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Daylighting simulation: methods, algorithms, and resources

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Daylighting Simulation:

Methods, Algorithms, and Resources

William L. Carroll

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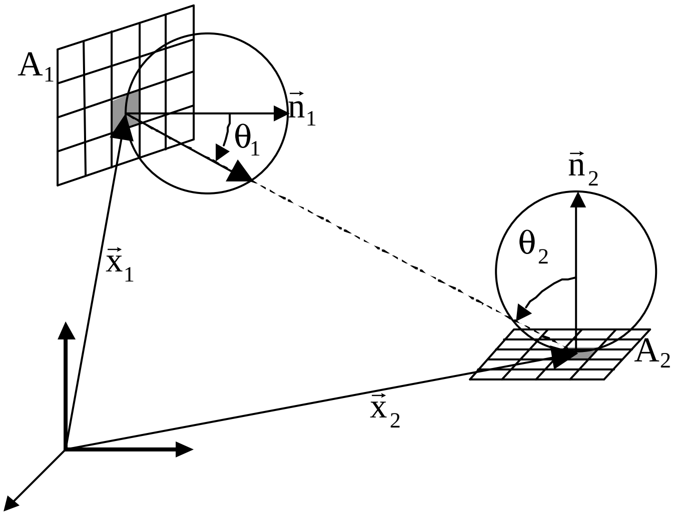

International Energy Agency

Energy Conservation in Buildings and Community Systems Programme

INTERNATIONAL ENERGY AGENCY
Solar Heating & Cooling Programme

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Solar Heating and Cooling Programme Task 21 /

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PREFACE

The main objectives of the IEA Solar Heating and Cooling Programme (SHC) Task 21 and the Energy Conservation in Buildings and Community Systems Programme (ECBCS) Annex 29 "Daylight in Buildings" are to advance daylighting technologies and to promote daylight conscious building design. Task 21 continues until December 1999, and will endeavour to overcome the barriers that are impending the appropriate integration of daylighting aspects in building design. The participants in this task are Australia, Austria, Belgium, Canada, Denmark, Finland, France, Germany, Italy, Netherlands, New Zealand, Norway, Sweden, Switzerland, United Kingdom and the United States. Denmark is the Operating Agent.

The objective of Subtask C "Daylighting Design Tools" of Task 21 is to improve the capability, accuracy and ease-of-use of daylighting design and analysis tools for building design practitioners, covering all phases of the design process. The practitioners will be able to predict the performance of different daylighting systems and control strategies and to evaluate the impact of the integration of daylighting in the overall building energy concept by using these design tools. Subtask C is divided into 5 Subgroups:

C1: Validation
C2: New Daylight Algorithms
C3: Integrated Systems
C4: Simple Design Tools
C5: ADELINE 3.0.

This report, "Daylighting Simulation: Methods, Algorithms, and Resources" was initiated and compiled within Subgroup C2.

EXECUTIVE SUMMARY

This document presents work conducted as part of Subtask C, ’’Daylighting Design Tools“, Subgroup C2, ’’New Daylight Algorithms“, of the IEA SHC Task 21 and the ECBCS Program Annex 29 ’’Daylight in Buildings“.

The search for and collection of daylighting analysis methods and algorithms led to two important observations. First, there is a wide range of needs for different types of methods to produce a complete analysis tool. These include:

- Geometry
- Light modeling
- Characterization of the natural illumination resource
- Materials and components properties, representations
- Usability issues (interfaces, interoperability, representation of analysis results, etc)

Second, very advantageously, there have been rapid advances in many basic methods in these areas, due to other forces. They are in part driven by:

- The commercial computer graphics community (commerce, entertainment)
- The lighting industry
- Architectural rendering and visualization for projects
- Academia: Course materials, research

This has led to a very rich set of information resources that have direct applicability to the small daylighting analysis community. Furthermore, much of this information is in fact available online.

Because much of the information about methods and algorithms is now online, an innovative reporting strategy was used: the core formats are electronic, and used to produce a printed form only secondarily. The electronic forms include both online WWW pages and a downloadable .PDF file with the same appearance and content. Both electronic forms include live primary and indirect links to actual information sources on the WWW. In most cases, little additional commentary is provided regarding the information links or citations that are provided. This in turn allows the report to be very concise. The links are expected speak for themselves. The report consists of only about 10+ pages, with about 100+ primary links, but with potentially thousands of indirect links. For purposes of the printed version, a list of the links is explicitly provided.

This document exists in HTML form at the URL address:

- *http://eande.lbl.gov/Task21/dlalgorithms.html*

An equivalent downloadable PDF version, also with live links, at the URL address:

- *http://eande.lbl.gov/Task21/dlalgorithms.pdf*

A printed report can be derived directly from either of the electronic versions by simply printing either of them. In addition to the live links in the electronic forms, all report forms, electronic and paper, also have explicitly listed link addresses so that they can be followed up or referenced manually.

CONTENTS

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INTRODUCTION

The purpose of these WWW pages is to provide a dissemination mechanism for information on daylighting methods, algorithms and related resources and documentation. This information is being identified, collected, and referenced here as one of the IEA Task 21 activities, as described in the formal work statement below.

Objective: To coordinate the country development activities, and to document and disseminate algorithms for the simulation of the performance of daylighting and control systems.

Methods: (1) Survey activities/needs. (2) In conjunction with Subtasks A and B, develop algorithms and models for selected systems. (3) Establish and maintain a system of electronic information exchange on daylighting simulation methods and algorithms.

Milestones / results: An electronic information exchange system on daylighting algorithms, based on WWW pages, is being developed. Current links to algorithm sets are below.

Observations on Available Information

After several years of searching for and identifying information useful for this effort, the following observations have emerged, which have consequences for the amount and usefulness of the information colleted, and the format in which it is reported.

First, there is a wide range of needs for different types of methods to produce a complete analysis tool. These include:

- Geometry
- Light modeling
- Characterization of the natural illumination resource
- Materials and components properties, representations
- Usability issues (interfaces, interoperability, representation of analysis results, etc)

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Report Approach

Because much of the information about methods and algorithms is now online, an innovative reporting strategy was used: the core formats are electronic, and used to produce a printed form only secondarily. The electronic forms include both online WWW pages and a downloadable .PDF file with the same appearance and content. Both electronic forms include live primary and indirect links to actual information sources on the WWW. In most cases, little additional commentary is provided regarding the information links or citations that are provided. This in turn allows the report to be very concise. The links are expected speak for themselves. The report consists of only about 10+ pages, with about 100+ primary links, but with potentially thousands of indirect links.

This form has other benefits: It is easily maintainable and evolvable, and has ongoing availability to anybody that wants to access it. Most importantly, updated information at the linked sites is automatically available.

This document exists in HTML form at the URL address: http://eande.lbl.gov/Task21/dlalgorithms.html [1], and an equivalent downloadable PDF version, also with live links, at the URL address: http://eande.lbl.gov/Task21/dlalgorithms.pdf [2].

A printed report can be derived directly from either of the electronic versions by simply printing either of them. As well as the live links in the electronic forms, all report forms also have explicitly listed link addresses so that they can be followed up or referenced manually.

Finally, it was not the function of this effort to evaluate or otherwise comment on the efficacy or correctness of referenced information - see the Disclaimer.

METHODS and ALGORITHMS

Most daylighting analysis methods and algorithms have their origins in lighting analysis applications, which in turn range from the very simple approximations, to more detailed simulations capable in principle of very high accuracy in complex environments. Advances in this field, and its cutting edge, have been strongly driven by the computer graphics community for the entertainment industry. The focus here is on these latter, detailed methods, and thus many of the information sources come from outside the building research community.

Primary approaches have been ray tracing methods and radiosity methods, which tend to have complimentary strengths and weaknesses. In practice, the methods are increasingly combined into hybrid tools.

Links and citations identified below may be grouped either by source, or research group, or citation from which they came, or alternately by topic, and may appear as multiple cross-links in an attempt to make access to the collection easier, particularly as it grows over time. The cross-linking is not necessarily exhaustive.

General Methods and Collections

- BRE ETSU Daylighting Algorithms [3]A comprehensive compendium of algorithms related to all aspects of daylighting analysis and visualization, including geometry, form factors, solar illumination resource, radiosity, raytracing, and the daylight factor method. (Contents [4] page is here.)
- Daylighting Calculation in DOE-2 [5] Classic LBL Report 11353 (May 1983) with complete and detailed description of daylighting calculations in DOE-2. Uses a split-flux interreflection calculation method. The FORTRAN implementation in DOE-2 has been ported to a C version which is currently implemented in the NREL program ENERGY-10.

- Graphics Software Archive [6] A collection of graphics software, which also more generally includes geometry, radiosity, and ray tracing algorithms. Includes bibliographies and secondary links.
- The ACM Transactions on Graphics Journal [7] has a Software Related Tools [8] WWW site that has links to a broad range of information in the following categories: General, Image Manipulation, File Formats, 2D Rendering, Computational Geometry, Modelers, 3D Object File Formats and Viewers, Hidden-Surface Rendering, Ray Tracing, Radiosity, Visualization, Volume Rendering.

Finite-Element Radiosity Methods

"Traditional, or finite-element radiosity methods account accurately for actual surface and workplane illumination levels by tracking luminous energy from all source surfaces to all destination surfaces.

- Two early papers that formed the methodological basis for the SUPERLITE program:
  - M. F. Modest, "Daylighting Calculations for Non-Rectangular Interior Spaces with Shading Devices," *Journal of the IES*, Vol. 12, July, 1983, 226-241
  - M.F. Modest, "A general Model for the Calculation of Daylighting in Interior Spaces," *Energy and Buildings*, No. 5, 1982, 69-79.
- An Empirical Comparison of Radiosity Algorithms [9], Andrew J. Willmott and Paul S. Heckbert, Carnegie Mellon University. Detailed comparison of different radiosity methods, providing much insight into the implementation of the individual methods, including source code for each of the methods, graphical and geometric utilities, and extensive bibliography. A rich resource, including RAD [10] , a source code distribution for CMU radiosity renderer
- A Rapid Hierarchical Radiosity Algorithm [11], Pat Hanrahan David Salzman Larry Aupperle. Stanford University reproduction of classic SIGGRAPH 91 paper.
- Importance-Driven Progressive Refinement Radiosity [12], P. Bekaert and Y.D. Willems, 1995. A simple way of using importance, also called visual potential, in progressive refinement radiosity and similar radiosity methods.
- Accurate and Reliable Algorithms for Global Illumination [13], Daniel Lischinski. PhD thesis, Cornell University, 1994.
- Radiosity Rendering With Specular Shading [14], Gary Thomas Shea, PhD thesis.
- Radiosity Lighting Simulation [15] U.C. Berkeley study by Thomas A. Funkhouser.
- DElight [16]: LBNL Advanced Daylighting Simulation Algorithms. Another part of the U.S. contribution to IEA Task 21 has been the LBNL development of a complete daylighting tool employing advanced methods. The DElight calculation engine, still under development, is based on DOE2.1d, Superlite 3.0, and newly developed daylighting algorithms.

Ray Tracing Methods

Backward Ray Tracing

Ray tracing methods (usually *backward* ray tracing), are good for producing photorealistic images of complex interiors, including specular reflections.

- The `comp.graphics.rendering.raytracing` FAQ (Part 1 [17] and Part 2 [18]) has much information on basic ray tracing methods and techniques.
- Ray Tracing News [19] is an electronic newsletter devoted to ray tracing methods and techniques, often with detailed descriptions of algorithms and links to source code.
- RADIANCE [20] is a public domain backward ray tracing tool developed at LBNL. The related WWW reference page has detailed secondary links to technical papers, documents, manual pages, seminars & course notes, e-mail archives, and other notes related to applications of and methods used by the program. In particular, daylighting methods and applications are discussed in SIGGRAPH '98 course notes [21].

Forward and Bi-directional Ray Tracing

Forward and bi-directional ray tracing methods may have application in simulation and consequent standardized characterization of the performance of complex fenestration systems (CFS). This is currently a nascent effort. See also next section and the list of commercial forward ray tracing tools further below.

- "A Monte Carlo Approach to Thermal Radiation Distribution within the Built Environment [22]", Neil Campbell, Univ. of Nottingham, 1993.

Additionally, forward ray tracing combined with Monte Carlo methods for surface reflection, and form factor and visibility determination have been combined into severeal variants on a new radiosity approach sometimes called particle tracing or photon mapping. Some important papers and sources are:

- "Robust Monte Carlo Methods for Light Transport Simulation [23]", Eric Veach, Ph.D. dissertation, Stanford University, December 1997.
- "Global Illumination using Photon Maps [24]", Henrik Wann Jensen.
- "Hierarchical and Stochastic Algorithms for Radiosity [25]", Philippe Bekaert, PhD Dissertation, 1999.
- "A framework for realistic image synthesis [26]", D. Greenberg, et al., in Turner Whitted, editor, SIGGRAPH 97 Conference Proceedings, Annual Conference Series, pages 477--494. ACM SIGGRAPH, Addison Wesley, August 1997
- "Global Illumination Using Local Linear Density Estimation [27]", Bruce Walter, P.M. Hubbard, P. Shirley, D. Greenberg, ACM Transactions on Graphics, Vol. 16, No. 3, July 1997, pp. 217-259.
- Particle Tracing Methods in Photorealistic Image Synthesis [28], Rázsó István Márk.
- ORNL Ray Tracing [29] Oak Ridge National Laboratory site describing computational algorithms for Monte-Carlo ray tracing. A daylighting example is shown.

Bi-directional Transmission / Reflection Distribution Functions (BT/RDFs)

BTDFs are used to characterize the transmission and reflection characteristics of complex fenestration systems. Methods and data formats for BTDF characterizations are an ongoing activity of IEA SH&C Task 21 Subtask A4 and C1. BRDFs are used to characterize the reflection characteristics of complex materials, including specularity and "depth". Because of commercial interests, more progress has been made on the latter. See also previous section.

- bv - a BRDF browser [30] an interactive browser for BRDFs. It includes several viewers (including goniometric and lit-sphere views), and many analytic and empirical BRDFs.

- brdfview [31] CMU BRDF viewer
- BRDF Research Links [32] - Stanford University

Geometric Algorithms

Many of the methods and related algorithms needed for a complete solution to the global illumination problem are related to 3D (or 2D) geometric calculations. Selected information resources are described below, many rich in secondary links.

Geometric transformations and graphics primitives

- comp.graphics.algorithms [33] Frequently Asked Questions (FAQ) contains many useful geometric algorithms and links to documentation, source code.
- Graphics Gems Repository [34] is the official on-line repository for the code from the Graphics Gems series of books (from Academic Press). This series focuses on short to medium length pieces of code which perform a wide variety of computer graphics related tasks. All code here can be used without restrictions. The code distributions here contains all known bug fixes and enhancements.
- The Computational Geometry Algorithms Library [35] is a collection of standard geometric algorithms in C++ which has the goals of being robust, easy to use, and efficient.
- The journal of graphics tools [36] is a quarterly journal whose primary mission is to provide the computer graphics research, development, and productioncommunity with practical ideas and techniques that solve real problems.

Form Factor calculations

A calculation of the form factor is necessary to determine how much light is interreflected between two surface patches that can see one another. This form factor determination can be very compute intensive. Much effort has been aimed at efficient solutions to this problem.

- The primary pre-graphics source is: *Thermal Radiation Heat Transfer*, R. Siegel and J. R. Howell, McGraw Hill, 1972.
- "On the Form Factor between Two Polygons [37]", Peter Schröder and Pat Hanrahan. Proceedings of SIGGRAPH 1993.
- "Numerical Integration for Radiosity in the Presence of Singularities [38]", Peter Schröder, Stanford University, 1993.
- "On the Form Factor between Two Polygons [39]," P. Schröder and P. Hanrahan, Proceedings of SIGGRAPH, 1993
- "A Multiprocessor Implementation of Radiosity," A. Ng, M. Slater, Computer Graphics Forum 12(5), 329-342, 1993. Title aside, this paper focuses on an efficient form factor algorithm using ray casting, BSP trees, and bounding box culling. Occlusions are accounted for (see next section).
- "Accelerated Radiosity Computation on Sequential and Parallel Distributed Memory MIMD Machines [40]," A. Ng, Ph.D. Thesis, 1994. Summary only.

Surface-to-surface Visibility (Occlusion)

In complex scenes, it is necessary to determine whether two surface patches can actually see one another in order to interreflect light. This determination can be very compute intensive. Much effort has been aimed at efficient solutions to this problem.

- "Visibility Computations for Global Illumination Algorithms [41]", Seth Teller and Pat Hanrahan, Stanford University, 1993.
- See Ng papers in previous section.

Surface Meshing

Surface subdivision, or meshing, is necessary to improve the solution accuracy in radiosity methods. Much work has been done in this area, for both computer graphics and finite element method modeling applications.

- Delaunay Triangulation [42]
- Stanford University Computer Graphics Geometry Seminar [43] Winter Quarter 1998-1999. Contains links to a number of recent papers on meshing issues and techniques.

Solar / Sky Illumination Models and Data Resources

Modeling of spaces dominated by natural light sources have special challenges, requiring characterizations of the resource and efficient methods of simulating the effects of typically complex naturally illuminated environments.

- U.S. National Renewable Energy Laboratory [44] Data and solar algorithms
- IDMP-CIE [45] International Daylight Measurement Program.
- The Development of Modelling Strategies for Whole Sky Spectrums under Real Conditions for International Use [46], G. Roy, et al., Murdoch University. Includes discussion of Standard Digital Form (SDF) for characterization of sky luminance distributions.
- Sky Modelling from Digital Imagery [47], Geoffrey G. Roy, Simon Hayman, Warren Julian, Murdoch University. Sky characterization application using SDF.
- "Method for Calculation of Sky Light Luminance Aiming at an Interactive Architectural Design," Y. Dobashi, K. Kaneda, H. Yamashito, T. Nishita, Computer Graphics Forum 15(3): C109-C118 (Proc. Eurographics '96), 1996.
- A Radiosity Approach for the Simulation of Daylight [48], S. Muller, W. Kresse, N. Gatenby, F. Schoffel, 1995.
- "A model of Skylight and Calculation of Its Illuminance," E. Nakamae, G. Jiao, K. Tadamura, F. Kato, Lecture Notes in Computer Science: Image Analysis Applications in Computer Science, Vol. 1024, 304-312, 1995.
- Efficient Re-Rendering Of Naturally Illuminated Environments [49], Jeffry Nimeroff, Eero Simoncelli, and Julie Dorsey, 1994.
- "Modeling of Skylight and Rendering of outdoor Scenes," K. Tadamura, E. Nakamae, K. Kaneda, M. Baba, T. Nishita, Computer Graphics Forum 12(3): C189-C200 (Proc. Eurographics '93), 1993.

- "Including Physical Light Sources and Daylight in a Global Illumination Model," E. Languenou, P. Tellier, Proc. Third Eurographics Workshop on Rendering, 217-225, 1992.

Validation and Datasets

A collection of datasets for debugging, testing, comparison, and validation of algorithms and tools. Selected validation studies are included.

- "Scale Model Measurements for a Daylighting Photometric Data Base," M. Spitzglas, M. Navvab, J.J. Kim, S. Selkowitz, J. Illum. Engrg. Soc., Vol. 15, No. 1, 1985, 41-61. Early validation of SUPERLITE algorithms and code.
- "Data Sets for the Validation of Daylighting Computer Programs," M. Aizlewood, P. Laforgue, W. Carroll, J. Butt, R. Mitanchy, R. Hitchcock, Proceedings of the International Daylighting Conference '98, 1998, 157-164. Preliminary summary of IEA SH&C Task 21, Subtask C1 activities and results.
- "Validation of a lighting simulation program under real sky conditions," J. Mardaljevic, Intl. Journal of Lighting Research and Technology, 27(4), 181-188, 1995. (See also Mardaljevic WWW page [50].)
- Comparison of two Methods of Global Illumination Analysis [51], Andrei Khodulev. Experimental comparison of two methods for finding global illumination distribution: the Deterministic Radiosity method and the Monte Carlo method based on Forward Ray Tracing.
- "A Comparison of Luminance Images: Lightscape, Radiance, and an IQCam," K. Houser, Public Works and Government Services Canada, Contract Number 993-6-018 Final Report, March, 1997.
- CIE TC 3.33 [52] The objective of the TC 3.33 is to develop a methodology aimed at testing lighting software in order to assess their relative accuracy, and in order to increase the confidence of their users, and to define the boundary of their field of application. The scope of the tasks deals with daylighting as well as artificial lighting.
- The Cornell Box [53] a simple physical environment with measured the lighting, geometry, and material reflectance properties. Synthetic images of this environment can be created and compared to images captured with a calibrated CCD camera. Published specifications and data.
- 11 Test scenes from the 5th Eurographics Workshop [54] are available for download. These diffuse, grey environments are designed for testing radiosity and Monte Carlo algorithms.
- Interesting and/or large geometric datasets [55] (Seth Teller).

SIMPLE METHODS

In addition to the detailed methods and related algorithms, there are a number of simple methods that have been developed. A recent 'Survey of Simple Design Tools [56]" has been conducted as part of the related IEA SH&C Task 21 / Subtask C4 effort. These tools should be explored for applicability for specific analysis needs.

- A particularly interesting new tool is LESO-DIAL [57], developed by EPFL-LESO (see organization list below).

ORGANIZATIONS

Research Groups - Specific

A listing of universities, institutes and groups, many associated with IEA SH&C Task 21, that are involved in daylighting research. Many secondary references are available.

- Building Research Establishment [58]
- Carnegie Mellon University Graphics Group [59]
- Cornell University Program of Computer Graphics [60]
- Danish Building Research Institute [61] (SBI) SBI's main fields of research are architecture, housing and welfare, urban development and policy, urban ecology and sustainability, condition surveys and durability assessment, productivity, wall and glass structures, low-energy buildings, indoor climate including Moulds in Buildings, daylight in buildings, ventilation requirements and environmental impact from building activities.
- EMPA [62] EMPA's activities include three main areas: materials, systems and environmental technology and safety and quality (of structures, installations, products and procedures).
- ENTPE-LASH [63]
- EPFL LESO-PB [64] The Solar Energy and Building Physics Laboratory (LESO- PB) is active in the fields of energy and building physics. It belongs to the Institute of Building Technology (ITB), one of three institutes of the EPFL Department of Architecture.
- European Commission - Joint Research Centre [65] (ISPRA)
- Fraunhofer Institute for Building Physics [66] The Fraunhofer Institute for Building Physics IBP is concerned with research, development, testing, demonstrating, and consultancy in all fields of building construction. This includes sound insulation in buildings, optimizing the acoustics of auditoria, energy-saving measures, lighting, heating and air conditioning, protection from damp and the weather, preservation of buildings and the care of ancient monuments.
- Fraunhofer Institute for Solar Energy Systems [67] The Fraunhofer Institute for Solar Energy Systems ISE conducts research and develops systems, components, materials and processes in the areas of thermal use of solar energy, photovoltaics, solar architecture, electrical power supplies, chemical energy conversion and rational use of energy.
- Fraunhofer Institute for Computer Graphics [68] (IGD). The Department Visualization and Virtual Reality an integrated radiosity and raytracing system (called Genesis) has been developed to combine the advantages of both the radiosity and the raytracing algorithms.
- ILB - Cologne [69]
- iMAGIS Group [70]
- LBNL [71] Building Technology Program. Developers of RADIANCE, SUPERLITE, and Delight. Also conducts research on Daylighting systems design and performance, and the development and characterization of advanced glazing materials and fenestration systems.
- Université Catholique de Louvain, Architecture et Climat [72]

- Katholieke Universiteit Leuven, Computer Graphics Research Group [73]
- Massachusetts Institute of Technology Computer Graphics Group [74]
- University of Michigan [75] Building Technology Research Facility
- Murdoch University School of Engineering [76] Develops tools for luminance modelling for complex skies (from digital imagery) and for modelling complex bi-directional tranmission of light for interior lighting studies.
- National Research Council of Canada [77]
- Stanford Computer Graphics Laboratory [78]
- University of Washington Graphics and Imaging Laboratory [79]

Research Groups - General

- Computer Graphics Groups [80]. Extensive links list maintained by UCSC Perceptual Science Laboratory.

Professional Societies

- CIE Division 3 [81] includes several Technical Committees involved in the measurement or modeling of daylighting.
- IBPSA [82] International Building Performance Simulation Association
- IESNA [83] Illuminating Engineering Society Of North America
- SIGGRAPH [84] ACM Special Interest Group on Computer Graphics
- Eurographics [85] European Association of Computer Graphics

TOOLS

Although algorithms are the primary focus of the Subtask C2 activity, links to some operational analysis and visualization tools related to daylighting are also presented here for convenience. Some of these are connected to other IEA Subtask C activities. Some of these products employ proprietary methods that are based on the approaches described above, some of these methods appear to have very advanced capabilities. No evaluations have been performed and no implied endorsements are made - see Disclaimer. Listed in alphabetical order.

- AccuRender [86]
- ADELINE - FhG-IBP, GER [87]
- ADELINE - LBNL, U.S. [88]
- DOE-2 [89]
- ENERGY-10 [90]
- Genelux-Web [91] Backward ray tracing daylighitng analysis, with special forward ray tracing to increase analysis efficiency for bright sources.
- Helios Radiosity Renderer [92] a freeware version of the Windows radiosity renderer presented in *Radiosity: A Programmer's Perspective* (I. Ashdown, John Wiley & Sons, 1994, see below).

- INSPIRER [93] primary application area is architecture design, including lighting design, visibility analysis, architectural visualization, and walk-through. Multiple module, multiple / hybrid approaches, including novel Bi-Directional Monte Carlo Ray Tracing. WWW pages have fairly detailed description of approaches used.
- LedaLite [94] A commercial site with lighting design software, including a downloadable demonstration daylight analysis module, and an information resources library with a primary focus on radiosity methods.
- LightCAD / BEEM [95] Commercial lighting design tool with daylighting analysis add-on, developed by the Electric Power Research Institute (EPRI).
- Lightscape [96] A commercial daylighting tool using a hybrid radiosity - ray tracing approach.
- LightWorks® [97] Object-oriented API software toolkit for rendering. Has both ray-tracing and radiosity methods.
- Lumen-Micro [98]
- Luxicon [99]
- **Passport-Light** Monte-Carlo backward ray tracing. Produced for Daylight-Europe project by Univ. of Athens. See Tsangrassoulis, A., M. Santamouris. 1997. "Daylight Modelling With Passport-Light." Proceedings of Building Simulation ’97, Volume 1: 73-78.
- RADIANCE [100] Backward ray tracing
- Radio Ray [101] A commercial daylighting tool using a radiosity approach.
- RenderPark [102] is a software package from the computer graphics research group at Katholieke Universiteit Leuven, in Belgium. It is a test bed for global illumination algorithms, and has a large number of radiosity related techniques implemented (Galerkin, Monte Carlo particle tracing variants, stochastic, bidirectional, etc.). It runs on Unix/Linux.
- SOMBRERO [103] External shading, visualization
- SUPERLITE [104] Radiosity

Forward Ray Tracers

- ASAP: Advanced Systems Analysis Program [105] optical engineering software for imaging or illumination applications.
- OptiCAD [106] flexible, easy to use non-sequential, stray light, and illumination optical system modeling program for Windows
- LightTools ® [107] provides Monte Carlo simulation of illumination systems with user-defined sources and Receivers.
- OSLO [108] applications include lens and optical system design, laser beam optics, illumination systems.
- TraceProTM [109] used for illumination analysis.

Tool Lists

- The Lighting Center [110] WWW pages profile lighting design, energy management, radiosity, visualization, photometric software, some of which are listed explicitly above.
- U.S. DOE Building Energy Software Tools Directory [111] Lists of broadly related building energy simulation tools, some of which have connections to, or integrated, lighting or daylighting analysis capabilities.

INFORMATION RESOURCES

Books and Papers

Basic foundational resources. Links provide additional information, often including tables of contents.

- *IES Lighting Handbook Reference Volume*, J. E. Kaufman and J.F. Christenses, Eds., IESNA, 1984.
- *Radiosity: A Programmer's Perspective* [112], I. Ashdown, John Wiley & Sons, 1994
- *Radiosity and Global Illumination* [113], F. X. Sillion and C. Puech, Morgan Kaufmann, 1994
- *Radiosity and Realistic Image Synthesis*, M. F. Cohen and J. R. Wallace, Academic Press, 1993
- *Principles of Digital Image Synthesis* [114], Andrew S. Glassner, Morgan Kaufmann, 1995. (ISBN 1-55860-276-3)
- *Rendering with Radiance* [115], Gregory Ward Larson, Robert Shakespeare, Morgan Kaufmann, 1998. (ISBN 1-55860-499-5)
- *Real-Time Rendering* [116], Tomas Möller, Eric Haines, A.K. Peters Ltd., 2000. (ISBN 1-56881-101-2)

Bibliographies

List of bibliographies, some referenced earlier, with relevant papers on related topics.

- RADIANCE reference [117] links to web sites and pages.

Funding for the ongoing maintenance of the following three bibliographies is provided by byHeart Consultants Limited (WestVancouver, BC), and a two-year ACM SIGGRAPH Special Projects grant.

- GITHESIS [118] - Global Illumination Theses
- IBR98 [119] - Image-Based Rendering and Modeling
- RADBIB98 [120] - Radiosity and Global Illumination

Other bibliographies

- Rosenfeld Bibliography, KWIC-Index [121] - Radiosity
- Radiosity Abstracts/Bibliography/Papers Library [122]
- Ray Tracing [123] online bibliography

- SIGGRAPH Bibliography Database Search[124]
- Publications of the Cornell University Program of Computer Graphics [125]

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IEA INFORMATION

OVERVIEW OF THE IEA AND THE SOLAR HEATING AND COOLING AGREEMENT

INTERNATIONAL ENERGY AGENCY

The International Energy Agency, founded in November 1974, is an autonomous body within the framework of the Organization for Economic Cooperation and Development (OECD) which carries out a comprehensive program of energy cooperation among its 24 member countries. The European Commission also participates in the work of the Agency.

The policy goals of the IEA include diversity, efficiency and flexibility within the energy sector, the ability to respond promptly and flexibly to energy emergencies, the environmentally sustainable provision and use of energy, more environmentally-acceptable energy sources, improved energy efficiency, research, development and market deployment of new and improved energy technologies, and cooperation among all energy market participants.

These goals are addressed in part through a program of international collaboration in the research, development and demonstration of new energy technologies under the framework of 40 Implementing Agreements. The IEA's R&D activities are headed by the Committee on Energy Research and Technology (CERT) which is supported by a small Secretariat staff in Paris. In addition, four Working Parties (in Conservation, Fossil Fuels, Renewable Energy and Fusion) are charged with monitoring the various collaborative agreements, identifying new areas for cooperation and advising the CERT on policy matters.

IEA SOLAR HEATING AND COOLING PROGRAM

The Solar Heating and Cooling Program was one of the first collaborative R&D agreements to be established within the IEA, and, since 1977, its Participants have been conducting a variety of joint projects in active solar, passive solar and photovoltaic technologies, primarily for building applications. The nineteen members are:

Australia	Japan
Austria	Mexico
Belgium	The Netherlands
Canada	New Zealand
Denmark	Norway
European Commission	Spain
Finland	Sweden
France	Switzerland
Germany	United Kingdom
Italy	United States

A total of 26 projects or "Tasks" have been undertaken since the beginning of the Solar Heating and Cooling Program. The overall program is monitored by an Executive Committee consisting of one representative from each of the member countries. The leadership and management of the individual Tasks are the responsibility of Operating Agents.

These Tasks and their respective Operating Agents are:

*Task 1:	Investigation of the Performance of Solar Heating and Cooling Systems - Denmark
*Task 2:	Coordination of Research and Development on Solar Heating and Cooling - Japan
*Task 3:	Performance Testing of Solar Collectors - Germany/United Kingdom
*Task 4:	Development of an Insulation Handbook and Instrument Package - United States
*Task 5:	Use of Existing Meteorological Information for Solar Energy Application - Sweden
*Task 6:	Solar Systems Using Evacuated Collectors - United States
*Task 7:	Central Solar Heating Plants with Seasonal Storage - Sweden
*Task 8:	Passive and Hybrid Solar Low Energy Buildings - United States
*Task 9:	Solar Radiation and Pyranometry Studies - Canada/Germany
*Task 10:	Solar Material Research and Testing - Japan
*Task 11:	Passive and Hybrid Solar Commercial Buildings - Switzerland
*Task 12:	Building Energy Analysis and Design Tools for Solar Applications - United States
*Task 13:	Advanced Solar Low Energy Buildings - Norway
*Task 14:	Advanced Active Solar Systems - Canada
Task 15:	Not initiated
*Task 16:	Photovoltaics in Buildings - Germany
*Task 17:	Measuring and Modelling Spectral Radiation - Germany
*Task 18:	Advanced Glazing Materials - United Kingdom
*Task 19:	Solar Air Systems - Switzerland
*Task 20:	Solar Energy in Building Renovation - Sweden
Task 21:	Daylighting in Buildings - Denmark
Task 22:	Building Energy Analysis Tools - United States
Task 23:	Optimization of Solar Energy Use in large Buildings - Norway
Task 24:	Solar Procurement - Sweden
Task 25:	Solar Assisted Cooling Systems for Air Conditioning of Buildings (Task Definition Phase)
Task 26:	Solar Combisystems - Austria

*****
**Completed*