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Mathematical Modelling of Optical Image Propagation in Water

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Mathematical Modelling of Optical Image Propagation in Water

B.W. Koerber

Land, Space and Optoelectronics Division
Electronics and Surveillance Research Laboratory

DSTO-TR-0155

ABSTRACT

The results are presented of a preliminary mathematical modelling study of optical image propagation in water using Monte Carlo methods.

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Mathematical modelling of optical image propagation in water

EXECUTIVE SUMMARY

A basic set of mathematical models using Monte Carlo methods and other mathematical techniques has been developed to provide information required to assess the performance of underwater imaging systems. In particular, information is provided directly applicable to the High performance UnderWater range-gated Imaging system (HUWI).

The models were validated in a program of measurements at Happy Valley reservoir carried out to provide accurate comparison radiometric data to validate the models.

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The author has worked for DSTO since 1955. His experience has included optical propagation effects for the Laser Airborne Depth Sounder program (LADS). In addition to mathematical modelling of both atmospheric and underwater light propagation, the author has been the principal in an experimental program to measure water optical properties including the design and utilisation of absorption, scattering and transmittance monitors.

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1. Introduction

A mathematical modelling study has been carried out to provide information on the propagation of optical images through water. This information is necessary for the efficient design and operation of underwater viewing systems. At present, information is required to assess the effectiveness of the High performance UnderWater Imaging system (HUWI).

Although a transmission window exists in the visible waveband of the electromagnetic spectrum, viewing underwater is severely limited due to the inherently high attenuation properties of water, even in the clearest water. Scattering and absorption are the fundamental mechanisms that affect the attenuation of light in water. Scattered light from the illuminating light source spreads a veiling glare over the target under observation. The HUWI system operates using a pulsed laser transmitter beam and range-gated techniques to provide optimum imaging performance by ensuring that only the scattering occurring near the target is seen by the receiver.

Since multiple scattering effects greatly complicate the light propagation process in water, mathematical modelling of light propagation in water involves extensive computations. For the present study, Monte Carlo methods have been found suitable for handling the difficult problem of modelling optical image propagation in water.

2. Propagation of light in water

2.1 Attenuation of a beam of light

A beam of monochromatic light propagating in uniform water is attenuated exponentially with distance. The beam transmittance is

$$T = e^{-cr} \tag{1}$$

where c is the total attenuation coefficient

and r is the distance travelled.

2.2 Absorption and scattering

The light beam is attenuated due to the effects of two independent processes: absorption and scattering. Absorption is a transformation of radiant energy into another energy form, generally into heat or chemical potential energy. Scattering refers to a process by which the direction of individual photons is changed without energy loss.

The attenuation coefficient is given by

$$c = a + b \tag{2}$$

where a is the absorption coefficient
and b is the scattering coefficient.

2.3 Volume scattering function

Light is scattered in all directions from the beam. The intensity of this scattered light varies with the angle from the beam (for natural waters, forward scattering is predominant).

The volume scattering function $\beta(\theta)$ is defined by the following equation (see reference 1)

$$\beta(\theta) = \frac{dI(\theta)}{Edv} \tag{3}$$

where $dI(\theta)$ is the radiant intensity of scattered light in the direction θ to the beam,
E is the irradiance at the volume element
and dv is the volume element.

The scattering coefficient b is obtained by integration of the volume scattering function:

$$b = \int_0^{4\pi} \beta(\theta)\, d\omega \tag{4}$$

where $d\omega$ is an element of solid angle in the direction θ to the beam.

For a light beam with circular symmetry, equation 4 may be rewritten in the form:

$$b = 2\pi \int_0^{\pi} \beta(\theta) \sin\theta\, d\theta \tag{5}$$

2.4 Multiple scattering

When light propagates over large distances in water, multiple scattering effects become important. Significant amounts of radiant flux may be produced by photons that have been scattered many times.

As a result of this scattering, an initially collimated light beam increases in width as it propagates in water. Since most of the scattered light energy is produced at very small angles to the beam (in natural waters), the beam spreads slowly at first. As the path length increases, the proportion of multiply-scattered light increases and the beam spreads significantly.

The effects of multiple scattering must be included in mathematical models describing light propagation in water. A Monte Carlo technique which models the passage of an ensemble of photons has been used to model the propagation of light.

3. Imaging of light through water

3.1 Point spread function

The point spread function (PSF) is an important function used in modelling the effects of multiple scattering on the quality of images propagating through water. The PSF is the distribution of light flux in the blurred image of a point source at a specified range from the source. Formal definitions of the PSF are provided in references 2 and 3. For the purpose of the present modelling study, the definition is used for the PSF which makes it identical with the impulse response function.

3.2 Optical transfer function

An object under observation may be regarded as a superposition of a complex series of sine waves that are imaged as sine waves. The optical transfer function (OTF) is the ratio of the spatial frequency spectrum of the image to that of the object. The modulus of the OTF is the modulation transfer function (MTF) and the phase of the OTF is the phase transfer function (PTF). For a purely particulate scattering medium (e.g. a water path with scattering particles present but negligible turbulence), there is no preferred orientation for best response and the transfer function has a real value (i.e. the PTF is zero).

3.3 Fourier transform for point spread function and optical transfer function

A switch can be made easily from the PSF in the space-domain to the OTF in the spatial-frequency domain using a Fourier transformation. The PSF and the OTF are a Fourier transform pair. If the scattered light has circular symmetry around the unscattered ray and only small angles are considered, the OTF may be expressed in terms of the Fourier-Bessel transform (reference 2)

$$H(\psi, R) = 2\pi \int_0^{\theta_{max}} h(\theta, R) J_0(2\pi\theta\psi)\theta \, d\theta \tag{6}$$

where $H(\psi, R)$ is the OTF at spatial frequency ψ (cycles/radian) and at distance R,
$h(\theta, R)$ is the PSF at angle θ (radians) and at distance R,
$J_0(2\pi\theta\psi)$ is the Bessel function of the first kind and order zero
and θ_{max} is an arbitrarily chosen upper limit to the region in which $\sin\theta \approx \theta$.

The inverse transform is

$$h(\theta, R) = 2\pi \int_0^{\infty} H(\psi, R) J_0(2\pi\theta\psi)\psi \, d\psi \tag{7}$$

3.4 Fourier transform for volume scattering function and restoring coefficient

It was Wells (reference 2) who first discovered another Fourier transform pair involving the volume scattering function $\beta(\theta)$ and the restoring coefficient $S(\psi)$ which appears in complete analogy to the PSF-OTF pair described in section 3.3. This second Fourier-Bessel transform pair is

$$\beta(\theta) = 2\pi \int_0^{\infty} S(\psi) J_0(2\pi\theta\psi)\psi \, d\psi \tag{8}$$

and

$$S(\psi) = 2\pi \int_0^{\theta_{max}} \beta(\theta) J_0(2\pi\theta\psi)\theta \, d\theta \tag{9}$$

The decay function is

$$D(\psi) = c - S(\psi) \tag{10}$$

where c is the attenuation coefficient.

Finally, the decay function, which is independent of range, is related to the MTF by

$$MTF(\psi, R) = \exp(-D(\psi)R) \tag{11}$$

where R is the range.

4. Monte Carlo modelling of propagation of light in water

4.1 General

The propagation of light in water is complicated greatly by multiple scattering effects. Mathematical modelling of this process has been developed using a variety of approaches, with various degrees of success. The Monte Carlo technique was shown to be an adequate modelling method in a previous study of laser light propagation conducted in sea water at Jervis Bay (see reference 4). The Monte Carlo model developed for that experiment has been modified appropriately to create additional versions which provide basic information required in the present study of image propagation in water.

4.2 Standard Monte Carlo model

The standard Monte Carlo model simulates the random passage in water of individual photons from the transmitted light beam through a series of scattering events. For each segment of the three-dimensional photon trajectory, values are determined for the distance travelled before scattering and for the scattering angles by making random selections from appropriate cumulative probability data for these parameters. Random numbers required for this procedure are generated by the computer. Weighting factors are computed for each photon trajectory to account for the absorption losses along that path (the photon can be conceived of as a large packet of identical photons travelling in the same direction along the trajectory with individual photons being absorbed at various points along the path). Transit times through the water are computed for each photon path. After the computations have been repeated for a large number of photons, a space-time map is built up of the distribution of light flux in the water.

The magnitude of chance variations in the results ("noise") due to the random Monte Carlo process is reduced by increasing the total number of computed photon trajectories. A considerable additional improvement is obtained by taking advantage of the symmetry of scattering around the light beam. This gain is accomplished by combining photons that pass through all sections of a specified annular region on a surface centred on the axis of the transmitter beam. Each incident photon is weighted appropriately to allow for the magnitude of the area of the particular annulus in which the photon is collected.

The standard Monte Carlo model is very suitable for computations of light flux received at the opposite end of a one-way path from a light source as a high density of photons is achieved. Thus for the study of the performance of the range-gated imaging system HUWI, the standard model is used to compute values of the distribution of transmitted light flux at the target plane. Circular symmetry is assumed about the axis of the transmitter beam and photons are collected in annular regions. Similarly, the standard model is used to compute values of the impulse response function over various ranges from the object plane by again utilising circular symmetry about the beam (in this case the beam is an impulse).

4.3 Limit of applicability of standard model

The Monte Carlo modelling methods are used to compute the envelope of back-scatter and target reflected signals at the receiver of the underwater range-gated imaging system. By comparing these results with measurements, the accuracy of the models can be verified. The standard Monte Carlo model is a purely statistical computation of an ensemble of photon trajectories through the medium, with the length and direction of each trajectory segment obtained from random selections made from the relevant probability functions applying for the medium. Results are produced by accepting only those photons which are collected within the defined receiver aperture area and within the specified field of view. For the receiver of the range-gated imaging system, the geometric constraints are very restrictive, resulting in a very small probability of success for any given photon trajectory. To use the standard Monte Carlo model, it is necessary to compute a very large number of photon trajectories, and to relax the geometric constraints on the receiver to provide a much larger collecting area and a much wider field of view. It was found that the latter procedure produced large errors in the computed magnitude and shape of the envelope of back-scatter and target reflected signals. Thus, it was decided to use a semi-analytic Monte Carlo model (reference 5) to conduct this aspect of the modelling study, since the semi-analytic method offers an effective means for modelling with realistic geometric constraints and hence should provide the required accuracy in the results.

4.4 Semi-analytic Monte Carlo model

The semi-analytic Monte Carlo model uses a combination of statistical and analytic techniques to determine the receiver signal. The photon is conceived of as a large packet of identical photons travelling along the same path through the water. Segments of the photon trajectory are computed using the standard Monte Carlo method. When a segment terminates at a point within the volume enclosed by the field of view of the receiver, the probability is computed of the fraction of photons that would be redirected towards the receiver. The receiver signal is increased by an amount representing the proportion of these photons arriving at the receiver without further attenuation.

The estimated value of the proportion of photons collected by the receiver is given by

$$S = p(\theta')d\omega \exp(-cr) \tag{12}$$

where $p(\theta')$ is the scattering phase function at angle θ',
θ' is the angle between the photon trajectory segment and the receiver direction,
$d\omega$ is the solid angle subtended by the receiver aperture,
c is the attenuation coefficient
and r is the distance to the receiver.

The phase function is

$$p(\theta) = \frac{\beta(\theta)}{b} \tag{13}$$

where $\beta(\theta)$ is the volume scattering function
and b is the scattering coefficient.

Since

$$\int_0^{4\pi} \beta(\theta)d\omega = b \tag{14}$$

it follows that

$$\int_0^{4\pi} p(\theta)d\omega = 1 \tag{15}$$

and hence $p(\theta')d\omega$ is the correctly scaled value of the probability of a photon scattering in the direction of the receiver.

When each scattering event occurs within the field of view of the receiver, the value S is added to the receiver signal, and the weighting factor for the packet of photons is reduced by the value $p(\theta)d\omega$. The remaining photon packet then proceeds to the next scattering point which is computed using the standard Monte Carlo method.

5. Model of image propagation in water

The mathematical modelling method used in this study of optical image propagation in water is based on a technique well known in the analysis of linear electrical and optical systems. This approach involves characterising the system (water path in the present case) by its response to an impulsive input. For a complete description of the theory of this technique see reference 6.

For the present study, the object (target) may be either self-luminous or irradiated by a transmitted beam of light. The object is regarded as a collection of independent point radiators, the strength of which varies from point to point according to the radiance of the object (radiance is the radiant flux emitted in a particular direction per unit of projected surface area per unit solid angle). The imaging system maps the radiance distribution of the object into an irradiance distribution at the image plane (irradiance is radiant flux per unit surface area).

Thus for the modelling, the input function is decomposed into a linear combination of delta functions (impulse functions) each appropriately weighted according to its location. Using information of the response of the system to a single delta function (impulse response function), this is applied separately to each of the input component delta functions and their separate output responses are determined. Since the system is linear, the overall output is calculated by simply adding together all the individual outputs corresponding to each of the separate inputs. Mathematically, this process is described as the convolution of the input with the impulse response function of the system.

In the present study, the standard Monte Carlo model is used to compute values of the impulse response function for the water path under consideration. Calculations are made assuming that the imaging system is an ideal thin lens. The response function is taken as the conjugate image of the apparent distribution of rays at the object plane determined by extrapolating backwards the final segments of the photon trajectories in the water at the lens surface. Results are obtained for various path lengths and for specified optical properties of the water.

6. Results of modelling studies

To analyse the performance of the laser range-gated imaging system, it is necessary to obtain three main types of information from the mathematical modelling studies. Information is required in respect of:

(1) the magnitude of light flux at the target plane from the transmitter beam
(2) the envelope of back-scatter and target reflected signals returned to the receiver
(3) the quality of the image of the target after propagation through the water back to the receiver.

Results obtained from these three studies are described in sections 6.1, 6.2 and 6.3, respectively.

6.1 Magnitude of light flux at the target plane

An extensive modelling study was carried out previously (reference 4) to compute light flux in the water and above the sea surface at various ranges and for various orientations of a laser light source located in the sea. The standard Monte Carlo model was used for these computations. This study was carried out for comparison with a series of experimental radiometric measurements of laser light propagation in sea water performed in 1991 at Jervis Bay. The results of these combined studies are given in detail in reference 4.

6.2 Magnitude of back-scatter and target reflected signals

The magnitude of back-scatter and target reflected signals at the receiver have been computed using the semi-analytic Monte Carlo model described in section 4.4. For the computations, the following values were assumed for the parameters involved:

(1) transmitter beam divergence 5 degrees
(2) receiver field of view 5 degrees
(3) target distance 10 metres
(4) target size 2.44 metres × 1.22 metres
(5) target a bar-chart with equal size bars and white bar reflectivity 0.90
(6) two sets of optical properties of water
  (i) $c = 0.200\ m^{-1}$, $a = 0.063\ m^{-1}$, $b = 0.137\ m^{-1}$
  (ii) $c = 0.600\ m^{-1}$, $a = 0.300\ m^{-1}$, $b = 0.300\ m^{-1}$.

The results obtained for the two types of water are shown in figures 1 and 2, respectively. It should, be noted that the backscatter plotted in the preceding figures is not significant for approximately the first 20 nanoseconds as the field of view of the receiver does not overlap the beam of the transmitter for some distance. Thus the geometry of the system shown in figure 3 precludes the reception of signal for the first 15 nanoseconds. Thereafter, the signal initial rise is determined by a combination of response time, intersection volume and the water properties. All of these factors have been included in the model.

6.3 Propagation of bar-chart images through water

The standard Monte Carlo model is used to compute data on the response of the water medium to a light impulse input. A special version of the model has been developed incorporating the convolution procedures necessary to compute the image of a bar-chart as it propagates through water (see section 5). Figure 4 shows the results of calculations of the impulse response function for the water having a value $c = 0.200\ m^{-1}$. Figure 5 shows the results of the calculations of the images of a series of bar-charts of fixed angular subtense at the imaging system (fundamental spatial frequency 250 cycles/radian) at various ranges in water with $c = 0.200\ m^{-1}$. For comparison, results are shown in figure 6 of the bar-chart images computed for water with $c = 0.600\ m^{-1}$ (these results are given at shorter ranges to compensate for the greater attenuation losses in the more turbid water). Figures 5 and 6 only show relative values of irradiance plotted on the Y axis. Absolute values may be obtained by utilising computed results of back-scatter and target reflected signals described in section 6.2.

Values of the MTF of the water with c = 0.200 m^{-1} have been calculated using Wells' theory described in sections 3.3 and 3.4. Figure 7 shows the results of calculating MTF directly from the volume scattering function using equations 9, 10 and 11. Figure 8 shows the results of calculating MTF from the impulse response function (point spread function) using equation 6. Values of MTF were also calculated at a frequency of 250 cycles/radian (and at several harmonics) using a fast Fourier transform on the results of the bar-chart image calculations shown in figure 5. Good agreement was obtained using the three methods for values of MTF at high frequencies while moderate agreement was obtained at low frequencies. These comparisons of computed values of MTF provide checks on the validity of Wells' theory and on the accuracy of the various modelling steps involved in the image propagation study.

7. Conclusions

(1) A basic set of mathematical models using Monte Carlo methods and other mathematical techniques has been developed to provide information required to assess the performance of underwater imaging systems. In particular, information is provided directly applicable to the underwater range-gated imaging system HUWI.

(2) A program of measurements at Happy Valley reservoir was carried out to provide accurate comparison radiometric data to validate the models. The results of this comparison are reported elsewhere (reference 7).

(3) It is desirable that a study should be carried out to determine whether "noise spikes" can be eliminated or reduced in the results obtained using the semi-analytic Monte Carlo model (see figures 1 and 2). The presence of these spikes may cause a significant loss in accuracy in the output data using this method.

(4) A study should be carried out to investigate some observed variation in computed values of MTF at lower frequencies using the various methods described in section 6.3. An attempt should be made to determine whether the observed effect is due to limitations of the theory or of the modelling procedures.

8. Acknowledgement

The author would like to thank Mr P. Wilsen for his efforts to bring this report to publication.

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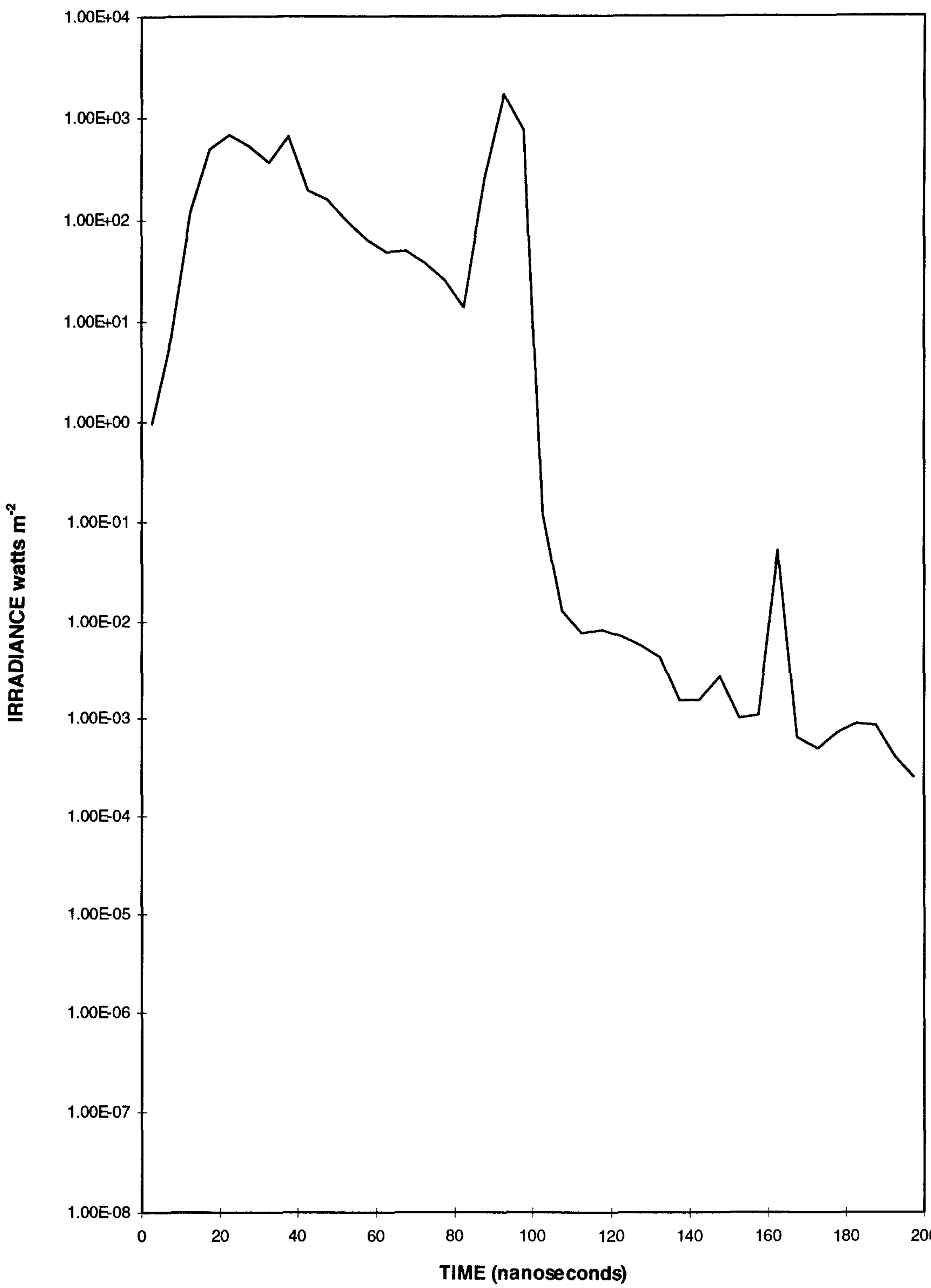


Figure 1 Target and backscatter signals for $c = 0.2m^{-1}$

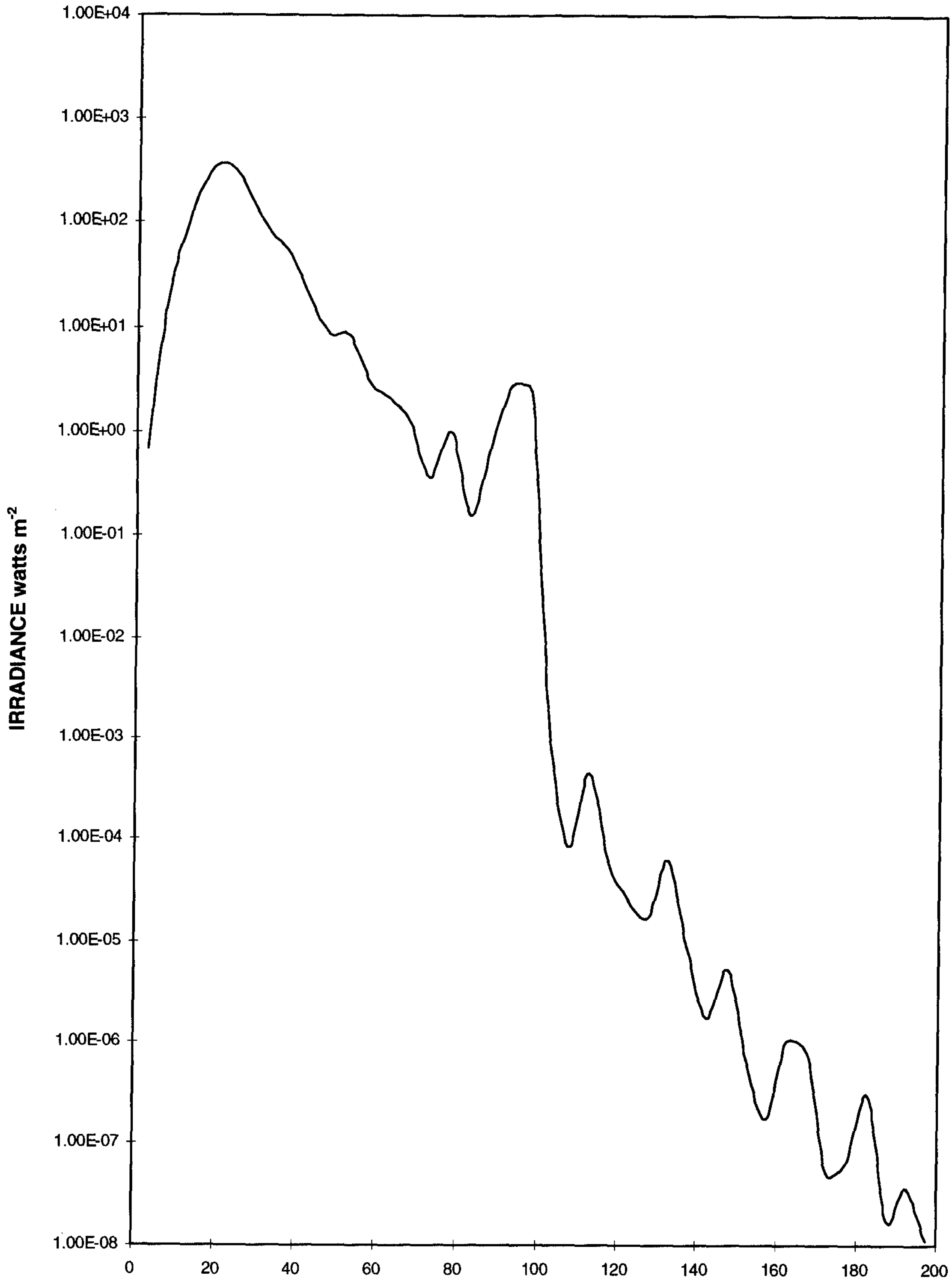
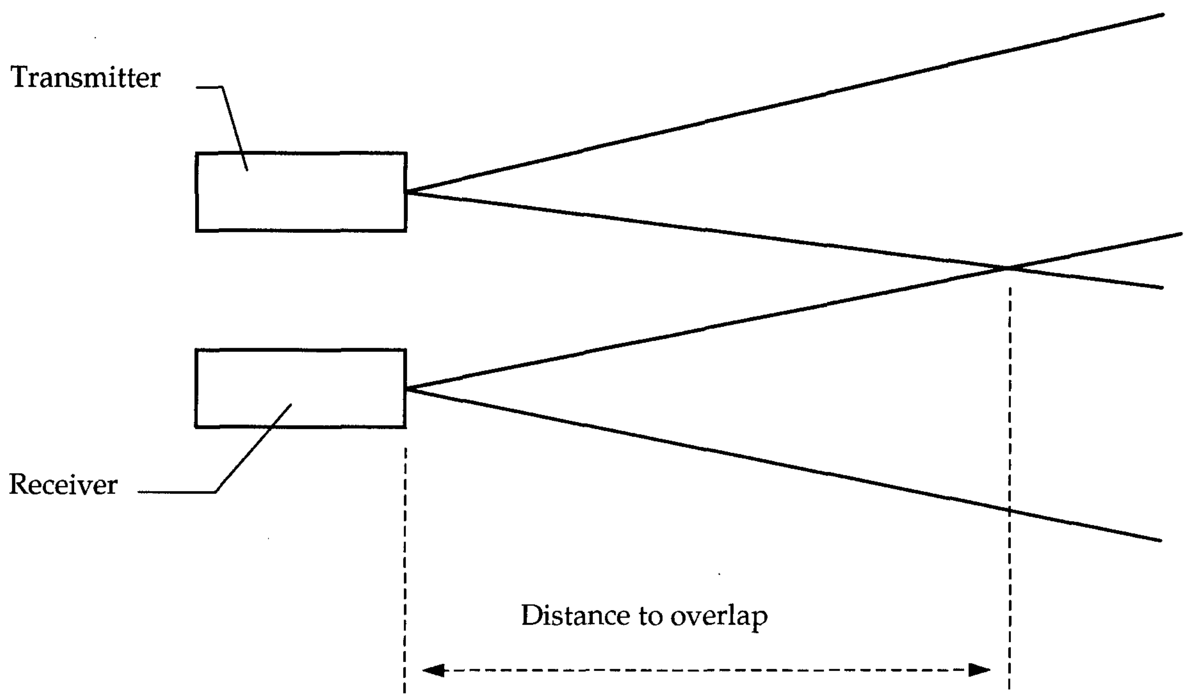


Figure 2 Target and backscatter signals for $c = 0.6m^{-1}$



NOTES:	
Transmitter to receiver spacing	0.1 metre
Approximate distance to overlap	2.3 metres
Transmitter beam divergence	5.0 degrees
Receiver field of view	5.0 degrees

Figure 3 Intersection of beam and field of view

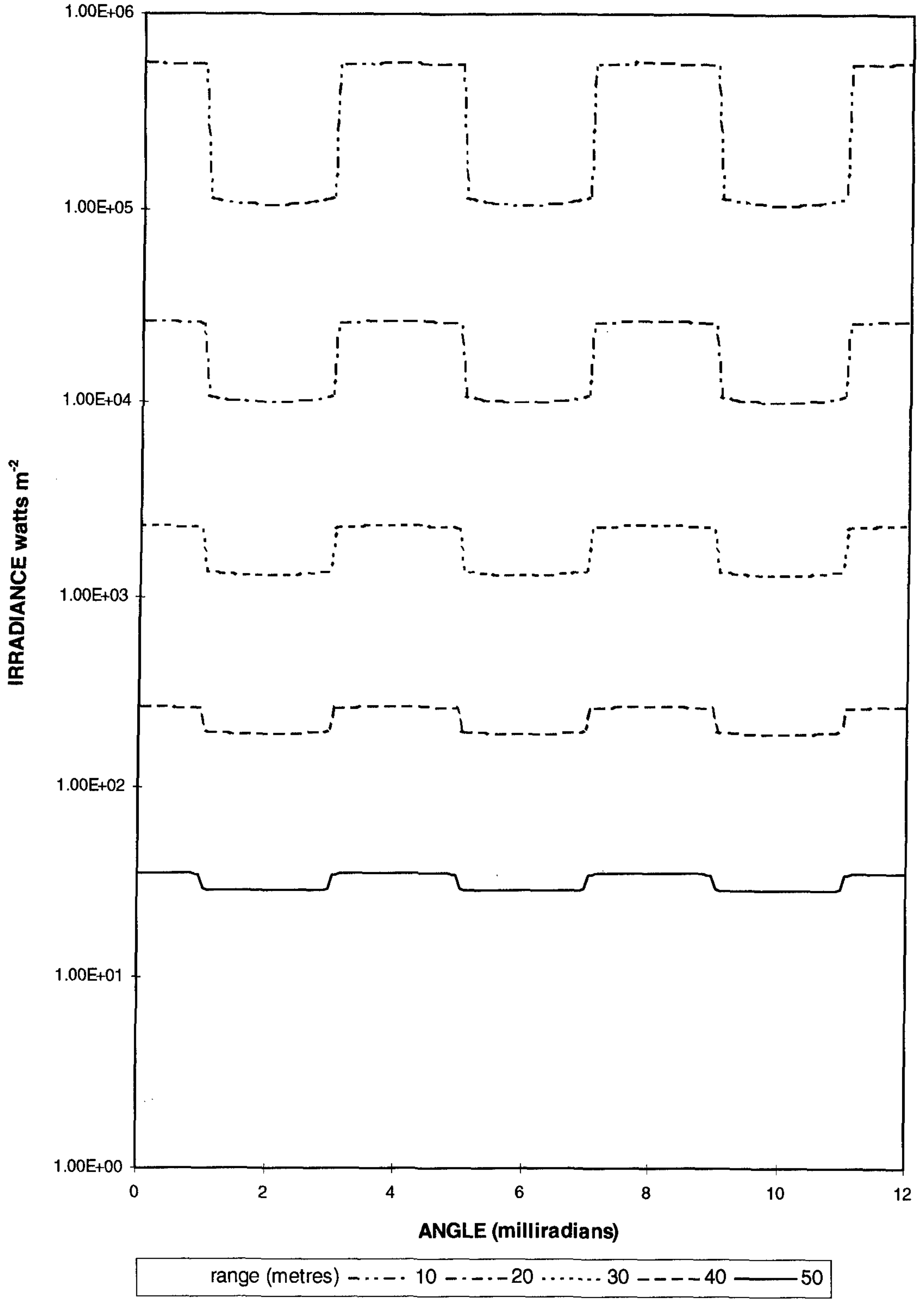


Figure 4 Impulse response functions for water for $c = 0.2m^{-1}$

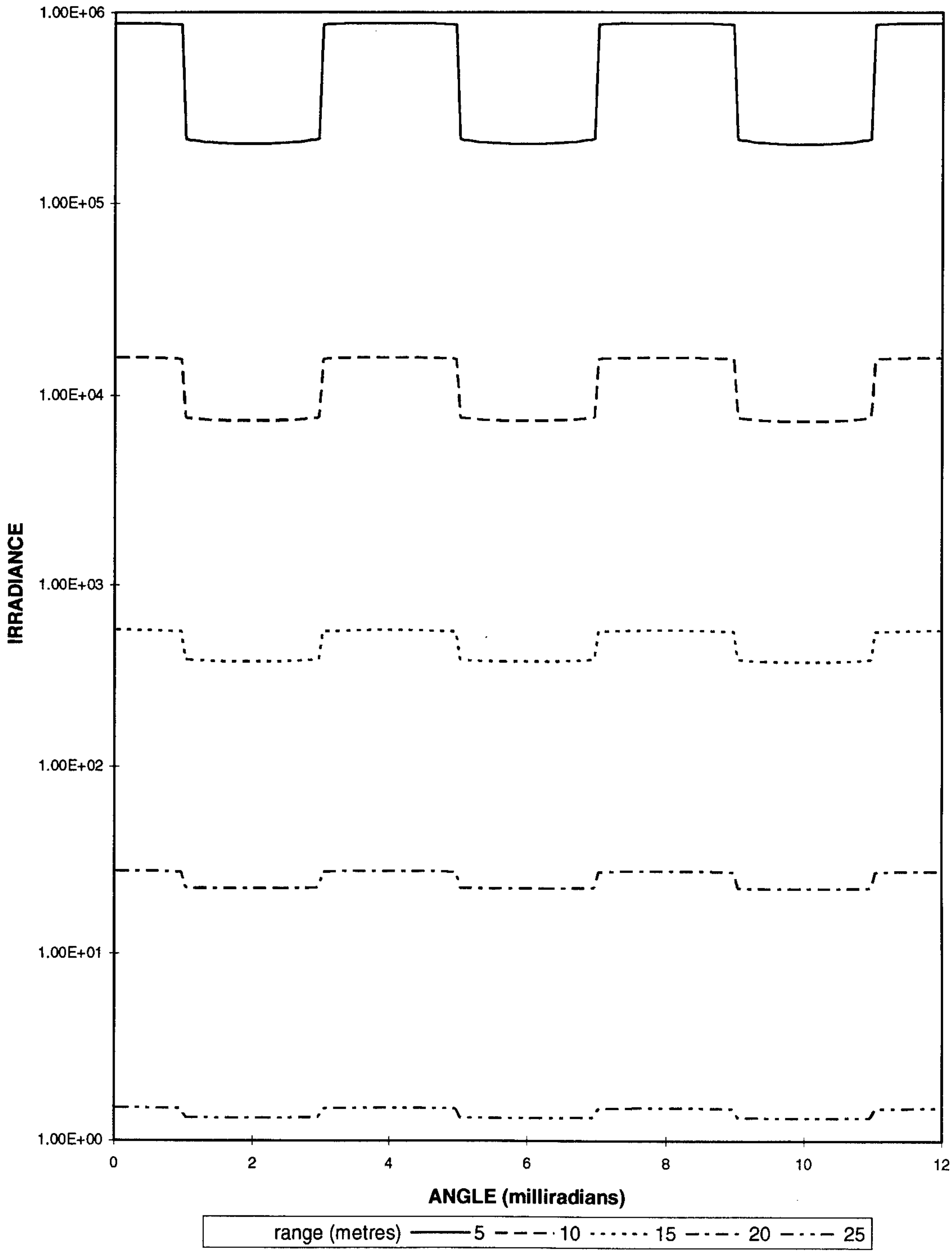


Figure 5 Bar chart images through water for $c = 0.2m^{-1}$

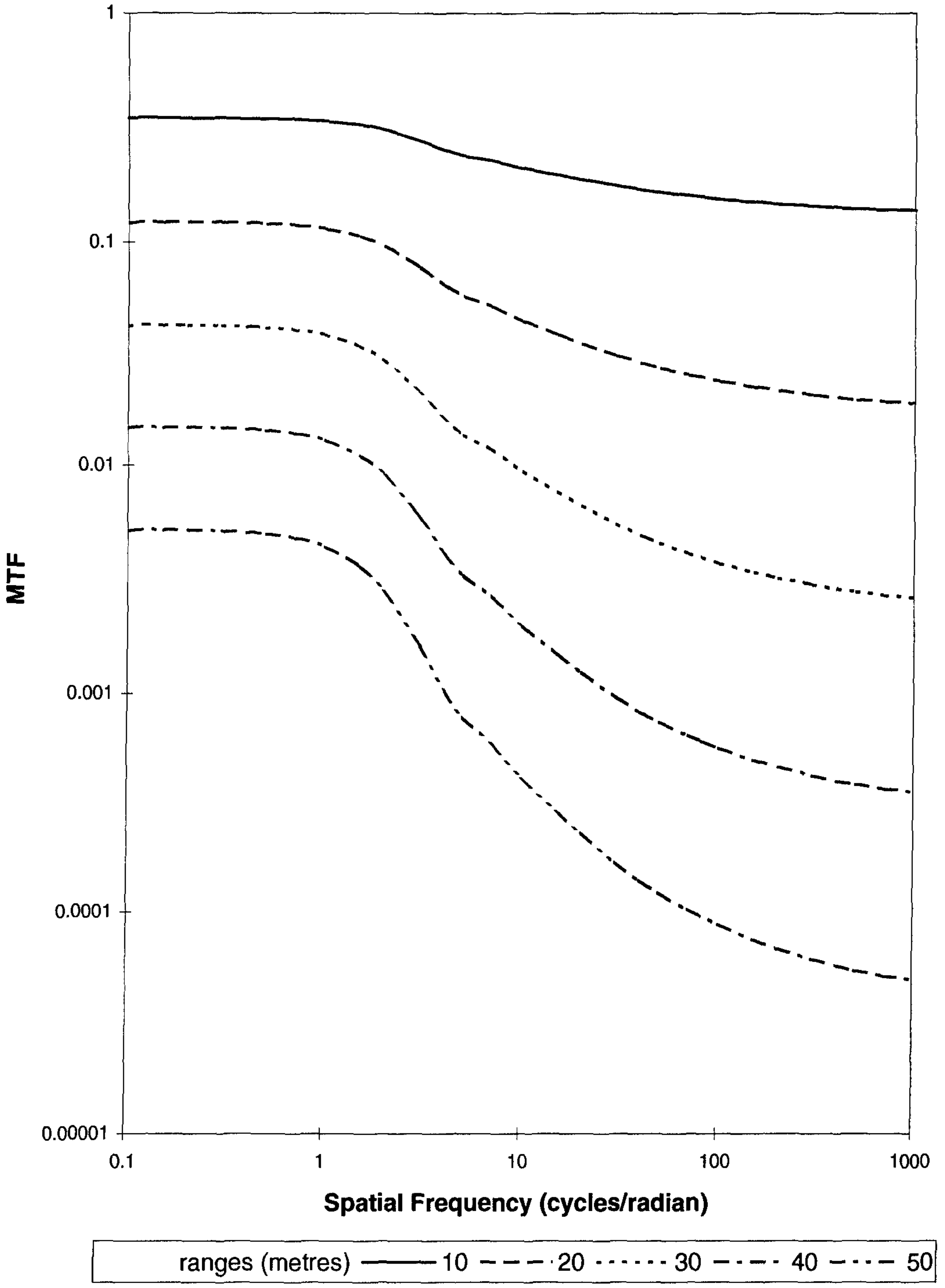


Figure 6 Bar chart images through water for $c = 0.6m^{-1}$

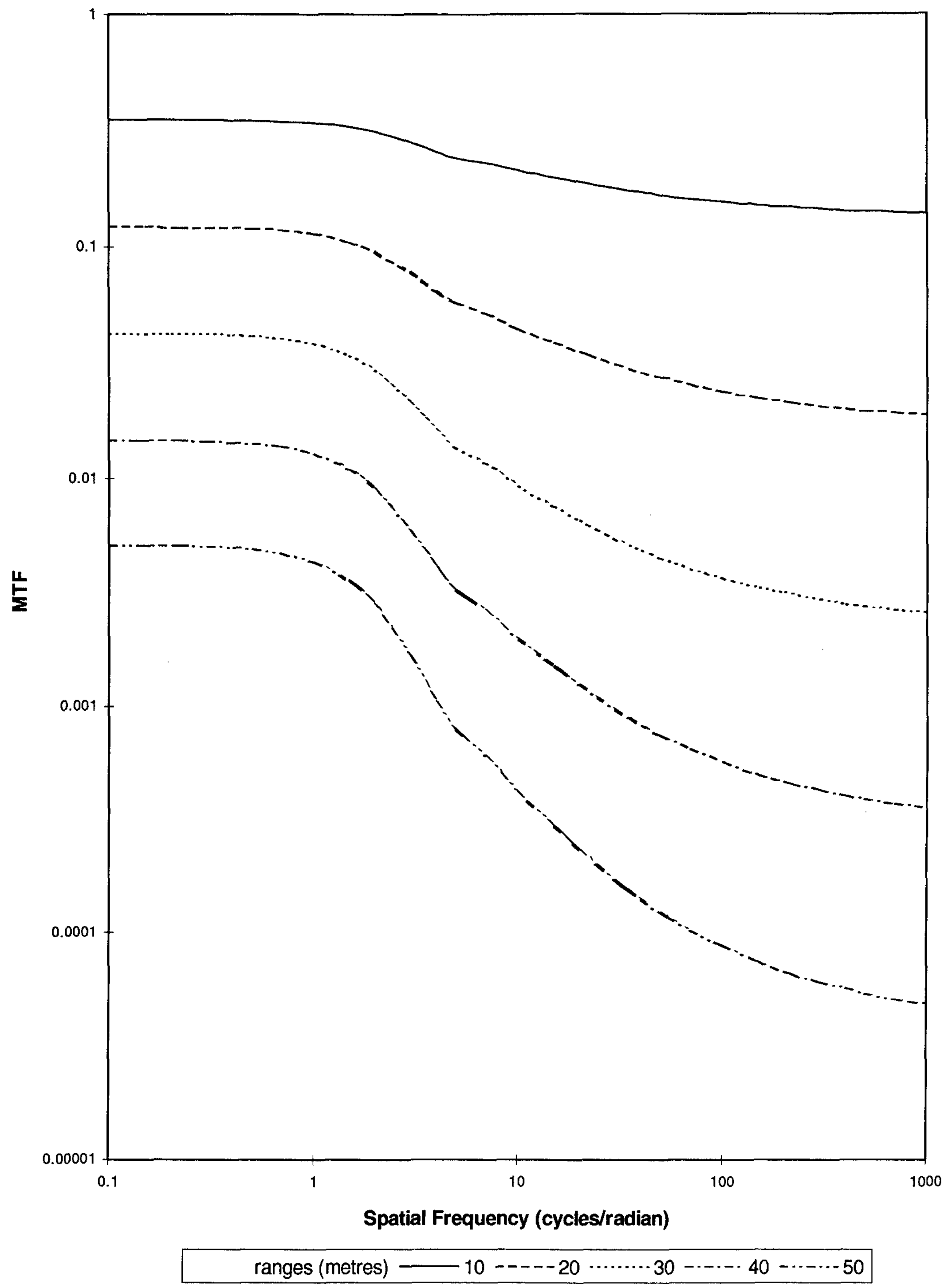


Figure 7 MTF calculated from VSF

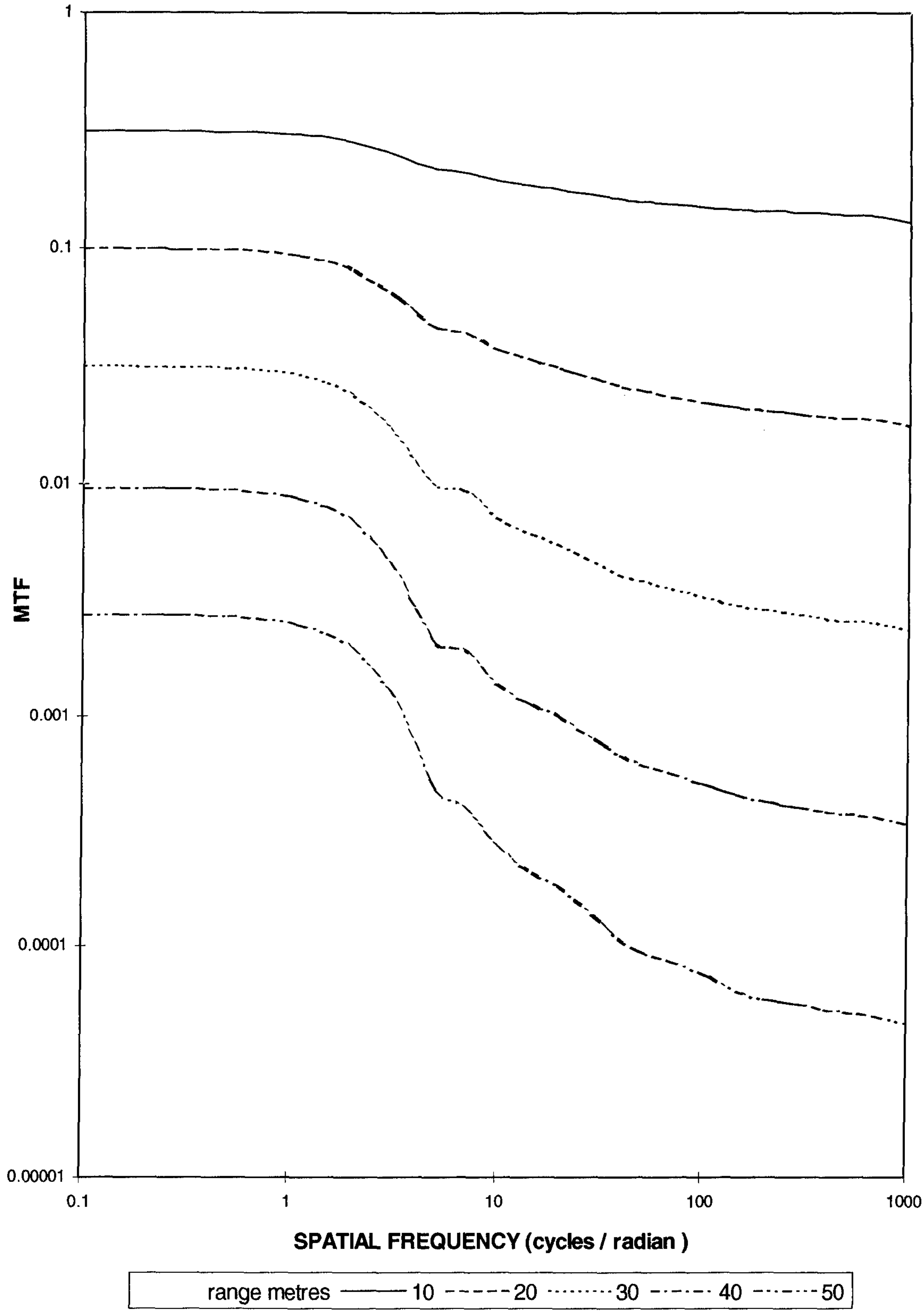


Figure 8 MTF calculated from impulse response function

Mathematical modelling of optical image propagation in water

B.W. Koerber

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