CHAPTER 2

REAL-TIME MEASUREMENT OF METEOROLOGICAL PARAMETERS FOR ESTIMATING LOW ALTITUDE ATMOSPHERIC TURBULENCE STRENGTH ($C_n^2$)

PREFACE.- The major factor that limits the performance of Free Space Optical Communication (FSOC) is atmospheric turbulence which fluctuates over time in accordance with the variations in local meteorological parameters. Estimating the atmospheric turbulence strength ($C_n^2$) with the measurement data becomes significant to find the data rate and the system is capable of operating under different outdoor local environmental conditions. Hence, a lowcost customized system for continuously measuring the local meteorological data is developed and presented in this chapter. A field test scintillometer setup is established for a link range of 0.5km at an altitude of 15.25m. Specialized sensors are interfaced to the digital architectures to acquire the real time data corresponding to atmospheric changes. The accuracy and performance of the measurement system are tested against standard instruments and the maximum correlation coefficients of 99.92%, 99.63%, 99.73% and 99.88% are achieved for windspeed, temperature, relative humidity and pressure respectively. Atmospheric turbulence strength is estimated for the diurnal period using measured meteorological data. The validations of the estimated results with the scintillometer measurement are also analyzed. The weather profile and corresponding $C_n^2$ variations at our test field for different seasons in one year period are presented and the results are analyzed.
KEYWORDS- Meteorological sensors, atmospheric turbulence strength \((C_n^2)\), scintillometer, Free Space Optical Communication, uncertainty and Finite State Machine (FSM).

2.1 INTRODUCTION

Free Space Optical Communication (FSOC) is an alternative emerging technology to meet the future requirements and Next Generation Networks’ (NGN) demands. FSOC is identified as an alternative to complement microwave (mm wave) and Radio Frequency (RF) links within the access network for the backhaul traffic (Muhammad Saleem Awan et al 2009). The performance of FSOC system is examined in two different categories namely: (i) internal parameters (optical power, wavelength, transmission bandwidth, divergence angle, optical loss, receiver sensitivity, etc.,) and (ii) external parameters (visibility, atmospheric attenuation, turbulence strength, scintillation, deployment distance, pointing loss, etc.,). All these parameters are not independent but are linked together in specifying overall system performance. The FSOC links are also influenced by atmospheric temperature that varies both in spatial and temporal domains. The variations of temperature in the FSOC channel are functions of atmospheric and geographical parameter variations (Arnold Tunick 2007b). This effect is commonly known as optical turbulences or scintillation effects (Carlos O Font et al 2006; Sitterle et al 1988). The atmospheric scintillations can be defined as the changing of light intensities in time and space at the plane of a receiver that detects a signal from a transmitter located at a distance (Lianwei Bao et al 2012). The received signal at the detector fluctuates as a result of the thermally induced changes in the index of refraction of the air along the transmit path (Muhammad Saleem Awan et al 2009). The time scale of these fluctuations is in the order of milliseconds, approximately equal to the time a volume of air takes to move across the path of beam size; and
therefore is approximately related to the wind speed. Overall scintillation causes rapid fluctuations of received power and in the worst case results in high BER (Scott Bloom et al 2003).

Maintaining a clear LoS between transmitter and receiver terminals is the biggest challenge to establish FSOC data link in the troposphere (Muhammad Saleem Awan et al 2009). As the near-ground FSOC system is deeply affected by the atmospheric turbulence (Freddie Santiago et al 2005), it is very important to analyze the channel behaviour in different sessions (Peng Liu Kazaura et al 2010). The continuous measurement of atmospheric turbulence strength and its effects on the laser beam propagation in different environmental conditions over a long period becomes significant (Gappmair 2011) to analyze the quality and reliability of FSOC system that the maximum bit rate the system could operate. Hence a low cost, precise and customized atmospheric parameter measurement system is developed and presented in this chapter. The atmospheric forecasting is made by collecting the real-time windspeed, temperature, relative humidity and pressure data using Cup Anemometer, Temperature & Relative Humidity Sensor (SHT11) and Absolute Pressure Sensor (SCP1000-D01) respectively. The sensor units are interfaced with the digital architecture developed in the Xilinx-Virtex-5 LX50T FPGA platform. A proper synchronization is maintained between the architecture and sensors by the clock manager for precise on-time data conversion and acquisition process.

The rest of the chapter is organized as follows: section 2.2 presents the background and related works, section 2.3 describes the experimental test-bed and measurement protocol, section 2.4 explains the pipelined digital architecture developed for sensor interfacing and data acquisition process, section 2.5 briefly explains the RS-232 Universal Asynchronous Receiver Transmitter (UART) digital circuit and communication frame format, section
2.6 describes the proposed measurement system calibration results along with the relevant uncertainty in detail, section 2.7 presents the overview of atmospheric turbulence strength estimation, section 2.8 discusses the experimental results and data analysis, section 2.9 presents the advantages of proposed measurement system and section 2.10 draws the summary.

2.2 BACKGROUND AND RELATED WORKS

In the last few years, a lot of in-situ field measurements related to environmental parameters monitoring and $C_n^2$ measuring have been remarkably carried out and these can be found in literature. The overviews of closely related works are reported in this section.

The theory of atmospheric turbulence related to the index of refraction model, Rytov method, intensity fluctuation, aperture averaging are described by Peng Liu et al (2010) and the seasonal changes of $C_n^2$ are presented. It is concluded that the beam steering is significant to mitigate the Angle of Arrival (AoA) error.

Steve Doss-Hammel et al (2004) described the fieldtest experimental setup and test protocol used for estimating $C_n^2$. The ascertaining of $C_n^2$ using PAMELA model is evaluated for optical horizontal path over land and water. The results are presented and analyzed.

Yahaya & Frangi (2004) described some dynamic characteristics of the optical and cup anemometers in terms of spectral intensity, frequency, wavenumber and power spectra. The experimental approach to measure the natural wind turbulence by both anemometers is briefed. The cup anemometer for long term wind velocity measurement is suggested.
Taylor et al (1977) proposed a digital automated wind measurement system. LED and phototransistors (opto-electronic conversion system) are used to count the driver shaft revolution. Laboratory, field experimental results and calibration errors are presented.

Pelegri-Sebastia et al (2012) proposed a Relative Humidity (RH) measurement method based on microcontroller and capacitive type RH sensor. An artificial neural network is used to linearize the sensor’s response and reduce the external hardware. Flowchart for capacitance measurement is given and explained.

Vladutescu et al (2012) described a community multiscale air quality model to provide air quality predictions that can be used for forecasts, better understanding of the interplay of meteorology, atmospheric emissions and chemistry. Mie-scattering and the effects of relative humidity are used to get vertical profile of aerosol distribution. The results are presented and analyzed.

Arnold Tunick (2007a) described an experiment developed for 2.33km near horizontal optical path and presented the results calculated using Rytov variance. The spectral analyses for measured laser signal intensity data are shown. The comparison results of scintillometer and calculated $C_n^2$ data are explained. Hunt (1999) presented empirical, statistical and combined modeling techniques for environmental forecasting and atmospheric turbulence with the forecasts construction sketch and calculation grid.

Fernando Lopez Pena & Richard J Duro (2003) presented an automatic calibrator developed for fast and accurate calibration of anemometers. Artificial Neural Network (ANN) aided virtual environment with many sensors is created to increase the accuracy of calibration even by inexperienced users. The performance improvement is highlighted by means of achieved uncertainty.
Eun Oh et al (2004) presented the environmental changes and optical turbulence estimation results calculated using the PAMELA model in different sessions. The humidity effects are analyzed. It is concluded that the humidity and turbulence are inversely proportional.

Arnold Tunick et al (2005) presented an overview of selected optical turbulence (scintillometer data) and meteorological data collected at the Army Research Laboratory (ARL) and Atmospheric Laser Optical Test bed (A_LOT) facility on different durations over 2.3km elevated optical path. Kusnerova et al (2013) discussed various methods for simplifying the method of evaluation of uncertainties in measurement results.

The $C_n^2$ is modeled as a function of altitude (h) in all the models except Hilbert-Huang Decomposition, Bulk method (Paul Frederickson et al1998), Hufnagel–Valley (Arun K Majmudar & Jennifer C Ricklin 2008) and PAMELA model (Oh et al 2004).

The Hufnagel- Valley model estimates the $C_n^2$ as the function of wind speed (Ws), ground level turbulence strength ($A_0$) and altitude (h). Most of the other models are based on optical turbulence similarity theory and predict similar results; however, the local meteorological and geographical parameters are not included but are the input to the PAMELA model. The $C_n^2$ would be estimated as a function of local meteorological and geographical data using the PAMELA model (Steve Doss Hammel et al 2004).

Mazin Ali A Ali (2013b) explained the Rytov variance for plane and spherical waves. Results of atmospheric turbulence effects on wavelength transmission (1550nm, 850nm, 633nm, 532nm) in free space are given and analyzed. Scintillation attenuations and log SNR are computed for different propagation distance and the results are discussed.
2.3 FIELD TEST EXPERIMENTAL SETUP AND MEASUREMENT PROTOCOL

A simplex Free Space Optical Link is established for the range of 0.5km at an altitude of 15.25m in Laser Communication Laboratory (LCL). A scintillometer experiment test setup is constructed with necessary opto-electronics components to measure $C_n^2$ field data (as a direct measurement) near the horizontal optical path as shown in Figure 2.1. The transmitting and receiving setups are mounted on vibration damped optical breadboards.

![Figure 2.1 Optical propagation path for the local $C_n^2$ field data measurement and acquisition with direct transmission test equipments (Scintillometer setups). The Receiver system is seen on the building at the left and the Transmitter system is seen on the tower at the right.](image)

Table 2.1 Parameters of the optical link

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Transmitter</strong></td>
<td></td>
</tr>
<tr>
<td>Laser diode</td>
<td>Peak wavelength 850nm</td>
</tr>
<tr>
<td></td>
<td>Maximum optical power</td>
</tr>
<tr>
<td></td>
<td>Beam size at aperture</td>
</tr>
<tr>
<td></td>
<td>Beam Divergence</td>
</tr>
<tr>
<td></td>
<td>Laser beam propagation model</td>
</tr>
<tr>
<td>Optical Lens</td>
<td>Diameter 3.9 mm</td>
</tr>
</tbody>
</table>
### Table 2.1 (Continued)

<table>
<thead>
<tr>
<th>Channel</th>
<th>Range</th>
<th>0.5km</th>
</tr>
</thead>
<tbody>
<tr>
<td>Altitude</td>
<td>15.25m</td>
<td></td>
</tr>
<tr>
<td>Length of surface roughness</td>
<td>0.03</td>
<td></td>
</tr>
<tr>
<td>Wind speed</td>
<td>0-38 mps</td>
<td></td>
</tr>
<tr>
<td>Temperature</td>
<td>22-58° C</td>
<td></td>
</tr>
<tr>
<td>RH</td>
<td>0-100%</td>
<td></td>
</tr>
<tr>
<td>Pressure</td>
<td>99-101.9</td>
<td></td>
</tr>
</tbody>
</table>

#### Receiver

<table>
<thead>
<tr>
<th>Telescope</th>
<th>Aperture</th>
<th>330.9 mm</th>
</tr>
</thead>
<tbody>
<tr>
<td>Type</td>
<td>Newtonian</td>
<td></td>
</tr>
<tr>
<td>Filter</td>
<td>Type</td>
<td>NBOIF</td>
</tr>
<tr>
<td>CWL</td>
<td>850nm</td>
<td></td>
</tr>
<tr>
<td>Optical Collimator</td>
<td>Collimation ratio</td>
<td>9:3</td>
</tr>
<tr>
<td>Photodetector</td>
<td>Active area</td>
<td>1mm²</td>
</tr>
<tr>
<td></td>
<td>Half angle field of view</td>
<td>±75°</td>
</tr>
<tr>
<td></td>
<td>Spectral sensitivity</td>
<td>0.59A/W</td>
</tr>
<tr>
<td></td>
<td>Rise and fall time</td>
<td>5ns</td>
</tr>
<tr>
<td>Data processing</td>
<td>FPGA</td>
<td>Virtex5</td>
</tr>
<tr>
<td>Data logging</td>
<td>PC</td>
<td>Quad processor</td>
</tr>
</tbody>
</table>

The main opto-electronic devices and their parameters are given in Table 2.1. The Rytov variance is a measure of the strength of scintillation. The ray propagation through a turbulent atmospheric medium will experience irradiating fluctuations called scintillation (Kenneth J Grant et al 2006b). The relation between turbulence strength ($C_n^2$) and the relative variance of optical intensity $\sigma_i^2$ was set by Rytov as (Arnold Tunick 2007a; Mazin Ali A Ali 2013a)

$$\sigma_i^2 = K C_n^2 k^\frac{\mu}{\lambda} L^\frac{\nu}{\lambda}$$  \hspace{1cm} (2.1)
where $C_n^2$ is the turbulence strength parameter, $k$ represents the wave number ($k=2\pi/\lambda$) and $L$ is distance between the transmitter and receiver of the optical wireless link and $K$ is a constant ($K=1.23$ for plane wave approximation and $0.5$ for spherical wave approximation). The signal intensity (scintillation) data at the receiver are continuously recorded and the scintillation index $\sigma_i^2$ is obtained by

$$\sigma_i^2 = \frac{\langle I^2 \rangle - \langle I \rangle^2}{\langle I \rangle^2}$$  \hspace{1cm} (2.2)$$

where $I$ is the measured irradiance of the optical wave and the angle brackets $\langle \cdot \rangle$ denote an ensemble average or equivalently a long-time average. From Equations (2.1) and (2.2), the $C_n^2$ can be calculated for the 850nm optical source and 0.5km link range as

$$C_n^2 = \frac{\sigma_i^2}{1.23k^2L^{1/6}}$$  \hspace{1cm} (2.3)$$

The $\sigma_i^2$ is computed from the irradiance of the optical wave observed by a point detector after propagating a distance $L$ (Scintec Corporation 2012). Classical studies on optical wave propagation have been classified in two major categories, either the theory of weak or strong fluctuations. It is customary to discriminate both cases for a problem of given propagation by determining the value of Rytov variance. The regime of weak fluctuations occurs when $\sigma_R^2 < 1$ and the regime of strong fluctuations associates with $\sigma_R^2 > 1$, while there is a regime of saturation when $\sigma_R^2 \to \infty$.

The weather sensors are mounted on the PCB and placed inside a sensor house in order to prevent them from the direct influence of external heat and rain impact as shown in Figure 2.2. A roof-top with membrane is
built to improve the response time and accuracy of the wind-speed (Ws), temperature (T), Relative Humidity (RH) and pressure (Pr) sensors. The side apertures of the Ws sensor section are kept open, so that the sensor is influenced by the wind irrespective of the direction. This weather station is positioned near the scintillometer receiver setup. The meteorological parameters are measured every second (at the rate of 1Hz) and one minute average data are recorded in the PC for several diurnal periods in different seasons.

**Figure 2.2** Photograph of sensors compartment – sensors are prevented from the direct influence of the environmental changes and kept in waterproof housing

### 2.4 SENSOR INTERFACING ARCHITECTURES AND DATA ACQUISITION PROTOCOLS

The weather sensors are connected to FPGA in which the global Pipelined-Parallel interfacing architecture is developed. A simple pulse counting, Two Wire Interface (TWI) and Serial Peripheral Interface (SPI) protocol are used for proper synchronization and data acquisition from sensors. Very high Speed Hardware Description Language (VHDL) is used for programming to develop the digital architectures inside the FPGA. The hardware interfacing circuit operations and data acquisitions are described in this section.
2.4.1 Wind Speed Measurement – Cup Anemometer

The cup anemometer assembly for wind speed measurement consists of hemispherical cups which rotate according to the wind speed, a drive shaft, magnetic bars and a singlepole reed switch. The angular movement of the magnet is directly proportional to the rotational speed of the cups i.e., wind speed. The reed switch is closed when any one of the magnetic pole comes closer to its central part and opens when the pole is away as shown in Figure 2.3. The number of contacts (pulse) per second is the measurement of wind speed (Fasinmirin et al 2011). There is a minimum wind speed which will set the cup in motion depending on the friction in the bearings of the wheel and the design parameters of the instrument (Rachael V Coquilla 2010). In a steady wind at the LCL, the cup performs well from almost $0.27\text{ms}^{-1}$ to $60\text{ms}^{-1}$. This is because the cup wheel, having inertia, accelerates more rapidly with an increasing wind speed than it decelerates with decreasing wind speed (Fernando Lopez Pena & Richard J Duro 2003).

![Figure 2.3 Components’ assembly and design structure of cup anemometer- kept in waterproof cabin](image_url)
The wind speed $\mu_a(t)$ is related to the angular velocity of the anemometer (Yahaya & Frangi 2004)

$$\mu_a(t) = Cs(t) + U_0$$

(2.4)

where $C$ is calibration constant (gain=0.6201m), $s(t)$ is angular velocity of the device in Hz and $U_0$ is offset speed. A JK Flip Flop is used to hold the pulse from anemometer and to reset it after reading the pulse. The anemometer interfacing circuit and digital architecture are shown in Figure 2.4. Every polling of the anemometer is actually a clock pulse to the JK FF and the pin ‘Q’ goes high for all the rising edge of the clock pulse. The level hold and reset controller continuously monitors the voltage changes at ‘Q’ and increments the value of 5-digit counter at the rising edge of the ‘Q’. After one milli second, it resets the JK FF by sending a low signal to the ‘clr’ pin. The LED glows every time when anemometer sends a signal to the FPGA.

![Figure 2.4 Circuit schematic and architecture of cup - anemometer interfacing for wind speed measurement](image)

A one second clock counter is designed to trigger the counter controller unit once in every second which keeps the counter in counting mode, shifting mode or reset mode. The clock manager generates the control and trigger signal at 5kHz rate in order to synchronize the measurement. The counter value ($000000100000_2$) for a given second, is equal to 16 in radix 10.
The Reed switch of anemometer polls for four times per cycle, hence the angular velocity \( s(t) \) of the anemometer is given by counter value/4. The offset wind speed of the anemometer and the calibration constant are 0.27\( \text{ms}^{-1} \) and 0.6201\( \text{m} \) respectively. The pseudo code of measurement algorithm and simulation timing response are shown in Figures (2.5) and (2.6) respectively.

**Declaration:**

```vhdl
ws_pulse, m_clk:=in: =0;
ws_reset:=out:=0;
ws_cunt, ws_value:=wire=[13:0]:=0
clk_div1, clk_div2, cunt_ctrl:=wire:=0;
cunt_state:=wire:=0;
i,j,k,l,n :=variable :=integer: =1;
```

**Process (1&2):**

```
when i:=l else i:=i+1
if ws_pulse:=1, cunt_ctrl<=1 else cunt_ctrl<=0;
wait(), ws_reset<=0 wait () ws_reset<=1;
```

**Process (3):**

```
if cunt_ctrl=1, if cunt_stat:=0,
ws_cunt<=ws_cunt+1;
elsif cunt_state:=1, ws_value<= ws_cunt;
elsif cunt_state:=2, ws_cunt<=0;
else ws_cunt<=ws_cunt+1; endif; endif
```

**Process (4&5):**

```
when k:=m;
else k:=k+1;
if clk_div2=1, j:=j+1; else j:=j;
if j:=60 count_state:=01
elsif j=61, count_state:=02 else count_state:=0.
endif, end
```

**Figure 2.5 VHDL pseudo code of wind speed measurement**

**Figure 2.6** Wind Speed measurement simulated timing diagram - Modelsim results for the value “(000000010000)\(2\)” = (16)\(10\) = 2.75\( \text{ms}^{-1} \)
2.4.2 Relative Humidity and Temperature Measurement – SHT11 Sensor

A low cost and low power surface mountable, 8 pin SHT11 sensor (Sensirion 2011) is used to measure the T in 14 bit resolution and RH in 12 bit resolution. The sensor consists of a capacitive sensing element, a polymer, which absorbs and desorbs water molecules depending on the surrounding conditions and provides a fully calibrated digital output. The Two Wire Interface (TWI) and internal voltage regulation allow for fast system integration. The SHT11 is interfaced with FPGA in which a digital architecture shown in Figure 2.7 is developed to transfer the communication / control sequence to the sensor. The digital architecture logical design encompasses two distinct parts : (i) data path processor unit performing the data processing operations consists of shift registers, multiplexers, counters, flip-flops, demultiplexers and tristate switch, etc., and (ii) control engine-finite state machine, that sends command to the data path processing unit to determine the sequence in which various actions like sending the sequence of connection reset, transmission start, address & command, etc., are performed.

Figure 2.7 Digital architecture for temperature and relative humidity measurement-TWI interfacing protocol
The serial clock (SCK) and data pins are accessed by architecture and SHT11 sensor for internal register programming, measurement data acquisition, reception of acknowledgement and mode selection etc. SCK is used to synchronize the communication between architecture and sensor. Since the interface consists of fully static logic, there is no minimum SCK frequency. The data pin is used to transfer data in and out of the sensor. The output SCK and inout data are connected to the SHT11 and are used for sending the sequence and reading the measurement values as per the execution command from the control engine. The control engine state transition flow occurs from state ‘a’ through state ‘k’ for every T and RH measurement cycle. The signal dmux1_ctrl is used to control the Dmux1 to transfer the rx_data either to Dmux2 (Mm_data) or control engine (ACK). This operation sequence is repeated to collect the T and RH data over a long period. The data shifting, circular rotations, enabling sequence register, data loading at the desired accumulator are performed by the control engine, multiplexer and demultiplexer. The tristate switch output is inout i.e., it is driven by the input when enabled otherwise driven by the SHT11. The timing diagram synchronization among all the operations of the measurement is maintained by the clock manager. The control engine state transition flow for T and RH measurement is shown in Figure 2.8 and explained below:

State(a): The connection reset sequence is stored in [25:0] circular shift register such as to toggle SCK nine times during data high followed by toggling SCK one time at data low and forcing SCK and data high again low. This sequence resets the status register of SHT11 with the default contents.

State(b): The transmission start sequence is stored in [9:0] circular shift register such as to lower the data while SCK high followed by a low pulse and rising data high while SCK high.
State(c): The temperature measurement address and command (0x03H) is stored in a [15:0] circular shift register and transferred to the SHT11 for the rising edge of the SCK.

![State transition diagram](image)

Figure 2.8 FSM control engine state transition flow for temperature & relative humidity measurement.

State(d): The SHT11 sensor indicates the proper reception of the address and command by pulling the data low after the trailing edge of the SCK (ACK1 Low).

State(e): Check for whether data are zero or not.

State(f): Delay for measurement approximately 320ms. The completion of the measurement is signaled by pulling the data low.

State(g): Reading the MSB (D15–D8) of the measurement value bitwise and loading into the [15: 8] of T value accumulator for the rising edges of SCK.

State(h): An acknowledgment is passed to the SHT11 by forcing the data low after reading MSB data followed by a pulse on SCK.

State(i): Reading the LSB (D7–D0) of the measurement value bitwise and loading into the [7:0] of T value accumulator.

State(j): Forcing the data high since the CRC is not used followed by the state(b) operation to read out the RH measurement data.
State(k): The RH measurement and command (0x05H) is stored in a [15:0] circular shift register and transferred to the SHT11 followed by state(d) to state(j) operations.

The signal dmux1_ctrl is used to control the Dmux1 to transfer the rx_data either to Dmux2 (Mm_data) or control engine (ACK). In state(g) and (i), the RH value accumulator is enabled by Dmux2_ctrl while the relative humidity measurement is being carried out.

Declarations: m_clk:=in:=0; sck:=out:=0;
data:=inout:=0; rx_ctrl,dmux1_ctrl, demux2_ctrl:=wire:=0;
global_ctrl_bus(en_sh,ld):=wire:=0;
variable i,j,sck5,sck6,data5,data6 :=integer:=1;
Process(1): clk_div1<=not clk_div1, i:=i+1; if i=j else i:=i+1;
Process(2): data<=tx_data when (trc_ctrl=0 else z;
rx_data<=data;
Process(3): @clk_div1: if seq_sel_cnt is = 0,
con_rest_seq_sck&data on: 2\mid 10, (i) temp_addcom_data & sck on,
(ii) rh_addcom_data on, 3\mid 11, trs_sck<=1; demux1_ctrl<=1,
check for ack high;
4\mid 12, check for ack low, delay (); 5\mid 13, check for ack high,
delay (), check for ack low;
6\mid 14, demux1_ctrl <=0; (i) demux2_ctrl<=0, (ii)
demux2_ctrl<=1, (i) read_temp_msb(); (ii) read_rh_msb();
7, trs_ctrl<=0, check for ack low; 8\mid 15, trs_ctrl<=1, (i)
demux2_ctrl<=0, (ii) demux2_ctrl<=1, (i) read_temp_lsb(),
(ii) read_rh_lsb(); end;
Process(4): mm_data<=rx_data if demux1_ctrl=0 else
ack<=rx_data
i<=mm_data if demux2_ctrl=0 else rh<=mm_data;
Process(5): @clk_div1, case seqSel is 0, crs_sck <= crs_sck
(24.0) & crs_sck(25.0);
end;
Process(6): if seq_sel is 0=>sck<=sck1; tx_data<=data1;
1\mid 9=>sck<=sck2; tx_data<=data2;
2\mid 10=>sck<=sck3; tx_data<=data3; 4=>sck<=sck4;
6\mid 8\mid 12\mid 14=>sck<=sck5;
7\mid 13=>sck<=sck6; tx_data<=data6; end;

Figure 2.9 VHDL pseudo code of RH and T measurement
This operation sequence is repeated to collect the T and RH data over a long period. The data shifting, circular rotations, enabling sequence register and data loading at the desired accumulator are performed by the control engine, multiplexer and demultiplexer. The tristate switch output is inout i.e., it is driven by the input when enabled otherwise driven by the SHT11. The timing synchronization among all the operations of the measurement is maintained by the clock manager.

Figure 2.10  Timing diagram of T and RH measurement simulated in Modelsim for the values “01100100010100” = (6420)$_{10}$ = 24.10°C and “010101111000” = (1400)$_{10}$ = 46.09 %.

The digital readout $T_{\text{meas}}$ conversion formula to calculate the equivalent temperature in °C is (Sensirion 2011)

$$\text{Temp} = T_{\text{in}^\circ\text{C}} = -40.1 + 0.01T_{\text{meas}} \quad (2.5)$$

The digital readout $R_{\text{Hmeas}}$ conversion second order formula to calculate the true RH in percentage with the temperature compensation is (Sensirion 2011)

$$R_{\text{Hin}\%} = (T_{\text{in}^\circ\text{C}} - 25)(0.01 + 0.00008R_{\text{Hmeas}}) + 0.0367R_{\text{Hmeas}} - 1.5955 \times 10^{-6} R_{\text{Hmeas}}^2 - 2.0468 \quad (2.6)$$
The due point temperature $T_d$ is calculated from RH and $T$ readings with the following approximation in good accuracy (Sensirion 2011)

$$
T_d = 243.12 \left( \frac{\ln \left( \frac{RH}{100} \right) + \left( \frac{17.72T}{243.12 + T} \right)}{17.62 - \ln \left( \frac{RH}{100} \right) - \left( \frac{17.62T}{243.12 + T} \right)} \right)
$$

(2.7)

The pseudo code of measurement algorithm and simulation timing response are shown in Figures (2.9) and (2.10) respectively.

2.4.3 Absolute Pressure Measurement–SCP1000-D01 Sensor

The SCP1000-D01 sensor is used to measure the absolute pressure in 19 bit resolution. The sensor consists of a silicon bulk micromachined sensing element chip and a signal conditioning Application Specific Integrated Circuit (ASIC).

Figure 2.11 Digital architecture of pressure measurement: SPI communication interface protocol
Overcoming the timing error, more accurate measurement can be carried out using SCP1000-D01 (John Witzel 2008). The pressure sensor element and the ASIC are mounted inside a plastic pre-mould package and wire bonded to appropriate contacts. The pressure output data are calibrated and compensated internally. The digital architecture of pressure measurement is shown in Figure 2.11. The pressure measurement digital architecture consists of two parts: one is data processor unit and another is control engine. The communication protocol between the digital architecture and SCP1000-D01 is a Serial Peripheral Interface (SPI) (VTI Technologies 2007). The SPI interface is a full duplex five wire serial interface. The communication between the architecture and sensor is done with data ready (DRDY), trigger (TRIG), SCK, Master out Slave In (MOSI) and Master In Slave Out (MISO) signals. The SPI communication frame consists of three 8 bit words. The first word defines the register address followed by the type of access i.e., ‘0’ for read and ‘1’ for write and one ‘0’ at LSB followed by the data words being read or written. The MSB of the words are sent first. Bits from the MOSI line are sampled for the rising edges of SCK while bits to the MISO are latched out for the trailing edge of SCK. The register address and data sequence are stored in the circular shift registers in the data processor unit. Finite state machine control engine pressure measurement state transition cycle occurs for every second. The register address, content sequence shifting, enabling the register, loading the content, writing and reading are performed at the data processor unit as per the command sequence from control engine. The SCK_ctrl controls issuing of clk_div1 to the SCK. The timing synchronization among various operations of the whole measurement is maintained by the clock manager. The register address and data sequence are stored in the circular shift registers in the data processor unit. FSM control engine state transition flow for pressure measurement is shown in Figure 2.12 and explained below:
State(a): The restart register (Add: 0X06H) is written with restart sequence (data: 0X01H)

State(b): Reading the content of status register(Add: 0X07H) and loading bitwise into the register content accumulator followed by checking the Least Significant Bit(LSB) to verify that startup procedure is finished.

State(c): Reading the content of datard8 register (Add: 0X1FH) and loading bitwise into the register content accumulator followed by checking the LSB to identify that the SCP100-D01 standby mode and waiting for measurement command.

State(d): The configuration register (Add: 0X00H) is written with 17 bit measurement sequence (data:0X05H).

State(e): Forcing the trigger signal high.

State(f): Forcing the trigger signal low.

State(g): Wait for measurement and computation delay till the data ready go high.
State(h): Writing the datard8 (Add:0X1FH) address sequence.

State(i): Reading the content of datard8 register and bitwise loading into pressure value accumulator.

State(j): Writing the datard16 (0X20H) address sequence.

State(k): Reading the content of datard 16 register and bitwise loading into pressure value accumulator.

State(l): Wait for delay to start next measurement cycle.

The pseudo code of measurement algorithm and simulation timing response are shown in Figures (2.13) and (2.14) respectively.

Declarations: m_clk, miso:=in:=0;
        drdy:=in:=1; sck, mosi, trig:=out:=0;
        clk_div1, wr_rd:=wire:=0; sck_ctrl:=wire:=1;
        amosi[17:0], bmosi[8:0], cmosi[8:0], dmosi[16:0],
        hmosi[8:0]:=wire:=value:=seq_sel[3:0]:=wire:=0;
        bmiso[7:0], cmiso[7:0], Mm_data[18:0]:=wire:=0;
        i,j,k:=variable:=integer:=1;

Process(1): while(1)
        clk_div1<=not clk_div, i:=0 if i:=k; else i:=i+1;

Process(2): if cmt:=0, wr_rd<= 0: sck_ctrl<= 1;
        elsif cmt:=2, wr_rd<= 1, delay(); wr_rd<=0;
        elsif cmt:=3 if lsb=0, cnt:=cnt+1: else cnt:=0;
        elsif cmt:=4 \ 9 \ 11, wr_rd<=1;
        elsif cmt:=5, wr_rd<=0, sck_ctrl<=0;
        elsif cmt:=6, if lsb=1, cnt:=cnt+1, else cnt:=0;
        elsif cmt:=7, sck_ctrl<=1; trig<=1, delay(); trig<=0;
        elsif cmt:=8, if drdy<=0; cnt:=8;else cnt:=cnt+1;
        elsif cmt:=10\12, wr_rd<=0;

Process (3): case seq_sel is
        if wr_rd=0, when 0:=>mosi<=amosi(n-1:0)&amosi(n); when 1:=>mosi<=bmosi(n-1:0)&bmosi(n);
        when 3\8:=>mosi<=cmosi(n-1:0)&cmosi(n);
        when 4:=>mosi<=dmosi(n-1:0)&dmosi(n);
        when 10: =>mosi<=hmosi(n-1:0)&hmosi(n);
        else when 2: =>bmosi<=bmosi(n-1:0)&miso;
        when 4: =>cmosi<=cmosi(n-1:0)&miso;
        when 3\6: =>Mm_data<=Mm_data(n-1:0)&miso; end;

Figure 2.13 VHDL pseudo code of P measurement
The transmission goes to state(e) after finishing the first measurement cycle and continues for collecting the pressure data over a long period. The register address, content sequence shifting, enabling the register, loading the content, writing and reading are performed at the data processor unit as per the command sequence from control engine.

Figure 2.14  Timing diagram of P measurement simulated in Modelsim for the value \((1100010111000010000)\)\(_2\) = \((405008)\)\(_{10}\) = 101.252 kPa

The SCK_ctrl controls issuing of clk_div1 to the SCK. The true pressure value \(P_r\) is calculated in kPa by (VTI Technologies 2007)

\[
P_r = 0.25(P_{\text{mean}})_{10}
\]  \hspace{1cm} (2.8)

The measurement starts when the ‘Start’ pin high and ‘Done’ goes high and then low to signal the completion of every measurement cycle.

2.5 COMMUNICATION PROTOCOL AND FRAME FORMAT

The meteorological data acquisition measurement is done every second and the values in radix-2 format are stored in the specified registers. This data are continuously shifted to the M/m data buffer during subsequent measurement without data conflict / loss. The measured data are plunged into
the communication architecture and propagated through the modules corresponding to Universal Asynchronous Receiver Transmitter (UART)–RS232 communication protocol to the data logging computer (Nhivekar & Mudholker 2011). The UART–RS232 standard serial communication protocol (Erik Cheever 2010; Joel M Esposito et al 2011) is implemented as a separate digital architecture inside the FPGA as shown in Figure 2.15(a). The contents of the buffer are shifted into the communication frame planner for every rising edge of data_rd signal. The communication frame planer splits the measurement data intact length into bytes, to introduce start bit (‘0’) before every byte and concatenate sufficient zeros with the bits, as shown in Figure 2.15(b), to form the communication frame and sends to mux1.

Figure 2.15  (a) UART – RS 232 communication protocol architecture and (b) communication frame format
In order to avoid the occurrence of communication conflict among the frames, two header (H1 & H2) frames are transferred followed by the measurements data frames and one footer (F1) frame as an appropriate coordination among the data, so that totally 12 frames are transferred for every measurement cycle. The count value of cnt2 informs to the byte shift controller about the completion of one frame transmission (i.e. 11 bits) and then the byte shift controller increments cnt3 to select the next input (frame) of mux1 to load it into the Parallel In Serial Out (PISO) shift register. The baud rate counter generates the bit’s transmission clock i.e baud rate clock clk_sig at the rate of 9600 from the master clock m_clk. The shift register performs a cyclic shift on its content sdata (sdata=frame format of H1,H2,Ws,T,RH,Pr,F1) for the rising edges of the transmission clock and the sdata (0) is forwarded to the first input of the mux2 when the mux_sig high otherwise the shift register is disabled. The timing diagram and simulation result of the above operation is shown are Figure 2.16.

![Timing diagram of UART communication protocol simulated in Modelsim for Ws= “0000100111100” =632<sub>10</sub> =98.2458 ms⁻¹, T=“11010000001” =6670<sub>10</sub> =26.6 °C, RH=“010010010” =1193<sub>10</sub> =39.63 %, and P=“1101000000110000” =410000<sub>10</sub> =102.5 kPa](image)

The bit shift controller maintains mux_sig at high for the entire duration of the frame transmission and pulls back to low till loading next frame into the PISO shift register and continues the similar transitions. The mux2 sends sdata(0) to the data logging computer when mux_sig high otherwise sends stop bit ‘1’.
2.6 PERFORMANCE CALIBRATION OF PROPOSED MEASUREMENT SYSTEM

The accuracy, repeatability, reproducibility and uncertainty (Kusnerova et al 2013; Uwe S Paulsen et al 2007) of the proposed measurement results are tested through extensive experiments. The proposed system can measure the wind speed from 0.27 ms\(^{-1}\) to 60 ms\(^{-1}\) with 0.25 ms\(^{-1}\) resolution, temperature from -40°C to 100°C with 0.01°C resolution, relative humidity from 0% to 100% with 0.05% resolution and pressure from 30 kPa to 120 kPa with 1.5 pa resolution (Fernando Lopez Pena & Richard J Duro 2003; Sensirion 2011; VTI Technologies 2007). However, the final accuracy of the measurement depends on sensor precision and linearity over the periods of experiment. The measured data are compared against the standard (Lutron) measurement instruments and uncertainty in measurements is estimated using Type A & Type B guidelines of National Accreditation Board for Testing and Calibration Laboratories (NABL) (NABL 2000) and National Physical Laboratory (NPL) (Cox M G & Harris P M 2006) as given by

\[
\text{Type A: } U(\bar{x}) = \sqrt{\frac{1}{n} \sum_{i=1}^{n} (x_i - \bar{x})^2} \quad (2.9)
\]

where \(U(\bar{x})\) is standard uncertainty (error mean), \(\bar{x}\) is arithmetic mean value (best measurement), \(n\) is number of samples, \(x_i\) is measurement elements

\[
\text{Type B: } U_c = \sqrt{U(\bar{x})^2 + U_{b_1}^2 + U_{b_2}^2 + U_{b_3}^2 + U_{b_4}^2} \quad (2.10)
\]

where \(U_{b_1}^2\) is Master Instrument uncertainty, \(U_{b_2}^2\) is Accuracy of the master instrument, \(U_{b_3}^2\) is Resolution of the test instrument and \(U_{b_4}^2\) is Instrumental error.
Figure 2.17 Comparison between the standard and proposed measurement data for ascending and descending input variations: standard (blue), test (red), linear regression (black) and residual (green)

The subsets of proposed and standard measurement data samples with 2000 elements obtained from the experiments are shown in Figure 2.17 and a good level of stability as well as accuracy between the proposed and standard measurements are observed. The minimum values of average errors are observed due to the tolerance of the sensor and errors introduced by the internal Analog to Digital converter (A/D) (Wekesa et al 2013). The wind speed and pressure measurement graphs in Figures 2.17 (a) & (d) show very good accuracy as the standard measuring instrument except a few data. From the graph of temperature and relative humidity in Figures 2.17 (b) & (c) it is clearly seen that there is very close agreement between the proposed and standard measurement system around 40°C for T and 50% for RH and the slight deviations arise with increasing / decreasing inputs with maximum average errors of ±1°C and ±2% respectively due to the non-linearity of the sensors. The highest correlation coefficients of $R=0.9992$ and $R=0.9988$ are
achieved for wind speed and pressure measurements and the correlation coefficients of $R=0.9963$ and $R=0.9973$ are obtained for temperature and relative humidity measurements respectively.

![Performance plots of coefficient of determination (red): a) Wind Velocity b) Relative Humidity c) Temperature and d) Pressure. The insert figures (black) show the achieved accuracy of measurement uncertainty (Ue) against the respective normalized environmental parameter.](image)

The gains, constants and conversion coefficients used in Equations (2.4) to (2.8) are obtained from the calibration experiments and the sensor manufacture data sheets to the maximum measurement accuracy (Andria et al 2005). Regression analyses for repeatability and reproducibility are carried out for different reference set-points. During these tests a set of ten measured samples are collected from the proposed and standard measurement system for every set-point variation and hence each test point yields 10x2 matrices. The statistical computations of coefficient of determination $R^2$ are carried out for the elements of matrices and the results are used to represent the degree of linearity between the proposed and standard measurements. Figure 2.18 shows the performance plots of $R^2$ for wind speed, temperature,
relative humidity and pressure. From Figures 2.18 (a) & 2.18(d), it is observed that the variations of the coefficient of determinations for the wind speed and pressure are approximately close to unity which exhibits that the proposed and standard measurement data fit exactly each other with very good linear relations. Further, the least value of $R^2$ is 0.982 and 0.973 respectively throughout the variations of the reference set-points. From Figures 2.18(b) & 2.18(c), it is observed that (i) $R^2$ appears below unity in some regime, (ii) slight non-linearity exists between proposed and standard measurement, (iii) increasing and decreasing trends are seen in $R^2$ with increasing set-point inputs, (iv) $R^2$ reaches maximum at 25°C and goes down with increasing / decreasing the reference set-points and (v) in contradiction to temperature, the $R^2$ values of relative humidity increase until the reference set-point reaches 30%, constant from 31% to 80% and decreases for the remaining values of set-points. The minimum and maximum $R^2$ values of temperature and relative humidity are (0.8812,0.9723) and (0.8661,0.9418) respectively. However, this resolution and accuracy are more sufficient for various applications including the estimation of low altitude atmospheric turbulence strength ($C_n^2$). The expanded uncertainty ($U_e$) is calculated using Equations (2.9) and (2.10) which increases the probability dispersion to 95% and thus the reliability of declared values as well (Kusnerova et al 2013). The effective degree of freedom is infinite and hence the expanded uncertainty ($U_e$) is calculated with the combined uncertainty (Fernando Lopez Pena & Richard J Duro 2003; Rachael V Coquilla 2010; NABL 2000) and the coverage factor ‘k’ is equal to 2 at the confidence level of 95.45%. The figures in box in Figure 2.18 show the expanded uncertainty of the proposed measurement system against the normalized inputs. The input ranges are normalized to the typical local atmospheric parameter fluctuations in outer scale and given in the xlabel of the figures in box. The inset figures clearly exhibits the exactness and capability of the proposed measurement system.
2.7 ATMOSPHERIC TURBULENCE STRENGTH ($C_n^2$) ESTIMATION

Although several dozens of turbulence profile models have been developed from the experimental measurements made at a variety of locations, no model provides generalization. Most of the models (SLC-day, Hufnagel-Vally Night and Greenwood etc., ) have the function of altitude ($h$) i.e., vertical path which is unfit for $C_n^2$ estimation for terrestrial FSOC (horizontal or slant path) and they yield reasonably good estimation only for the particular location/time i.e., daytime, nighttime, mountaintop location, China lack field-over land and over water, etc., (Arun K Majumdar & Jennifer C Ricklin 2008; Narottam Das 2012). Further, the turbulence fluctuation in the surface boundary layer does not only vary as a function of altitude, but also according to local conditions such as terrain type, geographical location, cloud cover, meteorological values and local time of day. The PAMELA model provides $C_n^2$ estimation within the surface boundary layer and it accepts all the parameters of test field geographical location, meteorological values and optical path as the inputs. Therefore, the PAMELA model is preferred and modified according to local test field parameters. A separate MATLAB code is developed to estimate the turbulence strength once in every sixty seconds.

The required geographical inputs are latitude ($10^\circ 38'46.7334''$ and $10^\circ 38'52.8468''$), longitude ($79^\circ 3'12.0774''$ and $79^\circ 2'56.6268''$), time of day (diurnal period; GMT+5.30), terrain type (0.03m-open flat terrain, grass, few isolated obstacles), number of days (as applicable), height above the ground (15.25m), and meteorological parameters at the desired altitude (15.25m) of the experimentation for estimating the strength of $C_n^2$ (Arnold Tunick et al 2005; Eun Oh et al 2004). The measured meteorological parameters are subsequently given to the software (MATLAB code) for estimating the
turbulence strength and subsequently updating the real time plot and data
logging table. The PAMELA model Mathcad version and its simplified form
can be found in (Arun K Majumdar & Jennifer C Ricklin 2008; Steve Doss-
Hammel 2004) and the background for estimating the $C_n^2$ are briefed in this
section. The estimated solar irradiance $R$ is used to determine the radiation
class $c_r = R/300$. For a wind-speed $W_s$ define the windspeed class $c_w = \{0.27$
if $W_s \leq 0.27$ else $W_s\}$ and then the Pasquill stability category $P$ can be
determined by

$$P = -\frac{(4 - c_w + c_r)}{2}$$

The length of the surface roughness for the open flat terrain, grass
and few isolated obstacles is estimated from tables, $z_r = 0.03\text{m}$, and from this
it is possible to calculate the Obukhov buoyancy length scale $b_l$

$$b_l = \left[ (a_1P + a_2P^3) z_r^{-(a_1-a_2P-a_3P^3)} \right]^{1/3}$$

where $a_1 = 0.004349$, $a_2 = 0.003724$, $a_3 = 0.5034$, $a_4 = 0.231$, $a_5 = 0.0325$. The
mean vertical velocity $W$ and fluctuating part $w$, horizontal velocity $U$ and
fluctuating part $u$, define vertical momentum flux in terms of the eddy
viscosity $K_m$ and mean potential temperature $\Theta$ and fluctuating part $\theta$, and
they also define vertical heat flux in terms of the eddy diffusivity of heat $K_h$
by

$$\overline{uw} = -K_m \left( \frac{\partial U}{\partial Z} \right) \text{ and } \overline{\theta w} = -K_h \left( \frac{\partial \Theta}{\partial Z} \right)$$

The mean specific humidity $Q$ and fluctuating part $q$ define the
vertical water vapor flux using the eddy diffusivity of water vapour $K_w$ by
The dimensionless wind shear \( \phi_m(\zeta) \) and the dimensionless potential temperature gradient \( \phi_h(\zeta) \) are expressed as functions of the scaled buoyancy parameter \( \zeta = z/L \). The turbulent exchange coefficients for heat \( K_h \) and momentum \( K_m \) are by

\[
K_h = \frac{ku \, z}{\phi_h(\zeta)} \quad \text{and} \quad K_m = \frac{ku \, z}{\phi_m(\zeta)}
\]

(2.10)

where \( k \approx 0.4 \) is the von Karman’s constant. \( K_h = K_m \) as per the optical turbulence model for laser propagation and imaging applications (Steve Doss-Hammel et al 2004). The friction velocity \( u_* \) and characteristic temperature \( T_* \) from the wind speed \( w_s \) and the roughness length \( z_r \), heat flux \( H \), specific heat \( c_p \), and mass density \( \rho \) are given by

\[
u_* = \frac{kW_s}{\ln(z/Z_r)} \quad \text{and} \quad T_* = \frac{kW_s}{c_p \rho u_*}
\]

(2.11)

The atmospheric refractive index \( n \) in terms of pressure \( Pr \) and temperature \( T \) is

\[
n - 1 = \frac{77.6 \times 10^{-6} \Pr}{T} \left( 1 + \frac{7.52 \times 10^{-3}}{\lambda^2} \right) \quad \text{and} \quad \frac{dn}{dz} = -\frac{77.6 \times 10^{-6} \Pr T \phi_h(\zeta)}{0.4 z T^2}
\]

The eddy dissipation rate \( \varepsilon \) and \( C_n^2 \) are estimated with the constant \( b \approx 2.8 \) as

\[
\varepsilon = \frac{u_*^2 (\phi_m - \zeta)}{0.4 z} \quad \text{and} \quad C_n^2 = \frac{2.8 K_h}{\varepsilon} \left( \frac{dn}{dz} \right)^2
\]

(2.12)
The direct relationship can be seen by expanding Equations (2.10) to (2.12) as

\[
C_n^2 = 5.152 \phi_n \left( \frac{1}{\phi_m - \zeta} \right)^{0.33} \left( \frac{77.6 \times 10^{-6} \text{Pr}}{T^2} \right)^2 h^{-0.667} \left( \frac{-H}{C_p \rho u_*} \right)^2
\]  

(2.13)

The important variations in the signals \(C_n^2\) and \(T_*\) are thus entirely produced by the fluctuations of the values of heat flux \(H\) and \(u_*\) as Equation (2.11) which is linearly scaled wind speed \(W_s\). As can be seen from Equations (2.11) and (2.13), \(C_n^2 \rightarrow \infty\) as wind-speed \(w_s \rightarrow 0\), the minimum wind speed must be bounded away from zero. Further, when there is little or no wind, there is little or no turbulence i.e., wind is required to mix the temperature gradient, and create turbulence (Jurado Navas et al 2006). Therefore, setting turbulence at a very low number or the threshold wind speed is the possible solution in this situation which does not introduce much inaccuracy. As per the wind sensor’s manufacturer data sheet, the threshold wind speed is taken as 0.27 m s\(^{-1}\) and all computations are carried out based on these specifications as suggested in (Eun Oh et al 2004; Steve Doss-Hammel et al 2004). Since the testing of developed low cost measurement system accuracy and correlation of PAMELA model estimation with the measured data are intention of this work, the PAMELA model is preferred and used.

2.8 EXPERIMENTAL RESULTS AND DISCUSSIONS

The meteorological profile data are acquired using the proposed measurement system. The outputs of the atmospheric sensors are of radix-2 format of different length. The sensor interfacing architectures transfer the measured atmospheric data framewise (11 bits) to the serial port of the computer where the MATLAB program reads the frames of atmospheric data every second. The frame data are manipulated to obtain the corresponding
real time changes of true values of atmospheric parameters. The corresponding plots and data recording work sheet file (.xls/.doc) in real time are updated every second. The low-altitude atmospheric turbulent strength $C_n^2$ is estimated using the PAMELA model from the extracted true values for statistical analysis on the weather and turbulence strength profiles for different environmental conditions. The accuracy of the estimation is validated by comparing the estimated $C_n^2$ with the measured $C_n^2$, i.e., using scintillometer data and Rytov method as discussed in section 2.3. A sample data logging.xls file worksheet generated on 17.04.2013 (Wednesday) is given in Table 2.2.

**Tables 2.2  A portion of measured meteorological data recording in excel work sheet**

<table>
<thead>
<tr>
<th>Observation ID</th>
<th>Sample Data &amp; Time</th>
<th>Wind Speed (ms$^{-1}$)</th>
<th>Temperature (°C)</th>
<th>Relative Humidity (%)</th>
<th>Pressure (kPa)</th>
</tr>
</thead>
<tbody>
<tr>
<td>41406</td>
<td>4/17/2013 11:30:03</td>
<td>2.2</td>
<td>37</td>
<td>38</td>
<td>100.6</td>
</tr>
<tr>
<td>41407</td>
<td>4/17/2013 11:30:04</td>
<td>2.4</td>
<td>36</td>
<td>37</td>
<td>100.6</td>
</tr>
<tr>
<td>41408</td>
<td>4/17/2013 11:30:05</td>
<td>2.3</td>
<td>37.4</td>
<td>38</td>
<td>100.6</td>
</tr>
<tr>
<td>41409</td>
<td>4/17/2013 11:30:06</td>
<td>2.5</td>
<td>37</td>
<td>38</td>
<td>100.6</td>
</tr>
<tr>
<td>41410</td>
<td>4/17/2013 11:30:07</td>
<td>2.3</td>
<td>36</td>
<td>37.6</td>
<td>100.6</td>
</tr>
</tbody>
</table>

The record consisting of minimum and maximum value of meteorological parameters and atmospheric turbulence strength as given in Table 2.3 are prepared at the end of every measurement day.
Table 2.3  A portion of daywise local meteorological data and estimated optical turbulence strength recorded

<table>
<thead>
<tr>
<th>Date</th>
<th>Ws (ms(^{-1}))</th>
<th>T (°C)</th>
<th>RH (%)</th>
<th>Pres. (kPa)</th>
<th>C2n (m(^{2/3}))</th>
<th>Comment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
<td>Min</td>
<td>Max</td>
</tr>
<tr>
<td>12Feb</td>
<td>1</td>
<td>1.5</td>
<td>29</td>
<td>32</td>
<td>77</td>
<td>84</td>
</tr>
<tr>
<td>22Feb</td>
<td>13</td>
<td>15</td>
<td>42</td>
<td>45</td>
<td>30</td>
<td>60</td>
</tr>
<tr>
<td>07Mar</td>
<td>2.10</td>
<td>3.11</td>
<td>29</td>
<td>30</td>
<td>70</td>
<td>84</td>
</tr>
<tr>
<td>27Mar</td>
<td>2</td>
<td>3</td>
<td>16</td>
<td>19</td>
<td>45</td>
<td>48</td>
</tr>
</tbody>
</table>

The local environmental data acquired for a diurnal period is recorded and the environmental change patterns are studied. Investigation on the validation of estimated \(C_n^2\) with the scintillometer readings is carried out and the accuracy of the estimation in terms of correlation is analyzed. Recording of real time meteorological profile data, variation levels and estimation and measurement analysis of optical turbulence \(C_n^2\) for five days in different local seasons i.e., winter, presummer, summer, monsoon and rainy season (since \(C_n^2\) is mainly season dependent) are described in this section.

2.8.1 Data for 28\(^{th}\) December 2012 - Winter

The diurnal behaviour of atmosphere real time updated plots corresponding to the weather history profile for the whole day from MN to Nn to MN is shown in Figure 2.19 (a-d). The variations from 0.27ms\(^{-1}\) to 3.528ms\(^{-1}\) with the Standard deviation (Std) of 0.959ms\(^{-1}\) for wind speed, 22°C to 26°C with the Std of 1°C for temperature, 61% to 94% with the Std of 7% for relative humidity and 100.7kPa to 101.1kPa with the Std of 0.112kpa for barometric pressure are observed from Figure 2.19 (a-d). The different conditions of the atmosphere observed on 28.12.2012 (Friday) are
mostly cloudy, hazy, light drizzle, overcast and misty. The Std on the Ws, T and RH are significantly low while the Pr is very low.

Figure 2.19 Diurnal time series updation of meteorological parameters over a day period: (a)-(d). A comparison of time series plot of atmospheric turbulence strength ($C_n^2$) estimated using PAMELA model (blue) and direct transmission measurement using scintillometer setup i.e, based on signal intensity ensemble average data (red): (e). Correlation statistic plot for measured and estimated $C_n^2$ values: (f). MN-Mid Night and Nn-Noon

The experiment local time series plot of $C_n^2$ data corresponding to the local meteorological data collected on 28th December 2012 proved that the estimated value could yield approximate close correlation to the measured values in almost all the time of the day as shown in the Figure 2.19 (e). The measurement analysis reveals the correlation coefficient (R) flicks in the inner scale between 95% and 97% and coefficient of determination ($R^2$) between 90% and 94%. Figure 2.19 (e) shows a low turbulence intensity $\approx 1.246 \times 10^{-16} \text{m}^{-2/3}$ and $1.726 \times 10^{-16} \text{m}^{-2/3}$ about 03.55 a.m and 06.50 p.m respectively. A high turbulence intensity $\approx 4.455 \times 10^{-12} \text{m}^{-2/3}$ is
seen in the daytime since the greatest fluctuation is observed in the wind speed, relative humidity, pressure and temperature values as shown in Figure 2.19(a-d). The average daytime turbulence intensity is about $4.354 \times 10^{-13} \text{m}^{-2/3}$. Further, the minute fluctuations are obtained in the friction velocity, characteristic temperature and $C_n^2$ when the wind speed oscillates around a smaller value. Typically the stronger minima are observed before early morning and after late evening. The larger fluctuations in the meteorological values from LT 05.30a.m to 08.30p.m generate unrealistically large sporadic $C_n^2$ values. Sustained and smooth steady variations are seen in the nighttime.

2.8.2 Data for 05\textsuperscript{th} March 2013-Pre-summer

The weather parameters variations from $0.63 \text{ms}^{-1}$ to $3.83 \text{ms}^{-1}$ with the Std of $0.906 \text{ms}^{-1}$ for wind speed, $28^\circ \text{C}$ to $43^\circ \text{C}$ with the Std of $4^\circ \text{C}$ for temperature, 22% to 74% with the Std of 14% for relative humidity and 100.3kPa to 100.8kPa with the Std of 0.173kpa for barometric pressure are observed from Figure 2.20 (a-d). The different conditions of the atmosphere observed on 05.03.2013 (Tuesday) are mostly cloudy, hazy, light drizzle, partly cloudy and scattered clouds. The Std on the Ws, T, RH and Pr are significantly low. The experiment local time series plot of $C_n^2$ data corresponding to the local meteorological data collected on 05\textsuperscript{th} March 2013 proved that the estimated value could yield close correlation to the measured values in almost all the time of the day as shown in the Figure 2.20(e).
The measurement analysis reveals the correlation coefficient (R) flicks in the inner scale between 97% and 98% and coefficient of determination (R²) between 95% and 97%. Figure 2.20(e) shows a low turbulence intensity ≈3.557x10⁻¹⁶ m⁻²/₃ about 04.15 a.m and 3.047x10⁻¹⁶ m⁻²/₃ about 05.50 p.m. A brief period of very high turbulence intensity ≈8.716x10⁻¹² m⁻²/₃ is seen about 05.00 p.m (late evening) since the relative humidity and pressure values are very low and the wind speed and temperature value are high as shown in Figure 2.20(a-d). The average daytime turbulence intensity is about 7.632x10⁻¹⁴ m⁻²/₃. Typically the stronger minima are observed at both ends of the day. The smooth changes in the meteorological values from LT 05.30 a.m to 05.45 p.m generate flat variations in Cₙ² values. Even variations are seen in nighttime.
2.8.3 Data for 17\textsuperscript{th} May 2013-Summer

The weather parameter variations from 0.194\,ms\textsuperscript{-1} to 3.8\,ms\textsuperscript{-1} with the Std of 0.940\,ms\textsuperscript{-1} for wind speed, 28\textdegree C to 43\textdegree C with the Std of 4\textdegree C for temperature, 22\% to 74\% with the Std of 14\% for relative humidity and 100.3\,kPa to 100.8\,kPa with the Std of 0.1746\,kPa for barometric pressure are observed from Figure 2.21(a-d). The different conditions in the atmosphere observed on 17.05.2013 (Friday) are mostly hazy, partly cloudy and scattered clouds. The Std on the T and RH are significantly large while the Ws and Pr are very low. Greatly uneven wind speed variation is observed as in Figure 2.21(a).

**Figure 2.21 Same as Figure 2.19 for 17\textsuperscript{th} May 2013**

The experiment local time series plot of $C_n^2$ data corresponding to this local meteorological data collected on 17\textsuperscript{th} May 2013 proved that the estimated value could yield much less correlation (since PAMELA
model keeps high sensitivity to the Ws) to the measured values in almost all the time of the day as shown in the Figure 2.21 (e). The measurement analysis reveals the correlation coefficient (R) flicks in the outer scale between 79% and 82% and coefficient of determination (R^2) between 71% and 73%. Figure 2.21 (e) shows a low turbulence intensity ≈2.05x10^{-16} m^{-2/3} about 05.20p.m. A greatly fluctuating turbulence intensity is seen from 04.30a.m to 05.30p.m due to random fluctuation in the wind speed, gradual decrease in relative humidity, low pressure and gradual increase in temperature as shown in Figure 2.21(a-d). The average daytime turbulence intensity is about 1.661x10^{-13} m^{-2/3}. Further, the minute fluctuations are obtained in the friction velocity, characteristic temperature and C_n^2 when the wind speed oscillates around a small value. Typically the stronger minima are observed at the late evening. The larger fluctuations in the meteorological values from LT 05.30a.m to 04.45p.m generate unrealistically large sporadic C_n^2 values. Sustained and smooth steady variations are seen in the night time.

2.8.4 Data for 13th June 2013- Monsoon

The weather parameter variations from 1ms^{-1} to 6ms^{-1} with the Std of 1ms^{-1} for wind speed, 28°C to 34°C with the Std of 2°C for temperature, 29% to 62% with the Std of 7% for relative humidity and 100kPa to 100.4kPa with the Std of 0.113kpa for barometric pressure are observed from Figure 2.22(a-d). The different conditions of the atmosphere observed on 13.06.2013 (Thursday) are overcast, cloudy and mostly hazy. The Std on the Ws is high while T, RH and Pr are low.
The experiment local time series plot of $C_n^2$ data corresponding to the local meteorological data collected on 13th June 2013 proved that the estimated value could yield less correlation to the measured values in almost all the time of the day as shown in the Figure 2.22(e). The measurement analysis reveals the correlation coefficient (R) flicks in the inner scale between 89% and 91% and coefficient of determination ($R^2$) between 86% and 88%. Figure 2.22(e) shows a very low turbulence intensity $\approx 5.538\times10^{-17}\text{m}^{-2/3}$ and $7.837\times10^{-17}\text{m}^{-2/3}$ about 04.50a.m and 05.30p.m respectively. A few short intervals of low turbulence intensity $\approx 9.654\times10^{-15}\text{m}^{-2/3}$ are seen about noon to 04.15p.m due to the very high wind speed and temperature and very low relative humidity and pressure values as shown in Figure 2.22(a-d). The meteorological change pattern is normal with high wind speed. The average daytime turbulence intensity is about $5.632\times10^{-14}\text{m}^{-2/3}$. Further, the minute fluctuations are obtained in the friction velocity, characteristic temperature and $C_n^2$ when the wind speed oscillates around a small value. Typically the stronger minima are observed at both ends of the day. The larger fluctuations
in the meteorological values from LT 06.30a.m to 11.00a.m generate unrealistically large sporadic $C_n^2$ values. Sustained and very smooth steady variations are seen in the nighttime.

2.8.5 Data for 16\textsuperscript{th} November 2013-Rainy Season

The weather parameter variations from 0.97ms\(^{-1}\) to 4ms\(^{-1}\) with the Std of 1ms\(^{-1}\) for wind speed, 21°C to 25°C with the Std of 1°C for temperature, 60% to 100% with the Std of 10% for relative humidity and 100.6kPa to 101.1kPa with the Std of 0.1727kpa for barometric pressure are observed from Figure 2.23(a-d). The different conditions of the atmosphere observed on 16.11.2013 (Saturday) are mostly cloudy, hazy, light rain, light drizzle and heavy rain. The Std on the Ws and RH are high while T and Pr are low. The experiment local time series plot of $C_n^2$ data corresponding to the local meteorological data collected on 16\textsuperscript{th} November 2013 proved that the estimated value could yield good correlation to the measured values in almost all the time of the day as shown in the Figure 2.23(e).

Figure 2.23 Same as Figure 2.19 for 16\textsuperscript{th} November 2013
The measurement analysis reveals the correlation coefficient (R) flicks in the inner scale between 98% and 99% and coefficient of determination (R^2) between 97% and 98%. Figure 2.23(e) shows a very low turbulence intensity ≈2.326x10^{-18} m^{-2/3} about 07.00p.m. A few short interval of very high turbulence intensity ≈4.505x10^{-12} m^{-2/3} is seen about 05.00a.m due to low wind speed, high relative humidity, normal pressure and relatively high temperature values as shown in Figure 2.23(a-d). The average daytime turbulence intensity is about 4.441x10^{-15} m^{-2/3}. Typically the stronger minima are observed only at the evening. The smooth variations in the meteorological values generate almost flat behaviour in the C^*_n^2 values. Sustained and smooth steady variations are seen in the daytime. The maximum value of C^*_n^2≈2.326x10^{-18} m^{-2/3} is observed around 05.00a.m as shown in Figure 2.23(e).

Thus estimation of more accurate turbulence strength at our test field for different outdoor environmental conditions using PAMELA model is difficult. Therefore, developing an empirical model based on the macroscale meteorological measurements to have a more accurate estimate for the local turbulence strength is important and it is a matter of subsequent research.

2.9 ADVANTAGES

- Measuring ability and accuracy make the proposed system more viable and less budgetary for various applications related to the environmental change.

- This system reduces trial experiment’s time and cost.

- This method is completely generalized and problem independent and hence it can be easily rehashed to other parameter measurements.
• Any specific/separate interfacing hardware/ data acquisition card, boards and software are not required.

• Moreover the cost of the existing stand-alone measurement instrument is high, further customization is additionally increasing the cost.

• Much more of other tasks could be performed along with the measurement modules.

2.10 SUMMARY

The establishment of scintillometer experimental setup for the link range of 0.5km at an altitude of 15.25m is described and the values of $C_n^2$ are measured. The meteorological sensors are connected with separate architectures created inside the FPGA to transfer the commands / address and read out the measurement data. An UART communication architecture as per the RS232 standard data frame format is also developed to transfer the measurement values to the data logging computer. A customized code is developed in the MATLAB environment to read the serial port data, manipulate them to find the true values, update the value & real time plots and perform the statistical analysis. The measurements are continued for several days in diurnal period cycle. The measurement performance of the proposed system is calibrated against the standard measurement instruments and an overall 98% correlation accuracy is achieved. The expanded uncertainties of measurements are estimated and the variations are reported. $C_n^2$ is estimated using PAMELA model with measured data. The estimated values of $C_n^2$ are validated with the scintillometer measurement values and the minimum and maximum values of correlation coefficient 0.79 and 0.97 respectively are observed from the investigation of five days data collected in different seasons during one year. Moreover, a close correlation between
estimated and measured $C_n^2$ is obtained for several days in a clear outdoor environment conditions and correlation coefficients oscillate almost closely around unity which conforms to the proposed measurement system’s accuracy. However, the maximum amount of deviation error of $\pm 0.000026$ is observed on some days especially in high turbulence and calm regime due to deficiency in PAMELA model. These results trigger a way to develop a model to have very accurate estimation at our test field to find the actual data rate the system is capable of operating under different outdoor local environmental conditions.