
Solar Engineering of Thermal Processes

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Preface

When we started to revise our earlier book, *Solar Energy Thermal Processes*, it quickly became evident that the years since 1974 had brought many significant developments in our knowledge of solar processes. What started out to be a second edition of the 1974 book quickly grew into a new work, with new analysis and design tools, new insights into solar process operation, new industrial developments, and new ideas on how solar energy can be used. The result is a new book, substantially broader in scope and more detailed than the earlier one. Perhaps less than 20 percent of this book is taken directly from *Solar Energy Thermal Processes*, although many diagrams have been reused and the general outline of the work is similar. Our aim in preparing this volume has been to provide both a reference book and a text. Throughout it we have endeavored to present quantitative methods for estimating solar process performance.

In the first two chapters we treat solar radiation, radiation data, and the processing of the data to get it in forms needed for calculation of process performance. The next set of three chapters is a review of some heat transfer principles that are particularly useful and a treatment of the radiation properties of opaque and transparent materials. Chapters 6 through 9 go into detail on collectors and storage, as without an understanding of these essential components in a solar process system it is not possible to understand how systems operate. Chapters 10 and 11 are on system concepts and economics. They serve as an introduction to the balance of the book, which is concerned with applications and design methods.

Some of the topics we cover are very well established and well understood. Others are clearly matters of research, and the methods we have presented can be expected to be outdated and replaced by better methods. An example of this situation is found in Chapter 2; the methods for estimating the fractions of total radiation which are beam and diffuse are topics of current research, and procedures better than those we suggest will probably become available. In these situations we have included in the text extensive literature citations so the interested reader can easily go to the references for further background.

Collectors are at the heart of solar processes, and for those who are starting a study of solar energy without any previous background in the subject, we suggest reading Sections 6.1 and 6.2 for a general description of these unique heat transfer devices. The first half of the book is aimed entirely at development of the ability to calculate how collectors work, and a reading of the description will make clearer the reasons for the treatment of the first set of chapters.

Our emphasis is on solar applications to buildings, as they are the applications developing most rapidly and are the basis of a small but growing industry. The same ideas that are the basis of applications to buildings also underlie applications to industrial process heat, thermal conversion to electrical energy generation, and evaporative processes, which are all discussed briefly. Chapter 15 is a discussion of passive heating, and uses many of the same concepts and calculation methods for estimating solar gains that are developed and used in active heating systems. The principles are the same; the first half of the book develops these principles, and the second half is concerned with their application to active, passive, and nonbuilding processes.

New methods of simulation of transient processes have been developed in recent years, in our laboratory and in others. These are powerful tools in the development of understanding of solar processes and in their design, and in the chapters on applications the results of simulation studies are used to illustrate the sensitivity of long-term performance to design variables. Simulations are the basis of the design procedures described in Chapters 14 and 18. Experimental measurements of system performance are still scarce, but in several cases we have made comparisons of predicted and measured performance.

Since the future of solar applications depends on the costs of solar energy systems, we have included a discussion of life cycle economic analysis, and concluded it with a way of combining the many economic parameters in a life cycle savings analysis into just two numbers which can readily be used in system optimization studies. We find the method to be highly useful, but we make no claims for the worth of any of the numbers used in illustrating the method, and each user must pick his own economic parameters.

In order to make the book useful, we have wherever possible given useful relationships in equation, graphical and tabular form. We have used the recommended standard nomenclature of the *Journal of Solar Energy* (21, 69, 1978), except for a few cases where additional symbols have been needed for clarity. For example, G is used for irradiance (a rate, W/m^2), H is used for irradiation for a day (an integrated quantity, MJ/m^2), and I is used for irradiation for an hour (MJ/m^2), which can also be thought of as an average rate for an hour. A listing of nomenclature appears in Appendix B, and includes page references to discussions of the meaning of symbols where there might be confusion. SI units are used throughout, and Appendix C provides useful conversion tables.

Numerous sources have been used in writing this book. The *Journal of Solar Energy*, a publication of the International Solar Energy Society, is very useful, and contains a variety of papers on radiation data, collectors of various types, heating and cooling processes, and other topics. Publications of ASME and ASHRAE have provided additional sources. In addition to these journals, there exists a very large and growing body of literature in the form of reports to and by government agencies which are not reviewed in the usual sense but which contain useful information not readily available elsewhere. These materials are not as readily available as journals, but they are referenced where we have not found the material in journals. We also call the reader's attention to *Gelio-*

tehnika (Applied Solar Energy), a journal published by the Academy of Sciences of the UZSSR which is available in English and the *Revue Internationale d'Helio-technique*, published by COMPLES in Marseille.

Many have contributed to the growing body of solar energy literature on which we have drawn. Here we note only a few of the most important of them. The work of H. C. Hottel and his colleagues at MIT, that of A. Whillier at MIT and McGill University, and that of B. Y. H. Liu and R. C. Jordan at Minnesota continues to be of basic importance. In space heating, the publications of G. O. G. Löf, S. Karaki and their colleagues at Colorado State University provide much of the quantitative information we have on that application.

Individuals who have helped us with the preparation of this book are many. Our graduate students and staff at the Solar Energy Laboratory have provided us with ideas, useful information and reviews of parts of the manuscript. Their constructive comments have been invaluable, and references to their work are included in the appropriate chapters. The help of students in our course on Solar Energy Technology is also acknowledged; the number of errors in the manuscript is substantially lower as a result of their good-natured criticisms.

Critical reviews are imperative, and we are indebted to S. A. Klein for his reading of the manuscript. He has been a source of ideas, a sounding board for a wide range of concepts, the author of many publications on which we have drawn, and a constructive critic of the best kind.

High on any list of acknowledgements for support of this work must be the College of Engineering and the Graduate School of the University of Wisconsin-Madison. The College has provided us with support while the manuscript was in preparation, and the Graduate School made it possible for each of us to spend a half year at the Division of Mechanical Engineering of the Commonwealth Scientific and Industrial Research Organization, Australia, where we made good use of their library and developed some of the concepts of this book. Our Laboratory at Wisconsin has been supported by the National Science Foundation, the Energy Research and Development Administration, and now the Department of Energy, and the research of the Laboratory has provided ideas for the book.

It is again appropriate to acknowledge the inspiration of the late Farrington Daniels. He kept interest in solar energy alive in the 1960s and so helped to prepare for the new activity in the field during the 1970s.

Generous permissions have been provided by many publishers and authors for the use of their tables, drawings and other materials in this book. The inclusion of these materials makes the book more complete and useful, and their cooperation is deeply appreciated.

A book such as this takes more than authors and critics to bring it into being. Typing and drafting help are essential and we are pleased to note the help of Shirley Quamme and her co-workers in preparing the manuscript. We have been through several drafts of the book which have been typed by our student helpers at the laboratory; it has often been difficult work, and their persistence, skill and good humor have been tremendous.

Not the least, we thank our patient families for their forbearance during the lengthy process of putting this book together.

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Madison, Wisconsin
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Contents

1	Solar Radiation	1
1.1	The Sun, 1	
1.2	The Solar Constant, 3	
1.3	Spectral Distribution of Extraterrestrial Radiation, 5	
1.4	Variation of Extraterrestrial Radiation, 6	
1.5	Definitions; Solar Time, 7	
1.6	Direction of Beam Radiation, 10	
1.7	Ratio of Beam Radiation on Tilted Surface to that on Horizontal Surface, 16	
1.8	Extraterrestrial Radiation on Horizontal Surface, 22	
1.9	Summary, 26	
2	Available Solar Radiation	28
2.1	Definitions, 28	
2.2	Pyrheliometers and Pyrheliometric Scales, 29	
2.3	Pyranometers, 34	
2.4	Measurement of Duration of Sunshine, 42	
2.5	Solar Radiation Data, 42	
2.6	Attenuation of Solar Radiation by the Atmosphere, 52	
2.7	Estimation of Average Solar Radiation, 57	
2.8	Estimation of Clear Sky Radiation, 62	
2.9	Distribution of Clear and Cloudy Days and Hours, 67	
2.10	Beam and Diffuse Components of Hourly Radiation, 70	
2.11	Beam and Diffuse Components of Daily Radiation, 73	
2.12	Beam and Diffuse Components of Monthly Average Radiation, 75	
2.13	Estimation of Hourly Radiation from Daily Data, 77	
2.14	Direction of Diffuse Radiation, 81	
2.15	Total Radiation on Fixed Sloped Surfaces, 83	
2.16	Average Radiation on Fixed Sloped Surfaces, 90	
2.17	Effects of Receiving Surface Orientation, 98	
2.18	Radiation Augmentation, 101	
2.19	Beam Radiation on Moving Surfaces, 105	
2.20	Summary, 107	

3	Selected Topics in Heat Transfer	111
3.1	The Electromagnetic Spectrum, 111	
3.2	Photon Radiation, 112	
3.3	The Blackbody, a Perfect Absorber and Emitter of Radiation, 112	
3.4	Planck's Law and Wien's Displacement Law, 113	
3.5	Stefan-Boltzmann Equation, 115	
3.6	Radiation Tables, 115	
3.7	Radiation Intensity and Flux, 119	
3.8	Infrared Radiation Heat Transfer Between Gray Surfaces, 121	
3.9	Sky Radiation, 122	
3.10	Radiation Heat Transfer Coefficient, 123	
3.11	Natural Convection Between Parallel Flat Plates, 124	
3.12	Convection Suppression, 128	
3.13	Vee-Corrugated Enclosures, 131	
3.14	Heat Transfer Relations for Internal Flow, 132	
3.15	Heat Transfer Due to Wind, 137	
3.16	Heat Transfer and Pressure Drop in Packed Beds, 139	
4	Radiation Characteristics of Opaque Materials	144
4.1	Absorptance and Emittance, 145	
4.2	Kirchoff's Law, 146	
4.3	Reflection from Surfaces, 148	
4.4	Relationships Among Absorptance, Emittance, and Reflectance, 152	
4.5	Measurements of Surface Radiation Properties, 154	
4.6	Selective Surfaces, 155	
4.7	Angular Dependence of Solar Absorptance, 166	
4.8	Specularly Reflecting Surfaces, 167	
5	Radiation Transmission Through Covers and Absorption by Collectors	171
5.1	Reflection of Radiation, 171	
5.2	Absorption of Radiation, 175	
5.3	Optical Properties of Cover Systems, 175	
5.4	Transmittance for Diffuse Radiation, 181	
5.5	Transmittance-Absorptance Product, 182	
5.6	Spectral Dependence of Transmittance, 184	
5.7	Effects of Surface Layers on Transmittance, 186	
5.8	Absorbed Solar Radiation, 187	
5.9	Monthly Average Absorbed Solar Radiation, 189	

6 Theory of Flat-Plate Collectors

197

- 6.1 General Description of Flat-Plate Collectors, 198
- 6.2 The Basic Flat-Plate Energy Balance Equation, 198
- 6.3 Temperature Distributions in Flat-Plate Solar Collectors, 199
- 6.4 Collector Overall Heat Transfer Coefficient, 201
- 6.5 Temperature Distribution Between Tubes and the Collector Efficiency Factor, 214
- 6.6 Temperature Distribution in Flow Direction, 222
- 6.7 Collector Heat Removal Factor and Flow Factor, 223
- 6.8 Mean Fluid and Plate Temperatures, 228
- 6.9 Effective Transmittance-Absorptance Product, 229
- 6.10 Effects of Dust and Shading, 231
- 6.11 Heat Capacity Effects in Flat-Plate Collectors, 233
- 6.12 Other Collector Geometries, 236
- 6.13 Collector Performance, 246
- 6.14 Summary, 247

7 Flat-Plate Collector Performance

250

- 7.1 Early Results, 250
- 7.2 Collector Performance Tests, 251
- 7.3 Collector Time Constant, 260
- 7.4 Incidence Angle Modifier, 262
- 7.5 Thermal Test Data Conversion, 264
- 7.6 Collectors in Series, 268
- 7.7 Test Data for Several Collectors, 270
- 7.8 *In Situ* Collector Performance, 274
- 7.9 Flow Distribution in Collectors, 274
- 7.10 Practical Considerations for Flat-Plate Collectors, 276
- 7.11 Summary, 280

8 Concentrating Collectors

282

- 8.1 Collector Configurations, 283
- 8.2 Concentration Ratio, 286
- 8.3 Thermal Performance of Concentrating Collectors, 288
- 8.4 Optical Characteristics of Nonimaging Concentrators, 293
- 8.5 Orientation and Absorbed Energy for CPC Collectors, 299
- 8.6 Performance of CPC Collectors, 305
- 8.7 Collectors with Linear Imaging Concentrators, 307
- 8.8 Paraboloidal Concentrators, 321
- 8.9 Central Receiver Collectors, 322

9	Energy Storage	326
9.1	Process Loads and Solar Collector Outputs, 327	
9.2	Energy Storage in Solar Process Systems, 328	
9.3	Water Storage, 329	
9.4	Packed Bed Storage, 336	
9.5	Phase-Change Energy Storage, 342	
9.6	Chemical Energy Storage, 346	
10	System Thermal Calculations and Experiments	350
10.1	Component Models, 351	
10.2	Collector Heat Exchanger Factor, 352	
10.3	Duct and Pipe Loss Factors, 355	
10.4	Controls, 358	
10.5	Meteorological Data; Loads, 360	
10.6	System Models, 362	
10.7	Information from Simulations, 365	
10.8	Simulations and Experiments, 367	
10.9	A Simulation Program, 369	
10.10	Summary, 374	
11	Solar Process Economics	376
11.1	Costs of Solar Process Systems, 377	
11.2	Design Variables, 380	
11.3	Economic Figures of Merit, 381	
11.4	Discounting of Future Costs: Inflation, 384	
11.5	Present Worth Factor, 386	
11.6	Life Cycle Savings Method, 389	
11.7	Evaluation of Other Economic Indicators, 394	
11.8	The P_1 , P_2 Method, 398	
11.9	Uncertainty Analysis, 403	
11.10	Summary, 406	
12	Solar Water Heating	408
12.1	Water Heater Systems, 408	
12.2	Freezing and Boiling, 411	
12.3	Auxiliary Energy, 414	
12.4	Forced Circulation Systems, 416	
12.5	Natural Circulation Systems, 419	
12.6	Economics of Solar Water Heating, 421	
12.7	Retrofit Water Heaters, 421	
12.8	Water Heating in Space Heating and Cooling Systems, 425	

Contents

- 12.9 Combined Collector-Storage, 426
- 12.10 Swimming Pool Heating, 428
- 12.11 Summary, 429

13 Solar Heating

431

- 13.1 Historical Notes, 432
- 13.2 Solar Heating Systems, 433
- 13.3 The Denver House, 439
- 13.4 CSU House II—Air System, 442
- 13.5 MIT House IV, 444
- 13.6 CSU House I—Liquid System, 448
- 13.7 A Heating System Simulation Study, 452
- 13.8 Solar Energy-Heat Pump Systems, 457
- 13.9 Solar and Off-Peak Electric Systems, 463
- 13.10 Phase Change Storage Systems, 466
- 13.11 Seasonal Energy Storage, 470
- 13.12 Solar Heating Economics, 473
- 13.13 Architectural Considerations, 477

14 Design of Solar Heating Systems

485

- 14.1 Review of Design Methods, 485
- 14.2 The f -Chart Method, 486
- 14.3 Calculation of Heating Loads, 491
- 14.4 The f -Chart for Liquid Systems, 493
- 14.5 The f -Chart for Air Systems, 498
- 14.6 Service Water Heating Systems, 503
- 14.7 f -Chart Results, 505
- 14.8 Parallel Solar Energy-Heat Pump Systems, 507
- 14.9 Summary, 510

15 Passive Solar Heating

512

- 15.1 Concepts of Passive Heating, 513
- 15.2 Comfort Criteria and Heating Loads, 514
- 15.3 Movable Insulation and Controls, 514
- 15.4 Shading, 515
- 15.5 Direct Gain Windows, 536
- 15.6 Collector-Storage Walls and Roofs, 538
- 15.7 Solar Load Ratio Design Method, 544
- 15.8 Resistance Network Design Method, 547
- 15.9 Greenhouses, 550
- 15.10 Examples of Passive Applications, 550
- 15.11 Summary, 553

16	Solar Cooling	556
16.1	Review of Solar Absorption Cooling, 557	
16.2	Theory of Absorption Cooling, 559	
16.3	Combined Solar Heating and Cooling, 565	
16.4	Simulation Study of Solar Air Conditioning, 567	
16.5	Operating Experience with Solar Cooling, 571	
16.6	Economics of Solar Air Conditioning, 572	
16.7	Solar Desiccant Cooling, 573	
16.8	Solar Mechanical Cooling, 578	
16.9	Solar-Related Air Conditioning, 581	
17	Solar Industrial Process Heat	588
17.1	Integration with Industrial Process, 588	
17.2	Mechanical Design Considerations, 589	
17.3	Economics of Industrial Process Heat, 590	
17.4	Air Heating Application, 591	
17.5	Once-Through Industrial Water Heating, 594	
17.6	Recirculating Industrial Water Heating, 594	
17.7	Shallow Pond Water Heaters, 597	
17.8	Summary, 599	
18	Thermal Design Methods	600
18.1	Utilizability, 601	
18.2	Generalized Utilizability, 604	
18.3	Daily Utilizability, 612	
18.4	The $\bar{\phi}$, f -Chart Method, 620	
18.5	Summary, 632	
19	Conversion to Mechanical Energy	633
19.1	Thermal Conversion Systems, 633	
19.2	The Gila-Bend Pumping System, 636	
19.3	Central Receiver Power Systems, 638	
20	Evaporative Processes and Salt-Gradient Ponds	641
20.1	Solar Distillation, 641	
20.2	Evaporation, 647	
20.3	Direct Solar Drying, 648	
20.4	Salt-Gradient Solar Ponds, 649	
20.5	Summary, 651	

Contents	xvii
Appendices	653
A Problems, 653	
B Nomenclature, 678	
C International System (SI) of Units, 682	
D Monthly \bar{R}_t as Function of $(\phi - \beta)$, ϕ , and γ , 685	
E Properties of Materials, 697	
F Present Worth Factors, 706	
G Meteorological Data, 713	
Author Index	751
Subject Index	757

CHAPTER 1

Solar Radiation

The sun's structure and characteristics determine the nature of the energy it radiates into space. This chapter notes the characteristics of this energy outside of the earth's atmosphere and the effects of the atmosphere in attenuating the radiation. Then the characteristics of the resulting energy resource available at the earth's surface are outlined, that is, its intensity, spectral distribution, and its directional characteristics. We are concerned primarily with radiation in a wavelength range of 0.3 to 3.0 μm , the portion of the spectrum that includes most of the energy radiated by the sun.

In general, it is not practical to start from knowledge of extraterrestrial radiation and predict the intensity and spectral distribution to be expected on the ground. Adequate meteorological data for such calculations are seldom available, and recourse usually is made to measurements. However, an understanding of the nature of extraterrestrial radiation, atmospheric attenuation, and the effects of orienting a receiving surface is important in understanding and using solar radiation data.

1.1 THE SUN

The sun is a sphere of intensely hot gaseous matter with a diameter of 1.39×10^9 m and is, on the average, 1.5×10^{11} m from the earth. As seen from the earth, the sun rotates on its axis about once every four weeks. However, it does not rotate as a solid body; the equator takes about 27 days and the polar regions take about 30 days for each rotation.

The sun has an effective blackbody temperature of 5762 K.* The temperature in the central interior regions is variously estimated at 8×10^6 to 40×10^6 K and the density at about 100 times that of water. The sun is, in effect, a continuous fusion reactor with its constituent gases as the "containing vessel" retained by gravitational forces. Several fusion reactions have been suggested to supply the

* This effective blackbody temperature of 5762 K is the temperature of a blackbody radiating the same amount of energy as does the sun. Other effective temperatures can be defined, for example, that corresponding to the blackbody temperature giving the same wavelength of maximum radiation as solar radiation (about 6300 K).

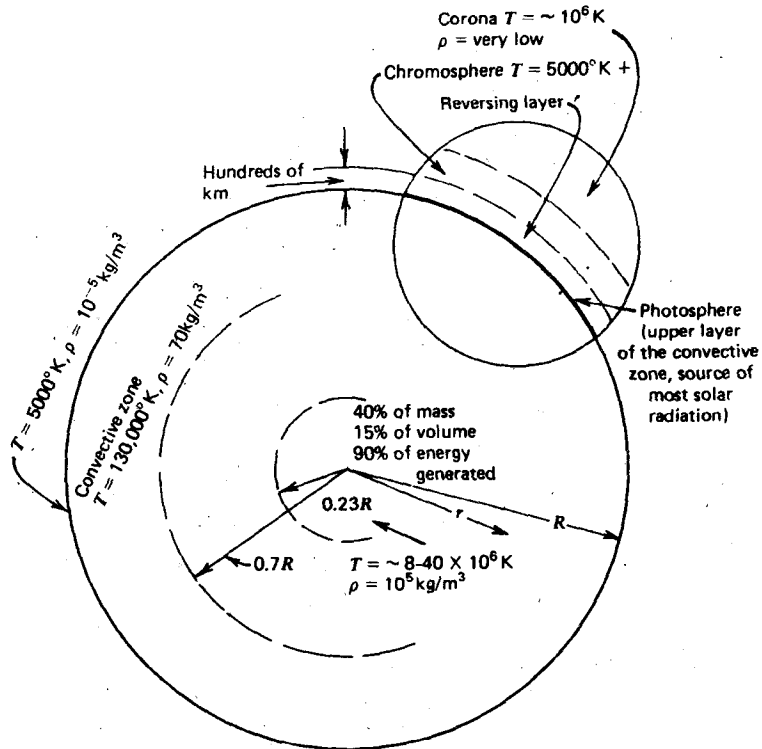


Figure 1.1.1 The structure of the sun.

energy radiated by the sun; the one considered the most important is a process in which hydrogen (i.e., four protons) combines to form helium (i.e., one helium nucleus); the mass of the helium nucleus is less than that of the four protons, mass having been lost in the reaction and converted to energy.

This energy is produced in the interior of the solar sphere, at temperatures of many millions of degrees. It must be transferred out to the surface and then be radiated into space. A succession of radiative and convective processes must occur, with successive emission, absorption, and reradiation; the radiation in the sun's core must be in the x-ray and gamma-ray parts of the spectrum with the wavelengths of the radiation increasing as the temperature drops at larger radial distances.

A schematic of the structure of the sun is shown in Figure 1.1.1. It is estimated that 90% of the energy is generated in the region of 0 to $0.23R$ (where R is the radius of the sun), which contains 40% of the mass of the sun. At a distance $0.7R$ from the center, the temperature has dropped to about 130,000 K and the density has dropped to 70 kg/m^3 ; here convection processes begin to become important and the zone from 0.7 to $1.0R$ is known as the *convective zone*. Within this zone, the temperature drops to about 5000 K and the density to about 10^{-5} kg/m^3 .

The sun's surface appears to be composed of granules (irregular convection cells), with dimensions of cells from 1000 to 3000 km and with cell lifetime of a few minutes. Other features of the solar surface are small dark areas called pores, which are of the same order of magnitude as the convective cells, and larger dark areas called sunspots, which vary in size. The outer layer of the convective zone is called the *photosphere*. The edge of the photosphere is sharply defined, even though it is of low density (about 10^{-4} that of air at sea level). It is essentially opaque, as the gases of which it is composed are strongly ionized and able to absorb and emit a continuous spectrum of radiation. The photosphere is the source of most solar radiation.

Outside of the photosphere is a more or less transparent solar atmosphere, which is observable during total solar eclipse or by instruments that occult the solar disk. Above the photosphere is a layer of cooler gases several hundred kilometers deep called the *reversing layer*. Outside of that is a layer referred to as the *chromosphere*, with a depth of about 10,000 km. This is a gaseous layer with temperatures somewhat higher than that of the photosphere and with lower density. Still further out is the *corona*, of very low density and of very high (10^6 K) temperature. For further information on the sun's structure see Thomas (1958) or Robinson (1966).

This simplified picture of the sun, its physical structure, and its temperature and density gradients, will serve as a basis for appreciating that the sun does not, in fact, function as a blackbody radiator at a fixed temperature. Rather, the emitted solar radiation is the composite result of the several layers that emit and absorb radiation of various wavelengths. The resulting extraterrestrial solar radiation and its spectral distribution have now been measured by various methods in several experiments; the results are noted in the following two sections.

1.2 THE SOLAR CONSTANT

Figure 1.2.1 shows schematically the geometry of the sun-earth relationships. The eccentricity of the earth's orbit is such that the distance between the sun and the earth varies by 1.7%. At a distance of one astronomical unit, 1.495×10^{11} m, the mean earth-sun distance, the sun subtends an angle of $32'$. The radiation emitted by the sun and its spatial relationship to the earth result in a nearly fixed intensity of solar radiation outside of the earth's atmosphere. The *solar constant*, G_{sc} , is the energy from the sun, per unit time, received on a unit area of surface perpendicular to the direction of propagation of the radiation, at the earth's mean distance from the sun, outside of the atmosphere.

Until recently, estimates of the solar constant had to be made from ground-based measurements of solar radiation after it had been transmitted through the atmosphere, and thus in part absorbed and scattered by components of the atmosphere. Extrapolations from the terrestrial measurements, which were