SOLAR ENERGY CONVERSION SYSTEMS

ENGINEERING AND ECONOMIC ANALYSIS

INPUT DEFINITION

Volume I

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ABSTRACT

After defining Solar Energy Conversion System Input characteristics, an analytical model of the atmosphere is developed. This model is capable of computing the Solar Energy Flux on the collector area for a techno-economic feasibility analysis of Solar Energy Systems.

A deterministic approach permits the evaluation of the energy input to the system, at proper intervals of time, on the basis of a few meteorological data. The selective interaction of the electromagnetic energy flux and atmospheric matter is described: the analytical model is derived and implemented on CIRR2 codes for the global energy flux computation; and comparison with experimental values is performed.

INTRODUCTION

"Felix qui potuit rerum cognoscere causas"

Virgil, Georg.: II 490

Energy Conversion Systems engineering may be considered as an interface between the energy load and the energy input. Upon definition of the energy load, Primary Energy Conversion Systems are engineered on the basis of an energy input that may be considered available any time at the desired intensity: this allows a quasi-steady state mode of operation of the system (and of the components) and reduces the excursion of the design parameters during operation. Solar Energy Conversion Systems must be designed taking into account a highly variable energy input to the system; they therefore operate in non-steady state conditions that strongly affect the performances of the system and the energy output itself. Consequently, economic evaluations of the system should take into account the transient mode of operation of the system.

Therefore, Solar Energy Conversion Systems engineering optimization, economic analysis and those energy strategies that strongly consider them, heavily rely on an adequate knowledge of the energy input to the system, i.e. on an adequate knowledge of the solar energy radiative flux on the collector area, both for system and components' analysis.

The quantity and reliability of experimental data available in the U.S. are discussed on Chapter 5 and Appendices A4 and A6. As will be shown, the availability, quality and quantity of the data will sensibly improve the standardization of instruments, number of stations, etc. being improved. The present situation, however, is somewhat more critical. Besides, the availability of the data for most other countries of the world, as concerns energy flux values, is particularly poor and the information unreliable, although these countries represent a highly attractive potential market.

The alternative to using experimental data is to compute them. A stochastic or a deterministic approach may be used. The former may be performed with regression models, e.g. through correlation of the various radiative components of the radiation flux or through Monte Carlo methods, but generally obtained through largely macroclimatic correlations using empirical algorithms or through time-consuming large-scale meteo-atmospheric models. The criteria adopted in this work are the construction of an analytical model of the atmosphere on the basis of a reduced number of "generally" available meteorological parameters (i.e., parameters already available through standard measurements), giving to the analytical model the characteristics of a physical model of the atmosphere rather than a mathematical algorithm of correlation, with a relative low time of computation.

This solution is consistent with the engineering of the system due to the fact that many aspects of this engineering (for components and systems) are achieved via computer (due to the large time-dependent number of variables), and optimization techniques and techno-economical feasibility analysis are implemented through computer models. It is attractive because of the worldwide dearth of solar energy flux data (but not of some standard meteorological measurements, such as pressure, temperature, relative humidity, etc.). The last point is particularly important. The measurement of most meteorological parameters is standardized; the instrumentation and techniques of measurements are simple and economical; a considerable amount of historical data are available; meteorological parameters do not change as rapidly--step function--as solar energy fluxes, and therefore a relatively reduced number of measurements would allow the computation, even on a minute basis, of the solar energy flux. The only exception to this are clouds, but their presence may be simulated with a stochastic approach without losing much precision and without losing information on the gradients of solar energy flux values. Besides, some information on clouds is generally available, in that they are an important component in determining the radiative equilibrium of the Earth. This information permits a day-to-day match of solar energy flux density with, for instance, experimental values. This is of paramount importance for load profiles (e.g., analysis of the homeostasis of electrical energy obtained through solar energy conversion with the utilities grid).

This approach has been chosen because it appears that an analytical model of the atmosphere may be realized, up to a certain degree of precision, using available standard meteorological measurements. Its precision appears to be comparable to the precision (or anyhow to the real information content) of the solar energy flux measurements (obviously affected by errors and "local" effects that distort their real information content). An increase in precision of the physical model is theoretically possible, but it would then be problematic to find the necessary input data, i.e., the phenomena involved in the selective interaction of electromagnetic solar flux and the components of the atmosphere may be described, in a relatively simple way, by the classic-physics approach, but the information needed to perform the calculation (information on the atmospheric system) is not available.

This same concept of information content approach has eliminated the regression models, e.g., computing the direct component of this energy flux from its global component or computing historical data from actual data.

Another reason why this approach has been used is that our purpose is to obtain a day-to-day (or hour-to-hour) match of computed to experimental data, as has been shown previously with the homeostasis example. That is, we are mainly interested in a deterministic approach; this is why other powerful stochastic (non-deterministic) approaches, although considered, have been abandoned (e.g., Monte Carlo methods).

The analytical model should therefore behave as a "transfer function: for the "normalization" of the solar energy input.

The solar energy radiative characteristics are presented in Chapter 1 and radiation laws are recalled in Appendix A1; the computation of astronomical parameters is performed in Chapter 2; the selective interaction between the electromagnetic energy and the components of the atmosphere is discussed in Chapter 3; the solar energy flux depletion model is presented in Chapter 4, where the mathematical algorithm is developed; the correlation of the energy flux depletion to the meteorological parameters (on a macro- and micro-climatic approximation) and the analysis of the meteorological input data (as well as alternative ways of computing some of the input data) are performed in Chapter 5 and Appendices A2, A3, A4, A5, and A6.

Chapter 6 (in Volume II) contains the implementation criteria of the global energy flux model. The characteristics of the CIRR2 code obtained upon implementation of the analytical model are reported in Appendix A7 (Volume II); the analysis of the final results and samples of output information are reported in Chapter 7 (Volume II). Direct and diffuse components computation will be performed in Volume III.

Finally, Volume IV will report overall analysis performed with CIRR's codes (all related to the input definition).

It should be noted that the input definition of Solar Energy Conversion Systems is viewed as an introduction and not as a conclusion to this work, which aims to develop a techno-economical feasibility and optimization analysis.

Therefore, the main criteria of development of the analytical model of the atmosphere are related to the fact that, due to the characterization of Solar Energy Conversion Systems, with respect to Primary Energy Conversion Systems, the solar energy input should be known following certain requirements. It has been briefly shown how those requirements are satisfied by the approach chosen. It would be proper, for the future development of the work, to stress the real content of those requirements, which follows directly from the characteristics of the Solar Energy Conversion Systems. Those characteristics become evident from a rigorous definition of Solar Energy Conversion Systems. The next paragraphs will be devoted to this task.

Any Energy Conversion System--including one-component systems--that has a partial or total energy input solar energy radiative flux, on either a passive or an active component, is here defined as a Solar Energy Conversion System. A further condition, imposed on the output of the energy conversion system, is that the output supplies a load that, independent of its entity or entropy content, would otherwise be covered by primary energy--i.e., energy available through conversion of natural high-available-energy "fuels"--or would not be covered at all. This is the definition that will be used in the following volumes, when performing the techno-economical feasibility analysis.

Many differentiations among Solar Energy Conversion Systems have been proposed and adopted, depending on the type of analysis performed either on systems or components differentiations, on materials technology differentiations, on the end use of the energy converted, or on the temperature at which this energy is available.

In this work, the definition of the different Solar Energy Conversion Systems will be based mainly on the type of physical phenomena involved in the conversion, or the level of availability of the energy output and/or the type of technology employed [1].

A Solar Energy System with no machinery, i.e., no dynamic component or dynamic artificial working fluid, whose main function is to trap and not to convert the solar energy within the system, will be defined as a Passive Solar Energy System, or as a Solar Energy System. The component definition is implicit above. It should be emphasized that the so-called passive systems are not considered as Solar Energy Conversion Systems, since they do not convert or even transport energy. This is non-trivial information, although it will be used mainly on the engineering optimization part of this work. As concerns the input definition, many--but not all--of the considerations that will be presented apply to any Solar Energy System [2].

The active systems definition follows, being antithetical. All Solar Energy Conversion Systems are active following these criteria; therefore, we will refer to them just as Solar Energy Conversion Systems.

A first subdivision considered is between direct and indirect conversion systems. The former converts the electromagnetic flux into electrical energy with no machinery or dynamic subsystem or component associated with the conversion phenomenon itself (electromagnetic radiation to electrical energy). Machinery or dynamic modules may be part of the system, though, but are not actively involved in the energy conversion phenomenon itself. The effect of their presence may only optimize the engineering or economic characteristics of the system as a whole. The latter do not convert the electromagnetic energy flux into electricity satisfying the above-mentioned constraints--i.e., they are not based on the same physical phenomenon--or do not convert the electromagnetic flux into electrical energy at all, but into energy generally at lower availability levels.

The indirect energy conversion systems may have, as energy output from the subsystem or component involved in the energy conversion, energy at high or low availability. The threshold between the two different levels of availability is arbitrarily taken as the availability that would correspond to energy furnished as heat at 100 °C and 1 atm. of pressure, with respect to the ambience at 20 °C. This is only a reference value, and varies, for instance, with location and period of the year. This apparently complex definition corresponds to the differentiation between low-temperature and high-temperature conversion systems.

Those are the considerations that concern the phenomena involved and the thermodynamics of the conversion ("physical phenomena").

The systems may also be differentiated by their technical or operative characteristics (concentrators or not, sun-tracking or fixed-collector areas, etc.). Those differentiations will be considered as second order, in the sense that all the systems will be primarily defined in the optic previously presented [3].

The engineering of these Solar Energy Conversion Systems requires the knowledge of both the values and the dynamics of variation of the design parameters. The latter is information of paramount importance to engineering optimization of the system, since the components and system's design approach employed is the classical non-steady state conditions of operation design (transient operation mode) [4,5]. The variations caused by this operation on some of the design variables may induce critical conditions of system operation (when approaching a limit curve of component operation) and strongly affects the reliability and efficiency of the system [6].

As has already been pointed out, those characteristics of the Solar Energy Conversion System affect not only the engineering but also the economics of the system, and act on the overall efficiency. They are important and should be considered in any energy policy analysis, since they impose certain limitations on the conversion system [7].

There is, indeed, a well-defined difference between the traditional approach to primary energy conversion systems and the also traditional approach to energy conversion systems, in that the differentiation of the energy input involves a different mode of operation of the two systems. Therefore, the overall performance of the Solar Energy Conversion System will depend upon all those parameters that affect the solar energy radiative flux [8].

Implications are : (i) A sensible variation in the instantaneous efficiency of the energy conversion: operating conditions cannot be generally identified with the optimal conditions of operation; this introduces: (ii) A difficulty in the optimization of the system and consequently, a greater importance of economic factors. (iii) The necessity of an energy storage facility. (iv) The energy input of the solar system depends upon the site of the installation (i.e., latitude, meteo-atmospheric conditions); therefore, the whole system's characteristics (i.e., positioning of the collector of Sun-tracking, temperatures, operation mode, etc.) also depends upon the site and so does, consequently, the cost of the energy produced.

The above mentioned "dependence factors" depend themselves upon a high number of variables. Hence the use of computing programs for the simulation of operating conditions for the correct design and optimization, and for an economic evaluation of the system, is both suitable and recommended.

It follows, from what has been said about the design criteria of Solar Energy Conversion Systems, that it is necessary to dispose of a certain amount of (reliable) data on all those parameters that affect the energy input to the system (e.g., astronomical parameters related to the beam's direction, beam, scattered, and global values of the energy fluxes on the collector area), at every "instant," the interval of time magnitude being related to the time constants of the components and the system and to the type of approach; it may go from minute to hourly or daily values [2,5].

Assuming that all the "solar-related parameters," except the solar energy radiative flux values, may be easily computed (and have to be computed: for instance, the inclination of the collector affects, ceteris paribus, the amount of scattered radiation collected, at such a point that, for proper inclinations and orientations and at certain regions of the globe, the global energy collected by the fixed surface might equal the amount of global energy collected by a Sun-tracking, concentrating collector). Let us focus our attention on the solar energy flux values. They should be available in a digitized array form, on the most restrictive conditions on a minute basis, in order to constitute a proper "transfer function;" they should be related both to a specific year (or month or day) and to a typical (not necessarily average) year (or month or day). They should be available for any "Standard Climatic Area" (S.C.A.) or, considering particularly drastic microclimatic condition differences within the S.C.A. considered, for any location. They should be available for the entire world (both for national reasons and for market expansion reasons).

All this implies the need to dispose of a "transfer function" for the "normalization" of the solar input, in order to consider the engineering of the Solar Energy Conversion System as an interface between the energy load and an energy input perfectly defined, following the requirements imposed by Solar Energy Conversion Systems themselves.

The Solar Energy flux data has been furnished by the Solar Energy Meteorological Research and Training Site at the Atmospheric Sciences Research Center of the State University of New York at Albany.

The meteorological data has been furnished by Mr. William J. Drewes, Meteorologist in charge of the Weather Service Forecast Office of N.O.A.A. at Albany, New York.

All the information related to SOLMET format, digitized records has been obtained through Mr. F. Quinlan, Chief Climatological Analysis Division, National Climatic Center, Environmental Data Service, U.S. Department of Commerce.

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CHAPTER 1

SOLAR RADIATION

The Sun's radiation covers practically the entire electromagnetic spectrum, from X-rays and cosmic rays through radio waves up to wavelengths of several tenths of meters. Some of these emissions are strongly limited in time—i.e., they are intensive only under very particular conditions—and the spectrum in which the Sun emits its maximum energy is sensibly more limited: an order of magnitude of variation of the wavelength around the visible range that lies between 4000 and 7000 Å.

The temperature at the center of the Sun is estimated to be about 15 million degrees Kelvin. However, the photosphere (having a depth of about 0.0005 solar radius), from which most detectable radiation is emitted, has a temperature ranging from 4500 to 7500 degrees Kelvin. The effective blackbody temperature, i.e., the temperature a perfect radiator would have in order to irradiate the measured amount of radiation, is about 5800 degrees Kelvin [9,10,11].

1.1 SOLAR CONSTANT COMPUTATION

The energy balance of the Sun-Earth system, under the hypothesis that the dynamics of energy exchange consists of one emission and one absorbance only, is easily derived by applying three basic laws of irradiance (see Appendix A1):

i. Stefan-Boltzmann's Law for the emission of the Sun, W_S is:

$$W_S = 4 \pi R_S^2 \varepsilon \sigma T_S^4 \quad [W] \tag{1.1}$$

where:

R_S	=	Sun's radius [m]
ε	=	Sun's emissivity (or graybody factor) [adimensional]
σ	=	Stefan-Boltzmann's constant [W m-2 K-4]
T_S	=	Sun's temperature [K].

ii. The "solar constant," i.e., the solar energy flux density outside the atmosphere, E_S, is:

$$\bar{E}_S = W_S/(4 \pi \bar{\rho}^2) = R_S^2 \varepsilon \sigma T_S^4/\bar{\rho}^2 \quad [W\ m^{-2}] \tag{1.2}$$

where:

$\overline{\rho}$ = average distance Sun-Earth between perihelion and aphelion [m].

iii. Stefan-Boltzmann's Law for the emission of the Earth, W_E, is:

$$W_E = 4 \pi R_E^2 \varepsilon \sigma T_E^4 \quad [W] \tag{1.3}$$

where:

R_E = Earth's radius [m]

T_E = Earth's temperature [K].

The energy balance of the Earth, under the above assumption, brings to (Kirchoff's Law):

$$R_S^2 T_S^4/\overline{\rho}^2 = 4 T_E^4 \tag{1.4}$$

Always assuming $\overline{\rho}$ as an average value between the apihelion and the perihelion of the Earth's orbit, $\overline{\rho}$, and T_E = 288 degrees Kelvin [12], from eq. 1.4 we obtain for T_S a value very close to 5900 degrees Kelvin. Hence, from eq. 1.2:

$$\overline{E}_S = R_S^2 \; \epsilon \; \sigma \; T_S^4 / \overline{\rho}^2 = 1380 \pm 30 \quad [W \; m^{-2}] \tag{1.5}$$

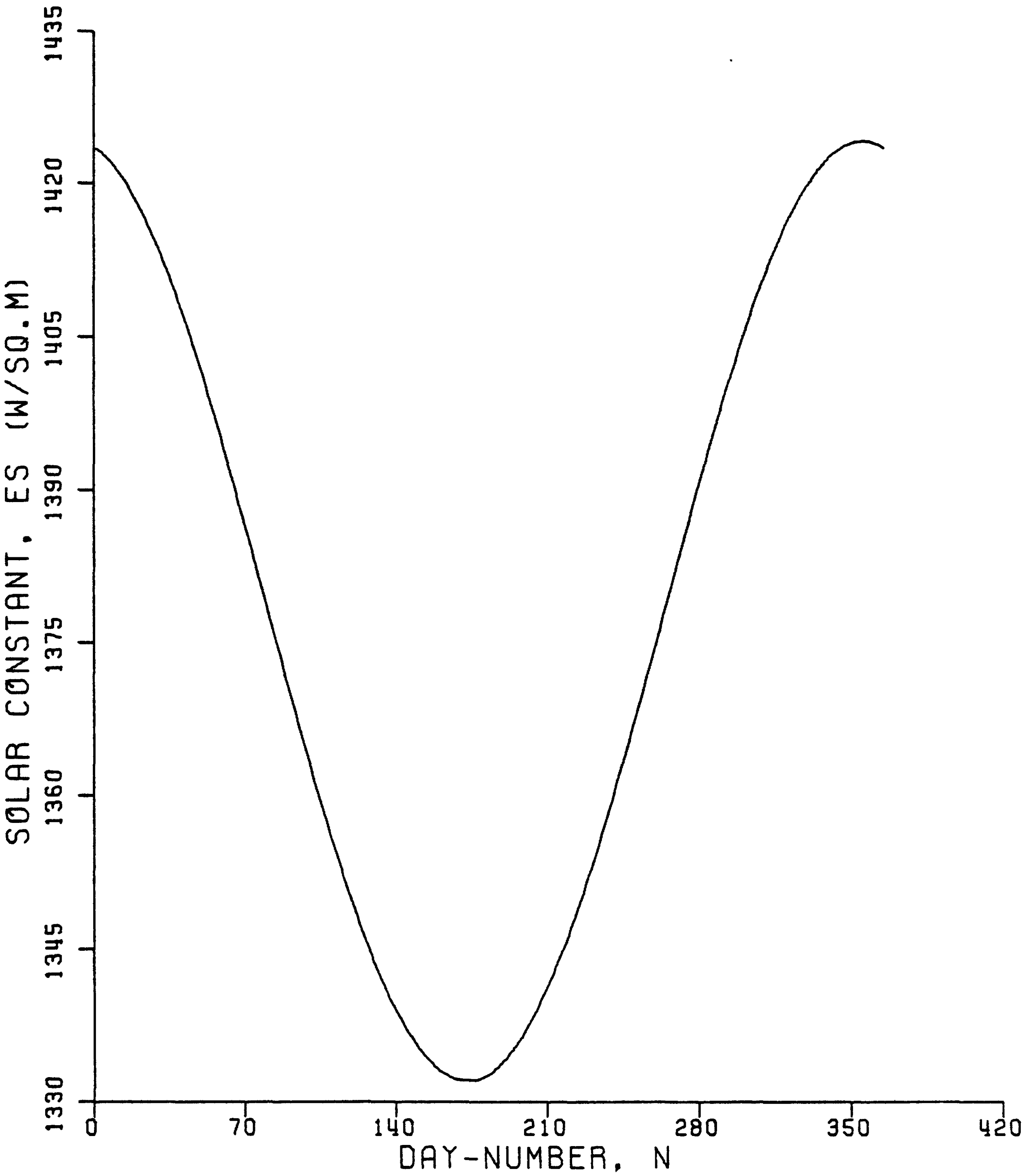
For the computation of the "instantaneous" values of the extraterrestrial density of energy flux, E_S, the "instantaneous" distance Sun-Earth, ρ, must be computed (eq. 2.1). Therefore:

$$E_S = (\overline{\rho}/\rho)^2 \; \overline{E}_S \quad [W \; m^{-2}] \tag{1.6}$$

The plottage of eq. 1.5 versus day number is reported on the following page.

Planck's Law, which is a compendium of all the irradiation laws, consents to make up the spectral analysis of the irradiation [13].

The solar spectrum is also furnished by the NASA-NASA Spectral Irradiance Values at mean Sun-Earth distance.


SOLAR CONSTANT, ES (W/SQ.M)
1330
1345
1360
1375
1390
1405
1420
1435
0
70
140
210
280
350
420
DAY-NUMBER, N

CHAPTER 2

ASTRONOMICAL PARAMETERS

2.1 SUN-EARTH DISTANCE

This section considers the ideal case of a pure Sun-Earth Newtonian system.

The parameters of the Earth orbit are known. From the equation of the ellipse in polar coordinates, it is possible to derive, through a trivial computation, the instantaneous distance between the Sun and the Earth, ρ, as a function of the anomaly ξ (see Figures 1 and 2):

$$\rho = p/[1 + e \cos(\xi)] \tag{2.1}$$

$$\xi = (N + 10)\ 2\ \pi/365 \tag{2.2}$$

where:

N = progressive number of the days of the year, first of January, N = 1.

2.2 DECLINATION ANGLE

The rotation axis of the Earth is inclined with respect to the normal to the plane of the ecliptic, at an angle $\zeta = 23^\circ\ 27'$.

This angle varies, owing to the precession motion; the period of such motion is 25,800 years. The correspondent variation of ζ is only a few seconds a year, and may be neglected.

The declination, δ, is defined as the angle between the line connecting the center of the Earth to the center of the Sun and the equatorial plane, i.e., the angle that the solar beam forms with the equatorial plane (see Figures 3, 4, and 5).

The declination takes into account the dependence of the inclination of the energy beam upon the Earth's position in its orbit, even being a constant.

The inclination ζ influences, ceteris paribus, the total irradiance on the ground and is the cause of the Earth's seasonal cycles. At the summer and winter solstices, δ equals $+\zeta$ and $-\zeta$ respectively; at the equinoxes, δ equals zero and the length of day equals the length of night, thus:

$$-23^{\circ}\ 27' \leq \delta \leq +23^{\circ}\ 27'.$$

The value of δ may be derived within an approximation of 20' - 30', from the following expression:

$$\delta = 23^{\circ}\ 27' \cos[180(A + N + T/24)/186]^{\circ} \quad [\text{deg}] \qquad (2.3)$$

where:

A = 13 (12 on leap years) [adimensional]

T = G.M.T. (Greenwich Mean Time) [hours].

The declination δ varies from 0 to $\pm\zeta$ every 365/4 days: a variation of about 15' a day. In the calculations we will assume a daily average value for δ, called δ_0, obtained from eq. 2.3 for $T = 12$.

2.3 AZIMUTH AND ALTITUDE OF THE SUN

The instantaneous position of the Sun with respect to a frame solidary with the Earth determines the trajectory of the apparent motion of the Sun.

We will determine the general law that relates the altitude, h, and the azimuth, ψ, of the Sun to the latitude, ϕ, the longitude, λ, and the period of the year, as a function of time.

The latitude and the longitude of point B, where the observer stands, are known.

Using the Eulero formulas, we solve the spherical triangle ABC ("position triangle"), where A is the subastral point of the Sun, B is the observer's position, and C is the extreme pole of the observer's hemisphere (see Figure 6):

$$BOC = a = 90^\circ - \phi \tag{2.4}$$

$$AOC = b = 90^\circ - \delta \tag{2.5}$$

$$AOB = c = 90^\circ - h \tag{2.6}$$

$$\cos(a) = \cos(b)\cos(c) + \sin(b)\sin(c)\cos(\alpha) \tag{2.7}$$

$$\cos(b) = \cos(c)\cos(a) + \sin(c)\sin(a)\cos(\beta) \tag{2.8}$$

$$\cos(c) = \cos(a)\cos(b) + \sin(a)\sin(b)\cos(\gamma) \tag{2.9}$$

2.3.1 Altitude

From eqs. 2.4, 2.5, 2.6, and 2.9 we derive the following equation:

$$\sin(h) = \sin(\delta)\,\sin(\phi) + \cos(\delta)\,\cos(\phi)\,\cos(\gamma) \qquad (2.10)$$

The pole angle, γ, of the position triangle varies with time, because the subastral point of the Sun, A, shifts during the day due to rotation.*

Conventionally, solar time, <u>t</u>, is zero when the subastral point of the Sun is on the antimeridian of the observer. Then:

$$\gamma = 180^\circ - t = 180^\circ - (T + \lambda) \qquad (2.11)$$

2.3.2 Azimuth

The azimuth, ψ, is the angle between the projection on the horizontal plane (plane of the observer) of the meridian and the (instantaneous) Sun-Earth axis. Conventionally, the azimuth is measured clockwise from the North, from 0 to 360 degrees. Thus, the azimuth is equal to the angle β for ψ between 0 and 180 degrees (see Figure 7) and is equal to the complement to 360 degrees of β for ψ between 180 and 360 degrees (see Figure 8):

---

*One complete rotation of the Earth takes 24 hours; one hour corresponds to 360/24 degrees. From now on, angles will be given either in degrees or in hours, assuming implicit conversion when necessary.

$$\psi = \beta_{EAST} \tag{2.12}$$

$$\psi = 360^\circ - \beta_{WEST} \tag{2.13}$$

The angle β varies between 0 and 180 degrees (see Figure 5), East in antimeridian and West in postmeridian hours; the general expression of β (eqs. 2.4, 2.5, 2.6, 2.8) is:

$$\cos(\beta) = [\sin(\delta) - \sin(h)\ \sin(\phi)]/[\cos(h)\ \cos(\phi)] \tag{2.14}$$

2.4 DAYTIME

We assume that the daytime period, D, is equal to the time between geometrical sunrise and sunset.

However, the daytime period is actually higher than the time we assume as D, since the Earth "sees" the Sun under an angle of about 30', and atmospheric refraction brings solar radiation to the ground when the Sun is one degree below the horizon.

From eq. 2.10, recalling that at the instant of sunrise *h* equals zero and calling γ' the angle γ at that instant, we derive the general expression for D as a function of the geographic position and the day of the year:

$$\sin(0) = \sin(\delta)\ \sin(\phi) + \cos(\phi)\ \cos(\delta)\ \cos(\gamma') \qquad (2.15)$$

$$= \mathrm{acos}[-\ \tan(\delta)\ \tan(\phi)] \qquad (2.16)$$

The daily average value of δ is obtained from eq. 2.3, with T = 12. Consequently, recalling the definition of the γ angle (Subsection 2.3.1):

$$D = 2\ \gamma' = [2\ \mathrm{acos}(-\ \tan(\delta_0)\ \tan(\phi))]/15 \quad [\text{hours}] \qquad (2.17)$$

It is easily verified from eq. 2.17, that at the equinoxes, $-\delta = 0$, the length of day is equal to the length of night.

It should be noted, for solar energy applications, that the daytime period does not generally correspond to the period of direct sunshine on an arbitrary surface for obvious astronomical reasons and due to the presence of nonhorizontal skylines (due to natural or artifical obstacles lying in the path of the radiation beam).

This paper will develop one way to compute such an "apparent" daytime on a surface for some typical cases, although the easier computation would be an implicit one, upon implementation of this model [14,15].

2.5 ZENITH ANGLE

The angle formed between the Sun's ray and the normal to the surface under consideration is called the zenith angle, θ (see Figure 9).

The inclination angle of the slant surface, ζ, will be defined as the angle formed between the normal to the surface and the horizontal plane (see Figure 9).

The orientation angle of the slant surface, ψ', will be defined as the angle formed between the projection on the horizontal plane of the normal to the surface and the superior pole. This angle can be visualized if it is thought of as the "azimuth" angle of the normal to the surface (see Figure 9).

It should be noted that, for the complete individuation of a slant surface, two angles are needed. The definition and the choice of the inclination and the orientation given above, however, are arbitrary and do not correspond to any "normalized" (and nonexistent) notation.

Using Eulero's formulas to solve the spheric triangles ABC and A'BC and using the spheric rectangular triangle formulas to solve the rectangular spheric triangles OAB, OA'B, and OBC (see Figure 9), an expression of the zenith angle as a function of Sun's altitude, azimuth, and the inclination and the orientation of the slant surface, is easily obtained:

$$\cos(\theta) = \cos(|\psi - \psi'|)\cos(\zeta)\cos(h) + [1 + \cos(|\psi - \psi'|)\cos^2(\zeta)]^{1/2} \sin(h)\sin(\gamma') \qquad (2.18)$$

where:

$$\gamma' = \mathrm{atan}[\tan(\zeta)/\sin(|\psi - \psi'|)]. \qquad (2.19)$$

2.6 EXAMPLES

This section performs a few computations with the formulas previously defined; they should be considered examples and will provide an idea of the order of magnitude of the computation error.

2.6.1 Declination angle computation

Derive the declination of 15 h 00 m G.M.T. on April 18th of a "common year."

The input data are:

$T = 15.00$ hours, $N = 108$, $A = 13$.

Therefore, using eq. 2.3:

$$\delta = -23^\circ\ 27'\ \cos[.9677(108 + 13 + 15/24)]^\circ = 10.90 \text{ degrees} = 10^\circ\ 54'$$

For a leap year, same day and time, the result would not change because the input data would be $T = 15$, $N = 109$, and $A = 12$. The total between parentheses would be the same.

The ephemerides values of the declination, for the day and time considered, are:

1970 ("common year"): $\delta = +\ 10^\circ\ 49'$

1972 ("leap year"): $\delta = +\ 11^\circ\ 00'$

It should be pointed out that the error changes with the date, but largely within the limits of accuracy.

2.6.2 Solar altitude computation

Derive the solar altitude at Nome, Alaska (lat.: 64° 30' N; long.: 165° 24' W) at 10 h 22 m on February 26th, 1972.

The input data are:

ϕ = 64° 30' N, λ = 165° 24' W, t = 10 h 22 m, N = 57,
A = 12

The longitude value shows that Nome is eleven hours West of Greenwich (the eleventh time zone West going from λ = 157° 30' to λ = 172° 30'). Therefore, the correspondent G.M.T. may be computed:

local time + 11 h 00 m = G.M.T.
10 h 22 m + 11 h 00 m = 21 h 22 m G.M.T.

Conversion of G.M.T. into degrees:

(21 h 00 m + 22/60)15 = 320.50 degrees = 320° 30'

The γ angle is computed from eq. 2.11:
γ = 180° - (320° 30' - 165° 24') = + 24° 54'

Proceeding as indicated by Subsection 2.5.1, the declination is computed:

$$\delta = -8^\circ\ 55'$$

The exact value of the declination, from the ephemerides, is $-8^\circ\ 48'$.

The solar altitude, <u>h</u>, is computed from eq. 2.10:

$$h = \text{asin}[\sin(-8^\circ\ 55')\ \sin(64^\circ\ 30') + \cos(-8^\circ\ 55')\ \cos(64^\circ\ 30')\ \cos(24^\circ\ 54')] = 14.23 \text{ degrees}$$
$$= 14^\circ\ 14'$$

or, with the exact value of the declination:

$$h = \text{asin}[\sin(-8^\circ\ 48')\ \sin(64^\circ\ 30') + \cos(-8^\circ\ 48')\ \cos(64^\circ\ 30')\ \cos(24^\circ\ 54')] = 14.34 \text{ degrees}$$
$$= 14^\circ\ 20'$$

2.6.3 Solar Azimuth Computation

Derive the solar azimuth at Nome, Alaska (lat: 64° 30' N; long.: 165° 24' W) at 10 h 22 m on February 26th, 1972.

The input data are:

$\phi = 64^\circ\ 30'$ N, $\lambda = 165^\circ\ 24'$ W, $t = 10$ h 22 m

and, from Subsections 2.5.1 and 2.5.2:

$\delta = -\ 8^\circ\ 55'$ (exact value: $-\ 8^\circ\ 48'$)

$h = 14^\circ\ 14'$ (exact value: $14^\circ\ 20'$)

From eq. 2.14 the β angle of the "position triangle" is computed:

$$\beta = \mathrm{acos}\left[\frac{\sin(-\ 8^\circ\ 55') - \sin(14^\circ\ 14')\ \sin(64^\circ\ 30')}{\cos(14^\circ\ 14')\ \cos(64^\circ\ 30')}\right]$$

$= 154.59$ degrees East $= 154^\circ\ 35'$ E

or, with the exact values of δ and $\underline{h}$:

$$\beta = \mathrm{acos}\left[\frac{\sin(-\ 8^\circ\ 48') - \sin(14^\circ\ 20')\ \sin(64^\circ\ 30')}{\cos(14^\circ\ 20')\ \cos(64^\circ\ 30')}\right]$$

$\psi = 154.48$ degrees East $= 154^\circ\ 29'$ E

Thus, from eq. 2.12:

$\psi = 154^\circ\ 35'$ (exact value: $154^\circ\ 29'$)

2.6.4 Geometrical Daylength Computation

Compute the length of the day at Nome, Alaska (lat: 64° 30' N; long.: 165° 24' W) for April 18th, 1970:

Since the precession motion is not being considered, the year datum will not be used as input. The longitude will not affect the daylength.

The input data are:

$\phi = 64^\circ\ 30'$ N, N = 108, A = 13

From Subsection 2.6.1:

$$\delta_0 = -\ 23^\circ\ 27'\ \cos[.9677(108 + 13 + \tfrac{12}{24})]^\circ = 10.85 \text{ degrees}$$
$$= 10^\circ\ 51'$$

From eq. 2.17:

$$D = [2\ \text{acos}(-\ \tan(10^\circ\ 51'))\ \tan(64^\circ\ 30')]/15$$
$$= 15.16 \text{ hours} = 15 \text{ h } 10 \text{ m}$$

or, with the exact value of the declination:

$$D = [2\ \mathrm{acos}(-\tan(10^\circ\ 49'))\tan(64^\circ\ 30')]/15$$

$$= 15.15 \text{ hours} = 15 \text{ h } 09 \text{ m}$$

2.6.5 Problems

Further examples might be:

1. Computation of the meridian altitude of the Sun (i.e., maximum daily altitude of the Sun for a given location):

$$h_{max} = 90^\circ - (\phi + \delta_o) ,$$

2. Meridian altitude at the tropics for solstices and equinoxes,

3. Pole angle, γ, value at noon,

4. Geometrical sunrise and sunset azimuth angles, for a given location on a given day,

5. Declination angle value at the equinoxes (as a function of latitude),

6. Declination angle value at the solstices,

7. Geometrical day length at the Equator for solstices,

8. Geometrical day length at the Arctic Polar Circle for solstices,

9. Geometrical day length for an equinox (is it possible, without specifying the location?), and

10. Geometrical length of the polar night.

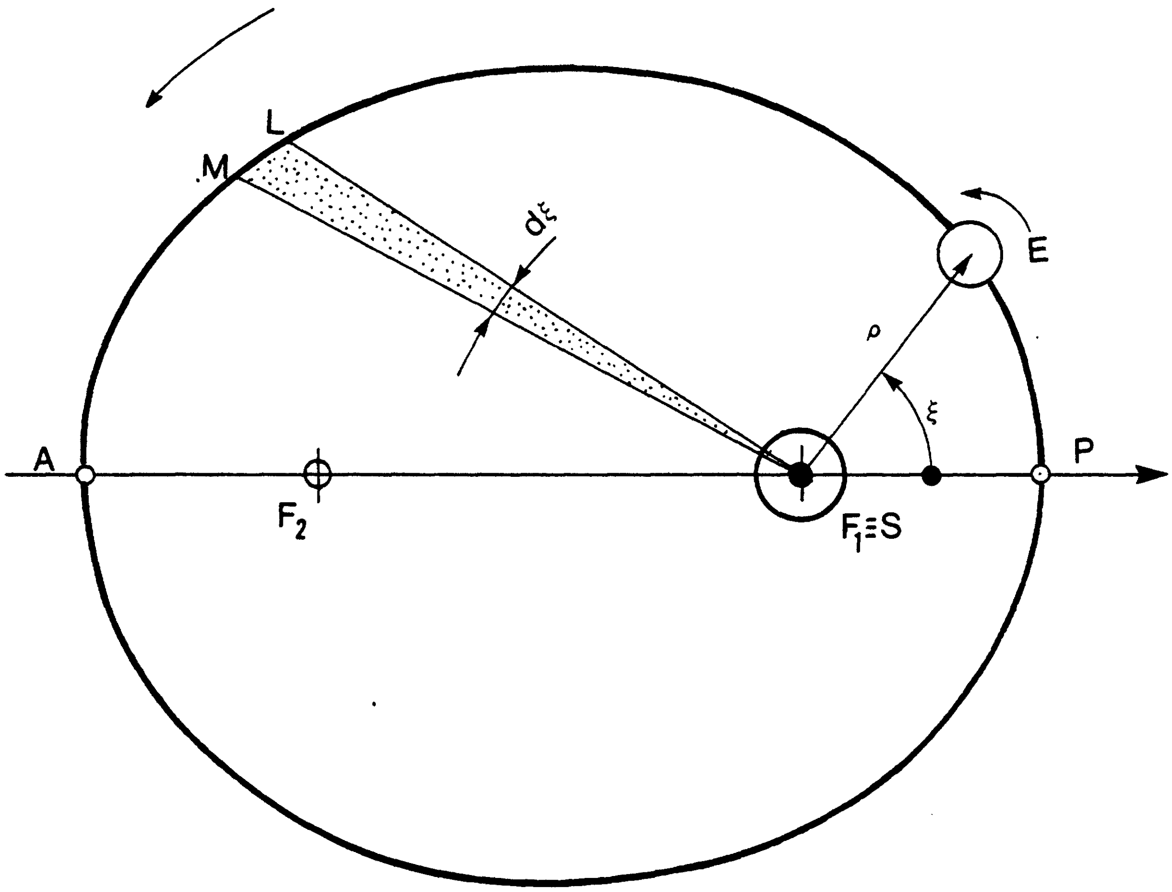


Figure 1 THE EARTH ORBIT

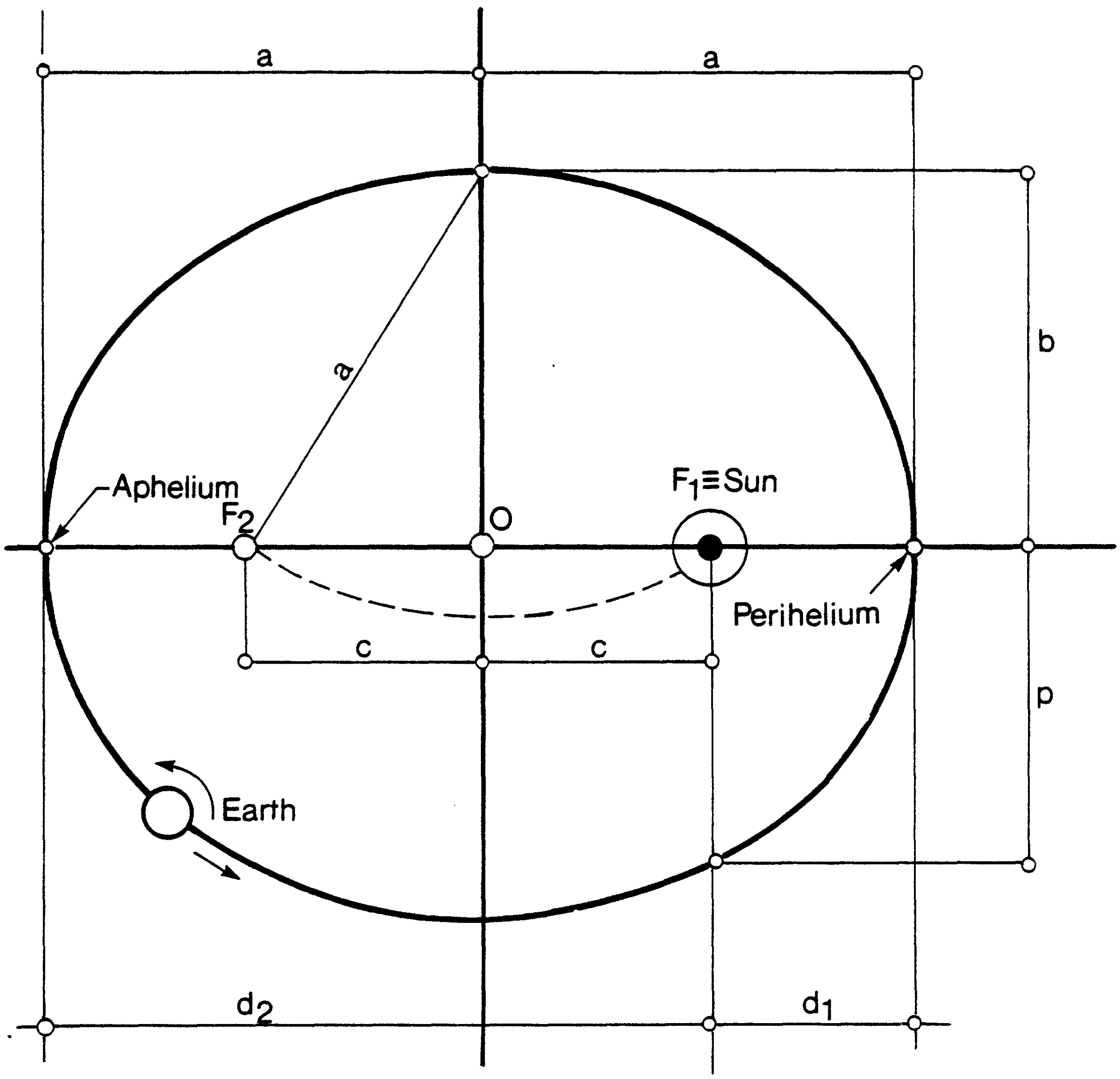


Figure 2 THE EARTH ORBIT

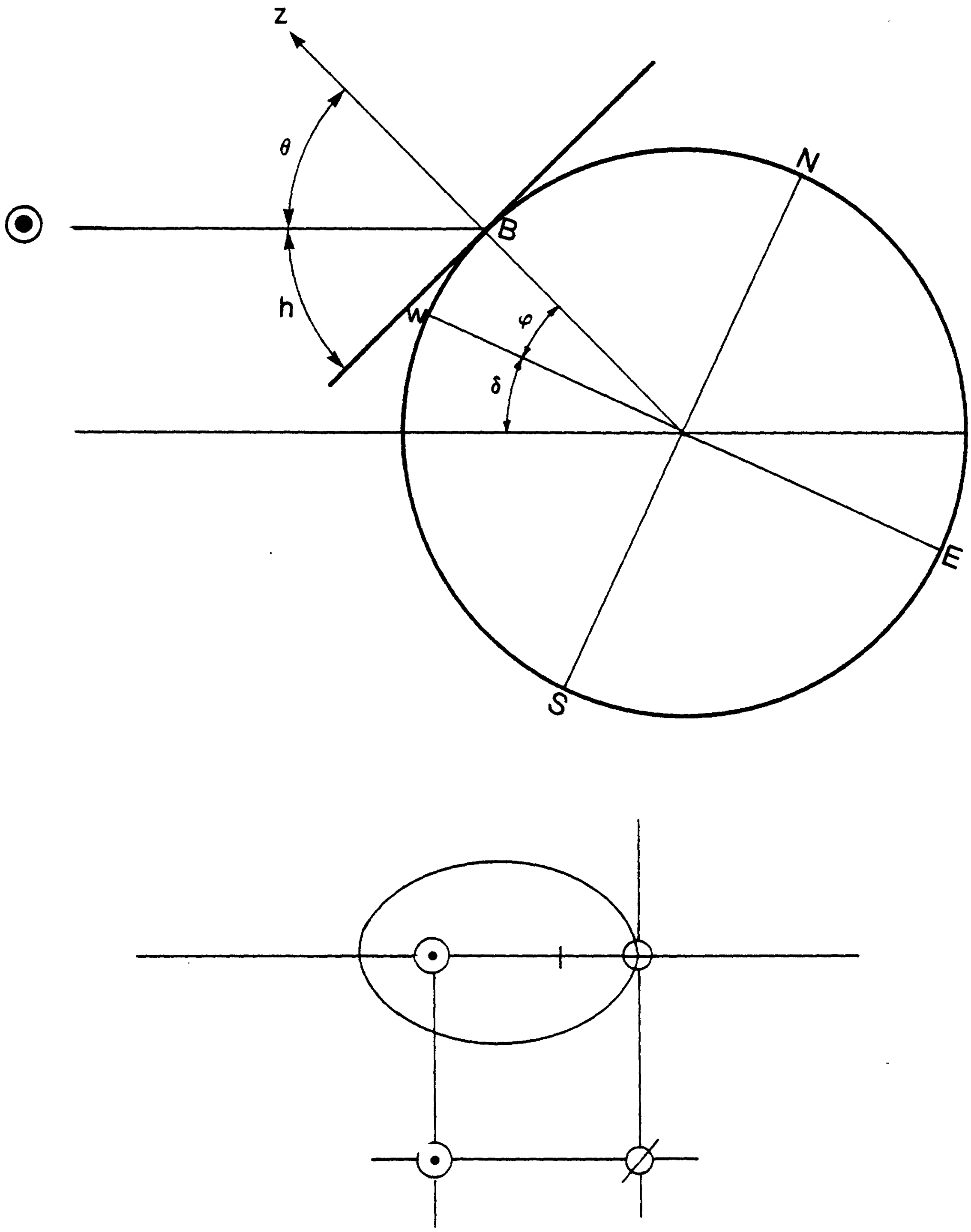


Figure 3 THE DECLINATION, THE ALTITUDE AND THE ZENITH

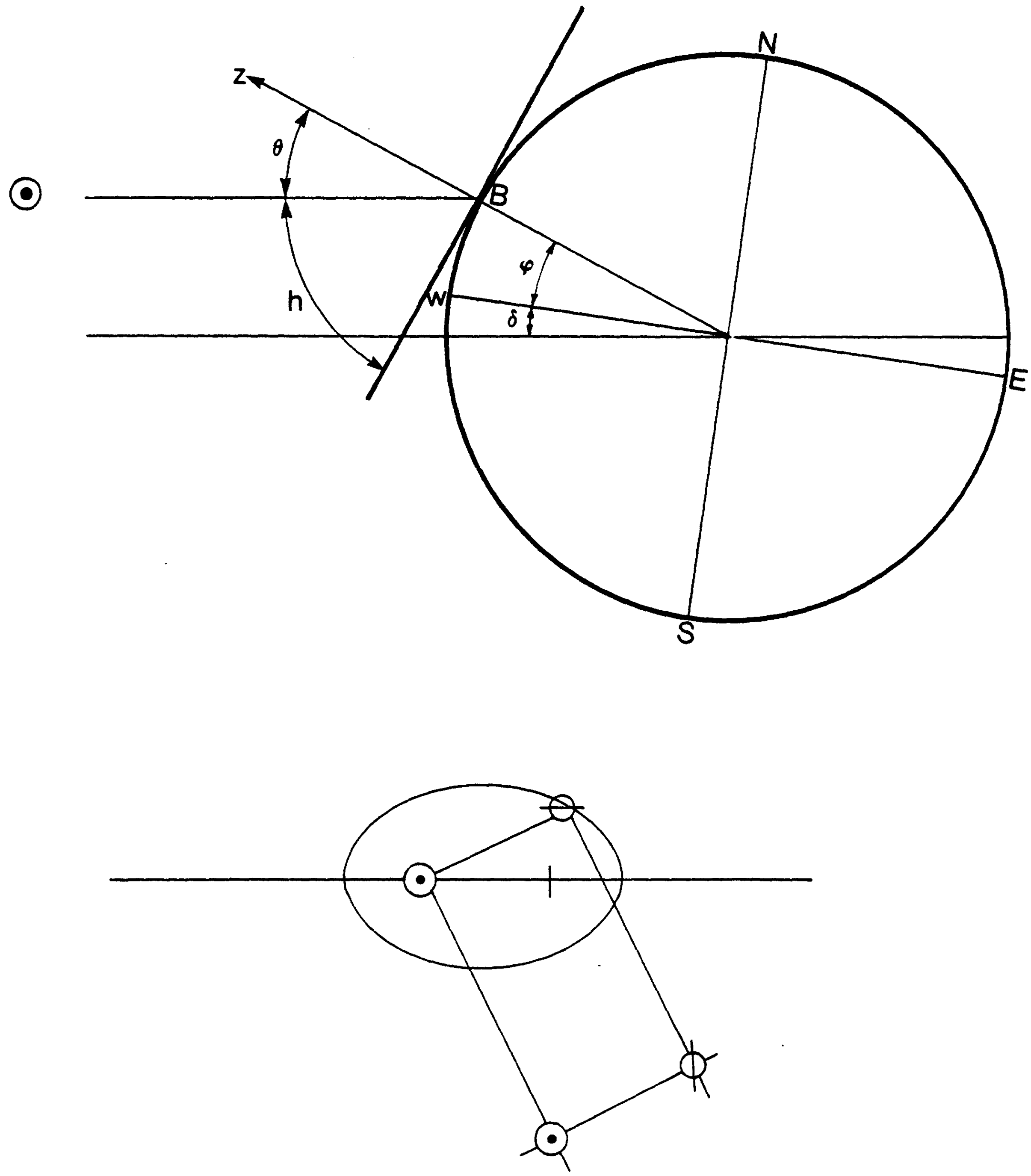


Figure 4 THE DECLINATION, THE ALTITUDE AND THE ZENITH

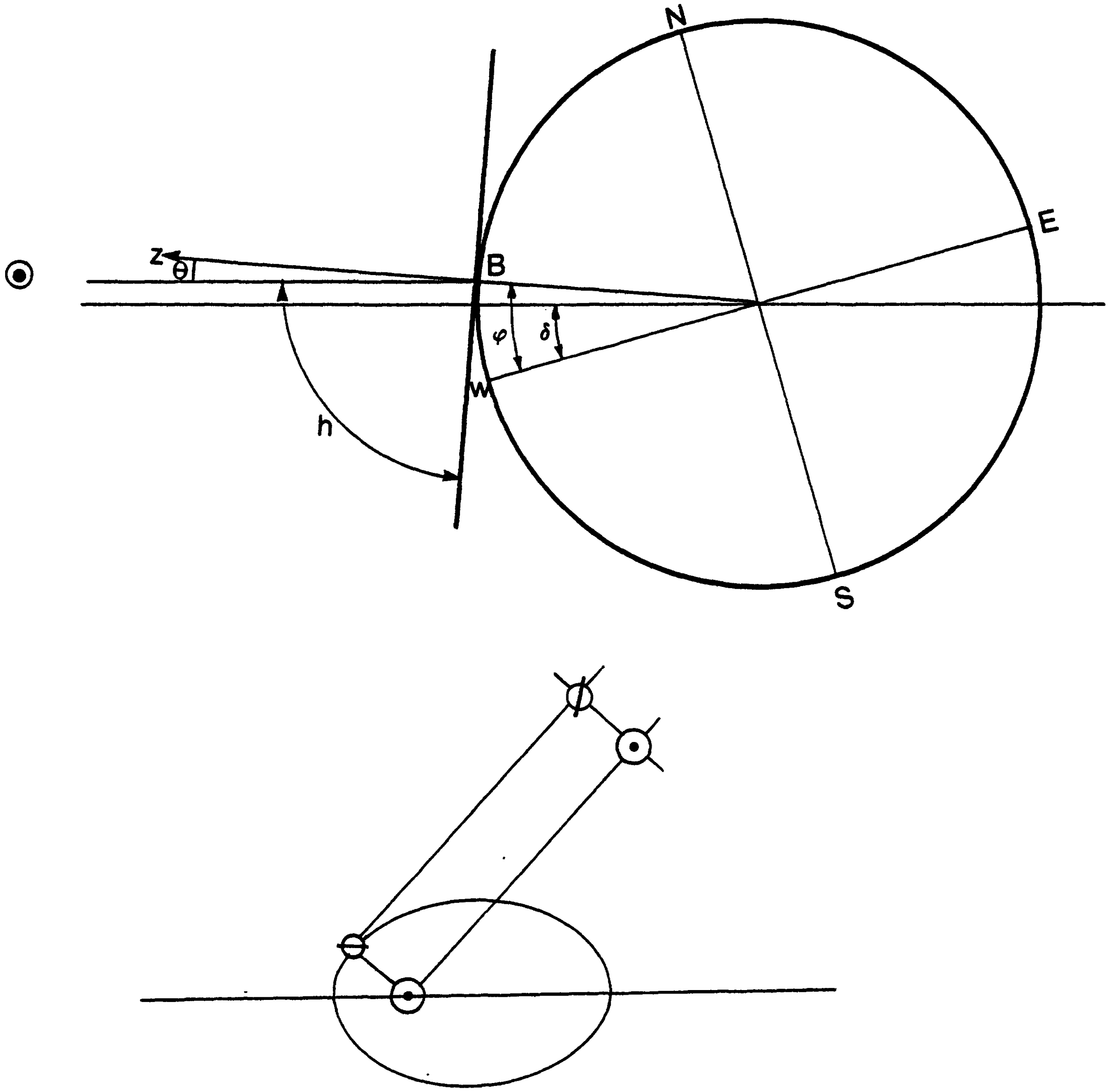


Figure 5 THE DECLINATION, THE ALTITUDE AND THE ZENITH

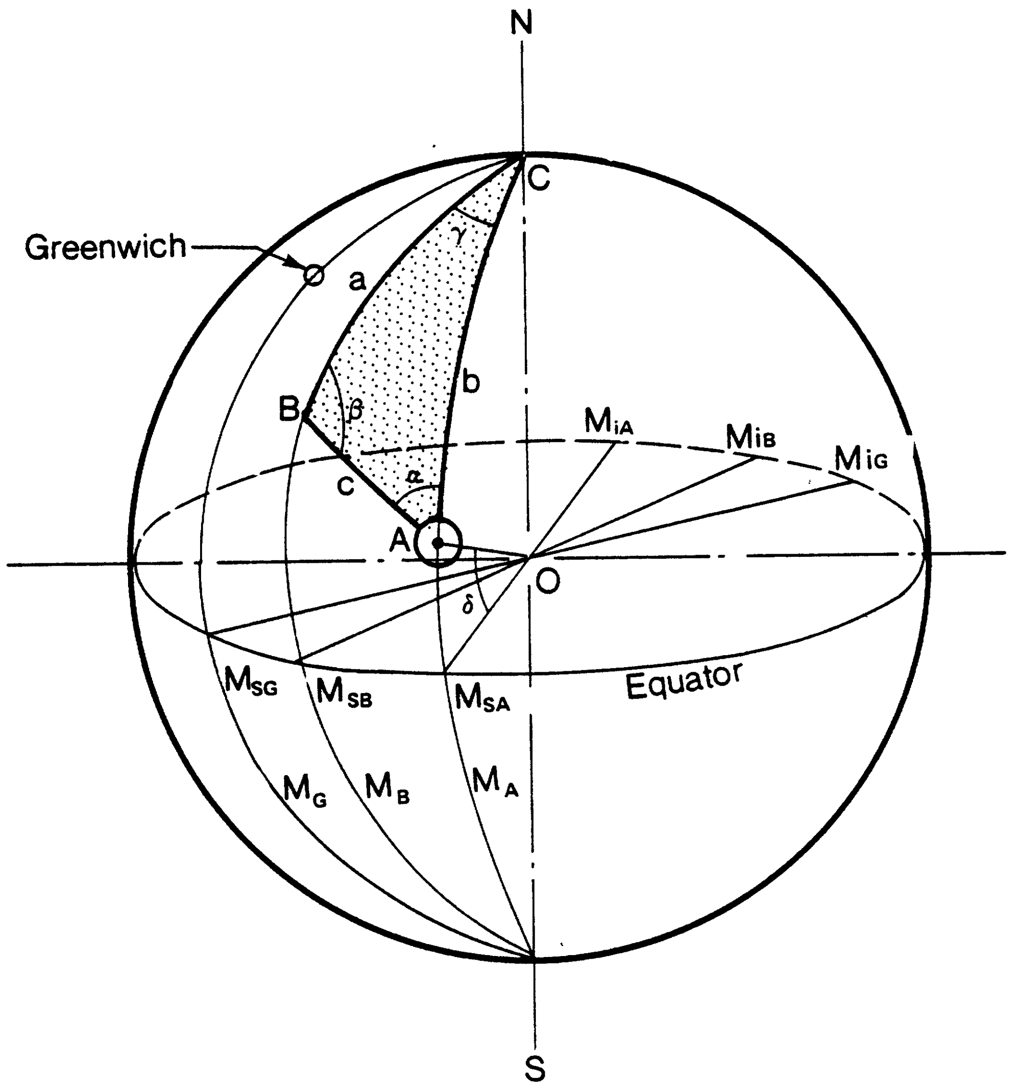


Figure 6 THE "POSITION TRIANGLE"

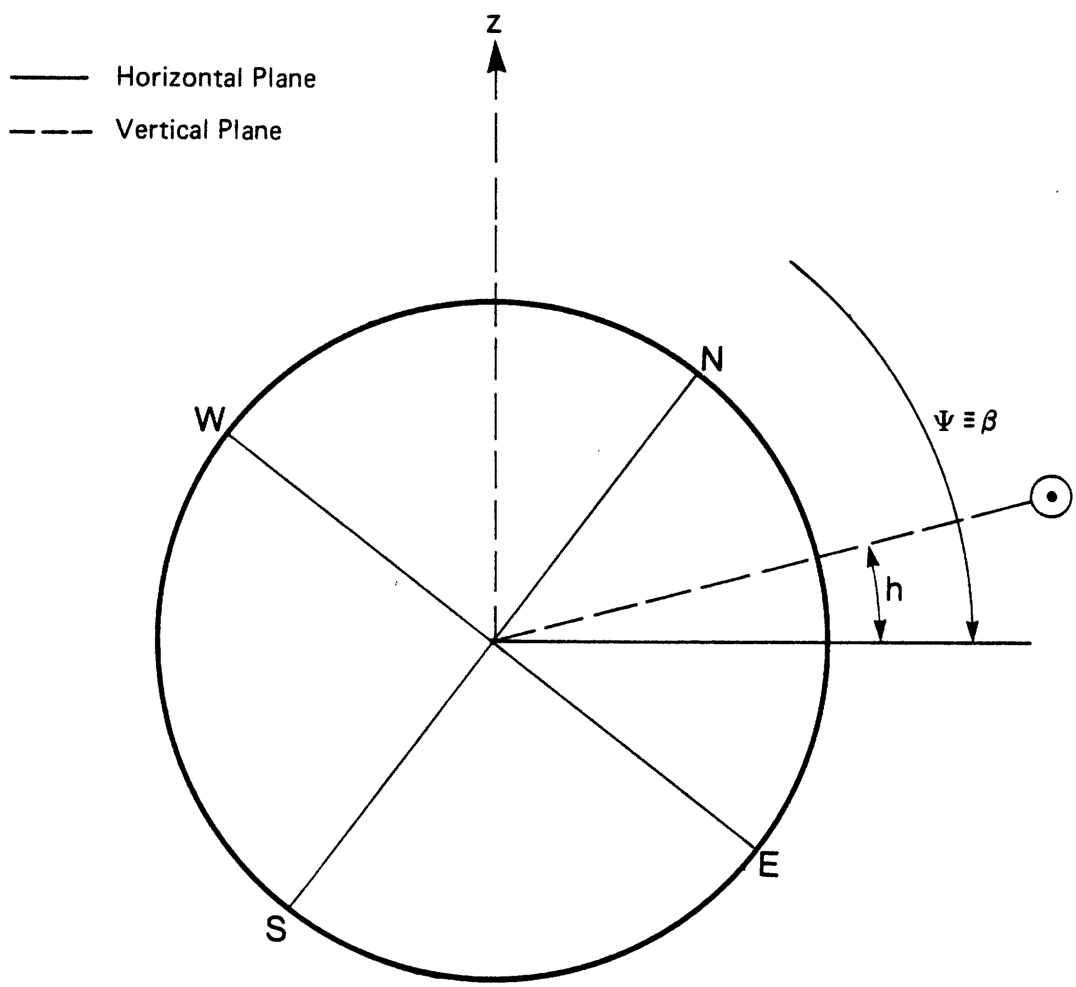


Figure 7 THE AZIMUTH

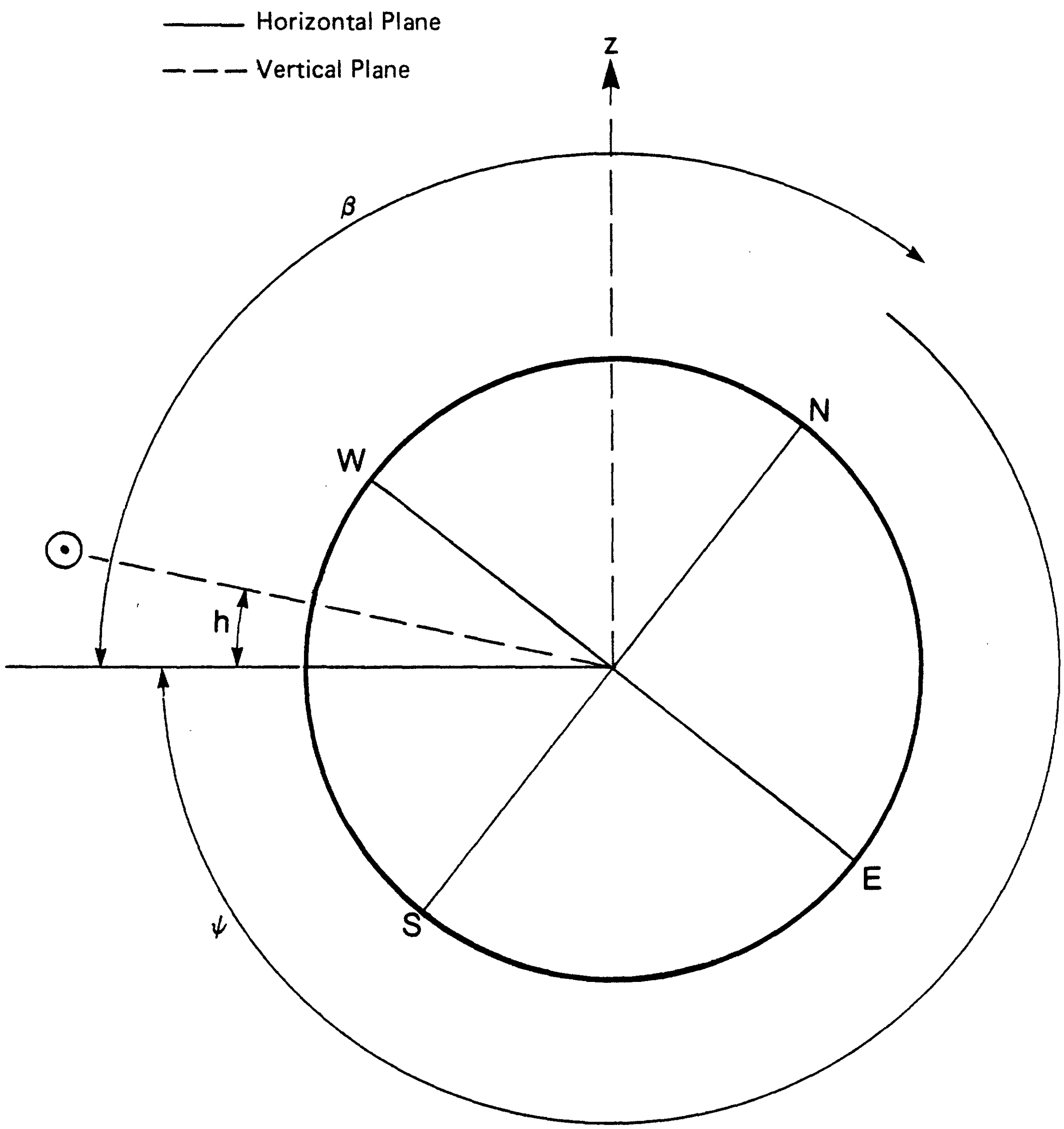


Figure 8 THE AZIMUTH

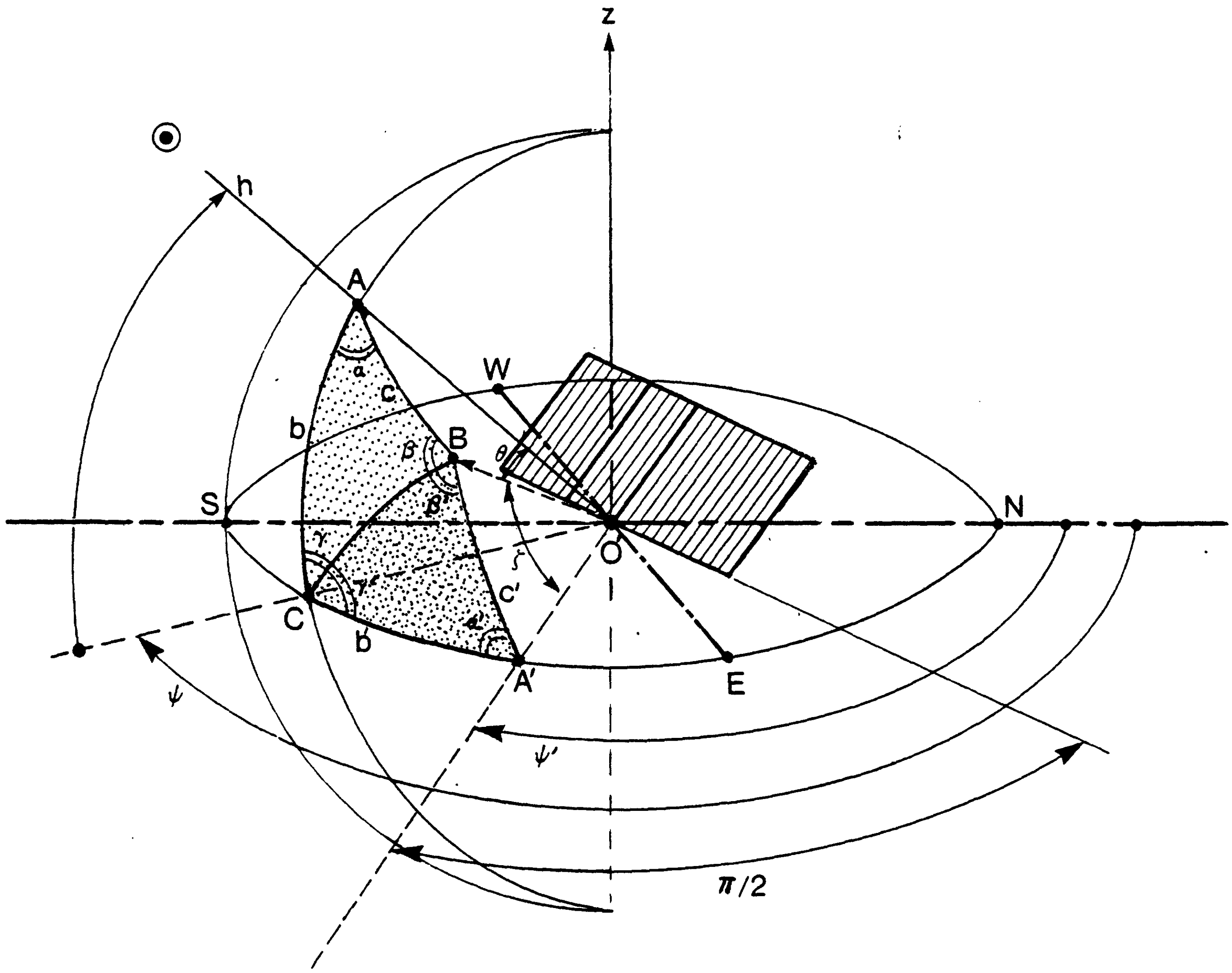


Figure 9 THE ZENITH ANGLE

CHAPTER 3

INTERACTION OF THE SOLAR RADIATION WITH THE ATMOSPHERE

The interaction of the beam of radiative energy with components of the atmosphere causes a depletion in the beam's intensity and an alteration in the beam's characteristics, i.e., its spectrum and anisotropy.

The interaction is relative to the corpuscular and wave characteristics of atmospheric components with respect to the solar energy beam spectrum.

This interaction may be quantitatively analyzed in terms of two phenomena: the radiation absorption and the radiation scattering in the atmosphere. Both phenomena affect the intensity and spectral composition of the radiation beam; the latter will also substantially alter the beam characteristic of the incident radiative energy.

3.1 RADIATION ABSORPTION IN THE ATMOSPHERE

The absorption spectrum of the atmosphere extends over an extremely wide range, from X-ray to ultrashort waves. Thus, due to the selective aspect of the interaction, the physical nature of the absorption is highly varied and extremely complicated [16,17].

One fundamental problem is determining the absorption function—or its "complement," the transmission function—for the entire solar spectral interval. It is useful to point out that even under an integral approach, we cannot avoid considering the spectral characteristics of the electromagnetic radiation and its spectral interaction with the atmosphere.

In all cases, the main factor affecting the analysis will be the atmospheric content of the radiation absorbent; however, its behavior is not solely dependent on the spectrum of the incident radiation or on its spectral lines but also in a number of cases on the pressure and temperature of the radiation absorbent.

Theoretically, when knowing the several principles of spectral radiation absorption, the energy distribution of the solar spectrum "outside" the atmosphere, and the dynamic behavior of the atmosphere, it is possible to develop an analytical model of the interaction and, consequently, the energy distribution of the solar spectrum on the Earth, after absorption interaction.

Physically, the definition of the absorption function may be obtained considering only the very fine structure of the absorption spectrum. This is an extremely complicated approach, due to the complexity of the spectrum considered, and even the lines-and-bands model approach is far more precise with respect to the meteorological data available [18-23].

On the other hand, the many empirical relations that furnish the transmittance function of the atmosphere [24] are obtained through largely macroclimatic approaches and the approximations made on the model may exceed the uncertainty and lack of meteorological data. This is probably why existing analytical models of the atmosphere are either extremely complicated, inconsistent with available data, or only empirical approximations.

In order to develop a proper approach for our purposes, let us first briefly and qualitatively examine the characteristics of the absorption spectrum of the various components of the atmosphere. A number of tabulations of the atmospheric components are available and are in fairly close agreement. We will consider the following computation, compiled from various sources by Glueckauf [25]:

Constituent	Percent by Volume	ppm*
	Permanent Gases	
Nitrogen	78.084	
Oxygen	21.946	
Carbon dioxide	0.003	
Argon	0.934	
Neon		18.180
Helium		5.240
Krypton		1.140
Xenon		0.087
Hydrogen		0.500
Methane (CH_4)		2.000
Nitrous oxide		0.500
	Important Variable Gases	
Water vapor	0 - 3	
Ozone		0 - 0.07 (ground level) 0.10 - 0.20 (20 - 30 km)

*ppm = parts per million

Finally, we will consider the atmosphere divided into regions, as shown in Figure 11, using the altitude as an extensive parameter.

Let us finally point out that three quarters of the total mass of the atmosphere is in the troposphere.

3.1.1 The absorption spectrum of water vapor and water

The atmospheric absorption spectrum is schematically presented in Figure 10 [26]: The most intensive absorption bands of the atmospheric gases are clearly individuated.

The main gases of the atmosphere, such as nitrogen and oxygen, contribute only slightly to the radiation absorption. The variable atmospheric constituents, such as water vapor, oxygen and ozone (for the shortwave radiation), and carbon dioxide, nitrogen, oxides, and hydrocarbon combinations (mainly for the thermal radiation) have a number of absorption bands (and lines) in various spectral regions.

As concerns solar radiation, the most intense absorption bands are related to water vapor and ozone in the ultraviolet region of the spectrum. The predominance of the water vapor in atmospheric absorption caused by vibrational-rotational transitions, is existent—and is a well-known effect—also due to the fact that the energy content of the solar spectrum to the frequencies affected by the ozone, is quite low.

The longwave radiation absorption, because it is affecting the re-emitted radiation interaction, although we have mentioned it, is not of interest and will not be discussed further.

Moller [27] has proposed an empirical formula for the calculation of the radiation absorption in the cloudless atmosphere:

$$\text{Rad. Abs.} = \exp[2.3026(-.740 - .347\log(m\,w_\infty)) - .056(\log(m\,w_\infty))^2 - .006(\log(m\,w_\infty))^3)]$$

[cal cm-2 min-1]

where:

m = atmospheric mass

w_∞ = total water vapor content in the atmosphere in the vertical direction [g cm-2].

In order to account for the influence of pressure on the radiation absorption, Moller proposed to use a value of the pressure equal to 7/9 of the pressure of zero altitude.

Ångstrom [28] proposed another formula that also takes into account the scattering of solar radiation:

$$\text{Rad. Abs.} = .10[.23\ w_\infty/(.23\ w_\infty + \beta)]$$
$$.21[1 - \exp(-\ m\ \beta)\ \exp(-.23\ m_\infty)]$$
$$[\text{cal cm}^{-2}\ \text{min}^{-1}]$$

where:

β = optical atmospheric mass caused by scattering.

Both these empirical relations and others available in the literature are in fairly bad agreement. After analyzing the available experimental data, it appears that a statistical approach is the best for the absorption band model.

The water exerts its influence mainly on the thermal radiation region, although water vapor has some nonintense bands on the visible region of the spectrum.

3.1.2 The absorption spectrum of ozone and oxygen

Ozone has several absorption bands in the ultraviolet and far-ultraviolet regions.

The computation of the integral of the solar radiation flux absorbed by the ozone shows that the effect of the ozone on the solar spectrum is extremely reduced (1 - 3 percent) [29].

As concerns the oxygen, there are two visible bands in the visible region, centered at .69 and .75 microns. Two other bands, the Schumann-Runge system and the Herzberg system, are located near the 2-micron region. Their influence on solar radiation absorption is not great. The 1-micron region—Holefield bands—is characterized by the presence of unidentified, nonintensive bands. The main interest in the study and analysis of these bands would be to individualize the bands responsible for the dissociation—ozone "source" bands.

Atomic oxygen intensively absorbs radiation, but only in the far-ultraviolet.

3.1.3 The absorption spectrum of minor radiation-absorbing atmospheric constituents

There are nitrogen oxides (NO, N_2O, N_2O_4, ...,), hydrocarbon combinations (CH_4, C_2H_4, C_2H_6, ...), sulfurous gases, heavy water (H_3O) and other very minor radiation-absorbing components. Their weak and very narrow absorption bands are located mainly in the infrared spectrum, from 3 to 5 microns [30].

As a conclusion we might state that in the case of shortwave radiation the absorption by water vapor strongly predominates, while in the case of longwave radiation (thermal radiation) carbon dioxide also plays an important role.

We will therefore consider water vapor as the only variable component of the atmosphere, at least under a macroclimatic approach, when calculating the transmission function. Although water vapor usually comprises less than 3 percent of atmospheric gases, even under the particularly moist conditions found at sea level, it may absorb up to five times as much solar radiative energy as do all the other gases combined. Although we are not interested in the phenomenon, water vapor's role is predominant also as concerns the gaseous absorption of the terrestrial radiation. A simple explanation of this may be given by analyzing the vibrational and rotational motions induced on the water molecules.

To compute the integral absorption function, two different methods are generally used: the "spectral" method (by Elsevier and by Kondratyev), which uses the spectral absorption characteristics, and the "integral" method (by Brooks and by Robinson), which uses integral absorption data.

3.2 RADIATION SCATTERING IN THE ATMOSPHERE

As has already been pointed out, the scattering of the radiation is the second main process that characterizes the interaction between the radiation beam and the components of the atmosphere, as concerns the solar radiation. For the longwave radiation, the medium's emission should also be taken into account.

The so-called diffuse component of the solar radiation beam on the Earth is the amount of scattered radiation that arrives on the Earth.

Scattering phenomena are present in any location where there is a spatial inhomogeneity of the dielectric constant of the medium in which the radiation is traveling. These spatial inhomogeneities that determine scattering may be caused by fluctuations of a physical parameter that individuates the state of the medium (e.g., air density) and by the localized presence of particular components (e.g., water droplets, dust particles, haze, smoke, etc.).

The first type of scattering is known as molecular scattering. This definition is clearly understood if we take into consideration that in this case the refraction index inhomogeneities are of the same order of magnitude as the conventional "physical" dimensions of molecules.

If the dimensions of the scattering particles are sensibly smaller than the wavelength of the incident radiation (e.g., if the dimensions of the scattering medium are sensibly smaller than the wavelength), then the scattering is Rayleigh scattering (or molecular scattering of Rayleigh).

The scattering caused by water droplets or other "large" components is known as aerosol scattering, or as dry aerosol in the case of dust particles.

Let us consider, in a chemical approach, a scattering medium and a radiation beam traveling within it. For each wavelength, the infinitesimal amount of radiant energy $dE(\lambda, \phi)$ scattered by the components present in an infinitesimal volume <u>dr</u> on an infinitesimal solid angle $d\phi$ on the direction of ϕ—ϕ being the angle between the scattered ray considered and the incident beam—will be:

$$dE_S(\lambda, \phi) = \alpha(\lambda, \phi)\ E(\lambda)\ dr\ d\phi \tag{3.1}$$

where $E(\lambda)$ is the monochromatic density of energy flux of the incident beam and $\alpha(\lambda, \phi)$ is a volume coefficient of radiation scattering, for the wavelength and angle of scatter considered. The α factor will also depend upon the optical properties of the scattering medium. We express α as:

$$\alpha(\lambda, \phi) = \rho(\lambda) \quad \Phi(\phi) \tag{3.2}$$

where $\Phi(\phi)$ is the scattering function that defines the intensity of the scattered ray at an angle ϕ, and $\rho(\lambda)$ is the parameter that takes into account the optical properties of the scattering medium.

To compute the density of energy flux scattered over a solid angle, by <u>dr</u>, eq. 3.1 may be rewritten (following eq. 3.2) as:

$$E_S(\lambda) = 2 \pi \rho(\lambda) \; E(\lambda) \; dr \int_0^{\pi} \Phi(\phi) \sin(\phi) \, d\phi \qquad (3.3)$$

Normalizing dr, the volume scattering coefficient, $\alpha(\lambda)$ may be defined as:

$$\alpha(\lambda) = \frac{E_S(\lambda)}{E(\lambda)} = 2 \pi \rho(\lambda) \int_0^{\pi} \Phi(\phi) \sin(\phi) \, d\phi \qquad (3.4)$$

The theory of electromagnetic scattering would consent the evaluation of the parameter $\rho(\lambda)$ and the function $\Phi(\phi)$. Under an empirical approach, the elaboration of the experimental data available would furnish approximated values of the $\alpha(\lambda, \phi)$ [31-33].

The electromagnetic scattering theory, although very accurate under nonlimitative assumptions in describing molecular and aerosol scattering, requires a complete definition of the scattering medium. This complete definition, particularly for local or aleatory aerosol conditions, is very difficult to obtain.

Once again, empirical relations that are largely macroclimatic are not of interest here. Instead, the widely used semi-empirical approach of Ångstrom [34] will be quoted.

This approach uses a so-called turbidity factor, which may be computed rather precisely from direct irradiance data.

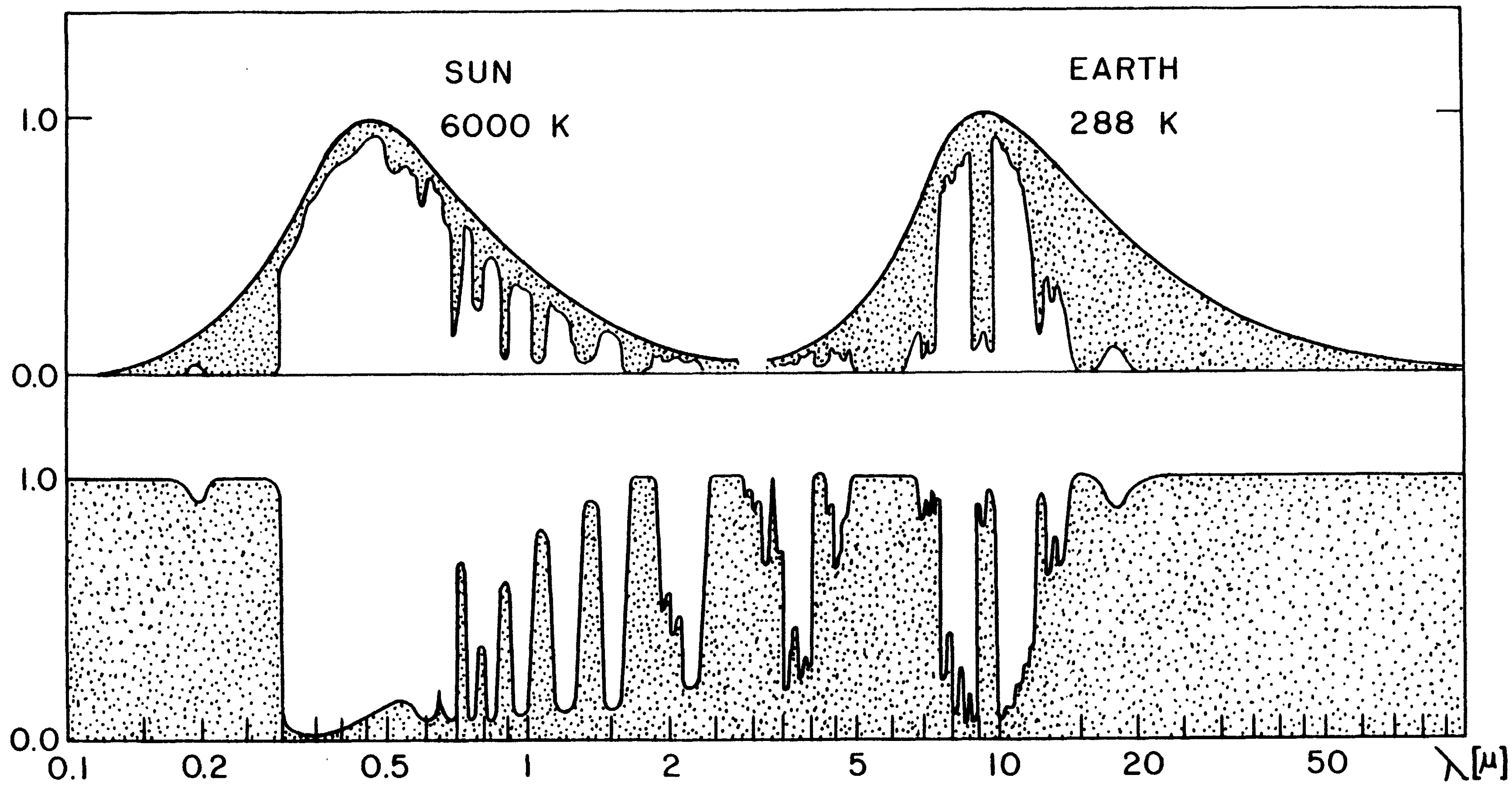


Figure 10 NORMALIZED CURVES OF EMISSION OF SUN AND EARTH
NORMALIZED CURVE OF ABSORBANCE OF THE ATMOSPHERE

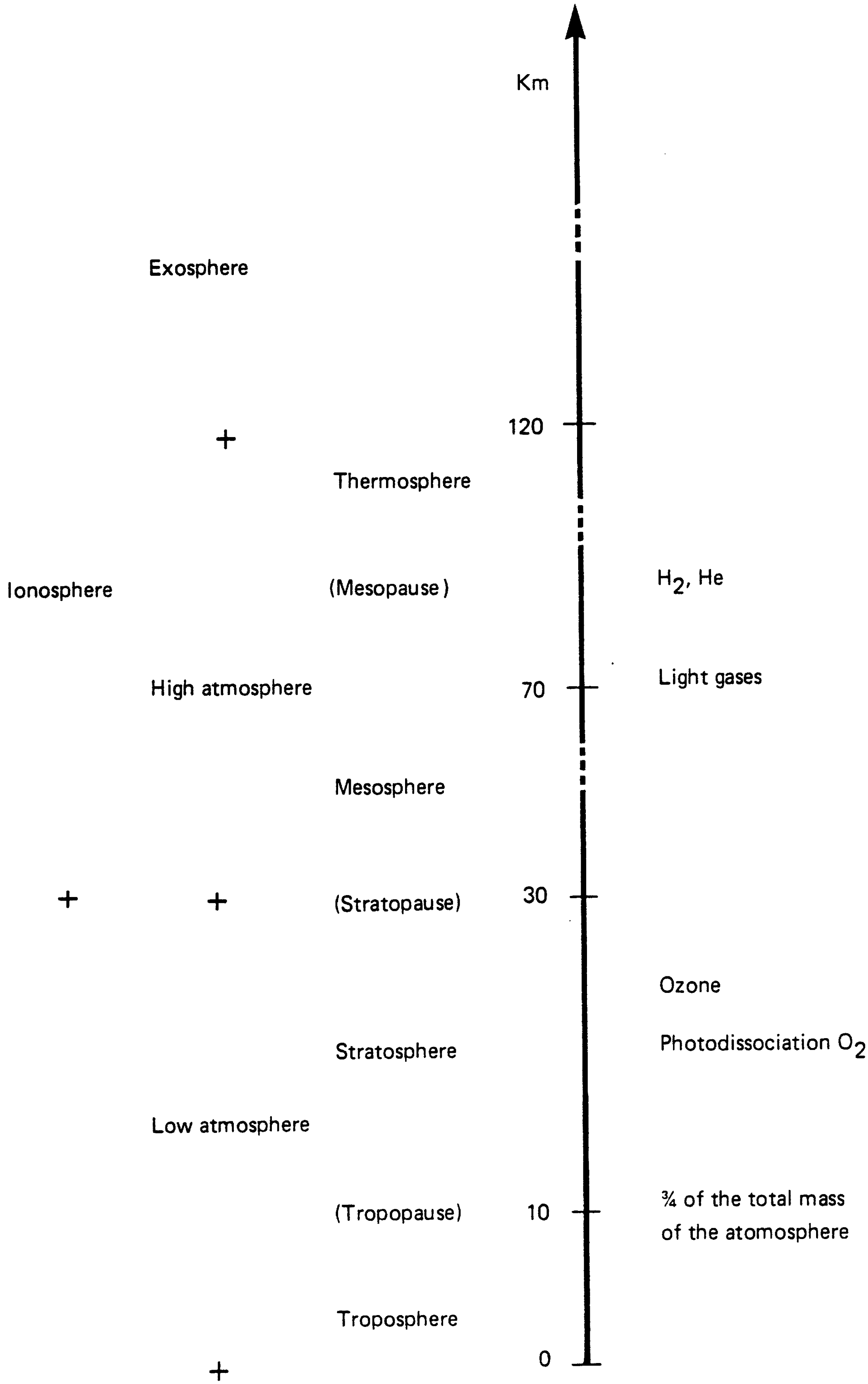


Figure 11 THE ATMOSPHERE

CHAPTER 4

SOLAR ENERGY RADIATIVE FLUX DEPLETION

Chapter 3 performed a general analysis of the interaction of the radiative energy beam with the components of the atmosphere.

This chapter will derive a physical model to describe the solar energy radiative flux depletion in its atmospheric path, taking the input data constraints into consideration.

A simple physical consideration of the interaction of the radiation beam with the atmosphere, accepting the nonlimitative assumption that the gas molecules do not "shadow" each other, will permit the evaluation of the attenuation of a flux of direct radiation, i.e., solar beam, through a slab, dz, of atmosphere of density $\rho(z)$ for each wavelength λ:*

---

*Equation 4.1 might be rewritten as follows: $dE(\lambda)/dz = K(\lambda)\ E(\lambda)\ \rho(z)$, which is the analytical representation of the fact that the attenuation of the beam on an arbitrary path dz in the atmosphere is linearly propotional, for every wavelength, to the number of nuclei per unit volume and to the intensity of the incident beam through a parameter of proptionality, here defined as $K(\lambda)$. Since the beam's depletion is linearly proportional to dz through a parameter which is a function of λ only, the beam's depletion with respect to z will be, as expected, exponential.

$$dE(\lambda) = E(\lambda) \quad K(\lambda)\ \rho(z)\ dz \tag{4.1}$$

where $K(\lambda)$ is the absorbance "constant" for a determined gas and wavelength λ, and $\underline{z}$ is the altitude of the slab $\underline{dz}$ considered.

Integration, between elevation zero and elevation Z of eq. 4.1, gives:

$$\ln \frac{E_Z(\lambda)}{E_0(\lambda)} = K(\lambda) \int_0^Z \rho(z)\ dz \tag{4.2}$$

or:

$$E_0(\lambda) = E_Z(\lambda)\ \exp[- K(\lambda) \int_0^Z \rho(z)\ dz] \tag{4.3}$$

where:

$E_Z(\lambda)$ = density of energy flux of wavelength λ at elevation Z [W m-2]

$E_0(\lambda)$ = density of energy flux of wavelength λ at elevation 0 [W m-2].

Equation 4.3 is often called Beer's (or Bouguer's) Law.

The exponent of the exponential factor in the second term of eq. 4.3 is often called "optical depth." Sometimes, the integral term of the exponent is also referred to as "optical depth," although it represents only a mass concept, being a "density integral."

If the Sun is at the zenith, the beam's path will be on the z axis (elevation or zenith axis), then an integration over all the atmospheric path—let us say from 0 to —will furnish the attenuation of the beam on its atmospheric path:

$$E_0(\lambda) = E_i(\lambda) \ \exp[- K(\lambda) \int_0^{\infty} \rho(z)\, dz] \qquad (4.4)$$

where:

$E_i(\lambda)$ = density of energy flux incident on the "upper limit" of the atmosphere [W m^{-2}].

4.1 OPTICAL DEPTH FOR A VERTICAL PATH

Halley's Law gives the variation of atmospheric density with the altitude, z; here it will be extended to the entire atmosphere. This will permit computation of the integral factor in eq. 4.4, a factor that will be defined as A_0. As stated in Halley's Law:

$$A(z{=}0) = A_0 = \int_0^{\infty} \rho(z)\ dz = \int_0^{\infty} \rho(0)\ \exp[-\ z\ \rho(0)\ g/P(0)]\ dz \tag{4.5}$$

where:

$A(z{=}0)$ = density integral of the atmosphere [kg m-2]

$\rho(0)$ = density of the atmosphere at z = 0 [kg m-3]

g = acceleration of gravity [m s-2]

$P(0)$ = atmospheric pressure at z = 0 [N m-2].

Developing the trivial integral in eq. 4.5:

$$A_0 = \rho(0)\ [P(0)/(\rho(0)\ g)] \tag{4.6}$$

The term between parentheses is often referred to as equivalent height (or scale height), H, of the atmosphere, i.e., the height the atmosphere would have given that its density is invariable with height and equal to $\rho(0)$. Thus:

$$H = P(0)/(\rho(0)\ g) \tag{4.7}$$

Equation 4.5 may be rewritten as:

$$A_0 = \rho(0)\ H = P(0)/g \tag{4.8}$$

Obviously, if the optical depth of the atmosphere is computed for a site at a certain altitude, its value will be different from A_0 $K(\lambda)$, since A_0 depends on the elevation.

For an altitude z_0, eq. 4.5 might be rewritten as:

$$A(z=z_0) = A_{z_0} = \int_{z_0}^{\infty} \rho(z)\, dz = \int_{z_0}^{\infty} \rho(0) \exp[- z\, \rho(0)\, g/P(0)]\, dz \tag{4.9}$$

Developing the trivial integral in eq. 4.9:

$$A_{z_0} = \rho(0)\, H \exp(- z_0/H) \tag{4.10}$$

As expected, the optical depth value for a zero elevation is the superior limit of the optical depth value.

The upper limit of integration (infinity) for the atmospheric density integral, although mathematically correct, might create some misunderstandings in its physical interpretation.

Initially assuming the elevation-observer's location, as always to be equal to 0, and computing A_0 as a function of $\underline{z}$, from eq. 4.9 the following is obtained:

$$A_0(z) = \int_0^{z} \rho(0) \exp[- z\, \rho(0)\, g/P(0)]\, dz \quad [\text{kg m}^{-2}] \tag{4.11}$$

or:

$$A_0(z) = \rho(0)\, H\, [1 - \exp(- z/H)] \qquad (4.12)$$

If the observer's elevation is z_0, eq. 4.11 may be rewritten as:

$$A(z) = \int_{z_0}^{z} \rho(0) \exp[- z\, \rho(0)\, g/P(0)]\, dz \qquad (4.13)$$

or:

$$A(z) = \rho(0)\, H\, [\exp(- z_0/H) - \exp(- z/H)] \qquad (4.14)$$

In Figure 12, eq. 4.14 is plotted for z varying from z_0 to 64,000 m for different parametrical values of z_0 (z_0 = 0 m; z_0 = 500 m; z_0 = 1,000 m; z_0 = 1,500 m; z_0 = 2,000 m). It is clear that the "time constant" of the exponential factor is relatively small and that the exponential term in z tends rapidly to zero, at an altitude of a few tenths kilometers. Therefore, the upper limit of integration for the density integral might be, say 50 km, which would give a physical sense to the integration.*

---

*For the 1962 Standard Atmosphere, P(0) = 101,325 N m^{-2} and $\rho(0)$ = 1.225 kg m^{-3}; the value adopted by the World Meteorological Organization for the acceleration of gravity is 9.80616 m s^{-2} at 45 degrees of latitude. Under this assumption, a standard value of the equivalent height of the atmosphere, H, would be 8.435 km and the correspondent value of the atmoshere density integral at zero elevation, A_0, would be 10,333 kg m^{-2}.

4.2 ATMOSPHERIC MASS: OPTICAL DEPTH FOR AN ARBITRARY INCLINED PATH

To compute the attenuation of the solar beam, it is first necessary to compute the optical depth along an arbitrary ray path, i.e., the ray path for a non-zenith position of the Sun. Instead of performing such a calculation for every ray path, i.e., for every position of the Sun, the optical depth of an arbitrary ray will be related to the optical depth in the direction of the vertical, as computed in Section 4.1.

Considering the fact that A_0 is a function of the zenith angle, θ, the following adimensional function must be computed:

$$A_1(\theta) = \frac{A_0(\theta)}{A_0(0)} \quad \text{[adimensional]} \tag{4.15}$$

The function $A_1(\theta)$ is often indicated as atmospheric mass. Obviously, being adimensional, it has no relation to any general or particular concept of atmospheric mass. It just indicates the lengthening of the beam's path with respect to the vertical path, i.e., it indicates how many times the optical depth along the arbitrary path exceeds the optical depth along the vertical path.

It will be computed then with a simple geometrical approach, therefore neglecting the deflection of the ray due to refraction, as follows.

Considering the frame (x, z), the equation of the circle of ray $R_E + H$ (see Figure 13) is:

$$x^2 + z^2 = (R_E + H)^2 \tag{4.16}$$

If the center of the circle is moved from 0 to 0' and the polar coordinates (s, h) (see Figure 13) are introduced, eq. 4.16 becomes:

$$s = - R_E \sin(h) + [R_E^2 \sin^2(h) + H^2 + 2 R_E H]^{1/2} \tag{4.17}$$

Obviously, the ratio s/H gives the lengthening of the atmospheric beam path with respect to the minimum (zenith) path:

$$A_1(h) = s/H = - R_E \sin(h)/H + [1 + 2 R_E/H + (R_E \sin(h)/H)^2]^{1/2} \tag{4.18}$$

For most computations in solar energy engineering (i.e., for all those that consider tilted surfaces) the meaningful parameter is the zenith angle, θ. For the horizontal surface, θ and $\underline{h}$ are complementary angles. Taking this into account, eq. 4.18 becomes:

$$A_1(\theta) = s/H = - R_E \cos(\theta)/H + [1 + 2 R_E/H + (R_E \cos(\theta)/H)^2]^{1/2} \qquad (4.19)$$

The assumption has been implicitly made that $A_1(h)$ is not dependent on the wavelength, which is rigorously true only for shortwave radiation. Furthermore, the deflection of the beam due to refraction has not been considered, and this is strictly true for those beam's paths close enough to zenith.

The error introduced by those approximations is extremely reduced: on the fourth significative figure of A_1 for zenith angles inferior to 60°; on the third for $60° \leq \theta \leq 70°$; and on the second for $70° \leq \theta \leq 80°$ (corresponding approximately to a 2 percent error in the A_1 evaluation and a 2.5 percent error in the exponential factor evaluation). However, since the approximation is excellent until θ values less than 70 degrees (0.4 percent error on the exponential factor evaluation) and since for larger values of θ we are considering instants in which the total amount of energy flux on the ground does not exceed, in the extreme conditions (i.e., winter days), the 30 percent of the daily energy flux, then the maximum error introduced in the transmission factor evaluation by the A_1 computation is certainly not larger than 1.2 percent, and the average error for the year is less than 0.5 percent.

Rewriting eq. 4.15 in an explicit form, the following equation is obtained:

$$A_1(\theta) = [\int_0^\infty K(\lambda)\ \rho(s)\ ds]/[\int_0^\infty K(\lambda)\ \rho(z)\ dz] \qquad (4.20)$$

Equation 4.20 might suggest that $A_1(\theta)$ is strongly dependent on atmospheric physical conditions (e.g., pressure and temperature). But eq. 4.20 also shows that pressure variations will not affect $A_1(\theta)$ values, the density integrals in numerator and denominator of eq. 4.20 being approximately proportional to the physical mass of one atmospheric column of unit section, which is itself proportional to the pressure at sea level.

The temperature dependence is significant only at very large zenith angles, where the density of energy flux of the radiative beam is very low and the energy flux on the horizontal of the observer is strongly affected by Lambert's Law. It therefore may be neglected.

For quick computations of the atmospheric mass, mainly for hand-pocket calculators, a simpler form of $A_1(h)$ is often used:

$$A_1(h) = \sec(\theta) = \operatorname{cosec}(h) \tag{4.21}$$

For h values less than 30 degrees but greater than 10 degrees, the following empirical formula is often used:

$$\begin{aligned} A_1(h) &= \text{(eq. 4.19) } \sec(\theta) - 2.8/(90 - \theta)^2 \\ &= \text{(eq. 4.17) } \operatorname{cosec}(h) - 2.8/h^2 \end{aligned} \tag{4.22}$$

where θ and h are expressed in degrees.

Equations 4.21, 4.18, and 4.22 are tabulated below; eqs. 4.18 and 4.22 in particular are computed for three different values of H:

$$H = 8.4 \text{ km};\ H = 20 \text{ km};\ H = 400 \text{ km}.$$

RELATIVE ATMOSPHERIC MASS

THETA = 90.0 - HH
HH = HEIGHT OF SUN (IN DEGREES)

COLUMN 1 = A1(HH) = 1.0/COS(THETA) <EQN. 4.21>
COLUMN 2 = A1(HH) = -R/H * SIN(HH) + (1.0 + 2.0 * R/H + (R/H)**2 * SIN(HH)**2)**0.5 H = 8.43 KM <EQN. 4.18>
COLUMN 3 = A1(HH) = -R/H * SIN(HH) + (1.0 + 2.0 * R/H + (R/H)**2 * SIN(HH)**2)**0.5 H = 20. KM <EQN. 4.18>
COLUMN 4 = A1(HH) = -R/H * SIN(HH) + (1.0 + 2.0 * R/H + (R/H)**2 * SIN(HH)**2)**0.5 H = 400. KM <EQN. 4.18>
COLUMN 5 = (COLUMN 2)/COS(THETA) - 2.8/(90.0 - THETA)**2 H = 8.43 KM <EQN. 4.22>
COLUMN 6 = (COLUMN 3)/COS(THETA) - 2.8/(90.0 - THETA)**2 H = 20. KM <EQN. 4.22>
COLUMN 7 = (COLUMN 4)/COS(THETA) - 2.8/(90.0 - THETA)**2 H = 400. KM <EQN. 4.22>

HH	1	2	3	--> 4 <--	5	6	7
0	28.6536	38.9002	25.2606	5.7319	1113.9297	723.1082	163.5404
1	19.1073	27.8815	20.3057	5.4607	532.4290	387.6763	104.0279
2	14.3356	20.6179	16.4815	5.2030	295.3950	236.0980	74.4125
3	11.4736	15.9183	13.5946	4.9586	182.5282	155.8667	56.7815
4	9.5667	12.7935	11.4224	4.7276	122.3136	109.1967	45.1495
5	8.2055	10.6248	9.7720	4.5095	87.1244	80.1266	36.9451
6	7.1853	9.0544	8.4975	4.3039	65.0146	61.0131	30.8812
7	6.3924	7.8745	7.4949	4.1106	50.3024	47.8759	26.2422
8	5.7588	6.9598	6.6916	3.9289	40.0520	38.5072	22.5978
9	5.2408	6.2324	6.0368	3.7584	32.6399	31.6149	19.6742
10	4.8097	5.6414	5.4949	3.5985	27.1140	26.4095	17.2885
11	4.4454	5.1523	5.0401	3.4487	22.8875	22.3887	15.3142
12	4.1336	4.7414	4.6538	3.3082	19.5844	19.2224	13.6605
13	3.8637	4.3917	4.3220	3.1767	16.9556	16.6864	12.2613
14	3.6279	4.0905	4.0344	3.0535	14.8292	14.6257	11.0669
15	3.4203	3.8288	3.7829	2.9380	13.0860	12.9290	10.0392
16	3.2361	3.5993	3.5614	2.8298	11.6388	11.5161	9.1488
17	3.0716	3.3965	3.3649	2.7284	10.4249	10.3276	8.3726
18	2.9238	3.2160	3.1894	2.6332	9.3960	9.3182	7.6921
19	2.7904	3.0546	3.0320	2.5440	8.5171	8.4541	7.0924
20	2.6695	2.9092	2.8900	2.4601	7.7602	7.7091	6.5614
21	2.5593	2.7781	2.7614	2.3813	7.1047	7.0620	6.0892
22	2.4586	2.6587	2.6443	2.3072	6.5318	6.4965	5.6676
23	2.3662	2.5500	2.5374	2.2374	6.0294	5.9995	5.2897
24	2.2812	2.4504	2.4395	2.1717	5.5857	5.5607	4.9500
25	2.2027	2.3591	2.3493	2.1098	5.1926	5.1710	4.6434
26	2.1301	2.2751	2.2664	2.0514	4.8426	4.8239	4.3061
27	2.0627	2.1973	2.1895	1.9963	4.5289	4.5130	4.1143
28	2.0000	2.1252	2.1184	1.9442	4.2474	4.2337	3.8852
29	1.9416	2.0581	2.0522	1.8949	3.9931	3.9816	3.6763
30	1.8871	1.9958	1.9907	1.8483	3.7636	3.7539	3.4851

RELATIVE ATMOSPHERIC MASS
(CONT'D)

Hd	1	2	3	--> .4 <--	5	6	7
31	1.8361	1.9380	1.9332	1.8042	3.5557	3.5469	3.3100
32	1.7883	1.8840	1.8796	1.7623	3.3668	3.3588	3.1491
33	1.7434	1.8330	1.8293	1.7227	3.1935	3.1870	3.0011
34	1.7013	1.7856	1.7822	1.6850	3.0358	3.0299	2.8646
35	1.6616	1.7412	1.7379	1.6493	2.8912	2.8857	2.7385
36	1.6243	1.6992	1.6962	1.6153	2.7580	2.7532	2.6218
37	1.5890	1.6599	1.6570	1.5831	2.6358	2.6312	2.5137
38	1.5557	1.6226	1.6200	1.5524	2.5225	2.5185	2.4133
39	1.5243	1.5876	1.5852	1.5232	2.4183	2.4146	2.3200
40	1.4945	1.5544	1.5522	1.4954	2.3215	2.3181	2.2332
41	1.4663	1.5229	1.5211	1.4689	2.2316	2.2288	2.1522
42	1.4396	1.4932	1.4914	1.4436	2.1480	2.1456	2.0767
43	1.4142	1.4653	1.4636	1.4196	2.0709	2.0684	2.0062
44	1.3902	1.4385	1.4371	1.3966	1.9984	1.9965	1.9402
45	1.3673	1.4133	1.4120	1.3747	1.9312	1.9294	1.8784
46	1.3456	1.3894	1.3880	1.3538	1.8684	1.8665	1.8205
47	1.3250	1.3665	1.3653	1.3339	1.8094	1.8079	1.7662
48	1.3054	1.3452	1.3438	1.3148	1.7549	1.7531	1.7153
49	1.2868	1.3245	1.3234	1.2967	1.7032	1.7019	1.6674
50	1.2690	1.3052	1.3039	1.2793	1.6553	1.6537	1.6224
51	1.2521	1.2864	1.2854	1.2627	1.6097	1.6084	1.5801
52	1.2361	1.2683	1.2677	1.2469	1.5668	1.5660	1.5403
53	1.2208	1.2517	1.2511	1.2318	1.5271	1.5263	1.5028
54	1.2062	1.2356	1.2349	1.2174	1.4895	1.4886	1.4675
55	1.1924	1.2207	1.2197	1.2036	1.4547	1.4535	1.4342
56	1.1792	1.2058	1.2053	1.1904	1.4210	1.4205	1.4029
57	1.1666	1.1919	1.1914	1.1779	1.3897	1.3891	1.3733
58	1.1547	1.1787	1.1785	1.1659	1.3603	1.3600	1.3455
59	1.1434	1.1665	1.1660	1.1544	1.3330	1.3324	1.3192
60	1.1326	1.1545	1.1538	1.1435	1.3069	1.3060	1.2944

RELATIVE ATMOSPHERIC MASS
(CONT'D)

HH	1	2	3	--> 4 <--	5	6	7
61	1.1223	1.1433	1.1426	1.1332	1.2825	1.2816	1.2711
62	1.1126	1.1328	1.1318	1.1233	1.2597	1.2586	1.2491
63	1.1034	1.1223	1.1216	1.1138	1.2377	1.2369	1.2283
64	1.0946	1.1128	1.1121	1.1049	1.2175	1.2167	1.2088
65	1.0864	1.1035	1.1028	1.0964	1.1982	1.1974	1.1904
66	1.0785	1.0947	1.0942	1.0883	1.1801	1.1796	1.1732
67	1.0711	1.0864	1.0862	1.0806	1.1631	1.1629	1.1569
68	1.0642	1.0784	1.0781	1.0734	1.1470	1.1467	1.1417
69	1.0576	1.0713	1.0708	1.0665	1.1325	1.1319	1.1274
70	1.0515	1.0645	1.0637	1.0600	1.1187	1.1179	1.1141
71	1.0457	1.0576	1.0574	1.0539	1.1054	1.1052	1.1016
72	1.0403	1.0515	1.0510	1.0482	1.0934	1.0929	1.0899
73	1.0353	1.0459	1.0454	1.0428	1.0823	1.0818	1.0791
74	1.0306	1.0403	1.0400	1.0378	1.0716	1.0714	1.0691
75	1.0263	1.0352	1.0352	1.0331	1.0619	1.0619	1.0598
76	1.0223	1.0303	1.0305	1.0287	1.0528	1.0531	1.0512
77	1.0187	1.0264	1.0261	1.0247	1.0451	1.0449	1.0434
78	1.0154	1.0225	1.0222	1.0210	1.0378	1.0375	1.0363
79	1.0125	1.0188	1.0186	1.0176	1.0311	1.0308	1.0298
80	1.0098	1.0154	1.0151	1.0145	1.0249	1.0247	1.0240
81	1.0075	1.0122	1.0125	1.0117	1.0194	1.0196	1.0189
82	1.0055	1.0100	1.0098	1.0092	1.0152	1.0149	1.0144
83	1.0038	1.0076	1.0073	1.0071	1.0110	1.0108	1.0105
84	1.0024	1.0061	1.0054	1.0052	1.0082	1.0074	1.0072
85	1.0014	1.0039	1.0037	1.0036	1.0049	1.0047	1.0046
86	1.0006	1.0027	1.0024	1.0023	1.0029	1.0027	1.0025
87	1.0002	1.0015	1.0015	1.0013	1.0013	1.0013	1.0011
88	1.0000	1.0005	1.0005	1.0006	1.0001	1.0001	1.0002
89	1.0002	1.0002	1.0000	1.0001	1.0001	0.9998	0.9999
90	1.0006	1.0005	0.9998	1.0000	1.0008	1.0000	1.0003

Although H has been indicated as the equivalent height of the atmosphere, the same symbol has been used here to define the denominator of s/H.

It should be stressed that the meaning of the latter is different from the meaning of the former, as explained in Section 4.1 and related to a physical property of the atmosphere (the pressure), thus to the mass of the atmosphere. The atmospheric height of the atmosphere used on the $A_1(h)$ definition is related, following the assumptions made, to a merely geometric characteristic of the beams' path, and its only purpose is to define the geometric "lengthening" of an arbitrary beam's path with respect to the vertical path. It still has implied, though, the concept of "scale" height, and that is the reason why the same symbol has been here adopted.

For instance the values that have been shown to give better results are the ones reported in column four of the previous tabulation.

Thus, as concerns the relative atmospheric mass computation, an atmospheric height of 400 km will be assumed as "scale" height and this value will not have to be identified with the equivalent height of the atmosphere, previously defined.

The atmosphere has different "scale" heights following the parameter to which this conventional magnitude is referred, as it is implicit in the "scale" height concept.

4.3 INTEGRAL TRANSMISSION FACTOR OF THE ATMOSPHERE

Having computed the optical depth of the atmosphere along any beam's path, eq. 4.4 may be rewritten (using eqs. 4.6 and 4.18), for a non-clouded real atmosphere at zero elevation (i.e., sea level), as follows:

$$E_0(\lambda) = E_i(\lambda)\ \exp[-\ K(\lambda) \cdot A_0\ \ A_1(h)] \qquad (4.23)$$

Note that eq. 4.23 is valid for any beam's path, while eq. 4.4 is applicable only for the zenith path (i.e., vertical path).

If the observer is at a z_0 altitude, eq. 4.23 becomes (from eq. 4.9):

$$E_0(\lambda) = E_i(\lambda)\ \exp[-\ K(\lambda)\ A_0\ A_1(h)] \qquad (4.24)$$

Rewriting eq. 4.23 as:

$$E_0(\lambda) = E_i(\lambda)\ \exp[-\ A_1(h) \int_0^\infty K(\lambda)\ \rho(z)\ dz] \qquad (4.25)$$

The monochromatic transparency coefficient, $p(\lambda)$, is then defined:

$$p(\lambda) = \exp[-\int_0^\infty K(\lambda)\ \rho(z)\ dz] \qquad (4.26)$$

Taking into consideration eq. 4.26, eq. 4.25 may be rewritten as:

$$E_0(\lambda) = E_i(\lambda)\ p(\lambda)^{A_1(h)} \qquad (4.27)$$

Integrating over λ:

$$E_0 = \int_0^\infty E_0(\lambda)\ d\lambda = \int_0^\infty E_i(\lambda)\ p(\lambda)^{A_1(h)}\ d\lambda \qquad (4.28)$$

where:

E_0 = energy density flux on the Earth at zero elevation $[W\ m^{-2}]$

Methods of analytical integration of eq. 4.28, under particular assumptions, are available. A numerical solution is more suitable, although this is a nontrivial problem due to the complex dependency of the function $p(\lambda)$ over λ.

Being mainly interested in an integral value with respect to the wavelength, of the density of energy flux on the ground, an integral approach versus the monochromatic transparency coefficient appears more coherent and more consistent with the precision and, mainly, with the quantity of meteorological data currently available.

Introducing a value of the transparency coefficient weight averaged over the whole spectrum, eq. 4.28 becomes:

$$E_0 = p^{A_1(h)} \int_0^{\infty} E_0(\lambda)\, d\lambda = p^{A_1(h)} E_S \qquad (4.29)$$

where:

E_S = density of solar energy flux outside the atmosphere, often referred to as solar "constant" [$W\ m^{-2}$]

p = integral transparency coefficient [adimensional].

The solar constant value will be computed on a daily basis, as indicated in Section 1.1, using eq. 1.6.

The integral transparency coefficient may be determined empirically; calculated values for the ideal atmosphere, using the theory of molecular scattering, are also available.

It is important to note that the transparency factors are a function of the atmospheric mass. This is due to the selective character of the interaction of the solar radiation with the atmosphere. For low atmospheric masses, most of the attenuation will happen near the "resonance" peaks of absorption; for higher atmospheric masses, the increase of attenuation will be slower due to the influence of the less intensively attenuating far wings of the band.

Fortunately, most of the integrated energy flux is obtained within low atmospheric masses: This decreases the importance of the variation of the transparency factor with respect to atmospheric mass, and thus this dependency may be neglected, introducing therefore an error inferior to .5 percent.

Using eqs. 4.5 and 4.26, eq. 4.29 may be rewritten as:

$$E_0 = E_S \exp[- K_T \ A_0 \ A_1(h)] \tag{4.30}$$

the definition of K_T being implicit.

The exponential factor on the second term of eq. 4.30 is the integral transmission factor of the atmosphere, defined on a cloudless day (i.e., the inverse of the integral attenuation factor of the atmosphere on a cloudless day). This factor is time-dependent (through $A_1(h)$) and will be correlated to meteorological conditions (through K_T).

As concerns eq. 4.28, the hypotheses until now have been nonrestrictive. This would permit a numerical computation of E_0 with a precision of a few percent--radiation data on the Earth are affected by at least a 1-2 percent error and the error on the determination of the solar spectrum (or solar constant) is at least 2 percent. Introducing the integral transparency does not substantially increase the error on the E_0 computation and furthermore the meteo correlation, which will be obtained for macro-, meso-, and microclimatic approximations, will be a far more important constraint.

4.4 ATTENUATION OF SOLAR RADIATION BY CLOUDS

It is well known that "large" particles are intensive "light" scatterers. Clouds consist of a large number of water droplets; thus, they play an important role in scattering solar radiation, i.e., in depleting the direct beam. Note that clouds may also absorb solar radiation; the quantitative dynamics of this process are still being studied.

The theoretical computation of the diffusion of radiation by clouds is particularly complicated. The available theoretical calculations are valid only for stratus clouds, which may be presented in the form of a homogeneous horizontal surface of relatively moderate thickness [35-37]. The phenomenon is, again, strictly selective and complicated by the presence of cumulus clouds, which have isolated, irregular formations and considerable vertical extension.

Furthermore, experimental data available on the clouds, i.e., cloud type, height, extension and thickness of the layers, percent of the celestial dome covered by clouds, etc., are so rare and approximate that a detailed model of the scattering and absorption process would be quite expensive, and unreliable. Finally, a "precise" model also should consider the "position" of the clouds on the dome—if it is not completely covered—and it would be utopic to expect to find this information.

In the literature there are many empirical expressions for the correlation of the irradiance on the ground with meteorological data, through parameters that are dependent upon the geographic position or meteorological conditions, and that assume two or three sets of values during the year [38,39]. It is worthwhile to mention some of these relations.

Reddy's Equation [40-42]:

$$F_0 = K\ \alpha/(h_r)^{1/2}$$

where:

F_0 = integrated solar energy flux on the ground (irradiance)

K = $K(\phi)$

α = $[1 + 8\ (S/D)\ (1 - .2\ (r/M))]$

S = minutes of sunshine per day

D = length of the day in minutes

r = number of rainy days in the month

M = number of days in the month

h_r = average relative humidity.

Ångstrom's Equation [43]:

$$F_0/(F_0)_{S=D} = a' + b'\ S/D$$

where:

$(F_0)_{S=D}$ = irradiance in the hypothesized absence of clouds.

Penman and Black's Equation [44]:

$$F_0/F_0' = a + b\ S/D$$

where:

F_0' = irradiance in the hypothesized absence of atmosphere.

A typical yearly average value of a and b in two different climatic zones of Europe, are:

Torino, Italy (45° N)	a = .238	b = .379
Trapani, Italy (38° N)	a = .281	b = .296

This clearly shows that the correlation is macroclimatic.

Other relations correlate the integrated flux directly with the presence of clouds, with parameters corresponding to the different classes of clouds [45]. Lumb considers nine classes of clouds and correlates the irradiance with a sine function of the altitude of the Sun [46]. Sherma and Pal introduce a particular albedo value, defined as the ratio between the total integrated flux in the case being examined and the correspondent integrated flux with a "standard" composition of the atmosphere, for each value of the altitude of the Sun.

All those empirical relations and others not reported here correlate the energy flux on the Earth with the clouds, using a largely empirical, macroclimatic approximation. The coefficients of correlation are probably obtained with regression techniques that use a "large" set of experimental data from different locations during the year. The results obtained are of interest, especially if compared with the simplicity of some of those relations, e.g., Ångstrom's, Penman and Black's—although they are not very accurate, and the precision itself may vary with respect to the period of the year—at the same location or from location to location—in the same "Standard Climate Area."

One piece of useful information derived from those relations is that the ratio S/D (minutes of sunshine over daylength in minutes) is used, directly or indirectly, as an extensive parameter to determine the cloud presence [40,43,44].

It is appropriate, instead of using empirical coefficients to "mediate" the ratio S/D (that is, to associate an "intensity" to S/D), to directly introduce an intensive factor that defines the "intensity" with which each type of cloud interacts with the radiative beam.

For this purpose, the albedo of the clouds (see Appendix A1) is introduced, and the effect of the clouds on the solar energy radiative flux's depletion may be taken into account as a function of the albedo (intensive factor), a, and of the ratio S/D (extensive factor).

Thus, eq. 4.30, for a cloudy day, becomes:

$$E_0 = f(a, S/D)\, E_S \exp[- K_T A_0 A_1(h)] \tag{4.31}$$

The use of the intensive factor previously mentioned, the albedo, appears inevitable. The choice of S/D as an extensive factor does not appear as inevitable, although it is reasonable. The amount of the celestial dome covered with clouds might also be used. If the latter is called η, the relation

$$S/D + \eta = 1 \tag{4.32}$$

should be always verified to justify the usefulness of the factor η.

Equation 4.32 is only approximately verified in most cases. This is because the η factor does not give any information on the position of the clouds, which might or might not be intercepting the beam.

Therefore, the parameter S/D (on an hourly or daily basis) will be used, and consequently the function f(a, S/D) will be defined as follows:

$$f(a, S/D) = 1 - c\ a \qquad (4.33)$$

where c is a function of S/D.

A very linear and simple approach, that follows from the definition of albedo (see Appendix A1), induces the following definition of c:

$$c = 1 - S/D \qquad (4.34)$$

Using eqs. 4.33 and 4.34, eq. 4.31 may be rewritten as:

$$E_0 = (1 - c\ a)\ E_S \exp[- K_T\ A_0\ A_1(h)] \qquad (4.35)$$

Equation 4.35 furnishes for any location a value of the instantaneous density of energy flux, provided that:

1. The extraterrestrial density of energy flux, E_S (i.e., the density of energy flux outside the atmosphere) is known, or computed;

2. The density integral of the atmosphere, A_0, is computed; A_0 may be expressed as a function of the atmospheric pressure although, with the standard measurements available, if A_0 must be computed for a given elevation, it will be expressed as a function of atmospheric pressure and temperature, at the considered elevation;

3. The atmospheric attenuation parameter, K_T, is computed as a function of the atmospheric constituents or "agents" of the considered effect: mainly water vapor and standard gases of the atmosphere, aerosol, clouds, and "molecular scatterers;"

4. The albedo of the clouds is indirectly computed through observation of the cloud cover;

5. The minutes of sunshine per interval of time must be known, in order to compute the c factor; and

6. $A_{1(h)}$ is computed, merely as a geometric factor.

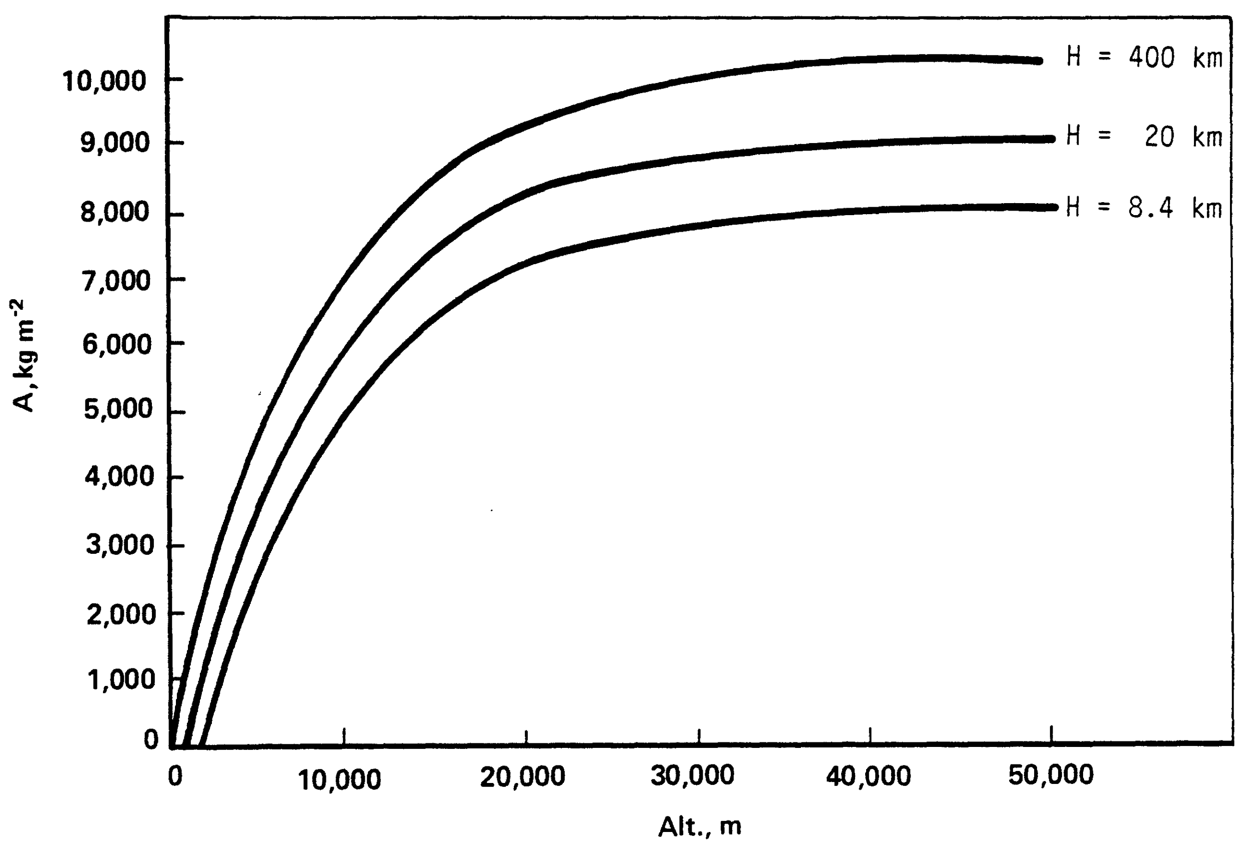


Figure 12 THE OPTICAL DEPTH

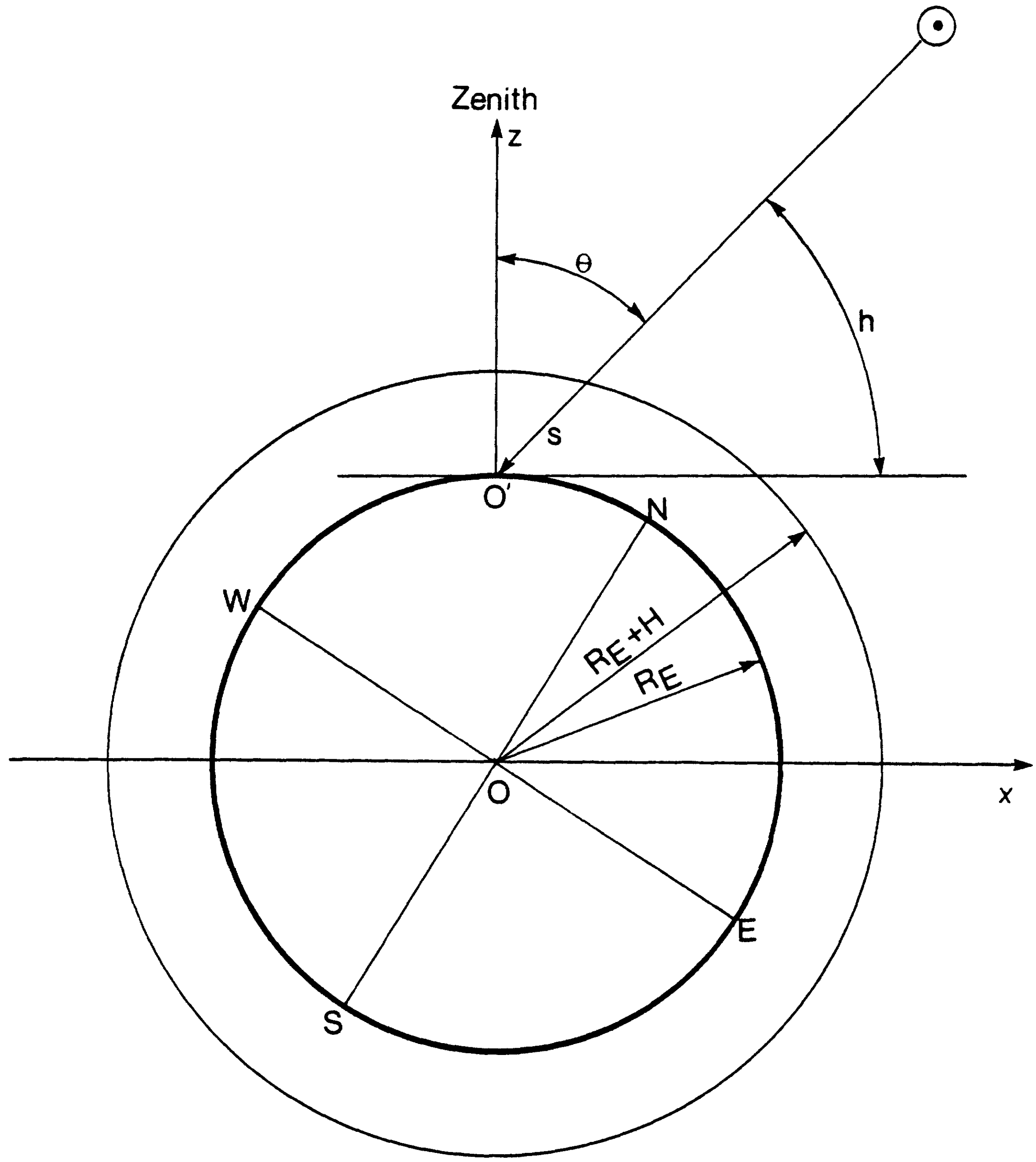


Figure 13 THE PATH OF THE ENERGY BEAM IN THE ATMOSPHERE

CHAPTER 5

CORRELATION OF THE SOLAR ENERGY RADIATIVE FLUX DEPLETION WITH METEOROLOGICAL CONDITIONS

This chapter will develop the concepts and techniques needed to compute those coefficients of eq. 4.35 that are dependent on meteorological conditions.

A macro- and microclimatic approximation for each coefficient of eq. 4.35 will be considered. Consequently, a mesoclimatic approximation will be defined.

The purpose of a macroclimatic approximation is to derive the energy flux values within "Standard Climatic Areas," for techno-economical feasibility studies of solar energy applications.

It is assumed, for these purposes, that no meteorological data are available.

The mesoclimatic approximation will reduce the "Standard Climatic Areas" to a relatively narrow zone, for which only standard meteorological data are available (i.e., pressure, temperature, and dew point or relative humidity), plus some information on the clouds (i.e., main cloud type or cloud layer, percent of dome covered by clouds, or minutes of sunshine)—this information being furnished on a daily average basis. This approximation will serve the engineering optimization of the solar energy conversion systems.

The microclimatic approximation will assume that local meteorological data are measured at the site under consideration, on an hourly basis—or at least a few times a day—and that some precise information on the clouds is available. This will allow solar maps of those regions that have good records, and/or a history of "standard" meteorological data that are absolutely unrelated to solar energy flux measurements.

The main criteria of this chapter will be:

i. to obtain the maximum precision of the correlation through a physical model, but

ii. to avoid those extremely precise physical models that, although they might theoretically be constructed, will be in high contrast with the amount and the quality of meteorological data "generally" available.

5.1 DEPLETION "CONSTANT" OF THE ATMOSPHERE

5.1.1 Macroclimatic approximation

Consider a clear day (i.e., no clouds), for which c equals zero (from eq. 4.34, setting S/D = 1), equation 4.34 then becomes identical to equation 4.30.

Equation 4.30 may be rewritten in explicit form over K_T as:

$$K_T = - \ln(E_0/E_S)\ (A_0\ A_1(h))^{-1} \quad [m^2\ Kg^{-1}] \tag{5.1}$$

where:

E_0/E_S = attenuation factor of the atmosphere [adimensional].

From the experimental values of the energy flux on the ground, E_0 -- or the experimental values of the attentuation factors--on clear days, in different "Standard Climatic Areas," and computing A_0 and $A_1(h)$, from eq. 5.1 it is possible to determine the K_T values under a macroclimatic approximation:

$$K_T = 2.5\ 10^{-5} \quad [m\ \ Kg^{-1}]$$

for temperate winter, continental climatic conditions or desert climates (particularly clear atmosphere and low level of humidity);

$$K_T = 3.0\ 10^{-5} \quad [m^2\ Kg^{-1}]$$

for temperate summer, continental climatic conditions (clear atmosphere and medium level of humidity);

$$K_T = 3.5\ 10^{-5}\ [m^2\ Kg^{-1}]$$

for humid (tropical) climatic conditions (clear atmosphere and high level of humidity).

It would not make sense, under this approximation, to determine whether those K_T values refer to the global or direct attenuation, since they are largely obtained through averaged meteorological conditions.

Particular polluting agents, such as dusts, haze, fog, smoke, etc., will cause a substantial increase of K_T (approximately, .6 10^{-5} in particularly critical conditions). Therefore, the range of variation of K_T is from 2.3 10^{-5} to 4.2 10^{-5}.

The computed K_T values appear to present a very low sensitivity with respect to the solar altitude; this confirms the methodology adopted for the relative atmospheric mass computation and the value chosen to be the height of the atmosphere for this computation.

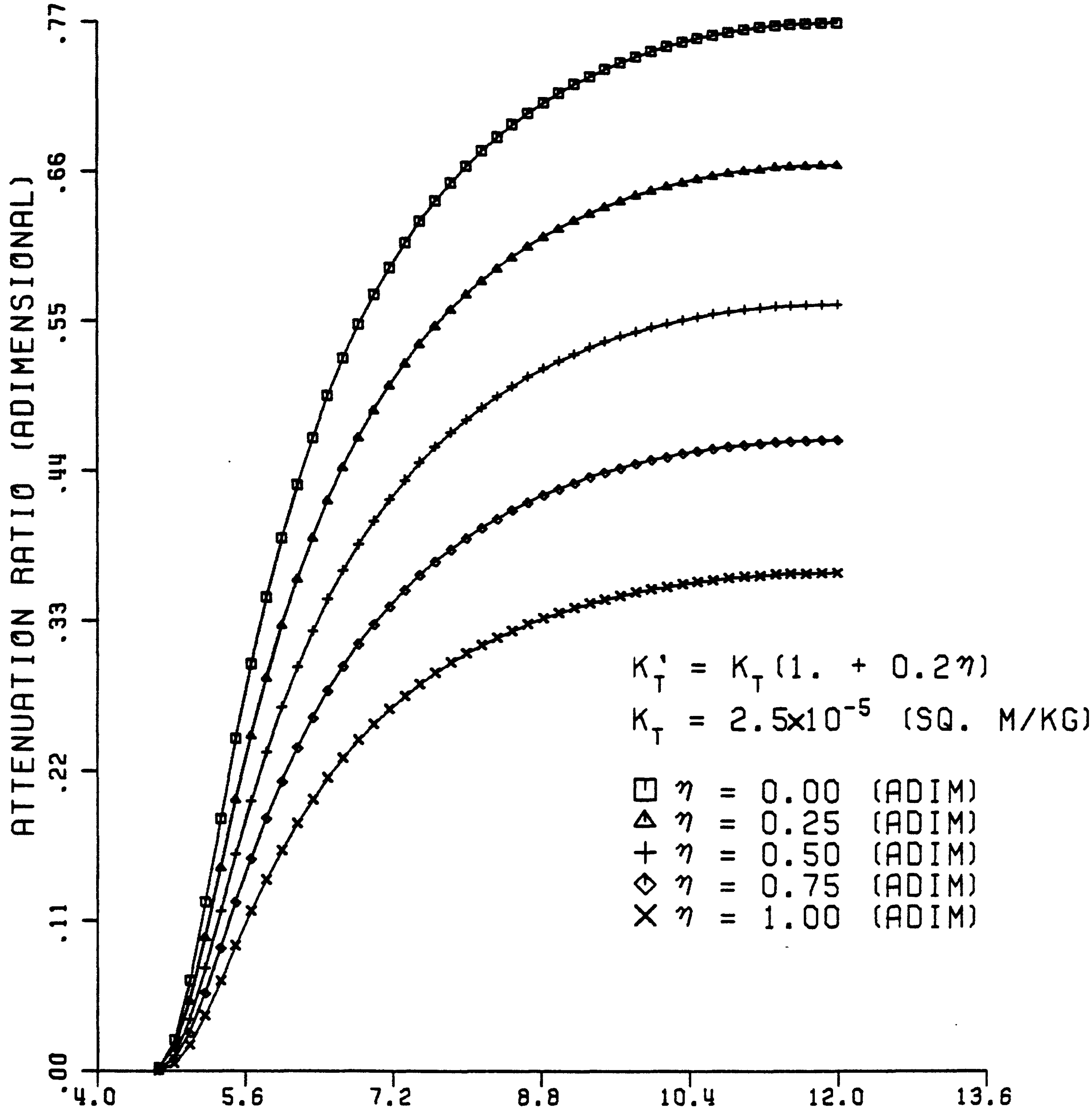
On the other hand, K_T does have a dependency with respect to the clouds' presence and this fact is independent of the clouds' absorbance.

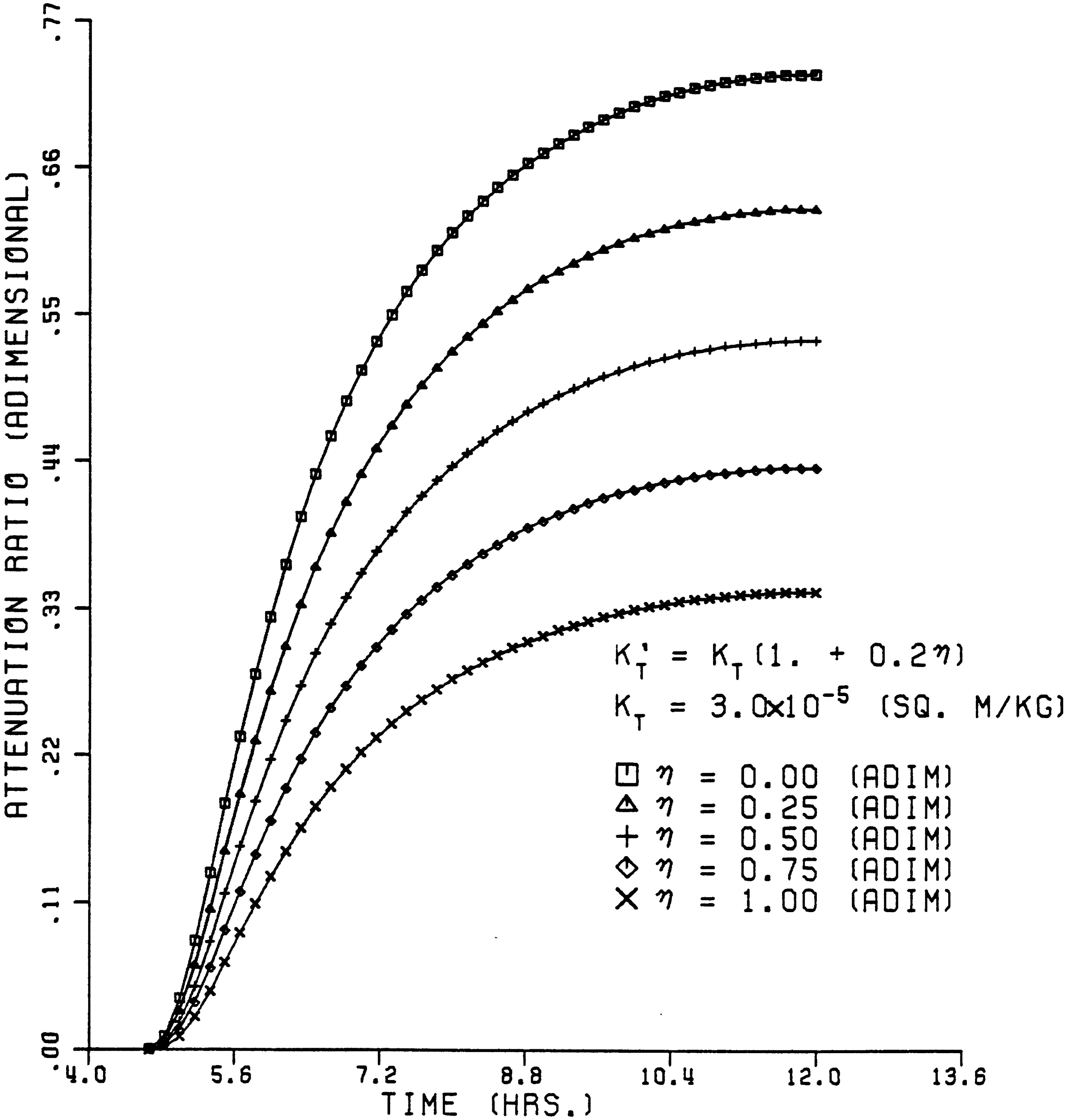
Using eq. 4.35, which gives the density of energy flux on a cloudy day, a better approximation is obtained if the K_T values previously defined are correlated to the clouds' presence through the following empirical relation, which takes into account the clouds' absorbance and the increase in water vapor in the atmosphere due to the clouds' presence:

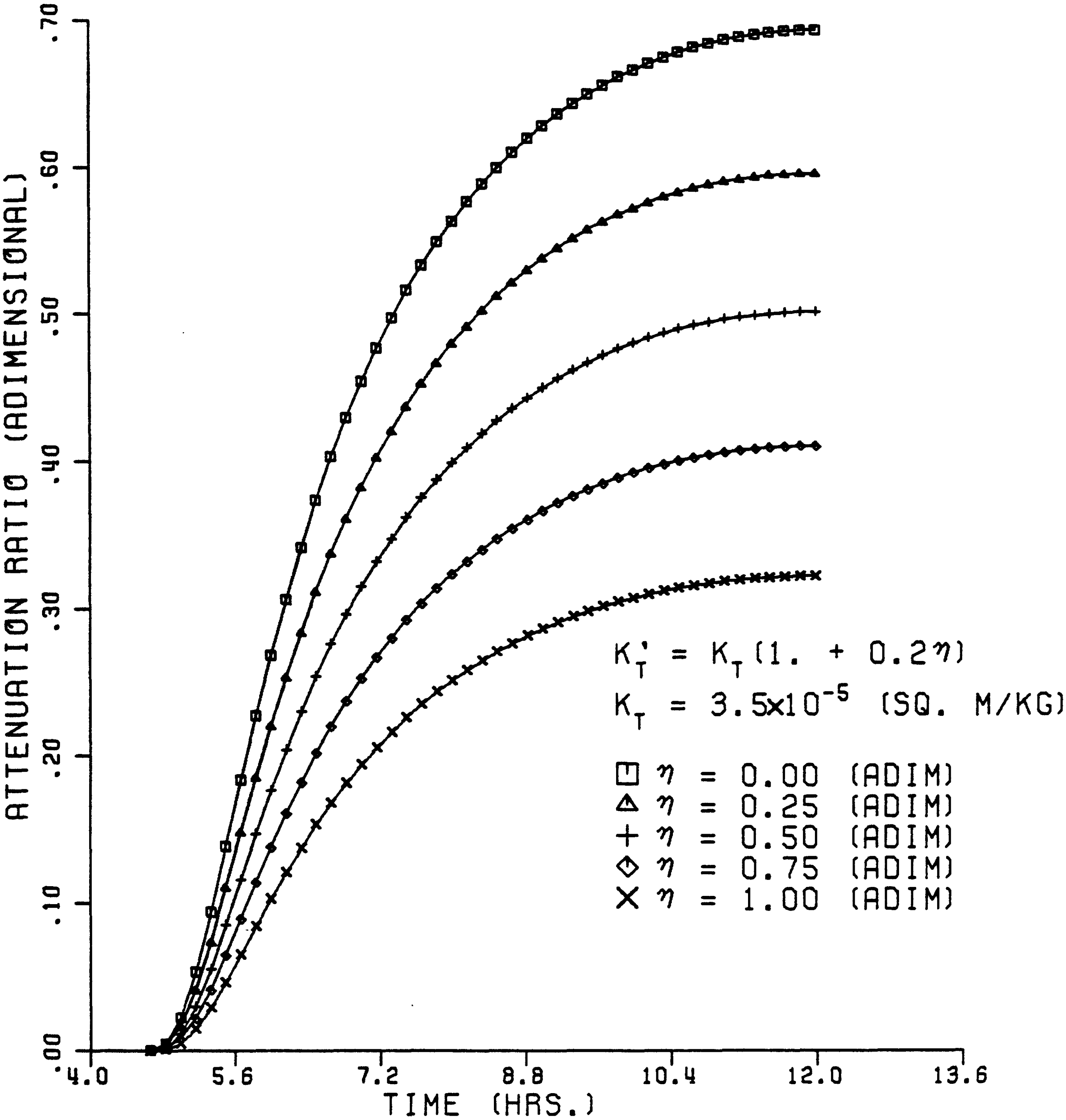
$$K_T' = K_T\ (1 + .3\ n) \quad [m^2\ Kg^{-1}] \tag{5.2}$$

Equation 5.2 states that, in the presence of clouds, K_T is increased by a quantity linearly proportional both to the clouds' quantity and K_T itself (up to a maximum value of 1.2 K_T), and K_T' is consequently defined. The constant of proportionality has been empirically determined, at this stage on a large macroclimatic approximation.

The attenuation factor, obtained from eq. 4.35, for a Standard Atmosphere and using eq. 5.2 for the $K_T^{'}$ computation, is plotted: The results for different values of η and for each of the "Standard Climatic Areas" previously mentioned (i.e., for each of the K_T values already computed) are reported below.


ATTENUATION RATIO (ADIMENSIONAL)
.00
.11
.22
.33
.44
.55
.66
.77
4.0
5.6
7.2
8.8
10.4
12.0
13.6
TIME (HRS.)
K'T = KT(1. + 0.2η)
KT = 2.5x10^-5 (SQ. M/KG)
η = 0.00 (ADIM)
η = 0.25 (ADIM)
η = 0.50 (ADIM)
η = 0.75 (ADIM)
η = 1.00 (ADIM)


ATTENUATION RATIO (ADIMENSIONAL)
.00
.11
.22
.33
.44
.55
.66
.77
4.0
5.6
7.2
8.8
10.4
12.0
13.6
TIME (HRS.)
$K_T' = K_T(1. + 0.2\eta)$
$K_T = 3.0\times10^{-5}$ (SQ. M/KG)
η = 0.00 (ADIM)
η = 0.25 (ADIM)
η = 0.50 (ADIM)
η = 0.75 (ADIM)
η = 1.00 (ADIM)



.70
.60
.50
.40
.30
.20
.10
.00
ATTENUATION RATIO (ADIMENSIONAL)
4.0
5.6
7.2
8.8
10.4
12.0
13.6
TIME (HRS.)
$K_T' = K_T(1. + 0.2\eta)$
$K_T = 3.5\times10^{-5}$ (SQ. M/KG)
η = 0.00 (ADIM)
η = 0.25 (ADIM)
η = 0.50 (ADIM)
η = 0.75 (ADIM)
η = 1.00 (ADIM)

5.1.2 Microclimatic approximation

For a meso- or microclimatic approximation, the K_T computation should be strictly related, in an explicit form, to the meteorological parameters.

It is evident that the number of parameters considered may be as high as required. Theoretically, since those parameters—here called meteorological parameters (to enhance their dependency with respect to time and location)—are nothing more than all those factors that qualitatively and quantitatively describe the components of the atmosphere as concerns their interaction with the electromagnetic beam, the higher the number of factors considered, the higher will be the precision of the model.

Nevertheless, in order to be able to use a physical model, all the parameters considered should be determined and, obviously, determinable. Furthermore, their measurement should generally be already available (e.g., because data have been developed for other purposes), or at least, they should be determinable (by computation or measurement) in a relatively simple and economic way.

Records of meteorological data are extremely rare, incomplete, and imprecise. It has been noticed, trying different methodologies of correlation, that relatively complete physical models are rather sensitive to a lack of strong approximation on the values of the input data needed. They often appear to be less precise, even drastically so, than simpler models for which the input data are available with a certain precision and extension.

Therefore, a general criterion for the microclimatic correlation has been adopted: implement as complete a model as possible but keep it always compatible with the meteorological input data "generally" available. This is rather hard to accomplish with clouds, as concerns the availability and significance of data, or for the amount of water vapor present in the atmosphere, as concerns the complexity, precision, and cost of necessary measurements. In these cases, the simplest possible approach has been used, and alternative ways of computation have been indicated, even when they imply an appreciable drop in precision.

With these criteria in mind, K_T will be expressed as a function of the standard components of the atmosphere, i.e., permanent gases, amount of water, and amount of polluting agents and dispersers, such as haze, fog, dust, etc. Thus:

$$K_T = K_T \text{ (standard components, water vapor, local factors)}$$

The following form will be used:

$$K_T = p_1 + p_2 w^{p_3} + p_4 p \qquad (5.3)$$

where:

p_1 = depletion due to permanent components of the atmospheric gas (N_2, O_2, Ar, O_3, etc.)

w = amount of precipitable water

p_2 = intensive factor of depletion due to precipitable water

p_3 = intensive factor of depletion due to precipitable water

p_4 = intensive factor of depletion due to "local" factors

p = extensive factor representing depletion due to "local" factors.

It is well known [47–49] (see Chapter 3) that water vapor exerts a considerable influence on atmospheric absorbance, and therefore on the radiative energy flux depletion. A nonlinear dependence of K_T with respect to the water vapor present in the atmosphere has been found, as may be seen from the following tabulation, obtained for S/D = 1 and no "pollution" [50]:

mm H_2O	0	1	10	20	40	60
10^{-5} K_T	1.32	1.82	2.58	2.98	3.50	3.89
E_0/E_S	0.87	0.82	0.76	0.73	0.69	0.67

As concerns the precipitable water term, the analytical expression of eq. 5.3 takes it into consideration in a satisfactory approach.

The introduction of an "integral" term as concerns the effect of the permanent gases of the atmosphere, is coherent, theoretically justified, consistent with the general ideas of this work, and should not pose any problem.

The factor p, here defined as the "local" factor, should take into consideration all these phenomena of the interaction of the electromagnetic beam with the atmosphere components, related to aerosol presence, dust, fog, haze, etc. These phenomena could be modeled with relative accuracy, and it is only the above-mentioned lack of data needed for the definition of the modeled system, that justifies such an approximation. As a matter of fact, it will also be hard to just tabulate the factor p!

Both the form and the parameters considered in eq. 5.3 permit the obtaining of a satisfactory relation between K_T and the atmospheric parameters. This relation is believed to be the most precise and realistic obtainable, considering the meteorological data records "generally" available. Furthermore, it appears to be quite independent from the geographic location to which it is applied, thus showing a physical content and a non- (totally) empirical formulation.

The integral transparency coefficient for a dry and clean atmosphere on a clear day with no clouds is known to be:

after Kastrov [51-52]	0.910
International Radiation Commission (1956)	0.915
after Sivkov [53]	0.907

Recalling the definition of the integral transparency coefficient from eqs. 4.26 and 4.29, and setting <u>w</u> and <u>p</u> equal to zero in eq. 5.3, the factor p_1 may be easily computed (or verified).

Once p_1 has been obtained, considering a real atmosphere on a particular clear day with no clouds or polluting agents, recalling eq. 4.29, assuming <u>p</u> equals zero, the factors p_2 and p_3 are obtained, using a best-fitting procedure (least-square regression technique).

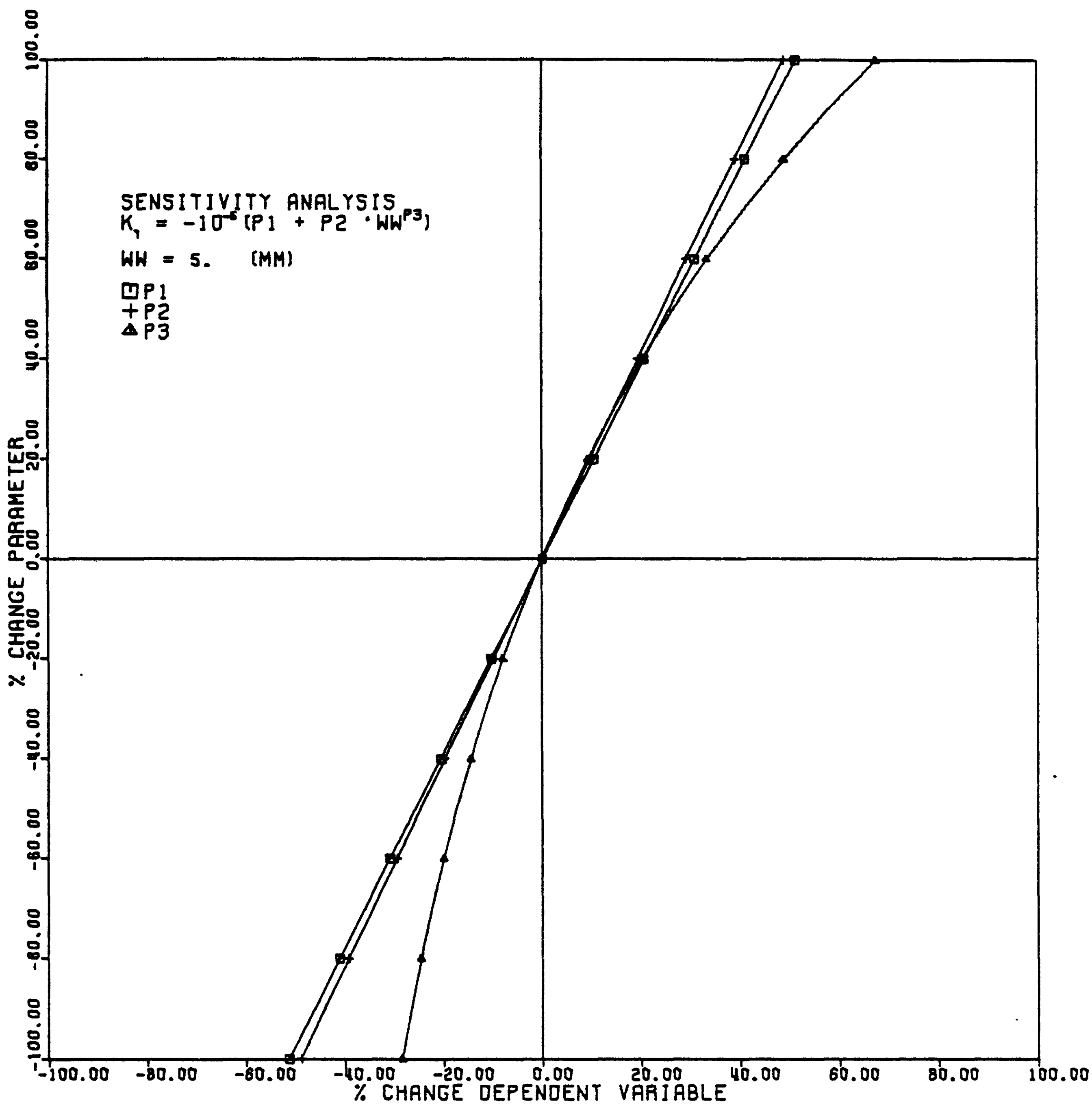
For the moment, and on a first approximation, eq. 5.3 will be considered without the "pollution" (or "local") factor p. Under these circumstances, eq. 5.3 may be rewritten as:

$$K_T = 10^{-5}\ (1.00 + .40\ w^{.40})\quad [m^2\ Kg^{-1}] \tag{5.4}$$

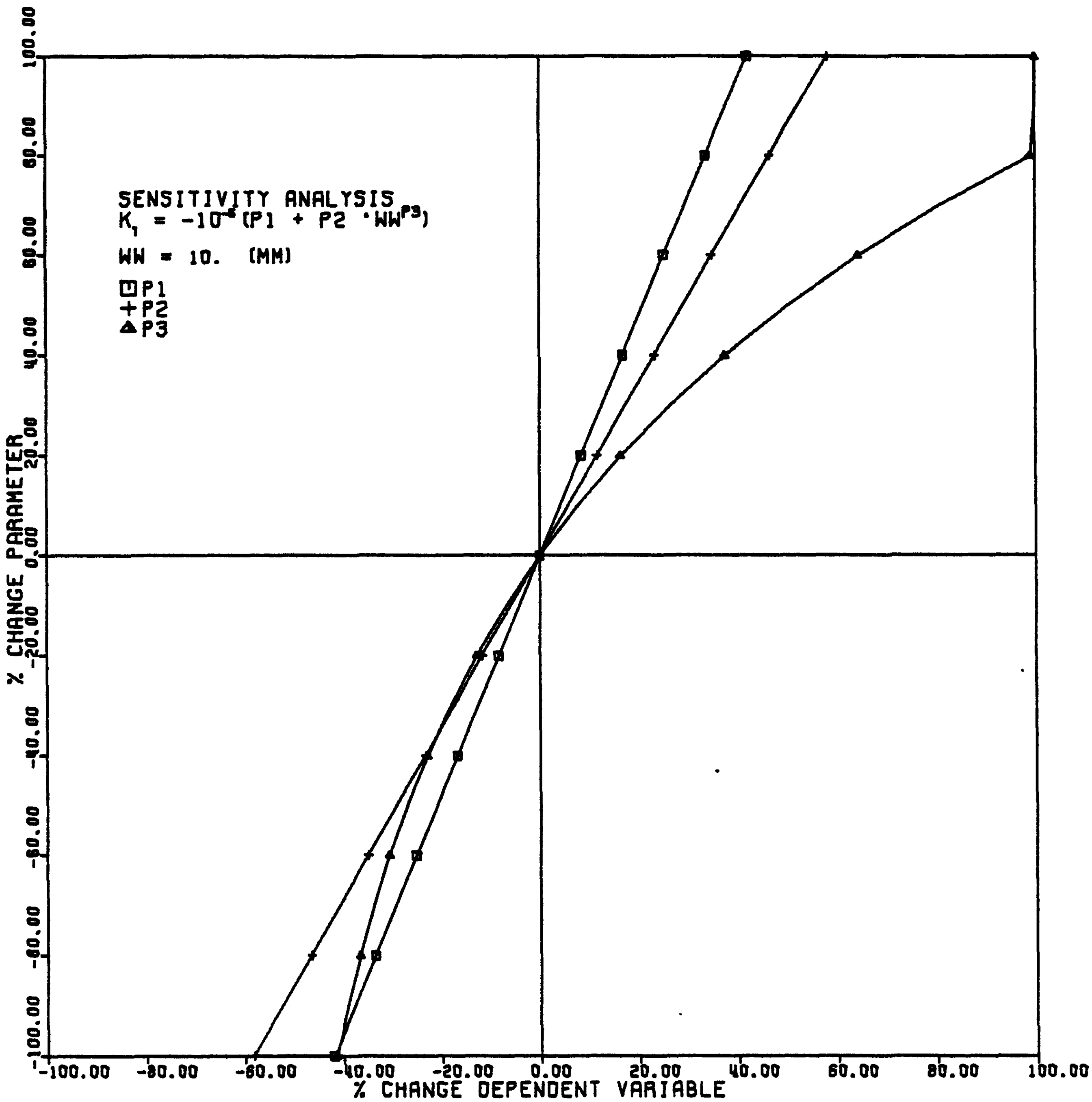
where the amount of precipitable water is expressed in millimeters, and p_2 and p_3 values correspond to a smooth best-fitting, accomplished with southern European data.

Measured values of precipitable water for the U.S. are available on the basis of two balloon measurements per day, at 0.00 and 12.00 hours, G.M.T. The basic raw data generally up to 500 mbars, needs to be elaborated and, sometimes, extrapolated (or multiplied by a 1.15 factor). An alternative way to compute the amount of precipitable water from pressure, dew point (or relative humidity), and temperature values, using the Clausius-Clapeyron equation and elementary concepts of physics of the atmosphere, is reported in Appendix A3.

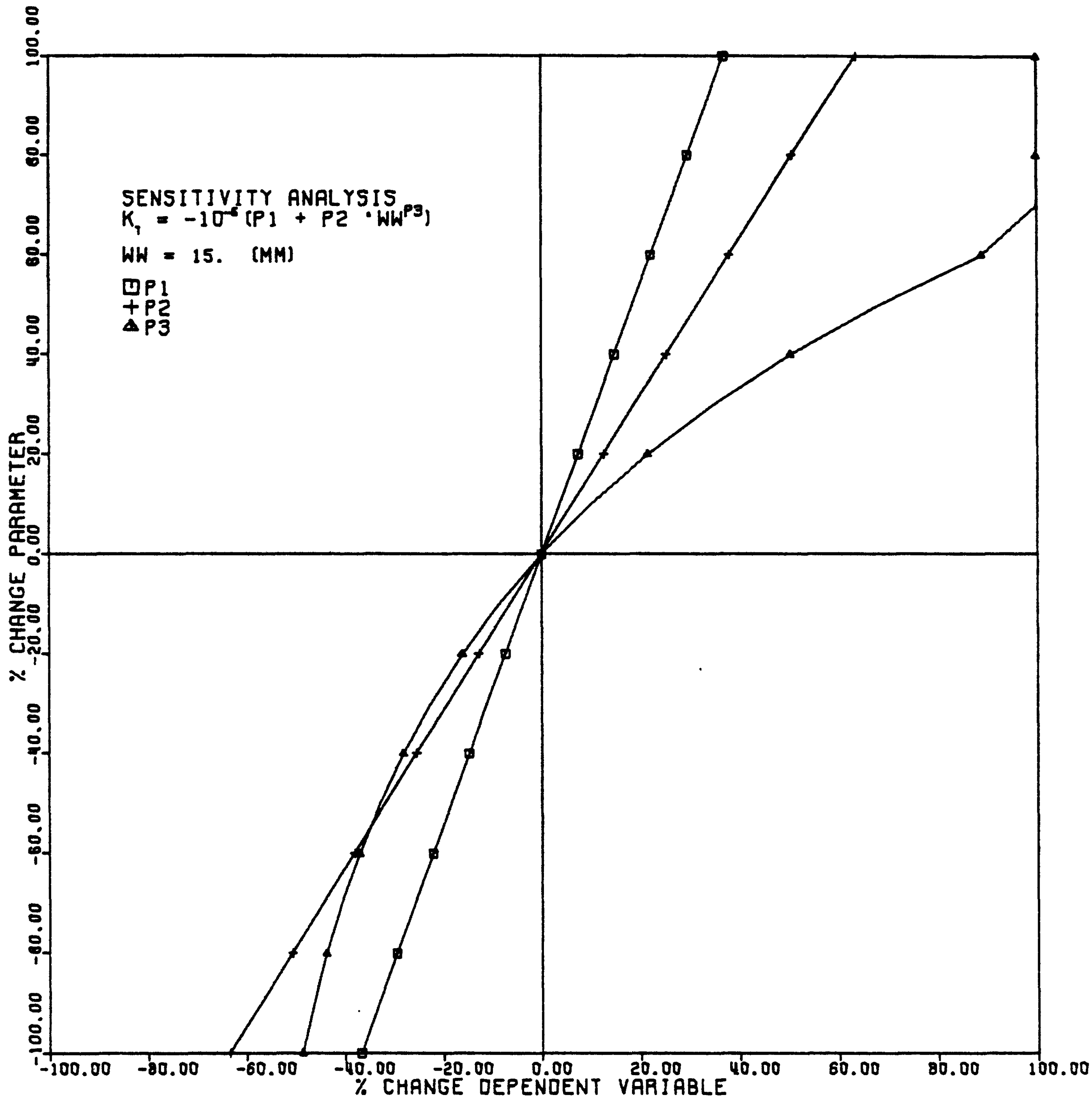
The sensitivity analysis of K_T with respect to the three parameters, p_1, p_2 and p_3, using the "spider" graph technique, is reported below for different values of w.

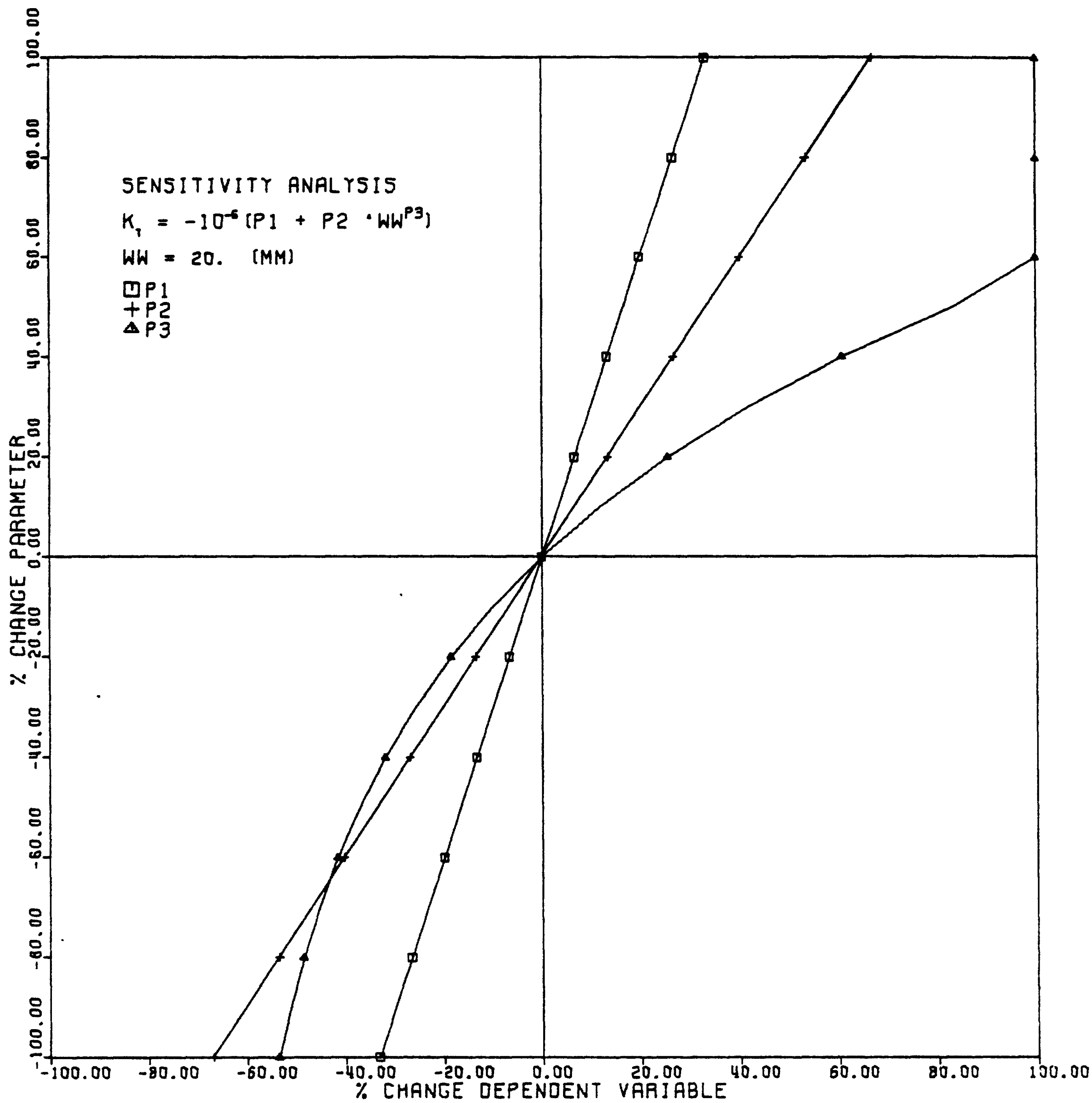


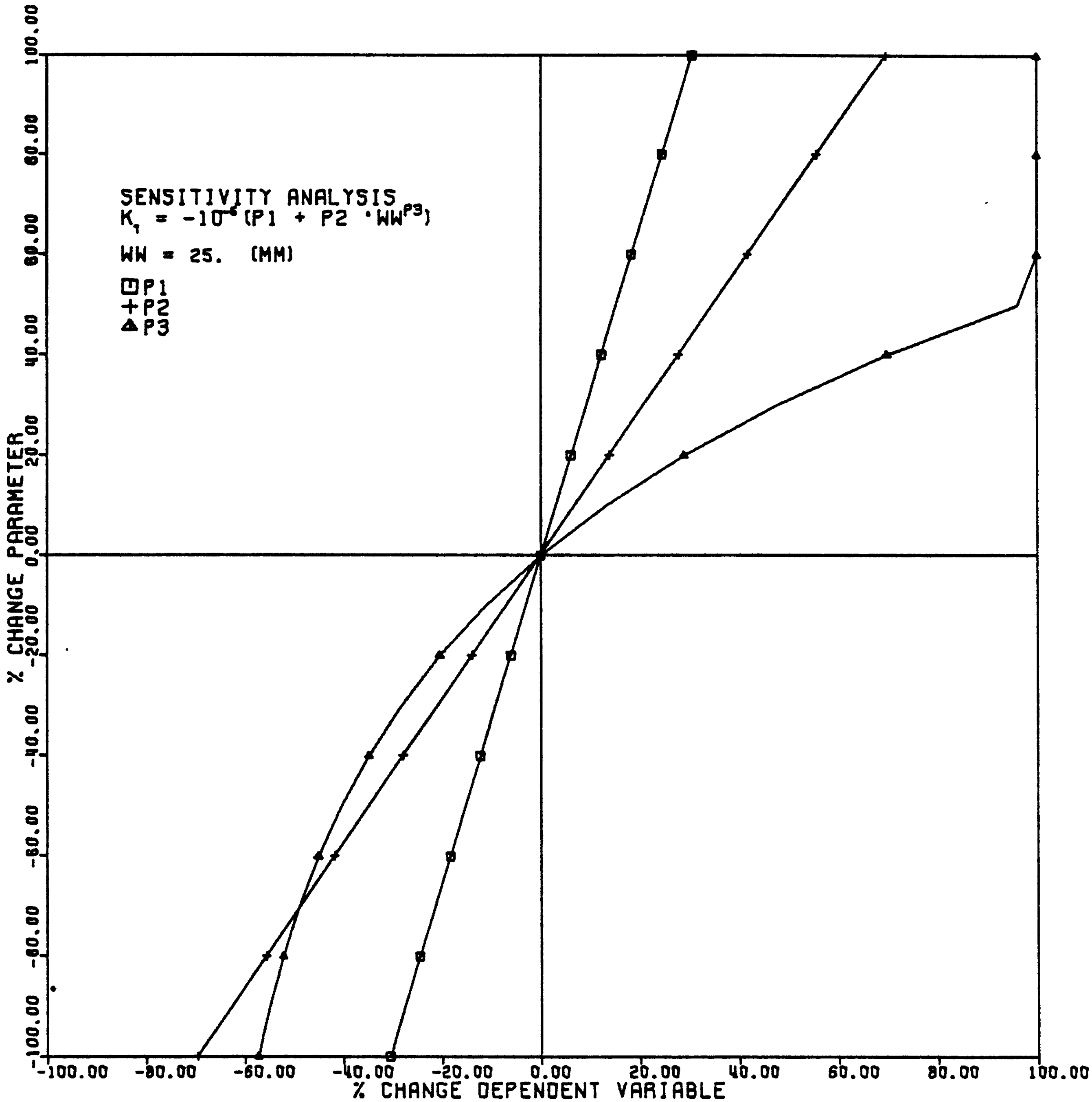
SENSITIVITY ANALYSIS
K, = -10⁻⁶ (P1 + P2 · WW^P3)
WW = 5. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00



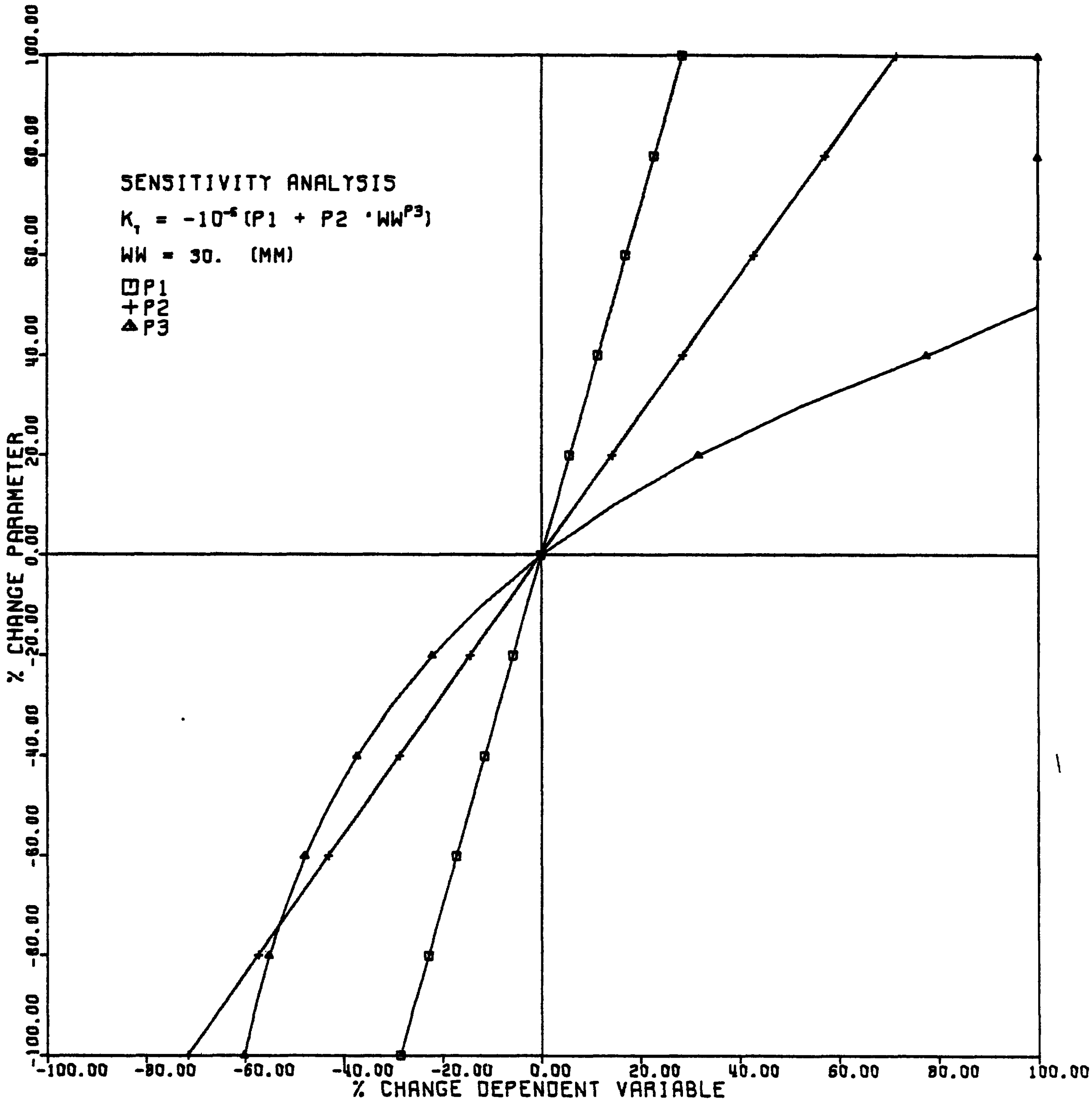
SENSITIVITY ANALYSIS
$K_1 = -10^{-6}(P1 + P2 \cdot WW^{P3})$
WW = 10. (MM)
P1
P2
P3
% CHANGE PARAMETER
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
% CHANGE DEPENDENT VARIABLE


SENSITIVITY ANALYSIS
K₁ = -10⁻⁶ (P1 + P2 ·WW^P3)
WW = 15. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00


SENSITIVITY ANALYSIS
K_T = -10^-6 (P1 + P2 ·WW^P3)
WW = 20. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00



SENSITIVITY ANALYSIS
$K_1 = -10^{-6}(P1 + P2 \cdot WW^{P3})$
WW = 25. (MM)
P1
P2
P3
% CHANGE PARAMETER
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00



SENSITIVITY ANALYSIS
K = -10^-6 (P1 + P2 ·WW^P3)
WW = 30. (MM)
P1
P2
P3
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
% CHANGE PARAMETER
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
% CHANGE DEPENDENT VARIABLE

Taking into consideration the explicit form of K_T (given in eq. 5.4), eq. 4.30, which computes the energy flux density for noncloudy days, may be rewritten as:

$$E_0 = E_S \exp[-(10^{-5}(1. + .4\, w^{.4})\;A_0\;A_1(h))] \qquad (5.5)$$

A self-explanatory example output of the E_0 computation, following eq. 5.5, is reported below.

ASTRONOMICAL, METEOROLOGICAL AND ENERGY FLUX DENSITY CALCULATIONS

ALBANY, NY (USA)

LAT. 42.7 DEG. NORTH   LONG. 73.83 DEG. WEST   ALT. 79.3 METERS

(REAL ATMOSPHERE, NO CLOUDS)

```
HH = ALTITUDE OF SUN
     PO = ATMOSPHERIC PRESSURE
          AO = DENSITY INTEGRAL
               A1 = RELATIVE ATMOSPHERIC MASS
                    WW = PRECIPITABLE WATER
                         KT = ATMOSPHERIC ATTENUATION 'CONSTANT'
                              TAU = ATMOSPHERIC ATTENUATION
                                    EO(ORT)I = ENERGY FLUX DENSITY, IDEAL ATMOSPHERE
                                         EO(ORT) = ENERGY FLUX DENSITY, REAL ATMOSPHERE
                                              EO(HOR) = ENERGY FLUX DENSITY, REAL ATMOSPHERE, ON THE HORIZONTAL
                                                   ES = EXTRATERRESTRIAL ENERGY FLUX DENSITY (SOLAR 'CONSTANT')
```

FEB. 1, 1979 DAY NUMBER 32

ES = 1413. [W/SQ.M] SUNRISE = 7.232 [HRS.] SUNSET = 17.059 [HRS.] GEOMETRICAL DAY LENGTH = 9.827 [HRS.]
(MERIDIAN TIME)

MERID. TIME	SUN'S AZIMUTH	SUN'S ALTITUDE	ATMOS. PRESSURE	DENSITY INTEGRAL	ATMOS. MASS	PRECIP. WATER	ATTEN. 'CONST.'	ATMOS. ATTEN.	ENERGY FLUX DENSITY			SOLAR TIME
[HRS.]	PSI [DEG.]	HH [DEG.]	PO [N/SQ.M]	AO [KG/SQ.M]	A1 [ADIM.]	WW [MM]	KT [SQ.M/KG]	TAU [ADIM.]	EO(ORT)I [W/SQ.M]	EO(ORT) [W/SQ.M]	EO(HOR) [W/SQ.M]	[HRS.]
8.00	121.41	7.52	98883.	10088.	4.01	4.4	2.16E-05	0.42	961.	590.	77.	7.85
9.00	133.02	16.30	98950.	10095.	2.80	4.5	2.17E-05	0.54	1080.	765.	215.	8.85
10.00	146.27	23.44	98984.	10098.	2.21	4.6	2.33E-05	0.59	1143.	840.	334.	9.85
11.00	161.28	28.32	99018.	10102.	1.93	4.7	2.34E-05	0.63	1174.	895.	425.	10.85
12.00	177.59	30.35	98984.	10098.	1.83	4.9	2.43E-05	0.64	1185.	901.	455.	11.85
13.00	194.08	29.23	98984.	10098.	1.88	4.9	2.59E-05	0.61	1179.	863.	421.	12.85
14.00	209.55	25.12	99018.	10102.	2.10	5.1	2.61E-05	0.57	1154.	812.	345.	13.85
15.00	223.32	18.57	99120.	10112.	2.58	5.1	2.62E-05	0.50	1102.	713.	227.	14.85
16.00	235.37	10.20	99221.	10123.	3.57	5.3	2.64E-05	0.39	1002.	545.	97.	15.85
17.00	246.08	0.59	99323.	10133.	5.57	5.4	2.65E-05	0.22	826.	317.	3.	16.85
18.00	255.99	-9.82	99323.	10133.	5.57	5.4	2.65E-05	0.22	0.	0.	0.	17.85

Recalling that eq. 5.5 furnishes the value of the density of energy flux (watts per square meter), the density of energy flux on the horizontal (Lambert's Law) can be directly derived:

$$E_0 = E_S \exp[- K_T \ A_0 \ A_1(h)] \cos(\theta) \tag{5.6}$$

where:

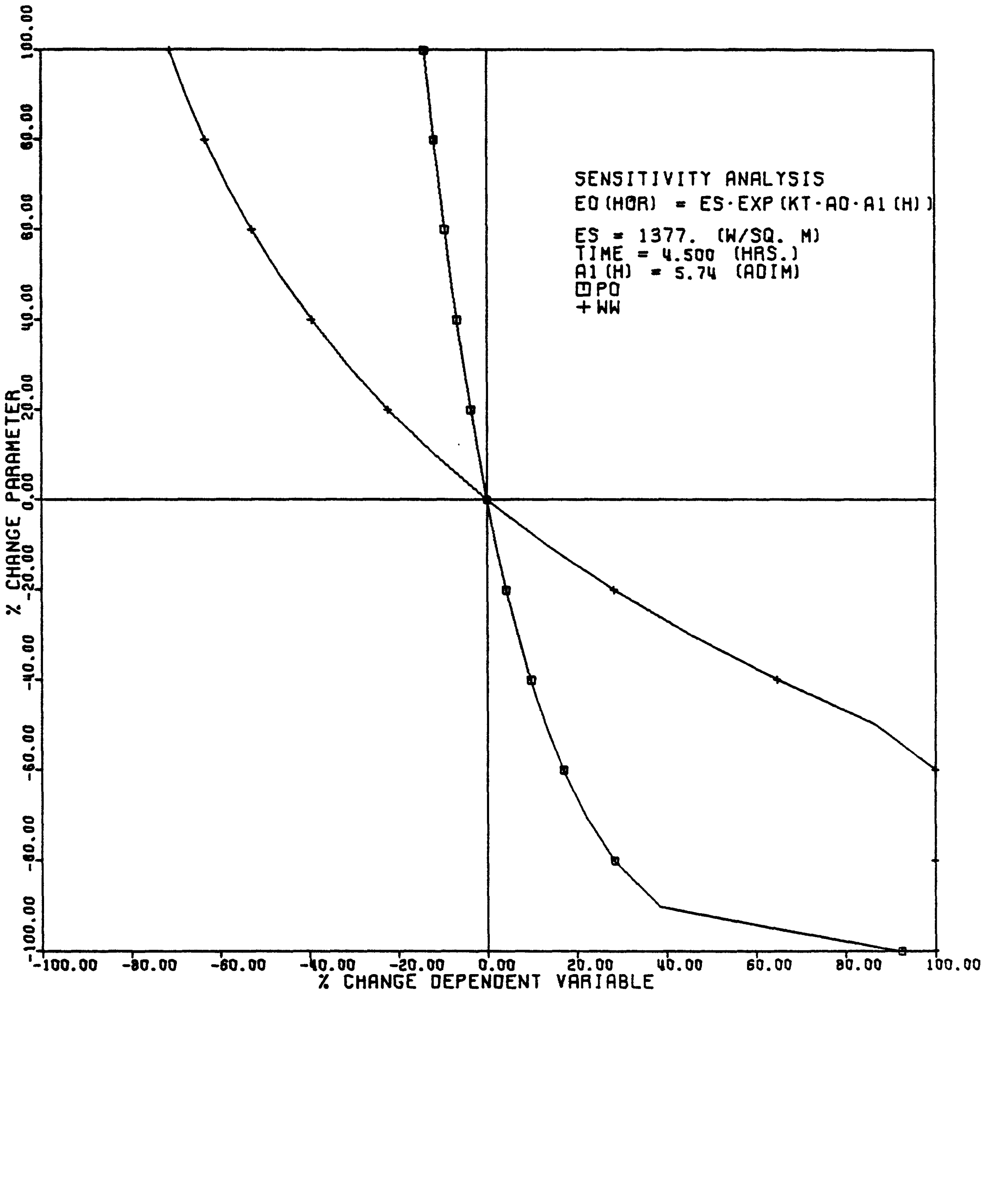
θ = angle between the beam's direction and the normal to the surface being considered (often called zenith angle)

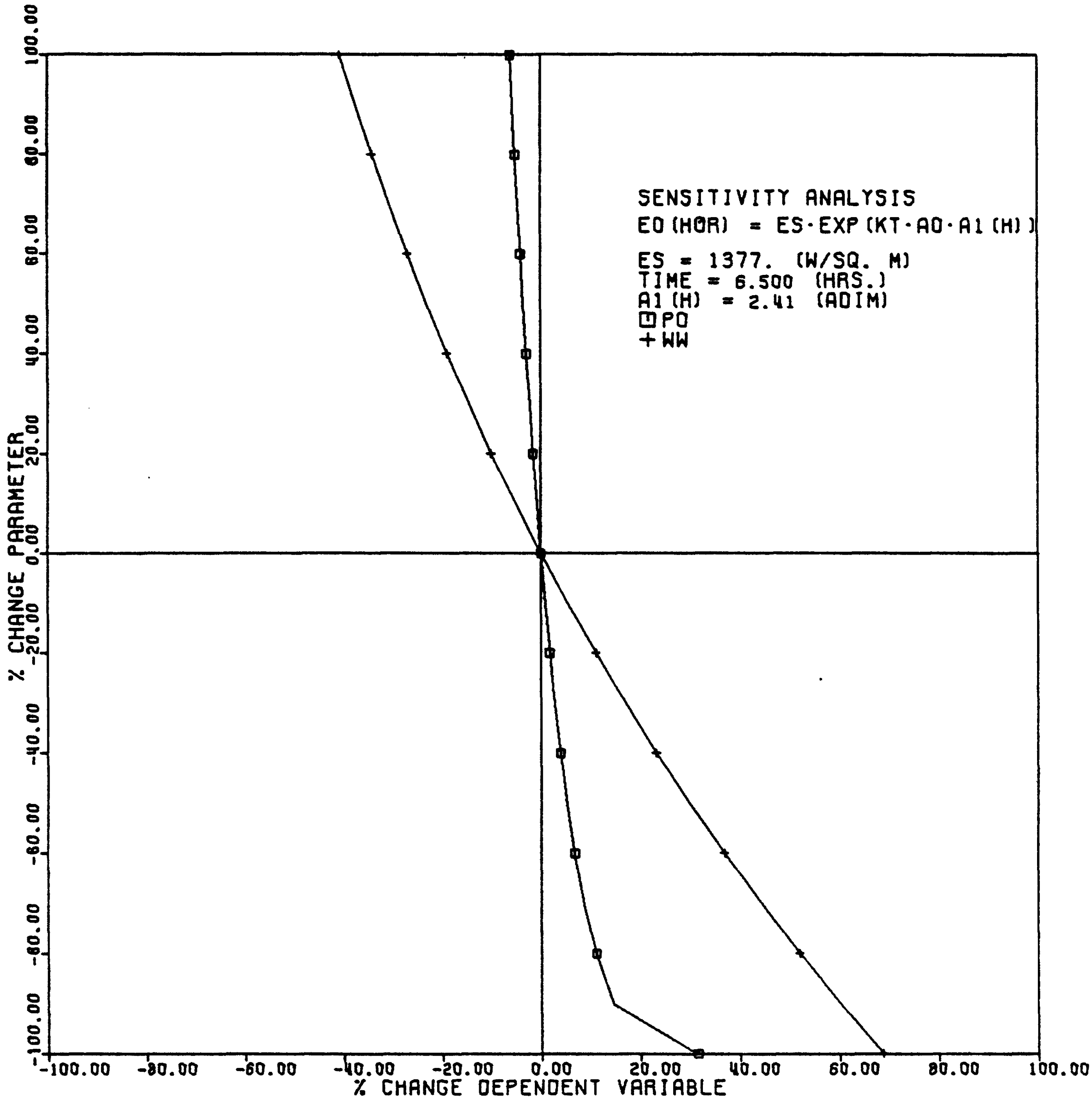
It should be noted, as concerns eq. 5.6, that as concerns the horizontal surface, the normal to the surface coincides with the zenith; recalling the definition of the altitude of the Sun, <u>h</u> (see Chapter 2), it is immediately seen that the altitude and the zenith are complementary angles. Thus, and only for the horizontal plane:

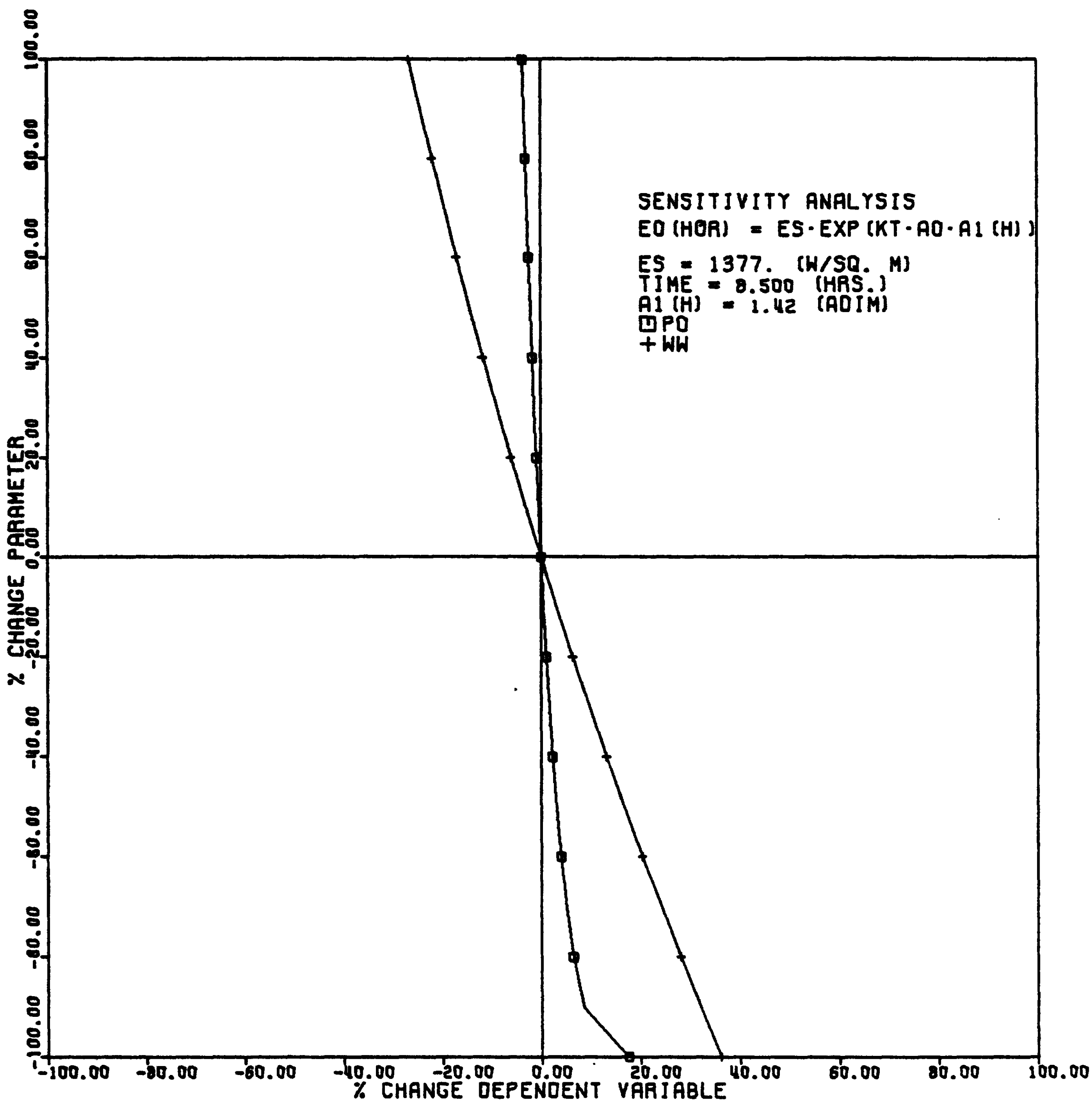
$$\cos(\theta) = \sin(h) \tag{5.7}$$

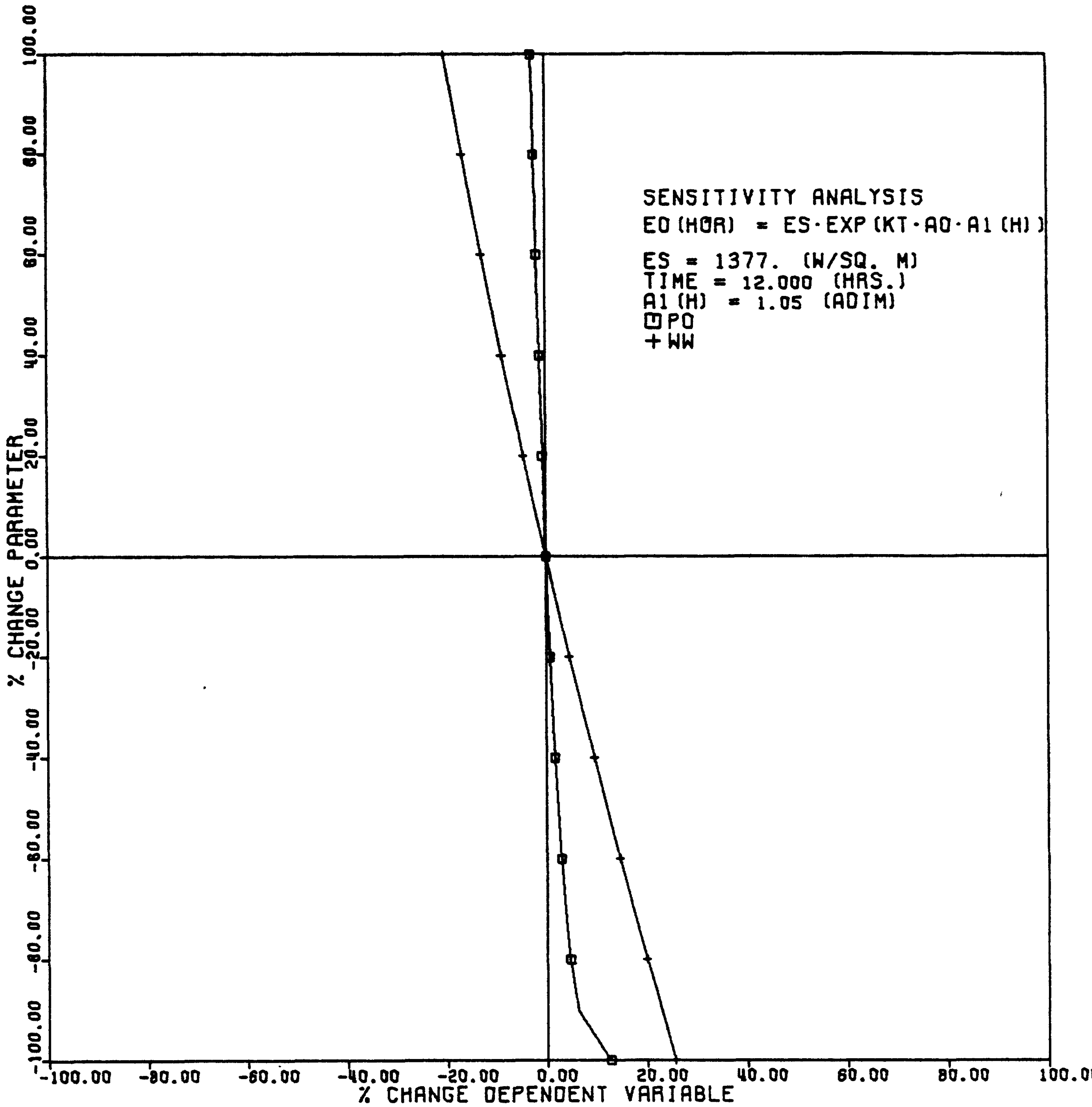
The symbol E_0 has been extensively used throughout this work to represent a density of energy flux; therefore the same symbol will be used when computing the density of energy flux for any surface. This implies a slight alteration in the physical meaning of the vector energy flux density, since the flux density of a vectorial magnitude is always computed through a surface perpendicular to the vector.

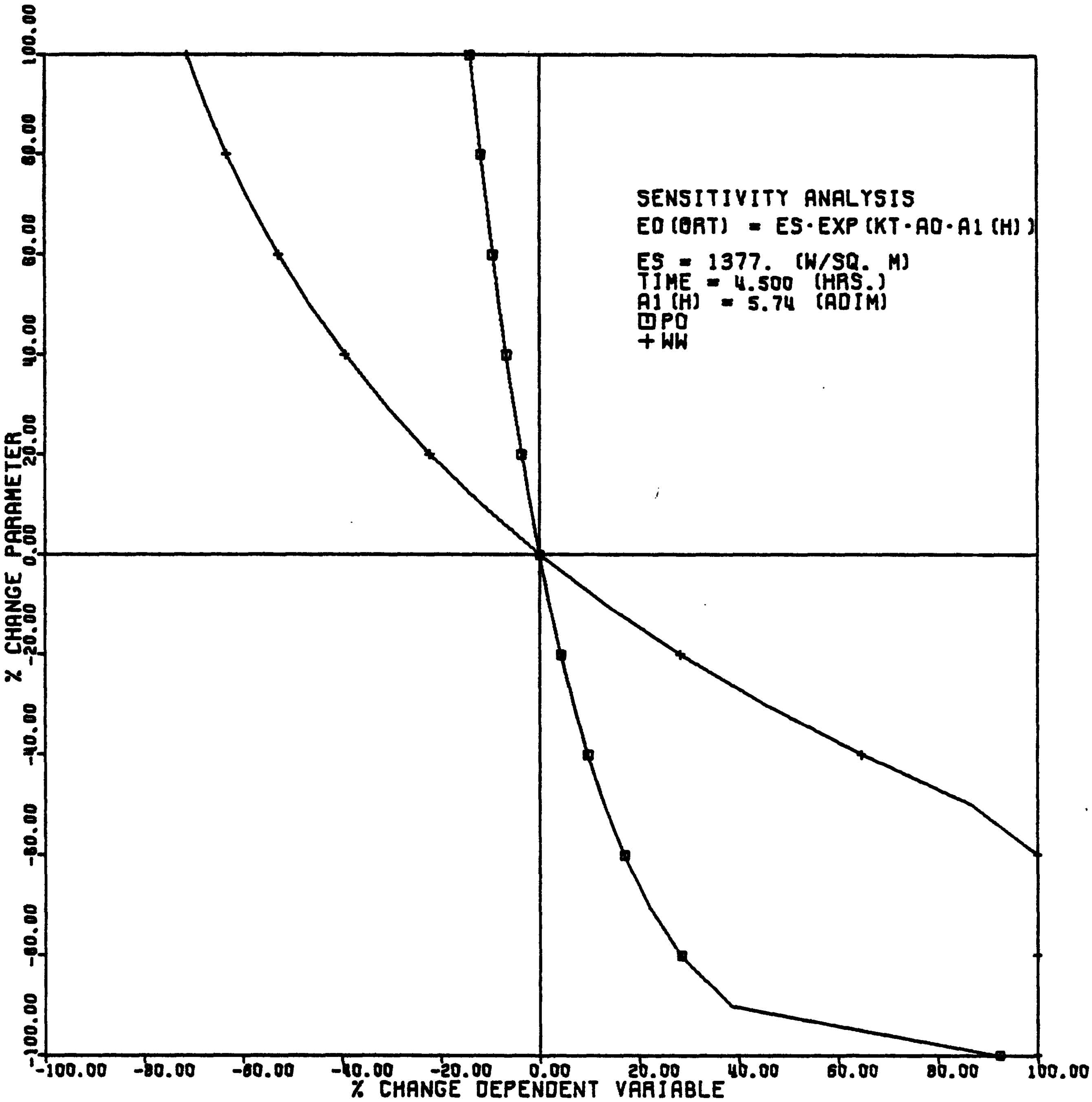
The "spider" technique sensitivity analysis is applied to eqs. 5.6 and 5.5, using the expression of K_T furnished by eq. 5.4, and the E_0 sensitivity is analyzed with respect to the atmospheric pressure and the amount of precipitable water values (the first independent variable will affect the A_0 computation--density integral; the latter will affect the K_T computation--atmospheric attenuation "constant") for four different hours of the day. The results are reported below, both for E_0 on the horizontal (eq. 5.6) (energy flux density on the horizontal) and E_0 ortogonal to the beam's direction (eq. 5.5) (energy flux density).

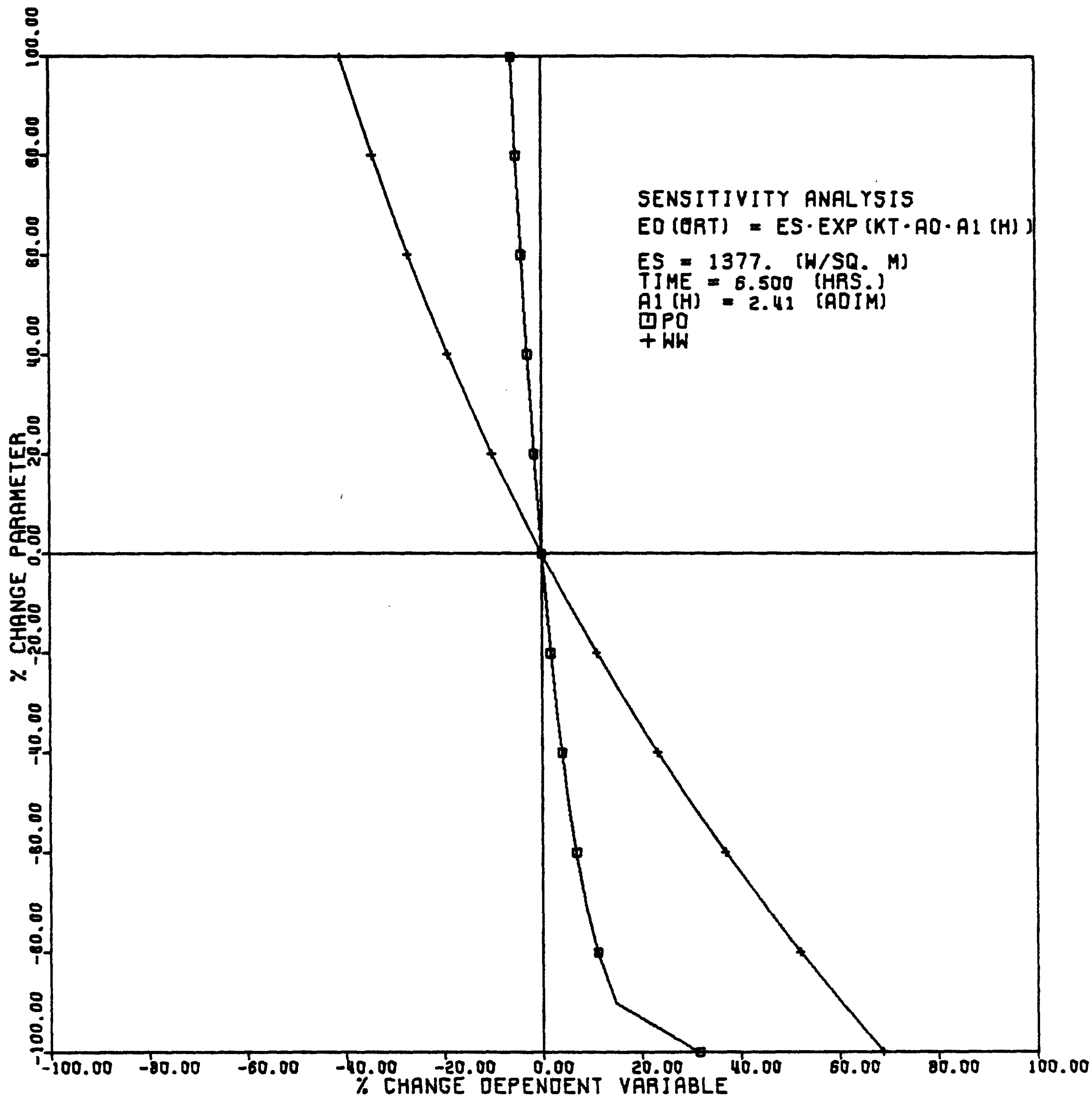

SENSITIVITY ANALYSIS
EO(HOR) = ES·EXP(KT·AO·A1(H))
ES = 1377. (W/SQ. M)
TIME = 4.500 (HRS.)
A1(H) = 5.74 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00


SENSITIVITY ANALYSIS
EO (HOR) = ES·EXP (KT·AO·A1 (H))
ES = 1377. (W/SQ. M)
TIME = 6.500 (HRS.)
A1 (H) = 2.41 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00

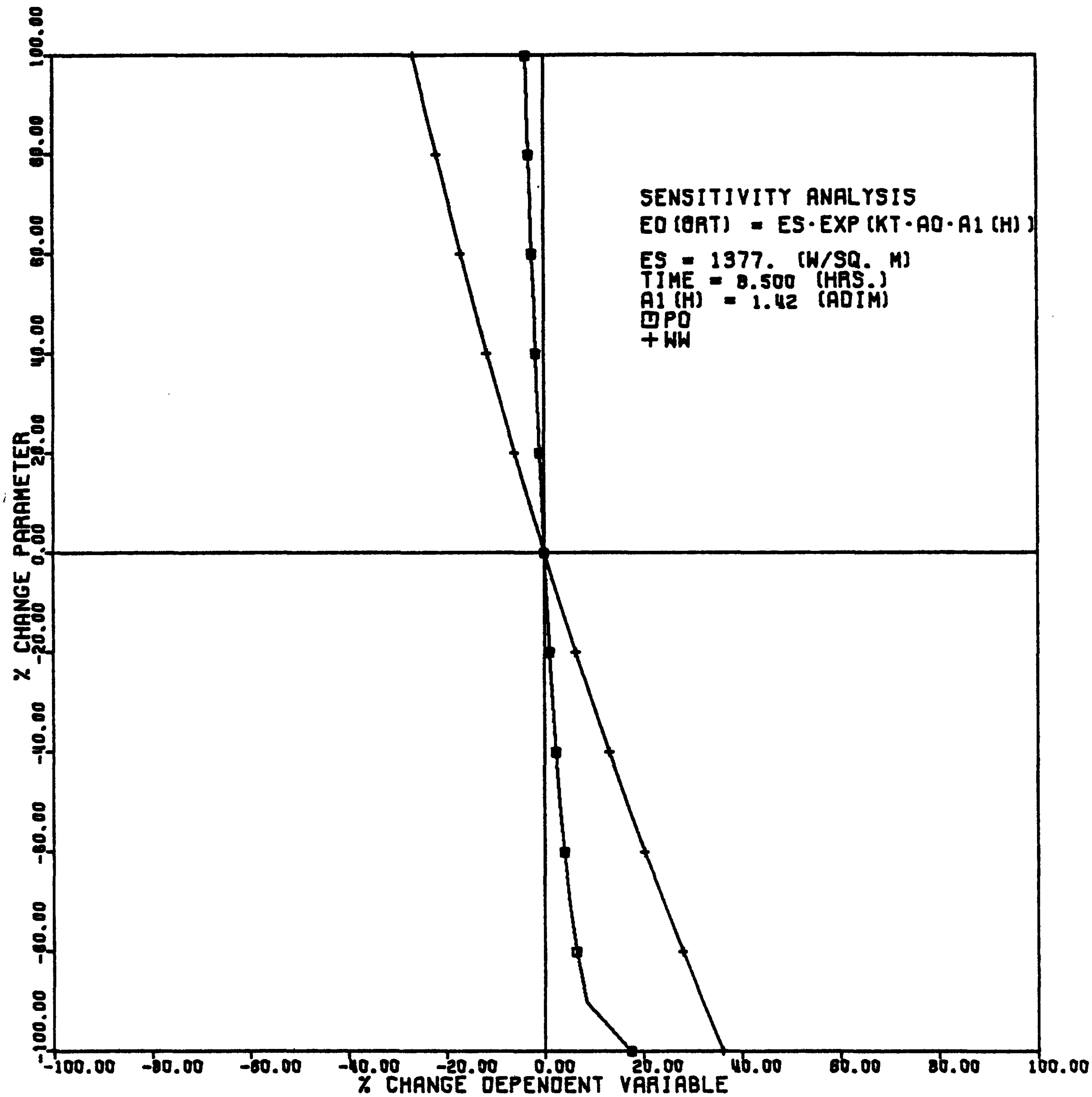

SENSITIVITY ANALYSIS
EO(HOR) = ES·EXP(KT·AO·A1(H))
ES = 1377. (W/SQ. M)
TIME = 8.500 (HRS.)
A1(H) = 1.42 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00


SENSITIVITY ANALYSIS
EO(HOR) = ES·EXP(KT·AO·A1(H))
ES = 1377. (W/SQ. M)
TIME = 12.000 (HRS.)
A1(H) = 1.05 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00

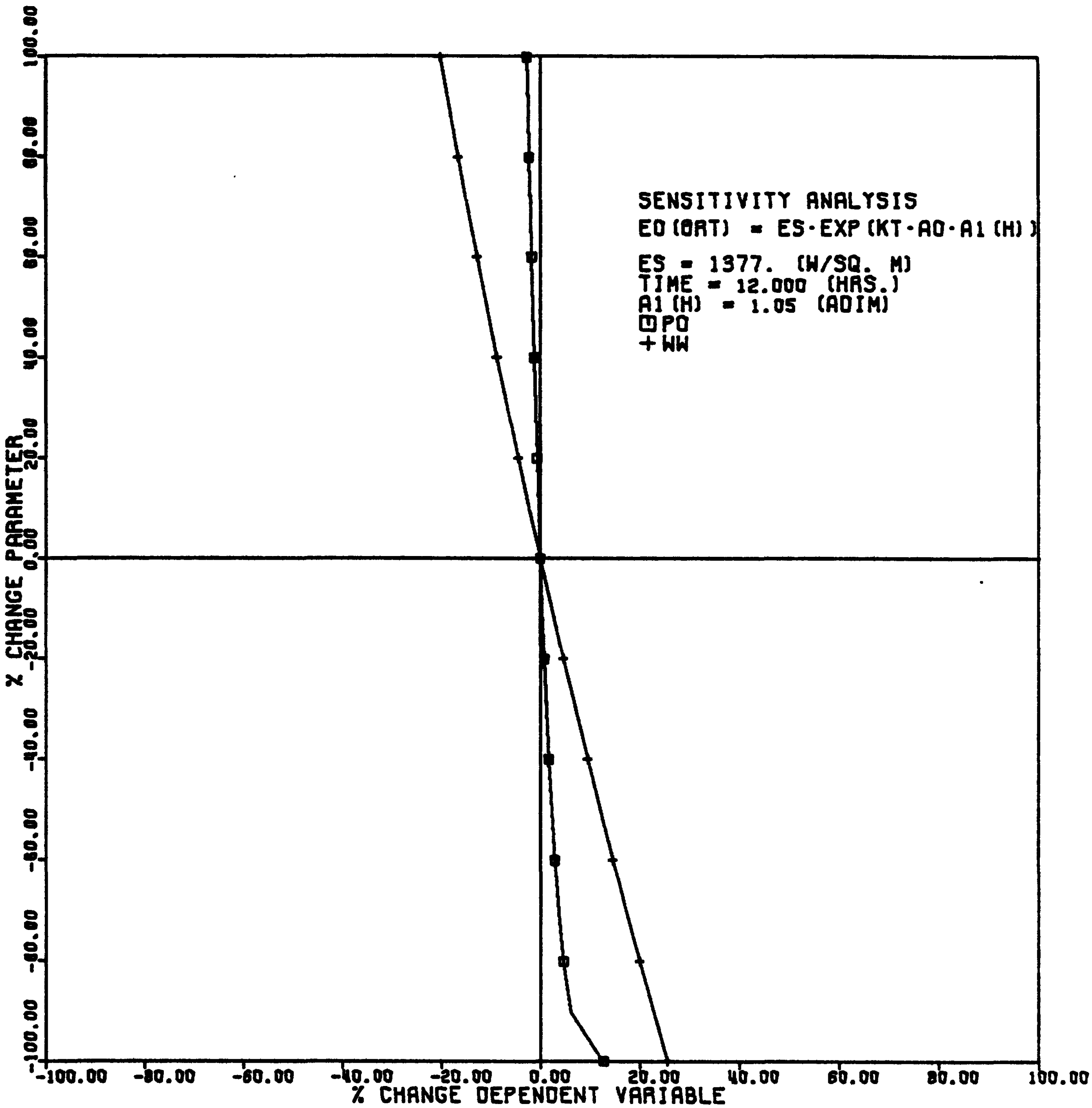

SENSITIVITY ANALYSIS
EO(BAT) = ES·EXP(KT·AO·A1(H))
ES = 1377. (W/SQ. M)
TIME = 4.500 (HRS.)
A1(H) = 5.74 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00



SENSITIVITY ANALYSIS
ED(ORT) = ES·EXP(KT·A0·A1(H))
ES = 1377. (W/SQ. M)
TIME = 6.500 (HRS.)
A1(H) = 2.41 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00



SENSITIVITY ANALYSIS
EO (BRT) = ES·EXP (KT·AO·A1 (H))
ES = 1377. (W/SQ. M)
TIME = 8.500 (HRS.)
A1 (H) = 1.42 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00

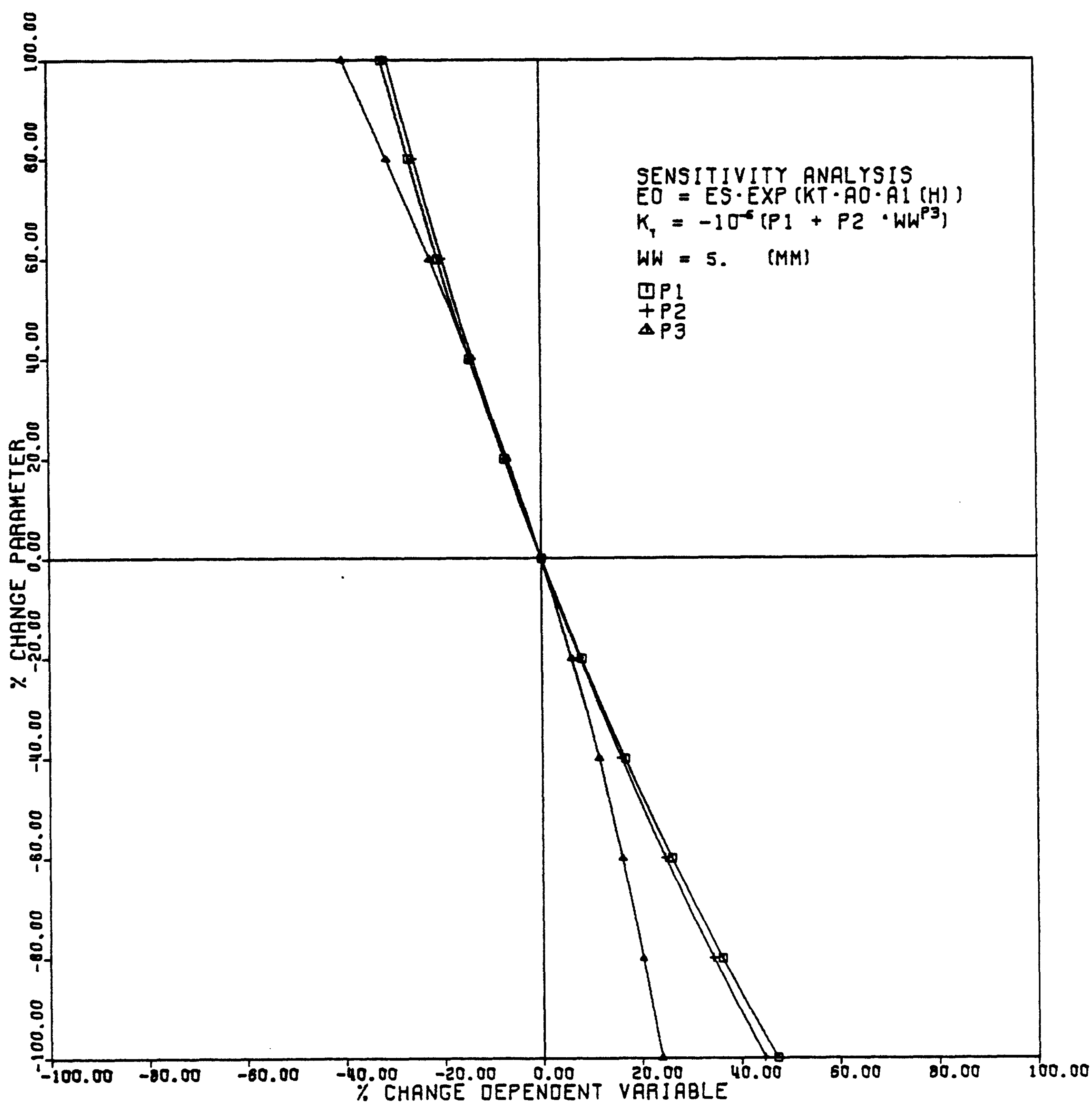

SENSITIVITY ANALYSIS
EO(ORT) = ES·EXP(KT·AO·A1(H))
ES = 1377. (W/SQ. M)
TIME = 12.000 (HRS.)
A1(H) = 1.05 (ADIM)
PO
WW
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00

Equation 5.4 differs from eq. 5.3 in that the parameter p, called "local" factor, appears in the latter equation but not in the former.

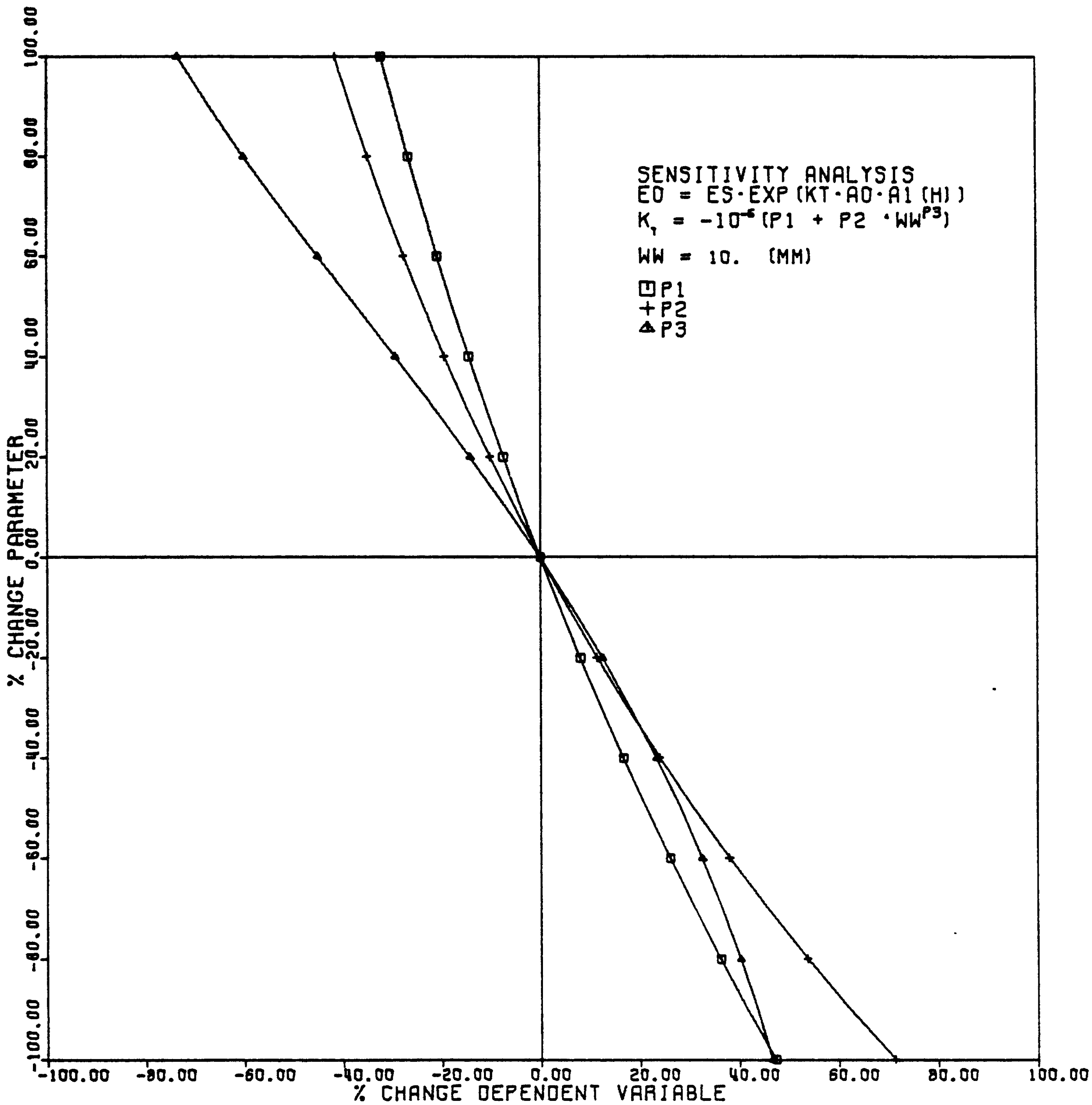
A tentative tabulation of the local factor will be attempted, and the correspondent p_4 "importance" (intensive) factor will be determined, using available experimental data.

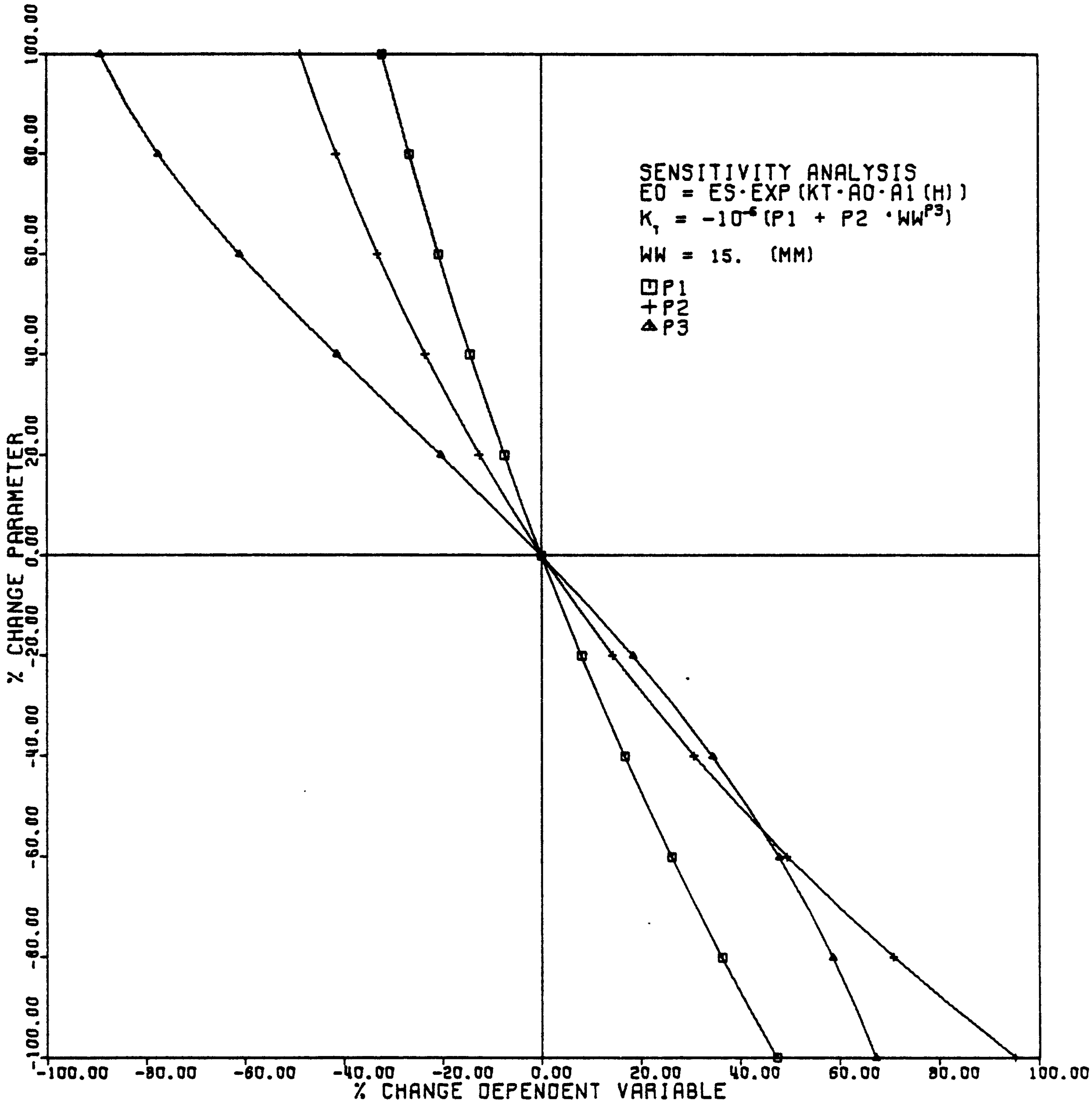
The order of magnitude of the importance of the term $p_4 p$ has been previously mentioned to have a maximum, in normal conditions, of .5-.6 10^{-5}. It then accounts for a maximum of approximately 20 percent of the K_T value.

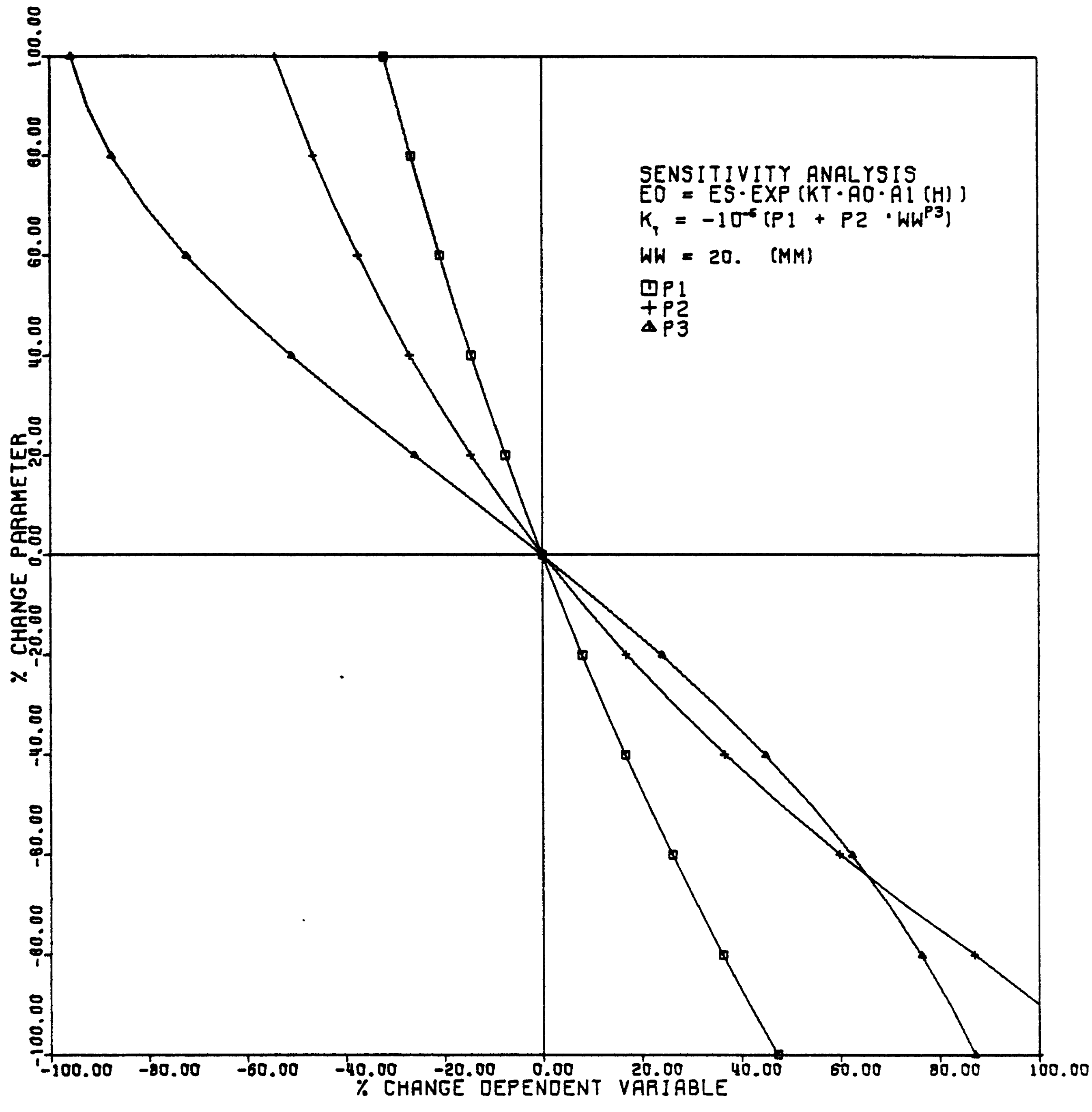
The "spider" technique sensitivity analysis is applied to eq. 5.5, using the expression of K_T furnished by eq. 5.4, and the E_0 sensitivity is analyzed with respect to the parameters p_1, p_2, and p_3, for different values of the amount of precipitable water.



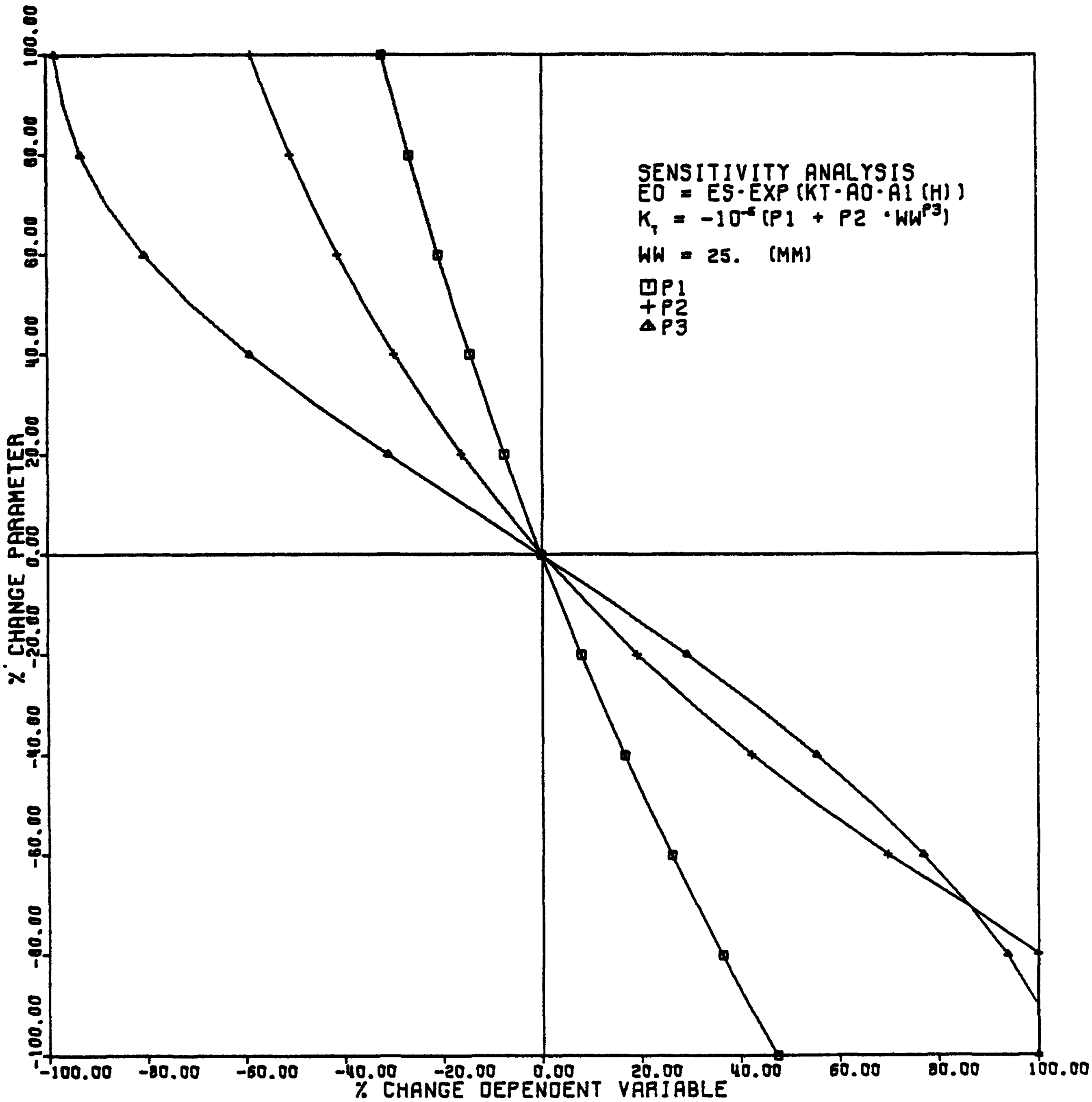
SENSITIVITY ANALYSIS
EO = ES·EXP (KT·AO·A1 (H))
$K_T = -10^{-6}(P1 + P2 \cdot WW^{P3})$
WW = 5. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00


SENSITIVITY ANALYSIS
EO = ES·EXP (KT·AO·A1 (H))
K_T = -10^-6 (P1 + P2 ·WW^P3)
WW = 10. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00

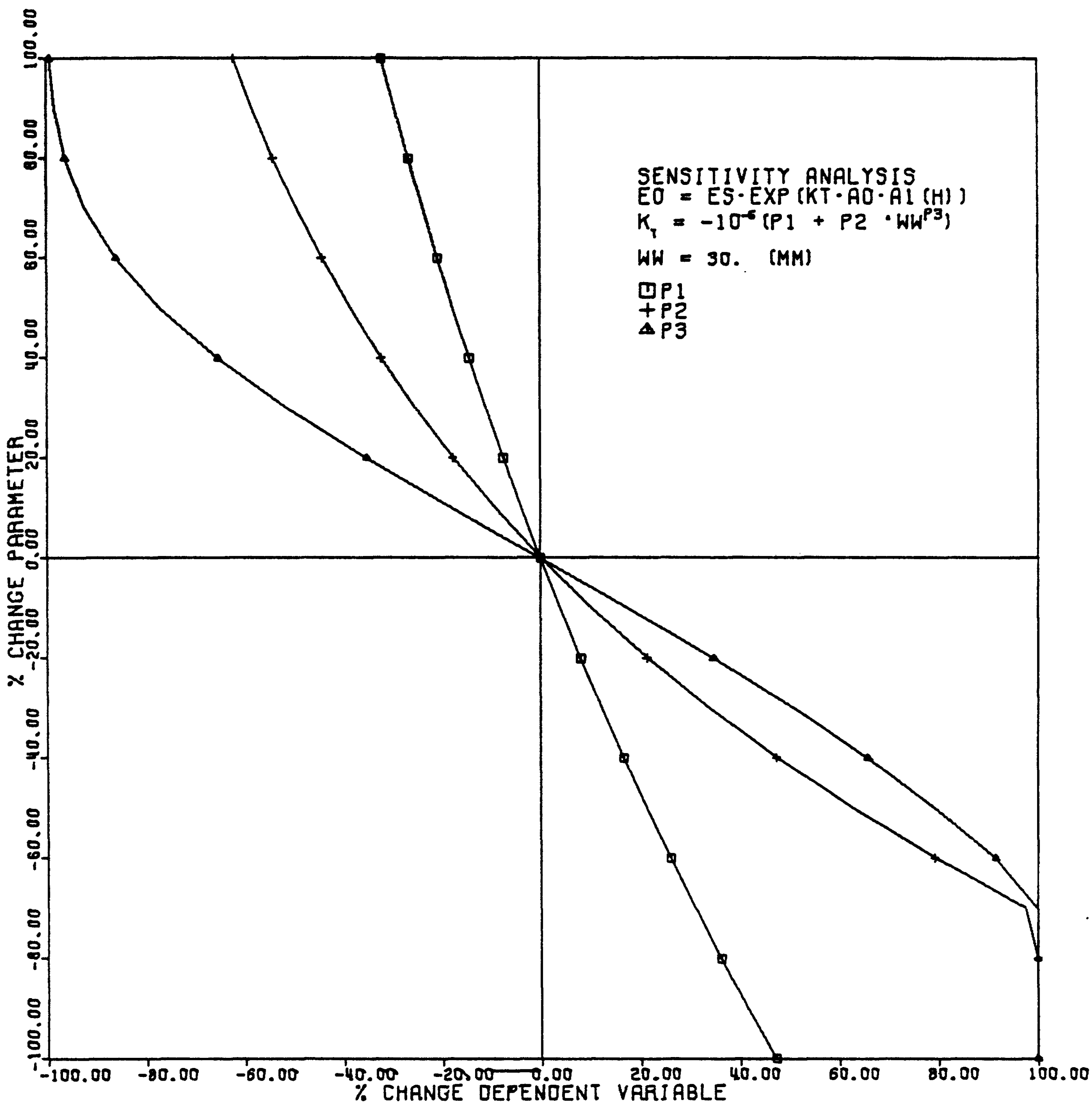

SENSITIVITY ANALYSIS
EO = ES·EXP(KT·AO·A1(H))
$K_T = -10^{-6}(P1 + P2 \cdot WW^{P3})$
WW = 15. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00



SENSITIVITY ANALYSIS
EO = ES·EXP (KT·AO·A1 (H))
K_T = -10^{-6} (P1 + P2 ·WW^{P3})
WW = 20. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00



SENSITIVITY ANALYSIS
EO = ES·EXP (KT·AO·A1 (H))
K_T = -10^-6 (P1 + P2 ·WW^P3)
WW = 25. (MM)
P1
P2
P3
% CHANGE PARAMETER
% CHANGE DEPENDENT VARIABLE
-100.00 -80.00 -60.00 -40.00 -20.00 0.00 20.00 40.00 60.00 80.00 100.00


SENSITIVITY ANALYSIS
EO = ES·EXP(KT·AO·A1(H))
K_T = −10⁻⁶(P1 + P2 ·WW^P3)
WW = 30. (MM)
P1
P2
P3
100.00
80.00
60.00
40.00
20.00
0.00
-20.00
-40.00
-60.00
-80.00
-100.00
% CHANGE PARAMETER
-100.00
-80.00
-60.00
-40.00
-20.00
0.00
20.00
40.00
60.00
80.00
100.00
% CHANGE DEPENDENT VARIABLE

5.2 QUANTITATIVE ASPECTS OF THE CLOUD PRESENCE

The dynamics of the interaction between the electromagnetic radiation and the clouds have been described in Chapter 3. There it was stressed that, as large particles are strong light scatterers, the clouds strongly deplete the radiation beam through diffusion (and absorption).

It has also been pointed out how a "differential" (punctual) approach to this interaction, in order to construct a physical model of the interaction itself, was almost impossible to accomplish.

Therefore, an "integral" approach, through an intensive factor (albedo) and an extensive factor (minutes of sunshine per interval of time), as deep as the available measured data allowed, has been attempted.

It should be stressed that the clouds' presence strongly affects the precision of any model, even assuming that a sensible amount of data on the clouds are available.

5.2.1 Macroclimatic approximation [54]

Worldwide, cloud cover is maximum at high latitudes and in the tropics, and minimum in the subtropics. The global mean albedo is 0.31 and the global mean cloud cover is 0.53. These values are quoted only as reference, but clearly cannot be adopted in any model. More precise data, quarterly and for "Standard Climatic Areas," are available and should be used for largely approximated computations [55-59].

The measurement of the minutes of sunshine per interval time may be a particularly simple relevation and, generally, predominant cloud types, for every region and climatic area, are available for many locations. Computing albedo as indicated in the next section, with the accuracy permitted by the available data, more realistic computations may be achieved, using eq. 4.35 and the macroclimatic values of K_T furnished in Subsection 5.2.1.

5.2.2 Microclimatic approximation

Cloud information, although aleatory, is generally available; most measurement techniques and terminology have been determined by the World Meteorological Organization. This is due to the great interest that meteorologists have in climate models. Since one of the fundamental climatic variables is the global mean temperature, which depends on the global albedo, an important part of which depends itself on the clouds, a relatively complete set of cloud data is "generally" available.

The parametrization of clouds assumed in this work will be the one adopted by the GISS Model [57], considering nine cloud layers, equally spaced in sigma coordinates, numbered from 1 to 9 from top to bottom. For each layer, the short-wave optical thickness is defined a priori from observations, ceteris paribus, of the analogous types of clouds.

The tabulation of the different cloud types and optical thicknesses, under these criteria, is given below.

CLOUD TYPE	LAYER	ANALOGY	OPTICAL THICKNESS
Supersaturation	2	Cirrus*	1
Supersaturation	3	"	2
Supersaturation	4	Altostratus*	4
Supersaturation	5,6	"	6
Supersaturation	7,8,9	Stratus	8
Penetrating convection	4-9	Cumulonimbus	32
Middle-level convection	5,6	Altocumulus	8
Low-level convection	7,8	Cumulus	16

*Depending on the available data, cirrus might be considered as having an optical thickness of 1.5 and altostratus as having an optical thickness of 5.0.

The albedo for the various analogies of the different cloud types* is computed from an approximate formula, based on the scattering theory [60]:

$$a = 0.13\ \tau/(1 + 0.13\ \tau) \tag{5.8}$$

This is the parametrization used in ref. 57 on a simulation of the January climatology, and the obtained results appear to be realistic [55].

Therefore, once the optical thicknesses of the different cloud types are derived from the previous tabulation, the cloud albedo will be computed using eq. 5.8.**

The minutes of sunshine per interval time (or the percent of the celestial dome covered by clouds—although this factor gives a lower precision in the calculation) should be known on an hourly or, at least, on a daily basis. The η factor is

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*From now on the "Analogies" of the previous tabulation will be defined as "cloud types."

**The information needed under this hypothesis of calculation is—or will be—furnished by the data recorded on the SOLMET tapes, prepared by the U.S. Department of Commerce, National Oceanic and Atmospheric Administration, Environmental Data and Information Service, National Climatic Center, Asheville, N.C., U.S.A. The analysis of the SOLMET data will be discussed further in this chapter. This information is being furnished now only to give an idea of the availability of the required data.

particularly sensitive to the minutes of sunshine per interval time information and, therefore, if the percent of sky cover is used, -the minutes of sunshine should be known on an hourly basis.

5.3 SOLMET - METEOROLOGICAL DATA

SOLMET tapes, both in FORTRAN and uniform format, furnish records of solar radiation and "related" periodical (hourly or tri-hourly) meteorological measurements in S.I. units [61,62].

Historical data are available, beginning in the early 1950s and ending in the mid-1970s. The data collection is not complete and the amount of information varies from station to station and with respect to time for each datum. It will be complete, however, because SOLMET now retrieves data from the "New National Weather Service network and cooperators." A description of SOLMET data and relative format is reported in Appendix A4.

Details on the acquisition systems are described in the National Weather Service Observing Handbook No. 3, "Solar Radiation Observations," here indicated as reference [63].

Due to incoherencies in calibration and problems in instrumentation, only modeled ("regression" techniques) direct hourly energy flux, from rehabilitated [64] observed hourly hemispherical and hourly direct energy fluxes, are available, at the moment, for 27 stations in the U.S. [65].

The meteorological data given in SOLMET tapes (see Appendix A4) cover 222 stations in the United States. The pressure, dry-bulb temperature and dew-point readings are made every three hours. Pressure values are in kPa; they should be converted into N m^{-2} (multiplying by a factor of 10); temperatures are given in degrees Celsius, to be, if needed, converted into degrees Kelvin (adding 273.16) or degrees Rankine).

As concerns the cloud cover and the clouds the SOLMET also reports visual evaluations (see Appendix A4) of:

i. total sky cover, i.e., tenths of celestial dome covered by clouds;

ii. total opaque sky cover, i.e., tenths of celestial dome covered by clouds or obscuring phenomena through which the sky or the higher cloud layers are invisible; and

iii. cloud types (14 different indexes, see Appendix A4) and amount of clouds in tenths, for the visible part of each of the four layers considered.

Since the model considers the cloud types classified in the synoptic table of Subsection 5.2.2, the cloud types furnished by SOLMET will have to be reduced to the cloud types considered in the model, if SOLMET has to be interfaced, as an input tape, to the model here discussed.

Recalling the classification of the clouds, adopted by the W.M.O.** (and reported in Appendix A5), SOLMET cloud type data have been regrouped, as follows:

TAPE FIELD No. 209 - TAPE CONFIGURATION 02-15

SOLMET CLASSIFICATION	ASSUMED OPTICAL DEPTH, τ
2 = Stratus*	8
3 = Stratocumulus*	12
4 = Cumulus*	16
5 = Cumulonimbus*	32
6 = Altostratus*	6 (lower layers) 4 (higher layers)
7 = Altocumulus*	8
8 = Cirrus*	2 (lower layers) 1 (higher layers)
9 = Cirrostratus*	2
10 = Stratus fractus*	8
11 = Cumulus fractus*	16
12 = Cumulonimbus mamma*	32
13 = Nimbostratus*	28
14 = Altocumulus castellanus*	8
15 = Cirrocumulus*	2

*Cloud definition in Appendix A5.

**The present W.M.O. classification is an outgrowth of a system published in 1803 in England by E. Howard and reviewed by Renoud and Hildebrandsson.

In the beginning of this section, it was stated that SOLMET furnishes digitized meteorological data until approximately 1975. The related solar data situation, however, is somewhat critical, mainly in that values furnished have been modeled or "massaged." Most of the available solar data for the U.S. and for the period actually covered by SOLMET data present this problem. This is clear if it is understood that SOLMET tapes are a digitized source of practically all available data, in logical or analogical form.

Post-1975 experimental values have not yet been implemented in SOLMET format. They are available, though, in an analogic form, from the U.S. Dept. of Commerce, N.O.A.A., National Weather Service as concerns all surface weather observations, and through the New National Weather Service network members or cooperators as concerns solar measurements (accomplished following an improved, standardized, and strict methodology).

In Appendix A6 the analogic data record format is presented; this refers to the second sheet of the daily surface weather observation records. A legend for reading and interpreting the data is also furnished.

5.4 SUMMARY AND MODEL INPUT DATA

Since the availability of input data has been one of the main concepts discussed throughout this work, a few words will now be devoted to the qualitative analysis of the data needed, under different operation options of the model, both for a clear atmosphere and for an atmosphere with clouds. The sensitivity analysis of all parameters involved in the computation has been performed in the previous chapters, using an "analytical" approach.

5.4.1 Energy flux density in a clear atmosphere (no clouds)

Equation 4.30 computes the energy flux density as a function of E_0, K_T, A_0, and $A_1(h)$.

E_S: Daily values of E_S are computed through equations 1.6, 2.1, and 2.2, assuming the solar "constant" to be 1377 W m^{-2}* and the W.M.O. values of the geometric parameters of the Earth's orbit.

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*Computed from the recommended values in reference [66] adjusted upwards 1.8 percent [67] to provide a value on absolute scale.

K_T': For a macroclimatic approximation, the K_T values furnished in Subsection 5.1.1 may be used. Equation 5.4 (or 5.5) may also be considered, inserting quarterly values for the amount of precipitable water and local factor (taking into consideration, for the latter, that the maximum value of the term P_4P is 0.5 10^{-5}).

For a microclimatic approximation, eq. 5.4 must be used and, again, K_T is expressed as a function of precipitable water, w (or precipitable water and "local" factor p, if eq. 5.3 is used). In this approximation, at least daily values of precipitable water should be known (it has been already pointed out that two daily readings are generally available--see Subsection 5.1.2--for a large amount of locations in the United States and throughout the world).

As an alternative, the amount of precipitable water may be computed, as reported in Appendix A3, from hourly (or daily) values of the atmospheric pressure, and from consistent dry-bulb and dew-point temperatures. Measurements of these three "state" parameters of the atmospheric conditions are available on both SOLMET tapes and analogic sheets provided by the National Weather Service.

A_o: For a macroclimatic approximation, the density integral value for the Standard Atmosphere, given in Section 4.1, may be used.

For a microclimatic approximation, A_0 may be computed from eq. 4.8, as a function of the atmospheric pressure (for a zero station elevation). If the equivalent height of the atmosphere is known (and if the station is at an altitude superior to a few hundred meters), the density integral may be computed again from eq. 4.8 (or from eq. 4.11, as a function of the zero elevation atmospheric pressure and temperatures and the station elevation). For this approximation, the A_0 computation should be performed on an hourly basis.

$A_1(h)$: The relative atmospheric mass, as defined in Section 4.2, is a strictly "astronomical" parameter. It may be computed for every instant from eq. 4.18, as a function of the Sun's altitude, h. The Sun's altitude is expressed in eq. 2.10 as a function of the latitude, of the declination (computed daily from eq. 2.3), and of the pole angle (computed as a time function from eq. 2.11).

5.4.2 Energy flux density for an atmosphere with clouds

Equation 4.35 computes the energy flux density as a function of E_S, K'_T, A_0, $A_1(h)$, c, and a.

The first four parameters are computed as indicated in Subsection 5.4.1.

<u>c</u>: For a macroclimatic approximation, <u>c</u> may be computed from eq. 4.34 (or as a function of η; see Section 4.4). Average (quarterly) values of S/D (or η) may be used.

For a microclimatic approximation, <u>c</u> is computed through eq. 4.34, using hourly (or daily) values of S/D.

<u>a</u>: For a macroclimatic approximation, average (yearly) values of the albedo may be used, either for the world or for "Standard Climatic Areas."

For a microclimatic approximation, hourly (daily) values of the albedo should be computed from eq. 5.8, either from SOLMET recordings (as indicated in Section 5.3 and in Subsection 5.2.2--format description in Appendix A4) or from the analogic format of the data furnished by the National Weather Service (as indicated in Section 5.3, and Subsection 5.2.2—format description in Appendix A6).

5.4.3 Energy Flux

The energy flux (J m^{-2}) computation is performed by numerical integration of eqs. 4.30 or 4.35.

The optimal integration interval will depend on the climatic option adopted (macro or micro) and on the frequency and quality of the meteorological data available. However, it should be between a maximum of one interval per hour (macroclimatic approximation, low quality, or "low frequency" meteorological data available) and six intervals per hour (microclimatic approximation, acceptable quality, and "frequency" of meteorological data).

The intervals of integration, for computing the energy flux on the horizontal, will be the instants of geometrical sunrise and sunset, computed, from eq. 2.17, as follows:

$$\text{sunrise} = t_i = 12 - D/2 \quad [\text{hours}] \tag{5.9}$$

$$\text{sunset} = t_f = 12 + D/2 \quad [\text{hours}] \tag{5.10}$$

where:

D = geometrical day length [hours].

For an arbitrary slant surface, the computation of the astronomical parameters should be made starting from t_i, but the start of the computation of the meteorological correlation functions (and energy density flux) should coincide with the first value of the zenith angle, θ, which is equal or inferior to $90°$. The computation will end for the next value of θ

superior to 90°. The zenith angle is computed from eqs. 2.18 and 2.19 as a function of the Sun's altitude (computed from eq. 2.11 as a function of the time, declination-day, and latitude), the Sun's azimuth (computed from eqs. 2.12, 2.13, and 2.14 as a function of the Sun's altitude), the surface inclination and orientation angles (as defined in Section 2.5).

APPPENDIX A1

IRRADIANCE: DEFINITIONS AND UNITS OF MEASURE

1. Units of Measure

In photometric measurements, two metric scales are widely used:

i. a radiometric scale, which tends to define the various physical parameters in "energy" terms.

ii. a photometric scale, which tends to define the various physical parameters in terms of a conventional amount of radiation (light), taking into account the sensitivity of the human eye through the International Curb of Sensitivity.

Obviously, as concerns most solar energy applications, the main interest is focused on the energy content—visible or not—of the radiation. However, for some particular cases, i.e., analysis of materials employed, etc., it is sometimes convenient to take into consideration values in photometric units of the parameters. That is why both scales and their correlation are presented.

1.1 RADIOMETRIC SCALE (S.I. UNITS)

- Radiative energy, I: the amount of energy present in the form of electromagnetic radiation; I is measured in joules [J].

- radiative flux, w: the amount of radiative energy per unit time received, or emitted, or that crosses an imaginary surface:

$$w = dI/dt$$

w is measured in watts [W].

It is often useful to consider:

- density of radiative flux, E: the amount of radiative energy per unit time that passes through the unit surface of a receiver, an emitter, or an imaginary surface:

$$E = dw/dA$$

E is measured in watts per square meter [W m-2].

- radiative energy intensity, R: the radiative flux per unit solid angle:

$$R = dw/d\omega = d^2I/(d\omega\ dt)$$

R is measured in watts per steradiant [W $ster^{-1}$].

- radiance, B: the flux per unit solid angle, per unit normal area, or the intensity per unit normal area:

$$B = dI/dA$$

B is measured in watts per steradian per square meter [W $ster^{-1}$ m^{-2}].

1.2 PHOTOMETRIC SCALE

- light intensity, R: the light flux emitted per unit solid angle:

$$R = dw/d\omega$$

where w is the conventional amount of light [lumen] irradiated by a source per unit time; R is measured in candles [cd].

- brillance of a surface, B: the light intensity emitted per unit area:

$$B = dR/dA_e$$

B is measured in candles per square meter [cd m-2].

- luminance of a surface, E: the light incident flux per unit area:

$$E = dw/dA_i$$

E is measured in lux [lux].

A coefficient that correlates to a given source, the light flux (photometric) with the radiative flux (radiometric) and often called the "light efficiency," is defined by:

$$K(\lambda) = W_p/W_r \quad [\text{lm W}^{-1}]$$

where $K(\lambda)$ has a maximum of λ = 5,550 Å. The sensitivity factor, $V(\lambda)$, defined as the ratio between $K(\lambda)$ and K(5,550), furnishes the visibility curve.

2. Definitions

Several dimensionless parameters that define the radiative properties of materials are introduced.

- emissivity, ε: the ratio between the radiative flux emitted by a body and the radiative flux emitted by a blackbody under the same conditions.

- absorptivity,* α: the ratio between the radiative flux absorbed by a body and the incident radiative flux.

- reflectivity,* ρ (or albedo, a): the ratio between the radiative flux reflected by a body and the incident radiative flux; it is also dependent on the incidence angle.

- coefficient of transmission, τ: the ratio between the radiative flux transmitted by a body and the incident radiative flux. The transmissivity is defined as the fractional part of

---

*Although absorptivity and reflectivity are generally defined in terms of a surface, they may be considered also in terms of the atmosphere. In a very simplified approach, we might say that if the state of oscillations (frequency) of the molecules of the gas is compatible with the frequency of the radiation, the molecules will absorb energy (resonance). Reflectivity might be justified by stating that in a gas, reflection phenomena are due to the back-scattering components.

the radiation transmitted through the medium per unit of distance (or mass) along the path of the radiant beam.

Obviously these coefficients vary between 0 and 1. They are strongly dependent also on the wavelength of the radiation. For every wavelength:

$$\rho(\lambda) + \tau(\lambda) + \alpha(\lambda) = 1$$

APPENDIX A2

RADIATION LAWS APPLIED TO COMPUTATION OF SOLAR ENERGY FLUXES

1. Lambert's Law

This Law states that the amount of radiation emitted or absorbed by the unit surface in the unit time is directly proportional to the cosine of the angle formed between the beam's direction and the normal to the surface—emitter or absorber.

In analytical form:

$$E(\theta) = E(n) \cos(\theta)$$

where:

$E(\theta)$ = density of radiative flux in the direction θ [W m-2]

$E(n)$ = density of radiative flux in the direction $\underline{n}$ [W m-2].

2. Stefan-Boltzmann's Law

This Law states that the quantity of radiant thermal emission from a unit area surface in the unit time into a 2-steredian solid angle is a function of the absolute temperature; it is given by the following relation* (in terms of power).

$$(W/A)_{2\pi} = \varepsilon(\lambda)\ \sigma\ T^4\ \ [W\ m^{-2}]$$

where:

σ = Stefan-Boltzmann's constant = 5.72 10^{-8} [W m-2 °K-4]

Earth and Sun are "greybodies," and their "greybody factor" is roughly .85, i.e., ε = .85.

3. Kirchoff's Law

Essentially, this Law states that the emissivity is a function of wavelength and temperature and that, for a given

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*Actually, Stefan-Boltzmann's Law has been initially stated for a perfect radiator, i.e., blackbody, for which $\varepsilon = 1$.

wavelength and temperature, the emissivity equals the absorptivity.

In analytical form:

$$\varepsilon(\lambda,T) = \alpha(\lambda,T)$$

For instance, clouds weakly absorb—and emit—the visible and ultraviolet radiation but strongly absorb—and emit (almost as a blackbody)—the infrared radiation emitted by the Earth.

4.1 First Wien's Law

This Law states that the wavelength correspondent to the maximum emission of radiative energy depends only upon the absolute temperature of the radiator, following the relation:

$$\lambda(E_{max}) = C_1 \frac{1}{T}$$

where:

C_1 = constant* = 2.899 10^{-6} [m °K].

---

*Actually, $C_1 = hc/(4.9651\ K)$
where:

h = Planck's constant = 6.626 10^{-34} [J sec]
c = "light speed" = 3 10^{8} [m sec^{-1}]
K = Boltzmann's constant = 1.3806 10^{-23} [J K^{-1}]

4.2 Second Wien's Law

This Law states that the maximum of the emission power on the semispace—that happens at the wavelength determined by the First Wien's Law—grows proportionally to the fifth power of the absolute temperature:

$$E(\lambda_{max}, T)_{max} = 12.61\ 10^{-6}\ T^5$$

5. Planck's Law

This Law furnishes the spectral distribution of the radiative energy emitted by a blackbody radiator, for a unit surface and per unit time, as a function of its temperature:

$$E(\lambda,T) = 2\ \pi\ h\ c^2\ \lambda^{-5}\ [\exp[h\ c/(\lambda\ K\ T)] - 1]^{-1}$$

or:

$$E(\lambda,T) = 3.719\ 10^{-16}\ \lambda^{-5}\ [\exp[0.014/(\lambda\ T)] - 1]^{-1}$$

where λ is in meters. $3.719\ 10^{-16}$ and 0.014 are known as the first and second radiation constants, respectively.

Actually, Planck's Law is a compendium of all the irradiance laws:

i. By integration between $\lambda = 0$ and $\lambda = \infty$, the Stefan-Boltzmann's Law is obtained;

ii. By setting its derivative with respect to λ equal to zero, First Wien's Law is obtained;

iii. The relation obtained by substituting $E(\lambda_{max}, T)_{max}$ onto the first term of its analytical expression and λ_{max} onto the second term, Second Wien's Law is obtained.

APPENDIX A3

COMPUTATION OF THE AMOUNT OF PRECIPITABLE WATER AND OF THE EQUIVALENT HEIGHT OF THE ATMOSPHERE

It will be assumed that the gases that constitute the atmosphere behave as perfect gases. Thus, for each:*

$$p_i \; v_i = R_i \; T \qquad (i = 1, 2, \ldots, n) \tag{A3.1}$$

where:

p_i = partial pressure [N m-2]

T = temperature [K]

v_i = specific volume [$m^3 \; Kg^{-1}$]

R_i = specific gas content of the i-th gas [$m^2 \; s^{-2} \; deg^{-1}$].

The R_i gas constant is related to the molar gas constant, R, and the molecular weight of the i-th gas, M_i by the relation:

$$R_i = \frac{R}{M_i} \tag{A3.2}$$

---

*Equation of a perfect gas.

According to Dalton's Law:*

$$P_D = \sum_{i=1}^{n} p_i \qquad \text{(A3.3)}$$

If $\underline{v}$ is the specific volume of dry air (i.e., the volume of one kilogram of air) and if m_i is the mass of the i-th gas in one kilogram of dry air, then:

$$v_i = \frac{v}{m_i} \qquad \text{(A3.4)}$$

Substituting in eq. A3.1, summing, and from eq. A3.3:

$$v \sum_{i=1}^{n} p_i = v\ P_D = T \sum_{i=1}^{n} m_i\ R_i \qquad \text{(A3.5)}$$

Define R_D as:

$$R_D = \sum_{i=1}^{n} m_i R_i \qquad \text{(A3.6)}$$

From eqs. A3.5, A3.3, and A3.6, the following may be written:

---

*". . . the pressure of the mixture equals the sum of the partial pressures."

$$P_D \; v = R_D \; T \qquad (A3.7)$$

Equation A3.7 is formally known as the equation of state of dry air. From eq. A3.2, the gas constant of dry air may be computed when the composition of the atmosphere is known. Thus:

$$R_D = 287 \quad [m^2 \; sec^{-2} \; deg^{-1}]$$

Moist air is a mechanical mixture of dry air and water vapor. Although the atmospheric temperatures are lower than the critical temperatures of water vapor, it will be assumed that the physical properties of water vapor approximate those of a perfect gas. Thus the equation of state of water vapor can be written as:

$$p_w \; v_w = R_w \; T \qquad (A3.8)$$

where:

p_w = partial pressure $[N \; m^{-2}]$
v_w = specif. volume $[m^3 \; Kg^{-1}]$
R_w = "water" vapor constant $[m^2 \; sec^{-2} \; deg^{-1}]$.

From eq. A3.2, R_w may be computed:

$$R_w = 461 \quad [m^2 \; sec^{-2} \; deg^{-1}].$$

The dry air and the water vapor are uniformly distributed within the entire volume, $\underline{v}$, of the moist air; the specific volumes of dry air, v_D, and water vapor, v_W, are:

$$v_D = v/(1 - S) \qquad (A3.9)$$

$$v_W = v/\alpha \qquad (A3.10)$$

where:

v = volume of α kilograms of water and $(1 - \alpha)$ kilograms of dry air.

The equation of state of the dry fraction of the moist air may be written as:

$$(P_M - p_W)\, v_D = R_D\, T \qquad (A3.11)$$

where:

p_M = total pressure of moist air [N m^{-2}]

p_W = partial pressure of water vapor [N m^{-2}].

From eq. A3.2, the following may be derived:

$$R_W/R_D = 1.608 \quad \text{[adimensional]} \qquad (A3.12)$$

By substituting eqs. A3.9, A3.10 and A3.12 into eqs. A3.8 and A3.11:

$$p_W \frac{v}{\alpha} = 1.608\ R_D\ T \tag{A3.13}$$

$$(P_M - p_W)\ v/(1 - \alpha) = R_D\ T \tag{A3.14}$$

Adding eqs. A3.13 and A3.14 gives:

$$P_M\ v = T\ R_D\ (1 + 0.608\ \alpha) \tag{A3.15}$$

Equation A3.15 is known as the equation of state of moist air. It may be rewritten as:*

$$P_M\ v = R_M\ T \tag{A3.16}$$

where:

$$R_M = R_D\ (1 + 0.608\ \alpha). \tag{A3.17}$$

It should be stressed that R_M is a function of the air humidity, α.

---

*If the factor $(1 + 608\ \alpha)$ is considered to affect the temperature term, the concept of virtual temperature, T, is introduced $(T = T(1 + .608\ \alpha))$ and the equation of the state of moist air may be written in terms of the dry air gas constituent. This is often done in meteorological applications.

Defining the mixing ratio as the ratio of the mass of water vapor per unit volume to the mass of dry air per unit volume, its numerical value will equal the amount of water vapor per unit mass of dry air.

From this definition and from equations A3.8 and A3.11, the relation between the mixing ratio, MR, and the air humidity, α, may be simply derived:

$$MR = \frac{\alpha}{1 - \alpha} \qquad (A3.18)$$

The difference between the mixing ratio and α is very small.

Recalling eq. A3.11 (equation of state of the dry fraction of moist air) and eq. A3.8 (equation of state of water vapor), the mixing ratio may be expressed as follows:

$$MR = (R_D/R_W)(p_W/(P - p_W)) \qquad (A3.19)$$

Therefore, the equation of state of moist air (eq. A3.17) may be rewritten as:

$$R_M = R_D\ (1 + 0.608\ MR) \qquad (A3.20)$$

1. Precipitable water computation

With all these concepts established, computation of the amount of precipitable water may be attempted.

It will be assumed that dry-bulb temperature and pressure are known. The amount of humidity will be considered through the dew-point "temperature," although other parameters, such as relative humidity, might be used.

The partial pressure of the water vapor in the gas mixture may be computed, using the following numerical solution of the Clausius-Clapeyron equation:*

$$\begin{aligned} \log_{10} P_w = {} & 10.79586(1 - T_{SK}/T_{DP}) + 5.02808 \log_{10}(T_{SK}/T_{DP}) \qquad (A3.21) \\ & + 1.50474\ 10^{-4}[1 - 10^{-8.29692(T_{DP}/T_{SK} - 1)}] \\ & + 0.42873\ 10^{-3}[10^{4.76955(1 - T_{SK}/T_{DP})} - 1] \\ & - 2.2195983 \end{aligned}$$

*From the Smithsonian Institution, Washington, D.C.

where:

p_w = partial pressure of water vapor [atm]

T_{SK} = 283.16 [K]

T_{DP} = station dew-point "temperature" [K].

Note that eq. A3.21 furnishes p_w in atmospheres; its conversion into S.I. units will be implicitly assumed from now on.

Recalling eq. A3.8, the water vapor density may be computed as:

$$\rho_w = p_w/(R_w\ T_{DBK}) \qquad \text{(A3.22)}$$

where:

ρ_w = water vapor density [Kg m^{-3}]

T_{DBK} = station dry-bulb temperature [K].

Recalling the concept of "equivalent height of the atmosphere," the amount of precipitable water may be computed from the following relation:

$$w = \rho_w\ H_w \qquad \text{(A3.23)}$$

where:

w = amount of precipitable water [mm]

H_w = "water vapor scale height" of the atmosphere [m]

ρ_w = water vapor density [Kg m-3].

A dimensional analysis will help to understand eq. A3.23. Recalling that 1 kg of water ≈ 1 liter of water = 1 dm3 of water, the dimensional analysis of eq. A3.23 would be:

$$[\text{Kg m m}^{-3}] = [\text{Kg m}^{-2}] \approx [\text{dm}^3 \text{m}^{-2}] = [10^6 \text{mm}^3\ 10^6 \text{mm}^{-2}] = \text{mm}$$

The "water vapor scale height" of the atmosphere (or the equivalent height of the atmosphere generally adopted in those applications) is two kilometers. Seasonally optimized values for different "Standard Meteorological Areas" have previously been computed.

Due to complete ignorance of the even low atmospheric movements here assumed, the precision of this calculation is low; final results may be obtained with an error range of 40 percent. The consequent error of the E_0 computation may be immediately derived from the sensitivity analysis plottages, reported in Chapter 5.

The results of the amount of precipitable water computation for a location at which temperatures, pressure, and experimental precipitable water daily values are available, follow:

AMOUNT OF PRECIPITABLE WATER AND EQUIVALENT HEIGHT OF THE ATMOSPHERE COMPUTATION

ALBANY, NY (USA)

LAT. 42.70 DEG. NORTH LONG. 73.83 DEG. WEST ALT. 79.30 [M]

INPUT DATA:

TDB = DRY BULB TEMPERATURE [K]
TDP = DEW POINT [K]
P = ATMOSPHERIC PRESSURE [N/SQ.M]
RW = WATER VAPOR 'GAS CONSTANT' [SQ.M/SEC.SQ. K]
RD = DRY AIR 'GAS CONSTANT' [SQ.M/SEC.SQ. K]
G = ACCELERATION OF GRAVITY [M/SEC.SQ.]
HW = WATER VAPOR EQUIVALENT HEIGHT [M]
HSA = EQUIVALENT HEIGHT OF THE STANDARD ATMOSPHERE [M]

OUTPUT DATA:

PW = WATER VAPOR PARTIAL PRESSURE [N/SQ.M]
WW = AMOUNT OF PRECIPITABLE WATER [MM]
ROW = WATER VAPOR DENSITY [KG/CUB.M]
MR = MIXING RATIO [ADIM.]
RMA = MOIST AIR 'GAS CONSTANT' [SQ.M/SEC.SQ. K]
ROMA= MOIST AIR DENSITY [KG/CUB.M]
H = EQUIVALENT HEIGHT OF THE ATMOSPHERE [M]

AMOUNT OF PRECIPITABLE WATER COMPUTATION:

THE EXPERIMENTAL VALUES OF THE AMOUNT OF PRECIPITABLE WATER DISPLAYED ARE OBTAINED BY LINEAR INTERPOLATION OF THE TWO DAILY MEASUREMENTS

PRECIPITABLE WATER COMPUTATION

FEB. 1, 1979 DAY NUMBER 32

RW = 461.0 [SQ.M/SEC.SQ. K]
G = 9.806 [M/SEC.SQ.]

TS = 273.16 [K]
HW = 2422.04 [M]

MERID. TIME	TDB	TDP	PW	ROW	WW COMPUTED	WW EXPER.	RELATIVE ERROR (%)	SOLAR TIME
8.00	262.2	256.2	162.0	0.001	3.25	4.42	-26.57	7.86
9.00	262.2	257.2	176.1	0.001	3.53	4.52	-21.93	8.86
10.00	263.2	257.2	176.1	0.001	3.52	4.64	-24.24	9.86
11.00	264.2	257.2	176.1	0.001	3.50	4.73	-25.96	10.86
12.00	265.2	257.2	176.1	0.001	3.49	4.85	-28.07	11.86
13.00	265.2	257.2	176.1	0.001	3.49	4.94	-29.38	12.86
14.00	265.2	257.2	176.1	0.001	3.49	5.06	-31.05	13.86
15.00	265.2	257.2	176.1	0.001	3.49	5.15	-32.26	14.86
16.00	265.2	258.2	191.3	0.002	3.79	5.27	-28.08	15.86
17.00	265.2	258.2	191.3	0.002	3.79	5.38	-29.55	16.86
18.00	265.2	258.2	191.3	0.002	3.79	5.49	-30.96	17.86

DAILY AVERAGE COMPUTED WW = 3.56
DAILY EXPERIMENTAL WW = 4.95
DAILY RELATIVE ERROR (%) = -28.16

PRECIPITABLE WATER COMPUTATION

FEB. 2, 1979 DAY NUMBER 33

RW = 461.0 [SQ.M/SEC.SQ. K]
G = 9.806 [M/SEC.SQ.]

TS = 273.16 [K]
HW = 2422.04 [M]

MERID. TIME	TDB	TDP	PW	ROW	WW COMPUTED	WW EXPER.	RELATIVE ERROR (%)	SOLAR TIME
8.00	262.2	256.2	162.0	0.001	3.25	4.93	-34.16	7.85
9.00	262.2	256.2	162.0	0.001	3.25	5.03	-35.47	8.85
10.00	263.2	257.2	176.1	0.001	3.52	5.14	-31.61	9.85
11.00	264.2	257.2	176.1	0.001	3.50	5.25	-33.29	10.85
12.00	266.2	258.2	191.3	0.002	3.78	5.35	-29.42	11.85
13.00	266.2	259.2	207.7	0.002	4.10	5.46	-24.92	12.85
14.00	266.2	259.2	207.7	0.002	4.10	5.56	-26.27	13.85
15.00	267.2	260.2	225.3	0.002	4.43	5.67	-21.86	14.85
16.00	267.2	260.2	225.3	0.002	4.43	5.77	-23.22	15.85
17.00	266.2	260.2	225.3	0.002	4.45	5.88	-24.37	16.85
18.00	265.2	260.2	225.3	0.002	4.46	5.99	-25.48	17.85

DAILY AVERAGE COMPUTED WW = 3.93
DAILY EXPERIMENTAL WW = 5.46
DAILY RELATIVE ERROR (%) = -27.94

PRECIPITABLE WATER COMPUTATION

FEB. 11, 1979 DAY NUMBER 42

RW = 461.0 [SQ.M/SEC.SQ. K]
G = 9.806 [M/SEC.SQ.]

TS = 273.16 [K]
HW = 2422.04 [M]

MERID. TIME	TDB	TDP	PW	ROW	WW COMPUTED	WW EXPER.	RELATIVE ERROR (%)	SOLAR TIME
8.00	250.2	240.2	38.2	0.000	0.80	1.02	-21.33	7.84
9.00	251.2	241.2	42.1	0.000	0.88	1.02	-13.70	8.84
10.00	253.2	241.2	42.1	0.000	0.87	1.02	-14.38	9.84
11.00	254.2	242.2	46.3	0.000	0.96	1.02	-6.15	10.84
12.00	255.2	243.2	50.9	0.000	1.05	1.02	2.78	11.84
13.00	256.2	243.2	50.9	0.000	1.04	1.02	2.38	12.84
14.00	257.2	243.2	50.9	0.000	1.04	1.02	1.98	13.84
15.00	258.2	244.2	55.9	0.000	1.14	1.02	11.59	14.84
15.00	258.2	244.2	55.9	0.000	1.14	1.02	11.59	15.84
17.00	257.2	243.2	50.9	0.000	1.04	1.02	1.98	16.84
18.00	256.2	242.2	46.3	0.000	0.95	1.02	-6.89	17.84

DAILY AVERAGE COMPUTED WW = 0.99
DAILY EXPERIMENTAL WW = 1.02
DAILY RELATIVE ERROR (%) = -2.74

PRECIPITABLE WATER COMPUTATION

FEB. 12, 1979 DAY NUMBER 43

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]
G = 9.806 [M/SEC.SQ.] HW = 2422.04 [M]

MERID. TIME	TDB	TDP	PW	ROW	WW COMPUTED	WW EXPER.	RELATIVE ERROR (%)	SOLAR TIME
8.00	251.2	246.2	67.3	0.001	1.41	2.06	-31.64	7.84
9.00	252.2	246.2	67.3	0.001	1.40	2.11	-33.53	8.84
10.00	254.2	246.2	67.3	0.001	1.39	2.15	-35.28	9.84
11.00	256.2	248.2	80.7	0.001	1.66	2.19	-24.38	10.84
12.00	258.2	248.2	80.7	0.001	1.64	2.23	-26.31	11.84
13.00	259.2	248.2	80.7	0.001	1.64	2.28	-28.20	12.84
14.00	260.2	248.2	80.7	0.001	1.63	2.32	-29.71	13.84
15.00	260.2	248.2	80.7	0.001	1.63	2.36	-30.90	14.84
16.00	260.2	247.2	73.8	0.001	1.49	2.40	-37.94	15.84
17.00	260.2	248.2	80.7	0.001	1.63	2.46	-33.71	16.84
18.00	260.2	247.2	73.8	0.001	1.49	2.50	-40.42	17.84

DAILY AVERAGE COMPUTED WW = 1.55
DAILY EXPERIMENTAL WW = 2.28
DAILY RELATIVE ERROR (%) = -32.13

PRECIPITABLE WATER COMPUTATION

FEB. 21, 1979 DAY NUMBER 52

RW = 461.0 [SQ.M/SEC.SQ. K]
G = 9.806 [M/SEC.SQ.]

TS = 273.16 [K]
HW = 2422.04 [M]

MERID. TIME	TDB	TDP	PW	ROW	WW COMPUTED	WW EXPER.	RELATIVE ERROR (%)	SOLAR TIME
7.00	269.2	265.2	335.0	0.003	6.54	3.56	83.70	6.85
8.00	269.2	266.2	362.0	0.003	7.07	4.47	58.07	7.85
9.00	271.2	267.2	390.8	0.003	7.57	5.38	40.76	8.85
10.00	273.2	268.2	421.7	0.003	8.11	6.28	29.16	9.85
11.00	274.2	269.2	454.8	0.004	8.71	7.19	21.21	10.85
12.00	276.2	269.2	454.8	0.004	8.65	8.10	6.81	11.85
13.00	276.2	269.2	454.8	0.004	8.65	9.02	-4.08	12.85
14.00	276.2	271.2	527.8	0.004	10.04	9.93	1.12	13.85
15.00	275.2	272.2	568.1	0.004	10.85	10.84	0.07	14.85
16.00	274.2	273.2	611.1	0.005	11.71	11.75	-0.33	15.85
17.00	275.2	273.2	611.1	0.005	11.67	12.65	-7.76	16.85
18.00	275.2	273.2	611.1	0.005	11.67	13.56	-13.95	17.85

DAILY AVERAGE COMPUTED WW = 9.27
DAILY EXPERIMENTAL WW = 8.56
DAILY RELATIVE ERROR (%) = 8.29

PRECIPITABLE WATER COMPUTATION

FEB. 22, 1979 DAY NUMBER 53

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]
G = 9.806 [M/SEC.SQ.] HW = 2422.04 [M]

MERID. TIME	TDB	TDP	PW	ROW	WW COMPUTED	WW EXPER.	RELATIVE ERROR (%)	SOLAR TIME
7.00	276.2	271.2	527.8	0.004	10.04	10.67	-5.89	6.85
8.00	276.2	271.2	527.8	0.004	10.04	10.35	-2.98	7.85
9.00	276.2	270.2	490.1	0.004	9.32	10.02	-6.95	8.85
10.00	276.2	270.2	490.1	0.004	9.32	9.72	-4.08	9.85
11.00	276.2	270.2	490.1	0.004	9.32	9.39	-0.70	10.85
12.00	276.2	271.2	527.8	0.004	10.04	9.07	10.71	11.85
13.00	276.2	271.2	527.8	0.004	10.04	8.76	14.63	12.85
14.00	276.2	271.2	527.8	0.004	10.04	8.44	18.98	13.85
15.00	276.2	271.2	527.8	0.004	10.04	8.13	23.51	14.85
16.00	276.2	271.2	527.8	0.004	10.04	7.81	28.57	15.85
17.00	276.2	271.2	527.8	0.004	10.04	7.48	34.25	16.85
18.00	275.2	271.2	527.8	0.004	10.08	7.18	40.36	17.85

DAILY AVERAGE COMPUTED WW = 9.87
DAILY EXPERIMENTAL WW = 8.92
DAILY RELATIVE ERROR (%) = 10.62

2. Equivalent height computation

The equivalent height of the atmosphere has been given in Chapter 2. There it was shown how it is possible, for a location at a zero elevation, to avoid its computation for the determination of the density integral, A_0.

However, H may be computed as follows.

i. the mixing ratio is computed from eq. A3.19;

ii. the moist air constant is computed from eq. A3.20;

iii. the moist air density computation may now be performed from eq. A3.15 (the equation of state of moist air).

Therefore, H may be computed from eq. 4.7:

$$H = P(0)/[\rho(0)\ g)$$

where:

H = equivalent height of the atmosphere [m]

P(0) = sea-level atmospheric pressure [N m-2]

$\rho(0)$ = moist air sea-level density [Kg m-3]

g = acceleration of gravity [m s-2].

The results of the equivalent height computation, for a location at which temperatures and pressures are known, are:

AMOUNT OF PRECIPITABLE WATER AND EQUIVALENT HEIGHT OF THE ATMOSPHERE COMPUTATION

ALBANY, NY (USA)

LAT. 42.70 DEG. NORTH LONG. 73.83 DEG. WEST ALT. 79.30 [M]

INPUT DATA:

```
TDB = DRY BULB TEMPERATURE [K]
TDP = DEW POINT [K]
P   = ATMOSPHERIC PRESSURE [N/SQ.M]
RW  = WATER VAPOR 'GAS CONSTANT' [SQ.M/SEC.SQ. K]
RD  = DRY AIR 'GAS CONSTANT' [SQ.M/SEC.SQ. K]
G   = ACCELERATION OF GRAVITY [M/SEC.SQ.]
HW  = WATER VAPOR EQUIVALENT HEIGHT [M]
HSA = EQUIVALENT HEIGHT OF THE STANDARD ATMOSPHERE [M]
```

OUTPUT DATA:

```
PW   = WATER VAPOR PARTIAL PRESSURE [N/SQ.M]
WW   = AMOUNT OF PRECIPITABLE WATER [MM]
ROW  = WATER VAPOR DENSITY [KG/CUB.M]
MR   = MIXING RATIO [ADIM.]
RMA  = MOIST AIR 'GAS CONSTANT' [SQ.M/SEC.SQ. K]
ROMA = MOIST AIR DENSITY [KG/CUB.M]
H    = EQUIVALENT HEIGHT OF THE ATMOSPHERE [M]
```

EQUIVALENT HEIGHT OF THE ATMOSPHERE COMPUTATION:

```
THE 1971 STANDARD ATMOSPHERE HAS THE FOLLOWING PROPERTIES:
          PRESSURE = 101325.  [N/SQ.M]
          DENSITY = 1.225  [KG/CUB.M]
```

EQUIVALENT HEIGHT OF THE ATMOSPHERE

FEB. 1, 1979 DAY NUMBER 32

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]

MERID. TIME	TDB	TDP	P	PW	ROW	MR	RMA	ROMA	H	HSA	REL. DIFF. (%)	SOLAR TIME
8.00	262.2	256.2	98883.	161.96	0.001	0.001	287.18	1.31	7677.60	8433.81	8.97	7.86
9.00	262.2	257.2	98950.	176.08	0.001	0.001	287.19	1.31	7678.01	8433.81	8.96	8.86
10.00	263.2	257.2	98984.	176.08	0.001	0.001	287.19	1.31	7707.30	8433.81	8.61	9.86
11.00	264.2	257.2	99018.	176.08	0.001	0.001	287.19	1.31	7736.59	8433.81	8.27	10.86
12.00	265.2	257.2	98984.	176.08	0.001	0.001	287.19	1.30	7765.87	8433.81	7.92	11.86
13.00	265.2	257.2	98984.	176.08	0.001	0.001	287.19	1.30	7765.87	8433.81	7.92	12.86
14.00	265.2	257.2	99018.	176.08	0.001	0.001	287.19	1.30	7765.87	8433.81	7.92	13.86
15.00	265.2	257.2	99120.	176.08	0.001	0.001	287.19	1.30	7765.86	8433.81	7.92	14.86
16.00	265.2	258.2	99221.	191.29	0.002	0.001	287.21	1.30	7766.31	8433.81	7.91	15.86
17.00	265.2	258.2	99323.	191.29	0.002	0.001	287.21	1.30	7766.30	8433.81	7.91	16.86
18.00	265.2	258.2	99391.	191.29	0.002	0.001	287.21	1.31	7766.30	8433.81	7.91	17.86

DAILY AVERAGE COMPUTED H = 7741.98
STANDARD ATMOSPHERE H = 8433.81
DAILY RELATIVE DIFF. (%) = -8.20

EQUIVALENT HEIGHT OF THE ATMOSPHERE

FEB. 2, 1979 DAY NUMBER 33

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]

MERID. TIME	TDB	TDP	P	PW	ROW	MR	RMA	RCMA	H	HSA	REL. DIFF. (%)	SOLAR TIME
8.00	262.2	256.2	100203.	161.96	0.001	0.001	287.18	1.33	7677.54	8433.81	8.97	7.85
9.00	262.2	256.2	100254.	161.96	0.001	0.001	287.18	1.33	7677.53	8433.81	8.97	8.85
10.00	263.2	257.2	100305.	176.08	0.001	0.001	287.19	1.33	7707.23	8433.81	8.62	9.85
11.00	264.2	257.2	100254.	176.08	0.001	0.001	287.19	1.32	7736.52	8433.81	8.27	10.85
12.00	266.2	258.2	100203.	191.29	0.002	0.001	287.21	1.31	7795.55	8433.81	7.57	11.85
13.00	266.2	259.2	100186.	207.67	0.002	0.001	287.23	1.31	7796.03	8433.81	7.56	12.85
14.00	266.2	259.2	100169.	207.67	0.002	0.001	287.23	1.31	7796.02	8433.81	7.56	13.85
15.00	267.2	260.2	100169.	225.29	0.002	0.001	287.24	1.31	7825.84	8433.81	7.21	14.85
16.00	267.2	260.2	100254.	225.29	0.002	0.001	287.24	1.31	7825.83	8433.81	7.21	15.85
17.00	266.2	260.2	100322.	225.29	0.002	0.001	287.24	1.31	7796.55	8433.81	7.56	16.85
18.00	265.2	260.2	100390.	225.29	0.002	0.001	287.24	1.32	7767.25	8433.81	7.90	17.85

DAILY AVERAGE COMPUTED H = 7763.79
STANDARD ATMOSPHERE H = 8433.81
DAILY RELATIVE DIFF. (%) = -7.94

EQUIVALENT HEIGHT OF THE ATMOSPHERE

FEB. 11, 1979 DAY NUMBER 42

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]

MERID. TIME	TDB	TDP	P	PW	FOW	MR	RMA	ROMA	H	HSA	REL. DIFF. (%)	SOLAR TIME
8.00	250.2	240.2	101998.	38.21	0.000	0.000	287.04	1.42	7322.65	8433.81	13.18	7.84
9.00	251.2	241.2	102032.	42.08	0.000	0.000	287.04	1.42	7352.03	8433.81	12.83	8.84
10.00	253.2	241.2	102032.	42.08	0.000	0.000	287.04	1.40	7410.58	8433.81	12.13	9.84
11.00	254.2	242.2	102032.	46.31	0.000	0.000	287.05	1.40	7439.97	8433.81	11.78	10.84
12.00	255.2	243.2	102032.	50.91	0.000	0.000	287.05	1.39	7469.37	8433.81	11.44	11.84
13.00	256.2	243.2	101964.	50.91	0.000	0.000	287.05	1.39	7498.64	8433.81	11.09	12.84
14.00	257.2	243.2	101896.	50.91	0.000	0.000	287.05	1.38	7527.92	8433.81	10.74	13.84
15.00	258.2	244.2	101863.	55.93	0.000	0.000	287.06	1.37	7557.34	8433.81	10.39	14.84
16.00	258.2	244.2	101863.	55.93	0.000	0.000	287.06	1.37	7557.34	8433.81	10.39	15.84
17.00	257.2	243.2	101880.	50.91	0.000	0.000	287.05	1.38	7527.92	8433.81	10.74	16.84
18.00	256.2	242.2	101913.	46.31	0.000	0.000	287.05	1.39	7498.52	8433.81	11.09	17.84

DAILY AVERAGE COMPUTED H = 7469.29
STANDARD ATMOSPHERE H = 8433.81
DAILY RELATIVE DIFF. (%) = -11.44

EQUIVALENT HEIGHT OF THE ATMOSPHERE

FEB. 12, 1979 DAY NUMBER 43

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]

MERID. TIME	TDB	TDP	P	PW	ROW	MR	RMA	ROMA	H	HSA	REL. DIFF. (%)	SOLAR TIME
8.00	251.2	246.2	101896.	67.31	0.001	0.000	287.07	1.41	7352.72	8433.81	12.82	7.84
9.00	252.2	246.2	101829.	67.31	0.001	0.000	287.07	1.41	7382.00	8433.81	12.47	8.84
10.00	254.2	246.2	101761.	67.31	0.001	0.000	287.07	1.39	7440.55	8433.81	11.78	9.84
11.00	256.2	248.2	101693.	80.75	0.001	0.000	287.09	1.38	7499.48	8433.81	11.08	10.84
12.00	258.2	248.2	101558.	80.75	0.001	0.000	287.09	1.37	7558.04	8433.81	10.38	11.84
13.00	259.2	248.2	101456.	80.75	0.001	0.000	287.09	1.36	7587.32	8433.81	10.04	12.84
14.00	260.2	248.2	101321.	80.75	0.001	0.000	287.09	1.36	7616.60	8433.81	9.69	13.84
15.00	260.2	248.2	101219.	80.75	0.001	0.000	287.09	1.36	7616.60	8433.81	9.69	14.84
16.00	260.2	247.2	101185.	73.76	0.001	0.000	287.08	1.35	7616.39	8433.81	9.69	15.84
17.00	260.2	248.2	101202.	80.75	0.001	0.000	287.09	1.35	7616.60	8433.81	9.69	16.84
18.00	260.2	247.2	101202.	73.76	0.001	0.000	287.08	1.36	7616.39	8433.81	9.69	17.84

DAILY AVERAGE COMPUTED H = 7536.60
STANDARD ATMOSPHERE H = 8433.81
DAILY RELATIVE DIFF. (%) = -10.64

EQUIVALENT HEIGHT OF THE ATMOSPHERE

FEB. 21, 1979 DAY NUMBER 52

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]

MERID. TIME	TDB	TDP	P	PW	ROW	MR	RMA	ROMA	H	HSA	REL. DIFF.(%)	SOLAR TIME
7.00	269.2	265.2	101338.	335.03	0.003	0.002	287.36	1.31	7887.60	8433.81	6.48	6.85
8.00	269.2	266.2	101388.	361.97	0.003	0.002	287.39	1.31	7888.40	8433.81	6.47	7.85
9.00	271.2	267.2	101287.	390.83	0.003	0.002	287.42	1.30	7947.88	8433.81	5.76	8.85
10.00	273.2	268.2	101168.	421.72	0.003	0.003	287.45	1.29	8007.45	8433.81	5.06	9.85
11.00	274.2	269.2	101033.	454.77	0.004	0.003	287.49	1.28	8037.78	8433.81	4.70	10.85
12.00	276.2	269.2	100881.	454.77	0.004	0.003	287.49	1.27	8096.43	8433.81	4.00	11.85
13.00	276.2	269.2	100694.	454.77	0.004	0.003	287.49	1.27	8096.46	8433.81	4.00	12.85
14.00	276.2	271.2	100593.	527.82	0.004	0.003	287.57	1.27	8098.72	8433.81	3.97	13.85
15.00	275.2	272.2	100593.	568.12	0.004	0.004	287.62	1.27	8070.63	8433.81	4.31	14.85
16.00	274.2	273.2	100440.	611.11	0.005	0.004	287.66	1.27	8042.64	8433.81	4.64	15.85
17.00	275.2	273.2	100356.	611.11	0.005	0.004	287.67	1.27	8071.99	8433.81	4.29	16.85
18.00	275.2	273.2	100288.	611.11	0.005	0.004	287.67	1.27	8072.00	8433.81	4.29	17.85

DAILY AVERAGE COMPUTED H = 8026.49
STANDARD ATMOSPHERE H = 8433.81
DAILY RELATIVE DIFF. (%) = -4.83

EQUIVALENT HEIGHT OF THE ATMOSPHERE

FEB. 22, 1979 DAY NUMBER 53

RW = 461.0 [SQ.M/SEC.SQ. K] TS = 273.16 [K]

MERID. TIME	TDB	TDP	P	PW	ROW	MR	RMA	ROMA	H	HSA	REL. DIFF. (%)	SOLAR TIME
7.00	276.2	271.2	101101.	527.82	0.004	0.003	287.57	1.27	8098.64	8433.81	3.97	6.85
8.00	276.2	271.2	101304.	527.82	0.004	0.003	287.57	1.28	8098.60	8433.81	3.97	7.85
9.00	276.2	270.2	101456.	490.09	0.004	0.003	287.53	1.28	8097.44	8433.81	3.99	8.85
10.00	276.2	270.2	101270.	490.09	0.004	0.003	287.53	1.28	8097.46	8433.81	3.99	9.85
11.00	276.2	270.2	101592.	490.09	0.004	0.003	287.53	1.28	8097.41	8433.81	3.99	10.85
12.00	276.2	271.2	101642.	527.82	0.004	0.003	287.57	1.28	8098.55	8433.81	3.98	11.85
13.00	276.2	271.2	101558.	527.82	0.004	0.003	287.57	1.28	8098.57	8433.81	3.97	12.85
14.00	276.2	271.2	101659.	527.82	0.004	0.003	287.57	1.28	8098.55	8433.81	3.98	13.85
15.00	276.2	271.2	101693.	527.82	0.004	0.003	287.57	1.28	8098.55	8433.81	3.98	14.85
16.00	276.2	271.2	101642.	527.82	0.004	0.003	287.57	1.28	8098.55	8433.81	3.98	15.85
17.00	276.2	271.2	101744.	527.82	0.004	0.003	287.57	1.28	8098.53	8433.81	3.98	16.85
18.00	275.2	271.2	101829.	527.82	0.004	0.003	287.57	1.29	8069.20	8433.81	4.32	17.85

DAILY AVERAGE COMPUTED H = 8095.83
STANDARD ATMOSPHERE H = 8433.81
DAILY RELATIVE DIFF. (%) = -4.01

APPENDIX A4

INSOLATION CLIMATOLOGY DATA ON SOLMET FORMAT

Pages 1 to 7 of the data and format description of SOLMET tapes, from SOLMET Vol. 1: User's Manual [61], are reported below.

IDENTIFICATION							SOLAR RADIATION OBSERVATION										
TAPE DECK #	WBAN STN #	SOLAR TIME				LST TIME	ETR KJ/m²	RADIATION VALUES KJ/m²									SUNSHINE MIN
		YR	MO	DY	HRMN			DIRECT	DIFFUSE	NET	TILTED	GLOBAL OBS	GLOBAL ENG COR	GLOBAL STD YR COR	A	B	
9724	XXXXX	XX	XX	XX	XXXX	XXXX	XXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	iXXXX	XX
FIELD NUMBER 001	002	003				004	101	102	103	104	105	106	107	108	109	110	111

SURFACE METEOROLOGICAL OBSERVATION

OBS TIME LST	CEILING dam	SKY COND	VSBY hm	WEATHER	PRESSURE kPa SEA LEVEL	PRESSURE kPa STATION	TEMP °C DRY BULB	TEMP °C DEW-PT.	WIND DIR deg	WIND SPD m/s	CLOUDS TOTAL	LOWEST AMOUNT	LOWEST TYPE	LOWEST HEIGHT dam	SECOND AMOUNT	SECOND TYPE	SECOND HEIGHT dam	SUM AMT	THIRD AMOUNT	THIRD TYPE	THIRD HEIGHT dam	SUM AMT	FOURTH AMOUNT	FOURTH TYPE	FOURTH HEIGHT dam	OPAQUE	SNOW COVER
XX	XXXX	iXXXX	XXXX	XXXXXXXX	XXXXX	XXXXX	XXXX	XXXX	XXX	XXXX	XX	XX	XX	XXXX	XX	XX	XXXX	XX	XX	XX	XXXX	XX	XX	XX	XXXX	XX	X
201	202	203	204	205	206		207		208		209																210

TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT
001	001 - 004	TAPE DECK NUMBER
002	005 - 009	WBAN STATION NUMBER
003	010 - 019	SOLAR TIME (YR, MO, DAY, HOUR, MINUTE)
004	020 - 023	LOCAL STANDARD TIME (HR AND MINUTE)
101	024 - 027	EXTRATERRESTRIAL RADIATION
102	028 - 032	DIRECT RADIATION
103	033 - 037	DIFFUSE RADIATION
104	038 - 042	NET RADIATION
105	043 - 047	GLOBAL RADIATION ON A TILTED SURFACE
106	048 - 052	GLOBAL RADIATION ON A HORIZONTAL SURFACE - OBSERVED DATA
107	053 - 057	GLOBAL RADIATION ON A HORIZONTAL SURFACE - ENGINEERING CORRECTED DATA
108	058 - 062	GLOBAL RADIATION ON A HORIZONTAL SURFACE - STANDARD YEAR CORRECTED DATA
109, 110	063 - 072	ADDITIONAL RADIATION MEASUREMENTS
111	073 - 074	MINUTES OF SUNSHINE
201	075 - 076	TIME OF COLLATERAL SURFACE OBSERVATION (LST)
202	077 - 080	CEILING HEIGHT (DEKAMETERS)
203	081 - 085	SKY CONDITION
204	086 - 089	VISIBILITY (HECTOMETERS)
205	090 - 097	WEATHER
206	098 - 107	PRESSURE (KILOPASCALS)
207	108 - 115	TEMPERATURE (DEGREES CELSIUS TO TENTHS)
208	116 - 122	WIND (SPEED IN METERS PER SECOND)
209	123 - 162	CLOUDS
210	163	SNOW COVER INDICATOR

NOTE: Except for tape positions 001-027 in fields 001-101, elements with a tape configuration of 9's indicate missing or unknown data.

TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT	TAPE CONFIGURATION	CODE DEFINITIONS AND REMARKS
001	001 - 004	TAPE DECK NUMBER	9724	
002	005 - 009	WBAN STATION NUMBER	01001 - 98999	Unique number used to identify each station.
003	010 - 019	SOLAR TIME		
	010 - 011	YEAR	00 - 99	Year of observation, 00 - 99 = 1900 - 1999
	012 - 013	MONTH	01 - 12	Month of observation, 01 - 12 = Jan. - Dec.
	014 - 015	DAY	01 - 31	Day of month
	016 - 019	HOUR	0001 - 2400	End of the hour of observation in solar time (hours and minutes)
004	020 - 023	LOCAL STANDARD TIME	0000 - 2359	Local Standard Time in hours and minutes corresponding to end of solar hour indicated in field 003. For Appendix A.2 listed stations, add 30 minutes to the local standard time on tape.
101	024 - 027	EXTRATERRESTRIAL RADIATION	0000 - 4957	Amount of solar energy in kJ/m^2 received at top of atmosphere during solar hour ending at time indicated in field 003, based on solar constant = $1377 J/(m^2 \cdot s)$. For Appendix A.2 listed stations, 0000 = nighttime values of extraterrestrial radiation, and 8000 = corresponding nighttime value in Field 108. For all other stations, 9999 = nighttime values defined as zero kJ/m^2 for all solar radiation data fields.
102	028 - 032	DIRECT RADIATION		Portion of radiant energy in kJ/m^2 received at the pyrheliometer directly from the sun during solar hour ending at time indicated in field 003.
	028	DATA CODE INDICATOR	0 - 9	
	029 - 032	DATA	0000 - 4957	
103	033 - 037	DIFFUSE RADIATION		Amount of radiant energy in kJ/m^2 received at the instrument indirectly from reflection, scattering, etc., during the solar hour ending at the time indicated in field 003.
	033	DATA CODE INDICATOR	0 - 9	
	034 - 037	DATA	0000 - 4957	
104	038 - 042	NET RADIATION		Difference between the incoming and outgoing radiant energy in kJ/m^2 during the solar hour ending at the time indicated in field 003. A constant of 5000 has been added to all net radiation data.
	038	DATA CODE INDICATOR	0 - 9	
	039 - 042	DATA	2000 - 8000	
105	043 - 047	GLOBAL RADIATION ON A TILTED SURFACE		Total of direct and diffuse radiant energy in kJ/m^2 received on a tilted surface (tilt angle indicated in station - period of record list) during solar hour ending at the time indicated in field 003.
	043	DATA CODE INDICATOR	0 - 9	
	044 - 047	DATA	0000 - 4957	
	048 - 062	GLOBAL RADIATION ON A HORIZONTAL SURFACE		Total of direct and diffuse radiant energy in kJ/m^2 received on a horizontal surface by a pyranometer during the solar hour ending at the time indicated in field 003.
106	048 - 052	OBSERVED DATA		
	048	DATA CODE INDICATOR	0 - 9	
	049 - 052	DATA	0000 - 4957	Observed value.
107	053 - 057	ENGINEERING CORRECTED DATA		

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TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT	TAPE CONFIGURATION	CODE DEFINITIONS AND REMARKS
	053	DATA CODE INDICATOR	0 - 9	
	054-057	DATA	0000 - 4957	Observed value corrected for known scale changes, station moves, recorder and sensor calibration changes, etc.
108	058 - 062	STANDARD YEAR CORRECTED DATA		
	058	DATA CODE INDICATOR	0 - 9	
	059 - 062	DATA	0000 - 4957	Observed value adjusted to Standard Year Model. This model yields expected clear sky irradiance received on a horizontal surface at the elevation of the station.
109, 110	063 - 072	ADDITIONAL RADIATION MEASUREMENTS		Supplemental Fields A and B for additional radiation measurements; type of measurement specified in station-period of record list.
	063, 068	DATA CODE INDICATORS	0 - 9	
	064-067	DATA		
	069-072	DATA		

NOTE FOR FIELDS 102-110: Data code indicators are:

0 Observed data
1 Estimated from model using sunshine and cloud data
2 Estimated from model using cloud data
3 Estimated from model using sunshine data
4 Estimated from model using sky condition data
5 Estimated from linear interpolation
6 Reserved for future use
7 Estimated from other model (see individual station notes at end of manual)
8 Estimated without use of a model
9 Missing data follows

(See model description in Volume 2.)

TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT	TAPE CONFIGURATION	CODE DEFINITIONS AND REMARKS
111	073 - 074	MINUTES OF SUNSHINE	00 - 60	For Local Standard Hour most closely matching solar hour.
201	075 - 076	TIME OF TD 1440 OBSERVATION	00 - 23	Local Standard Hour of TD 1440 Meteorological Observation that comes closest to mid-point of the solar hour for which solar data are recorded.
202	077 - 080	CEILING HEIGHT	0000 - 3000	Ceiling height in dekameters (dam = m x 10^1); ceiling is defined as opaque sky cover of .6 or greater. 0000 - 3000 = 0 to 30,000 meters
			7777	7777 = unlimited; clear
			8888	8888 = unknown height of cirroform ceiling
203	081 - 085	SKY CONDITION		
	081	INDICATOR	0	Identifies observations after 1 June 51.
	082 - 085	SKY CONDITION	0000 - 8888	Coded by layer in ascending order; four layers are described; if less than 4 layers are present the remaining positions are coded 0. The code for each layer is: 0 = Clear or less than .1 cover 1 = Thin scattered (.1 - .5 cover) 2 = Opaque scattered (.1 - .5 cover) 3 = Thin broken (.6 - .9 cover) 4 = Opaque broken (.6 - .9 cover) 5 = Thin overcast (1.0 cover) 6 = Opaque overcast (1.0 cover) 7 = Obscuration 8 = Partial obscuration

TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT	TAPE CONFIGURATION	CODE DEFINITIONS AND REMARKS
204	086 - 089	VISIBILITY	0000 - 1600	Prevailing horizontal visibility in hectometers (hm = m x 10^2). 0000 - 1600 = 0 to 160 kilometers
			8888	8888 = unlimited
205	090 - 097	WEATHER		
	090	OCCURRENCE OF THUNDERSTORM, TORNADO OR SQUALL	0 - 4	0 = None 1 = Thunderstorm - lightning and thunder. Wind gusts less than 50 knots, and hail, if any, less than 3/4 inch diameter. 2 = Heavy or severe thunderstorm - frequent intense lightning and thunder. Wind gusts 50 knots or greater and hail, if any, 3/4 inch or greater diameter. 3 = Report of tornado or waterspout. 4 = Squall (sudden increase of wind speed by at least 16 knots, reaching 22 knots or more and lasting for at least one minute).
	091	OCCURRENCE OF RAIN, RAIN SHOWERS OR FREEZING RAIN	0 - 8	0 = None 1 = Light rain 2 = Moderate rain 3 = Heavy rain 4 = Light rain showers 5 = Moderate rain showers 6 = Heavy rain showers 7 = Light freezing rain 8 = Moderate or heavy freezing rain
	092	OCCURRENCE OF DRIZZLE, FREEZING DRIZZLE	0 - 6	0 = None 1 = Light Drizzle 2 = Moderate drizzle 3 = Heavy drizzle 4 = Light freezing drizzle 5 = Moderate freezing drizzle 6 = Heavy freezing drizzle
	093	OCCURRENCE OF SNOW, SNOW PELLETS OR ICE CRYSTALS	0 - 8	0 = None 1 = Light snow 2 = Moderate snow 3 = Heavy snow 4 = Light snow pellets 5 = Moderate snow pellets 6 = Heavy snow pellets 7 = Light ice crystals 8 = Moderate ice crystals Beginning April 1963 intensities of ice crystals were discontinued. All occurrences since this date are recorded as an 8.
	094	OCCURRENCE OF SNOW SHOWERS AND SNOW GRAINS	0 - 6	0 = None 1 = Light snow showers 2 = Moderate snow showers 3 = Heavy snow showers 4 = Light snow grains 5 = Moderate snow grains 6 = Heavy snow grains Beginning April 1963 intensities of snow grains were discontinued. All occurrences since this date are recorded as a 5.

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TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT	TAPE CONFIGURATION	CODE DEFINITIONS AND REMARKS
	095	OCCURRENCE OF SLEET (ICE PELLETS), SLEET SHOWERS OR HAIL	0 - 8	0 = None 1 = Light sleet or sleet showers (ice pellets) 2 = Moderate sleet or sleet showers (ice pellets) 3 = Heavy sleet or sleet showers (ice pellets) 4 = Light hail 5 = Moderate hail 6 = Heavy hail 7 = Light small hail 8 = Moderate or heavy small hail Prior to April 1970 ice pellets were coded as sleet. Beginning April 1970 sleet and small hail were redefined as ice pellets and are coded as a 1, 2 or 3 in this position. Beginning September 1956 intensities of hail were no longer reported and all occurrences were recorded as a 5.
	096	OCCURRENCE OF FOG, BLOWING DUST OR BLOWING SAND	0 - 5	0 = None 1 = Fog 2 = Ice fog 3 = Ground fog 4 = Blowing dust 5 = Blowing sand These values recorded only when visibility less than 7 miles.
	097	OCCURRENCE OF SMOKE, HAZE, DUST, BLOWING SNOW, BLOWING SPRAY	0 - 6	0 = None 1 = Smoke 2 = Haze 3 = Smoke and haze 4 = Dust 5 = Blowing snow 6 = Blowing spray These values recorded only when visibility less than 7 miles.
206	098 - 107	PRESSURE		
	098 - 102	SEA LEVEL PRESSURE	08000 - 10999	Pressure, reduced to sea level, in kilopascals (kPa) and hundredths.
	103 - 107	STATION PRESSURE	08000 - 10999	Pressure at station level in kilopascals (kPa) and hundredths. 08000 - 10999 = 80 to 109.99 kPa
207	108 - 115	TEMPERATURE		
	108 - 111	DRY BULB	-700 to 0600	°C and tenths
	112 - 115	DEW POINT	-700 to 0600	°C and tenths -700 to 0600 = -70.0 to +60.0°C
208	116 - 122	WIND		
	116 - 118	WIND DIRECTION	000 - 360	Degrees
	119 - 122	WIND SPEED	0000 - 1500	m/s and tenths; 0000 with 000 direction indicates calm. 0000 - 1500 = 0 to 150.0 m/s

TAPE FIELD NUMBER	TAPE POSITIONS	ELEMENT	TAPE CONFIGURATION	CODE DEFINITIONS AND REMARKS
209	123 - 162	CLOUDS		See following explanatory "NOTES."
	123 - 124	TOTAL SKY COVER		
	125 - 126	LOWEST CLOUD LAYER AMOUNT		
	127 - 128	TYPE OF LOWEST CLOUD OR OBSCURING PHENOMENA		
	129 - 132	HEIGHT OF BASE OF LOW-EST CLOUD LAYER OR OBSCURING PHENOMENA		
	133 - 134	SECOND LAYER AMOUNT		
	135 - 136	TYPE OF SECOND CLOUD LAYER		
	137 - 140	HEIGHT OF BASE OF SECOND CLOUD LAYER		
	141 - 142	SUMMATION OF FIRST 2 LAYERS		
	143 - 144	THIRD LAYER AMOUNT		
	145 - 146	TYPE OF THIRD CLOUD LAYER		
	147 - 150	HEIGHT OF BASE OF THIRD CLOUD LAYER		
	151 - 152	SUMMATION OF FIRST 3 LAYERS		
	153 - 154	FOURTH LAYER AMOUNT		
	155 - 156	TYPE OF FOURTH CLOUD LAYER		
	157 - 160	HEIGHT OF BASE OF FOURTH CLOUD LAYER		
	161 - 162	TOTAL OPAQUE SKY COVER		

NOTES: (1) Tape Configuration and Remarks for Total Sky Cover, Cloud Layer Amount, Summation of Cloud Layers and Total Opaque Sky Cover

Configuration	Remarks
00 - 10	Amount of celestial dome in tenths covered by clouds or obscuring phenomena. Opaque means clouds or obscuration through which the sky or higher cloud layers cannot be seen.

(2) Tape Configuration and Remarks for Type of Cloud or Obscuring Phenomena.

Configuration	Remarks
00 - 16	Generic cloud type or obscuring phenomena. 0 = None 1 = Fog 2 = Stratus 3 = Stratocumulus 4 = Cumulus 5 = Cumulonimbus 6 = Altostratus 7 = Altocumulus 8 = Cirrus 9 = Cirrostratus 10 = Stratus Fractus 11 = Cumulus Fractus 12 = Cumulonimbus Mamma 13 = Nimbostratus 14 = Altocumulus Castellanus 15 = Cirrocumulus 16 = Obscuring phenomena other than fog

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(3) Tape Configuration and Remarks for Height of Base of Cloud Layer or Obscuring Phenomena.

Configuration	Remarks
0000 - 3000	Dekameters
7777	7777 = Unlimited, clear
8888	8888 = Unknown height or cirroform layer

210	163	SNOW COVER INDICATOR	0 - 1	0 indicates no snow or trace of snow on ground; 1 indicates more than trace of snow on ground.

APPENDIX A5

W.M.O. CLOUD DEFINITION AND CLASSIFICATION

1. Cloud Classification

The W.M.O. classification [68] does not consider as a classification criterion the forming process of the clouds; it tries instead to consider their general appearance, their obscuration characteristics, and their shape or particular visible optical effects.* This is done to allow visual recognition of the sky dome.

Principally, 10 genera of clouds are considered in ascending order as follows:

1. Cumulonimbus
2. Cumulus
3. Stratus
4. Stratocumulus
5. Nimbostratus
6. Altostratus

---

*Reference [68] also reports photographs of the different types of clouds.

7. Altocumulus
8. Cirrostratus
9. Cirrocumulus
10. Cirrus

Stratus and stratocumulus clouds are generally found in the lower layer; altocumulus in the middle layer; and cirrus, cirrocumulus and cirrostratus in the higher layer. Altostratus clouds are generally located in the middle-higher layers. Nimbostratus, cumulus, and cumulonimbus extend over more than one layer, generally starting from the higher limit of the lower layer.

The layer definition is aleatory, in the sense that it varies, mainly with latitude. An approximate description of the height of the layers, i.e., elevation of the inferior limit of the layer, would be as follows (for temperate regions):

Low layer: surface to 2,000 m

Medium layer: from 2,000 to 8,000 m

High layer: from 5,000 to 14,000 m

In tropical regions, the highest layer maximum elevation would be approximately 40 percent higher than in the temperature regions, all the other layers being the same.

Every genus may be further divided into species and varieties.

2. Cloud definition (from reference [68])

1 Cumulonimbus:

Heavy and dense cloud, with a considerable vertical extent, in the form of a mountain or huge towers. At least part of its upper portion is usually smooth, fibrous, or striated, and nearly always flattened: this part often spreads out in the shape of an anvil or vast plume. Under the base of this cloud, which is often very dark, there are frequently low ragged clouds either merged with it or not, and precipitation sometimes in the form of virga.

Species or Varieties: Cumulonimbus mamma (among others)

2 Cumulus:

Detached clouds, generally dense and with sharp outlines, developing vertically in the form of rising mounds, domes, or towers, of which the bulging upper part often resembles a cauliflower. The sunlit parts of these clouds are mostly brilliant white. Their base is relatively dark and nearly horizontal. Sometimes, cumulus is ragged.

Species or Varieties: Cumulus fractus (among others)

3 Stratus:

Generally gray cloud layer with a fairly uniform base . . . When the Sun is visible through the cloud, its outline is clearly discernible . . . Sometimes stratus appears in the form of ragged patches.

Species or Varieties: Stratus fractus (among others)

4 Stratocumulus:

Gray or whitish, or both gray and whitish, patch, sheet or layer of cloud which almost always has dark parts, composed of tasselations, rounded masses, rolls, etc. which are nonfibrous (except for virga) and which may or may not be merged; most of the regularly arranged, small elements have an apparent width of more than 5 degrees.

5 Nimbostratus:

Gray cloud layer, often dark, the appearance of which is rendered diffuse by more or less continuously falling rain or snow, which in most cases reaches the ground. It is thick enough throughout to blot out the Sun. Low, ragged clouds frequently occur below the layer, with which they may or may not merge.

6 Altostratus:

Grayish or bluish cloud sheet or layer of striated, fibrous, or uniform appearance, totally or partly covering the sky, and having parts thin enough to reveal the Sun at least vaguely as through ground glass . . .

7 Altocumulus:

White or gray, or both white and gray, patch, sheet or layer of cloud, generally with shading, composed of laminae, rounded masses, rolls, etc., which are sometimes partly fibrous or diffuse and which may or may not be merged; most of the regularly arranged small elements usually have an apparent width of between one and five degrees.

Species or Varieties: Altocumulus castellanus (among others)

8 Cirrostratus:

Transparent, whitish cloud veil of fibrous (hair-like) or smooth appearance, totally or partly covering the sky . . .

9 Cirrocumulus:

Thin, white patch, sheet or layer of cloud without shading, composed of very small elements in the form of grains, ripples, etc., merged or separate and more or less regularly arranged; most of the elements have an apparent width of less than one degree.

10 Cirrus:

Detached clouds in the form of white, delicate filaments or white or mostly white patches or narrow bands. These clouds have a fibrous (hair-like) appearance.

APPENDIX A6

ANALOGIC RECORDS OF SURFACE WEATHER OBSERVATION

Surface weather observation chart: Form MF1-10B

LEGEND

Reading the chart from left to right:

Time (L.S.T.)	=	Local Standard Time. This recording represents the actual time at which the meteorological readings were made [hours, minutes].
Station Pressure	=	Barometric pressure (air pressure) as measured at the recording station [inches of mercury].
Dry Bulb	=	Dry-bulb temperature [degrees Fahrenheit].
Wet Bulb	=	Wet-bulb temperature [degrees Fahrenheit].
Relative Humidity	=	Relative humidity [percent].
Total Sky Cover	=	Amount of the celestial dome covered by clouds or other obscuring phenomena. Values are in tenths, e.g., a reading of 2 indicates that a total to two tenths, or 20 percent, of the celestial dome was covered by clouds or other obscuring phenomena. A reading of 10 would indicate that 100 percent of the sky was covered by clouds or other obscuring phenomena.
Clouds and Obscuring Phenomena	=	The term "lowest layer" refers to that layer of clouds that is closest to the surface of the Earth; "second layer" refers to the next layer up, and so on through to the "fourth layer."

Amount = Amount of the celestial dome, in tenths, covered by the layer.

Type = Type of clouds present in the layer.

Height = Height, in thousands of feet, of the base of the layer. An E before a reading indicates that this measurement is estimated, e.g, E45 means "estimated to be 45,000 feet." An M before a reading indicates that the reading is the result of an actual measurement of the height.

Total Opaque Sky Cover = Amount of celestial dome, in tenths, that is covered by any sort of opaque covering.

Pressure Tendency = 1-digit code indicating the tendency of the barometric pressure (going up, going down, no variation).

Net 3-Hr. Change = Net change in barometric pressure for the past three hours [inches of mercury].

Sunshine = Number of minutes of direct sunshine [minutes].

Precipitation = Amount of precipitation (of all types), e.g., snow, rain that has fallen during this particular hour, measured in inches. T indicates that a "trace" of precipitation fell, i.e., the amount of precipitation was less than 0.01 inch, but was still detectable.

MF1-10B
(2-77)

U. S. DEPARTMENT OF COMMERCE
NOAA
NATIONAL WEATHER SERVICE

SURFACE WEATHER OBSERVATIONS

STATION: ALBANY, N. Y. (COUNTY AIRPORT)

DATE: JUL 1 1979

To convert LST to GMT ADD 5 hrs.

TIME (L.S.T.) 16	STATION PRESSURE (Ins.) 17	DRY BULB (°F) 18	WET BULB (°F) 19	REL. HUMIDITY (%) 20	TOTAL SKY COVER 21	LOWEST LAYER AMT. 22	LOWEST LAYER TYPE 23	LOWEST LAYER HEIGHT 24	SECOND LAYER AMT. 25	SECOND LAYER TYPE 26	SECOND LAYER HEIGHT 27	SUMMATION TOTAL 28	THIRD LAYER AMT. 29	THIRD LAYER TYPE 30	THIRD LAYER HEIGHT 31	SUMMATION TOTAL 32	FOURTH LAYER AMT. 33	FOURTH LAYER TYPE 34	FOURTH LAYER HEIGHT 35	TOTAL OPAQUE SKY COVER 36	PRESSURE TENDENCY 37	NET 3-HR. CHANGE (Ins.) 38	SUNSHINE (Min.) 39	PRECIPITATION (Ins.) 40	HR.
0051	29.545	67		93	10	10	Sc	M28												10	7	.040			00-01
0153	29.520	67		93	10															10					01-02
0251	29.510	67		93	8															8					02-03
0351	29.520	68		90	9	9	Sc	M28												9	5	.025			03-04
0451	29.520	67		93	10															10					04-05
0554	29.520	70		77	8															5					05-06
0652	29.520	73		82	10	1	Sc	50	1	Ac	110	2	8	Ci	250	10				3	4	.000			06-07
0752	29.510	74		79	10															6					07-08
0851	29.500	75		74	8															6					08-09
0952	29.485	77		69	9	5	Cu	23	2	Ac	E110	7	2	Cs	250	9				8	7	.035			09-10
1052	29.465	78		69	9															8					10-11
1152	29.445	80		65	9															7					11-12
1252	29.425	81		63	10	4	Cu	30	3	Ac	E110	7	3	Cs	250	10				8	7	.060			12-13
1352	29.425	67		84	10															10				.07	13-14
1451	29.425	75		74	10															9				.01	14-15
1552	29.400	74		71	10	2	Cu	35	5	Ac	80	7	3	Ci	250	10				10	8	.025			15-16
1652	29.400	74		74	10															10					16-17
1750	29.390	75		71	8															6					17-18
1851	29.400	72		79	7	1	Cu	35	2	Ac	100	3	4	Ci	E250	7				6	5	.000			18-19
1950	29.400	71		79	7															1					19-20
2050	29.400	69		84	8															6					20-21
2151	29.395	68		87	8	2	Cu	40	5	Ac	E70	7	1	Ci	350	8				7	8	.005			21-22
2255	29.400	68		90	9															9					22-23
2352	29.390	67		84	7															7					23-24

SYNOPTIC OBSERVATIONS

TIME (G.M.T.) 41	TIME (L.S.T.) 42	NO. 43	PRECIP. (Ins.) 44	SNOW FALL (Ins.) 45	SNOW DEPTH (Ins.) 46	MAX. TEMP. (°F) 47	MIN. TEMP. (°F) 48	PRECIP. ORIGIN 49	STATE OF GRND. 50	51	52	53	54	55	SOIL TEMP. 56	57	58
	MID. TO 2047	X	0	0	X	68	67	X	X						X		
	0047	1	.08	0	0	73	67		2								
	0648	2	0	0	0	73	67		1								
	1247	3	0	0	0	82	73		0								
	1845	4	.08	0	0	83	67		1								
	MID.	X	0	0	0	72	67	X	X						X		

STATION PRESSURE COMPUTATIONS

TIME (L.S.T.) 59	0051	0652	1252	1851
ATT. THERM. 60				
OBSRVD. BAR. 61				
TOTAL CORR. 62				
STA. PRESS. 63	29.545	29.520	29.425	29.400
BAROGRAPH 64	29.530	29.500	29.430	29.400
BAR. CORR. 65	+.015	+.020	-.005	±0

SUMMARY OF DAY (MIDNIGHT TO MIDNIGHT)

24-HR. MAX. TEMP. (°F) 66	24-HR. MIN. TEMP. (°F) 67	24-HR. PRECIP. WATER EQUIV. (Ins.) 68	24-HR. SNOWFALL UNMLTD (Ins.) 69	SNOW DEPTH (Ins.) 70	PEAK WIND SPEED (Kts.) 71	PEAK WIND DIRECTION 72	PEAK WIND TIME (L.S.T.) 73	THICKNESS OF ICE ON WATER (Ins.) 74	FROZEN GROUND LAYER TOP 75	FROZEN GROUND LAYER BASE 76	RIVER GAGE 77	SKY COVER SUNRISE TO SUNSET 78	SKY COVER MIDNIGHT TO MIDNIGHT 79	WATER EQUIV. (Ins.) 80	81
83	67	.08	0	0	41	SW	1347E					9	9		

WEATHER & OBSTRUCTIONS TO VISION

TYPE 82	BEGAN 83	ENDED 84	TYPE 86	BEGAN 87	ENDED 88
RW+	1346	1350			
RW-	1350	1403			

90. REMARKS, NOTES AND MISCELLANEOUS PHENOMENA

TIME: SUNRISE 0412E SUNSET 1937E

TOTAL SUNSHINE 521 (MIN.) PERCENT OF POSSIBLE SUNSHINE 57 CHARACTER OF SUNRISE CLDY CHARACTER OF SUNSET CLDY

FASTEST OBSERVED 1-MINUTE WIND SPEED M.P.H. OR FASTEST MILE 31 M.P.H. ASSOCIATED DIRECTION SW TIME 1347E

TIME CHECK: 8 SEC SLOW @ 2359E
3 SEC SLOW @ 1405E

MF1-10B

☆ U.S.GPO:1977-0-765-008/1131

CONVERSION TABLE (in alphabetical order)

To convert from	to	multiply by	(power of 10)
Acceleration:			
$foot/sec^2$	$meter/sec^2$	3.048	-1
$inch/sec^2$	$meter/sec^2$	2.540	-1
$meter/sec^2$	$foot/sec^2$	3.281	0
$meter/sec^2$	$inch/sec^2$	3.937	1
Area:			
sq. foot	sq. meter	9.290	-2
sq. inch	sq. meter	6.452	-4
sq. mile	sq. meter	2.590	6
sq. yard	sq. meter	8.361	-1
sq. meter	sq. inch	1.550	3
sq. meter	sq. foot	1.076	1
sq. meter	sq. yard	1.196	0
sq. meter	sq. mile	3.861	-7
Energy:			
BTU	joule	1.056	3
calorie	joule	4.185	0
kilocalorie	joule	4.185	3
kilowatt hour	joule	3.600	6
joule	BTU	9.470	-4
joule	calorie	2.390	-1
joule	kilocalorie	2.390	-4
Joule	Kilowatt hour	2.778	-7
Energy/Area Time:			
$BTU/foot^2$ sec	W/m^2	1.135	4
$BTU/foot^2$ min	W/m^2	1.891	2
$BTU/foot^2$ hr	W/m^2	3.152	0

CONVERSION TABLE (in alphabetical order) (continued)

To convert from	to	multiply by	(power of 10)
Energy/Area Time: (continued)			
BTU/inch2 sec	W/m2	1.634	6
calories/cm2 min	W/m2	6.973	2
W/cm2	W/m2	1.000	4
W/m2	BTU/foot2 sec	8.811	-5
W/m2	BTU/foot2 min	5.288	-3
W/m2	BTU/foot2 hr	3.173	-1
W/m2	BTU/inch2 sec	6.120	-7
W/m2	calories/cm2 min	1.434	-3
W/m2	W/cm2	1.000	-4
Force:			
dyne	Newton	1.000	-5
kilogram force	Newton	9.807	0
pound force	Newton	4.448	0
Newton	dyne	1.000	5
Newton	kilogram force	1.020	-1
Newton	pound force	2.248	-1
Length:			
inch	centimeter	2.540	0
foot	meter	3.048	-1
yard	meter	9.144	-1
mile	meter	1.609	3
meter	mile	6.214	-4
meter	foot	3.281	0
centimeter	inch	3.937	-1
millimeter	inch	3.937	-2

CONVERSION TABLE (in alphabetical order) (continued)

To convert from	to	multiply by	(power of 10)
Power:			
BTU/sec	watt	1.054	3
BTU/min	watt	1.757	1
calories/sec	watt	4.184	0
calories/min	watt	6.973	-2
horsepower	watt	7.460	2
watt	BTU/sec	9.488	-4
watt	BTU/min	5.692	-2
watt	calories/sec	2.390	-1
watt	calories/min	1.434	1
Pressure:			
atmosphere	N/sq. meter	1.013	5
bar	N/sq. meter	1.000	5
inch of mercury (60°F)	N/sq. meter	3.377	3
inch of water (60°F)	N/sq. meter	2.488	2
millibar	N/sq. meter	1.000	2
mm of mercury (0°C)	N/sq. meter	1.333	2
Pascal	N/sq. meter	1.000	0
torr (0°C)	N/sq. meter	1.333	2
N/sq. meter	atmospheres	9.872	-6
N/sq. meter	bar	1.000	-5
N/sq. meter	inches of mercury (60°F)	2.961	-4
N/sq. meter	inches of water (60°F)	4.019	-3
N/sq. meter	millibars	1.000	-2
N/sq. meter	mm of mercury (0°C)	7.502	-3
N/sq. meter	torr (0°C)	7.502	-3

CONVERSION TABLE (in alphabetical order) (continued)

To convert from	to	multiply by
Temperature:		
Fahrenheit	Celsius	$t_c = (5/9)(t_f - 32)$
Fahrenheit	Kelvin	$t_k = (5/9)(t_f + 459.67)$
Celsius	Fahrenheit	$t_f = (9/5)(t_c) + 32$
Celsius	Kelvin	$t_k = t_c + 273.15$
Rankine	Kelvin	$t_k = 5/9\ t_r$
Kelvin	Rankine	$t_r = 9/5\ t_k$

NOMENCLATURE

A = parameter on the delination computation; in Appendix A1, area

A_0 = density integral of the atmosphere

A_1 = relative atmospheric mass

B = radiance in Appendix A1 (Subsection 1.1) or brilliance (Subsection 2.1)

D = geometrical day length

E = energy flux density; in Chapter 2, East; in Appendix A1 (Subsection 1.2), luminescence

$\overline{E}_S$ = extraterrestrial solar energy flux density for average Sun-Earth distance

E_S = extraterrestrial solar energy flux density for daily computed Sun-Earth distance

E_0 = solar energy flux density on the ground

F_0 = irradiance (integrated energy flux)

F_0' = irradiance in the hypothesized absence of atmosphere

H = equivalent height

I = energy as electromagnetic radiation

K = absorbance function of the atmosphere

K_T = integral absorbance function of the atmosphere without clouds

K_T' = integral absorbance function of the atmopshere with clouds

M = number of days in the month

M_i = molecular weight of gas i

MR = moist ratio

N = progressive number of the days of the year, first of January N = 1

P = pressure

R = radius; in Appendix A1 radiative energy intensity (Subsection 1.1) or light intensity (Subsection 1.2); Appendix A3 molar gas content

R_i = gas constant of gas *i*

R_D = gas constant of dry air

R_W = gas constant of water vapor

S = minutes of sunshine

S/D = minutes of sunshine for interval time (hour or day)

T = G.M.T. (Greenwhicn Mean Time); in Chapter 1 and Appendixes absolute temperature

T_{DBK} = dry-bulb temperature

T_{DP} = dew-point

V = sensitivity factor (associated with the visibility curve)

W = energy emission (electromagnetic waves) in Chapter 1; otherwise, west

W_p = light flux (photometric units)

W_r = radiative flux (radiometric units)

Z = elevation Z

a = albedo

c = $1 - S/D$ is the extensive factor of the cloud presence; in Appendix A1, velocity of the electromagnetic radiation

e = Earth orbit parameter

g = acceleration of gravity

h = altitude of the Sun; in Appendix A1, Planck's constant

h_r = relative humidity

m = mass

ρ = "local" factor of the K_T expression; in eq. 2.1, Earth orbit parameter and in eqs. 4.27, 4.28, and 4.29, transparency coefficient of the atmosphere; in Appendix A3, partial pressure

ρ_1 = intensive factor of depletion due to permanent components of the atmosphere

ρ_2 = intensive factor of depletion due to precipitable water

ρ_3 = intensive factor of depletion due to precipitable water

ρ_4 = intensive factor of depletion due to "local" factors

r = number of rainy days in a month

s = generic beam direction abscissa

t = solar time

t_f = sunset time (solar time)

t_i = sunrise time (solar time)

w = amount of precipitable water; in Appendix A1, radiative flux

w_∞ = total water vapor content in the atmosphere in the vertical direction

x = generic abscissa

z = zenith (vertical) axis abscissa

z_o = elevation z_o

Greek

α = angle of the "position triangle"; in Appendix A1, absorptivity

β = angle of the "position triangle" (azimuth computation)

γ = angle of the "position triangle" (hourly angle)

γ' = hourly angle value at sunrise (or sunset)

δ = declination

δ_o = daily averaged declination

ϵ = emissivity coefficient

ζ = angle between the Earth axis and the normal to the plane of the ecliptic; in Chapter 2 (Subsection 2.5) inclination angle of an inclined surface

η = total cloud cover

η' = total opaque cloud cover

θ = zenith angle

λ = wavelength; in astronomical computations, longitude

ξ = anomaly of the Earth in its orbit

π = 3.1415927

ρ = density; in Chapters 1 and 2, daily average value of the Sun-Earth distance; in Appendix A1, reflectivity coefficient

$\bar{\rho}$ = average between aphelion and perihelion of Sun-Earth distance

σ = Stefan-Boltzmann's constant

τ = transmission coefficient

ϕ = latitude

Φ = function symbol

ψ = azimuth

ψ' = orientation angle of an inclined surface ("azimuth" of the normal)

ω = solid angle

Superscripts

$^{\circ}$ = degrees

$'$ = minutes

Subscripts

D = dry air

E = Earth

i = incident; in Appendixes, i-th gas

l = local

m = meridian

M = moist air

max = maximum

S = Sun

W = water vapor

Z = elevation Z

0 = zero

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