

Terminology and Units in Optical Oceanography

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Abstract This document presents fundamental terms describing the transfer of radiative energy and relevant optical properties of natural waters. These are primarily based upon the terminology of the "Système International d'Unités (SI)" and the "International Commission on Illumination (CIE)." Quantities and Symbols as proposed in the present terminology follow and extend the terminology that was recommended by the Committee on Radiant Energy in the Sea (of the International Association of Physical Oceanography, IAPO), as published by Jerlov (1968, *Optical Oceanography*, Elsevier Oceanography Series, Vol. 5; 1976, *Marine Optics*, Elsevier Oceanography Series, Vol. 14).

Introduction

This document presents fundamental terms describing the transfer of radiative energy in natural (sea and lake) waters and relevant optical properties of this medium. The table is divided into four parts:

Marine Geodesy, Volume 5, Number 4

0149-0419/82/010335-00\$02.00/0

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(1) fundamental quantities; (2) radiant energy in natural waters; (3) material characteristics; and (4) inherent optical properties of natural water.

The first aim of this document is to recommend a standard terminology for underwater optics that fully respects the rules of the "Système International d'Unités." Consequently, Quantities, Symbols, and Units in Part 1 are transcribed from the table ISO 31/VI (International Organization for Standardization, 1973) dealing with light and related electromagnetic radiations. Quantities in Part 3 are based partly on the same ISO Table and also on the more detailed nomenclature developed by the Commission Internationale de l'Eclairage (1957).

Parts 2 and 4 deal more specifically with quantities and parameters belonging to optical oceanography. Basically, this vocabulary derives from and complements a previous terminology recommended by the Committee on Radiant Energy in the Sea, set up by IAPO (International Association of Physical Oceanography) and published by its chairman, N. G. Jerlov, in 1964 (and thereafter in 1968 and 1976, as introductory material in his books, *Optical Oceanography* and *Marine Optics*). This IAPO standard terminology on underwater optics introduced some specific new definitions following the recommendations contained in a preliminary work prepared by Preisendorfer (1960) which have proved very useful. The symbols a , b , and c , respectively for absorption, scattering, and attenuation coefficients, and β for the volume-scattering coefficient, were adopted at that time. Also the word "attenuation" was definitively preferred to the word "extinction" to describe simultaneous scattering and absorption.

During the last 15 years the rapid expansion of theoretical and experimental research in the marine optics field has evidenced the need for a more complete set of terms and symbols in order to limit anarchic uses—or misuses—and difficulties of communication. An attempt to fulfill this need is the task of Parts 2 and 4, in which appear new definitions with respect to the previous terminology. When extending the list, several basic principles have been taken into consideration:

1. A compromise between laxity and rigidity must be maintained. If a very detailed terminology is proposed, at the price of many superscripts or subscripts for the derived quantities, the obvious risk is to see such recommendations never followed and to finally become useless. Our choice was to limit the list of new symbols to those now widely

used quantities, not considered in 1964, and for which a relative consensus already seems to exist.

2. The revised terminology must not change or contradict the previous one. The IAPO standard terminology has been adopted slowly by marine opticians. Marine biologists, who have their own tradition about light measurements and symbols and often follow the vocabulary in use in limnology (International Biological Program, 1971), have become interested in, or at least have the knowledge of, the IAPO terminology. A change now, when the use of this terminology is more generally accepted, would certainly be ill advised.

3. A logical approach to the matter must be kept. For that, the distinction between "apparent" and "inherent" optical properties, as introduced by Preisendorfer (1960, 1961, 1976) has been adopted. The "hybrid" properties, however, have not been defined according to the limitation explained above (1).

4. Discrepancies between the proposed terminology and others existing in pure and applied radiometry have to be admitted. Not only traditions, but also interdictions, exist in the different fields, which go against a desirable unification in terminology and notation. A good example of such difficulties is provided by the use of the Greek letter σ . In many classical works in scattering theory (see e.g., Van de Hulst, 1957), σ denotes exclusively the scattering coefficient. In atmospheric optics (IAMAP- Radiation Commission of the International Association of Meteorology and Atmospheric Physics, 1978), the same letter, with the appropriate subscripts, designates three coefficients, the absorption, scattering, and extinction coefficients, σ_a , σ_s , and σ_e (a , b , and c in marine optics). * In physical oceanography, σ , for more than 80 years, has designated a fundamental quantity, the density excess (Knudsen's parameter). It is thus a "prohibited" symbol in optical oceanography, especially when considering that optical properties are often discussed in conjunction with the density stratification within the ocean. Interdisciplinary glossaries can solve the problem of mutual understanding when differences subsist in spite of trials to unify terminologies.

5. To build a complete system of simple, coherent, and mnemoni-

*Besides the three symbols a , b , and c mentioned, the main discrepancy between marine and atmospheric optics is in the choice of the symbol (β and γ , respectively) for the volume-scattering function.

cally suggestive notations is an ideal aim. It can be approached, at least, if the system is conceived *ex nihilo* and in absence of any kind of constraint. With a reduced number of degrees of freedom, the result cannot appear entirely satisfying, and the present table certainly will motivate further improvements, additions, and revisions.

Miscellaneous Additional Remarks

As in ISO Table, the statements in the definition column are given merely for identification; they are not intended to be complete and perfect definitions.

The quantities considered concern unpolarized radiation. The definitions dealing with the most general state of polarization and the corresponding symbols (as developed by Stokes, for instance) are not given or recalled here.

The convention has been adopted that if a quantity is used to describe monochromatic radiation, its name can be preceded by the adjective "spectral." This adjective is used to designate quantities that are functions of wavelength (or frequency) or are spectral concentration (dimension of a derivative with respect to wavelength). The functional dependence may be indicated by a subscript (λ , or ν) or preferably as an argument put in parentheses.

Only radiometric quantities are considered, and the luminous (photometric) quantities are not defined. These quantities refer to "light," i.e., to radiant energy evaluated with respect to its ability to stimulate sense of sight of a human observer (the "photometric standard observer for photopic vision"). They are consequently of little interest, if any, in marine optics, although they have been irrelevantly used in some photosynthesis studies (Tyler, 1973). For such studies, and more generally for in-water primary production studies, radiant energy must be evaluated in terms of radiometric quantities and is adequately measured and expressed in terms of quanta within a given spectral range (UNESCO, 1966).

Table 1

<u>Quantity</u> *	<u>Symbol</u>	<u>Definition and Remarks</u>	<u>SI unit</u>
<u>1. Fundamental Quantities</u>			
Wavelength (F. longueur d'onde)	λ	Distance between two successive points of a periodic wave in the direction of propagation, for which the oscillation has the same phase. <u>Note</u> : The wavelength of monochromatic radiant energy depends on the refractive index of the medium. Unless otherwise stated, values of wavelength are those <u>in vacuo</u> . Recommended units : nm (10^{-9} m) and μm (10^{-6} m)	m
Wave number (F. nombre d'ondes)	σ	$\sigma = 1 / \lambda$	m^{-1}
Circular wave number (F. Nombre d'ondes circulaires)	k, κ	$k = 2\pi / \lambda$	m^{-1}
Frequency	ν	Number of cycles divided by time. (1 Hz = 1 s^{-1})	Hz
Refractive index (F. indice de réfraction)	n	The ratio of the velocity of electromagnetic radiation <u>in vacuo</u> , to the phase velocity of electromagnetic radiation of a specified frequency in a medium.	1

*In this column, "F" means "in French"

Photon	A photon is a quantum of electromagnetic radiation that has an energy equal to the product of the frequency of the radiation by the Plank's constant h (Quantum is entity of energy postulated in quantum theory).	J
	With : $h = (6.626\ 176 \pm 0.000\ 036) \times 10^{-34} \text{ J.Hz}^{-1}$	
Quantity of radiant energy (F. Quantité d'énergie rayonnante)	W, Q Energy emitted, transferred, or received as radiation	J
Radiant flux (F. flux énergétique).	Φ, F The time rate of flow of radiant energy. Relation : $\Phi = dW / dt$ <u>Note</u> : The symbol Φ , rather than F recommended by IAP0 has been adopted by the International Organization for Standardization (ISO) and by the International Association of Meteorology and Atmospheric Physics (IAMAP).	W
Radiant intensity (of a source in a given direction) (F. intensité énergétique).	I The radiant flux emitted by a point source, or by an element of an extended source, in an infinitesimal cone containing the given direction, divided by that element of solid angle. Relation : $I = d\Phi / d\omega$ <u>Note</u> : For a source that is not a point source, the quotient of the radiant flux received at an elementary surface and the solid angle that this surface subtends at any point of the source, when this quotient is taken to the limit as the distance between the surface and the source is increased.	W.sr^{-1}

Radiance (F. luminance énergétique)	L	Radiant flux in a given direction per unit solid angle per unit projected area. Relation : $L(\theta, \phi) = d^2\Phi / dA \cos\theta d\omega$	$W.m^{-2}.sr^{-1}$
Irradiance (at a point of a surface) (F. éclaircissement)	E	The radiant flux incident on an infinitesimal element of a surface containing the point under consideration, divided by the area of that element. Relation : $E = d\Phi / dA$	$W.m^{-2}$
Radiant exitance (at a point of a surface) (F. ex itance)	M	The radiant flux emitted by an infinitesimal element of a surface containing the point under consideration, divided by the area of that element. Relation : $M = d\Phi / dA$	$W.m^{-2}$
Radiant exposure (irradiation at a point of a sur- face) (F. irradiation)	H	The product of an irradiance and its duration Relation : $H = d\omega / dA$ $= E.t$ for constant irradiance, E, and for variable irradiance, $E(t)$: $H = \int_{t_1}^{t_2} E(t) dt$ (t_2-t_1) is the duration.	$J.m^{-2}$

2. Radiant Energy in Natural Waters

Downward irradiance (F. éclaircissement descendant.)	E_d	The radiant flux on an infinitesimal element of the upper face (i.e., facing zenith) of a horizontal surface containing the point being considered, divided by the area of the element. Alternatively, downward irradiance is the integral of the radiance, weighted by the cosine of the zenith angle (θ), over the upper hemisphere. Relation : $E_d = d\Phi/dA$	$W.m^{-2}$
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$$= \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L(\theta, \phi) \cos\theta \sin\theta d\theta d\phi$$

where ϕ is the azimuthal angle.

Upward irradiance E_u
(F. éclaircissement
ascendant)

The radiant flux incident on an infinitesimal element of the lower face (i.e., facing nadir) of a horizontal surface containing the point being considered, divided by the area of the element. Alternatively, upward irradiance is the integral of the radiance, weighted by the cosine of the nadir angle, $(\pi - \theta)$, over the lower hemisphere.

W.m^{-2}

Relation : $E_u = d\Phi/dA$

$$= \int_{\phi=0}^{2\pi} \int_{\theta=\pi}^{\pi/2} L(\theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

Downward vector
irradiance, net
(downward) irra-
diance
(F. éclaircissement
vectoriel (ou net)
descendant)

\vec{E}

The net irradiance or the modulus of the vector is given as the difference between the downward and upward irradiance, with a horizontal plane as reference. Alternatively, the net irradiance is the integral of the radiance, over all directions, weighted by the cosine of the zenith angle (θ) .

W.m^{-2}

Relation : $\vec{E} = (E_d - E_u) \vec{z}$

where \vec{z} is the unit vector in the direction of the nadir

and $E_d - E_u = \int_{4\pi} L(\theta, \phi) \cos\theta \, d\omega$

$$= \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} L(\theta, \phi) \cos\theta \sin\theta \, d\theta \, d\phi$$

Scalar irradiance $\overset{\circ}{E}$, E_0
(F. éclaircissement
scalaire)

The integral of radiance distribution at a point over all directions about the point.

W.m^{-2}

Relation : $\overset{\circ}{E} = \int_{4\pi} L(\theta, \phi) \, d\omega$

$$= \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi} L(\theta, \phi) \sin\theta \, d\theta \, d\phi$$

<p>Downward and upward scalar irradiance (F. éclaircissement scalaire descendant et ascendant)</p>	$\overset{\circ}{E}_d, \overset{\circ}{E}_u$ or E_{od}, E_{ou}	<p>The integral of the radiance distribution at a point over the upper and the lower hemisphere, respectively.</p>	
		<p>Relations : $\overset{\circ}{E}_d = \int_{\phi=0}^{2\pi} \int_{\theta=0}^{\pi/2} L(\theta, \phi) \sin\theta \, d\theta \, d\phi$</p>	
		$\overset{\circ}{E}_u = \int_{\phi=0}^{2\pi} \int_{\theta=\pi/2}^{\pi} L(\theta, \phi) \sin\theta \, d\theta \, d\phi$	
		$\overset{\circ}{E} = \overset{\circ}{E}_d + \overset{\circ}{E}_u$	
<p>Spherical irradiance (F. éclaircissement sphérique)</p>	E_δ	<p>Limit of the ratio of radiant flux onto a spherical surface to the area of the surface, as the radius of the sphere tends toward zero with its center fixed.</p>	W.m^{-2}
		<p>Relations : $E_\delta = \Phi_\delta / 4\pi r^2$, Φ_δ being the radiant flux onto the sphere of radius r, and : $E_\delta = (1/4) \overset{\circ}{E}$</p>	
<p>Average cosines (F. cosinus moyens)</p>	$\bar{\mu}, \bar{\mu}_d, \bar{\mu}_u$	<p>The ratio of the net (downward) irradiance to scalar irradiance.</p>	<p>1</p>
		<p>Relation : $\bar{\mu} = \frac{\overset{\circ}{E}}{\overset{\circ}{E}} = \frac{E_d - E_u}{\overset{\circ}{E}}$</p>	
		<p><u>Note</u> : Average cosines for the upper and the lower hemisphere can be defined in a similar way:</p>	
		$\bar{\mu}_d = \frac{E_d}{\overset{\circ}{E}_d} ; \bar{\mu}_u = \frac{E_u}{\overset{\circ}{E}_u}$	
<p>Vertical attenuation coefficient of a radiometric (X) quantity (such as any of the radiances or irradiances defined above) (F. coefficient d'atténuation verticale)</p>	K	<p>Vertical gradient of the naperian logarithm of the quantity.</p>	m^{-1}
		<p>Relation : $K = - \frac{d\text{Ln}(X)}{dz} = - \frac{1}{X} \frac{dX}{dz}$ (z = depth)</p>	
		<p>The negative sign originates from the orientation toward nadir of the vertical (depth) axis.</p>	

<p>Irradiance ratio R (F. réflectance, rapport d'éclairement)</p> <p>Asymptotic radiance distribution. Asymptotic radiative regime. (F. distribution asymptotique des luminances. Régime asymptotique)</p>	<p>The ratio of the upward to the downward irradiance at a given depth in the sea. Relation : $R = E_u / E_d$</p> <p>The radiance distribution, which is the limit of the distribution in the hydrosphere, as the (geometrical or optical) depth increases infinitely and with the proviso that the water is optically homogeneous. This asymptotic distribution is symmetrical around the vertical axis, independent of the radiance distribution above the surface and exclusively dependent on the inherent optical properties. In the asymptotic radiative regime (which corresponds to the asymptotic radiance distribution)</p> <ul style="list-style-type: none"> • $\bar{\mu}, \bar{\mu}_d, \bar{\mu}_u$ and R become constant and depth-independent • The various K coefficients for the various radiometric quantities take the same and constant value, also depth-independent. <p>The subscripts ∞ or \lim are often associated with the above-mentioned symbols to indicate that these quantities are considered in their asymptotic values.</p>	<p>1</p>
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3. Material characteristics

3.1. General characteristics

<p>Emittance ϵ (F. émittance)</p>	<p>The ratio of the radiance exitance of a surface to that of a black body at the same temperature. Relation : $\epsilon = M / M_{\text{black body}}$</p>	<p>1</p>
<p>Absorbance A (F. absorbance)</p>	<p>The ratio of the radiant flux (Φ_a) lost from a beam by means of absorption, to the incident flux (Φ_0). Relation : $A = \Phi_a / \Phi_0$</p>	<p>1</p>
<p>Scatterance B</p>	<p>The ratio of the radiant flux (Φ_b) scattered from a beam, to the incident flux (Φ_0). Relation : $B = \Phi_b / \Phi_0$</p>	<p>1</p>

Forward scat- terance	B_f	The ratio of the radiant flux scattered through an- gles $0-90^\circ$ from a beam to the incident flux.	1
Backward scat- terance	B_b	The ratio of the radiant flux scattered through an- gles $90-180^\circ$ from a beam to the incident flux.	1
Attenuance (F. atténuation)	C	The ratio of the radiant flux lost from a beam of infinitesimal width by means of absorption and scat- tering to the incident flux. Relation : $C = A + B$	1
Reflectance (F. réflectance)	ρ	The ratio of the reflected radiant flux to the inci- dent radiant flux. <u>Note</u> : Irradiance ratio, R , is a particular case of reflectance ρ , defined under specified conditions (horizontal plane, see above).	1
Transmittance (F. transmittance)	T	The ratio of the transmitted (Φ_t) radiant flux to the incident radiant flux (in either irradiance or ra- diance form) Relation : $T = \Phi_t / \Phi_0$ <u>Note</u> : for a beam : $1 - C = T$ (beam transmittance)	1

3.2. Particle characteristics

Efficiency factor for absorption (F. (facteur d') efficacité d' absorption)	Q_a	The ratio of the radiant flux absorbed within a par- ticle to the radiant flux incident onto the geome- trical cross-section of this particle. (the geometrical cross-section of a particle is the projected area of this particle in the direction of propagation of the incident radiation).	1
Efficiency factor for scattering (F. (facteur d') efficacité de diffusion)	Q_b	The ratio of the radiant flux scattered from a par- ticle to the radiant flux incident onto the geome- trical cross-section of this particle.	1

Efficiency factor Q_c 1
 for attenuation
 (F. (facteur d')
 efficacité d'
 atténuation)

The ratio of the radiant flux absorbed within and scattered from a particle to the radiant flux incident onto the geometrical cross-section of this particle.

$$\text{Relation : } Q_c = Q_a + Q_b$$

Note : The cross-sections of the particle for absorption, scattering, and attenuation are the product of the geometrical cross-section, respectively, by Q_a , Q_b and Q_c .

4. Inherent Optical Properties of Natural Waters

4.1. Coefficients

Absorption coefficient a m^{-1}
 (F. coefficient
 d'absorption)

The absorptance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness (Δx) of the layer.

$$\text{Relation : } a = - \Delta A / \Delta x = - \frac{\Delta \Phi_a}{\Phi_0 \Delta x}$$

Note 1 : for homogeneous medium of finite thickness λ

$$a = - \frac{1}{\lambda} \ln (1 - A)$$

Note 2 : for passive medium (no internal source)

$$\text{div } \vec{E} = - a \vec{E}$$

and for practical applications (i.e., negligible horizontal gradients)

$$d\vec{E} / dz = - a \vec{E}$$

Volume-scattering function $\beta(\theta)$ $m^{-1}sr^{-1}$
 (F. coefficient
 angulaire de
 diffusion)

The radiant intensity, from a volume element in a given direction, per unit of irradiance on the cross-section of the volume and per unit volume (V).

$$\text{Relation : } \beta(\theta) = dI(\theta) / E dV$$

Convention: $\theta = 0$ for the direction of propagation of the incident beam (plane waves).

<p>Total scattering coefficient (F. coefficient total de diffusion)</p>	<p>b</p>	<p>The scatterance of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness (Δx) of the layer.</p>	<p>m^{-1}</p>
		<p>Relation : $b = \Delta B / \Delta x = - \frac{\Delta \Phi_b}{\Phi_0} / \Delta x$</p>	
		<p><u>Note 1</u> : an alternative definition is : the total scattering coefficient is the integral over all directions of the volume-scattering function.</p>	
		<p>Relation : $b = \int_{4\pi} \beta(\theta) d\omega$</p>	
		<p>and for scattering with rotational symmetry</p>	
		<p>$b = 2\pi \int_0^\pi \beta(\theta) \sin\theta d\theta$</p>	
		<p><u>Note 2</u> : for homogeneous medium of finite thickness λ</p>	
		<p>$b = - \frac{1}{\lambda} \ln (1 - B)$</p>	
<p>Forward scattering coefficient (F. coefficient de diffusion pour l'avant)</p>	<p>b_f</p>	<p>The coefficient that relates to forward scatterance</p>	<p>m^{-1}</p>
		<p>Relation : $b_f = 2\pi \int_0^{\pi/2} \beta(\theta) \sin\theta d\theta$</p>	
<p>Backward scattering coefficient (F. coefficient de rétrodiffusion)</p>	<p>b_b</p>	<p>The coefficient that relates to backward scatterance</p>	<p>m^{-1}</p>
		<p>Relation : $b_b = 2\pi \int_{\pi/2}^\pi \beta(\theta) \sin\theta d\theta$</p>	
<p>(Total) attenuation coefficient (F. coefficient (total) d'atténuation)</p>	<p>c</p>	<p>The attenuation of an infinitesimally thin layer of the medium normal to the beam, divided by the thickness (Δx) of the layer.</p>	<p>m^{-1}</p>
		<p>Relation : $c = - \Delta C / \Delta x = - \frac{\Delta \Phi_c}{\Phi_0} / \Delta x$</p>	
		<p>and $c = a + b$</p>	
		<p>for homogeneous layer of finite thickness λ :</p>	
		<p>$c = - 1/\lambda \ln(1 - C)$</p>	

4.2. Dimensionless parameters

<p>Probability of photon survival</p>	<p>$\bar{\omega}, \tilde{\omega}$</p>	<p>The ratio of the scattering coefficient to the attenuation coefficient.</p>	<p>1</p>
		<p>Relation : $\tilde{\omega} = b / c$</p>	
		<p><u>Note</u> : this quantity is also called "single scattering albedo"</p>	

Absorption number	\bar{a}, \tilde{a}	<p>The ratio of the absorption coefficient to the attenuation coefficient. 1</p> <p>Relation : $\bar{a} = a/c$ $\bar{a} = 1 - \bar{\omega}$</p> <p><u>Note</u> : this quantity is the probability of photon disappearance.</p>
Normalized volume-scattering function	$\bar{\beta}(\theta), \tilde{\beta}(\theta)$	<p>The dimensionless function obtained by dividing the volume-scattering function by the total scattering coefficient (its integral over all solid angle is 1) sr⁻¹</p> <p>Relation : $\bar{\beta}(\theta) = \frac{1}{b} \beta(\theta)$</p> <p>and $\int_{4\pi} \bar{\beta}(\theta) d\omega \equiv 1$</p> <p><u>Note</u> : the phase function, $P(\theta)$, is related to $\bar{\beta}(\theta)$ by : $P(\theta) = 4\pi \bar{\beta}(\theta)$ and $\int_{4\pi} P(\theta) d\omega \equiv 4\pi$ Its integral overall directions is 4π.</p>
Forward and backward scattering ratio	$\overline{b_f}, \overline{b_b}$ or \tilde{b}_f, \tilde{b}_b	<p>The ratio of the forward or the backward scattering coefficient to the total scattering coefficient. 1</p> <p>Relations : $\overline{b_f} = b_f / b$ $\overline{b_b} = b_b / b$</p>
Optical length (or depth, or thickness) (F. épaisseur ou profondeur optique)	τ	<p>The geometrical length of a path multiplied with the (total) attenuation coefficient associated with the path 1</p> <p>Relation : $\tau = c \cdot \ell$</p> <p>or, for an inhomogeneous medium, where c varies along the pathlength :</p> $\tau = \int_0^\ell c(\ell) d\ell$ <p><u>Note 1</u> : Despite the words "length" or "depth," these quantities are dimensionless.</p> <p><u>Note 2</u> : Similar dimensionless quantities are obtained by multiplying a depth interval, Δz, with the various vertical attenuation coefficients, K. No name and no symbol is proposed.</p>

Acknowledgments

The authors wish to thank N. Højerslev, G. Kullenberg, A. Ivanoff, K. S. Shifrin, V. A. Timofeeva, and J. R. V. Zaneveld, members of the IAPSO Working Group on Optical Oceanography, and also H. R. Gordon, R. W. Preisendorfer, and D. Spitzer for their help and encouragement in this work. A considerable amount of correspondence was exchanged on this matter, and several drafts were written and discussed before a final consensus was reached in December 1979 during the XVII IUGG General Assembly held in Canberra.

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