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Whole-Sky Luminance Distribution Maps from Calibrated Digital Photography

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Abstract
Sky luminance is an essential component in assessing the appearance and performance of internal spaces which are highly sensitive to the often dynamic luminance of the visible sector of the sky. Therefore, whole sky luminance distributions representative of real-sky sectoral dynamics over short time intervals are required. A modified scientific-grade digital camera was used to measure whole-sky luminance distributions of various sky conditions. Results showed acceptable correlation between the measured and calculated results for overcast and clear skies demonstrating the viability of using hemispherical digital photography for mapping whole-sky luminance distributions. However, intermediate skies showed distinct sectoral variations and dynamics supporting the argument for more accurate and representative luminance distribution data.

Keywords: Luminance distribution, digital photometry, daylight design.

1. Introduction
The application of CCD photometry and radiometry techniques is well developed in the disciplinary fields of astronomy, metrology and in biomedical applications among others. CCD development for scientific applications has also advanced with a detailed understanding of the potentials and limitations of different device designs. This paper explores possibilities and limitations of using this same technology to generate whole-sky luminance maps as a source of data for subsequent architectural daylight design.

Sky luminance is an essential component in assessing the appearance and performance of internal spaces. The spaces are highly sensitive to the luminance of the sector of the sky visible from the interior of the building. This luminance can change quickly under intermediate sky conditions and differ considerably from other sectors. To design spaces to respond to and fully utilise daylight under all possible sky luminance variations it is first necessary to employ as complete and accurate a representation of the external luminous environment as is possible. More specifically, to pursue ‘real-time’ design, where long-term and rapid temporal variations can be accounted for, whole sky luminance distributions reflective of real-sky variations over representative time intervals are required.

Sky luminance can be represented by both mathematical models and empirical datasets. In addition to the reference models of the Commission Internationale de l’Eclairage (CIE), efforts have been made to both categorize and represent, mathematically, all states of the sky between the extremes of overcast and clear skies [1-4]. Empirical measurements can be both terrestrially and extra-terrestrially based. For example, the International Daylight Monitoring Programme (IDMP) [5] and the Satel-Light programme [6] respectively. Unfortunately, none
of these represent sky sector-specific whole-sky luminance distributions over time periods sufficiently short to carry out analysis that is considerate of real daylight design requirements.

This paper presents a first step to developing a dynamic daylight design methodology; the viability of using a scientific grade photometric digital camera to map the luminous distribution of the dynamic sky.

![Image of camera front and rear and setup for measuring.](image)

**Fig 1. View of camera front and rear and setup for measuring.**

### 2. The Radiant ProMetric 1400 Camera

The ProMetric 1400 (PM-1400) used in these measurements was designed by Radiant Imaging Inc., Seattle, US for use in measurement, calibration and defect detection applications in both production and laboratory environments [7] and was adapted for use in this research to measure whole-sky luminance distributions.

The CCD sensor used in the PM-1400 is a scientific grade front illuminated Kodak KAF-1001E Image Sensor. It is a high-density, 1 million pixel (1024 x 1024), full-frame ‘Blue Plus’ image sensor [8]. It consists of one vertical CCD shift register and one horizontal CCD shift register. The vertical register consists of relatively large 24µm x 24µm photo-capacitor sensing elements (pixels) which also serve as the transport mechanism. The sensor includes an additional 12 columns and 8 rows of non-imaging pixels added as dark reference. The sensor has a 100% optical fill factor with no data loss across the captured scene. The dimension of the KAF-1001E is 24.6mm x 24.6mm corresponding to a total sensor surface area of 605.16mm². Due to the circular projection of the projected image, 66.3%, or approx. 693,048 pixels of a possible 1,045,506 were utilised and represented 693,048 individual and simultaneous measurements distributed across the sky hemisphere with a resolution of 9x10⁻⁶sr per pixel.

The PM-1400 camera also employs a two-stage Peltier cooler with fan assisted heat dissipation (Fig 1.) to maintain a low CCD sensor temperature and thus minimise dark current, or thermal noise, in measurements. The CCD temperature was set to -10°C during measurements as recommended by Radiant.

### 3. The Sigma 8mm EX Fisheye Lens

To map the luminance distribution of the hemispherical sky it was necessary to use a lens with a field-of-view of at least 180°. The Sigma 8mm EX Fisheye lens was selected for reasons of build quality and cost.
As it is impossible to project a hemispherical field of view on a finite image plane, such as a CCD sensor, fisheye lenses are typically designed to use projection models, or mapping equations [9]. The Sigma 8mm EX fisheye lens used was designed to follow the equisolid-angle projection model [10].

While the KAF-1001E CCD sensor provides a wide dynamic range, helped by its relatively large pixel dimensions, it was necessary to employ ND filtering to avoid saturation of the CCD at the luminance levels being measured. ND2 and ND3 (1% and 0.1% light transmission respectively) filters were used. These were mounted internally in the camera as the convex form of the fisheye lens prevented them being threaded to the front.

4. Potential Sources of Inaccuracy and System Calibration

There are a number of possible error sources associated with CCD technology. These include errors inherent in the device itself and those generated in its operation. Potential sources of noise generated in-use can limit the photometric accuracy of CCD images. The primary noise sources in CCD detectors are thermal noise, read noise and shot noise. In this application, thermal noise was of particular concern due to the high dynamic ranges of some measurements. The PM-1400 cooling system helped to minimise dark current or thermal noise in measurements. This was further helped by the relatively high saturation limit of the KAF-1001E at 650,000 electrons due primarily to its pixel dimensions.

4.1 Camera Calibration

Flat-field matrix calibration was carried out for each lens f-stop in combination with each ND filter used. The flat-field correction matrix acts as a correction map to and compensates for lens cosine fall-off, vignetting and, of particular importance, the pixel-to-pixel non-uniformity of the CCD chip.

4.2 Fisheye Lens Calibration

The manufacturing process of lenses often results in small geometric inaccuracies. To overcome this, and to ensure accuracy, it was necessary to apply a geometric calibration technique. Literature from a range of scientific fields [9, 11, 12] showed that there was no accepted single or simple process of calibrating fisheye lenses but that most techniques employed a similar series of steps [13] based on the analysis of distortion of a specific and regular pattern.

The distortion of a fisheye lens follows a polynomial equation [11]. For lenses with moderate distortion, a third order polynomial is sufficient [11, 14]. However, the fifth order polynomial provides a more accurate model for fisheye lenses [9]. Using Imatest software [15] to calibrate the photographic system, distortion coefficients were calculated.

6. Results

All measurements were taken in Dublin, Ireland at latitude 53.4° and longitude -6.2°. Dublin’s weather is influenced by its proximity to a low-level mountain range to the south and the Irish Sea to the east. Ireland’s climate is strongly influenced by the North Atlantic and its associated weather systems which can be characterised as highly changeable or dynamic.

Figures 2-5 provide a sample of skies to illustrate the varying luminance distributions measured during the two week measuring period.
Fig 2. Overcast sky with mixed cloud cover and luminance distribution, dynamic. (20th April 2006 @ GMT 15:44)

Fig 3. Clear sky with some low-level atmospheric turbidity near solar disc. (21st April 2006 @ GMT 15:36)

Fig 4. Intermediate sky, mixed clear sky and clouds. Highly dynamic. (26th April 2006 @ GMT 10:27)
Fig 5. Overcast sky. Static. (30th April 2006 @ GMT 10:19)

Figures 3 and 5 correlate most closely with the CIE standard clear and overcast sky models respectively. The remaining samples, representative of 75% of the measurements taken, cannot be matched to existing models due to their random distributions. Many of these also exhibited dynamic luminance distributions in light to moderate wind speeds. Unfortunately, the dynamics of the measurements over the measured intervals cannot be illustrated here.

The operation of the camera proved straightforward despite all adjustments being manual. An ND2 filter was used most frequently. Adjustments to f-stop were specific to a sky type and so did not require regular adjustment. However, adjustments to exposure times were required regularly, particularly under dynamic skies.

7. Conclusion

The majority of measurements taken over the two week monitoring period represented intermediate sky types (clear with varying turbidity, partly cloudy, cloudy with varying sectoral luminosity, etc.) that were both dynamic and sectorally varied. These luminance distributions can only be represented by empirical data and are reflective of the real skies to which internal spaces respond.

Calibrated digital photometry provides an accurate and efficient means of mapping whole-sky luminance distributions for use in daylight design. The high dynamic range of the Kodak KAF-1001E sensor meant that little adjustment was necessary to avoid pixel saturation. This was an important feature as all adjustments on the camera system were manual.

The results demonstrate the importance of using accurate whole-sky luminance data for daylight design. Follow-on work will extend measurements to generate a database of dynamic sky sequences that can be used to test design scenarios under replicable ‘real-sky’ dynamic conditions.

8. References

10. Sigma. 2005. Email communication with Sigma USA.