Chapter 4

Water turbidity measurement using smartphone

In this chapter, the design of a smartphone based nephelometric platform is discussed which has been used to monitor turbidity in natural and drinking water resources. This chapter includes the importance of water turbidity monitoring, and a detailed theoretical background of nephelometric sensing principle used for such purpose application. The usability of the developed platform will be investigated by measuring turbidity of field collected water samples and comparing its results with a sophisticated laboratory grade nephelometer. Finally, a detailed analysis of evaluation of important sensoristic parameters of the the designed nephelometric platforms has been discussed.

4.1 Introduction

The aquatic lives in water bodies are significantly affected by the presence of suspended organic and inorganic μ - particles such as silt, clay, algae and other organic matters [1]. An elevated amount of suspended μ - particles in water body strongly scatter the incident sunlight which in turn causes the reduction of photosynthesis process of aquatic flora and eventually affect the production of dissolved oxygen in aquatic medium [2]. Moreover, there may be a subsequent rise of temperature in the water bodies due to the absorption of more sunlight by these suspended μ - particles, which may affect the eco-system of aquatic species [3]. Besides the environmental impact, long term consumption of water containing the suspended μ - particles cause serious health hazard such as gastrointestinal illness [4]. Drinking water resources and drinking water distribution systems with an elevated amount of suspended μ -particles is a favorable condition for growth of waterborne pathogens and also, presence of such suspended particles reduces the effect of disinfection processes such as chlorination which stimulate the growth of bacteria and thus leads to various waterborne disease outbreaks [5-7]. Surface water is one of the primary source of drinking water for many regions of India. As reported by WaterAid India, 37.7 million people in India are affected by waterborne diseases every year where most of the cases are from rural regions [8]. Thus, de-centralized and continuous monitoring of any form of contamination in water resources of such remote and rural regions bears a great importance.

Turbidity is considered as a measure of the presence of suspended μ - particles in water medium or the relative clarity of water. According to the International Organization for Standardization (ISO) turbidity is defined as the reduction of transparency of a liquid caused by the presence of undissolved matter [9]. The reduction in transparency is caused by the strong scattering of sunlight by the suspended μ - particles present in the water medium. The measurement of scattered light intensity is considered as a detection parameter for evaluation of water turbidity. This leads to the development of optical scattering based instrumentation namely nephelometers for turbidity monitoring [10]. Nephelometry is considered as the standard method for turbidity measurement. In nephelometry, light scattering measurements are carried out at a fixed angle 90° to the direction of the incident beam and turbidity is determined by comparing the intensity of the scattered light from a given water sample under investigation to a laboratory prepared standard reference medium of known turbidity such as formazin standard suspension. Sediments such as clays (less than 2 μm), slits (2 μ m to 50 μm) and sands (50 μm to 2000 μm) are considered as the primary source of turbidity [11,12]. During sedimentation most of the large particles settle down only the fine particles such as clay remains suspended, therefore in the present study Mie scattering theory is considered as the theoretical background. A detailed theoretical background and the working of a nephelometer has been discussed in the subsection below.

4.1.1 Light scattering and measurement of turbidity in a particle suspension

When a collimated monochromatic light beam of intensity I_0 propagates through a suspension of non-absorbing particles then there is subsequent reduction in intensity of the transmitted beam I due to scattering which is given by [13]

$$I = I_0 e^{-\tau(\lambda)L} \tag{4.1}$$

where, L is the scattering path length and τ is defined as the extinction coefficient of turbidity of the medium at wavelength λ. In the absence of multiple scattering, the turbidity τ of a monodisperse system of N isotropic and non-absorbing spherical particles with radius a is given by [14]

$$\tau = \pi N a^2 Q(a, \lambda, m) \tag{4.2}$$

where, Q is known as the scattering coefficient which is a function of the wavelength λ, particle size a and the ratio of refractive index of the particle μ_p to the refractive of the medium μ_m, given as m. The scattering coefficient can be computed using the Mie scattering theory and can be expressed in the following form

$$Q(a, \lambda, m) = \frac{2}{\alpha^2}\sum_{n=1}^{\infty}(2n+1)\{|a_n|^2 + |b_n|^2\} \tag{4.3}$$

where, $\alpha = \frac{2\pi a}{\lambda}$ is the size parameter and $|a_n|$ and $|b_n|$ are complex functions of α and m which can be evaluated computationally [15,16]. Moreover, for known values of α and m, the scattering coefficient Q can be determined from the existing computational platforms such as MiePlot from Philip Laven [17].

Now, the intensity of light scattered by a unit volume containing N identical spherical particles, illuminated with unpolarized light of intensity I_0 measured at a distance r is given by

$$I_\theta = I_0 \frac{N(i_1 + i_2)}{2k^2 r^2} \tag{4.4}$$

where, $k = \frac{2\pi}{\lambda}$ with λ as the wavelength in the medium. Where i_1 and i_2 are the functions representing the the intensities of the scattered light with the electric vector vibrating perpendicular and parallel to the plane containing the incident and scattered beams. Both i_1 and i_2 depends on the scattering angle θ, size parameter α and refractive index ratio m. These functions can be computed using the following equations derived based on Mie theory

$$i_1 = \{\sum_{n=1}^{\infty}(A_n \frac{P_n^1(\cos\gamma)}{\sin\gamma} + B_n \frac{d}{d\gamma} P_n^1(\cos\gamma))\} \tag{4.5}$$

and

$$i_2 = \{\sum_{n=1}^{\infty}(A_n \frac{d}{d\gamma} P_n^1(\cos\gamma) + B_n \frac{P_n^1(\cos\gamma)}{\sin\gamma})\} \tag{4.6}$$

where $\mathrm{P_n^1}(\cos\gamma)$ is the Legendre polynomial function and γ is the angle $90° - \theta$. A_n and B_n are the functions of α and m alone which can be determined with rigorous computation as shown by the Pangonis et al. [18]. Pangonis et al. has developed a table of calculated values of i_1 and i_2 by computing A_n and B_n for α values from 0.2 to 25.6 for each values of m in the range 1.05 to 1.30 at an angle $\gamma = 90°$. The developed table can be used directly to measure the required values of i_1 and i_2 in the considered range of α and m.

From equation 4.2, it can be inferred that the turbidity of a particular suspension depends on the total number of scatterer N and scattering coefficient Q which is a function of the λ, a and m. Now, from equation 4.5 and equation 4.6, it can be seen that the scattered light intensity I_θ depends on the same parameters which is linearly dependent on$N$ for fixed λ, a and m. The turbidity of a suspension of known size parameter α and refractive index ratio m can be determined by measuring the scattered intensity I_θ at a particular angle [19-21].

4.1.2 Nephelometric determination of water turbidity

Measurement of turbidity in environmental water samples is not directly possible due to the large size distribution of the suspended particles and their irregular shapes. Moreover,the form of the size distribution of the suspended particles may vary from place to place depending on geophysical parameters [22]. Therefore, turbidity in water is measured in terms of standard reference turbid solution. As per the standard methods, turbidity in water samples can be measured with a nephelometer by comparing the degree of scattering of the considered sample with that of a standard particle suspension of defined turbidity in 'nephelometric turbidity units' (NTU) [23]. Figure 4.1 show the schematic of a basic nephelometer used for turbidity monitoring. It consists of a light source, a detector placed at

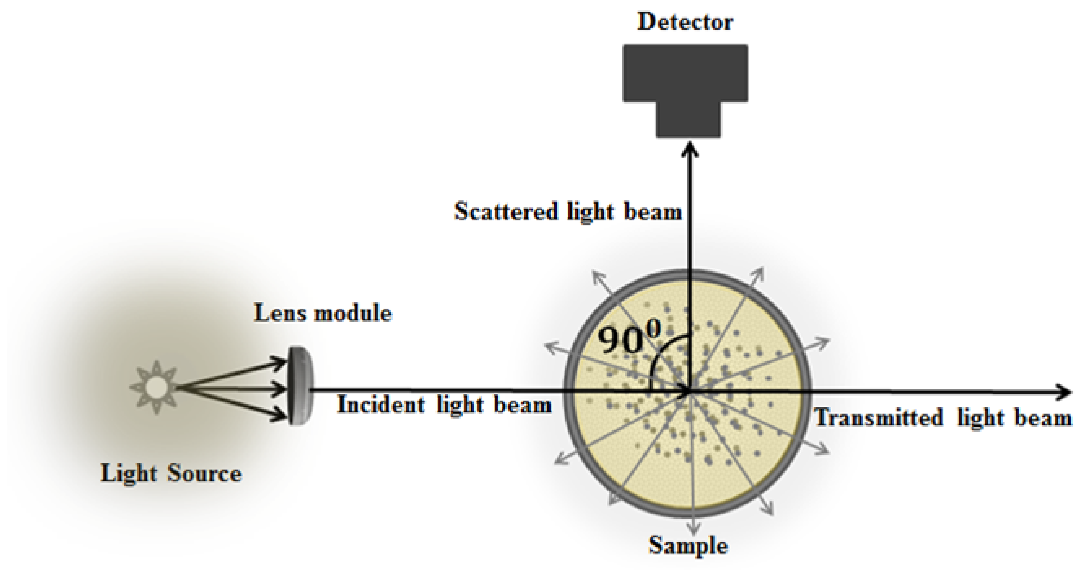

Figure 4.1: schematic of a basic nephelometer.

90° to the incident light beam and delivering optics. As regulated by United States Environmental Protection Agency (USEPA) and International Organization for Standardization (ISO), formazin suspension is considered as turbidity standard because formazin suspension can be easily prepared from raw materials with a reproducibility within ± 1% and using this suspension one can produce a wide range of particle with different sizes shapes. This enable us to replicate an environmental turbid water sample [24,25]. Since, the scattering of light from a nephelometer depends on many instrumental parameters such as wavelength, detection angle, path length and spectral characteristic of the detector, therefore the same turbidity of a sample may be read differently by different instruments. The USEPA Method 180.1 and International Organization for Standardization (ISO) 7027 method are commonly used for development of a nephelometer [26,27]. The USEPA Method 180.1 recommends the following criteria while developing a nephelometer for water turbidity measurement [26]:

1. The light source should preferably be a tungsten lamp (color temperature: 2200°K to 3000°K).
2. The distance propagated by the incident and scattered light within the sample should not exceed more than 10 cm.
3. The detector should be placed an $90° \pm 30°$ to the incident light path and

The detector.

Similar to the above method **ISO 7027 method** recommends the following criteria while developing a nephelometer for water turbidity detection [27]:

1. The detector should be placed at $90° \pm 1.5°$.

2. The light source should preferably be a LED or filter integrated tungsten filament lamps with a peak emission wavelength 860 ± 30 nm.

Based on the above recommendations many research groups have demonstrated the development of optical instruments for determination of water turbidity. Optical fiber based nephelometric sensors have been widely developed for water turbidity monitoring [28,29]. Bilro et al. has demonstrated the development of a low cost plastic optical fiber based platform for continuous monitoring of turbidity in water resources [30]. Wang et al. has demonstrated nephelometric platforms based on single photon counting technique for monitoring of turbidity in liquid medium which can measure water turbidity as low as 0.1 NTU [31,32]. Optical instruments with different optical configuration have also been proposed for determination of water turbidity [33-37]. One of the important requirement of any environmental monitoring system more specifically for water quality monitoring is the real-time data transfer facility which surprisingly not available in any of the reported works. Also, use of sophisticated source detector pair significantly increases the overall fabrication cost. Compact and field portable commercial systems such as 2100Q portable turbidimeter from Hach Inc is available but in consideration of its use for the rural regions on India it is still a costly device ($1,633.70). The de-centralized monitoring requires the involvement of the local community which may not have the required scientific expertise to run a sophisticated electronic equipment. Due to the vast availability of smartphones which in general are equipped with good quality rear and front camera, ALS sensor, wi-fi facility along with high speed processor and data storage ability, it is possible to design a nephelometer on such platform. Also the smartphone can be used for data processing and data transfer. The inbuilt ALS can be considered as a detector and the battery of the smartphone can be used to power an external light source. These facilitates the smartphone to develop it as a low cost alternative for similar applications. Similar to the photometric platform discussed in the previous chapter, this chapter demonstrates a low cost, robust and field portable smartphone based nephelometric platform which is specifically developed for turbidity monitoring in resource limited settings. The usability of the proposed device will be investigated by measuring the turbidity of field collected water samples. The performance of the designed system has been compared with the lab grade nephelometer and a good correlation has been observed. The proposed nephelometric platform has been developed following the recommendation of ISO 7027 method and formazin suspension has been considered as standard samples for calibration of the tool.

4.2 Preparation of formazin calibration standard

The chemicals used for the present experimental work have been procured from the following sources: analytical grade reagent hexamethylenetetramine ($(CH_2)_6N_4$) (product no. 398160) and hydrazine sulfate ($H_6N_2O_4S$) (product no. 489735) are procured from Sigma-Aldrich Inc. All chemicals were used as received without further processing. The formazin standard suspension has been prepared by following the standard methods [23]. A formazin suspension of turbidity 400 NTU has been prepared initially in the laboratory. 1.000 g of $H_6N_2O_4S$ is dissolved in 100 mL of distilled water in a volumetric flask and labeled as solution 1. 10.000 g of $(CH_2)_6N_4$ has been dissolved in 100 mL of distilled water in a volumetric flask and labeled it as solution 2. Now in a 200 mL volumetric flask 5 mL each of the solution 1 and 2 are mixed and total volume of the solution is made to 100 mL by adding 90 ml of distilled water. The resultant solution would be ready for use after keeping it for 24 hours in room temperature. The turbidity of the resultant solution would be 400 NTU. The prepared stock suspension will be stable for up to 1 year if properly stored. From the stock solution other low turbid medium can be prepared by diluting the sample with DI water. Formazin standard suspensions of different turbidity value ranging from 40 NTU to 400 NTU have been prepared in steps of 40 NTU from the 400 NTU stock solution. To investigate the response of the developed platform in low turbidity regime, 20 more samples of Formazin suspension with turbidity value ranging from 0.1 NTU to 1 NTU in step increment of 0.1 NTU and 1 NTU to 10 NTU in step increment value of 1 NTU have been prepared in the laboratory environment. Figure 4.2 shows the photo images of 10 different turbid medium obtained through diluting the stock 400 NTU formazin standard solutions.

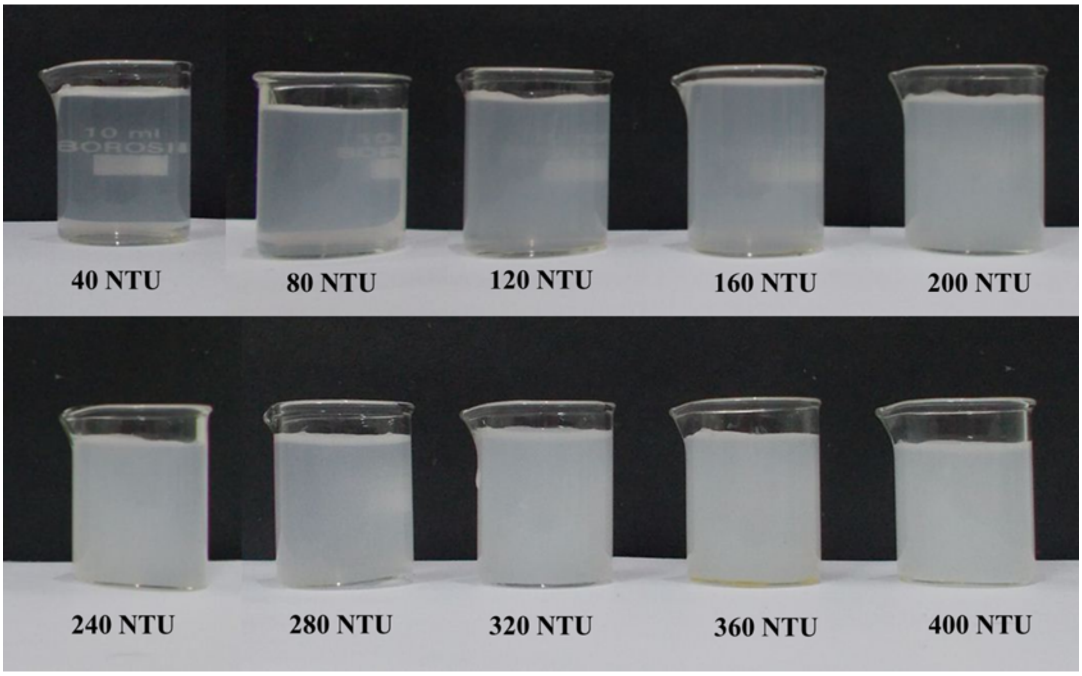

Figure 4.2: Photo image of the prepared formazin standard.

4.2.1 Optical layout and device fabrication

The ISO 7027 method recommends the use of IR LED in the wavelength range 830 nm to 890 nm. At this wavelength the smartphone camera becomes insensitive. The embedded smartphone ALS is sensitive both in visible and NIR spectral regime, therefore the ALS is a perfect detector for the considered work. In the present study, Sony Xperia E3 smartphone has been used to develop the proposed nephelometer. Since, determination of water turbidity by nephelometry is based on the comparison of the degree of scattering of water sample to that of a standard turbid suspension, therefore in designing of the smartphone nephelometric platform no rigorous optics design such as polarization control has been considered. While designing the proposed platform, effort has been made to keep the overall fabrication cost as low as possible. Figure 4.3 (a) shows the schematic of the designed smartphone based nephelometric platform and Figure 4.3 (b) shows the corresponding photo image of the developed system. The USB-OTG protocol has been considered to use the inbuilt battery of the smartphone as power source

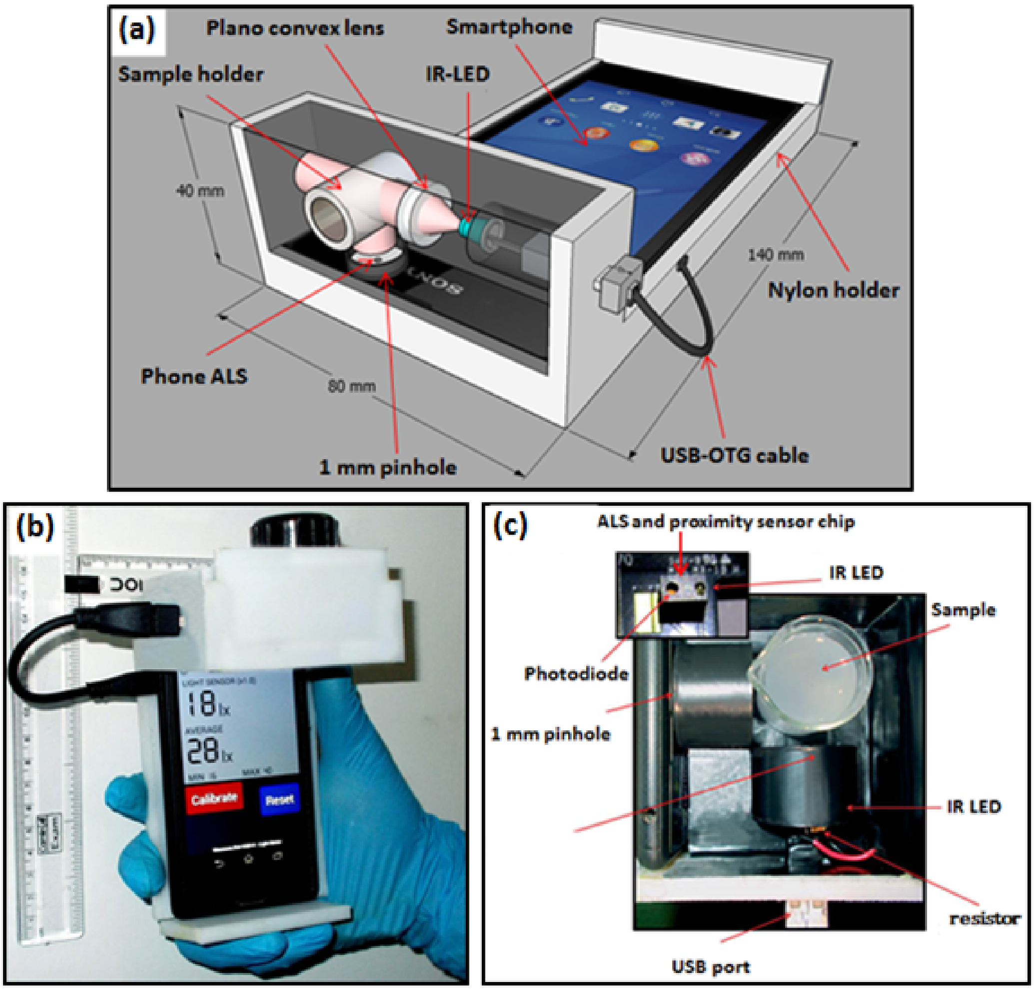

Figure 4.3: A schematic diagram of the proposed setup with different components (b) photo image of the designed smartphone turbidimeter (c) inside view of the turbidimeter compartment.

for illuminating the external LED. A high intensity IR LED with peak emission wavelength 870 nm (Product no. L12756 Hamamatsu) has been used as a light source. A resistor with resistance 220 Ω has been used to limit the current current passing though the LED. In the present study, the IR LED is connected to the USB-OTG through a 220 resistor. The light beam from the LED has been collimated by using a plano-convex lens (7 mm diameter, focal length 11 mm, Edmund Optics 32-404) and the transmitted collimated beam is allowed to interact with the turbid medium placed in a 10 ml glass beaker which is considered as a sample holder for the present work. The compact optical set-up has been attached to the smartphone in such a way that the scattered light from the turbid medium is received by the ALS at 90° to the direction of the incoming light. In order to ensure detection of scattered light received by the ALS nearly at 90°, a 1 mm diameter pinhole is placed in front of the ALS. The separation between the pin hole and the sample holder is 25 mm. Considering that the light scattering is taking place from the center of the sample holder, the scattered light arriving at the ALS will vary within the range $90° \pm 1.14°$ which is well within the recommended detection angle in ISO 7027 method. All optical components including the smartphone have been mounted in a custom developed plastic holder made of Nylon. The inner wall of the Nylon block is blackened to mitigate the affect of the ambient light on the ALS. The overall dimension of the setup is measured to be 140 mm in length, 80 mm in both breadth and 40 mm in width; the weight of the proposed device along with the phone was approximately 250 g. The small dimension and comparatively lower weight makes the designed smartphone based nephelometric platform ideal for in-field application.

4.2.2 Development of the smartphone application

Many scientific smartphone application are readily available. In this work, at first, two freely available applications **Lightmeter** for measurement of light intensity and **stanXY** for calibration and analysis of the sensing data have been used [38,39]. The problem of using these softwares is that two separate applications are required to run separately for detection of intensity and data analysis. Moreover, for measuring any parameters it is required to calibrate the tool every time since there is no option in the "stanXY" application to save the calibration curve within the phone database, which is found to be a time consuming process. To avoid this, an smartphone application **TurbiditySense** has been developed as a standalone computational platform. This can be used for detection, data analysis and data transfer. Figure 4.4 shows the process flow of the application with the required screenshots. The algorithms used for device calibration, data processing as discussed in the previous chapter has been used again in developing the **TurbiditySense** application. The developed application provides same sets of options as shown shown in figure 4.4 (a). By clicking the 'Determine Turbidity' button, the user can go to the main detection window as shown in figure 4.4 (b). After inserting the water sample in the designed nephelometric platform and on

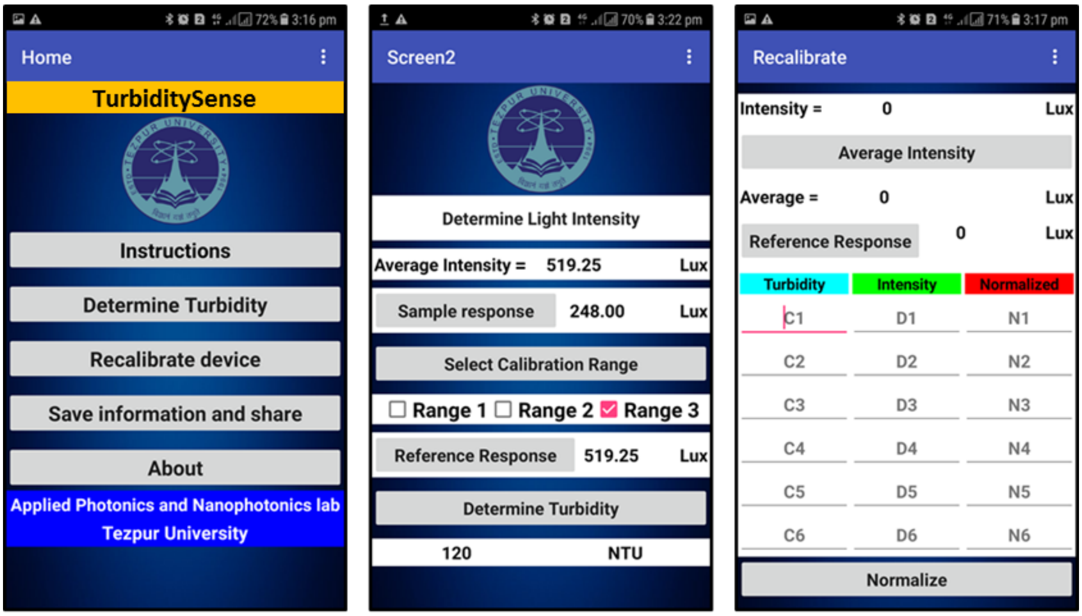

Figure 4.4: workflow of the designed smartphone based application.

clicking the 'Determine Light Intensity' button the application determines the average light intensity measured by the ALS of the phone. The sample response can be recorded for further calculations by clicking the 'Sample response' button. Now, on clicking the 'Select Calibration Range' button, the application will determine the calibration range by using the sample response and a look out table developed in the application database. After this step, the application will automatically select the desired range to be considered. After selecting the desired calibration range, user needs to insert the corresponding reference solution. For instance, 400 NTU formazin standard solution and similarly record the corresponding reference response. Then, by clicking the 'Determine Turbidity' button the smartphone application will determine the turbidity level of the water sample from the respective calibration curve. The designed application has an additional option of recalibrating the device if required. For all field based turbidity measurement studies it is often required to recalibrate the nephelometer on-site.

4.2.3 Device calibration

According to Indian standards (IS), the permissible value of turbidity in drinking water is 1.0 NTU and in the absence of alternate source, this value can be as high as 5.0 NTU [40]. Therefore, the developed smartphone nephelometric platform has been calibrated to include these turbidity levels. We have initially calibrated the device in the following ranges: low turbidity level, 0 NTU to 1.0 NTU considering 1.0 NTU as reference and medium 1.0 NTU to 10 NTU considering 10 NTU as a reference level. Further, the device has been calibrated with prepared standard formazin standard samples in the range 40 NTU to 400 NTU considering again 400 NTU as a reference to measure the high turbidity levels in water samples. The response of each standard solution has been recorded for 5 seconds (with sampling time 1 second) and the average of 10 such measurements has been considered. Here, 0.0 NTU is considered for distilled water when it was placed in the optical path of the designed platform. Figure 4.5 shows the characteristic plot of the normalized scattered signal intensity with the variation of turbidity of formazin standard samples. The coefficient of determination for the considered turbid samples are observed to be $R^2 = 0.991$ for 0 NTU to 1.0 NTU, $R^2 = 0.997$ for 1.0 NTU to 10 NTU and $R^2 = 0.997$ for 40 NTU to 400 NTU. These values suggest that turbidity of any sample in the range of 0 NTU to 400 NTU can be measured almost precisely and accurately with the designed smartphone nephelometer. From these regression analysis, the following calibration equations have been generated.

The calibration equation in the turbidity range 0 NTU to 1.0 NTU

$$\text{Turbidity} = \frac{\text{Normalized intensity} - 0.760}{0.243} \tag{4.7}$$

The calibration equation in the turbidity range 1.0 NTU to 10 NTU

$$\text{Turbidity} = \frac{\text{Normalized intensity} - 0.093}{0.092} \tag{4.8}$$

and for turbidity range 40 NTU to 400 NTU, the calibration equation is

$$\text{Turbidity} = \frac{\text{Normalized intensity} - 0.251}{0.002} \tag{4.9}$$

Above three calibration equations have been implemented in the designed smartphone application to calibrate the proposed tool. Turbidity of water samples outside these ranges can be determined by successive dilution.

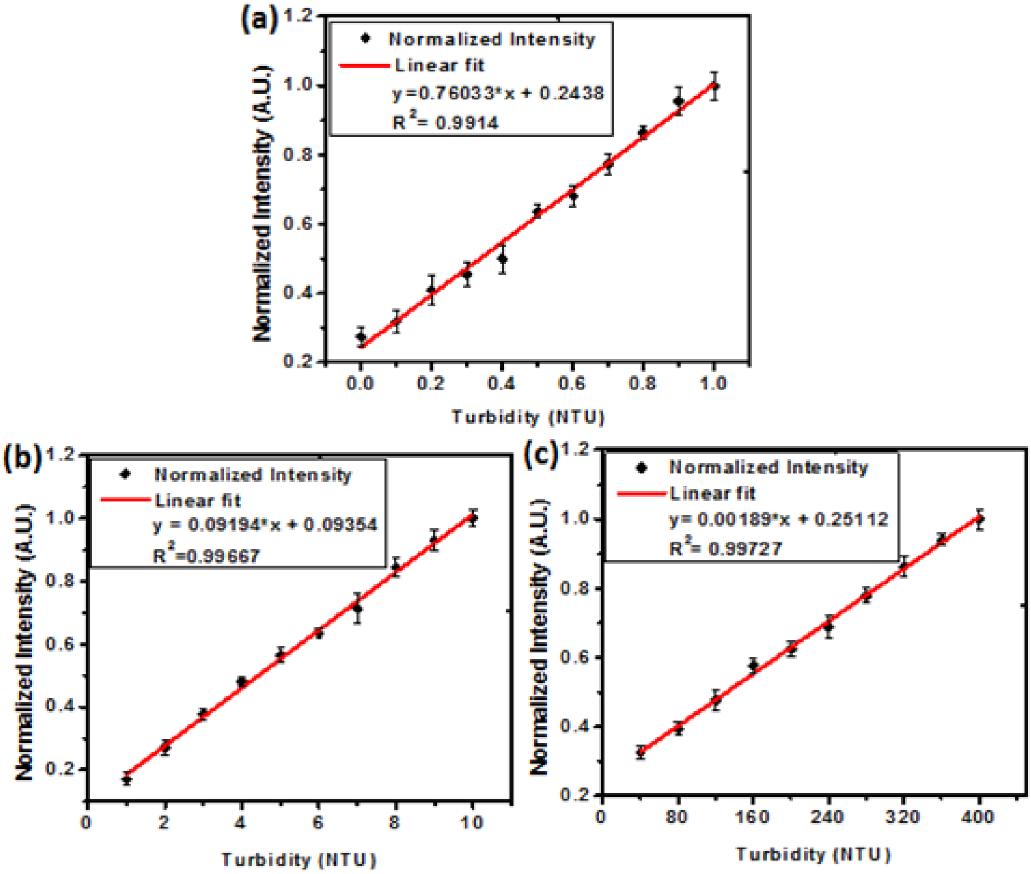

Figure 4.5: Response characteristics of the designed smartphone based nephelometric platform in the turbidity ranges (a) 0 NTU to 1.0 NTU (b) 1.0 NTU to 10 NTU, and 40 NTU to 400 NTU.

4.2.4 Evaluation of different sensoristic parameters of the designed smartphone nephelometric platform

Parameters defining the device performance have been evaluated for the designed smartphone nephelometric platform.

Evaluation of sensitivity and resolution: The sensitivity and resolutionare determined from the response characteristic in low turbidity range as shown in figure 4.5 (a). Equation3.9 defined in chapter 3 has been used to compute the sensitivity. The change in device response $\triangle S = 0.73$ A.U. for the turbidity range of 0 to 1.0 NTU $\triangle T = 1$ NTU. Using these values the sensitivity of the sensor is found to be 0.73 A.U./NTU.

The resolution of the designed system can be determined by plotting response characteristic shown in figure 4.5 (a) in the corresponding intensity units. Figure 4.6 shows the corresponding characteristics response curves in the considered range in terms of intensity units. The sensitivity of the developed nephelometric platform in terms of intensity unit is found to be S = 16 Lux/NTU. The resolution of the embedded ALS as R_{ALS} is 0.01 Lux. The corresponding resolution of the developed platform can be obtain by putting the value of R_{ALS} and S in equation 3.10. This yields the resolution as 6.25×10^{-4} NTU.

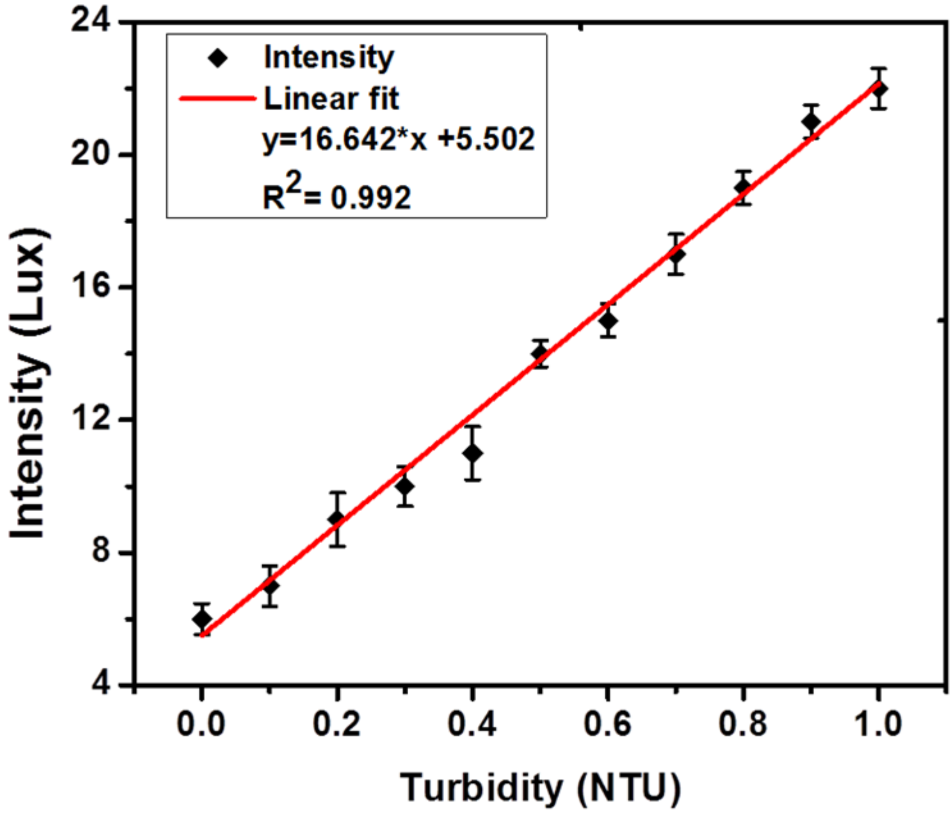

Figure 4.6: Response characteristics of the designed smartphone based nephelometric platform in the turbidity ranges 0 NTU to 1.0 NTU in terms of intensity units.

Evaluation of uncertainty of measurement: The uncertainty of measurement is a parameter associated with the result of a measurement, that characterizes the dispersion of the values that could reasonably be attributed to the measurand [41]. According to Joint Committee for Guides in Metrology (JCGM) [42], the uncertainty of measurement can be expressed in terms of experimental standard deviation of the mean (σ_m) yield in n consecutive measurements and the uncertainty defined in this way is called standard uncertainty of type A (u) is given by

$$u = \frac{\sigma_m}{\sqrt{n}} \tag{4.10}$$

Figure 4.7 shows the uncertainty in measurements produced for 10 sets of readings for each sample in the turbidity range 0.0 NTU to 1.0 NTU. The maximum uncertainty in measurement is found to be approximately 0.065 NTU. This indicates that with the proposed smartphone nephelometric platform one can reliably measure the turbidity variation as low as 0.1 NTU.

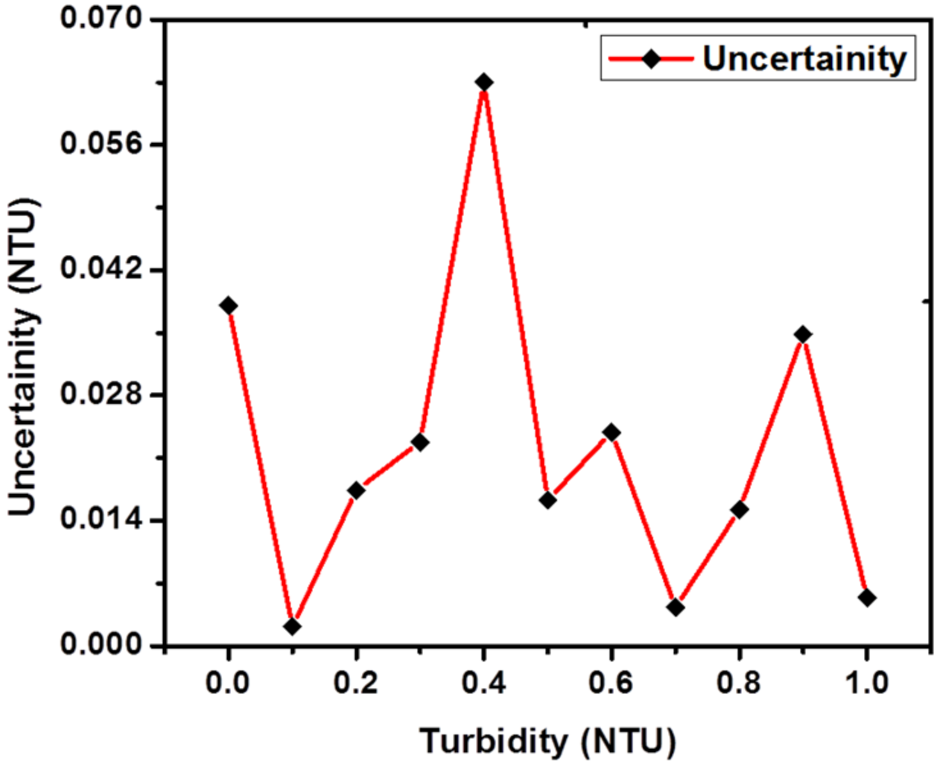

Figure 4.7: The uncertainty of measurement found for 10 sets of measurement of turbidity of standard formazin samples in the turbidity range 0 NTU to 1.0 NTU.

4.2.5 Comparison of the designed smartphone based nephelometric platform with a standard laboratory grade tool

To demonstrate the field applicability of the designed smartphone nephelometer, its performance has been compared with the lab grade commercial nephelometer

(Systronics India, μC turbidity meter, model no. 135) which is specifically developed for this purpose. Water samples from different locations of Sonitpur district of Assam, namely Solmara gaon (WS1), Bali chapari (WS2), Hazara pukhuri Tezpur (WS3), Tezpur University Lake (WS4) and Brahmaputra river (WS5) have been collected. In addition, 3 more clay mixed water samples with clay concentrations 100 mg/L (C1), 300 mg/L (C2), and 500 mg/L (C3) have been prepared in the laboratory. Turbidity value of the field collected and clay mixed water samples are measured with both the tools. Figure 4.8 illustrates the histogram representation of the turbidity measurements provided by the designed smartphone sensor and the standard turbidimeter. These experimental data recorded by both the tools suggests that the proposed smartphone turbidimeter is highly reliable.

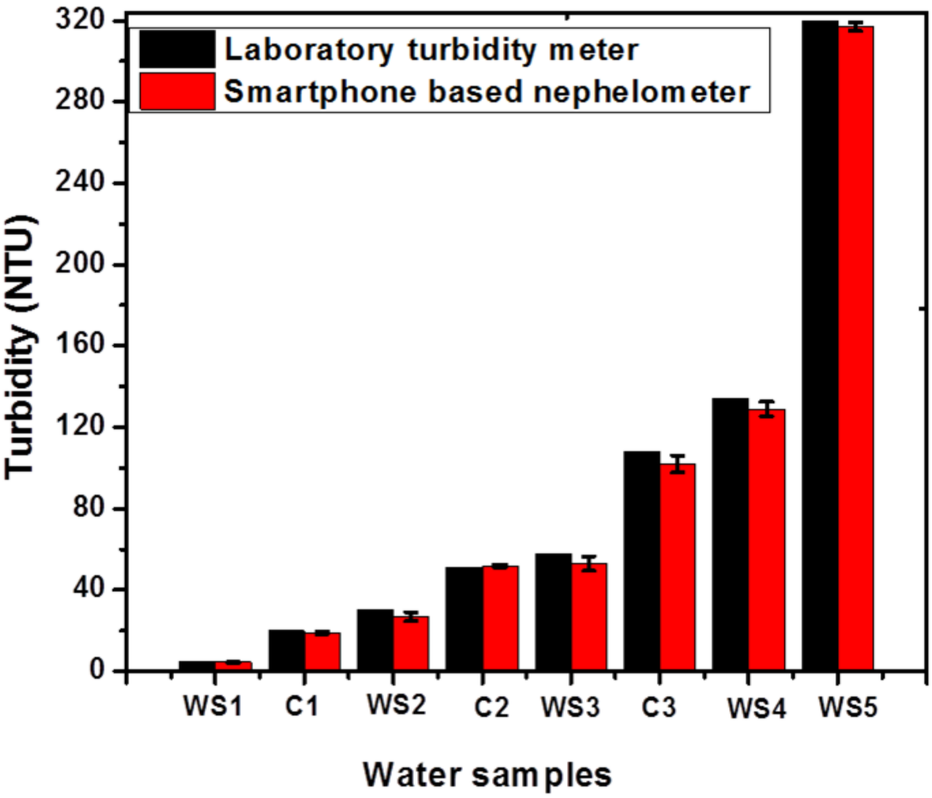

Figure 4.8: Histogram representation of comparison of turbidity measurement of the field collected and laboratory prepared clay-mixed water samples by the standard turbidity meter and by developed smartphone based nephelometric platform.

4.2.6 analysis of interference in measurement from color

Natural water body can produce distinguishable color which can interfere the turbidity analysis. The main motive of using IR LED in ISO 7027 method is to reduce the effect of color in turbidity measurements. Therefore, the device characteristic has further been evaluated for different colored turbid medium. Four standard formazin suspension with different turbidity values 10 NTU, 20 NTU, 30 NTU and 40 NTU have been prepared and then mixed with four different colored dyes namely red, green, yellow and blue prepared in distilled water. Figure 4.9

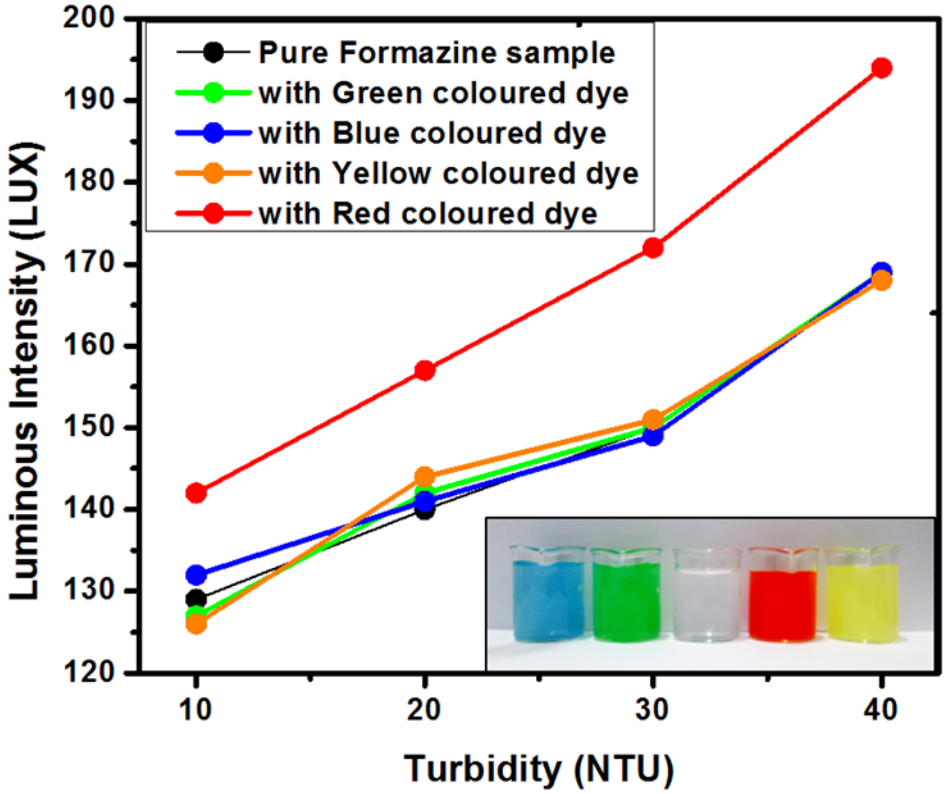

Figure 4.9: Response characteristics of the designed smartphone based nephelometric platform in measuring different colored turbid water samples.

shows the corresponding response characteristic of these sample with reference to the clean formazin samples in intensity units. Inset figure in the same figure shows photograph of the prepared colored Formazin samples along with the clear Formazin sample. It has been observed that except the red colored turbid medium, the response of the designed nephelometric platform for all other colored media and clear Formazin sample are found to be same. This is attributed to response characteristic of the ALS which has its peak response condition in the wavelength range 635 nm to 700 nm (red) which accounts for shifts in the sensor response for red turbid colored medium. To measure the turbidity of red colored medium, an IR filter with peak transmission wavelength within 850 nm to 860 nm should be placed in the path between the ALS and the sample holder.

4.3 Summary

In summary, an affordable and easy to use smartphone based nephelometric platform has been demonstrated which is specifically developed for monitoring of water turbidity. The ISO 7027 standards has been implemented in the designed platform. Use of embedded ALS as a detector and smartphone battery as a source for an external LED makes the designed platform a self-content and self-sufficient tool. Moreover, the custom designed smartphone application **TurbiditySense** promotes onboard computation which is required for detection and data analysis. The same application can be used for data transfer or reporting which is essential for various in-field water quality motoring purposes. It has been observed that the developed optical platform works at par to that of its commercial counterparts. The designed platform promotes a decentralized monitoring of water turbidity system which may find its application in many remote and resource poor regions. It is further envisioned that the proposed nephelometric platform also finds its applicability in many clinical and biological sensing investigations.

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