Modelling The Sky - A Standard Digital Form

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*The simulation of daylighting performance requires some knowledge about prevailing sky conditions, especially luminance. Commonly the CIE standard models (clear and overcast, and often some combination of both) are used to provide the necessary estimates to obtain the temporal and spatial variance of luminances and the consequent illuminance levels in buildings. We know from data analysis of measurements recorded at the Research Class measurement station located at the Sydney International Airport, Mascot, and from other data from the International Daylight Measurement Program **(IDMP)** that CIE models do not provide accurate indications of the sky conditions in some countries. Nor do combinations of the standard models provide a realistic estimate of intermediate sky conditions. An attempt is now Boeing made using recorded data to come to terms with the luminance distributions of actual sky conditions both in Australia and overseas.*

This paper presents some proposals which are aimed at defining a modelling strategy which will facilitate a much more realistic approach to the estimation of sky luminance. In particular we suggest that it is possible to define a digital form which enables the standard empirical models, as well as data from sky scanning devices, to be integrated into a common modelling framework. In addition it will be proposed that this standard form will provide a basis for the construction of model skies for particular locations given some local knowledge of the atmospheric conditions. These sky models are intended to be used directly by simulation packages or other software systems requiring information on the distribution of luminance across the sky dome.

Introduction

Current research in building physics and architectural science is concentrated on problems of energy efficient design utilising daylight in buildings. In order to estimate the amount of daylight penetrating a window of a building several components must be taken into consideration; the amount of direct light received from the sun, the amount of light externally reflected from other buildings and the external environment, the amount of diffuse light from the sky which is visible through the window and the internal reflection characteristics of the interior.

This paper is concerned with the daylight source and the meteorological/climatic base which we need as input to the daylighting calculations. Basically, a knowledge of the direct beam illuminance from the sun and the distribution of luminances across the sky dome (for the required location and climatic conditions) are required to enable predictions of daylight availability to be made.

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Skylight is generally specified by standard patterns of luminance (or radiance) distributions. The present international standards, the ISO/CIE Overcast and Clear skies (CIE, 1973 and 1990) provide definitions of "standard" skies. These have been combined in various ways in attempts to model average, or partly cloudy, sky conditions. By and large these interpolated skies lack verification from measured data. The International Daylight Measurement Program is targeted at this problem and will hopefully provide appropriate data in the next few years.

There appears to be a significant need to provide an integrated approach which will enable these various modelling strategies, and the availability of measured data to be analyzed and compared. Ultimately the development of more realistic luminance models which better account for local conditions will allow reliable models to be developed for locations where there are no detailed data records (eg. scanner data).

This paper presents a new approach to modelling the sky, in particular the luminance distribution across the sky dome. In addition it will be proposed that the same approach be used to build models of the sky to better represent local conditions. The SKYMAP (SKY Modelling and Analysis Package) system provides an integrated approach to modelling the sky which allows both empirical models and measured data to be evaluated and integrated into a common modelling framework. In this sense SKYMAP provides a tool for the analysis of models and data, and will allow new models to be constructed to suit local conditions.

The development of SKYMAP is still underway, but most of the conceptual design is now complete. A description of these concepts together with some sample output and an overview of its facilities is presented here.

Modelling Strategies

Models of the luminance distribution of the sky have to date been defined in the form of analogue expressions which describe the luminance at any point on the sky dome. These have been derived from various theoretical assumptions pertaining to the diffusion characteristics of the atmosphere validated with limited measured data (CIE 1973, CIE 1990, Perez et al 1991, Harrison 1991 and Kittler 1985). The resulting empirical relationships provide an estimate of the luminance distribution with some level of reliability or accuracy. While such models may be defined for a given location their use at other locations is, arguably, unreliable.

Models of this kind are classified as *Analogue Empirical Models* (AEMs). An AEM is an empirically derived expression composed of a set of parameters and/or coefficients, which allow the luminance of any point on the sky dome to be computed. This type of model is very convenient for computational purposes as input comprises only the necessary parameters (including location, time, solar altitude and atmosperhic conditions).

Given the renewed interest in modelling sky conditions through the International Daylight Measurement Program, we also have another form of model, the *Measured Data Model* (MDM). MDMs are defined by sets of data resulting from various types of measurements which allow the luminance levels at various parts of the sky dome to be described. Typically these measurements are made with a scanning device which can record the luminance at a set of (well defined) points on the sky dome. From these data the luminance distribution on the sky dome can be determined.

MDMs naturally provide "good" quality data for the location of the measuring device, and for the time at which the measurements were recorded. In addition these data may be used to validate, or design, AEMs. It is also possible to use MDMs directly in simulation programs, where the "real" luminance data can be used to study the lighting conditions, or the behaviour of lighting control devices, over periods of time. In this case the MDM can naturally account for turbidity and cloudiness.

MDMs typically involve large amounts of data, and so are difficult to work with. There is a natural tendency to use them to build AEMs which can be defined compactly in the form of an expression and a relatively small set of coefficients or parameters.

The sky modelling approach adopted accepts both these model forms as being useful. An integrated framework is therefore proposed which allows both to be used and manipulated to obtain the best results.

In addition a third modelling strategy is proposed. The *Hybrid Data Model* (HDM) will facilitate the construction of new artificial models which can be derived from other models, especially AEMs and MDMs. For example a sky model could be constructed from a selected AEM, scaled using data from local measurements, with cloud cover and type included to represent local sky conditions. The resulting model is thus a hybrid of the MDM and AEM models combined to represent the local conditions.

Each of these model types has its own particular value and area of application. AEMs are very convenient for computation purposes, but generally lack accuracy. MDMs can provide accurate estimates for specific locations, but are complex to process. HDMs offer the promise of building locally specific models based on more general models, or on models defined for other locations.

Model Representations

As a way of facilitating the representation and manipulation of each of these model forms in an integrated and consistent way, a common representation scheme is proposed which will allow:

- Each model form to be transformed into a common description.
- Different models to be directly compared.
- Models to be manipulated using the same set of tools.
- The definition of a set of operators to take data from models of any type and to construct new models.
- Any form of model to be used for the common analysis tasks (daylight analysis, simulation studies, etc).

This common representation should be a digital model, the *Standard Digital Form* (SDF).

The Standard Digital Form

The SDF is intended to provide a means of representing the luminance distribution over the sky dome in a digital form. Data from each of the three model types can be represented in an SDF using a common and consistent definition of the data.

The luminance distribution across the sky dome is a complex phenomenon and not appropriately represented by uni-dimensional statistics such as mean, standard deviation and other measures of dispersion or variance. The representation scheme must therefore include the spatial component in a formal way.

While the classic digital representation approach to spatially variant data is often based on a grid scheme, a different approach has been adopted in this research project. Grid based data schemes (which includes most MDMs) can reasonably represent most spatially variant data, but the amount of data quickly expands if the required accuracy is increased (ie. if a finer grid is required). In addition grid based schemes tend to lose a significant amount of information where the luminance distributions are rapidly varying or where they have actual discontinuities.

For relatively continuous sky conditions (CIE clear and overcast) various AEMs have been shown to represent reasonably the luminance distributions (Hayman et al, 1993). For partly cloudy sky conditions the data need to be analysed where there are clouds and where parts of the sky dome may be obstructed by local horizon effects (eg. vegetation or buildings which reduce the amount of visible sky and which have their own light reflection characteristics).

A representation format is therefore proposed which has the following properties:

- Allows the distribution of luminance to be described at varying levels of detail and resolution, dependent on the underlying theories, empirical relationships or measured data.
- Avoids the complexity problems of having to increase the resolution of grid based schemes to capture rapidly varying luminance levels.
- Facilitates the representation of discontinuities due to effects of clouds and other obstructions to the sky dome.
- Provides a common representation scheme which can be used to describe all model forms (AEMs, MDMs and HDMs).
- Minimises the loss of information in the representation so that the original spatially variant data can be recovered with acceptable precision.

The proposed digital form will permit a convenient means of comparing and analysing various models as well as manipulating them in a consistent way.

The SDF is composed of sets of appropriate parameters and polylines (sets of connected vectors). The parameters define any necessary data to characterize the luminance distribution (eg. location, date, time) while the polylines describe sets of contours of constant luminance and sets of edges which define areas of discontinuity in the luminance distribution. For a more detailed description of the SDF see Reid et al (1992).

For the sky shown in Figure 1 which has a bank of cloud and a local obstruction, but is otherwise a clear sky, the SDF would contain the polylines as shown in Figure 2.

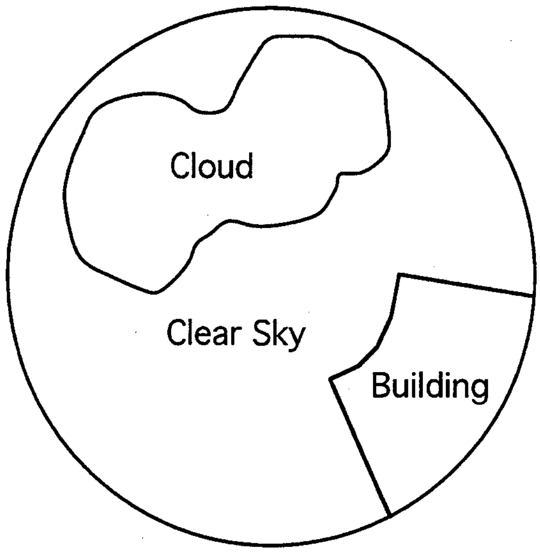

Figure 1: A Sample Real Sky

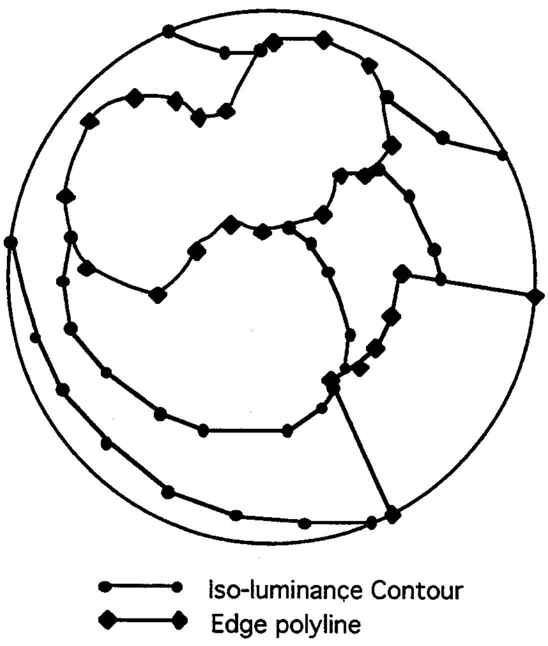

Figure 2: The SDF Polylines for the Sample Real Sky

In practice the cloud bank and the obstruction will each have their own set of contours to describe the luminance distribution within their boundaries. The detail which can be expressed in this form depends only on the level of accuracy of the original data source. For example if the CIE clear sky provides a good representation for a particular location, the iso-luminance contours can be computed at some appropriate level of resolution, ie. closely or broadly spaced commensurate with the accuracy of the source data. Given the largely empirical nature of all AEMs, the resolution of the SDF can be limited to match the reliability of the AEM without the need to resort to very closely spaced contours.

Edges are generated where there are discontinuities in the luminance distribution. The edge defines the discontinuity (edge of a cloud or obstruction). This definition enables the design of a suitable interpolation strategy (for estimating luminance levels between contours) accounting for the discontinuity.

Operation of SDF Model

An SDF model will operate through a set of standard functions which are provided to return properties from the model. For example functions are defined to compute:

- the luminance at any point (azimuth and altitiude),
- the average luminance over a polygon patch of sky, and
- a small set of functions to access and manipulate SDF models.

In practice the SDF is defined by a set of data (a computer file) which contains the sets of parameters. This file is accessible through a set of pre-defined primitive operators. These appear as a set of function calls (from within a computer program) which can create, read and modify models in this SDF representation.

The general structure also permits users to define their own parameters, to add these to the model definition and to access them again, through their own software systems.

Sky models in this form represent the state of the sky at a point in time. A complete model may therefore be made up of sequences of data sets. For example a study of daylighting may only require some typical dark and bright skies (the extremes) to be modelled for use in a static daylight factor analysis. In this case only a small number of models need to be constructed. For simulation purposes, where hourly data is required over a long period of time (eg. several months) then the SDF will contain many sky models, one for each hour of the day for the period being studied. In either case, the user of a SDF model has available a set of primitive functions to extract the required model(s) as, and when, required by the analysis or simulation package.

The SKYMAP System

The SDF provides the basic structure to build the SKYMAP system. SKYMAP is intended to provide a set of facilities to enable various luminance models to be incorporated, studied and manipulated. It also provides the means of building SDF models.

SKYMAP has the following main features:

- The ability to incorporate any AEM for which the appropriate parameters and coefficients are available. (At this stage the CIE clear and overcast skies, and the Perez all weather model (Perez, Seals and Michalasky, 1992) have been implemented.) Each of these models must be hard-coded, as there is no simple way of generally describing all AEMs.
- The ability to incorporate any MDM for which the data is available. Currently facilities to access the data from the PRC scanner located at the Sydney measurement station have been included. The format of scanner data must be well defined, and (most likely) a translator written for each type of scanner or recording device.
- The ability to convert any of these models into SDF.
- The ability to manipulate sky models in SDF to enable new HDMs to be constructed.

In essence, therefore, SKYMAP provides a toolbox for analysing and comparing models from different sources and of different types. It will also enable new models to be built.

At this stage the display capabilities of SKYMAP relate only to luminance distributions as shown in the shaded map in Figure 3. Contour maps can also be displayed. Figure 4 shows the Perez model (Perez et al, 1992a) for the same time and location. Figure 5 shows the actual sky (as recorded photographically) for the same time. This shows a partially cloudy sky with a bank of clouds in the north-west segment of the sky dome.

The SKYMAP system is currently being developed on a UNIX/X11 platform, which means that, in due course, it will be readily portable within this domain.

Including Edge Information

Edges in the SDF are intended to define the discontinuities. that exist in the luminance distribution due to clouds and obstructions. If the cloud cover is "uniform" then the CIE overcast sky could define sky conditions relatively close to the luminance distribution data, although scaling may be required to take into account the type of clouds. An approach as proposed by Perez (Perez, Seals, Michalsky and Ineichen, 1992) where some ordered/random (fractal like) variance is applied to the luminance levels over the sky dome, may be quite suitable for fully or lightly overcast skies, but has yet to be validated.

It is with partially cloudy skies that the problems arise. Obstructions to the sky dome from adjoining buildings, vegetation, etc are a similar class of problem. The net effect is that the luminance patterns and luminance levels across the sky dome can change rapidly. Also, the luminance levels within the edge may have little to do with the background sky but more to do with the local reflectivity conditions (and clearly the type and density in the case of clouds).

One attempt has been made (Davies, et al, 1992) to extract the edges of clouds from a digitised image using edge detection methods as developed for computer vision systems. Their approach used an image photographed through a red filter to enhance the edge definition of the clouds in the photograph. While these authors report some success (with selected images) it is not clear they have solved the problem in any comprehensive way.

The data recorded by the sky scanner at the Sydney measurement station includes data measured using three filters: a filter sensitive to the eye's response, and blue and red filters. Research is currently being carried out to identify the edges of clouds using these data.

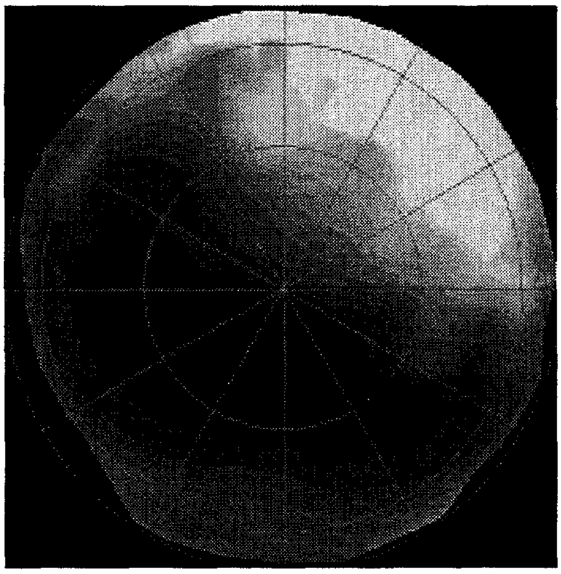

Figure 3: Luminance distribution from PRC scanner (Sydney: 7/7/92 at 12:45)

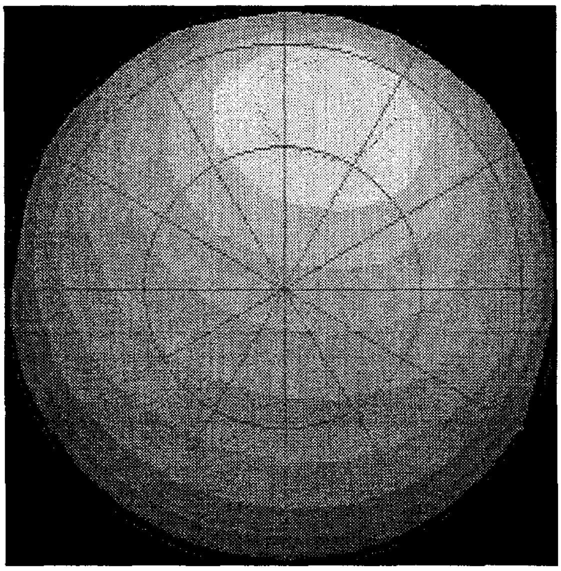

Figure 4: The Perez model (Sydney: 7/7/92 at 12:45)

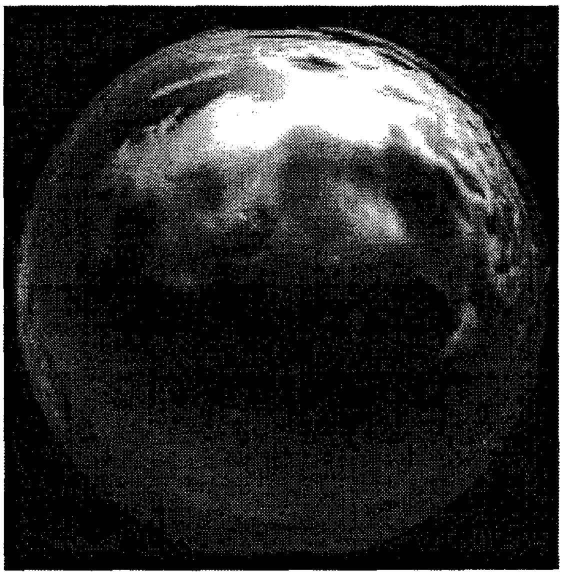

Figure 5: The actual sky (from a photograph) (Sydney 7/7/92 at 12:45)

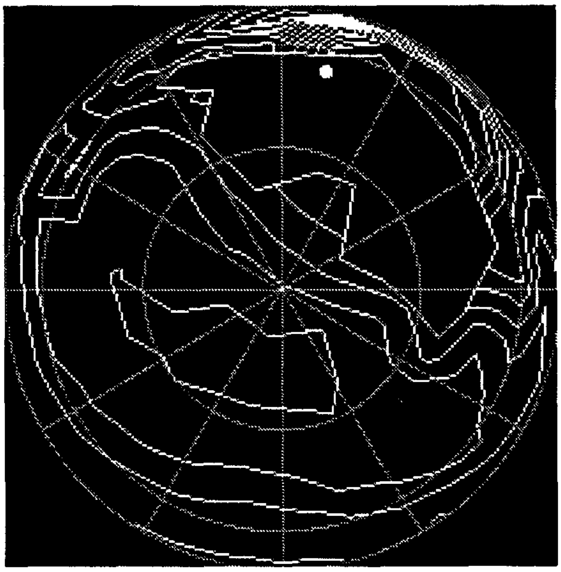

Figure 6: Example of a cloud edge definition (Sydney 7/7/92 at 12:45)

The major task will be to include the edge effects into the SDF, and to provide means to analyse models which have these edge effects. In fact one reasonable approach to this problem is to allow the user to provide the necessary judgement and to indicate the edges through some interactive process (eg. they are sketched/drawn on the screen in the appropriate places). If this is achieved then the defined edges can be readily incorporated into the SDF. Figure 6 shows an example where a user has interactively defined the edge of the cloud from Figure 5. In this case a contour map is displayed.

In Figure 6, that part of the sky dome inside the edge has been removed, leaving just the clear sky part. The defined edge is then formally incorporated into the model. The removed part can be retained for addition into other sky models. Iso-luminance contours would normally be expected to exist within an edge boundary. Edges resulting from other forms of obstructions can be treated in much the same way.

It would be desirable to have available more automatic methods for cloud edge (and other obstructions to the sky dome) detection. These would allow detailed analysis of the impact of cloudiness and daylight dynamics on the evaluation of sky images which could lead to new modelling techniques. They would also allow a range of cloud coverage statistics to be computed directly from MDMs.

Operations of SKYMAP

Once the data has been represented in SDF we can define a set of basic operations which will allow manipulation of the sky models. The simplest operations available in SKYMAP enable different models to be accessed and displayed side-by-side for comparison. In due course more quantitative measures will be computed to aid these comparisons (eg. various statistical measures of central tendency and variance).

Once an AEM or MDM is accessed for display, it can be saved in SDF. From SDF it can be re-displayed and further manipulated without any additional loss of information. The basic operations to be implemented are:

Scale: Scales the luminance of a model by some constant factor.

Normalise: The normalise operator produces a model normalised to the zenith luminance.

Difference: Takes two models A and B and produces a result which has a luminance map defined by the value of the difference between the luminances at corresponding points on the sky dome.

Ratio: Takes two models A and B and produces a result which has a luminance map defined by the ratio of the values at corresponding points in the sky dome.

Overlay: Takes two sky models (A and B) and overlays A on top of B, replacing the luminance values of B with the values of A at the corresponding points on the sky dome.

Extract patch: Takes a model and produces a new model containing only the luminance values within the edges defined in the model.

Extract rest: Takes a model and produces a new model containing only the luminance values that lie outside the edges defined in the model.

Clearly the *difference* and *ratio* are essential to allow models to be compared directly. *Scale* and *normalize* are basic tools to allow models from different times, locations, etc to be compared. *Scale* is also a basic tool for adjusting the average luminance of a model. *Extract patch/rest* are intended to be used to extract parts of a sky, eg. a bank of clouds, to be examined by itself or to be overlayed on another model.

These operators will provide a set of basic tools for the users of SKYMAP. Other operators may be added once their need is recognised.

Using SDF Models for Daylighting Studies

In a large number of locations measurements to create MDMs would not be available, nor sufficient data to validate AEMs. The most readily available data (from meteorological stations) will comprise diffuse and global radiation measurements. SKYMAP has the potential to create new models (HDMs) using such data.

Consider the problem of developing a suitable model for daylighting studies in Sydney using real data from the Sydney daylight measuring station. In SDF these data can be made available for simulation studies as an alternative to using some linear combination of CIE clear and overcast skies. SKYMAP provides the means to transform the MDMs from the scanner data into a form that can be used directly by simulation programs (given some minor changes to incorporate the SKYMAP functions which access the SDF models).

In addition, SKYMAP functions will be used to study the performance of lighting control devices over extreme cycles of dark and bright sky conditions by using scanner data to build a sequence of models as input to the simulation software.

Spot luminance measurements will be used to scale and modify the standard models or an MDM from a remote location. Limited amounts of global luminance or radiance data can be also used to scale a standard model to achieve a better fit to the local conditions.

Conclusions

A fundamentally new approach to modelling the luminance characteristics of the sky has been proposed and is currently being implemented with the SKYMAP system. Its purpose is to provide an integrated and co-ordinated approach to the study of the sky dome luminances particularly for application to building daylighting and energy simulation studies.

Empirical sky models (AEMs) and measured data models (MDMs) are handled in a consistent way. In addition the concept of the hybrid model (HDM) has been introduced which can be constructed for particular locations, when given given suitable data from other sources and locations.

To ensure that these model forms can be easily analysed, compared and utilised in computer software a standard digital form (SDF) has been introduced. The SDF is a digital modelling strategy which allows most of the detail of the luminance distribution, including edge effects, to be modelled with little loss of information. Using this method a consistent set of operators can be used to manipulate sky models regardless of their origin.

The SKYMAP system is currently being developed to facilitate these requirements and when complete will provide a set of integrated tools for sky modelling and model manipulation. These will reduce the problems of building sky models for locations and situations where data is limited or unreliable.

Acknowledgments

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