HAGIA SOPHIA'S SIXTH CENTURY DAYLIGHTING

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Abstract

Since its construction in the sixth century, Hagia Sophia has been praised for its lighting. While some aspects of its illumination can be studied in the present building, the totality of its primal appearance has been lost due to supporting measures, additions, and later changes. An attempt is made to analyse this illumination, and to understand the day-lighting concepts inherent in Hagia Sophia's outstanding architecture, employing computational simulation based on the reconstruction of the building's geometry at the time of its second dedication. Accounted for are the original distribution and properties of the surfaces enclosing the architectural space, including the detailed marble decoration; the original gilding of sculptural elements; and the optically complex gold mosaics. Daylight simulation under a synthetic sky with varying solar geometries and cloud coverage reveals differences between the historic and present states, e.g. higher diffuse illumination originating from the windows of the aisles and galleries; effects of light scattering by window glass; and the unimpaired appearance of marble, gold mosaics, and gilded surfaces. The results allow to ascertain how the contributions of different groups of windows affect the dynamic interplay of direct sunlight, diffuse illumination, and the specular reflections on mosaics and marble, changing with the exterior sky conditions. The results further show that the orientation of the building produces particularly impressive lighting on the Christmas morning.

Keywords: Daylight, reconstruction, simulation, Hagia Sophia

AYASOFYA'NIN 6. YÜZYILDA GÜN IŞIĞI AYDINLATMASI

Özet

Ayasofya'nın aydınlatması, 6. yüzyıldaki inşaatından bu yana yapının önemli bir unsuru olarak dikkat çekmektedir. Binanın gün ışığı aydınlatması Neoplatonik ışık metafiziği açısından yorumlanmış ve tartışılmıştır. Ayasofya'nın aydınlatma özellikleri, dini ve astronomik analojilerden yola çıkan bir hiyerarşik düzen çerçevesinde incelenmiştir. Bu yaklaşım, yan pencerelerin egemen olduğu ve gün ışığının eşit dağılımına dayanan tez ile karşılaştırılmıştır.

Sanat ve mimarlık tarihi alanlarındaki araştırmalar Ayasofya'nın aydınlatmasını niceliksel boyutta irdelemektedir. Ancak ışığın optik bir fenomen olarak niteliksel değerlendirilmesi, ve optik simulasyonun mekan algısına olan etkisi üzerine yapılmış çok az sayıda araştırma bulunmaktadır. Ayasofya'nın aydınlatmasının bazı yönleri zamanla değişmemiş ve binanın günümüze ulaşmış durumunda incelenebilir olsa da, taşıyıcı elemanlardaki destekleyici eklemeler ve kullanıma bağlı çeşitli değişiklikler, binanın özgün tasarımından farklılıklar yaratmıştır.

Bu çalışma, hem Ayasofya'nın seçkin mimarisinin gün ışığına olan katkılarını anlamak, hem de aydınlatmanın özgün tasarım ve günümüzdeki farklarını analiz etmek için planlanmıştır. Bu amaçla, binanın ikinci adamasının yapıldığı dönemdeki şekli bir rekonstrüksiyon modeli kullanılarak yeniden oluşturulmuş ve bilgisayar simülasyon yöntemi uygulanarak aydınlatma değerleri hesaplanmıştır. Binanın yakın dönemdeki durumu ise, iskelelerin olmadığı bir zaman diliminde, birkaç gün süren ve gün doğumundan gün batımına kadar toplanan piksel boyutunda ışıklılık (lüminans) değerleri ölçümleri ile kaydedilmiştir. Bu iki yöntem aydınlatmanın miktarı ve dinamik değişimini ayrıntılı bir şekilde analiz etmemizi sağlamıştır.

En gelişmiş bilgisayar simülasyon teknikleri kullanılarak, ayrıntılı mermer dekorasyon da dahil olmak üzere, mimari alanı çevreleyen yüzeylerin orijinal ışık yansıtma özellikleri, heykel ögelerinin orijinal yaldızları, ve optik olarak karmaşık altın mozaikleri aslına uygun olarak modellenmiştir. Simülasyonlar, farklı mevsimlerde, günün farklı saatlerinde, iki farklı güneş pozisyonunu analiz etmek üzere Noel sabahı ve Paskalya günü öğlen saati için bulutlu ve orta bulutlu gökyüzü koşullarında tekrarlanmıştır. Her pencere grubunun aydınlatmaya bireysel katkısı hesaplanmıştır. Ölçümlerin yapıldığı tarihlerde kaydedilen gökyüzü koşullarına ait değişkenler (parametreler) kullanılarak yapay bir gökyüzü modeli oluşturulmuştur. Elde edilen yapay gökyüzü ve rekonstrüksiyon modellerine dayanan simülasyonlar aracılığı ile 6. yüzyılda binadaki aydınlatma değerleri hesaplanmış ve günümüzdeki mekanda ölçülmüş aydınlatma değerleri ile karşılaştırılmıştır.

Genel olarak, zemin yüzeyde bulunan yansıtıcı beyaz mermerin, ışığın dağınık yansımasında önemli bir rol oynadığı gözlemlenmektedir. Güneşin Ayasofya'nın pencerelerinden biri ile aynı düzleme gelmesi sonucu ortaya çıkan "ışık havuzları", mermer ve mozaik yüzeylerde parlak yansımalar oluşturmakta ve iç mekanda ışık oyunlarına sebep olmaktadır. Güneşin hareketine bağlı olarak bu havuzların yer değiştirmesi ile dinamik bir aydınlatma elde edilmektedir.

Değişen güneş açıları ve bulut kapsamı göz önünde alınarak yapılan gün ışığı simülasyonu, tarihi ve günümüzdeki aydınlatma arasındaki farklılıkları ortaya çıkartmaktadır. Rekonstrüksiyon modelleme ile nef alanında beş kat daha yüksek aydınlatma seviyeleri saptanmıştır. Ayrıca, özgün tasarımda, koridorlar ve galerilerde bulunan pencereler daha yüksek oranda dağınık aydınlatmaya sebep vermektedir. Koridor ve nef alanındaki ışık dağılımı hiyerarşisi, günümüzde tespit edilen hiyerarşi ile zıtlık göstermektedir. Mermer, altın mozaik ve yaldızlı yüzeylerin yıllar içinde yıpranmamış durumları daha parlak yansımalara ve daha belirgin bölgesel ışıklılık kontrastına sebep olmaktadır. Rekonstrüksiyon modelinde kubbe, nef, koridorlar ve galerilerdeki tonozlar, altın mozaiğin tüm yüzeylerini kaplayan parlak yansımalar göstermektedir.

Antik dönemde üretilmiş pencere camlarının ışık saçılımına etkileri günümüzden farklıdır. Simülasyon sonuçları, farklı pencere gruplarının doğrudan güneş ışığı ve dağınık gökyüzü aydınlatması ile mozaik ve mermer üzerindeki speküler yansımalarının gökyüzü koşullarıyla değişen dinamik etkileşimini göz önüne açıkça sermektedir. Ölçümlerin aksine, rekonstrüksiyon modelde, kubbe pencerelerinden gelen ışık, kuzey-batı ana direğinin duvarlarında parlak bir ışık havuzuna neden olur.

Nef, farklı yönlerden ve birçok pencere aracılığı ile aydınlatılmaktadır. Galeriler ve koridorlardaki pencereler nef bölgesinin aydınlatılmasına önemli bir katkı sağlamaktadırlar. Noel sabahı, apsisteki pencereler de nefin aydınlatmasında benzer bir katkı oluşturur, ancak Paskalya'da bu etkinin azaldığı gözlemlenilmiştir. Güneş daha yüksek bir açı ile binaya ulaştığından, Paskalya'da nef üstündeki tonozlarda bulunan pencerelerden gelen ışık miktarı Noel'e göre çok daha fazladır.

Aydınlatma karakteri açısından, apsis ve sunak alanının binanın geri kalanından bağımsız olduğu gözlemlenilmiştir. Bu bölge, apsisteki pencerelerden ve yukarıdaki yarı kubbeden ışık alır. Sunak ve nefin merkezinin üç gün boyunca karşılaştırılması, sunak alanının genel olarak neften çok daha parlak olduğunu göstermiştir. Ortaya çıkan etki, sunak alanını vurgulayacak kadar büyüktür.

Ayasofya'nın boylamsal ekseninin yönü, Noel'de (kış gündönümünde) güneşin doğduğu yönde ufuk ile birleşir. Binanın yönlendirmesi, Noel sabah ayininde iç mekanın belirgin bir şekilde aydınlatılması planlanarak yapılmıştır. Güneş ışığı, binaya güney - doğudan, koridorlara ve galerilere paralel olacak şekilde düz bir açıyla girer. Işık batı duvarlarına, en belirgin olarak da, imparatorların girişindeki duvara çarpar ve göz kamaştırır. Diğer duvarlar, tonozlar ve amboda ışık seviyesi çok düşük olduğundan, bu yüzeyler pencerelerle yüksek kontrast oluştururlar. Yüzeylerin renk görünürlükleri azalır. Bu yüzeyler, Paulus Silentiarus'un tarif ettiği şekilde, mumlar ve kandiller aracılığı ile oluşturulan yapay aydınlatmanın etkisini daha dramatik hale getirmek için karanlık olarak tasarlanmışlardır.

Paskalya günü öğle saatinde, güneş açısı yüksek olduğundan, gün ışığı pencerelere doğrudan ulaşmaktadır. Parlak pencereler ve mozaiklerden parlak yansımalar ile bölgesel kontrastlar açısından zengin bir görsellik elde edilmektedir. Paskalya'da gözlemlenen parlaklık seviyeleri, Noel sabahına kıyasla çok daha fazladır. Duvar dekorasyonlarındaki yaldızlar ile altın mozaikler birbirlerini tamamlayan estetik elemanlar olarak öne çıkmaktadırlar.

Simülasyon çalışmaları ile Ayasofya'daki gün ışığını farklı saatler, günler ve aylarda incelenerek hem benzerlikleri, hem de farklılıkları araştırılmıştır. En tutarlı gözlem ışığın dinamizmidir. Geometrik olarak statik aydınlatma kaynakları (gökyüzünden gelen dağınık ışık), yöne bağlı olarak değişkenlik gösteren aydınlatma kaynakları (yüzey yansımaları ve güneşin ortaya çıkardığı ışık havuzları) ile karışarak zengin bir kompozisyon oluşturur. 6. yüzyılda bina çevresinin boş ve açık olması da gün ışığının binaya engelsiz ulaşımına olanak verdiğinden, rekonstrüksiyon modelinde gözlemlenen dinamizm günümüzden daha belirgindir.

Figure 1. Impression of the brightness and contrast in Hagia Sophia in the early morning on the day of its second consecration, Christmas 562.

Ayasofya'nın gün ışığı aydınlatması üzerine yapılan geçmiş araştırmalar, genellikle aydınlatmanın dinamik ve asimetrik karakterini yeterince vurgulamamışlardır. Görme sistemimizin parlaklığa olan adaptasyon yeteneğine tartışmalarda yer verilmemiştir. Düşük dinamik ölçekli fotoğraflama yöntemi ile kaydedilen görsellerde ise, bu ortamın ışık kaydetmedeki sınırlamaları hakkında eleştirel bir yaklaşım görülmemektedir. Bu makalede, Ayasofya'nin geç antik ve Bizans dönemindeki mimari özellikleri simülasyon tekniği ile hesaplanmış ve sonuçlar 6. Yüzyıl döneminden günümüze ulaşmış yorumlarla değerlendirilmiştir. Ayrıca, binanın 6. yüzyıl dönemindeki mimarisi ile günümüzdeki koşulları, simülasyon ve yüksek dinamik ölçekli fotoğraf yöntemi ile kaydedilen ölçümlerle karşılaştırılmıştır.

Anahtar Kelimeler: Gün ışığı, rekonstrüksüyon, simülasyon, Aya Sofya

INTRODUCTION

Complementing the introduction of challenges in daylight simulation, and potential methodical approaches to its application to historic states of buildings,[1] this article focuses on the results of the application of the proposed methods to Hagia Sophia. It provides an extract of a larger data-set of results and wider analysis of the day-lighting of Hagia

1 Lars O. Grobe et al., "Challenges in the simulation of the daylight distribution in late antique Hagia Sophia".

Sophia in its sixth-century state as part of the first author's doctoral dissertation.[2]

The current state of the building is well documented through the comprehensive survey by van Nice[3], its history through the extensive analysis by Mainstone.[4] Two important sources inform us of the primary state of the building: Procopius' *De Aedificiis*[5] and the detailed ekphrasis of Paulus Silentiarius.[6] The aforementioned sources guided a reconstruction of the building's state in the sixth century (after its re-erection following the damage of the earthquake in 557), which was translated into a 3D computer model.[7]

The day-lighting of the building has been interpreted from the perspective of Neoplatonic metaphysics of light. In analogy to the ecclesiastical and celestial hierarchies of the probably contemporary *corpus areopagiticum*, a hierarchical structure of lighting with darker aisles, narthex, and exonarthex, and brighter nave and cupola has been proposed.[8]

2 Andreas Noback, "Tageslichtsimulation verlorener Gebäudezustände am Beispiel der Hagia Sophia Justinians" (PhD diss. in preparation), Faculty of Architecture, Technische Universität Darmstadt, 2020.

3 Robert L. van Nice, *Saint Sophia in Istanbul: An Architectural Survey*, (Washington: Dumbarton Oaks, 1995).

4 Rowland J. Mainstone, *Hagia Sophia: architecture, structure and liturgy of Justinians great church*, (London: Thames & Hudson, 1988).

5 Procopius Caesariensis, *On Buildings,* trans. Henry Bronson Dewing and Glanville Downey, (Cambridge: Harvard University Press, 1940).

6 Procopius Caesariensis and Paulus Silentiarius, *Werke*, trans. Otto Veh, (München: Heimeran, 1977).

7 Oliver Hauck et. al., "Computing the 'Holy Wisdom'," *Scientific Computing and Cultural Heritage*, Contributions in Mathematical and Computational Sciences 3, ed.: Hans Georg Bock, Willi Jäger, and Michael J. Winckler. (Berlin: Springer, 2013) pp. 205–216; Grobe et. al., "Das Licht in der Hagia Sophia - Eine Computersimulation," *Byzanz - Das Römerreich im Mittelalter*, Vol. 2,1 Schauplätze, ed.: Falko Daim and Jörg Drauschke, (Mainz: Verlag des Römisch-Germanischen Zentralmuseums, 2010), pp. 97 – 111; Noback "Tageslichtsimulation verlorener Gebäudezustände am Beispiel der Hagia Sophia Justinians".

8 Nadine Schibille, *Hagia Sophia and the Byzantine Aesthetic Experience*, (Franham: Ashgate Publishing, 2014), p. 46 sqq.

Schibille has contrasted this view with the idea of an even distribution of daylight, dominated by the lateral windows. She compares the lighting of Hagia Sophia with other sixth century buildings. Schibille shows similarities with Sergios and Bacchus, often characterised as a prototype for the architecture of Hagia Sophia, and San Vitale in Ravenna, which was built a few years later.[9] All three are central-plan buildings, and were commissioned by Iustinian. Compared to earlier late antique architecture, e.g. Santa Costanza in Rome, they feature extensive fenestration on the sides and more even lighting levels between the sides and the centre.

Visual inspection of Hagia Sophia in its current state results in the impression that the galleries are more luminous than the nave, while the aisles appear generally darker. An important exception is the centre of the south aisle, when direct sunlight hits the windows in the afternoon. Sparse measurements of horizontal illuminance by Schibille are in line with this impression.[10] Earlier results of daylight simulation with the reconstruction model at TU Darmstadt suggest that illumination at the floor level had been more even in the sixth century before some of the buildings surrounding Hagia Sophia, and in particular its massive reinforcements, were added.[11]

Extensive luminance measurements over the course of several days by Inanici[12] allow a more detailed analysis of the illumination and its dynamic. The diffuse illumination benefits from the highly reflective marble floor, especially in the aisles and galleries. "Pools of light" originating from multiple windows, and glossy reflections in the marble and the mosaics contribute to the play of light.

9 Schibille, *Hagia Sophia and the Byzantine Aesthetic Experience*, p. 87 sqq.

10 Nadine Schibille, "Light as an aesthetic constituent in the architecture of Hagia Sophia in Constantinople," *Manipulating light in premodern times: Architectural, artistic, and philosophical aspects*, ed.: Vladimir Ivanovici and Daniela Mondini, (Mendrisio: Mendrisio Academy Press, 2014), p. 34.

11 Grobe et. al., "Das Licht in der Hagia Sophia - Eine Computersimulation," p. 109.

12 Mehlika İnanıcı, "Lighting Analysis of Hagia Sophia," *Annual of Hagia Sophia Museum*, Publications of the Hagia Sophia Museum 17 (Istanbul: Directory of the Hagia Sophia Museum, 2014), p. 166–202.

OPEN RESEARCH QUESTIONS AND OBJECTIVES

The ample analysis of lighting in the fields of art and architectural history is contrasted by only a few attempts of quantitative research on light as a phenomenon of optics, and a stimulus for human response. The authors propose that anecdotal evidence of individual impressions has to be complemented with systematic measurements and analysis of the luminance distributions and spatial contrast and their impact on perception, as well as the contribution of translucent and reflective materials and the multitude of windows in the building. Particular care is necessary to account for the dynamic aspects of day-lighting over the course of days and seasons. External effects such as the surroundings and weather conditions have to be inspected. Of particular interest in the analysis of the artistic intentions are the probable differences between the current and the original state of the building.

This research shall compare previous luminance measurements of the sky and in the building, with simulations based on the reconstruction model and an artificial sky model parameterised to fit the appertaining sky conditions. It further utilises the reconstruction model to inspect the lighting of the building in the state of the sixth century under various daylight conditions, and study the contributions of interior materials and different groups of windows.

RECONSTRUCTION

Mainstone's analysis revealed that the current state of the building differs from that of the year 562 with respect to Byzantine and Ottoman additions in the interior, and surroundings. The massive structural reinforcements obstruct daylight, and particularly occlude the windows in the aisles, the galleries, and to some extent in the vaults. Figure 5provides an overview. Of the building windows that have been closed or reduced in area, most prominent differences are in the tympanum walls. Subsequent re-constructions of the dome have altered the size and position of its windows in the east and in the west. The model reverts all these alterations, and adds a reconstruction of the liturgical architecture based on Paulus' description. It is important to restore the optical properties of the transparent and the reflective surfaces to study the light distribution inside the building, but even more importantly, the visual impression of the lighting and the visual effects. This task entails proper models of window glass, the different marble varieties, and gold mosaics. A systematic reconstruction of the wall decoration has to include the gilding of its sculptural elements as described by Paulus. Figure 6 shows an exemplary overview of the structure of the wall decoration at the main and secondary pillars.[13] Accounting for the appearance of detailed elements such as opus sectile, and fine-structured materials such as the gold mosaics or marble, requires an integrated approach to geometric and material modeling.

SIMULATION

The simulation method follows the principles given in the accompanying paper.[14] The simulation environment was parameterised for seven time-steps over the course of three days: Christmas (few days before the winter solstice), Easter in the year 564, and St. John's day (close to the summer solstice). These dates were chosen to provide different lighting conditions, and to analyse the day-lighting on important days for the building's initial use. Timestamps follow temporal hours; i. e. the time from sunrise to sunset is divided into twelve hours, leading to hours of varying length, but corresponding with the liturgical practice in the sixth century.

Models of an intermediate sky were generated for each timestamp with the Radiance gensky program. For some timestamps, the simulation was repeated with clear and overcast skies according to the Commission Internationale de l'Eclairage's (CIE's) standard.[15]

The window glass is represented by a model fitted to the measurement of blown Roman window glass from the Rhineland. A clear float glass was used for comparison. The models of the marble materials are

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13 Noback "Tageslichtsimulation verlorener Gebäudezustände am Beispiel der Hagia Sophia Justinians" provides a comprehensive depiction and analysis of the wall decoration in the nave, altar and apsis, the model includes the galleries and aisles.

14 Lars O. Grobe et al., "Challenges in the simulation of the daylight distribution in late antique Hagia Sophia".

15 Commission Internationale de l'Eclairage, *Spatial distribution of daylight,* (CIE *003/E-1996*).

based on photographs and light scattering measurements on glossy and matte surfaces of modern samples. Parameters of the reflection models of gilded surfaces and silver objects were set according to literature values. The model for the gold mosaic is based on measurements on a modern sample, and parameterised for size and variation of the surface orientation in accordance with in-situ observations. To further analyse the contributions of different sets of windows to the illumination, and the effect of the marble floors and the gold mosaic on the indirect illumination, theses surface models and window glass were selectively replaced with opaque or black variations and the simulations were repeated.

The simulation resulted in sets of High Dynamic Range (HDR) images in orthogonal and perspective projections. These images comprise distributions of luminance and illuminance encoded in pixel values. Perspective views were visualised for a human response of contrast and brightness.

COMPARING MEASUREMENTS OF TODAY'S DAY-LIGHTING TO SIMULATIONS BASED ON THE RECONSTRUCTION

HDR measurement of the interior resulted in luminance distributions recorded in HDR images. The camera optics, forming a fish-eye projection, maximised the field of view. These measurements are correlated with HDR acquisition of the sky conditions at the same time. Additional measurements of horizontal illuminance at the centre of the nave, and Global Horizontal Illuminance (GHI) on an almost unobstructed nearby rooftop were provided. The interior data were used for the comparison; while outdoor measurements guided the parameterisation of the the sky model for the simulation.

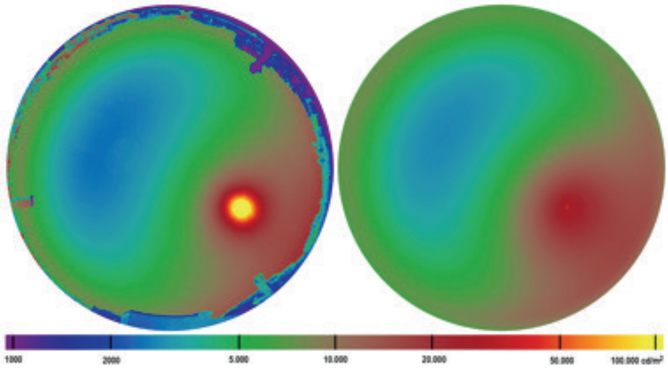

Figure 2. Luminance distribution of the clear sky model with sun (left) in comparison to the measurement (right) for Sept. 24. 13:00 EEST. The orientation of the model is along the building's axis, the apsis is at the bottom. The sun appears larger in the HDR measurement. Source: Inanici 2014, p. 172 (right).

According to the sky conditions a *sunny sky* model was chosen. It is parameterised by time and location, ground reflection, and a *turbidity factor* that reflects the scattering by dust and vapour in the atmosphere. The last two parameters are estimated. Ground reflection was set to the default value of 0.2, while the *turbidity factor* (5) was iterated until the computed Global horizontal Illumination (GHI)[16] and the luminance distribution (Figure 2) approximate the measurements:

	Global horizontal Illumination
Measured	86,500 lx
Computed from Simulation	76,488 lx
Deviation	13 %

RESULTS OF THE COMPARISON

The simulation resulted in distinct higher levels of illumination in the centre of the nave then the measurement:

	Illuminance E_V
Measurement	48 lx
Computed from Simulation	280 lx

16 Greg Ward Larson et al., *Rendering with Radiance: The art and science of lighting visualization,* (San Francisco: Morgan Kaufmann, 1998), p. 357.

The overall higher luminance values in the fish-eye views predicted with the simulation, when compared to the measurements (Figure 7), reveal further details:

- The windows in the south and north aisles are significantly brighter. High luminances extend to their reflections in the gold mosaic of the vaults above them. This is also observed with the windows on the east wall.
- The vaults in the galleries show similar, bright reflections.
- The hierarchy of luminance distributions between the nave and the aisles is reversed. The overall impressionfrom the simulated image favors a continuous space, in which the windows in the aisles appear as part of the main room.
- Dome and pendentives that are entirely covert with gold mosaic show bright reflections in the simulation. The windows of the dome including the bright adjacent vaults are prominently visible.
- Semi-domes, the domes of the exedra, and prominently the semidome of the apsis show significant contrast and bright reflections.
- The undersides of the circumferential cornices that appear dark in the measurements are less accentuated and show small bright reflections in the simulation.
- The à jour work of the framings, capitals, and archivolts, that are gilded in the simulation, show bright reflections, similar to the Venetian dentils.
- The contrast in the marble decoration is visibly enhanced.
- Light from the dome's windows results in a bright light pool on the walls of the north-west main pillar. No distinct pool of light is visible in the HDR measurements. The probable cause is translucent glass in the modern fenestration of the corresponding windows.

CONTRIBUTIONS OF DIFFERENT WINDOW GROUPS

For a better understanding of the lighting mechanisms, window groups were independently simulated to ascertained their contributions. In each of the simulations, all other window panes were replaced by an opaque material. The simulations were repeated for Christmas morning and midday Easter to analyse two different solar positions at different times of the day in different seasons. A sunny standard sky with intermediate cloudiness was chosen. Each window group's individual contribution to the illumination (E_V), and the percentile contribution was computed from the results for the centre of the nave and on top of the altar:

	Nave				Altar			
	Christmas		Easter		Christmas		Easter	
Window Group	**E_V [lx]**	**%**	**E_V [lx]**	**%**	**E_V [lx]**	**%**	**E_V [lx]**	**%**
Apsis incl. dome	2,2	21,9	5,9	6,9	37	87,8	331	92,5
Dome	1,2	11,9	13	15,1	1,3	3,1	6	1,7
Galleries & Aisles	3,5	34,8	33	38,4	2,8	6,6	10	2,8
Tympanon wall	0,7	7,3	11	12,8	0,2	0,5	3	0,8
Semidomes & Exedrae	1,5	14,9	12	14	0,5	1,3	4,6	1,3
West wall	0,9	9,2	11	12,8	0,3	0,7	3,4	0,9
Sum	**10,1**		85,9		42,1		358	

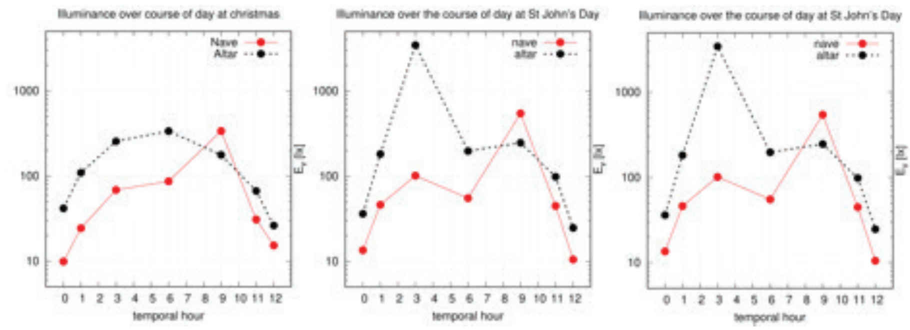

Figure 3. Comparison of computed illuminance (EV) at the centre of the nave and the altar over the course of the day in temporal hours at Christmas (left), at Easter (centre) and at St John's Day (right).

The illumination of the nave receives a significant contribution from the windows in the galleries and aisles. On Christmas morning, windows in the apsis account for a similar contribution, but to a lesser extent at mid-day Easter. Windows in the vaults over the nave provide similar contributions to both daylit scenes. The dome contributes more at Easter when the sun stands at a higher altitude. Overall, the nave receives direct light from many directions of the sky corresponding with the distribution of the many windows in the building.

The contributions to the illumination of the altar show that the apsis and altar area is independent from the rest of the building. It receives light nearly exclusively from the windows in the apsis and its semi-dome above.

COMPARISON OF THE ILLUMINATION OF THE ALTAR AREA AND THE NAVE

A comparison of the altar and the centre of the nave over the course of three days shows that the altar area is in general significantly brighter lit than the nave (Figure 3). The effect is large enough to accentuate the altar area. This rule is only broken when pools of direct light wander through the centre of the nave.

CHRISTMAS MORNING AND THE ORIENTATION OF THE BUILDING

The orientation of Hagia Sophia's longitudinal axis intersects the horizon at the point where the sun rises at Christmas, i. e. at the winter solstice. It is hard to imagine that this is by coincidence, and corroborated by the fact that the orientation differs from its surroundings.[17] The orientation affects a distinct illumination of the interior at the time of a morning mess. Direct light enters the building from the east at a very flat angle and parallel to the aisles and galleries. The light hits the western walls, most prominently the wall over the emperors' entrance, and dazzles the entering congregation. Other walls, the vaults, and the ambo are sparsely lit, leading to high contrast to the windows and reduced colour visibility. The darkness in the building probably pronounces the effect of artificial illumination by candles and oil lamps, as described by Paulus. An outstanding effect is due the octagonal pyramid, that forms the roof of the ciborium. It reflects direct daylight to the semi-dome of the apsis, where it is scattered by the gold mosaic (Figure 1, Figure 4 (top)).

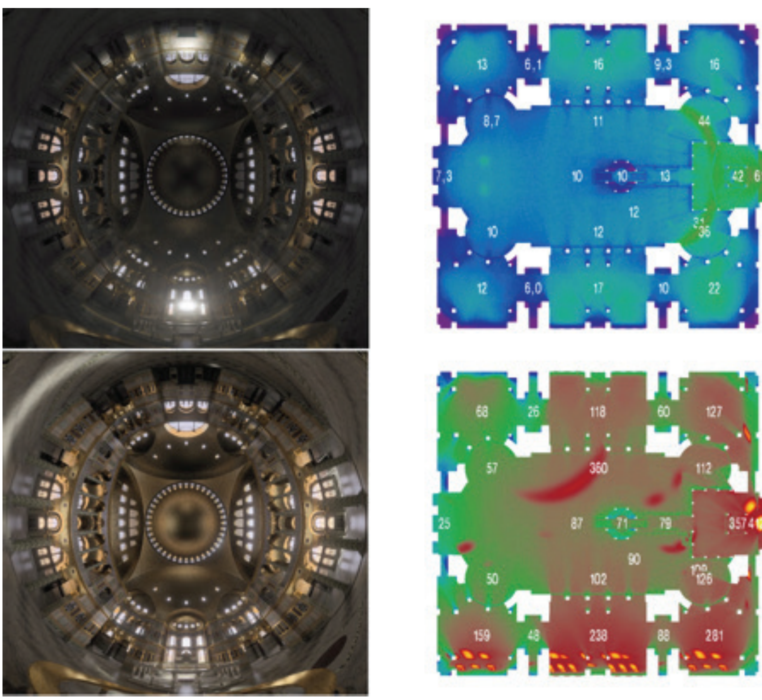

Figure 4. Fish-eye images adjusted for human response and illuminance (EV [lx]) of the ground floor at Christmas morning (top) and mid-days at Easter (bottom).

17 Nadine Schibille, "Astronomical and optical principles in the architecture of Hagia Sophia in Constantinople," *Science in Context,* 22.01 (2009), p. 27–46.

MIDDAY AT EASTER

Mid-day at Easter was selected as a timestamp to evaluate lighting at higher solar altitudes. The visualisation of brightness and contrast impression shows a similarity to the simulation results in the comparison above. Unobstructed windows and many golden glossy reflections dominate the scene. The overall impression is bright and rich of local contrast. Contrast between the windows, and the walls and vaults is reduced. The latter appear brighter in comparison to the scene at Christmas morning. The gilding of the sculptural elements of the wall decoration corresponds with the gold mosaic leading to a more continuous aesthetic (Figure 4 (bottom)).

THE DYNAMIC DAYLIGHTING OF HAGIA SOPHIA

Simulation results over the course of days, and over the seasons of the year reveal some similarities and many variations of the daylighting of Hagia Sophia. Dynamism is the most constant observation. Geometrically static lighting elements, e.g. diffuse light from the sky, are mixed with view dependent elements such as the reflections of windows in the mosaics, and bright pools of direct light that depend on the sun's position. The latter modulate the diffuse reflection of light by floor and vaults. The variability of sky conditions, and the short-term dynamic of a partly cloudy sky on a windy day cannot be captured by the static standard sky models, but only imagined based on the results. The aesthetic effects of glossy surfaces and unobstructed windows of the building in its original state depended on, or was or was enhanced with the dynamic conditions of daylight.

CONCLUSION AND FURTHER RESEARCH

The complete data-set allows a comprehensive analysis that includes the examination of the influence of scattering by the window glass, indirect light distribution by the marble floor and the gold mosaics of the vaults. It allows to explore standard clear, overcast, and intermediate skies or the measurement–based dynamic conditions over multiple days of the year. Consequently, it can serve as a groundwork for a more detailed analysis, and can be extended for more specialised interest. The Darmstadt model of Hagia Sophia, having evolved over the course of 20 years, lends itself to further improvements and research.

Daylight simulation based on the reconstruction of geometry and surface properties can provide a significant contribution to the research of the artistic means of architecture and interior decoration, and to the interpretation of lighting in religious and social contexts. In the case of Hagia Sophia, it reveals that lighting was similar to that in other buildings of the sixth century, in which light from windows in the sides contributed significantly. The accentuation of the altar area fits this context. A hierarchical understanding of lighting, e.g. from the dome down to the floor or from the centre to the sides, is hindered by this contribution and cannot be confirmed. Additionally, the reconstruction of the glossy surfaces of the marble decoration and the gilded sculptural elements complement the gold mosaics of the vaults to a more continuous visual appearance of the interior decoration.

The discussion of day-lighting in literature generally underestimates the dynamic and asymmetric nature of Hagia Sophia's lighting. It often lacks an understanding of human response to brightness, and refers to photographic images without a critical discussion of the limitations of this medium. A juxtaposition of these simulation results with existing interpretations and architectural developments around the sixth century promises an enhanced understanding of day-lighting in late antique and Byzantine architecture. However, the most interesting direction for further research may be the augmentation of the model with a reconstruction of the artificial lighting according to the description of Paulus Silentiarius.

Figure 5. Daylight obstructions and later additions at the galleries (top) and the ground floor (bottom): structural reinforcements before (red) and after 562 (green), Byzantine (black) and Ottoman (blue) exterior additions, and later additions.

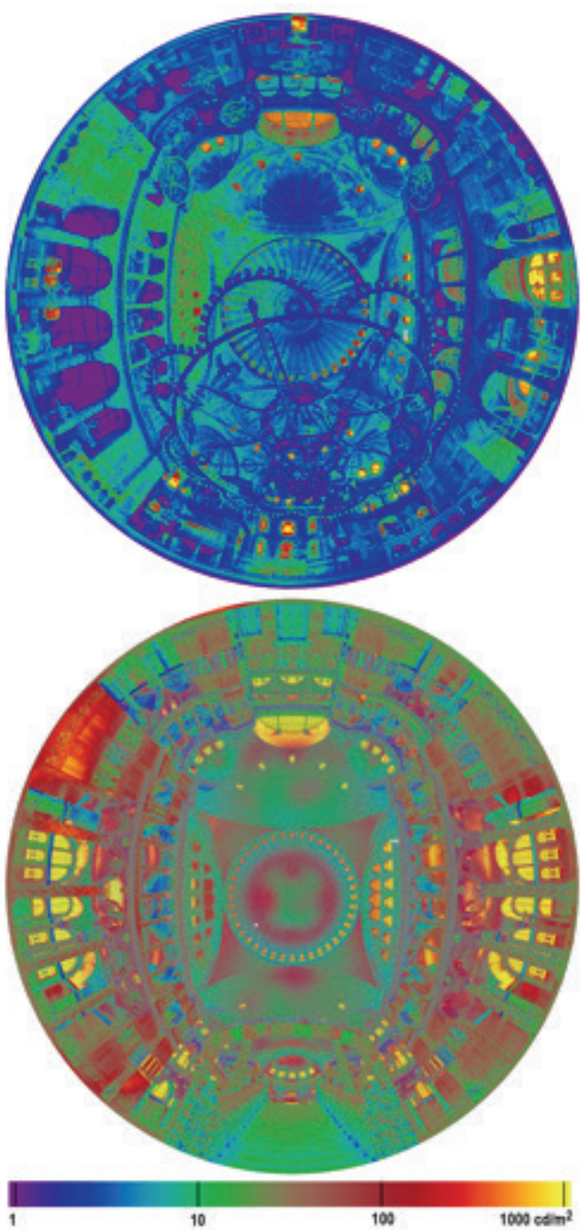

Figure 6. Structure of the wall decoration at the main and secondary pillars with marble varieties.

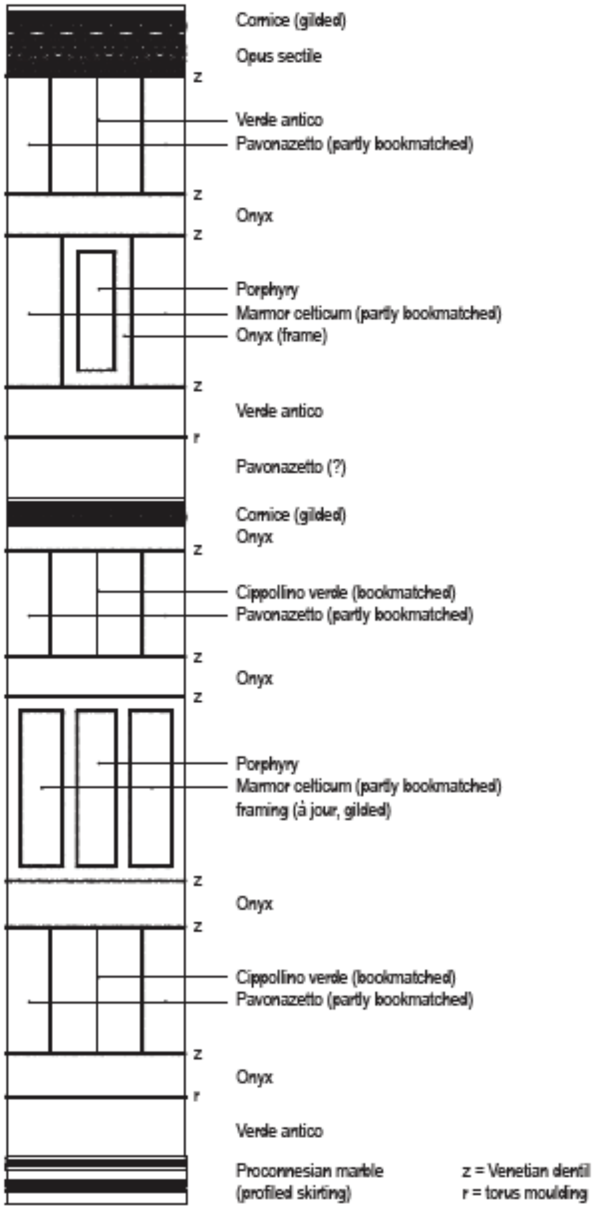

Figure 7. Comparison of the luminance in fish-eye projection in the centre of the nave in the reconstruction (left) and today (right). Source: Inanici 2014, p. 172 (right).