SOLAR RADIATION ENERGY (FUNDAMENTALS)

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Keywords: Sun, earth, astronomy, radiation, solar constant, energy, irradiance, irradiation, extraterrestrial radiation, declination, time, mean solar time, true solar time, hour angle, inclined surface, slope, zenithal angle, azimuth, scattering, atmosphere, global, direct, diffuse, spectral distribution, clearness index, clouds, terrestrial radiation, total radiation.

Contents

Summary

The fundamentals of solar radiation are presented in this chapter. Irradiance and irradiation are defined; we explain the origin of the energy emitted by the sun and reaching the ground and its amount as a function of the wavelength – the spectral distribution. The energy reaching the earth depends on the geometry of the earth relative to the Sun. This geometry is described as well as its variation throughout the year. The concept of time is very important in solar radiation. It is detailed here and the notions of mean solar time and true solar time are dealt with. The apparent course of the sun in the sky is described; the zenithal, elevation and azimuth angles are defined. We offer a series of equations to compute the radiation at the top of the atmosphere at any instant of time and on any inclined surface. During its path downwards to the ground, the constituents of the atmosphere deplete the incident light. We introduce the concepts of scattering and absorption. We discuss the main processes affecting the incident radiation

in clear and cloudy atmospheric conditions, and especially the effects of molecules, aerosols, gases and clouds. Several examples are given that illustrate atmospheric effects as a function of the solar zenithal angle and atmospheric optical properties. The spectral distribution of the irradiance is discussed for several different conditions. The direct, diffuse and reflected components of the irradiance are defined. How to compute them on an inclined surface is briefly discussed. Many equations are given in this contribution that can be easily introduced in e.g., a spreadsheet or a computer routine, to reproduce the figures.

1. Introduction

The sun is the seat of thermonuclear processes and produces a vast amount of energy. The energy emitted by the sun is called solar energy or solar radiation. Despite the considerable distance between the sun and the earth, the amount of solar energy reaching the earth is substantial. It is the earth's primary natural source of energy and by a long way. Other sources are: the geothermal heat flux generated by the earth's interior, natural terrestrial radioactivity, and cosmic radiation, which are all negligible relative to solar radiation.

At any one time, the earth intercepts approximately 180 $\times 10^6$ GW. The amount of power received at a given geographical site varies in time: between day and night due to the earth's rotation and between seasons because of the earth's orbit. And at a given time it also varies in space, because of the changes in the obliquity of the solar rays with longitude and latitude. Accordingly, the amount of power received at a given location and time depends upon the relative position of the sun and the earth. This is why both sun-earth geometry and time play an important role in solar energy conversion and photo energy systems. A major part of this chapter is devoted to this matter.

The amount of solar radiation intercepted by the earth, is called extraterrestrial radiation. As it makes its way towards the ground, it is depleted when passing through the atmosphere. On average, less than half of extraterrestrial radiation reaches ground level. Even when the sky is very clear with no clouds, approximately 20 % to 30 % of extraterrestrial radiation is lost during the downwelling path. A good knowledge of the optical properties of the atmosphere is necessary to model the depletion of the radiation. The role of the clouds is of paramount importance: optically thin clouds allow a small proportion of radiation to reach the ground, optically thick clouds create obscurity by stopping the radiation downwards. In clear skies, aerosols and water vapor are the main contributors to depletion. The description and modeling of the optical processes affecting solar radiation's interaction with the atmosphere is called radiative transfer. The fundamentals are described in this text.

The spectral distribution of extraterrestrial radiation is such that about half of it lies in the visible part of the electromagnetic spectrum. It produces daylight and is well perceived by the human vision system. Other parts of it are in the near-infrared and ultraviolet ranges. This spectral distribution is modified as the radiation crosses the atmosphere downwards; changes are mainly due to gases and aerosols. The spectral distribution has an impact on photo energy systems, since the latter have a response in preferred ranges of the electromagnetic spectrum. The amount of radiation integrated over the whole spectrum is called total radiation or broadband radiation.

Several quantities are necessary to describe radiation. It is recalled that power is energy divided by a time interval. The use of area densities, i.e., energy flux density per unit area, is very practical in energy conversion systems. Irradiance is defined as a power received per area; unit is watt per square meter (W m^{-2}). It is represented by E in this text, as recommended by the S.I. (*système international d'unités*). Irradiation is the energy received per area; unit is joule per square meter (J m^{-2}). The International Solar Energy Society recommends the symbol H. In commercial metering of electrical energy, a frequently used unit is watt-hour (Wh). though this should not be used in scientific and technical work since it is not part of the S.I.; H may be expressed in Wh m^{-2}. The conversion is defined by:

$$H = 1\ \mathrm{Wh\ m^{-2}} = 3600\ \mathrm{J\ m^{-2}} \qquad (1)$$

Instruments at ground level often record irradiation values. The conversion from irradiation into irradiance is performed by dividing irradiation by the duration of the measurement. Reciprocally, irradiance is converted into irradiation by multiplying by time duration. If T is the duration of measurement:

$$E = H/T \qquad (2)$$

The irradiation received at ground level on a horizontal flat surface consists of a direct component, i.e., the part of the irradiation that is coming from the sun's direction, and of a diffuse component, originating from the sky vault, clouds and neighboring objects. The sum of these components is called global irradiation. This decomposition may be of importance for several solar energy conversion systems. For example, concentrators only deal with direct components. Conversely, a flat collector without a concentrator is sensitive to global irradiation.

2. Energy Emitted by the Sun

Any object emits electromagnetic radiation, provided its temperature is above 0 K. The spectral radiance is entirely determined by temperature and the emitting properties of the surface of the object. The laws of Kirchhoff and Planck describe this process. Solar radiation is approximately that of a blackbody (i.e., a perfect radiative body) at a temperature of 5 780 K. The emitted radiation spans over a very large spectrum, from X-rays to far infrared. Nevertheless, approximately 99.9 % of the radiation emitted is located between 0.2 μm and 8 μm and 98 % between 0.3 μm and 4 μm.

Figure 1 displays the spectral distribution of extraterrestrial radiation for the wavelength ranges [0.3, 1] μm and [0, 5] μm. The spectral distribution shows how much energy there is for each wavelength. A very large part of energy is located in the visible part of the spectrum [0.39, 0.76] μm. The spectrum departs from the smooth Planck spectral curve, particularly at wavelengths below 0.8 μm. It exhibits numerous lines that are due to selective absorption and emission in the sun. The spectral distribution may change according to the level of solar activity, especially at very small wavelengths. On the scale of interest for energy applications, solar activity is negligible.

The distribution of energy in the solar radiation spectrum can be determined either by direct measurements or by extrapolation beyond the atmosphere of spectrometric measurements made at ground level. Very reliable measurements have been made by Labs and Neckel, and they are exploited in many numerical models for radiative transfer in the atmosphere. Figure 1 is based on such a spectrum. Research on this subject is on-going, and new spectra are regularly published in scientific literature. Although they differ slightly from the Labs and Neckel spectrum, unless very detailed parts of the spectrum are being considered, this spectrum provides an adequate basis for solar energy applications.

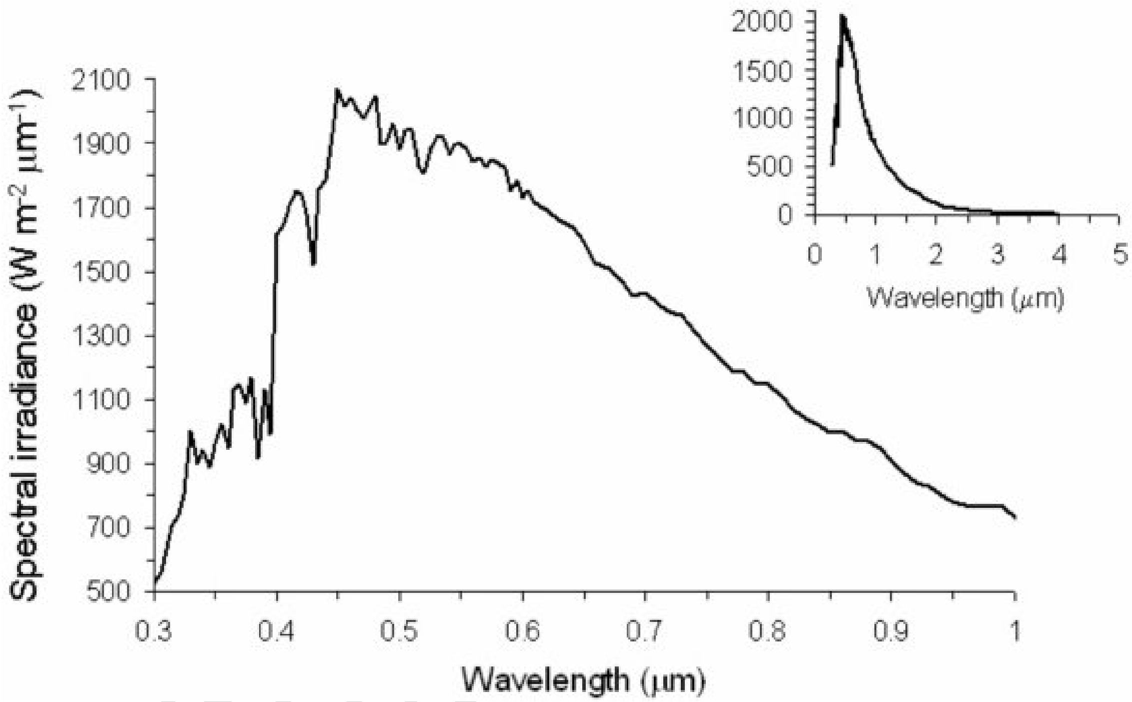

Figure 1: Spectral distribution of extraterrestrial radiation for wavelengths from 0.3 µm to 1 µm (central graph) and 0 µm to 5 µm (upper right-hand corner)

Extraterrestrial radiation varies because of variations in sun-earth distance and, to a much lesser extent, day-to-day variations in the spectrum due to solar activity. Of particular interest, is extraterrestrial irradiance E_0 . The solar constant is the name given to this quantity when the distance from the earth to the sun is equal to the average radius of the earth's orbit; it is represented by E_{SC} in this chapter. The value of E_{SC} has varied over the years with the increasing accuracy of instrumentation. In 1981, the World Radiometric Reference for E_{SC} was 1 370 W m^{-2} $\pm$ 6 W m^{-2}. Today, a value of 1 367 W m^{-2} is used. The relative influence of day-to-day solar activity on E_{SC} is of the order of 0.15 % and is negligible for engineering calculations.

3. Sun-Earth Geometry - Time

The amount of radiation that reaches a given point at the top of the atmosphere is governed by the specific astronomical situation of the earth on its orbit around the sun, its rotation around its polar axis and the location of this point on the earth.

3.1. Sun-Earth Astronomy

The earth describes an elliptical orbit with the sun at one of the foci (Fig. 2). The eccentricity of the earth's orbit is very small (0.01675); this means that the orbit is almost circular. The mean distance between the sun and the earth is approximately equal to 1.496 x 10^8 km. This distance is called 1 astronomical unit (ua).

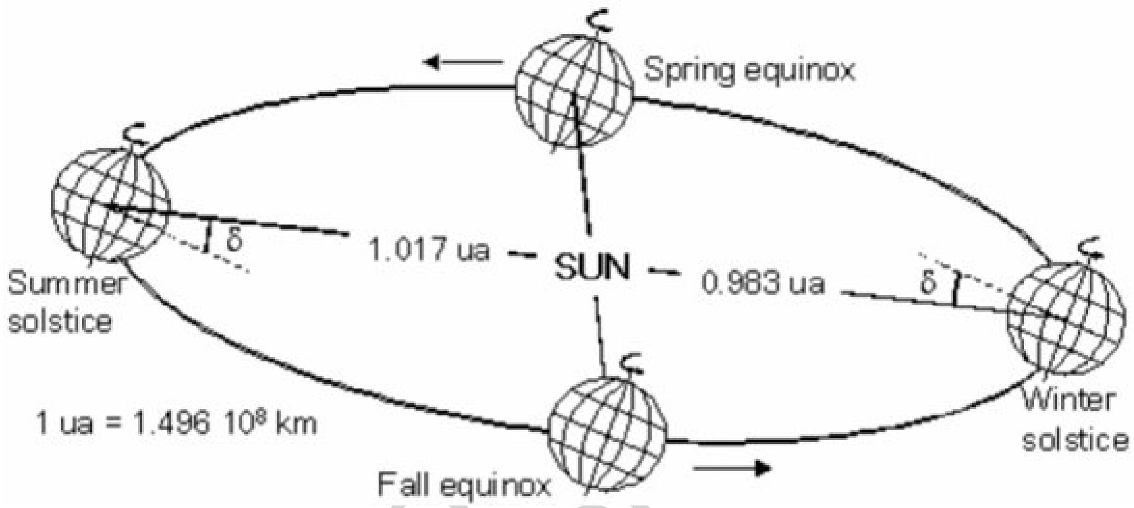

Figure 2: Scheme showing the earth's orbit around the sun. The distance between the sun and the earth is reported for the summer and winter solstices. The angle δ is the solar declination. Adapted from Perrin de Brichambaut and Vauge (1982)

In Fig. 2, it can be noted that the equatorial plane of the earth inclines by 0.40928 rad (23.45°) on the plane containing the earth's orbit. This is equivalent to saying that the axis of the earth's daily rotation passing by the two poles is inclined by this angle with respect to the orbit plane. Because of this inclination, the northern hemisphere is closer to the sun in July than the southern hemisphere is. This defines the astronomical summer which begins on 21-22 June, known as the summer solstice, and which ends three months later. Conversely, the northern hemisphere is farther from the sun than the southern hemisphere during the astronomical winter, which begins on 21-22 December, a date known as the winter solstice. These summers and winters differ from the meteorological summers and winters that exist in both hemispheres: the boreal and austral seasons.

Lastly, the daily rotation of the earth on itself induces the notion of a mean solar day divided into 24 h of 60 min each. The time parameters (year, day, hour) are essential in order to compute the apparent position of the sun in the sky and, accordingly, the radiation at ground level that may be exploited.

3.2. Sun-Earth Distance

The mean distance between the earth and the sun, r_0, is 1 ua (Fig. 2). This value is reached for spring and fall equinox. The actual distance varies during the year depending on the number of the days in the year d: it is maximum for summer solstice (1.017 ua) and minimum for winter solstice (0.983 ua). A number of mathematical expressions of this distance are available; they are usually expressed in terms of Fourier series type of expansion. The following expression is adopted from the European Solar Radiation Atlas (2000).

d ranges from 1 (1^{st} January) to 365, or 366 in case of a leap year. Whatever the year, it is convenient to define the day angle j, in rad, as

$$j = d2\pi/365.2422 \qquad (3)$$

The day angle is almost zero on 1st January (0.0172), equal to π on 1st July and 2π on 31^{st} December.

The sun-earth distance r is given by

$$\left(r/r_0\right)^2 = 1+\varepsilon \qquad (4)$$

where ε can be set to

$$\varepsilon \approx 0.03344\cos\left(j-0.049\right) \qquad (5)$$

with an accuracy sufficient for solar engineering. ε is called the relative eccentricity correction. As the amount of solar radiation intercepted by the earth depends upon the sun-earth distance, the extraterrestrial irradiance E_0 is computed from the solar constant E_{SC} using the relative correction ε

$$E_0 = E_{SC}\left(1+\varepsilon\right) \qquad (6)$$

The relative correction ε is comprised between −0.03 and +0.03. The change in the sun-earth distance may be neglected in a first approximation if engineering calculations do not require a relative accuracy better than 3 %.

A consequence of the large distance between the sun and the earth is that despite its formidable size, the sun appears as a small spot to an observer on the earth. The solid angle under which the sun appears is equal to 0.68×10^{-4} sr. The sunrays can be considered as parallel as they hit the top of the earth's atmosphere.

3.3. Solar Declination

As it can be seen in Fig. 2, the direction of the solar rays is not always parallel to the equatorial plane. The angle composed by the direction to the sun and the equatorial plane is called the solar declination, represented by δ. The convention for counting the declination is the same as that for latitudes. Latitudes Φ are counted positive in the northern hemisphere and negative in the southern hemisphere. In Fig. 2, δ is positive for the summer solstice and negative for the winter solstice. δ is a function of the longitude λ. By convention, longitudes are counted positive east of the meridian 0 rad and negative west of this meridian.

The solar declination varies from −0.40928 rad to +0.40928 rad. These extremes are reached at respectively the winter and summer solstices. At equinoxes, the declination is 0. A mean daily value is accurate enough for solar radiation estimation.

Thus δ can be computed from d, the longitude λ and the year y. Let n_0 represent the spring-equinox time expressed in days from the beginning of the year, i.e. the time in decimal day that elapses from 0.0 h on 1st January to the spring equinox at longitude 0 in the year y.

Let t_1 represent the time, in days, from the spring equinox and ω_t the day angle counted from the spring equinox. If INT denotes the integer part of an expression (i.e., the truncation), these quantities are given by:

$$n_0 = 78.8946 + 0.2422(y - 1957) - \mathrm{INT}\left[(y - 1957)/4\right] \quad (7)$$

$$t_1 = -0.5 - \lambda/(2\pi) - n0 \quad (8)$$

$$\omega_t = (2\pi/365.2422)(d + t_1) \quad (9)$$

The declination is then given by:

$$\begin{aligned}\delta = {} & b_1 + b_2 \sin(\omega_t) + b_3 \sin(2\omega_t) + b_4 \sin(3\omega_t) \\ & + b_5 \cos(\omega_t) + b_6 \cos(2\omega_t) + b_7 \cos(3\omega_t)\end{aligned} \quad (10)$$

where:

$b_1 = 0.0064979$, $b_2 = 0.4059059$, $b_3 = 0.0020054$,

$b_4 = -0.0029880$, $b_5 = -0.0132296$, $b_6 = 0.0063809$,

$b_7 = 0.0003508$

Figure 3 displays the variation of the solar declination as a function of the number of the day in the year for longitude 0 and for the year 2006. The declination is 0 for days 80 (21 March) and 266 (22 September), minimum for day 356 (22 December) and maximum for day 172 (21 June).

Neglecting the longitude, i.e., making the calculations by setting λ to 0 in Eq. (8), induces an error in the solar declination that is less than 0.001 rad in absolute value. Such an error is acceptable in solar engineering calculations; the influence of the longitude can be neglected.

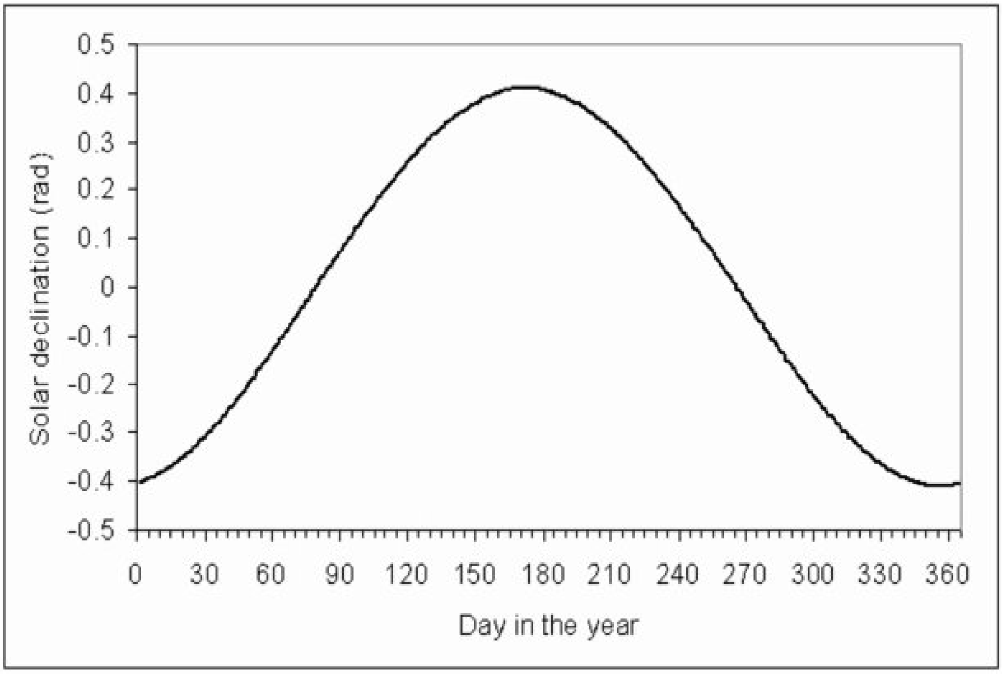

Figure 3: Variation of the solar declination throughout the year. The year is 2006. Longitude is 0.

3.4. Geocentric and Geographic Coordinates

The equations given in this chapter are derived in geocentric coordinates, i.e., by considering the earth as a perfect sphere.

These coordinates are the latitude Φ_c and the longitude λ. The earth is not a perfect sphere and is slightly elongated in the equatorial plane. The radius to the poles R_{pole} is equal to 6 356.752 km, while the radius at Equator $R_{equator}$ is 6 378.137 km.

Accordingly, there is a difference between the geocentric latitude Φ_c and the actual geographic latitude Φ. This difference is zero at the poles and the equator and maximum at geographic mid-latitudes $\pi/4$, where it reaches 0.0033 rad (0.19°).

This corresponds to an error in the north-south distance of approximately 21 km. If this effect is to be taken into account, the geographic latitude Φ should be replaced in all equations by the geocentric latitude Φ_c that is given by

$$\tan \Phi_c = \left(R_{pole} / R_{equator}\right)^2 \tan \Phi \qquad (11)$$

In an initial approximation, the discrepancy between the geocentric and geographic latitudes can be neglected.

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Bibliography

Dogniaux R., Grueter J. W., Kasten F., Page J. K., Perrin de Brichambaut C., Treble F. C., Palz W. (1984). Solar meteorology (units and symbols). *International Journal of Solar Energy* **2**, 249-255. [This provides an extensive nomenclature of quantities used in this domain].

Duffie J.A., Beckman W.A. (1991). *Solar Energy of Thermal Process*, 2nd edition. Wiley & Sons, New York. [A classic and fundamental text on solar thermal engineering. It provides procedures and data for calculating solar resources and designing solar conversion systems].

Goswami Y., Kreith F., Keider J.F. (2000). *Principles of Solar Engineering*. Taylor & Francis, 666 pp. [A recent and complete textbook on solar engineering. It includes the fundamentals and covers a broad range of topics in solar energy applications].

Greif J., Scharmer K. Eds (2000). *European Solar Radiation Atlas. Vol. 2: Database and Exploitation Software*. Published for the Commission of the European Communities by Les Presses de l'Ecole, Ecole des Mines de Paris, France, 296 pp. [Equations describing the sun position with respect to an observer can be found. Several models for converting global horizontal irradiance into diffuse and direct irradiances on an inclined plane surface are described. The software exploits these equations, models and included database].

Liou K.N. (1980). *An Introduction to Atmospheric Radiation*. International Geophysics Series, vol. 26, Academic Press, 392 pp. [A detailed and precise description of the physical processes affecting electromagnetic radiation and occurring in the atmosphere].

Neckel H., Labs D. (1984). The Solar Spectrum Between 3300 and 12500 nm, *Solar Physics*, Vol. 90, 1984, pp. 205-258 [Describes the spectral distribution of the extraterrestrial radiation].

Muneer T. (2004). *Solar Radiation and Daylight Models*. Elsevier, 346 pp. [A recent book on solar radiation that will become a classic. A full Chapter is devoted to the spectral distribution of the sunlight].

Perrin de Brichambaut Ch., Vauge Ch. (1982). *Le Gisement Solaire*. Published by Technique et Documentation (Lavoisier), Paris, France, 222 pp. [This book in French offers a practical description of solar radiation for solar engineering purposes].

WMO (1981). *Meteorological Aspects of the Utilization of Solar Radiation as an Energy Source*. Technical Note 172, WMO-No.557, World Meteorological Organization, Geneva, Switzerland, 298 pp. [Contains a description of solar radiation and instruments and measuring techniques].

Biographical Sketch

Lucien Wald was born in 1953. He graduated in theoretical physics in Marseille and Paris, France, in 1977. He specialised himself in fluid dynamics in geophysics and atmosphere optics. He obtained the Ph.D. degree in 1980 (Paris, France) and the Doctorat d'Etat ès Sciences in 1985, both on the applications of remote sensing to oceanography. Since 1991, he is a Professor at Ecole des Mines de Paris, where he is currently the Head of the Remote Sensing Group, and is focusing his own research in applied mathematics as well as solar radiation. He obtained the Autometrics Award in 1998 and the Erdas Award in 2001 for articles on data fusion. His career in information technologies has been rewarded in 1996 by the famous French Blondel Medal.

Regarding solar radiation, his group was the author of the well-known method Heliosat for the assessment of the solar radiation at ground from satellite images. This method spread throughout the world and gave rise to several enhanced versions made by various laboratories. Lucien Wald contributed to harmonise these versions and to further improvements. By exploiting the method Heliosat, the group created a unique family of databases of irradiance, called HelioClim, that are updated in real-time. The group manages the collaborative web service SoDa (www.soda-is.com) which is offering advanced information on solar radiation by exploiting databases and applications geographically dispersed and provided by partners institutes and companies. Users of the SoDa Service are in the domain of solar energy but also in architecture and building engineering, agronomy and horticulture, health and materials weathering.