THE ENERGY AND RESOURCES INSTITUTE
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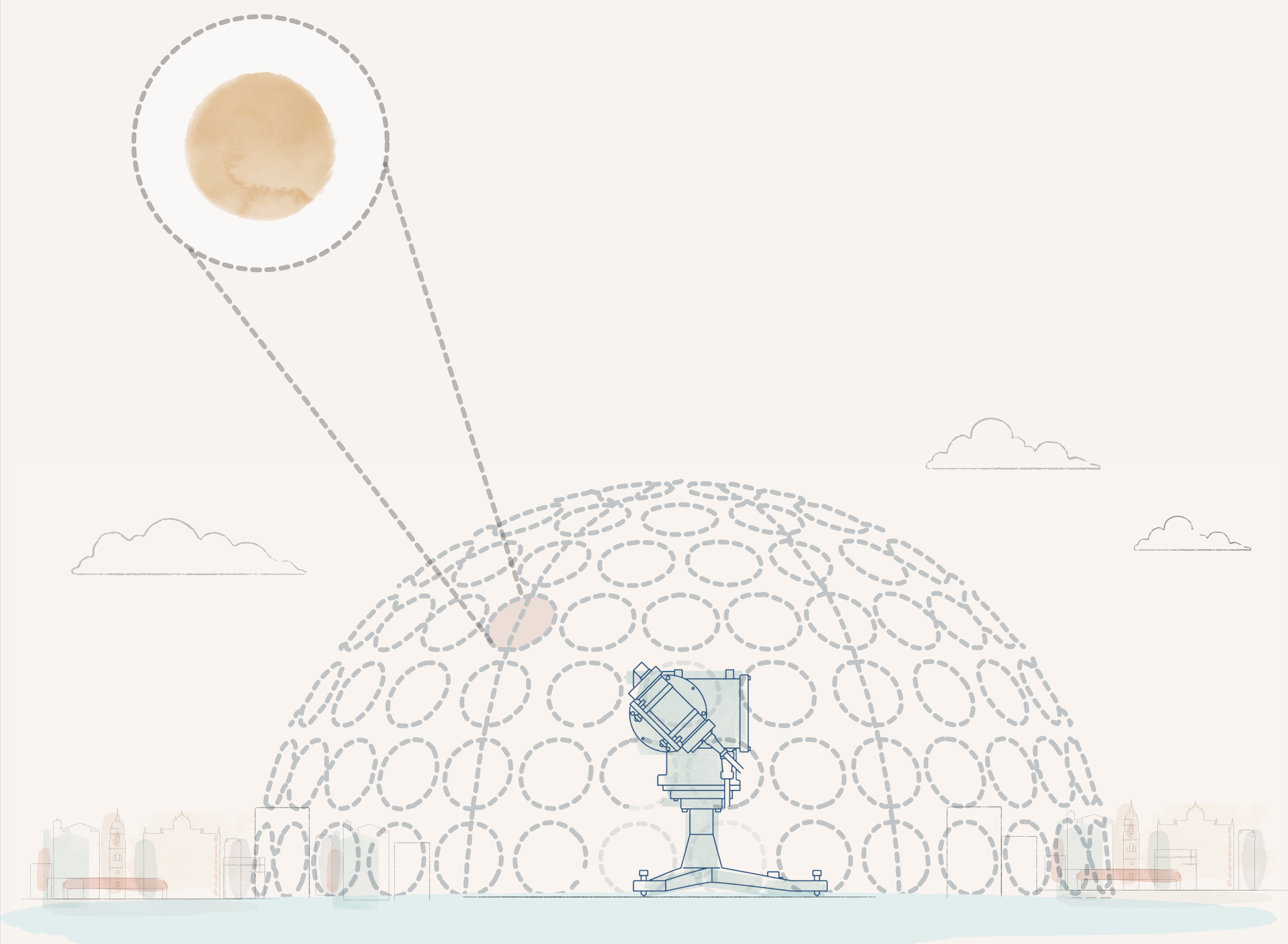
Sky Modelling

for the Location of Gurugram, India

Abridged Version
2022



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Foreword

The Mahindra-TERI Centre of Excellence (MTCoE) is a joint research initiative of Mahindra Lifespaces Developers Limited (MLDL) and The Energy and Resources Institute (TERI). The vision of the MTCoE is to provide science-based solutions that will improve occupant comfort, resource efficiency, and sustainable building practices for India's built environment in the future. Under the 1st phase of the five-year research scope, the CoE has developed a repository of innovative materials, guidelines, toolkits, and handbooks to mainstream principles of energy efficiency, thermal & visual comfort, sustainable water uses in habitats and Sky Modelling study for Indian sky conditions.

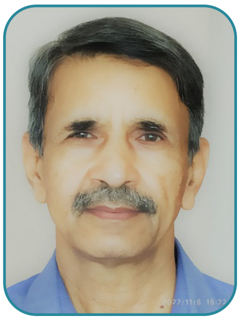
Numerous factors and various design conditions can be linked to the use of daylight in buildings. The fact that daylight saves energy and minimises emissions is a huge advantage. The physiological and psychological effects of daylight on individuals as well as the comfort of the occupants, are additional design factors related to the use of daylight in buildings. These positive outcomes turn daylight into an aesthetic tool for the architect and a valuable resource for building occupants. The effective use of daylight is mainly a function of the luminance of the sky exposed to the glazing system. Therefore, accurate data about the luminance and radiance distribution of the sky are needed for the optimum use of daylight. An accurate estimation of the available solar radiation and daylight is to acquire the total amount of radiation and light coming from the sky and the radiance and luminance patterns over the sky vault to define the sky conditions.

The Sky Modeling research at the Mahindra-TERI Centre of Excellence aims to define the sky conditions from the CIE standard general sky that best represents the sky luminance distribution for the Gurugram location in India. The main objective of this activity is to develop the sky model with extensive luminance and radiance data collection to generate realistic simulation background for daylight integration in buildings for a given location. Luminance and radiance data collection and sky modelling analysis at such an extensive scale is the first-of-its-kind in the country.

I hope these findings will provide architects and building designers with a reliable and straightforward alternative incorporating the daylight coefficient approach to predict indoor daylight illuminance under realistic sky conditions. The data can be used for accurate daylight simulations and analysis by incorporating measured CIE sky type instead of using the default overcast sky as the input parameter. Further, it can also be used for intelligent building control (e.g., fenestration automation or advancement in electro-opaque glass). The developed CIE Standard sky type finder is a tool that showcases the prevailing sky distribution model for New Delhi and NCR locations using CIE standard Skies. As our team is replicating this research for Chennai, I sincerely acknowledge the support of all those associated with developing this report. I look forward to their continuing guidance for its improvement.

Mr Sanjay Seth
Senior Director,
Sustainable Habitat Programme, TERI

Testimonials



Dr Ashutosh Pathak is a civil engineering graduate from G.B Pant University, Uttarakhand. He completed his master's degree in Building Science & Construction Management in 1982 from IIT Delhi. He joined CPWD through the 1983 Central Engineering Services examination (Group A) and served in various capacities in Delhi PWD, CPWD & Ministry of Transport, Government of India. Dr Pathak completed his transdisciplinary PhD from TERI School of Advanced Studies in 2021 and is an IGBC-accredited professional. He has expertise in Building Science, Sustainable Construction and Project Management and is a PMI-accredited PMP (Project Management Professional. He was an advisor to GRIHA Council from January 2016 till December 2017.

His current transdisciplinary research interests include ESG (Economic, Society and Governance), Disaster Management, and qualitative & quantitative aspects of green buildings— including solar motion geometry and daylighting. More about his work is available on his blog https://www.ashutoshp.in/

Testimonial

"Congratulations, TERI, for filling the research gap that enables evidence-based daylight design. I sincerely appreciate and compliment the research team for putting together various complex project components and collecting data despite all odds and devastating Corona times. The accrued benefits outweigh your hard work.

While the title 'Sky Modelling for the Location of Gurugram, India Technical Report' fits the primary requirement of selecting an appropriate input to available daylight software, the work done by the TERI team is much more valuable. The use cases for the data compilation are limited only by our imagination. Two such broad categories, one for optimising buildings and city design – the other (with concurrent meteorological data) on giving insights and predictability for climate-induced uncertainties, may be drawn up.

Additional value creation is realisable, as observed above. While the present report would enhance input to the existing software, the inferences made from the measured data raise the quality and ambition of integrative habitat design. The data analysis would enable the creation of scenarios that the differing requirement of habitat demands. The research empowers a quantum qualitative jump to daylight design for buildings and cities."

Amanda Thounaojam is Senior Technical Associate at IIHS, providing technical support for monitoring the building energy performance for the new campus. She is a Programme Manager for the Solar Decathlon India program, and oversees the development of content for the learning modules, and the technical review of submissions. She has worked as a Visiting Scholar at Energy Studies in Buildings Laboratory at the University of Oregon, USA, as a part of a fully funded scholarship program by DST and IUSSTF. She worked on prototyping a High Dynamic Range Imaging (HDRI) sensor for façade controls and explored the software developing platform for processing sensor inputs and outputs. Her postgraduate thesis was titled "Evaluation of Low-cost method High Dynamic Range (HDR) Photography for daylight Assessment" and it won the Aluplast Best Capstone Project Award. She is proficient at conducting simulations in terms of energy, daylighting, and lighting and also has experience in handling building environmental monitoring equipment and experimentation.

Testimonial

"This is a very interesting study and is also a much-needed one. With daylight simulations becoming significantly important for façade and fenestration optimisation, this study of defining a realistic sky luminance model will help in optimisation of the design accurately. This is also a good start for making sky luminance data available for other parts of the country, which will help to provide accurate daylight prediction."

Dr. Kartik Kumar is deputy director at Saint Gobain R&D, India, located at IIT Madras research park. He has an Industrial R&D experience of 23 years. He first started in developing new products in soaps, bodywash, cosmetics and detergents at Hindustan Unilever Ltd (HUL) for 12 years. He then worked for 3 years to develop paints for wall and wood coatings at AkzoNobel R&D. He worked in Reckitt Benckiser (RB) R&D for 4 years in doing research on mosquitoes and insect repellent. From 2018, he is working at Saint Gobain R&D at Chennai, and collaborates with scientists from IIT Madras and academic institutions on materials like glass, gypsum and plastics for light and sustainable construction solutions. He has worked in Netherlands, Europe for 4 years. He holds 6 patents, 2 scientific journal papers and participated in Cannes innovation hackathon on air pollution.

Testimonial

"Sky models are essential data for architects and building planners across the world. Collection and modelling sky light for India is certainly a need for our development. I am happy for initiatives of TERI to have this technical report on this topic. From our building science team at Saint Gobain, I see this as a very useful development towards enhancing daylighting simulations and bringing realism to the models."

Dr. Purushottam has over 25 years of sustainability strategy and environmental consultancy experience in the areas of environmental impact assessment; air pollution modelling and meteorology; GHG emissions inventory and carbon offsets; carbon neutrality strategy; waste management strategy; and water risk, technology solutions for sustainability and CSR. She is a physics postgraduate with Phd, in environmental science and engineering from IIT Mumbai.

Sunita has worked with regulatory bodies in UK and India in various infrastructure development projects, city planning and construction projects covering environmental impacts and mitigation. She is well versed with various reporting/disclosure frameworks such as SASB, GRI, CDP and GRESB and Integrated Reporting. She has helped large companies globally to streamline their sustainability strategy through a systematic process-oriented approach and enabled the selection of right tools for systematic sustainability disclosure management. She is well versed with the use of technology in Sustainability management and has been associated with a startup for creation of a platform on Sustainability data management. She has helped companies develop an understanding of ESG risks and the importance of embedding in enterprise risk management systems.

Sunita has executed over fifty engagements in sustainable business strategy, sustainable development and corporate social responsibility across the UK, United States, Mexico, South Africa and India. She has a deep understanding of Climate Change Science and adaptation and has driven sustainability strategies for companies in the construction, real estate, banking, telecom, automotive, steel and IT sectors.

During her career spanning 25+ years, she has served in Infosys, SENES Consultants and Casella Stanger; and as founding member of a startup in the area of Sustainability Tech Solutions. She has authored many white papers on Sustainability and is a speaker in national and international forums.

In her spare time, Sunita likes to bake, read, or tend to her garden. She is a perpetual cleaner and nature lover.

Table of Contents

Introduction

Daylight integration into the building spaces has proven to be one of the efficient ways of saving energy. It improves upon the visual quality available on a work plane and is recognized as an important and useful strategy in the design of energy-efficient buildings [1]. It is necessary to establish the overall design technique for the thermal and luminous environment to implement energy conservation and to ensure the quality of the indoor environment [2]. Understanding the sky conditions helps to design appropriate daylighting measures for the building, that is, anything that would allow for natural light to enter the building for the occupants' purposes. At any point, the amount of daylight illuminance inside a building is influenced by the luminance levels and patterns of the sky in the direction of views of the surface, the quantity and character of daylight, the buildings and orientation of the streets, and by the surrounding buildings. It also depends on the nature of the building apertures the daylight penetrates inside [3] [4]. To harness the daylight effectively and accurately for the designing of a building, the foremost step is to predict the daylight availability at the preliminary design stage to optimize and delineate the façade and fenestration. The traditional method of predicting indoor daylight illuminance is not flexible enough to assess daylighting performance. The indoor daylight illuminance depends on the luminance levels and patterns of the sky viewed from a window [5]. The availability of consistent climatic information is vital for indicating the sky luminance distribution to estimate indoor daylight illuminance. Sky luminance is an essential component in assessing the appearance and performance of internal spaces, which are highly sensitive to the dynamic luminance of the visible sector of the sky [6]. Geometrically, the sky is simple to describe: the sky always has the same "shape" and "position", however, the brightness pattern of the sky is different for each location, which can be quite difficult to characterize. The sky brightness distribution can alter substantially over very short time frames when clouds are present. For these reasons, it has been necessary to devise ideal sky brightness patterns known as 'sky models'. These sky models are used for the majority of daylight simulation applications to generate sky brightness patterns from basic daylight quantities.

There are several studies available in the public domain on the sky model distribution pattern. The International Commission on Illumination (CIE) in France has defined a set of 15 general sky types that represent different sky conditions. These models help to assess sky luminance under various weather conditions ranging from clear to overcast sky. It was observed from the literature review that researchers in the past have attempted to propose methodologies and have identified suitable CIE sky types for some tropical countries, however, a similar type of comprehensive study for Indian tropical climate has not been done. Furthermore, there appears to be no widely available study that proposes design recommendations for the passive design of windows for daylighting in tropical climates considering that sky luminance varies according to a series of meteorological, seasonal, and geometric parameters that are difficult to specify [7]. To devise the CIE sky type of any location the actual measurements of the luminance data are required. In 1991, under the International Daylight Measurement Program (IDMP), the daylight availability parameters under a common set of guidelines were measured worldwide including in India. However, no measurements have been done since the data was last recorded in the IDMP. The unavailability of measured luminance data limits the use of the CIE sky model for passive window design in many countries.

The CIE Standard Sky type for any Indian location is fairly unidentified. To overcome this gap, Mahindra TERI Centre of Excellence (MT CoE) for Sustainable Habitats, a joint research initiative of Mahindra Lifespaces and TERI is working on a sky modelling research study, which is likely to predict with certainty, what kind of standard sky conditions prevail on the selected location of data recording. Once the data is gathered, it could be converted into algorithms to facilitate the formulation of plugins that could support building information modelling (BIM) software. These kinds of inputs could supplement intelligent building control (e.g., fenestration automation or advancement in electro-opaque glass) in the future. Furthermore, these findings will provide architects and building designers with a reliable and simple alternative that incorporates the daylight coefficient approach to predict indoor daylight illuminance under realistic sky conditions.

This report presents the approach, methodology, key findings, observations and way forward to the 'Sky Modelling Study for the Location of Gurugram, India'.

Objectives

The main objective of this activity undertaken is to categorize a sky model, to generate realistic simulation background for daylight integration in buildings for a given location. One of the key exercises under the activity is data collection to facilitate close to an accurate daylighting analysis by simulation of hourly sunlight/daylight/skylight available for internal daylight illumination.

The following objectives are identified to carry out the study:

» State-of-the-art review of existing sky models used for daylight simulation.

» To define the prevailing sky distribution model for Gurugram, Delhi-NCR using "CIE standard skies".

» To evaluate the prediction accuracy of the existing sky model used for daylight simulation software.

Scope and Methodology of the Study

To achieve the above objectives, the sky luminance model evaluation is based on the measured luminance data collected in Gurugram, India from **May 2020 to April 2021**. Statistical methods will be further used to identify which subset of the CIE standard general skies is the best fit to describe the daylight climate in Gurugram. Comparative, correlation and predictive analysis methodology will be used to analyse the dataset.

The detailed methodology chart for the study is showcased in Figure 1.

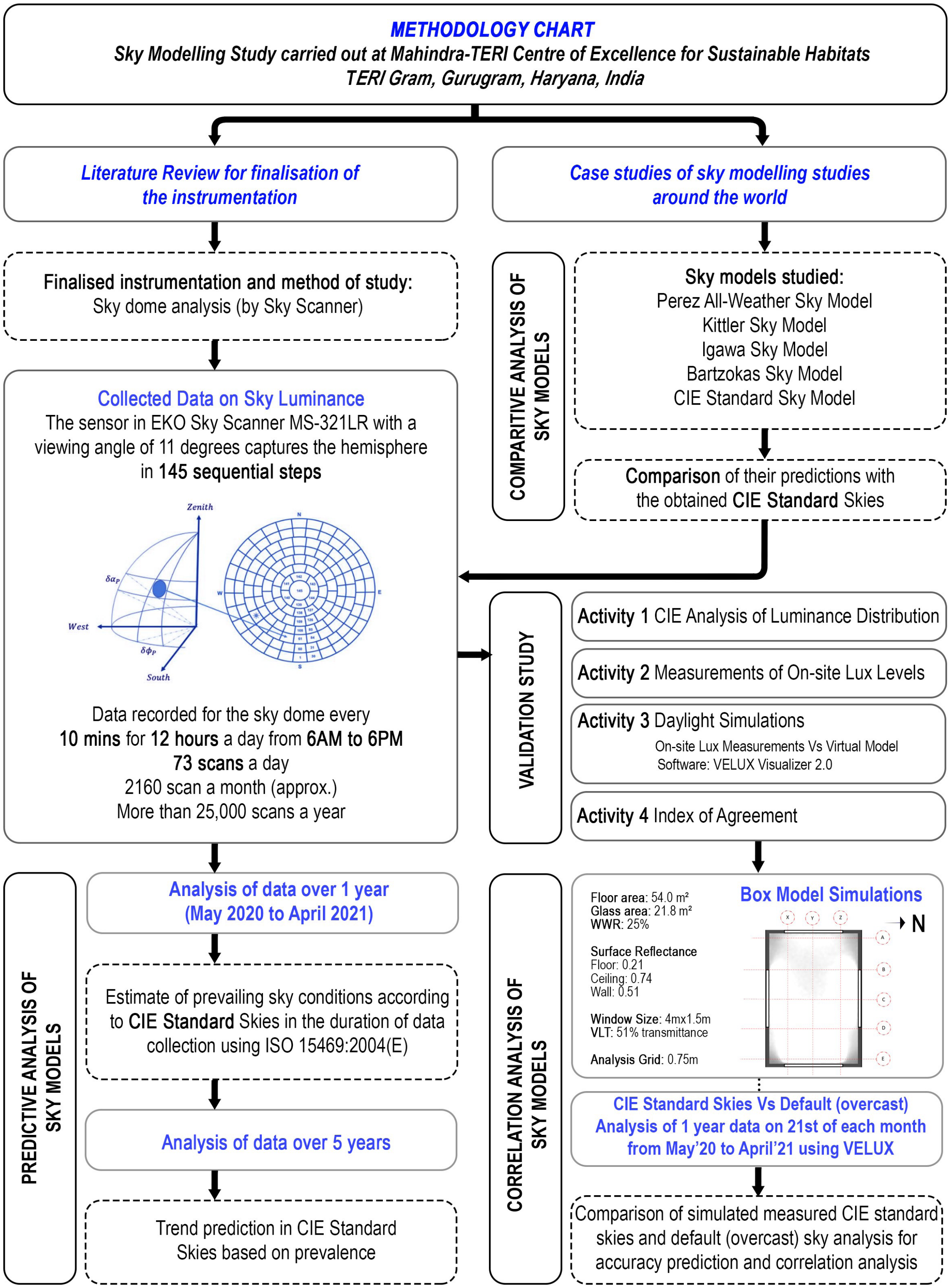


Figure 1: Detailed methodology chart for the study

Need of the Study

The first step in effectively and correctly utilising daylight in building design is forecasting its availability at the early design stage in order to best define and optimise the façade and fenestration. Designers use various daylight performance metrics and methods like Daylight Factor, Daylight Autonomy, Useful Daylight Illuminance and Climate-based daylight modelling to determine the availability of daylight in an interior space. However, in order to assess these parameters through daylight simulation software three major input factors are required by the simulation engine; the climate files, the building and its surrounding description and the input of the cloud cover or the sky conditions prevailing at the location. It is important to understand that the availability of reliable meteorological data is therefore essential for determining the sky luminance distribution. Presently, the metrological stations in India do not record the illuminance data and thus limit the use of the CIE sky model in countries like India further making it difficult for building practitioners to determine the actual sky type for simulation purposes. Furthermore, as seen in the literature review, most daylighting software does not have the flexibility to select the 15 CIE standard sky types for daylight assessment. Moreover, the overcast or clear sky conditions are set as a default input that again provides inaccurate results for the availability of daylight in any space. Therefore, it is not only essential to record illuminance data for a country like India but it is equally important to derive the actual sky conditions for the prediction accuracy of daylight and have user-friendly tools that consider the actual sky conditions. In the coming years to broadly cover the measured sky conditions; sky scanners are required to be installed in various parts of the country to cover all the climate zones and regions, cites such as Chennai, Mumbai to cover the coastal data, Kolkata to cover humid sub-tropical region, Bangalore to cover semi-arid and Jammu for mountain range. Hence, it is crucial to determine the prevalent sky conditions for optimization of the building envelope and to economize the cost by the right selection of glass and best-fit WWR% of the project to achieve energy efficiency and meet visual comfort requirements. The quantitative analysis would also enable the assessment and demonstration of climate change impacts by trend analysing of the accurate sky conditions. As per World Metrological Organizations recommendation; 30 year standard reference periods should be updated every decade in order to better reflect the changing climate and its influence on our day to day weather experience. Setting up sky scanner set up and logging radiation data would be a starting point for India.

Daylighting and Sky Models

The use of daylight simulation in building design and control applications can be beneficial. Sky models aid in the simulation of sky conditions and the prediction of daylight availability in indoor situations. It is difficult to generate a sky model because of dynamic sky brightness that depends on the weather, the season of the year, and the time of day. Therefore, simplified sky models are currently used for computational simulation that does not take into account these constant changes. It is critical to see if a sky model can be created that closely resembles the properties of the real sky and gives architects more accurate daylight predictions. The luminous efficacy of daylight (in lm/W) is defined as the ratio of daylight illuminance to solar irradiance [8]. The luminous efficacy of horizontal and/or vertical surfaces can be evaluated with the availability of measured horizontal and/or vertical solar data.

CIE sky models are mathematical models that can be used to replicate day and time-specific sky brightness distributions. The sky luminance distributions are caused by various factors including solar position, atmospheric turbidity, air pollution, and the cloud amount, type, and pattern that can affect unpredictably sunlight and skylight [9], which can only be assessed through sky-measured data. To develop CIE sky models and further accomplish the daylight simulations accurately it is generally recommended that illuminance data be collected over a lengthy period to determine trends in occurrences and eliminate any abnormalities.

Components of Computing Daylighting

Daylighting simulation software uses site location (latitude and longitude), date, and time of the simulation to compute the solar position. In most simulation programmes, the input for the sky type is used as CIE overcast or CIE clear sky. These extreme sky types are important for window design but for energy simulations, these do not completely represent conditions occurring in reality. For example, the programme SUPERLITE generates the luminance distribution under the uniform sky, CIE Overcast Sky, and CIE Clear Sky with or without sun. These sky conditions are also applied in the geeky programme, which is incorporated in the RADIANCE package [7]. The standard methods are required for harmonies daylight design and daylighting consequences. Similarly, the VELUX Daylight Visualizer incorporates the different CIE sky conditions but only for the 21st day of every month. Currently, advanced computational tools like the grasshopper in Rhino and other programming tools provide the user flexibility to design plug-in(s) to perform various simulations and analyses at ease. But there is a very less daylighting plug-in(s) that incorporates the CIE 15 sky model distribution.

By comparing the daylight simulation software as mentioned in Table-1, VELUX daylight visualizer 3.0 is selected for the study to perform various daylight simulation as it supports all 15 CIE sky types. However, the simulations can only be performed for 21st date of each month.

Table 1: Comparison of various daylight software

Parameters	Ease of use (Modelling)	Daylight metrics					Simulation Speed	CIE SkyType
Ecotect	Ecotect is an easy to use software, modeling can be done in the software including additional external shading	Daylight Factor (DF)	Daylight Autonomy (DA)				Fast	Overcast sky
Design Builder	DesignBuilder is an easy to use software. It is more flexible in designing shading	Daylight Factor (DF)	Special Daylight Autonomy (sDA)	Annual Sunlight Exposure (ASE)	Useful Daylight Illuminance (UDI)		Fast	Overcast sky
Diva	Diva is a Rhino plugin, hence it gives flexibility of using the same complex architectural model for daylight simulation.	Daylight Factor (DF)	Daylight Autonomy (DA)	Useful daylight Illuminance (UDI)	Annual Sunlight Exposure (ASE)	Glare Analysis	Fast	Overcast sky
Open studio	Open studio is a sketchup plugin, modeling in openstudio is simple and easy to learn.	Daylight Factor (DF)	Daylight Autonomy (DA)	Useful Daylight Illuminance (UDI)			Fast	Overcast sky
VELUX	The VELUX Daylight Visualizer accurately calculates daylight levels to make complex analysis accessible at the start of a building project.	Visualize luminance, illuminance and daylight factor levels.	See the daylight factor with and without rooflights.	Simulate complex fenestration systems (CFS) and shading products with BSDF materials.			Fast	All 15 CIE Sky types

Daylight: Monitoring and Data Collection

As suggested by the literature review, there are two ways, or rather two sets of equipment, daylight studies have been carried out across the world in the past decade for monitoring and data collection. The first is by High Dynamic Range (HDR) imaging and the other is by Sky Scanner. Sky Scanner is relatively a newer technology. HDR imaging uses capturing images with a commercially viable camera and a fisheye lens that is mounted on a tripod. As a general rule, it is preferred to fix the aperture size and vary the shutter speed only. The number of captured images varies based on the luminance breadth to be recorded. Ten or more images are captured as the shutter speeds varied between 15 and 1/8000 seconds, using the three-stop increments. The shutter speed range is usually shortened under heavily cloudy skies, such that the longest exposure is not all washed out and the shortest exposure is not all black. A set of multiple exposure images are then fused and then processed to get false colour images that could correspond with the luminance level in the sky [14]. Figure 2 shows HDR imaging to study sky luminance.

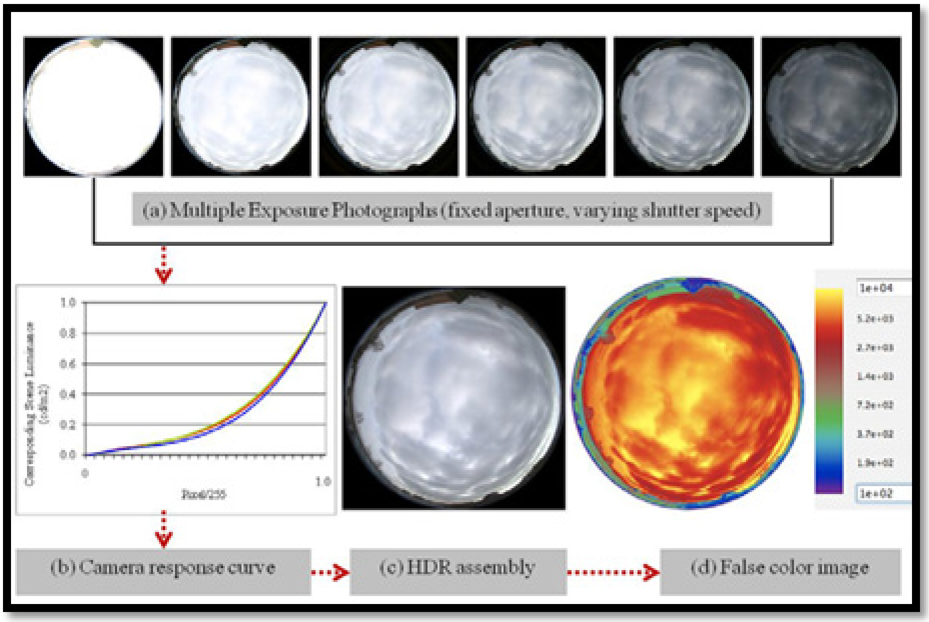


Figure 2: **HDR imaging to study sky luminance**

A sky scanner measures the sky luminance distribution every 5–15 minutes, depending on the set calibration. Each scan consists of 145 readings according to the pattern recommended by the CIE and takes approximately 2 seconds to complete a reading. Each of these 145 measurements taken is for 145 unique positions of the sky vault (Figure 3). The sensor in the sky scanner moves at an angle of 11 degrees sequentially to record these 145 positions, covering the whole hemisphere, horizon to zenith. Sky scanner analyses have been published for Hong Kong, Singapore, Bangkok, Thailand, England, France, Spain, and Italy.

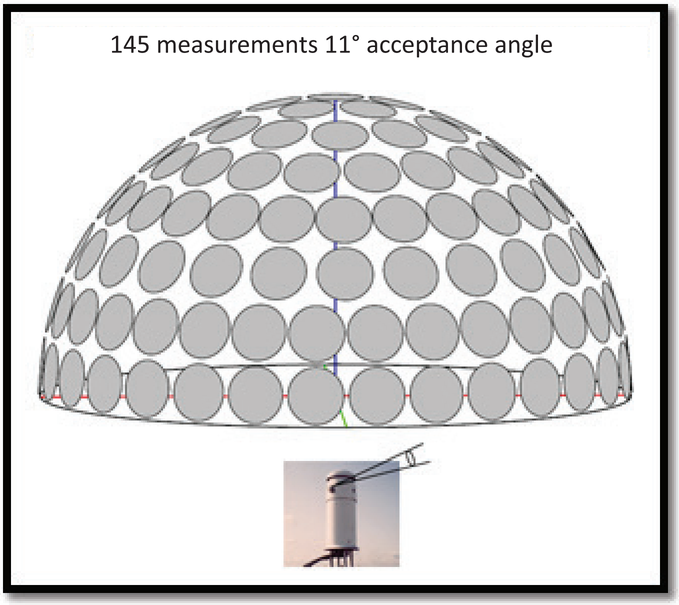


Figure 3: Representation of sky vault and number of patches studied by the Sky Scanner

Instruments

Sky Scanner

The model procured for the activity is manufactured by EKO, called Sky Scanner MS-321LR (Image 1).

Image 1: Sky Scanner installed at the location Gurugram, India

The automatic Sky Scanner MS-321LR (Figure 4) is designed only to measure the Luminance and Radiance of the sky hemisphere. The sensor has two highly sensitive detectors, which respond to the low light levels of the diffuse sky and will automatically block direct radiation by the active shutter function. The sensor with a viewing angle of 11 degrees will capture the hemisphere in 145 sequential steps. The sensor is attached to a tracker positioner with two-axis control. The MS-321LR features a precise tracking mechanism that achieves high durability and repeatability. Measurements are based on the

CIE108-1994 recommendation (CIE - International Commission on Illumination, IDMP - International Daylight Measurement Program). The luminance values are measured per kcd/m^2 and radiance value per W/m^2/sr. The Sky Scanner is predominantly used to study the radiation contribution of the diffuse sky, which is an important parameter for building automation, building design, daylight software modelling, and light pollution research. The advanced software control functions give full flexibility to export data for extensive research analysis and purposes.

Sky Scanner MS-321LR Sky Luminance and Radiance distributions

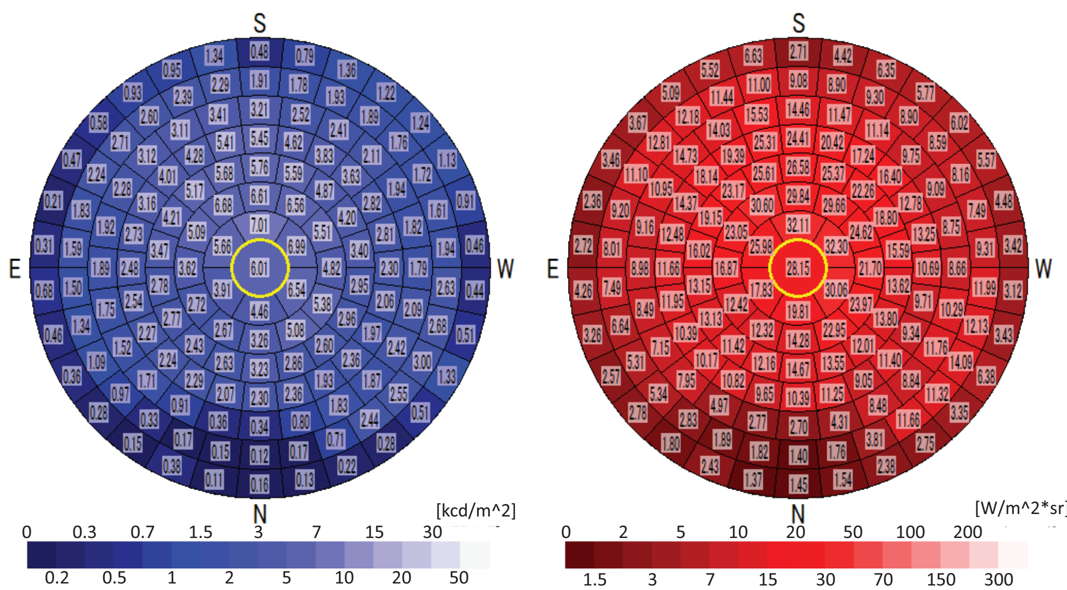


Figure 4: **Sky Scanner MS-321LR sky luminance and radiance distributions**

Solar Monitoring Station

To compare the sky type defined by CIE Standard General Sky based on sky luminance with other relevant models based on solar radiation, a solar monitoring unit was also installed at TERI-Gram (28.4595° N, 77.0266° E), and the unit provides global, diffuse, and direct radiation measurements.

The Solar Monitoring Unit consists of a pyranometer and pyrheliometer on a sun-tracking mechanical system (Figure 5). The pyrheliometer measures the direct normal irradiance (DNI) of the sun, whereas the pyranometer measures the sky's diffuse horizontal irradiance (DHI). Using these parameters, an empirical sky brightness model can be modelled for the Indian sky.

Figure 5: Solar Monitoring Unit installed at the location Gurugram, India

Raw Database (Extrapolation/Interpolation)

A measuring station at the TERI GRAM, Gurugram, Haryana, India, took solar irradiance and sky luminance measurements. All the instruments were placed on the roof in a location that was reasonably free of external impediments and easily accessible for examination, cleaning, and maintenance. Every day, data collection for sky luminance begins at 0600 hours and ends at 1800 hrs; on the other hand, data for solar irradiance is recorded every minute. All the data was collected roughly at the same time in true solar time, which aided in the computation of solar geometry and subsequent data comparison at other places.

The global and diffuse irradiance measurements on a horizontal surface and the global irradiance on the vertical planes facing the four cardinal directions were carried out using a solar monitoring device consisting of a pyranometer and a pyrheliometer (i.e., north, east, south, and west). The irradiance measurements were taken in real-time every minute, and the data were averaged over 10-minute intervals for analysis. A sky scanner is used to scan the luminance distributions in the sky (EKOMS321LR). By scanning the skydome, it records the luminance at 145 locations. The scanner's full view angle is 11, which allows each sky patch to be regarded as a point source with minimal inaccuracy.

The sky scanner's critical components are encased in a weatherproof housing for continued outdoor operation. The information from the scanner is saved on a computer. The analysis was conducted using 10-minute data collected between May 2020 and April 2021. A significant amount of work was put into obtaining a continuous record of data. Some periods of missing data were unavoidable for different causes such as instrumentation malfunction, power outage, and sensor calibration. Data were extrapolated for the missing information by considering the changing seasons, solar angle, and previously accessible data.

Analysis

The CIE Standard General Sky consists of a family of luminance distributions with 15 sky types that can be compared with the measured sky brightness patterns. The adequacy of the proposed sky model is assessed using the root mean square errors (RMSE) method in representing the actual sky conditions as detailed in Section 5 Defining the sky models for India. The results of the CIE standard sky type monthly analysis of May 2020 to April 2021 findings of outdoor illuminance and sky luminance are showcased below. The daily analysis graphs are present in Annexure 2 – Daily Analysis of the detailed report.

TABLE 2: One – Year Pre-dominant Sky Type Analysis Summary

Month		May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Jan	Feb	Mar	Apr
Pre-dominant Sky Type		14	14	9	9	15	14	14	14	14	14	14	14
Sky Type Occurrence	1	1	0	0	3	8	90	108	241	252	157	243	4
	2	0	0	0	0	6	0	0	0	0	0	0	0
	3	1	0	2	5	9	25	21	42	17	12	16	7
	4	1	0	0	0	4	0	0	0	1	0	1	0
	5	263	378	150	194	158	30	27	23	38	17	37	48
	6	2	0	0	0	0	6	27	16	10	9	10	2
	7	0	0	0	0	0	10	2	1	5	0	5	0
	8	0	0	0	0	0	0	0	0	0	0	0	0
	9	525	507	873	959	821	51	70	109	195	51	193	444
	10	67	77	22	26	1	25	21	22	21	21	21	45
	11	0	0	0	9	1	22	7	2	4	12	4	17
	12	494	498	470	386	86	200	123	195	528	126	557	350
	13	1	0	0	1	3	4	8	2	0	3	0	0
	14	809	659	527	613	138	1574	1408	1165	1079	1430	1056	1259
	15	99	71	219	67	955	226	368	445	113	206	120	14

Conclusion and Way Forward

Phase one sky modelling activity at Mahindra-TERI Centre of Excellence consists of the following three deliverables as part of the sky modelling activity:

1. Publications on research outcomes
2. Online Toolkit: CIE sky type
3. Detailed report with outcomes and findings

Publications on Research Outcomes

It is very important to peer review the conclusions of any research study for maintaining ethical standards of publication and to ensure high-quality scientific publications, public trust in scientific findings, and that researchers receive credit for their work and ideas. Through publications in journals or conferences of repute data fabrication and falsification can be curbed and the authenticity of the study and acceptance can be attributed. The aim would be authenticating the data capture methodology, CIE sky type defined from the data, and validation of the outcomes from the study. In view of this, the team has filled two papers in the below-mentioned conferences and shall be continuing to apply in the upcoming call for research papers in Q1 and Q2 journals and conferences in the domain of the study area.

i Name of the conference: PLEA 2022

Theme for the conference: WILL CITIES SURVIVE? The future of sustainable buildings and urbanism in the age of emergency.

Venue of the conference: Santiago, Chili

Date of the conference: November 23–25, 2022

Research paper topic: Analysis of summer sky type using CIE standard sky model for the location of Gurugram, India.

ii Name of the conference: IBPSA England: Building Simulation and Optimization in the Global South

Venue of the conference: Bath, UK

Date of the conference: September 12, 2022, 9.00 am to September 13, 2022, 5.00 pm

Research paper topic: Comparative analysis of daylight levels in an office space considering standard overcast sky condition and measured CIE sky type of Gurugram, India.

iii Name of the conference: The Fourteenth International Conference on Advances in System Simulation (SIMUL 2022)

Venue of the conference: Lisbon, Portugal

Date of the conference: 16th – 20th October 2022

Research paper topic: A validation study of simulated illuminance levels of office space in Gurgaon, India under actual CIE sky conditions

Published papers shall be made available at: https://mahindratericoe.com/research-paper.php

Online Toolkit: CIE Sky Type

An online user-friendly and simplified sky type data repository shall be made available in the public domain for architects, designers, researchers, academicians, students and consultants and other stakeholders of the research and building construction fraternity to identify the measured sky type on a particular day, time, and month of a year. This data can be used for the passive design of windows, daylight assessment, energy savings, visual comfort assessment, etc., for the locations falling under the respective climatic zones.

The data will be available at: https://mahindratericoe.com/toolkit.php

Report with Outcomes and Findings

This detailed report has been prepared to specify an introduction to daylighting, background research on sky modelling along with objectives of the study. The need and importance of the work, scope and methodology adopted have been well explained. Primitive sky models developed and adopted internationally have been discussed in the report, and based on literature research; the best fit sky model approach has been explained with calculations. Sky monitoring instruments were used and the set-up has been explained. Based on the data collected, designed sky models for Gurugram, India have been clarified with the help of graphs and plots.

Way Forward

As part of the phase two development, three key steps are proposed, which are as follows:

» **Establishing additional scanner set-up in other climate zones of India**

According to the measured sky luminance data of other tropical countries and established sky luminance prediction models, the sky luminance varies as the distance from the sun changes (both in azimuth and altitude). Therefore, it is essential to set up additional sky scanner set-up in other climate zones of the county to establish, how impactful climate change is to affect daylighting and the way we can use it in our building spaces getting constructed in India. In the second phase of the study, we are expanding the sky modelling research for the location of Chennai, India.

» **Measured data validation**

Data validation is another very important aspect of research and this shall be executed by capturing lux data at the test bed (MTCoE lab) over a span of at least a year to establish relationships with simulated data and will act as a major marker for the next steps of plugin development. The process is already validated for the 21st of March 2022 and the same methodology will be used to assess the one-year data at the MTCoE lab, Gurugram and as well as for the new sky scanner set up in Chennai, India.

» **Development of a plugin for daylight simulation software**

Through coding, a plugin or a tool or a simulation engine (similar to raytracing, daysim, etc.) to be established based on the data accumulation for the location of Delhi and Chennai simultaneously (of at least 5 years) and validation process; for precision, it is advisable that validated data of more than one location is available.

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Analysis of Summer Sky Types Using CIE Standard Sky Model for the Location of Gurgram, India

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ABSTRACT: Daylighting is recognized as a significant approach for designing energy-efficient buildings. It can be apprised from the literature review that researchers in the past have attempted to propose methodologies for defining suitable measured CIE sky types for some tropical countries, but a similar type of comprehensive study for Indian tropical climate was attempted 3 decades back. This paper aims to determine the representative CIE standard general sky model(s) for the summer months of 2020 & 2021 for the location of Gurugram, India. For the collection of luminance distribution data, the EKO Sky Scanner MS-321LR instrument has been set up. The sensor with a viewing angle of 11 degrees captures the hemisphere in 145 sequential steps. The data is recorded for the sky dome every 10min for 8 hours between 1000 hours to 1800 hours i.e., for 49 scans in a day. The adequacy of the proposed sky model is assessed using the root mean square errors (RMSE) method. For the analysed sample set of summer months, it is perceived that the clear sky condition pertains for almost 60% of the measured time. Therefore, the researchers, academicians, and industry experts may consider clear sky conditions while computing their daylight analysis for the summer months for accurate daylight analysis results.
KEYWORDS: Daylighting, sky model, illuminance, CIE, Sky scanner

1. INTRODUCTION

Daylighting is a key component in designing energy-efficient buildings. The appropriate combination of daylighting, electric lighting controls and fenestration design and size can result in significant energy savings by reducing 20-30% electric lighting loads and associated cooling loads (Riya Malhotra, 2021). It is further associated with enhanced occupant visual comfort, productivity, health, and well-being. The foremost step for illuminating a building's interior is to acquire information on daylight availability. At any point, the amount of daylight illuminance inside a building is influenced by the luminance levels and patterns of the sky in the direction of views of the surface, the quantity and character of daylight and the nature of building apertures it penetrates (Danny H. W. Li, 2002) (Mardaljevic, 2013) (Nancy Ruck, 2001).The availability of methodical climatic information is vital for indicating the sky luminance distribution to evaluate indoor daylight illuminance, wherein the climate-based daylight modelling encompasses outdoor climatic conditions that change continuously (Munoz C, 2014). It is observed from the literature review that researchers in the past have attempted to propose methodologies and have identified suitable CIE sky types for some tropical countries, but a similar type of comprehensive study with real time measured data for Indian tropical climate is rarely found. Currently, most of the applications work with simplified sky luminance models. Various research teams worldwide had carried out studies to determine the luminous efficacy constants. For instance, Perez presented a model known as the "all-weather model" for luminance distribution from routine irradiance measurements, the mean instantaneous sky luminance angular distribution patterns for all sky conditions from overcast to clear, through partly cloudy, skies (R. Perez, 1993). Igawa proposed sky radiance and luminance distribution models for all-sky conditions, from clear to overcast (Norio Igawa, 2001). Bartzokas adopted Kittler's standard sky luminance distribution (SSLD) method to define the typical daylight conditions for Central Europe and the Mediterranean with special attention to partly cloudy sky conditions (A. Bartzokas, 2003). Kittler's proposed SSLD method defines the fifteen sky types of relative luminance distributions; five overcast, five clear and five transitional skies that are modelled by the combination of gradation and indicatrix functions (Richard Kittler, 1998). The developed model is adopted as a CIE standard for sky luminance prediction by the International Commission on Illumination as per ISO 15469:2004 standards (CIE International Commission on Illumination, 2004) (Refer to Table-1).

The CIE model is currently the most comprehensive sky model, covering 15 typologies that depict a wide variety of sky circumstances from substantially overcast to cloudless weather. Some of the elements that affect sky luminance distributions are the solar position, atmospheric turbidity, air pollution, cloud amount, type, and pattern, which can impact unpredictable sunlight and skylight (Stanislav Darula, 2004) and can only be determined from sky measurement data. The CIE model predicts the sky luminance better than the Perez model in the Indian tropical condition if one knows the correct CIE sky type (Nabeel Ahmed Khan, 2020). Currently, the most widely utilized sky conditions for computer-based daylight simulations are CIE overcast and clear sky conditions. It's critical to see if a sky model can be created that closely resembles the properties of the real sky and gives building professionals more accurate daylight predictions. A sky scanner can be used to analyse the diffuse sky's radiation contribution, which is an important parameter for daylight software modelling, light pollution research, building automation, and design. It is generally recommended that illuminance data be collected over a lengthy period of time to determine trends in occurrences and eliminate any abnormalities.

Sky luminance is affected by several difficult-to-specify meteorological, seasonal, and geometric factors (Mardaljevic, Daylight Simulation: Validation, SKy Models and Daylight Coefficients, 2000). The goal of this study is to determine the CIE standard general sky model(s) for the summer months of 2020 and 2021 in Gurugram, India.

2. METHODOLGY

For this study, EKO Sky Scanner MS-321LR (Refer to Figure-2) is set up at the Mahindra-TERI Centre of Excellence (MT CoE) lab for the collection of luminance distribution data located at 28.4595° N, 77.0266° E Gurugram, India. The sensor with a viewing angle of 11 degrees captures the hemisphere in 145 sequential steps (Refer to Figure-1). The data is recorded for the sky dome every 10min for 8 hours between 1000 hours and 1800 hours, i.e., 49 scans a day. A combination of 2/3rd of measured data and 1/3rd of extrapolated and interpolated data is used to analyse the CIE standard sky type for the summer months (March-September) of 2020 and 2021.

Table 1:
CIE 15 sky types as per ISO 15469:2004

Sky type	Gradation Group	Indicatrix Group	Description of luminance
1	I	1	Overcast with a steep gradation and azimuthal uniform
2	I	2	Overcast with a steep gradation and slight brightening toward the sun
3	II	1	Overcast moderately gradated, azimuthal uniformity
4	II	2	Overcast moderately gradated and slightly brightening toward the sun
5	III	1	Overcast or cloudy with overall uniformity
6	III	2	Partly cloudy with a uniform gradation and slight brightening toward the sun
7	III	3	Partly cloudy with a brighter circumsolar effect and uniform gradation
8	III	4	Partly cloudy, rather uniform with a clear solar corona
9	IV	2	Partly cloudy with a shaded sun position
10	IV	3	Partly cloudy with brighter circumsolar effect
11	IV	4	White – blue sky with a clear solar corona
12	V	4	Very clear / unturbid with a clear solar corona
13	V	5	Cloudless polluted with a broader solar corona
14	VI	5	Cloudless turbid with a broader solar corona
15	VI	6	White – blue sky, turbid with a wide solar corona effect

Figure 1:
Sky dome showing 145 patches

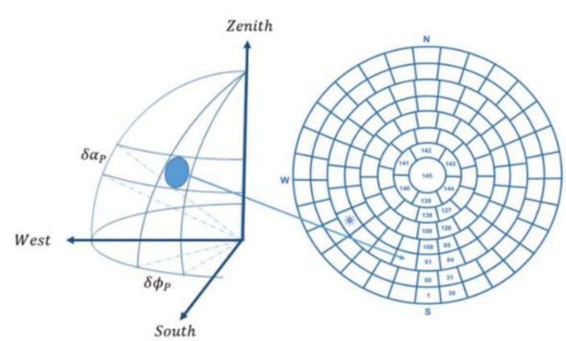


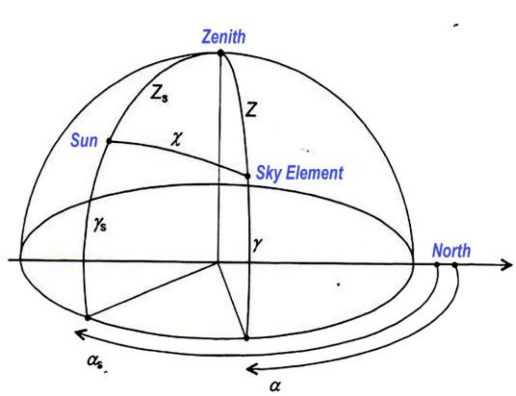
Figure 2:
Sky Scanner installed at the location

2.1 Analysis

A set of luminance distributions that can be utilized to harmonise observed sky brightness patterns is determined as the CIE standard general sky. Further, the concise and effective statistical distribution of the CIE General Sky types with the most desirable sky brightness patterns that transpire on the site location can be used to identify the site's daylight climate. The luminance distributions of various sky standards were modelled using Equations 1–8 and compared to the scanned sky luminance data to establish the set of standard skies (CIE International Commission on Illumination, 2004). The CIE sky model requires the measured value of Zenith luminance (kcd/m2), Zenith angle (Z), and the azimuth difference between the element and the sun, |α-αs| to determine the position of any sky element. If Z_s is the zenith angle of the sun, the angular distance between the element and the sun is given by,

$$\chi = \arccos(\cos Zs . \cos Z + \sin Zs . \sin Z . \cos|\alpha - \alpha s\,|) \quad (1)$$

Figure 3:
Angles defining the sun and the position of the sky element



Alternatively, the angle of elevation, γ, may be used instead of the zenith angle, Z, to define the position of an element. (Refer Figure-3)

$$Z = \frac{\pi}{2} - \gamma \quad (2)$$

Similarly, the zenith angle of the sun may be obtained from the solar elevation by,

$$Z = \frac{\pi}{2} - \gamma s \quad (3)$$

The ratio of the luminance, L*a*, of an arbitrary sky element to the zenith luminance, Lz, is

$$\frac{La}{Lz} = \frac{f(\chi).\varphi(Z)}{f(Zs).\varphi(0)} \quad (4)$$

The ratio of the luminance gradation function, ϕ, relates the luminance of a sky element to its zenith angle:

$$\varphi(Z) = 1 + a.\exp\left(\frac{b}{\cos Z}\right), \text{ when } 0 \le Z \le \frac{\pi}{2} \quad (5)$$

$$\varphi\left(\frac{\pi}{2}\right) = 1, \quad \text{at the horizon}$$

Equation 4 requires the value at the Zenith;

$$\varphi(0) = 1 + a.exp\ b \quad (6)$$

The function f is a scattering indicatrix that relates the relative luminance of a sky element to its angular distance from the sun:

$$f(\chi) = 1 + c.\left[\exp(d\chi) - \exp\left(d\frac{\pi}{2}\right)\right] + e.cos^2\chi \quad (7)$$

Its value at the Zenith is,

$$f(Zs) = 1 + c.\left[\exp(dZs) - \exp\left(d\frac{\pi}{2}\right)\right] + e.cos^2 Zs \quad (8)$$

Where,

a, b	-Luminance gradation parameters;
α	-Azimuthal of sky element (Clockwise from north) [rad];
$α_s$	-Azimuth of the sun (Clockwise from north) [rad];
C, d, e	-Scattering indicatrix parameters;
x	-Shortest angular distance between a sky element and the sun [rad];
y	-Angle of elevation of a sky element above the horizon [rad];
y_s	-Angle of elevation of the sun above the horizon [rad];
φ(Z)	-Gradation function of the sky element;
φ(0°)	-Gradation function for Zenith;
f(χ)	-Indicatrix function of the sky element;
$f(Z_s)$	-Indicatrix function for Zenith;
L_a	-Luminance of a sky element [cd/m2];
L_z	-Zenith luminance [cd/m2];
Z	-Angular distance between a sky element and the zenith [rad];
Z_s	-Angular distance between the sun and zenith [rad].

The performance of each standard sky luminance model was evaluated using the root-mean-square error (RMSE) after the measured luminance was normalised with regard to horizontal illuminance and solar elevation.

The modelled sky brightness should be first standardised to horizontal diffuse illuminance by multiplying all luminance values by the normalisation ratio (NR) as follows:

$$NR = \frac{\Sigma Lmea\ cos\alpha.sin\alpha.d\alpha.d\varphi}{\Sigma lpred\ cos\alpha.sin\alpha.d\alpha.d\varphi}$$

Where L_{mea} is the measured sky point luminance (cd/m2); L_{pred} is the predicted sky point luminance in relative form (dimensionless).

The following formula is used to determine the root mean square error:

$$\text{RMSE} = \sqrt{\frac{1}{N}\Sigma\left(\frac{L_{pred} - L_{mea}}{L_{mea}}\right)^2}$$

N is the number of readings (dimensionless) [N=145 for 145 patches].

The procedures mentioned in the above equations are repeated for every measured luminance scan by an in-house excel based calculator tool where the inferred CIE General sky is the one with the lowest RMSE in each scan. Thereafter, the frequency of the 15 CIE General Standard Skies is detected and the RMSE may be computed. The daily and monthly data for the summer months of 2020 and 2021 were analysed using the same methodology. The cumulation of each sky type for 49 scans per day i.e. 5978 scans from March to September, was computed as percentage occurrences.

3. OBSERVATIONS AND RESULTS

A comparative analysis for the summer months 2020 and 2021 (Refer Figure-4 to Figure-10) analysed through RMSE expresses that CIE standard general sky type 14 described as 'Cloudless turbid with a broader solar corona' is the most occurred sky type with 40% average sky type occurrence (Refer Table-2 and Figure-12).

Table 2:
%Occurrence of Sky-type 14 during summer months 2021 & 2021

Month	2020	2021
MAR	53%	48%
APR	49%	51%
MAY	41%	34%
JUN	36%	39%
JUL	25%	29%
AUG	26%	33%
SEP	54%	35%

Although, it was observed that sky type 9 described as 'Partly cloudy with a shaded sun position' is the predominant sky type for July and August with a 25% average sky type occurrence for the summer months (Refer to Table-3 and Figure-8, 9 & 12) which justifies the monsoon months in India.

Table 3:
%Occurrence of Sky-type 9 during summer months 2021 & 2021

Month	2020	2021
MAR	7%	11%
APR	26%	27%
MAY	24%	23%
JUN	20%	15%
JUL	40%	38%
AUG	43%	33%
SEP	16%	33%

The adequacy of the proposed sky model is assessed using the root mean square errors (RMSE) method in representing the actual sky conditions. The monthly RMSE analysis of the summer months of 2020 and 2021 is showcased in Figures 4 to 10.

Figure 4:
March CIE sky Type RMSE Analysis

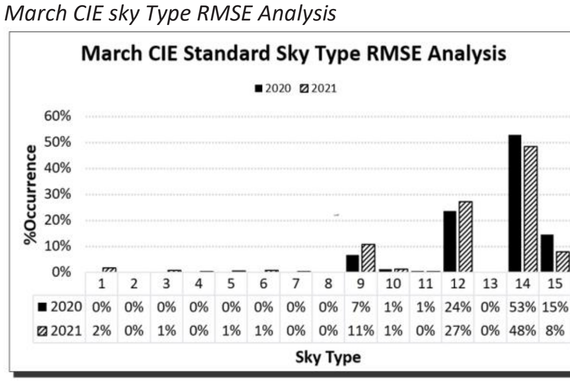


Figure 5:
April CIE sky Type RMSE Analysis

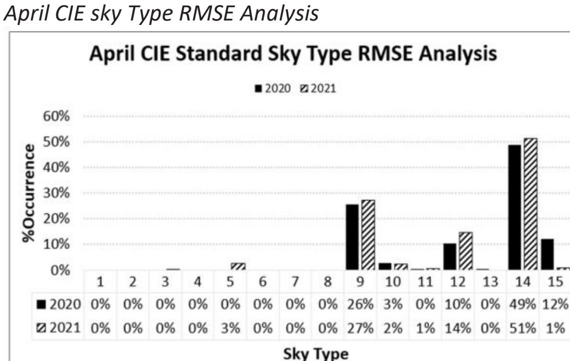


Figure 6:
May CIE sky Type RMSE Analysis

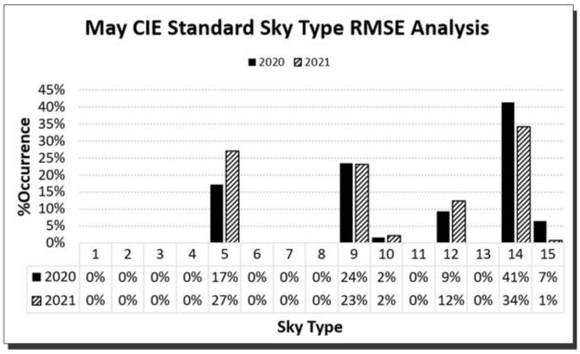


Figure 7:
June CIE sky Type RMSE Analysis

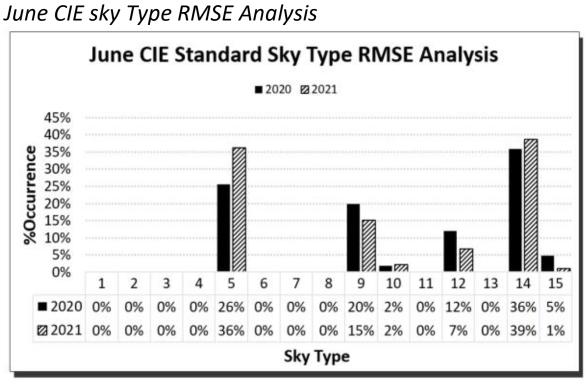


Figure 8:
July CIE sky Type RMSE Analysis

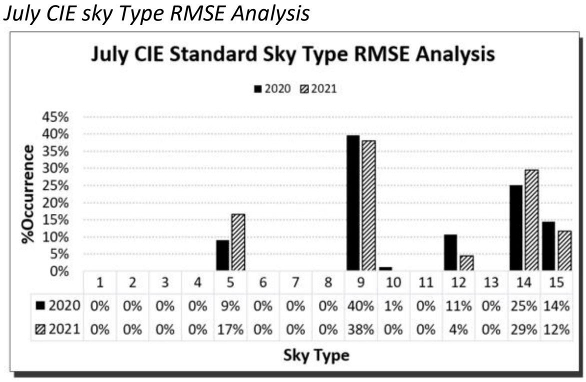


Figure 9:
August CIE sky Type RMSE Analysis

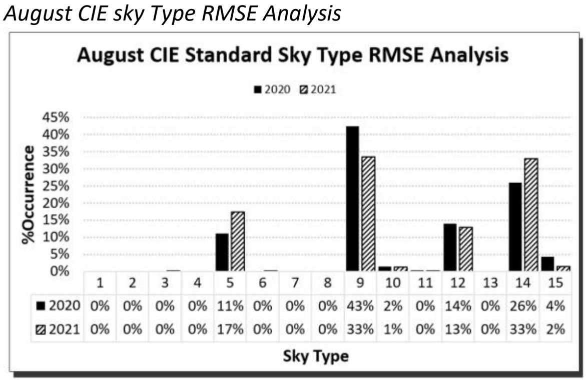
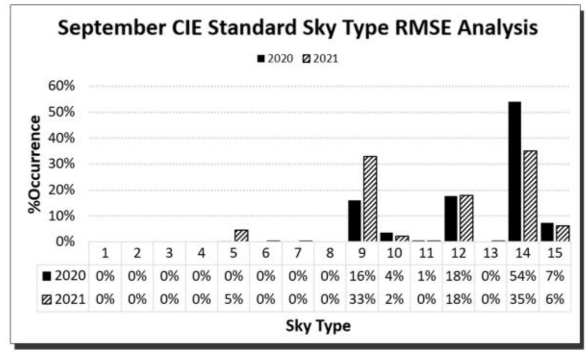


Figure 10:
September CIE sky Type RMSE Analysis



A 6% increase with a 15% weighted average in the occurrence of sky type 5 described as 'Overcast or cloudy with overall uniformity' is observed from April in the year 2021 compared to a 9% weighted average in 2020 (Refer Figure-5). Similarly, a 5% decrease in the occurrence of sky type 15 described as 'White – blue sky, turbid with a wide solar corona effect' was observed for the subsequent year. A slight increase of 1% was observed for sky type 9 and a decrease of 1% for sky type 14. Whereas, a consistent trend was observed for sky type 10 described as 'Partly cloudy with brighter circumsolar effect' and sky type 12 described as 'Very clear/unturbid with a clear solar corona' with a weighted average of 2% and 12% respectively during the summer months 2020 and 2021 (Refer Table-4 and Figure-11).

Table 4:
Percentage Average, Percentage weighted average Sky-type occurrence during summer months 2020 & 2021

Sky Type	%Average	%Weighted Average 2020	%Weighted Average 2021
1	0.14	0.03	0.26
2	0.00	0.00	0.00
3	0.09	0.03	0.14
4	0.01	0.01	0.01
5	12.04	9.04	15.03
6	0.08	0.03	0.12
7	0.03	0.00	0.06
8	0.00	0.00	0.00
9	25.36	24.88	25.83
10	1.82	1.98	1.66
11	0.24	0.29	0.20
12	13.88	13.98	13.78
13	0.05	0.06	0.05
14	39.51	40.49	38.54
15	6.75	9.18	4.32

Figure 11:
Weighted average sky type occurrence: Summer Months 2020 & 2021

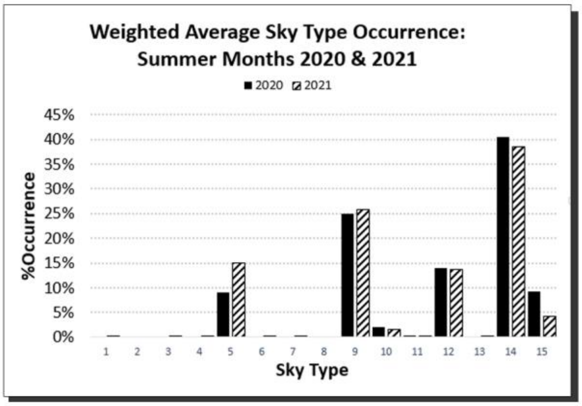
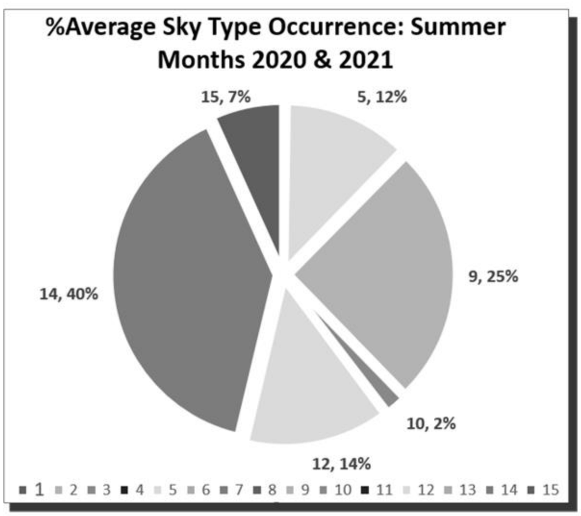


Figure 12:
%Average Sky Type Occurrence July-Aug-Sep 2020 & 2021



4. CONCLUSION

The sky luminance distribution data is measured from a sky scanner installed at Gurugram, India, and is analysed using the CIE standard root mean square errors (RMSE) method. For the summer months of 2020 & 2021, it is perceived that clear sky condition pertains for almost 60% of the measured time. However, it was observed that %Average sky type occurrence for July to September showcases sky type 9 i.e. nearly equal to the %Average occurrence of sky type 14 from the summer months of 2020 and 2021 (Refer to Figure-11 & 12). Therefore, for daylight analysis, the researchers, academicians, and industry experts may consider clear sky conditions while computing their daylight analysis for the summer months.

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A Validation Study of Simulated Illuminance Levels of an Office Space in Gurgaon, India under actual CIE Sky Conditions

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Abstract — **In the past decade, numerous daylighting practitioners, architects, engineers, and researchers have progressively used daylighting simulation tools to estimate the daylight areas of building design. Most of these tools employ overcast sky conditions for daylight simulations. However, the accuracy and pertinence of such simulation tools for the tropical sky are uncertain. This study aimed to validate the computer-simulated result of overcast and actual sky models with physical test bed results measured under a real tropical sky. The considered space is modelled as per the constructed test bed space (Mahindra-TERI Centre of Excellence (MTCoE), Gurgaon, India) model to be tested under a real sky measurement. The same model was configured in VELUX Daylight visualizer 3.0 to perform daylighting simulation for March 21st, 2022, from 8:00hrs to 18:00hrs. All the illuminance measurements in the test bed were carried out under prevailing sky conditions in Gurgram, India. In contrast, related CIE sky conditions and overcast sky conditions were used for simulations to compare the results using the agreement of the index method. The International Commission on Illumination (CIE) sky conditions are very dissimilar from the actual tropical sky; simulated absolute value results such as external illuminance, absolute work plane illuminance and surface luminance recorded moderate mean differences from the measured results. Results indicate that the accuracy of illuminance levels increased by almost 24% through daylight simulations under actual sky conditions on March 21st (equinox day). Aimed at imminent research, other parameters can be validated, such as orientations, angle of the overhang, glazing, window sizes, colours, environment settings, and electric lighting.**

Keywords- Illuminance; daylight; validation; office; CIE.

I. INTRODUCTION

Daylight is an essential and effective aspect of the sustainable development approach for reducing energy consumption [1], the impact of climate change [2], and for improving well-being and productivity [3], visual comfort [4], and the built environment development [5]. For colour rendering, daylight is the best available light source, and its high quality makes it the only light source suitable for human visuals. The internal spaces are brightened by natural daylight, which mainly enters the space via window openings and establishes a visual link between the area of interest and exterior environments. An important stage in daylighting designs is calculating the daylight illuminance for a specific location in a building [6]-[9].

For daylighting, several guidelines and conceptual design strategies are available; the most common way to predict daylight illuminance is to use the Daylight Factor (DF). The method is simple, and analysis can be carried out analytically or derived via particular design aids. The DF calculation is based on overcast sky conditions and does not account for direct sunlight [10]. DF is frequently described in daylight design guidelines and is an extensively used technique for practitioners in many countries [11]. The DF method has effectively established the connection between the daylight controls and efficiency; as per the split-flux theory, the Average Daylight Factor (AFD) required for any area of interest is directly proportional to the window area and involves a smaller amount of data than DF [12][13].

The sky luminance varies as the distance from the sun changes (both in azimuth and altitude), according to recorded sky luminance data from other tropical nations and accepted sky luminance prediction models [14][15]. Aside from that, the Indian design sky does not consider the changes in sky circumstances when climatic zones shift. As detailed above, azimuthal uniformity, climatic invariance, and insufficiency for calculating annual energy savings owing to daylight are among the limitations of the present Indian design sky model. Because of these flaws, the designers had no choice but to use different sky luminance forecast models for window design and annual building energy load estimates. The sky models of Perez [16] and the International Commission on Illumination (CIE) [17] are commonly used for predicting sky brightness distribution.

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The daylight availability is primarily determined by the sky's luminance levels and patterns [18]. In 2003, the CIE approved a set of 15 sky types illustrated in Table I, which presents an overall practical framework for representing the skies in various environments, including different climates such as tropical humid and temperate maritime [19][20]. The respective standard sky characterizes a distinct pattern of sky illuminance. However, the mathematical equations can be rather complicated, particularly for the non-overcast sky, which depends on the various sun positions [21]. The shading properties of nearby buildings can dramatically reduce the amount of sunshine entering the interior of the buildings, specifically in densely populated zones [22][23]. With the advancement in computer technology, computer simulation tools can be utilized to evaluate the building's daylight requirement. On the other hand, full-scale computer simulation programs can be highly complex, costly, and time-consuming, particularly during the early stages of design when numerous architectural possibilities and design schemes are studied and evaluated [24]. Simple simulation tools provide insight into the interdependency of numerous daylight variables for building professionals. In earlier investigations, many researchers have used simulation techniques to accurately validate the light environment in the tropics under an overcast sky with no external obstruction [25], however the studies were not performed under real sky conditions. Once the design schemes have been finalized, the practitioner performs computer simulations, and the calculation results will be used to verify the simulated findings.

The provisions, standards, and criteria for adequate natural light in buildings are specified in several regulations, codes of practice and design handbooks. A measuring station at the TERI Gram, Gurugram, Haryana, India, took solar irradiance and sky luminance measurements. All instruments were placed on the roof in a reasonably free of external impediments and easily accessible for examination, cleaning, and maintenance. Every day, data collection for sky luminance begins at 600hrs and ends at 1800hrs; on the other hand, data for solar irradiance is recorded every minute. All of the data was collected roughly simultaneously in true solar time, which aided in the computation of solar geometry and subsequent data comparison at other places.

TABLE I. A SET OF 15 STANDARD SKY TYPES AND THEIR PARAMETRIZATION (CIE, 2003)

Sky Type	Type of Sky	Standard gradation parameters	Standard indicatrix parameters
1	Overcast with the steep gradation and azimuthal uniformity	I: a=4 b=-0.7	1.c=0 d=-1 e=0
2	Overcast with the steep gradation and slight brightening toward sun	I : a=4 b=-0.7	2.c=2 d=-1.5 e=0.15
3	Overcast moderately graded with azimuthal uniformity	II : a=1.1 b=-0.8	1.c=0 d=-1 e=0
4	Overcast moderately graded and slight brightening toward sun	II : a=1.1 b=-0.8	2.c=2 d=-1.5 e=0.15
5	Overcast, foggy or cloudy with overall uniformity	III : a=0 b=-1	1.c=0 d=-1 e=0
6	Partly cloudy with a uniform gradation and slight brightening toward sun	III : a=0 b=-1	2.c=2 d=-1.5 e=0.15
7	Partly cloudy with a brighter circumsolar effect and uniform gradation	III : a=0 b=-1	3.c=5 d=-2.5 e=0.3
8	Partly cloudy, rather uniform with a clear solar corona	III : a=0 b=-1	4.c=10 d=-3 e=0.45
9	Partly cloudy with a shaded sun position	IV : a=-1 b=-0.55	2.c=2 d=-1.5 e=0.15
10	Partly cloudy with brighter circumsolar effect	IV : a=-1 b=-0.55	3.c=5 d=-2.5 e=0.3
11	White-blue sky with a clear solar corona	IV : a=-1 b=-0.55	4.c=10 d=-3 e=0.45
12	Very clear / unturbid with a clear solar corona	V : a=-1 b=-0.32	4.c=10 d=-3 e=0.45
13	Cloudless polluted with a broader solar corona	V : a=-1 b=-0.32	5.c=16 d=-3 e=0.3
14	Cloudless turbid with a broader solar corona	VI : a=-1 b=-0.15	5.c=16 d=-3 e=0.3
15	White-blue turbid sky with a wide solar corona effect	VI : a=-1 b=-0.15	6.c=24 d=-2.8 e=0.15

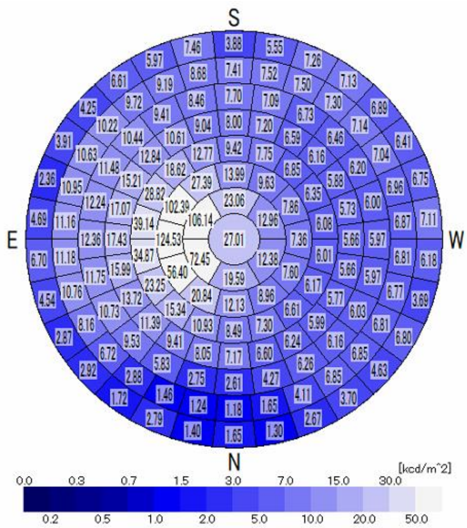

Figure 1. Measurement points for the sky scanner

The EKO MS321LR sky scanner is used to scan the luminance distributions in the sky that presents the sky grid pattern for the sky dome; it records the luminance at 145 sky patches, as shown in Figure 1. The scanner's full view angle is 11 degrees, which allows each sky patch to be regarded as a point source with minimal inaccuracy. This study looks at luminance data measurements and validation of the recorded data by utilizing the VELUX software.

II. METHODOLOGY

The study is divided into four sub-activities where the first activity (see Figure 2) focuses on the CIE analysis of the raw luminance data obtained from the installed sky scanner instrument at the MTCoE lab, Gurugram, India. For the second activity (see Figure 4) of the study, a room was selected in the vicinity of the sky scanner instrument to measure the actual daylight illuminance levels of the space. The considered space is further modelled as per the constructed test bed space as a part of the third activity of the study (see Figure 7). The model was configured in VELUX Daylight Visualizer 3.0 to perform daylighting simulation for equinox day that is 21st March from 800hrs to 1800hrs. All the illuminance measurements in the test bed were carried out under prevailing sky conditions in Gurugram, India. In contrast, related CIE sky conditions and overcast sky conditions were used for simulations to compare the results using the agreement of the index method (see Figure 10).

A. *Activity-1 CIE Analysis of Luminance Distribution Data*

The performance of each CIE standard sky luminance model was evaluated for 21st March 2022 using the Root Mean-Square Errors (RMSE) adapted from ISO 15469:2004 that defines a set of outdoor daylight conditions linking sunlight and skylight for theoretical and practical purposes [18] for the extracted luminance distribution data from the sky scanner instrument. The analyzed measured CIE sky-type for half-hourly data from 800hrs to 1800hrs as mentioned in Table II which is further used as an input for sky type consideration for CIE measured sky simulations as described in Activity-3.

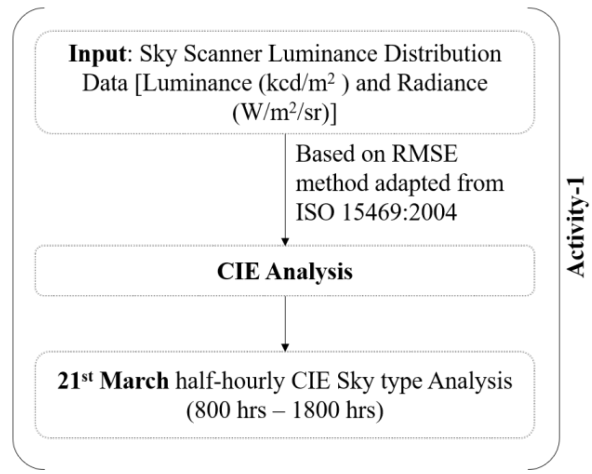

Figure 2. CIE Analysis of Luminance Distribution Data

TABLE II. CIE ANALYSIS MEASURED SKY TYPE FOR 21ST MARCH

Date	Time (hrs)	CIE Analysis Measured Sky-type	CIE Overcast sky-type
21st Mar 2022	800	14	1
	830	14	1
	900	14	1
	930	14	1
	1000	14	1
	1030	14	1
	1100	12	1
	1130	12	1
	1200	12	1
	1230	12	1
	1300	14	1
	1330	14	1
	1400	14	1
	1430	14	1
	1500	14	1
	1530	14	1
	1600	14	1
	1630	15	1
	1700	14	1
	1730	14	1
	1800	14	1

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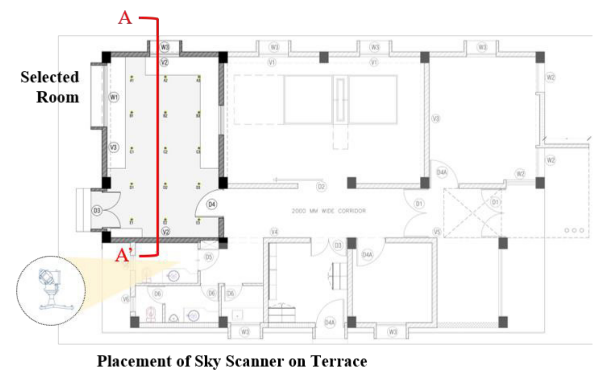
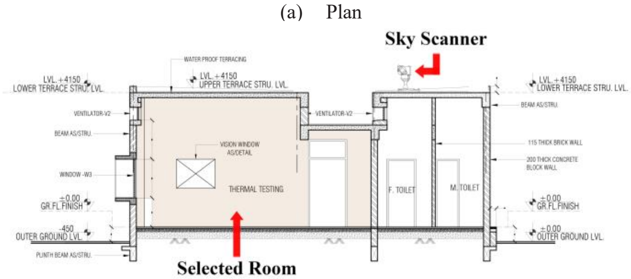
B. Activity-2 Measurements of Daylight Iluminance levels

For the second activity of the study, a room was selected in the 100m vicinity of the sky scanner instrument, as shown in Figure 3.



(a) Plan



(b) Section A-A'

Figure 3. Placement of the Sky Scanner instrument and the selected room;

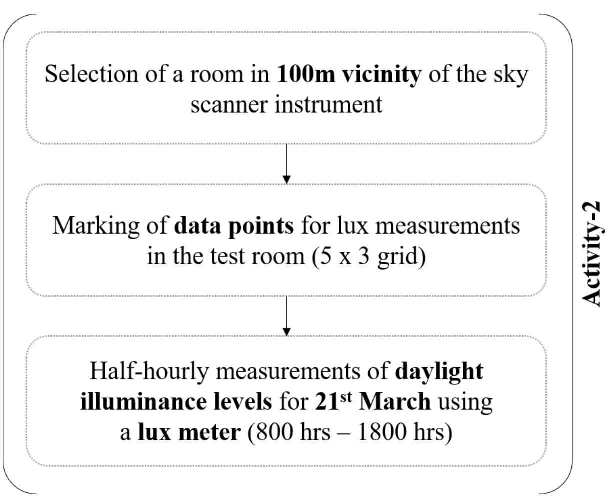


Figure 4. Daylight Illuminance Measurements

Figure 5. Measurements of illuminance levels using a Lux Meter at the MTCoE lab test bed

A set of 15 grid points (see Figure 6) is marked in the selected room and spatially distributed for data set points to measure the daylight illuminance levels for 21st March (800 hrs -1800 hrs) using testo 540 - Light meter, the light sensor is modelled on the spectral sensitivity of the human eye and is ideal for measuring lighting conditions in the workplace at 750mm work plane as shown in Figure 5.

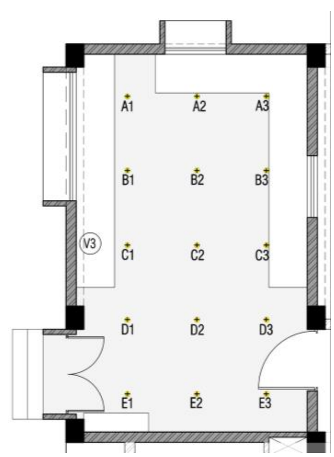


Figure 6. Data points in the selected room

C. Activity-3 Daylight Simulations

A 3D Model of the selected room (MTCoE test bed) was developed to perform the daylight simulations under CIE overcast sky type and CIE measured sky type (see Table II). The simulation results in illuminance (lux) for the same data points as shown in Figure 6 grid as the measured case. Under the scope of the study, the simulations were performed for the 21st of March using VELUX Daylight Visualizer 3.0 software that allows the user to perform daylight simulations considering any sky condition out of the CIE 15 general sky type (see Table I) only for the 21st day of each month.

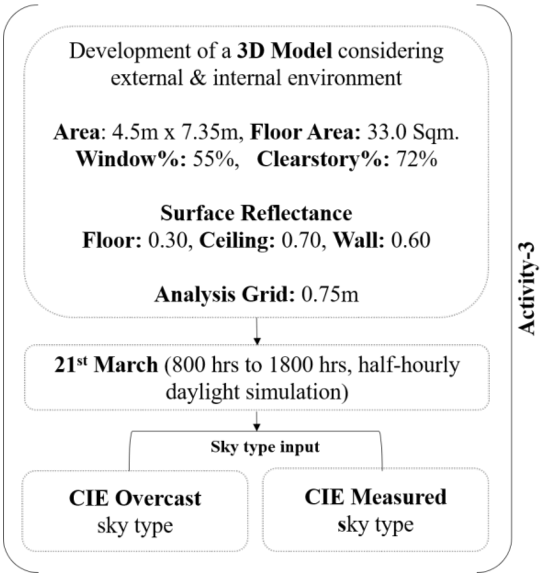


Figure 7. Run Chart for the daylight simulations

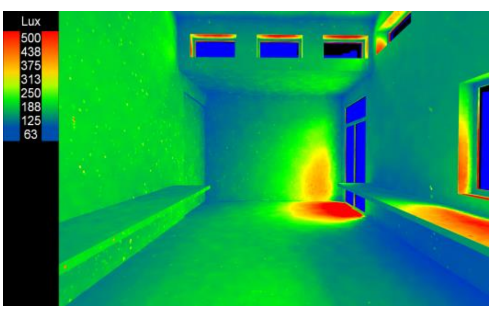


Figure 8. CIE Overcast Sky type daylight simulation for 21st March, 800 hrs with input sky type-1 described as ‘Overcast with a steep gradation and azimuthal uniform’

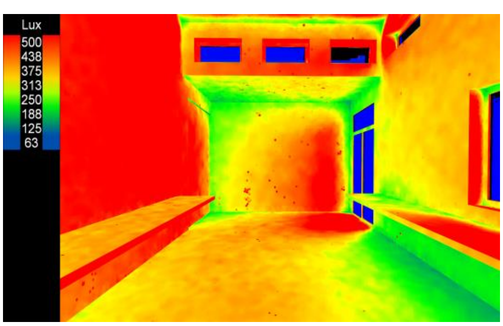


Figure 9. CIE Measured Sky type daylight simulation for 21st March, 800 hrs with input sky type-12 (see Table II) described as ‘Very clear/unturbid with a clear solar corona’

D. Activity-4 Index of Agreement

The daylight illuminance levels obtained from the second activity for actual measurements were compared with the simulated lux levels from the third activity. The index of Agreement method is used to assess the differences between the two cases as shown in Figure 10.

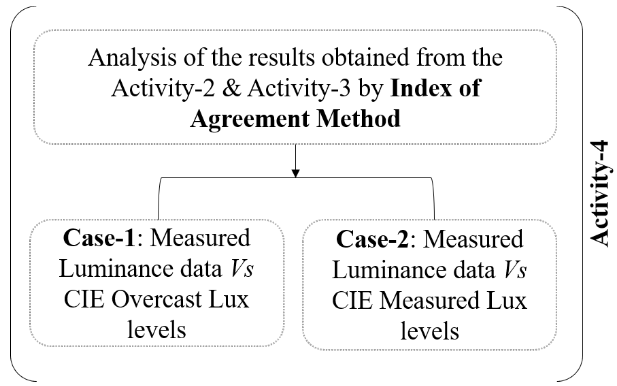


Figure 10. Analysis of the results

The comparison of model-produced estimates with observed/reliable data is an important stage in any modelling investigation. The index of agreement is used to validate this study (also known as the Willmott index); Willmott (1981) recommended a standardized measure of model forecast error called the index of agreement (d), which ranges from 0 to 1 [26]. The index of the agreement represents the ratio of the mean square error and the potential error. A value of one indicates a perfect match, while a value of zero indicates no agreement at all. The index of agreement can identify additive and proportional differences between observed and simulated means and variances; however, due to squared differences, d is susceptible to extreme values.

$$d = 1 - \frac{\Sigma_{i=1}^{n}(O_i - P_i)^2}{\Sigma_{i=1}^{n}(|P_i - \bar{O}| + |O_i - \bar{O}|)^2}\ ,\ \ 0 \leq d \leq 1$$

where O_i is the observed value and P_i is the predicted value and O_{bar} is the average observed value.

III. OBSERVATIONS

Results from the index of agreement method (see Table III and Figure 11) reveal that under overcast sky type illuminance levels were 79% closer to the measured lux levels at 800hrs whereas illuminance levels were only 71% closer to the measured lux level under real sky type, however, at 830hrs the lux levels were calculated to be 80% and 60% closer to the measured illuminance results under overcast sky type and measured CIE sky type. At 900hrs, a decrease in the percentage was observed as the illuminance level was 73% closer to the measured data under measured CIE type as compared to overcast sky type data measurement which was 79% closer to the measured data. Further at 930hrs the illuminance level was 85% and 91% closer to the measured lux level under overcast sky type and measured CIE sky type, it is at this time of the day where the percentage difference between overcast sky type and measured CIE type data was just one percent. At 1000hrs the illuminance level under overcast sky type and measured sky type were observed to be 88% and 91% closer to the measured data readings. At 1030hrs the illuminance levels

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under overcast sky type and measure sky type were observed to be 82% and 91% closer to the measure data reading however at 1100hrs there was a dip in percentage observed where the illuminance level was 93% closer to measure data under overcast sky type and 60% closer to the measure data under CIE measured sky type which is the maximum percentage closer to the measure readings and at 1130hrs the percentage dropped to 89% and 91%.

As observed during the noon, the illuminance level under overcast sky type and measured sky type were observed to be 68% and 84% closer to the measured illuminance levels and at 1230hrs the levels further dropped to 62% and 26%. At 1300hrs the illuminance level under overcast and CIE measure sky type were observed to be 75% and 95% closer to the measured data readings. Analysis indicates that at 1330hrs the luminance levels under the overcast and CIE Measured sky type were observed to be 39% and 89% during this hour of the day the difference between CIE measured sky type and overcast sky type was 50%. At 1400hrs the illuminance level under overcast and CIE measured sky type was observed to be 43% and 89% closer to the measured illuminance data, however a decrease in the percentage was observed at 1430hrs as the luminance levels under overcast sky type and CIE measured sky type was 24% and 87% closer to the measured illuminance data.

At 1500hrs the illuminance level under overcast and CIE measured sky type were analyzed to be the lowest, as they were just 3% and 73% close to the measured data, moreover by 1530hrs the percentage increase was observed to be 4% and 66%. The percentage increase continued for the next hour and the illuminance level was under overcast and CIE measured sky type were analyzed to be 6% and 73% at 1600hrs and 6% and 83% at 1630hrs closer to the measured illuminance level. By 1700hrs the illuminance level under overcast and CIE measured sky type were analyzed to be 3% and 23% closer to the measured illuminance data, which was lower than the previous hour this percentage, however, increased to 5% and 85% by 1730hrs.

The last reading of the day at 1800hrs demonstrated that the illuminance level was under overcast and CIE measured sky type were zero percent closer to the measured illuminance data.

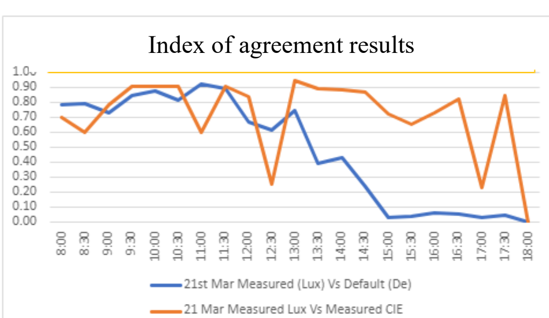

Figure 11. Index of agreement results

TABLE III. EX OF AGREEMENT RESULTS MEASURED LUX LEVEL V/S OVERCAST SKY TYPE (DE) & MEASURED LUX V/S MEASURED CIE SKY TYPE (DA).

Time	Measured (Lux) V/s Overcast sky type (D_e)	Measured Lux V/s Measured CIE sky type (D_a)
0800	0.79	0.71
0830	0.80	0.60
0900	0.73	0.79
0930	0.85	0.91
1000	0.88	0.91
1030	0.82	0.91
1100	0.93	0.60
1130	0.89	0.91
1200	0.68	0.84
1230	0.62	0.26
1300	0.75	0.95
1330	0.39	0.89
1400	0.43	0.89
1430	0.24	0.87
1500	0.03	0.73
1530	0.04	0.66
1600	0.06	0.73
1630	0.06	0.83
1700	0.03	0.23
1730	0.05	0.85
1800	0.00	0.00
Average	0.48	0.72
Standard Deviation	0.34	0.20
Median	0.68	0.83

For the 21st of March 2022 under overcast sky type the daily average of the illuminance level was 48% closer to the measured illuminance level and under CIE sky type data the illuminance level was 72% closer to the measured illuminance data with a standard deviation of 0.34 and 0.2 was observed for overcast sky type and CIE sky type with respect to measured data.

IV. CONCLUSION

The actual set of CIE design skies given in Table II can be selected for daylight simulation analysis for Gurgaon and Delhi NCR region to get 24% more accurate results than the current practice of analyzing under a worst-case scenario of overcast sky conditions. This would help architects and designers to select the glass with optimum visual light transmission and consider the optimum window-wall ratio of the project.

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The Mahindra-TERI Centre of Excellence (MTCoE) is a joint research initiative of Mahindra Lifespaces (MLDL) and The Energy and Resources Institute (TERI). It focuses on developing science-based solutions for India's future built environment, with a view to reduce the energy footprint of the real estate industry.

The overall scope of the project includes standardization and measurement of building material, thermal and visual comfort study, development of performance standard matrices, guidelines and numerical toolkits and water related activity for sustainable water use in habitats.

MTCoE is located at TERI Gram, Gual Pahari, Gurugram, Faridabad, Haryana.

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