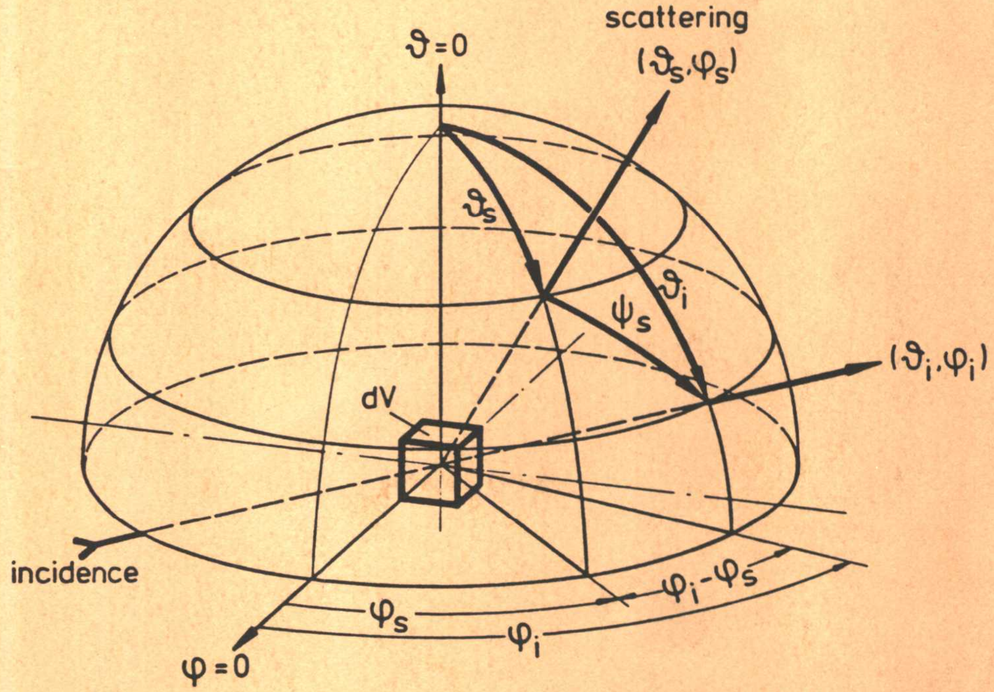
International Association of Meteorology and Atmospheric Physics (IAMAP)

Radiation Commission

TERMINOLOGY AND UNITS OF RADIATION QUANTITIES AND MEASUREMENTS



Boulder, Colorado, USA April 1978

INTERNATIONAL ASSOCIATION OF METEOROLOGY

AND ATMOSPHERIC PHYSICS (IAMAP)

RADIATION COMMISSION

TERMINOLOGY AND UNITS

OF

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April 1978

(Final corrections by Editor made August 1978)

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Printed at NCAR, which is operated by the private non-profit University Corporation for Atmospheric Research under sponsorship of the National Science Foundation.

PREFACE

The increased availability of means for the interchange of ideas among members of the scientific community has made visible a fundamental need for a common scientific language to be used by scientists and their colleagues. Nowhere is that need more apparent than in discussions of radiative transfer and in descriptions of the radiation field and its quantities.

Over a period of years different scientists have come to use different terms and symbols for the same quantities defining various parameters of the radiation field. A major reason for this disparity in nomenclature is that scientists often approach the subject matter of radiative transfer from different backgrounds and traditions. Although the basic physics of radiative theory is the same, the area of application (i.e., meteorology, astronomy, spectroscopy, etc.) may be, at least superficially, different. Tradition often plays an important role in the way we do things. It should not, however, act as a deterrent to adequate communication among colleagues.

In response to the recognized need for a universally agreed upon rational, precisely defined and internally consistent set of units, the Eleventh General Conference of Weights and Measures in 1960 defined and officially sanctioned the International System of Units (SI). This action was supported by the International Union of Geodesy and Geophysics which passed the following resolution at its General Assembly in Grenoble, France (August, 1975):

"*Noting* the generally increasing use of the Système International des Unités (SI) by scientists of all disciplines and

noting that many Unions of ICSU have recommended that adoption of SI units for their purposes, *recommends* that SI units be used in geodesy and geophysics

and

instructs the officers of the Union, its Associations and other bodies to encourage the use of SI units in all publications of the Union."

The Radiation Commission (IAMAP) had already in 1972 formed an ad hoc Working Group on Units and Nomenclature with Dr. John Howard as Chairman. The Working Group was continued and chaired by Professor Raschke after 1975. The present report represents the recommendations of that ad hoc Working Group for a system of units, nomenclature and symbols to be used to describe radiation quantities. It is proposed that these recommendations be considered for adoption by scientists dealing with problems of radiative transfer theory and measurements. The Radiation Commission is grateful to the members of the Working Group and others named in the report for their conscientious and productive efforts in preparing this report.

Julius London
President

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TERMINOLOGY AND UNITS

OF

RADIATION QUANTITIES AND MEASUREMENTS*

Abstract

The fundamental terms describing the transfer of radiative energy, relevant material characteristics and derived directional quantities have been summarized in this report. They are primarily based on the terminology of the "International System of Units" and the recommendation of the "International Commission on Illumination (CIE)," and generally accepted usage in radiative transfer problems.

1. Introduction

The fields of research on the transfer of radiative energy in the atmosphere and on its measurement have expanded rapidly during the last few decades. These activities are well documented in the scientific literature. They provide an important contribution to a better understanding of the energetics of circulation patterns in planetary atmospheres, as well as to methods of remote sensing of atmospheric and ground surface properties. Unfortunately, a wide variety of units, terms, and symbols are still in use--a fact which increases the difficulty of communication among scientists working in the different fields.

In response to discussions on these problems, the *"Radiation Commission of the International Association for Meteorology and*

*This report was prepared by an ad-hoc group on "Units and Terminology" of the Radiation Commission of IAMAP. The members of this ad-hoc group and other contributors to this document are listed in Section 9.

Atmospheric Physics (IAMAP)" formed an ad-hoc Working Group on *"Units and Terminology"* at its meeting at Sendai, Japan, in June 1972. After a considerable amount of discussion and correspondence on the problem, the ad-hoc Working Group prepared the present report. Its purpose is to recommend, on the basis of the International System of Units (SI: *Système International)*, a uniform and coherent set of terms and symbols for the physical quantities required to describe the transfer of radiative energy in radiative systems. The adoption of these recommendations may require certain modifications of the terminology and nomenclature which was previously adopted by the *World Meteorological Organization* (WMO, 1971) for routine meteorological observations. Any modification of the previous terminology would, of course, have to be worked out in cooperation with the WMO Commission on Instruments and Methods of Observations (CIMO).

Since the CIE terminology was developed after long consideration by international organizations (CIE, 1970), it has been taken as the basic framework for the present recommendations. Considerable difficulties arise, however, in selecting symbols for quantities which have often been defined in the scientific literature in terms of a variety of dimensions. In such cases, alternate symbols have been proposed, even though such symbols deviate from those of the CIE nomenclature.

In this report are considered only the basic quantities describing the fields of unpolarized radiation. An extension to polarized radiation and other features of the radiative field is anticipated for a future addendum.

2. The "International System of Units" and General Definitions

In its 11th meeting in 1960, the General Conference of Weights and Measures (CGPM) adopted the name *"International System of Units"* with the international abbreviation SI (Système International) for a practical system of measurements, and laid down rules for the prefixes, as well as the derived and supplementary units. The system has been described in detail, for instance, by Page and Vigoreux (1974). In a later recommendation of the *"International Committee of Weights and Measurements"* (CIPM) the expressions *"SI units," "SI prefixes,"* and *"SI supplementary units"* have been adopted within this SI system.

These SI units formed the basis for international agreements upon many basic physical quantities by the International Union of Pure and Applied Physics (IUPAP, 1965). The radiometric and photometric quantities are described and defined in very specific detail in the multilingual vocabulary of the International Commission on Illumination (CIE, 1970). There have also been agreements on the use of the SI by many other international and national organizations and many scientific journals adhere very strictly to the use of SI terminology and units. The SI units are divided into three classes:

base units

derived units

supplementary units

The *SI-base units* are the basis of the SI. They are regarded by convention as being dimensionally independent of each other (symbols are given in brackets behind each name):

the meter (m), the kilogram (kg), the second (s),

the ampere (A), the kelvin (K), the mole (mol),

and the candela (cd).

SI-derived units are expressed algebraically in terms of base units by means of the mathematical symbols of multiplication and division, where a dot (·) may be used for multiplication, a solidus (/) or a horizontal line or negative power for division. The solidus must not be repeated on the same line, while the dot may be deleted, leaving some distance between the symbols (e.g., m s, instead of ms = millisecond). All units used in radiative transfer work belong to this class. They may be expressed either in terms of base units (e.g., radiant flux: 1 W $= 1\ m^2 \cdot kg \cdot s^{-3}$) or in terms of other derived units (radiant flux: W = J/s).

SI-supplementary units are the *radian* (rad), and *steradian* (sr) describing the plane and solid angle, respectively. These units have not yet been classified under either base or derived units. The SI-derived units can also be formed from these supplementary units (e.g., radiance: $W\ m^{-2} sr^{-1}$).

Radiometric and photometric quantities are represented by the same symbols, but an appropriate subscript (e for energetic, and v for visible) should be used if there is a possibility of misinterpretation.

If a quantity is used for monochromatic radiation, its name can be preceded by the word "spectral," or the symbols for wavelength (λ), frequency (ν), or wavenumber (κ) may be added as an argument for the same symbol.

Unfortunately, in most textbooks on the radiative transfer theory the symbol ν, which has been strictly reserved for the *frequency*, is used for the wavenumbers. However, in view of the frequent use of the latin letter k for wavenumber and the desire to use greek symbols, the κ has been chosen for *wavenumber*. The symbol for spectral density of a quantity requires the symbol λ, ν or κ as a subscript. For instance, the spectral irradiance is defined by

$$E(\lambda) = \int_{\lambda - \frac{\Delta\lambda}{2}}^{\lambda + \frac{\Delta\lambda}{2}} E_\lambda(\lambda)\, d\lambda \quad , \qquad (1)$$

where the unit of the spectral density, $E_\lambda(\lambda)$, of the irradiance is $W\ m^{-2}\mu m^{-1}$, when $d\lambda$ is given in μm.

The solid angle element $d\Omega$ is defined in Fig. 1 (page 5). Integrating it over a hemisphere above an element of area dA, the solid angle of the hemisphere (2π) is given by the relation

$$\int_{2\pi} d\Omega = \int_{\varphi=0}^{2\pi} \int_{\vartheta=0}^{\pi/2} \Omega_o \sin\vartheta\, d\vartheta\, d\varphi = 2\pi\ \Omega_o = 2\pi\ sr \ , \qquad (2)$$

where $\Omega_o = 1$ sr is the unit solid angle. ϑ and φ are the polar and azimuthal angle, respectively.

3. Radiometric Quantities

The radiometric quantities, listed in Table 1 (see page 5), are derived units in the International System (SI). They form a set of

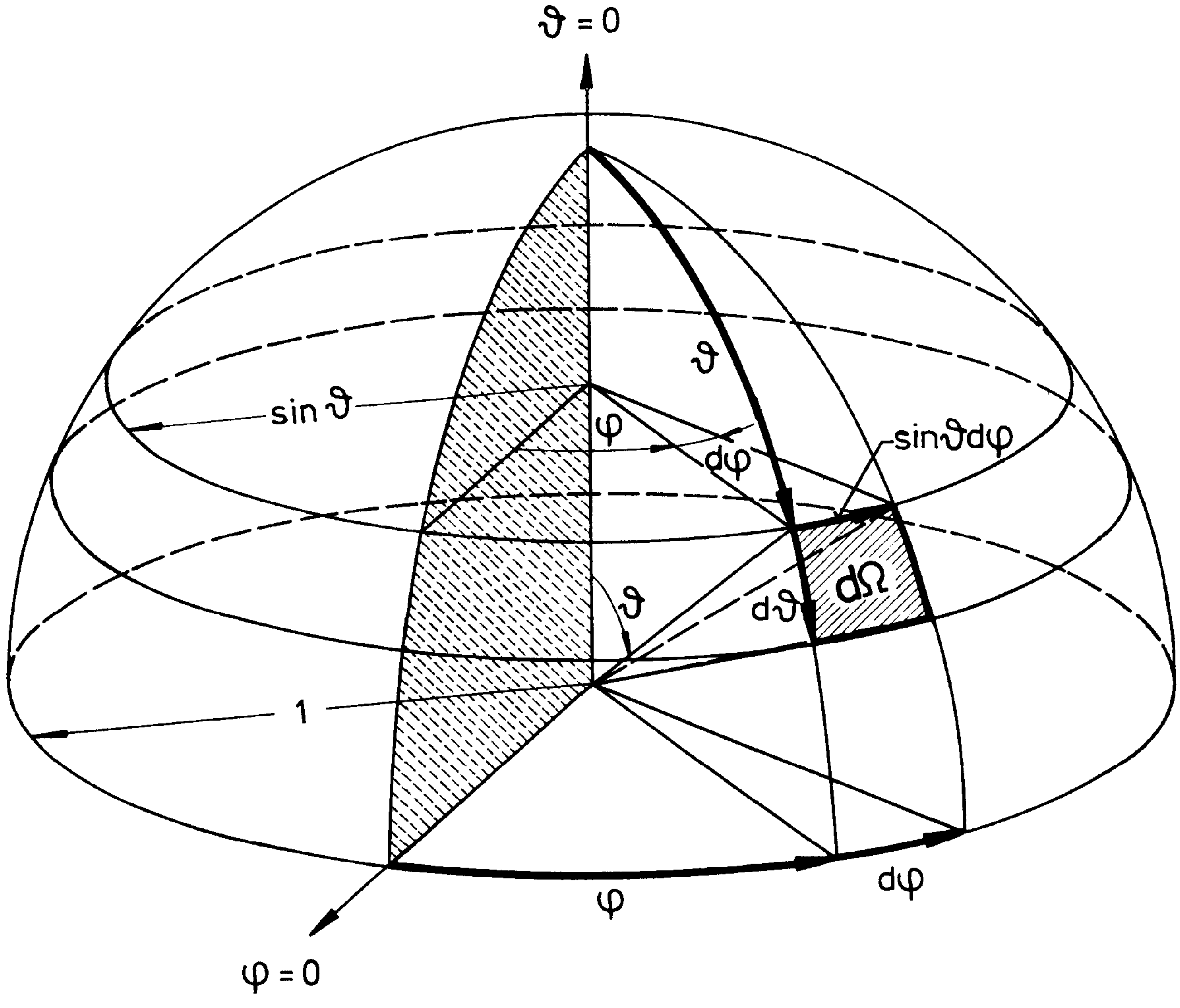

Fig. 1: Definition of the solid angle element dΩ.

Table 1: Radiometric quantities (described in Section 3). Symbols in brackets are proposed for alternative use.

NAMES	SYMBOL	UNIT	RELATION	REMARKS	CIE-no.
radiant energy	Q, (W)	J = W s			45-05-130
radiant flux	Φ, (P)	W	$\Phi = \frac{dQ}{dt}$	power	45-05-135
radiant flux density	(M), (E)	$W\ m^{-2}$	$\frac{d\Phi}{dA} = \frac{d^2Q}{dA\ dt}$	Radiant flux of any origin crossing an area element	45-05-155
radiant exitance*	M	$W\ m^{-2}$	$M = \frac{d\Phi}{dA}$	Radiant flux of any origin emerging from an area element	45-05-170
irradiance	E	$W\ m^{-2}$	$E = \frac{d\Phi}{dA}$	Radiant flux of any origin incident onto an area element	45-05-160
radiance	L	$W\ m^{-2} sr^{-1}$	$L = \frac{d^2\Phi}{d\Omega\ dA \cos\vartheta}$	The radiance is a conservative quantity in an optical system	45-05-150
radiant exposure	H	$J\ m^{-2}$ (per exposure time)	$H = \frac{dQ}{dA} = \int_{t_1}^{t_2} E\ dt$ t_1, t_2: time	May be used for daily sums of global radiation, etc.	45-05-165
radiant intensity	I	$W\ sr^{-1}$	$I = \frac{d\Phi}{d\Omega}$	May be used only for radiation outgoing from "point sources"	45-05-145

*The name radiant exitance has been proposed in CIE (1970) to avoid confusion with the name emittance which has previously been used for this quantity (see also page).

quantities describing the amount of radiative energy available in radiation fields. Here, the capital letter Φ (phi) is recommended for the *flux*, since it is a common symbol for all fluxes in physics and illumination engineering. The CIE (1970) also lists the capital letter P (power) as a proper symbol, and in the meteorological and astrophysical literature the symbol F has been used quite commonly for flux. The continued use of the latter, however, is not encouraged.

In Table 1 a somewhat new and uncommon expression, the *exitance* (symbol M), is also listed. This term has been proposed by the CIE for the description of the *radiant flux density* emerging from a surface, either by reflection, transmission from underneath, thermal emission, or by the simultaneous action of all these three processes (CIE, 1970). An analogous term, *irradiance* (symbol E), describes the radiant flux density of all possible origins incident onto an area element. To avoid confusion with the material characteristics defined below, the CIE abandoned the previous name *emittance* for the description of the radiation which is due to thermal emission only. For the time interval ($\Delta t = t_2 - t_1$) of the exposure, a proper indication should be given behind the unit, e.g., Jm^{-2} (per day). The symbols + (or ↑) and − (or ↓) could be added as a superscript to each radiative quantity to indicate the direction of flow into the upward (+, ↑) or downward (−, ↓) hemisphere, respectively.

It is important to note that there are differences in nomenclature between terms proposed here and terms used in standard reference textbooks (e.g., Chandrasekhar, 1960) or glossaries (e.g., Hopkins, 1976).

4. Material Characteristics

The material characteristics describe the behavior of materials with respect to the radiation field in their environment. Their definitions are listed in Table 2. These quantities are dimensionless (dimension = 1); for their description only greek symbols (ε, α, ρ, τ) have been recommended.

It might be appropriate to point out that the CIE terminology is not consistent in the use of the suffix "...ivity." There, the term *emissivity* is used for the description of the emission properties of a

Table 2: Material characteristics. For the use of the name emittance and the symbol τ, see text on pages 9 and 10.

CHARACTERISTICS	SYMBOL	DEFINITION	REMARKS
emittance	ε	$\varepsilon = \frac{M_{\varepsilon}}{M_{\varepsilon=1}}$	$\varepsilon = 1$ for a black body
absorptance	α	$\alpha = \frac{\Phi_a}{\Phi_i}$	Φ_a and Φ_i are the absorbed and incident radiant flux, respectively
reflectance	ρ	$\rho = \frac{\Phi_r}{\Phi_i}$	Φ_r and Φ_i are the reflected and incident radiant flux, respectively
transmittance	τ	$\tau = \frac{\Phi_t}{\Phi_i}$	Φ_i is the incident flux and Φ_t is the radiant flux transmitted through a layer or a surface

surface for thermal radiation with respect to that of a black body at the same temperature. All other material characteristics end with the suffix "...ance." Therefore, to keep the nomenclature consistent for all material characteristics, the Radiation Commission proposes to use the name *emittance* instead of emissivity.

The material characteristics α, ρ, τ are dependent on the angle of incidence. They are simply the ratios of absorbed, reflected, and transmitted fluxes respectively, to the incident flux. The CIE (1970) also defines their roots with the suffix "-ivity" as described below (from CIE, 1970; CIE-numbers are given after the explanations):

absorptivity: "Internal absorptance of a layer of material such that the path of the radiation is of unit length and under conditions in which the boundary of the material has no influence." (CIE no: 45-20-125)

reflectivity: "Reflectance of a layer of material of such a thickness that there is no change of reflectance with increase in thickness." (CIE no: 45-20-050)

transmissivity: "Internal transmittance of a layer of material such that the path of the radiation is of unit length and under conditions in which the boundary of the material has no influence." (CIE no: 45-20-95)

These terms with the suffix ...ivity are inconsistent with respect to their dimensions. While the reflectivity is dimensionless, the absorptivity and transmissivity are referred to unit path length. The definition given in Table 2 provides for a consistent set of material characteristics involving the radiation field.

It is very common in meteorological and astronomical literature to use the term *albedo* for the reflectance of a surface. Over most natural surfaces, some radiation emerges from layers underneath of the respective surfaces into atmospheric layers above them. In these cases the measured or calculated albedo of these surfaces should be considered as the reflectance of the entire system.

The *extinction coefficient* σ_e of an absorbing and scattering medium for a collimated beam of radiation with the radiance L during traversal at normal incidence of an infinitesimal layer ds of that medium is defined according to the law of Bouguer-Lambert:

$$\sigma_e = -\frac{1}{L}\frac{dL}{ds}, \quad \text{unit: } m^{-1} \quad . \tag{3}$$

Instead of σ_e, the symbols σ_a and σ_s should be used in cases of pure absorption or scattering, respectively. These symbols have not been used in the CIE-report (1970); instead the symbol μ is proposed there. It is possible that here the use of the symbol σ may cause some confusion, since σ is generally used for the Stefan-Boltzmann constant. However, since μ is a very common symbol for the cosine of the zenith angle ϑ in radiative transfer studies, and σ is already in widespread use for these coefficients, the Radiation Commission here adopts the symbol σ.

The ratio

$$\tilde{\omega} \equiv \frac{\sigma_s}{\sigma_e} = \frac{\sigma_e - \sigma_a}{\sigma_e} = 1 - \tilde{\alpha} \tag{4}$$

is called *single scattering albedo* and $\tilde{\alpha}$ is the *absorption number*. To avoid confusion with the symbol ω or ω_o for angular frequency, $\tilde{\omega}$ should be used exclusively for single scattering albedo.

For the *transmittance* (see Table 2), the Radiation Commission proposes the symbol τ, which is also used in CIE (1970). This conflicts with the very common use of the symbol τ for the *optical depth.* Since the transmittance and optical depth are linked in the same expression, it is necessary that these terms be distinguished by different symbols. The Radiation Commission therefore recommends that the lower case delta (δ) be used as the symbol for the optical depth. Thus the transmittance is given by

$$\tau = e^{-\delta} , \tag{5}$$

where $\delta(s) = \int_o^s \sigma_e(s')ds'$.

5. Derived Directional Quantities

Several directional properties of material characteristics need to be considered. An attempt to define reflection and transmission terminology, in analogy to scattering terminology, has been undertaken by Kasten and Raschke (1974). Based on the definition of all angular quantities describing the single scattering of radiation in a volume element dV, as shown in Fig. 2, these authors developed an analogous set of expressions to describe reflection at a surface and transmission through a surface or layer. This terminology is arranged in Table 3 (see pages 12 and 13) according to the geometry (directional, or spherical and hemispherical, respectively) of incident and outgoing radiation.

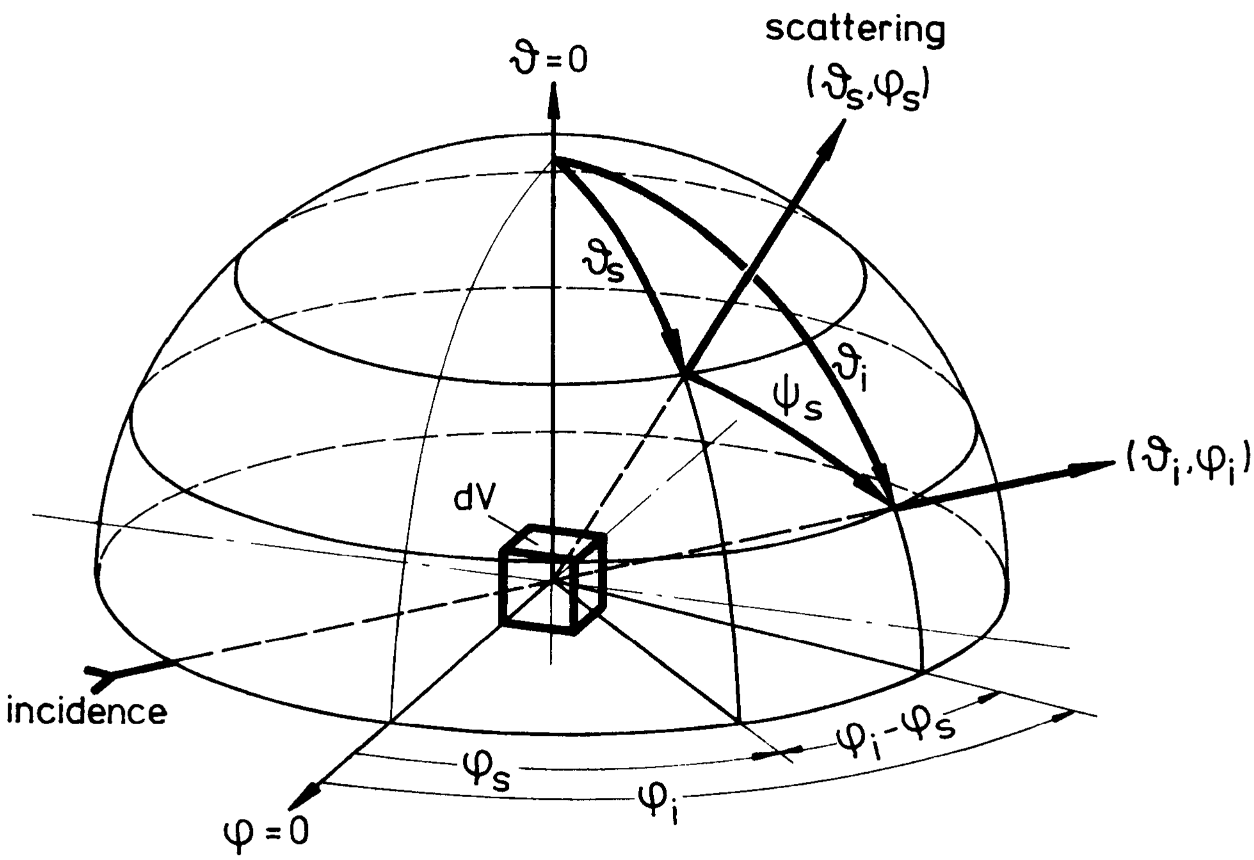

Fig. 2: Definition of the scattering angle ψ_s

$$\cos\psi_s = \cos\vartheta_i \cos\vartheta_s + \sin\vartheta_i \sin\vartheta_s \cos(\varphi_i - \varphi_s).$$

Table 3: Definition of derived directional quantities. $\Omega = (\vartheta,\varphi)$ specifies the directions of incidence (i), scattering (s), reflection (r), or transmission (t); see Fig. 2.

S C A T T E R I N G in a volume element dV $[m^2]$	R E F L E C T I O N at an area element dA in m^2	T R A N S M I S S I O N through an area element dA $[m^2]$
For directional incoming and outgoing radiation		
scattering function $\gamma_s(\Omega_i,\Omega_s) \equiv \frac{d^3\Phi_s(\Omega_i,\Omega_s)}{dV\cdot d\Omega_s\cdot dE_i(\Omega_i)}$ $[m^{-1}sr^{-1}]$	reflection function $\gamma_r(\Omega_i,\Omega_r) \equiv \frac{d^3\Phi_r(\Omega_i,\Omega_r)}{\cos\vartheta_r\cdot d\Omega_r\cdot d^2x}$ $[sr^{-1}]$ where $d^2x = \cos\vartheta_i dE_i(\Omega_i)dA$	transmission function $\gamma_t(\Omega_i,\Omega_t) \equiv \frac{d^3\Phi_t(\Omega_i,\Omega_t)}{\cos\vartheta_t\cdot d\Omega_t\cdot d^2x}$ $[sr^{-1}]$
scattering indicatrix (or scattering phase functions $p(\psi_s)$) $\xi_s(\psi_s) \equiv \xi_s(\Omega_i,\Omega_s) \equiv \frac{4\pi\Omega_o}{\sigma_s}\cdot\gamma_s(\Omega_i,\Omega_s)$	reflection indicatrix $\xi_r(\Omega_i,\Omega_r) \equiv \frac{\pi\Omega_o}{\rho(\Omega_i)}\cdot\gamma_r(\Omega_i,\Omega_r)$	transmission indicatrix $\xi_t(\Omega_i,\Omega_t) \equiv \frac{\pi\Omega_o}{\tau(\Omega_i)}\cdot\gamma_t(\Omega_i,\Omega_t)$
For directional incoming, but multidirectional outgoing radiation		
scattered into a sphere	reflected or transmitted into a hemisphere	
scattering coefficient $\sigma_s = \int_{4\pi\cdot\Omega_o}\gamma_s(\Omega_i,\Omega_s)\,d\Omega_s$ $[m^{-1}]$	hemispherical reflectance for directional incidence $\rho(\Omega_i) = \int_{2\pi\cdot\Omega_o}\gamma_r(\Omega_i,\Omega_r)\cos\vartheta_r d\Omega_r$	hemispherical transmittance for directional incidence $\tau(\Omega_i) = \int_{2\pi\cdot\Omega_o}\gamma_t(\Omega_i,\Omega_t)\cos\vartheta_t d\Omega_t$