 Sensitivity deviations (in dB) for two couplers CPL 12,396 (length = 4.7 mm) & CPL 12,398 (length = 9.4 mm) of diameter 9.3 mm for B&K 4180 microphone in MP.EXE programme
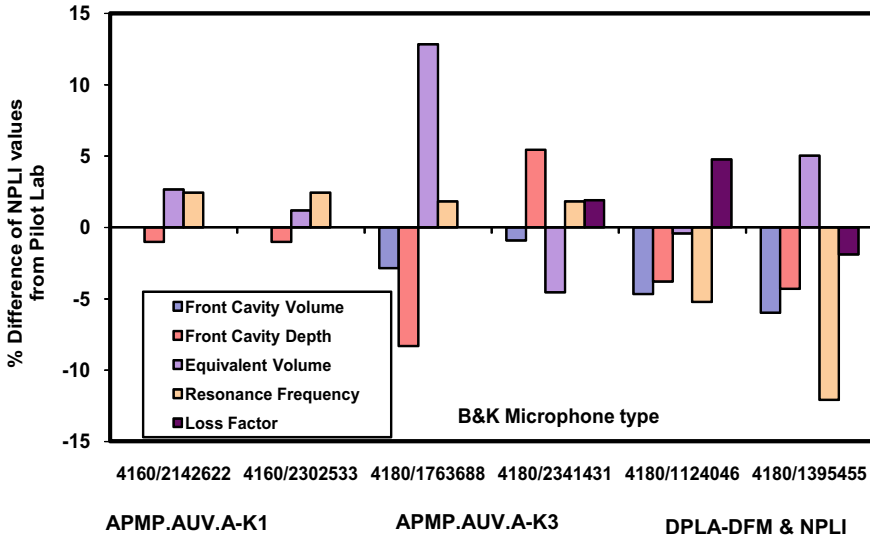
Fig. 8.20 Difference in measurement values (in %) of NPL, India with respect to the pilot laboratories (NMI, Japan, KRISS, Korea, and DPLA-DFM, Denmark) for each microphone parameters [42–44]

The validation of CSIR-NPL CMCs in the Reciprocity measurements has been confirmed from the degree of equivalence values in comparison to the other reputed NMIs for LS1P and LS2P microphones. The APMP.AUV.A-K1 comparison for LS1P microphones was piloted by NMI, Japan with nine participating laboratories [41]. NPL, India further participated in APMP.AUV.A-K3 comparison piloted by KRISS, Korea for LS2P microphones with 10 participating laboratories [42]. Figure 8.20 shows the percentage difference of NPL, India values with respect to the pilot laboratories for each microphone parameters [42–44]. The maximum deviation of 0.06 dB in sensitivity for LS1P microphone was observed at higher frequencies with respect to the pilot laboratory. In the case of the LS2P microphone, the maximum deviation of 0.11 dB in sensitivity determination with respect to the pilot laboratory was observed at 25 kHz [42]. The precise measurement of microphone parameters is very important for reducing the measurement uncertainty in the sensitivity determination of reference standard microphones, especially at higher frequencies. The conventional methodology followed was the use of nominal parameters specified by manufacturer and deviations up to 13% in equivalent volume and 6.4% in front cavity volume had been observed in Key comparison exercises. Figure 8.21 shows the parametric sensitivity analysis of microphone parameters affecting the sensitivity in dB re 1 V/Pa of reference standard microphones at 10 kHz using Analysis of Variance (*ANOVA*) method [44]. Thus, efforts are in progress to decrease the measurement uncertainty in sensitivity determination by conducting precise measurements for the front cavity volume of the reference standard microphone, which is one of the most critical parameters [44].
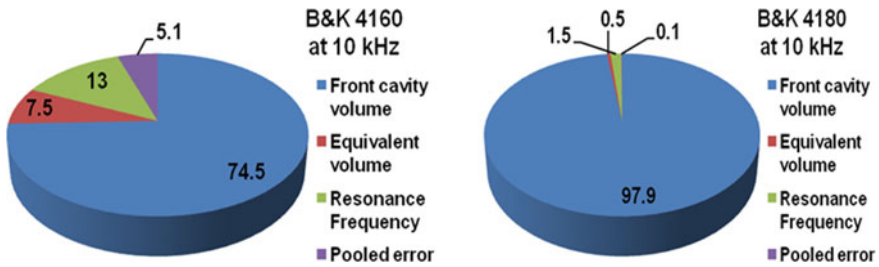
Fig. 8.21 Parametric sensitivity analysis of microphone parameters affecting the sensitivity in dB re 1 V/Pa of reference standard microphones at 10 kHz using the *ANOVA* method [44]

Also, with the precise dimensional characterization of front cavity depth and volume and the other microphone parameters, the measurement uncertainty in microphone parameters can be reduced especially at higher frequencies leading to reduced uncertainty in sensitivity determination of reference standard microphones. The precise dimensional characterization of microphone parameters in conjunction with use of latest signal processing techniques, inclusion of all corrections as recommended in IEC 61094–2 standard shall be crucial to reduce the random uncertainty and overall uncertainty in the measurements.

Thus, efforts are targeted to reduce the measurement uncertainty in primary sound standard and extension of the frequency range by focussing on the various aspects as follows:

- Dimensional characterization of the front cavity volume and precise determination of other microphone parameters of the reference standard microphones,
- Replacement of old hardware with a PULSE based system for reducing the signal-to-noise ratio, distortion, and random uncertainty,
- Inclusion of low-frequency option from 1 to 20 Hz for low-frequency calibrations of reference standard microphones and participation in a key comparison exercise with other NMIs.

These up-gradations shall help to realize the complete range of 1 Hz to 25 kHz with a measurement uncertainty ranging from ± 0.05 to 0.15 dB. The Primary vibration calibration standard is based on the principle of sine approximation method as per ISO 16063–11 and employs a laser interferometer for measurement of displacement of the transducer when excited at varied amplitudes and frequencies in the range 0.1 Hz to 20 kHz. CSIR-NPL, India realizes the complete frequency range from 5 Hz to 10 kHz using two systems: TMS 9155D system in the frequency range 5 Hz to 20 kHz and medium frequency B&K 3629 calibration system in the range 5 Hz to 5 kHz. The measurement uncertainty of the medium frequency system ranges from 0.7% at 160 Hz to 1.0% at 5 kHz [40]. The Calibration and Measurement Capabilities (CMCs) in range 40 Hz to 5 kHz had been earlier validated in an international key comparison exercise. The APMP.AUV.V-K1.2 with NIM China as a pilot laboratory and KIM-LIPI Indonesia as another participating laboratory was initiated in

2009. The degree of equivalence between NPL, India and NIM China at 160 Hz for single-ended accelerometer was observed to be 4.6×10^{-4} pC/ms^{-2} and that for back to back sensor was 4.2×10^{-4} pC/ms^{-2}. At 5 kHz, the degree of equivalence between NPL, India, and NIM China was observed to be 3.1×10^{-4} pC/ms^{-2} for single-ended accelerometer and 9.6×10^{-4} pC/ms^{-2} for back to back sensor [45]. With the installation of the TMS 9155D primary vibration calibration standard in 2011 as shown in Fig. 8.18b, the highest levels of accuracy and precision are realized in complete frequency range from 0.1 Hz to 20 kHz using an air bearing shaker. The hardware of the system comprises of an excitation and measurement subsystem. The excitation system contains a power amplifier, shaker (PCB Air bearing shaker 396C11), and function generator located on the PCI card for data acquisition. The long-stroke shaker APS 113AB is used for low-frequency calibration and provides a sufficient maximum stroke of 158 mm [46]. Continuous efforts are targeted to reduce the measurement uncertainty in the sensitivity and phase determination of the reference standard vibration transducer. The multi-point laser positioning approach is followed for the precise determination of the sensitivity of the transducer in the frequency range of 5 Hz to 20 kHz [39]. Figure 8.22a shows the multi-point laser positions on a PCB 396C11 shaker and Fig. 8.22b shows the random uncertainty observed in symmetrical laser positions used for the measurement of the sensitivity of the PCB 353B04 sensor. It can be observed that the maximum random uncertainty in the sensitivity calibrations using a multi-point laser positioning approach, was measured as 0.25% and that in phase calibrations was 0.13°. The basic motive behind the selection of symmetric laser positions is to restrain the effects of any non-rectilinearity of motion.

The secondary standards are used for providing calibration services for accelerometers, working standard microphones, sound calibrators, piston phones, multifunction acoustic calibrators, vibration meters, accelerometer calibrators, etc. The back to back comparison calibration as per ISO 16063–21 is done using a Spektra CS 18 MF system that utilizes an electrodynamic shaker, SE-10 for performing accelerometer calibrations in range 5 Hz to 10 kHz. The measurement uncertainty realized in the secondary accelerometer and vibration meter calibrations is 1.2–2.5% in the frequency range 5 Hz to 10 kHz. The transverse motion has been one of the significant sources of error in the vibration calibrations, that causes an error component

Fig. 8.22 a, b Vibration sensitivity measurements using multi-point laser positions
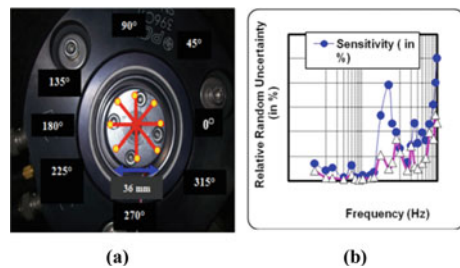
in the acceleration amplitude in conjunction with the transducer transverse sensitivity. Transverse motion limits are required by ISO 16063–11 to be less than 1% for frequencies below 10 Hz, less than 10% for frequencies below 1 kHz, and less than 20% for frequencies below 10 kHz. The secondary microphone calibration system of NPL, India is B&K 9721 that utilizes a traceable microphone for performing secondary microphone calibrations using an insert voltage method and frequency response measured using an electrostatic actuator. The measurement uncertainty achieved in the calibration of measurement microphones ranges from 0.1 to 0.35 dB in frequency range 31.5 Hz to 20 kHz. The uncertainty in measurement in the calibration of sound calibrators and multifunction calibrator range from ± 0.12 to ± 0.25 dB in frequency range 31.5 Hz to 16 kHz. The sound level meter calibration is carried out with an uncertainty of ± 0.30 dB to ± 1.0 dB in the frequency range 125 Hz to 10 kHz [47]. Participation in the APMP.AUV.A-S1 supplementary comparison for multifunction acoustic calibrator (B&K 4226) with NIMT, Thailand as the pilot laboratory has validated CMCs for sound pressure level determination. The maximum deviation of −0.13 dB for the sound pressure level of 94 dB and of −0.17 dB for the sound pressure level of 114 dB with respect to the Supplementary Comparison Reference values (SCRV) was observed [48].

Apart from the primary and secondary standards of sound and vibration parameters, the activity also undertakes various testing of noise and vibration and acoustical products with a theme of *Centre of Excellence for Noise and Vibration Control Facilities.* The Indian industry is in the process of developing indigenous technology wherein performance, evaluation of acoustical products, instruments of systems are very helpful. In this respect, acoustics and vibration activity undertakes the testing of a variety of acoustical products as per relevant Indian Standards. Major acoustical facilities available in the parameter are (i) Anechoic Chamber and (ii) Reverberation Chamber has been built to meet the ISO recommendations. Besides, there are various types of equipment such as the (iii) Building Acoustics measurement and Impedance Tube facility, (iv) Vibration measurement facility and (v) SODAR system for ABL (Atmospheric Boundary Layer) height measurement.

Anechoic Chamber

Precision acoustical measurements like sound power output and directional characteristics, calibration in electro-acoustic, psycho-acoustic experiments, etc. require a test space that is free from reflection from nearby surfaces and is sufficiently quiet. This is achieved artificially by treating the available surfaces of the room by special wedge absorbers, adopting double-wall construction, and isolation from other structures. The working space is 3.5 m × 3.5 m × 3.5 m and cut-off frequency is 70 Hz of the anechoic chamber available with CSIR-NPL shown in Fig. 8.23.

Fig. 8.23 Anechoic chamber facility at CSIR-NPL

Fig. 8.24 Reverberation chambers facility at CSIR-NPL

Reverberation Chamber

Absorption and transmission characteristics of acoustic materials and measurements like noise power levels of instruments are carried out in reverberation chambers. The essential requirements of a reverberation chamber are (i) absence of interfering noise, (ii) adequate sound diffusion and (iii) long reverberation time over the frequency range of measurement. These are achieved by non-parallel highly polished walls, duo-decahedral loudspeakers systems, and suspension of diffusing plates from the ceiling, oriented at random as shown in Fig. 8.24. The specifications of the reverberation chamber are listed in Table 8.12.

Table. 8.12 Specifications of reverberation chamber of CSIR-NPL

Volume of the chamber	257 m^3
Average RT	5.6 s
Cut off frequency	80 Hz
Type of construction	Double-wall, room inside a room
Ambient noise level	20 dB
No. of chambers	2 (Coupled to each other)

Fig. 8.25 Impedance tube facility at CSIR-NPL

Building Acoustic Measurement System and Impedance Tube Facility

The new facilities that had been established in CSIR-NPL, India include the Building Acoustic Measurement System and Impedance Tube facility used for the testing of a variety of acoustical products as per relevant Indian Standards. This includes Omni-directional sound source and pre-amplifier and dual-channel building acoustics analyzer. The parts of Building Acoustic measurement system conform to the following: Omni-directional sound source conforms to the ISO 140, ISO 3382 standards; Dual-channel real-time Analyzer for sound pressure level measurements conforms to the IEC 61672–1-2013 for sound insulation and reverberation time measurement and Airborne Sound Insulation measurement conforms to standards ISO-140 and RT measurement conforms to ISO-3382 standards. The Impedance tube system as shown in Fig. 8.25 is used for research and developing products by characterizing acoustic material properties and designing acoustic comfort in aircraft and vehicle interiors, by selecting optimal acoustic treatments and barriers. For testing specified material characteristics and verifying material compliance with regulations before materials are incorporated into manufactured assemblies such as components and for validating and calibrating computational methods such as acoustical modelling impedance tube facility is used. The uncertainty of measurement of different testing facilities is listed in Table 8.13. The subsystems of impedance tube facility are as follows:

Table 8.13 Uncertainty of measurement of different testing facilities

Parameters covered	Testing facilities available for	Range and uncertainty (Expanded) at $k = 2$ and 95% confidence level
Sound transmission class (STC)	Sound insulation materials	$\pm$ 1.0 dB (100 Hz to 4 kHz)
Noise reduction coefficient (NRC)	Sound absorbing materials	$\pm$ 5% (100 Hz to 4 kHz)

- AFD1000 Base Module Set (801022.5 Speaker Module, Amplifier, 971024.1, ¼ inch microphones)
- AFD1000 Absorption Tube 30 mm
- AFD1200 Transmission Tube 30 mm
- AFD1000 Absorption Tube 100 mm
- AFD1200 Transmission Tube 100 mm
- Measurement of sound absorption Coefficient AFD 1000−AcoustiTube®Analysis Software AFD 1001
- Measurement of Sound Transmission Loss AFD 1200−AcoustiTube® and Analysis Software AFD 1201

Measurements based on the two-microphone transfer-function method according to ISO 10534–2 and ASTM E1050–08 standards for absorption coefficient and ASTM E 2611–09 for transmission loss.

Noise and Vibration Measurement Facility

Excess noise and vibration are harmful to the human well being and stability of structures/machines. Efforts have thus to be concentrated to mitigate their harmful effects. CSIR-NPL was the first institute in the country to initiate the scientific evaluation of environmental noise pollution in the late 50 s with a systematic survey of prevailing noise levels in the cities of Delhi, Bombay, and Calcutta. The survey included noise due to vehicular traffic, trains, aircraft, factories, in and around shopping centres, residential areas, schools, hospitals, etc. both during day and night. Analysis has shown that the major contribution of city noise comes from vehicles like diesel buses, cars, and motorcycles. During the last five decades, the acoustics section of the laboratory has not only made the measurement of traffic noise but has also carried out measurements of noise and vibration in industry and has given suggestions/recommendations for remedial measures to avoid occupational hazard risks. This activity is also involved with several national committees in the country to formulate norms and standards to monitor and control noise in cities and industries.
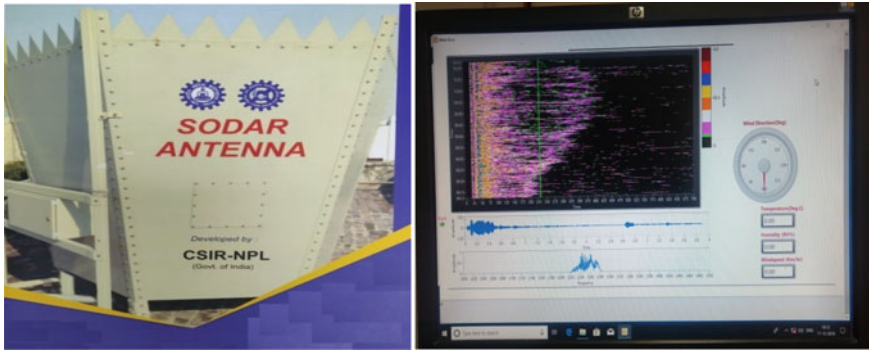
Fig. 8.26 Mono-static SODAR system

SODAR (SOund Detection and Ranging) System

Measurements related to many indiscernible physical parameters are also required in comparison to the physical quantity measurements like mass and length. Therefore, NPL's activities diversified into higher frequency ranges leading to studies on troposphere and lower atmospheric science by the mid-1970s. The design of SODAR was undertaken to study the atmospheric turbulence to map the thermal structures in the lower boundary layer. A SODAR is essentially an acoustic radar that provides a pictorial view of the thermal structure dynamics of the atmospheric boundary layer. SODAR was firstly designed, developed and operated in CSIR-NPL, India. In 1973, SODAR system using the reflector horn antenna as a receiver and a square array antenna as the transmitter and operating at 2 kHz became functional. A phased array wind profiling SODAR, capable of measuring boundary layer atmosphere winds, was also developed as shown in Fig. 8.26. Numerous developments had been carried out on SODAR which enabled the development of high-resolution SODAR with higher efficiency to carry out the research effectively. Table 8.14 shows the characteristics of CSIR-NPL Monostatic SODAR.

8.3.3.2 Calibration and Measurement Capabilities

The Acoustics and Vibration activity has 34 Calibration and Measurement Capabilities (CMCs) enlisted in the BIPM database. 23 CMCs are for the sound parameter, while 11 CMCs are for the vibration parameter. The pressure sensitivity determination of LS1P, LS2P and working standard microphones in the frequency range of 31.5 Hz to 25 kHz as per ISO/IEC 61094–2 constitutes 14 CMCs, sound pressure level measurements as per ISO/IEC 60942 constitutes 4 CMCs, charge sensitivity determination of vibration transducers as per ISO 16063–11 and ISO 16063–21 in the range 40 Hz to 5 kHz constitutes 6 CMCs and acceleration level (modulus) constitute 2 CMCs. Figure 8.27 shows the parametric description of Calibration and

Table 8.14 Characteristics of CSIR-NPL (New Delhi) Monostatic SODAR

|	
Transmitted power (electrical)	90 W
Transmitted power (acoustical)	15 W
Pulse width	100 ms
Pulse repetition period	6 s
Operational range	1000 m
Receiver bandwidth	50 Hz
Frequency of operation	2250 Hz
Acoustic velocity	340 m/s (average)
Receiver gain	80 dB
Transmit –receive antenna	Parabolic reflector dish surrounded by a conical acoustic cuff
Receiver area	2.5 m^2
Preamplifier sensitivity	A fraction of a micro-Volt
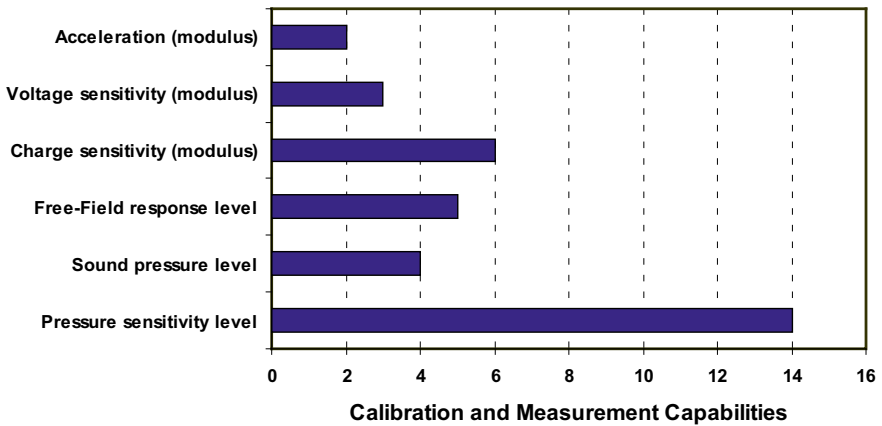
Fig. 8.27 Parametric description of calibration and measurement capabilities of acoustics and vibration area of CSIR-National physical laboratory, India in the BIPM database

Measurement Capabilities of Acoustics and Vibration Standards of CSIR-National Physical Laboratory in the BIPM database.

Table 8.15 List of key comparisons participated in sound and vibration parameter

S. No.	Key comparison details	Artefact	Result/comments
1	NPL-DPLA Bilateral Comparison	B&K 4160 and 4180 microphones	Successfully participated in the frequency range of 31.5 Hz to 25 kHz
2	APMP.AUV.A-K1	B&K 4160 microphones	Successfully participated in the frequency range of 63 Hz to 8 kHz
3	APMP.AUV.A-K3	B&K 4180 microphones	Successfully participated in the frequency range of 31.5 Hz to 25 kHz
4	APMP.AUV.A-S1	B&K 4226 Multifunction Acoustic Calibrator	Successfully participated in the frequency range of 31.5 Hz to 16 kHz
5	CCAUV.V-K1.1	B&K 8305 accelerometer	Successfully participated in a frequency range of 40 Hz to 2.5 kHz
6	APMP.AUV.V-K1.2	B&K 8305 accelerometer	Successfully participated in a frequency range of 40 Hz to 5 kHz
7	APMP.AUV.V-K3.1	Single-ended quartz-flexure accelerometer SA 704	Successfully participated in a frequency range of 0.1 Hz to 40 Hz

8.3.3.3 Participation in International Key Comparisons

Table 8.15 enlists the participation in the Key Comparison exercises in sound and vibration parameters. Participation in key comparison exercises for sound and vibration parameters has led to the inclusion of CMCs in the BIPM database. The recent participation in low-frequency vibration comparison, APMP.AUV.V-K3.1 in a low-frequency range of 0.1–40 Hz will be helpful for the inclusion of low-frequency CMCs also in the BIPM database [49].

8.3.3.4 Potential Services for Future Requirements

The continuous up-gradation of the primary and secondary standards with the latest technology is very essential for reducing the measurement uncertainties. Various services are planned to be developed in the future for serving the industry and regional laboratories in India as follows:

- Noise mapping studies for controlling the noise pollution of various cities for various pollution control boards,
- Development of sound power level standard (unit Watt in airborne sound),
- Facility for calibration of microphones in the low-frequency range from 1 to 20 Hz,

- Primary and Secondary Free-Field Calibration Standard,
- Facility for complete electrical and acoustical calibration of sound level meters as per ISO/IEC 61672.
- Development of primary vibration standard in ultra-low frequency range using a very long-stroke shaker and in the high-frequency range (5–50 kHz),
- Realization of Shock standards in range 10–1000 g using laser interferometer for providing traceability to defense, space research, and the automotive sector in India.

8.3.3.5 A Decade of Clients and Services

Calibration and Testing

The Acoustics and Vibration activity has provided calibration and testing services to various clients for the past few decades. Some of the major clients are:

- Shriram Institute for Industrial Research, Delhi,
- National Thermal Power Corporation Ltd., Korba,
- Maruti Suzuki India Ltd., Gurugram,
- Hindustan Aeronautics Limited, Lucknow,
- Fluid Control Research Institute, Palakkad, Kerala,
- Central Power Research Institute, Noida,
- Central Institute of Mining and Fuel Research, Dhanbad,
- Central Mechanical Engineering Research Institute (CSIR-CMERI), Durgapur,
- Electronics and Quality Development Centre (EQDC), Gandhinagar,
- Automotive Research Association of India, Pune,
- National Thermal Power Corporation Ltd., Auraiya, U.P,
- G E Power India Ltd., Noida,
- National Research and Technical Consortium, Parwanoo,
- Escorts Ltd., Faridabad,
- MKU, Kanpur,
- Central Pollution Control Board, New Delhi,
- Bharat Heavy Electricals Limited, Haridwar,
- Opto Electronics Factory, Raipur,
- Ramco Industries Ltd, Mylapore, Chennai,
- Rapid Metro Rail Gurgaon Limited, Gurgaon,
- Envirotech System Pvt. Ltd., Noida,
- Diamond International Index Private Limited, Gurgaon,
- Shivathene Linopack, Industrial Area, Parwanoo,
- Fluid Control Research Institute, Palakkad−(Kerala),
- USG Boral Building Products (India) Pvt. Ltd Gurgaon,
- Everest Industries Limited, New Delhi,
- ALP AEROFLEX India Pvt. Ltd., Road, Rudrapur, Udham Singh Nagar,
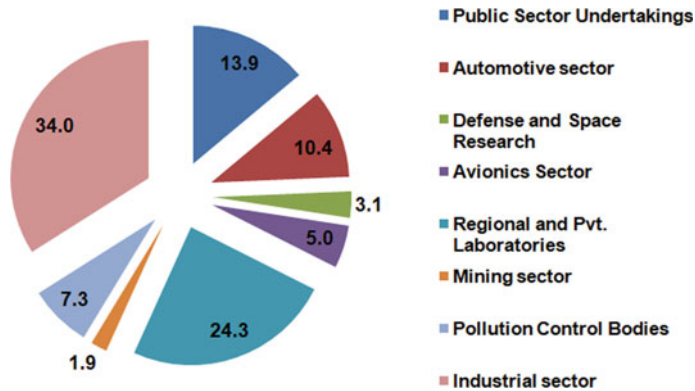- Magneti Marelli UM Electronic Systems Pvt. Ltd. Gurgaon,
- RITES, Chennai,

Fig. 8.28 Pie chart describing the percentage distribution of clients from various sectors

- Delhi Metro Rail Corporation Ltd. Pragati Vihar, New Delhi,
- Advance Paints Pvt. Ltd. Andheri (E), Mumbai,
- Pooja Elastomers, Mumbai,
- Shahsahib Woodwool Enterprises, New Delhi,
- BBM Acoustics India Pvt. Ltd. Pune,
- Haama Limited, India Office, Bangalore,
- Vibgyor Paints & Chemicals Pondicherry, Chennai,
- Sound Wud, Sattvaa Enterprise, Bangalore,
- Diamond International Inex Private Limited Gurgaon,
- Milton Industries Ltd., Ahmedabad,
- Envirotech Systems Pvt. Ltd., Noida,
- Ecotone Systems Pvt. Ltd. New Delhi,

The percentage distribution of clients from various sectors is shown in Fig. 8.28. It can be observed that regional and private laboratories and industrial sectors are the major clients.

Consultancy and Technical Services

The Acoustics and Vibration activity provides consultancy and technical services to various government and private organizations for solving noise and vibration issues. The major customers are Delhi Metro Rail Corporation, Bangalore Metro Rail Corporation Ltd., Archaeological Survey of India, Delhi Development Authority, Central Pollution Control Board, Dhyuthi Synthtex LLP, Soundworks, New Era Interior Collection Pvt. Ltd., Armacell India Pvt. Ltd., Annutone Acoustics Limited, Rashtrapati Bhawan, Power Grid Corporation Limited, UP Samaj Kalyan Nirman Nigam Ltd, Maple Consultants, Vijay Power Electricals, etc. The consultancy services provided in this area have been very helpful in solving the problems related to noise and vibration faced by these organizations.

Acoustics and Vibration Metrology activity offers institutional consultancy services in various fields like building acoustics, noise and vibration control, monitoring boundary layer in the lower atmosphere, installation of SODAR systems in industrial complexes to monitor air pollution & other boundary layer parameters, etc. Besides these, the activity also participates in the programmes of the Bureau of Indian Standards (BIS) and the Department of Environment in their work of laying down suitable standards for acoustical products and noise, etc. and in carrying out experimental investigations where necessary in the drafting of such standards.

Training and Academic Services

The activity is also responsible for providing training to the industry and government bodies on acoustic and vibration metrology, type approval testing of Diesel Gensets, fundamentals of noise and vibrations. This activity contributes to the Certification in Precision Measurement and Quality Control (PMQC) course every year by providing lectures and practical demonstrations to the young students for imparting knowledge about the measurement methodology and uncertainty evaluation as per the international guidelines. The activity also provides practical demonstrations and lectures to engineering students from the Indian Institute of Technology, National Institute of Technology, and Delhi Technological University. Also, the students in Physics and Engineering stream are guided for B. Tech, M. Tech, and Doctoral dissertations and summer internships. Trainings to officers of CPCB, New Delhi; staff of Boral Gypsum India and staffs of ERTL (North), and National Test House (NIT) had been provided. Also, workshops on noise and vibration control, celebrations of International Noise Awareness Day and World Hearing day, National and International conferences on Acoustics had been organized with an objective of *Make Listening Safe: A CSIR-NPL initiative to promote safe listening practices.*

Technology Development and Commercialization

Technology development and commercialization play a very significant role in the development of high quality and economical products that not only benefit the industries, but also the end users. The development of the portable secondary sound standard is one of technology that can be transferred to the relevant industries, laboratories, and manufacturers for developing low-cost systems with reduced uncertainty levels traceable to NPL. The Acoustic & Vibration Metrology has developed various technologies and commercialized them. Two such technologies are *Acoustical Light weight Interior Dry Wall Panel for High Sound Insulation* and *Noise Absorptive barrier for Metro/Railway/ Highway/Airport Noise Abatement.*

The main objective of this development is to develop a new partition panel with higher insulating value and higher STC rating value by involving new design and combinations and employing novel processing techniques. Figure 8.29 shows CSIR-NPL developed panel for this purpose.
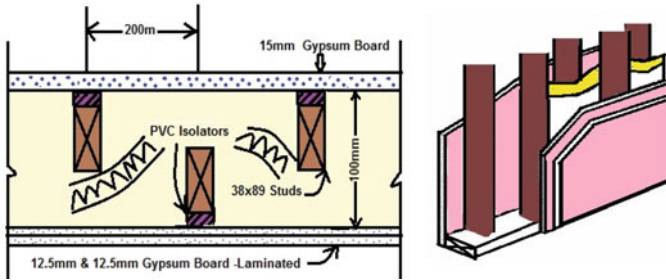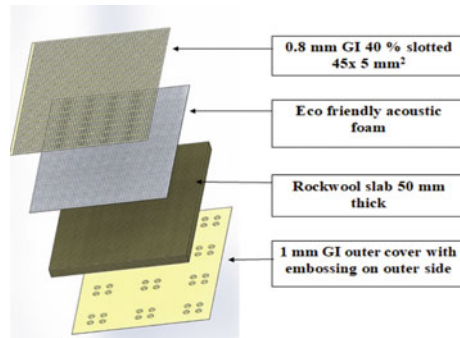
Fig. 8.29 Technology of acoustical light weight interior dry wall panel for high sound insulation to M/S. Sehgal doors, New Delhi

Fig. 8.30 Technology of noise absorptive barrier for metro/railway/highway/airport noise abatement to M/S Reliable Diesel Engineers (P) Ltd, Gurugram

The problem of sound in buildings and residential areas through Metro, Railways, Highways, and Airports is growing nowadays. Noise barriers are the most effective method of mitigating noise from various sources such as road, railway, metro, airport and industry. Figure 8.30 shows CSIR-NPL developed Noise Absorptive barrier for this purpose.

8.3.4 Major Documentary Standards, Guides, and SOPs

The major documentary standards, guides, and Standard operating procedures are listed in Table 8.16 as follows:

8.3.5 Possible Gaps and Suggestions for Their Redressal

The major hurdle faced in the development of new standards and measurement methodologies is the economic constraints and participation of the private sector

Table 8.16 Major documentary standards, ISO Standards used in the realization of primary and secondary acoustics, and vibration standards

S. No	Documentary standard/SOP/Guide	Applications	Comments
1	IEC 61094–1, IEC standard: Measurement Microphones-Part 1-specifications for laboratory standard microphones, International Electrotechnical Commission, Switzerland, 2000	Microphones	International Standard
2	IEC 61094–2, Measurement Microphones-Part 2-Primary method for pressure calibration of laboratory standard microphones by reciprocity technique, International Electrotechnical Commission, Switzerland, 1992	Microphones	International Standard
3	IEC 61094–5, Measurement Microphones-Part 5: Method for pressure calibration of working standard microphones, by comparison, International Electrotechnical Commission, Switzerland, 2001	Microphones	International Standard
4	IEC 61094–6, Measurement microphones-Part 6: Electrostatic actuators for determination of frequency response, International Electrotechnical Commission, Switzerland, 2001	Microphones	International Standard
5	IEC 60942 Electroacoustics-Sound Calibrators, International Electrotechnical Commission, Switzerland, 1997	Sound Calibrators	International Standard, Corresponding Indian Standard IS 15059:2001

(continued)

Table 8.16 (continued)

S. No	Documentary standard/SOP/Guide	Applications	Comments
6	IEC 61672–1: Electroacoustics−Sound level meters-Part 1: Specifications	Sound Level Meters	International Standard Corresponding Indian Standard IS 15,575 (Part 1):2005
7	ISO 16063–21:2003, Vibration calibration by comparison to a reference transducer, International Electrotechnical Commission, Switzerland	Vibration transducers	International Standard
8	ISO 16063–11:1999, Methods for the calibration of vibration and shock transducers-Part 11: Primary vibration calibration by laser interferometry	Vibration transducers	International Standard
9	IS-9901(Part-III)-1981, DIN: 52210, Part VI-1989, ISO:10140(Part II)-2010/ASTM-E-90	Sound Transmission Class (STC)	International Standard
10	IS:8225–1987 Equivalent to ISO: 354–1985 and ASTM 423–90	Noise Reduction Coefficient (NRC)	International Standard
11	ISO 3744–1994 €, ISO 8528–10:1998 €; GSR 97€29th Jan 2018 Ministry of Environment, Forest and Climate Change	DG Sets	International Standard
12	ISO 3744–1994 €, ISO 8528–10:1998 €	Mechanical Electrical Machine	International Standard
13	IS: 8225–1987 Equivalent to ISO: 354–1985 and ASTM 423–90	Multipurpose halls/Theatres	International Standard
14	ISO 20816-Part 1: 2016	Ground Vibration	International Standard
15	ISO 1996-2:2017	City Noise Mapping	International Standard

in R&D towards the development of new measurement facilities. However, efforts are focused on overcoming these hurdles by taking the following measures:

- Submission of Grant-in-aid and Consultancy projects for the involvement of private sector and overcoming funding constraints,
- Interacting with the industry for jointly working on the various issues for solving noise and vibration problems,

- Organizing Workshops/Conferences and training services every year for developing mutual collaborations and awareness.

8.4 Conclusions

It is now evident from the discussion in the chapter that the establishment of metrological standards and facilities for temperature; optical radiation; and acoustics and vibration metrology play a vivacious part in establishing traceability chain and disseminations for exclusive industrial growth of the country. The PMPs related to temperature, optical radiation and acoustics and vibration are realized with the highest levels of accuracy and precision, which enables them to serve the strategic sector, MSMEs, public and private sector undertakings, government organizations, regulatory bodies as well. The measurement capabilities are reaffirmed by periodic participation in the international inter-comparisons with other NMIs that enable to acquire the global competence and recognition.

The implementation of new SI system based on redefined SI units on 20th May, 2019, i.e. the World Metrology Day has thus diverted the attention and efforts of every country towards the development of new measurement methodology and strategies for realizing the SI units through the fundamental constant, invariant of time and space. Realization process of 2 SI base units, i.e. *kelvin* and *candela*, are described in details alike 2 SI base units, kilogram and metre in Chap. 7. CSIR-NPL is also continuously focused on realizing the temperature using the *Boltzmann constant* by *Acoustic Gas Thermometry*. The new calibration and testing facilities developed for IR thermometers at CSIR-NPL is a welcome and vital step for moving away from the era of mercury thermometer to an era of mercury-free thermometer in healthcare applications as mercury devices need to be phase-out as per WHO and *Minamata convention* so as to improve the quality of life.

It is now evident that the precision and traceable measurements of related photometric, radiometric, colorimetric and spectrometric parameters become utmost importance as they lie in the visible region of electromagnetic spectrum and thus play a vital role in human life. Efforts being made at CSIR-NPL in this direction are highlighted for the establishing state of the art, national test and calibration facilities as per the International standards for next-generation energy-efficient light products. These initiatives will not only support the energy saving by promoting the energy-efficient lamps, on 'green technology', but also eliminate sub-standard products from the market and cater to the needs of lighting industries. Also, the efforts made towards the development of photons metrology are emphasized. Photons metrology is crucial to realize standards for few photon sources for futuristic quantum optical technologies so as to meet the global objectives.

The acoustics and vibration activity is continuously focused on developing the new measurement standards and facilities for providing calibration, testing, training, academic, consultancy, and technology development services to the industry, laboratories, and other government organizations in the country. Efforts are in progress

for the development of national standard facilities for calibration of sound intensity probes, noise monitoring terminals, free-field microphones, primary and secondary shock calibration and testing. The development of facility for Audiometer calibration for providing traceability to the medical institutions of the country is also at under planned stages. Also, in light of the recent orders of National Green Tribunal to CPCB for noise mapping of the cities, focussed efforts are being made on developing the noise maps of the cities in collaboration with CPCB and SPCB's and devising remedial action plans for reducing noise pollution in the country. Efforts are targeted to establish SODAR centers in different parts of the country for air pollution studies.

To date, there are total 52 CMCs registered in the KCDB of BIPM in all these PMPs, 4 in thermal, 14 in optical radiation and 34 CMCs in acoustic and vibration. Keeping in view of the vast potential of these parameters in various sectors, more efforts are continuously targeted to enhance the number of CMCs so that more industries can be benefitted from calibration, testing, and consultancy services. The overall exertions in conjunction with the strengthening of NQI, in no doubt, would play a vibrant role in economic growth of the country and realizing the ambitions of government of India for making '*Atma Nirbhar Bharat or Self Reliant India*'.

References

1. T.J. Quinn, *Temperature* (Elsevier, 1990)
2. B. Fellmuth, C. Gaiser, J. Fischer, *Determination of the Boltzmann Constant—Status and Prospects* (Measurement Science and Technology, 2006)
3. J. Fischer, The Boltzmann constant for the definition and realization of the Kelvin. Ann. Phys. **531**, 1800304 (2019)
4. M.P. White, D. Gugan, Direct measurements of the dielectric virial coefficients of 4He between 3 K and 18 K. Metrologia **29**, 37–57 (1992)
5. L. Pitre, L. Risegari, F. Sparasci, M.D. Plimmer, M.E. Himbert, A.P.A. Giuliano, Determination of the Boltzmann Constant K From the Speed of Sound in Helium Gas at the Triple Point of Water (Metrologia, 2015)
6. L. Pitre, F. Sparasci, D. Truong, A. Guillou, L. Risegari, M.E. Himbert, Measurement of the Boltzmann Constant kB using a Quasi-spherical acoustic resonator Int. J Thermophys (2011)
7. J.B. Johnson, *Thermal Agitation of Electricity in Conductors* (Nature,1927)
8. C.J. Bordé, *Atomic Clocks and Inertial Sensors* (Metrologia, 2002)
9. J.A. Hall, *The Early History of the International Practical Scale of Temperature* (Metrologia, 1967)
10. J.A. Hall, C.R. Barber, *The Evolution of the International Practical Temperature Scale* (Metrologia, 1967)
11. B. Fellmuth, *Supplementary Information for the ITS-90* (BIPM, 2013)
12. H. Preston-Thomas, The International temperature scale of 1990 (ITS-90). Metrologia **27**, 3–10 (1990)
13. https://www.bipm.org/utils/common/pdf/ITS-90/Guide_ITS-90_1_Introduction_2018.pdf

14. https://www.bipm.org/utils/common/pdf/ITS-90/Guide-ITS-90-Platinum-Resistance-Thermo metry.pdf
15. K. Anhalt, *Radiometric Measurement of Thermodynamic Temperatures During the Phase Transformation of Metal-Carbon Eutectic Alloys for a New High-Temperature Scale Above 1000 °C* (2008)
16. U. Pant, H. Meena, G. Gupta, D.D. Shivagan, Development and long-term stability assessment of Co–C eutectic fixed point for thermocouple thermometry, Int. J. Thermophy **40**, 80 (2019)
17. U. Pant, G. Gupta, H. Meena, K. Bapna, D.D. Shivagan, Development and realization of Fe C and Co–C eutectic fixed-point blackbodies for radiation thermometry at CSIR-NPL, Int. J. Thermophy **41**, 101 (2020)
18. Definition agreed by the 26th CGPM (November 2018), implemented 20 May 2019, BIPM, website https://www.bipm.org
19. CIE, *The Basis of Physical Photometry*. CIE Publication No. 18.2 (Central Bureau of the Commission Internationale de I'Eclariage, 1983)
20. G. Wyszecki, W.S. Stiles, *Color Science: Concepts and Methods Quantitative Data and Formulae.* (Wiley-Interscience Publications, New York, 1982)
21. F. Grum, R.J. Becherer, *Optical Radiation Measurements. Volume 1: Radiometry* (Academic Press, New York, 1979)
22. V.I. Sapritsky, Black-body radiometry. Metrologia **32**, 411–417 (1995)
23. J.E. Martin, N.P. Fox, P.J. Key, A Cryogenic radiometer for absolute radiometric measurements, metrologia. **21**, 147–155 (1985)
24. M. Krumrey, C. Herrmann, P. Muller, G. Ulm, Synchrotron-radiation-based cryogenic radiometry in the X-ray range, Metrologia. **37**, 361–364 (2000)
25. G. Zhizhong, W. Zhenchang, P. Dazhi, M. Shihua, Y. Chiuhong, Realization of the candela by electrically calibrated radiometers. Metrologia **19**, 85–92 (1983)
26. E. Ikonen, P. Karha, A. Lassila, F. Manoochehri, H. Fagerlund, L. Liedquist, Radiometric realization of the candela with a trap detector. Metrologia **32**, 689–692 (1995)
27. S.P. Morozova, V.A. Konovodchenko, V.I. Sapritsky, B.E. Lisiansky, P.A. Morozov, U.A. Melenevsky, A.G. Petic, An Absolute cryogenic radiometer for laser calibration and characterization of photodetectors. Metrologia **32**, 557–560 (1995)
28. S. Castelletto, M.L. Rastello, Luminous and photon standards by trap detectors. IEEE Trans. Instrument. Measur. **47**, 900–906 (1998)
29. Committee on Optical Science and Engineering, *National Research Council, Harnessing Light: Optical Science and Engineering for the 21st Century* (National Academy Press, Washington, USA, 1998)
30. S.H. Yun, S.J.J. Kwok, Light in diagnosis, therapy and surgery. Nat. Biomed. Eng. **1** (2017)
31. M.E.R. Darnell, K. Subbarao, S.M. Feinstone, D.R. Taylor, Inactivation of the coronavirus that induces severe acute respiratory syndrome, SARS-CoV. J. Virol. Methods **121**, 85 (2004)
32. NIST, USA Website: https://www.nist.gov/
33. PTB, Germany website: https://www.ptb.de/
34. NPL, UK website, https://www.npl.co.uk/
35. J.Y. Cheung, C.J. Chunnilall, E.R. Woolliams, N.P. Fox, J.R. Mountford, J. Wang, P.J. Thomas, The quantum candela: a re-definition of the standard units for optical radiation. J. Mod. Opt. **54**, 373–396 (2007)
36. https://www.bipm.org/utils/en/pdf/CCPR-strategy-document.pdf
37. https://www.ptb.de/emrp/siqute-home.html
38. N. Garg, M. Singh, O. Sharma, V. Mohanan, Current status of acoustic measurement standards at National Physical Laboratory of India (NPLI), New Delhi, Part 1: sound pressure. MAPAN-J. Metrol. Soc. India **22**(2), 77–90 (2007)
39. N. Garg, K. Soni, A. Kumar, T.K. Saxena, Applications of Laser Interferometry in providing traceable vibration measurements in India. MAPAN-J. Metrol. Soc. India **30**(2), 91–104 (2015)
40. N. Garg, M. Singh, O. Sharma, V. Mohanan, Current status of Acoustic measurement standards at National Physical Laboratory of India (NPLI), New Delhi, Part 2: acceleration amplitude. MAPAN-J. Metrol. Soc. India **22**(2), 91–101 (2007)

41. R. Horiuchi, H. Takahashi, T. Fujimori, S. Sato, Final report on key comparison, APMP.AUV.A-K1. Metrologia **44**, 09001 (2007)
42. H.S. Kwon, S.J. Suh, J.G. Suh, Final report on the key comparison, APMP.AUV.A-K3. Metrologia **49**, 09002 (2012)
43. S.B. Figueroa, L. Nielsen, K. Rasmussen, Report on the bilateral comparison between DPLA-DFM and NPLI. Metrologia **44**, 09005 (2007)
44. N. Garg, S. Maji, Analysis of the effect of microphone parameters in reciprocity calibrations using the taguchi method. MAPAN-J. Metrol. Soc. India **30**(3), 179–190 (2015)
45. Q. Sun, A. Liu, Report on the key comparison, APMP.AUV.V-K1.2. Metrologia **47**, 09004 (2010)
46. N. Garg, O. Sharma, A. Kumar, M.I. Schiefer, A novel approach for the realization of primary vibration calibration standard by homodyne laser interferometer in the frequency range of 0.1 Hz to 20 kHz. Measurement **45**, 1941–1950 (2012)
47. N. Garg, O. Sharma, Measurement accuracy of secondary standards of sound pressure in comparison to primary standards, MAPAN-J. Metrology Society of India **27**, 219–229 (2012)
48. V. Plangsangmas, S. Leeudomwong, A. Scott, Y. ZhongBo, Y. Huang, Final report on the regional supplementary comparison APMP.AUV.A-S1. Metrologia **51**, 09004 (2014)
49. T.U. Tsung-Hsein, W. Sheng-Han, Y. Lifeng, P. Rattanangkul, Y.B. Lee, I. Veldman, M. Singh, N. Garg, Final Report of APMP.AUV.V-K3.1: *Key Comparison in the Field of Acceleration on the Complex Voltage Sensitivity, APMP.AUV.V-K3.1* (2019)