Modeling the effects of daylight scattering by window glass

The case of 6th century Hagia Sophia in Istanbul

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TECHNISCHE UNIVERSITÄT DARMSTADT

Objectives
Daylight simulation in building history

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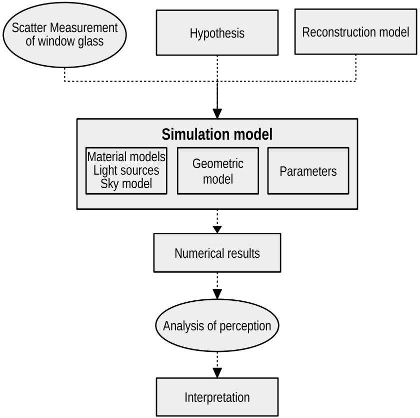

- Develop a method to assess perception of lost or modified building interiors under natural illumination
- Account for the light scattering properties of glazing affecting the spatial distribution of admitted daylight
- Evaluate importance of illumination for the perception of interiors
- Apply the method to a model of 6th century Hagia Sophia to demonstrate its applicability

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Section 1

Glazing and daylight in Hagia Sophia

Hagia Sophia, Istanbul, today

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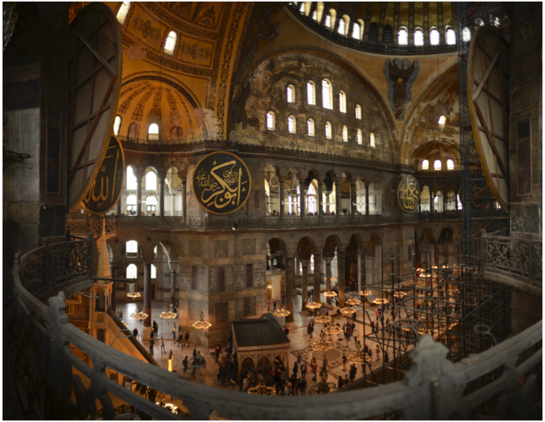

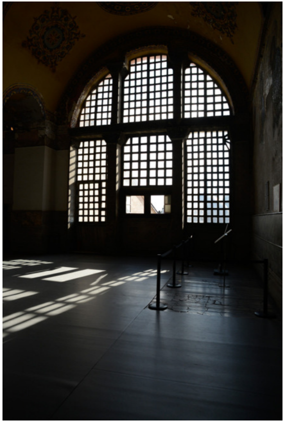

Roman window glass
Exemplary samples

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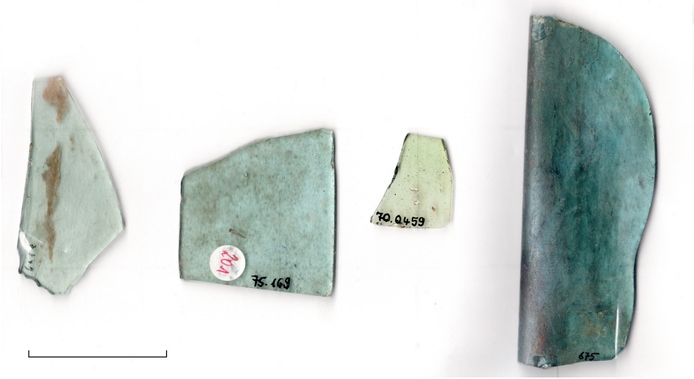

l = 50 mm

A plausible glazing type for Hagia Sophia

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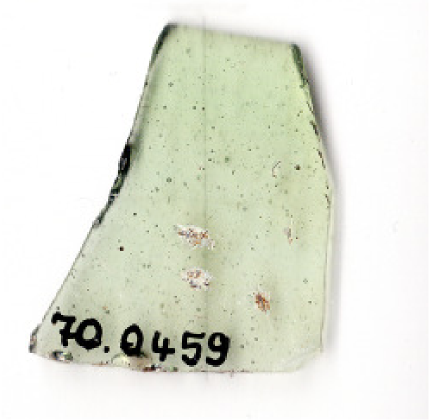

- Blown window-glass
- Type of glass that can be expected in the entire Roman empire starting from the end of 2nd century AD
- Origin of this sample is Northrine-Westfalia (Germany) - our assumption that glass-making techniques at this time were similar has to be backed by future research
- Are there samples of glass that can be directly associated to Hagia Sophia?

Geometry causing light scattering

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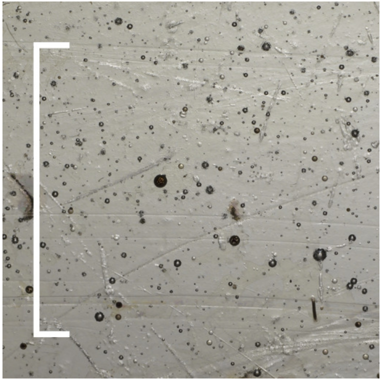

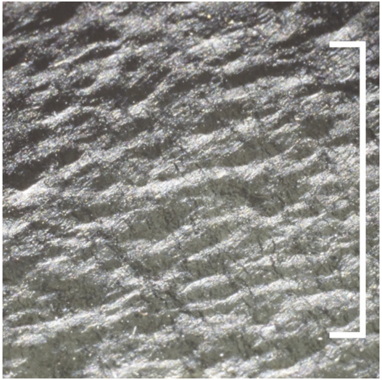

$l = 10mm$

Employed coordinate system

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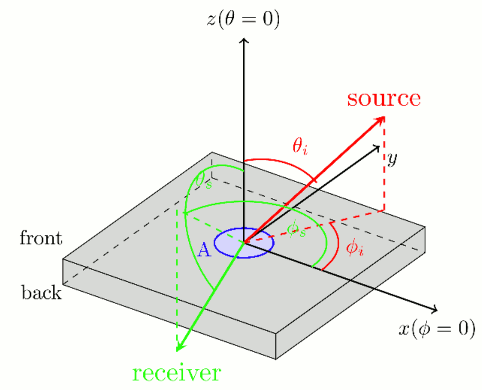

- Scattering is a function of incident (i, to light source) and scattered (s, to receiver) directions
- Directions written spherical coordinates $\theta_i, \phi_i, \theta_s, \phi_s$)
- Defined for any pair of incident and outgoing directions
- Measurement samples this continuous functions at a given directional resolution

Asymmetric resolution in light scattering measurement

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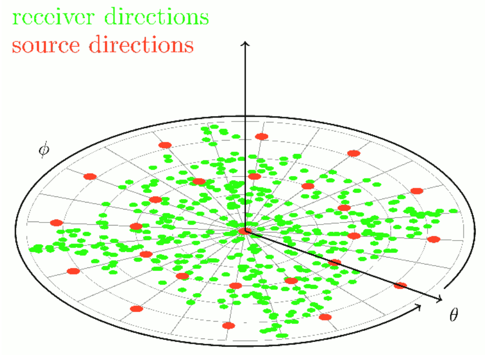

For a set of few incident directions (red), the outgoing distributions (green) are captured at high resolution.

Assumptions:

- Assumption: Outgoing distribution changes only gradually with varying incident direction
- High resolution of random outgoing directions to capture e.g. sharp peaks (transparency, mirror-like reflection) *typical range: 150,000 to 250,000 directions*
- Low resolution of incident, regular directions (*typical: 145 directions for anisotropic, 9 for isotropic samples*)

Instrumentation

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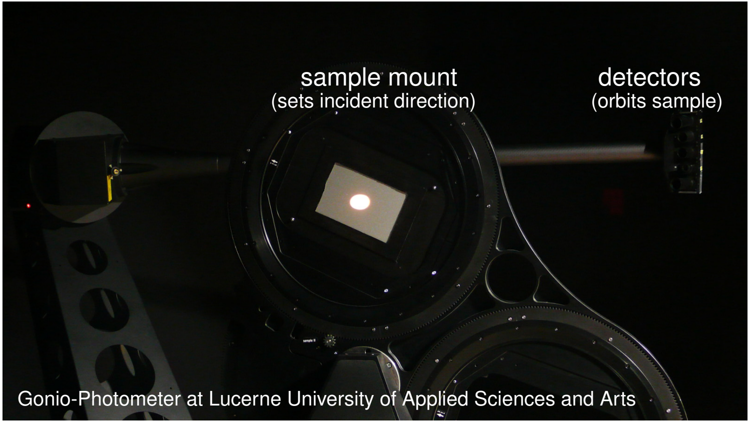

Scanning of scattered light

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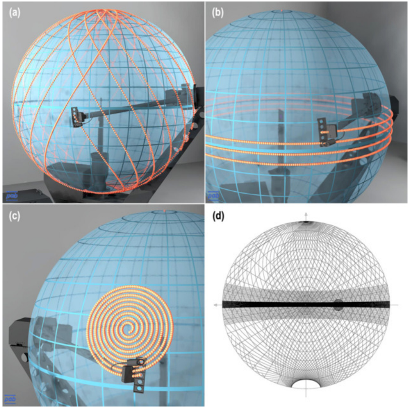
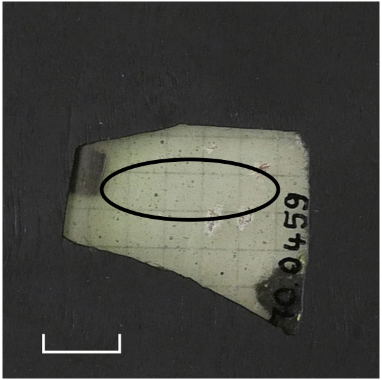
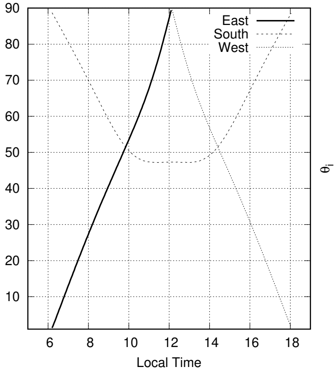


- Full scan (a) records diffuse background and locates peak directions
- In-plane scan (b) refines measurement of pure upward or downward deflection
- Peak scan (c) refines measurement at peaks
- Projected data-points from scans for one incident direction (d)

(a-c): Image courtesy pab advanced technologies Ltd, Freiburg, Germany.

Geometric limitations of measurements
Extension of sampling aperture





$$\tan(\theta_i) = \sqrt{\tan(h)^2 + \tan(a + 90)^2} \quad (1)$$

Section 2

Modeling light scattering by window glass

Data-driven model

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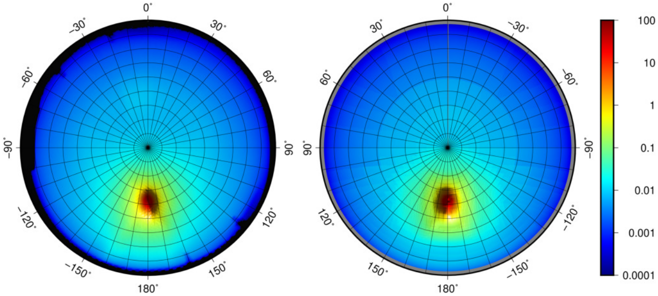

Transmission distribution (Differential Scattering Function, DSF) for one incident direction θ_i = 30 degree as measured (left) and predicted by model (right).

- Direct use of measurement data
- Example based on 7 incident directions θ_i = 0 to 70 degrees
- General approach, can replicate any reflection and transmission properties
- Interpolation for incident directions that were note measured
- Unfortunately there is no general method for extrapolation!

Fitting an mathematical model

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Radiance `trans`-model:

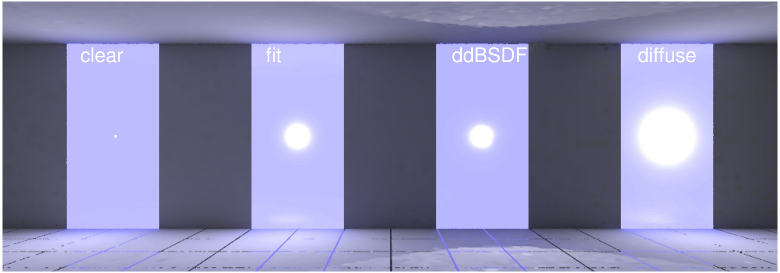
- Extends reflection-model by Ward, Dür, Geisler-Moroder to transmission
- Defined for any pair of incident and outgoing direction
- Physically plausible if parametrization within defined range
- Combines constant, diffuse background with Gaussian peak t_s

$$t_s(\theta_i, \phi_i, \theta_s, \phi_s) = \frac{\exp\left(\left(2 \cdot (\vec{i}, \vec{t}) - 2\right) / \alpha^2\right)}{\pi \cdot \alpha^2 \cdot \sqrt{\cos(\theta_i) \cdot (-\cos(\theta_s))}} \tag{2}$$

- Model fit to measured data (2D, only profiles along constant ϕ_i)
- For details please refer to Grobe et al. Transfer of measured transmission distribution data into Radiance. 9th Radiance Workshop, Freiburg, 2010.

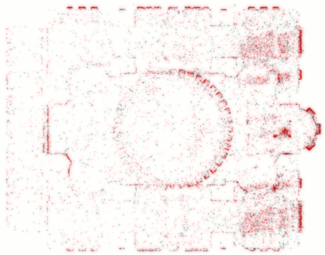
Visual appearance
Four transmission models in Radiance

- clear: `glass` model, no scattering
- fit: fit of the `trans` model to measured BSDF
- ddBSDF: data-driven BSDF model compiled from measurement
- diffuse: diffuse `trans` model



Bidirectional modelling of light transport Forward photon-mapping and backward ray-tracing

- Radiance backward ray-tracing provides realistic imagery
- Optically complex geometry and reflection properties challenge ray-tracing
- Combining forward (photon-mapping) and backward (ray-tracing)
- Radiance Photon-Map extended to replicate specular reflection of sources



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Section 3

Effects on illuminance distribution

Plan view, illuminance
Model fit to measurement

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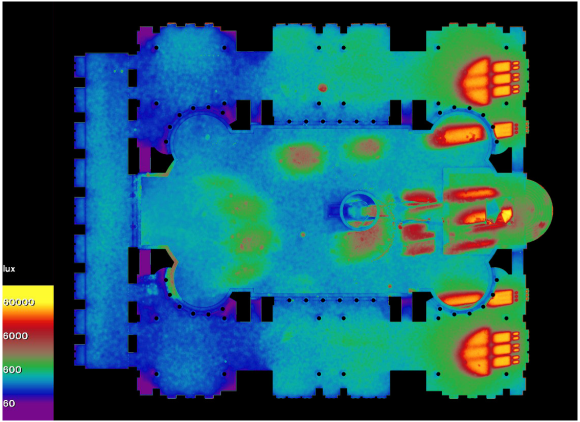

Plan view, illuminance
No scattering

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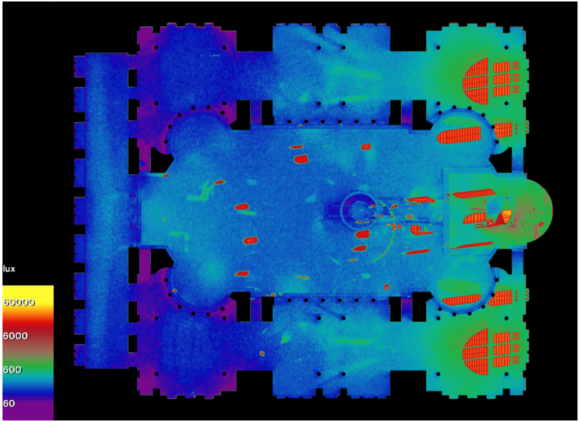

Plan view, illuminance
Diffuse scattering

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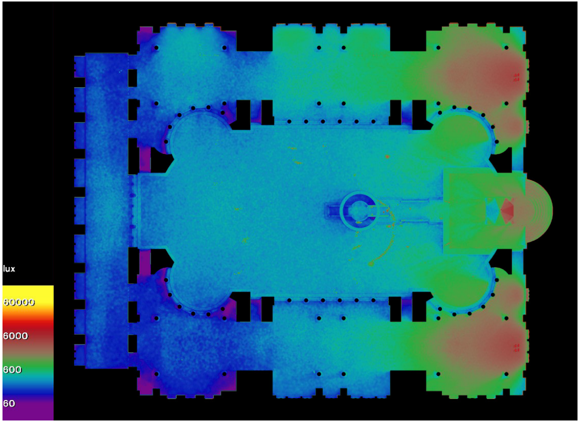

Section 4

Effects on visual perception of the interior

Plan view, luminance, sunny and overcast sky
Model fit to measurement

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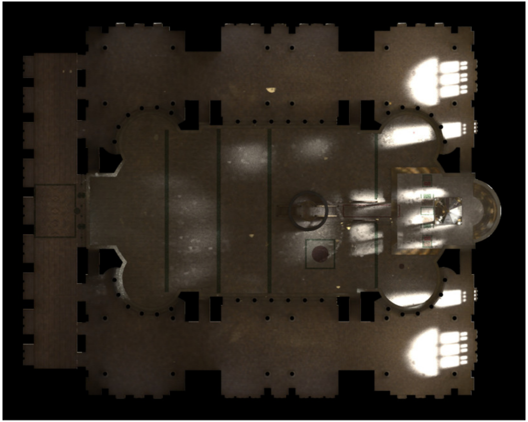

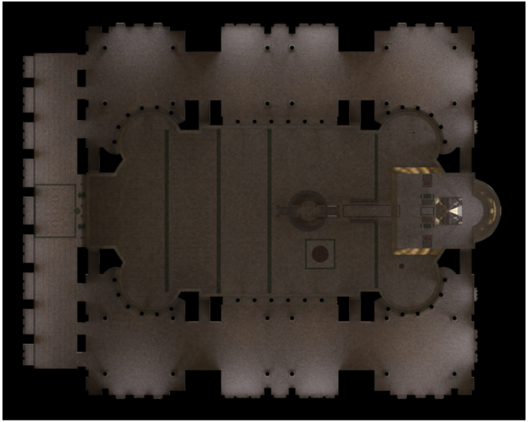

Perspective view, perception model
Model fit to measurement

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Perspective view, perception model
No scattering

Perspective view, perception model
Diffuse scattering

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Entrance wall, perception model
Model fit to measurement

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Entrance wall, perception model
No scattering

Entrance wall, perception model
Diffuse scattering

Contours of directly illuminated regions, Comparison of three glazing types

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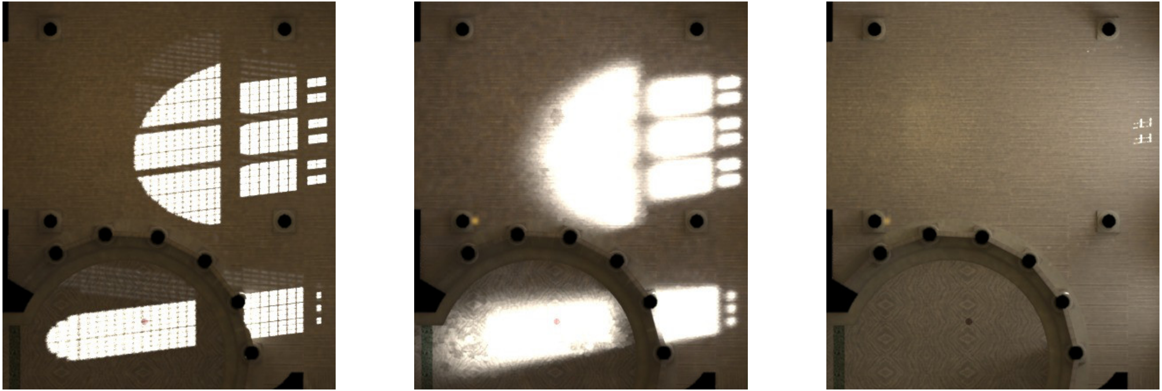


Left to right: No scattering, model fit to measurement, diffuse scattering.

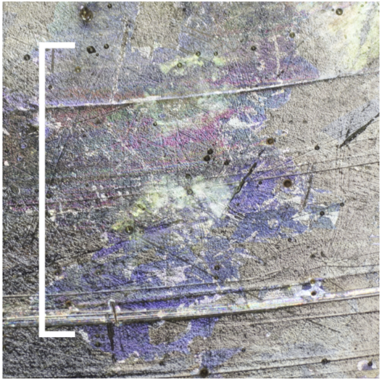
Perception of depth and surface relief
Comparison of three glazing types

Left to right: No scattering, model fit to measurement, diffuse scattering.

Section 5

Conclusion and future research

Limitations



$l = 10mm$

- Incident light at grazing angles is extrapolated in the model and could not be compared to measurements.
- The impact of ageing can not be quantified as a source of error at this stage.
- Our knowledge about the properties of window glass of Hagia Sophia in the 6th century is limited.

Conclusions

- The scattering properties of window glass have a relevant impact on the daylighting of Hagia Sophia in the 6th century and very likely on other antique and late antique buildings.
- The scattering properties of windows glass is a worthwhile new field of glass research as it has implications for the functional and stylistic development of historic architecture.
- The method is a means to study the impact of such scattering properties including the aspect of perception.

Future research

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- Measurement of a sufficient amount of samples to estimate the range of optical properties of Roman window glass. This includes the modification of the instrumentation to measure small samples and the advancement of modelling techniques.
- A case study comprising a building that can be reconstructed with sufficient probability and that can be closely associated with found window glass. This includes the advancement of simulation methods for historic interiors with complex material and spatial properties.
- An in-depth analysis of most important geometric parameters affecting light scattering. This includes effects of ageing as error source.

Thank you for your attention! For further information and contact:

http://www.archaeologie.architektur.tu-darmstadt.de

http://www.hslu.ch/ccease

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