Underwater Optical Wireless Communications

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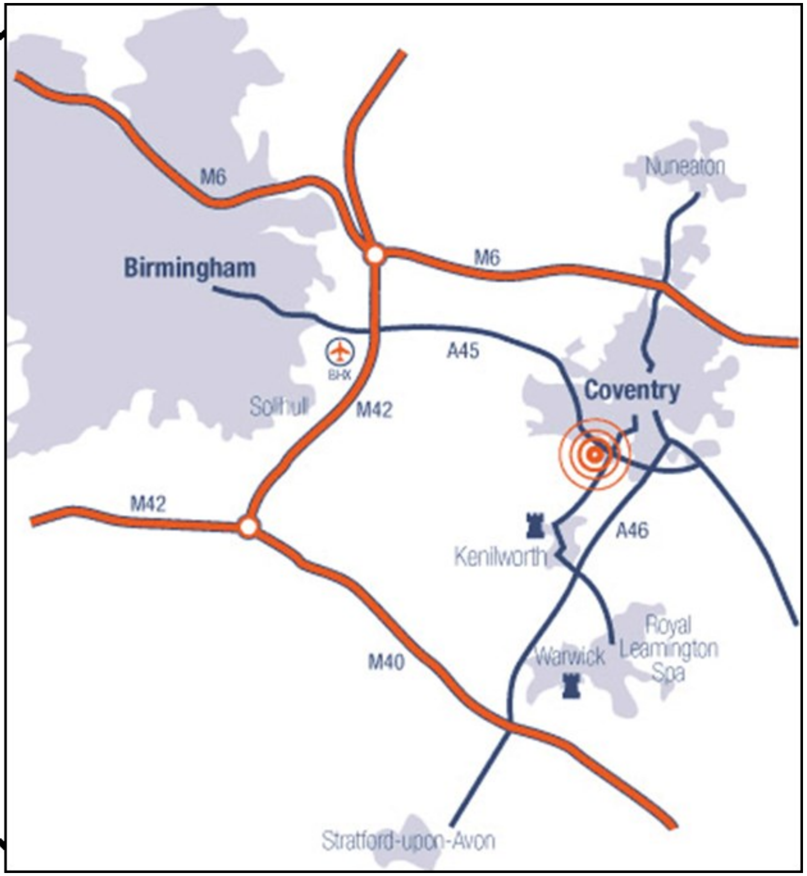
Acknowledgements:

EPSRC THALES
com sys lab

Contents

Where is the University of Warwick?



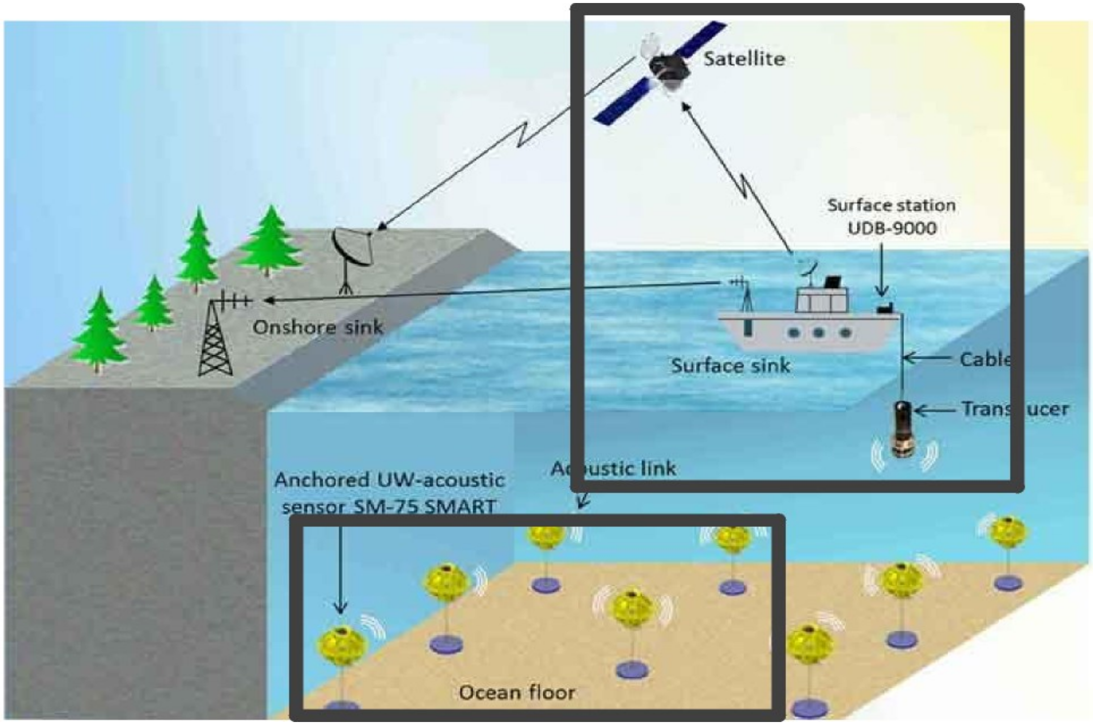
Connected Systems Research Group

Within Connected Systems, the Communication Systems Lab (https://www2.warwick.ac.uk/fac/sci/eng/research/grouplist/connectedsystems) is home to research in **Photonic Systems, Optical Technology, Wireless Communications, Machine Learning** and **Nanoscale Communications**. The fundamental advances in the laboratory will produce impact in areas such as next generation mobile data networks, vehicular communications and future healthcare monitoring systems.

Current Underwater Technology

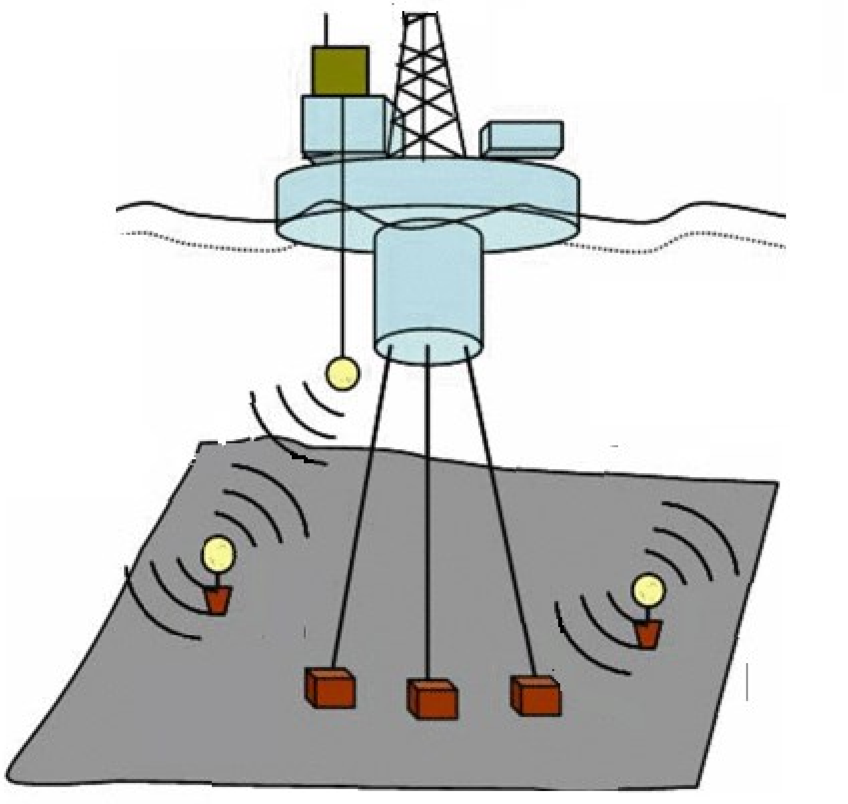
Applications:

- Ocean biology
- Environmental research
- Surveillance
- Seismic monitoring
- Ship hull monitoring
- Communicating with submarines
- Diver communications



Kulhandjian et al., Proc. IEEE Underwater Comm. Conf. and Workshop, pp. 12-14, Los Angeles, 2012

Acoustics: Current Technology



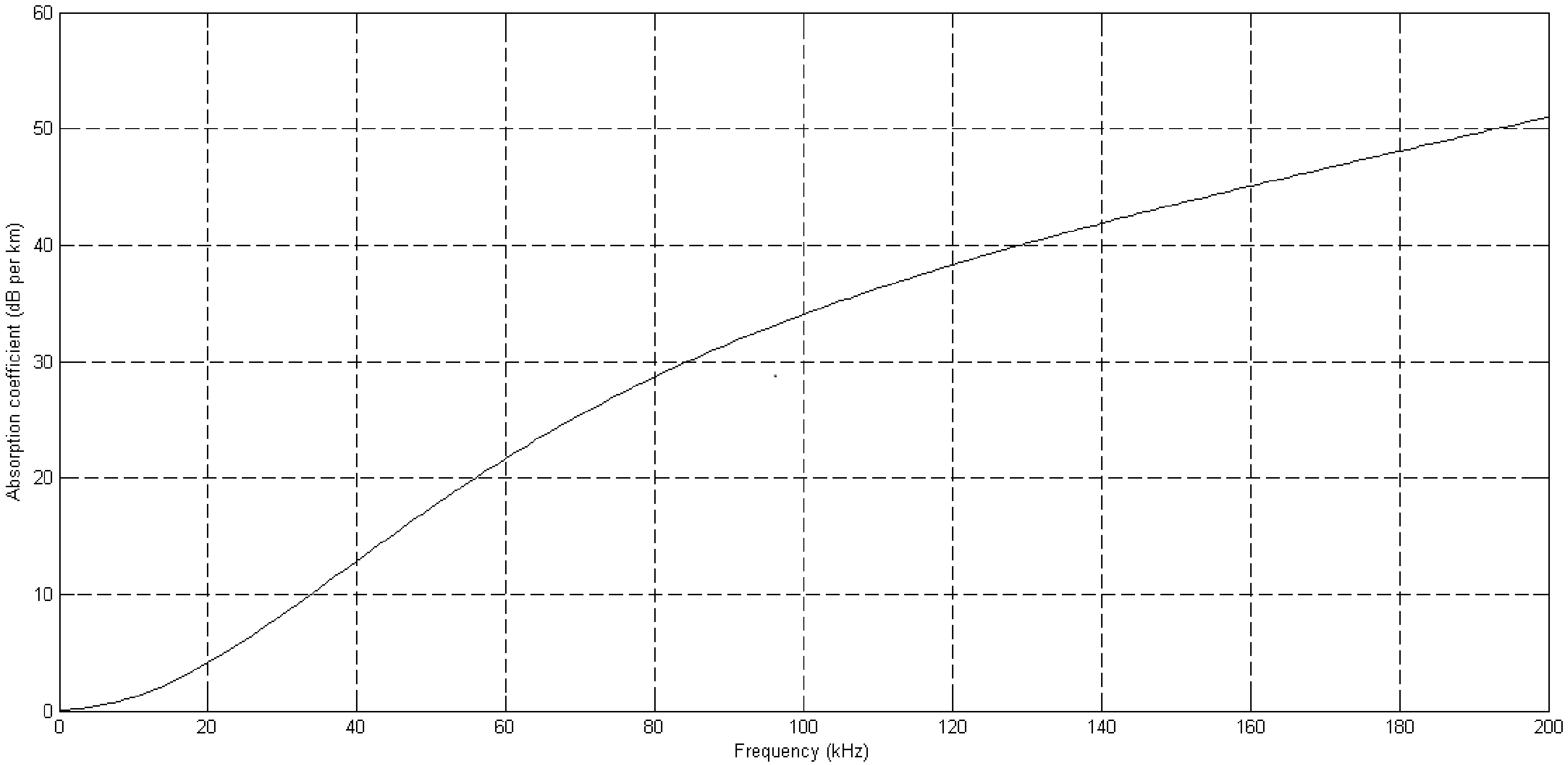
Typical application, adapted from Heidemann et al., IEEE WCNC Conference, pp. 228-235,2006.

Typical modem
(Evo Logics)

Path Loss –absorption

signal loss from conversion of acoustic energy to heat, denoted by *a*(*f*)

Thorp's empirical approximation:



Path Loss -Spreading Loss

Use path loss exponent k to produce a combination of absorption and the spreading loss over a distance l in km:

$$A\{l,f\} = l^k\{a(f)\}^l$$

The value of k depends on the propagation environment:

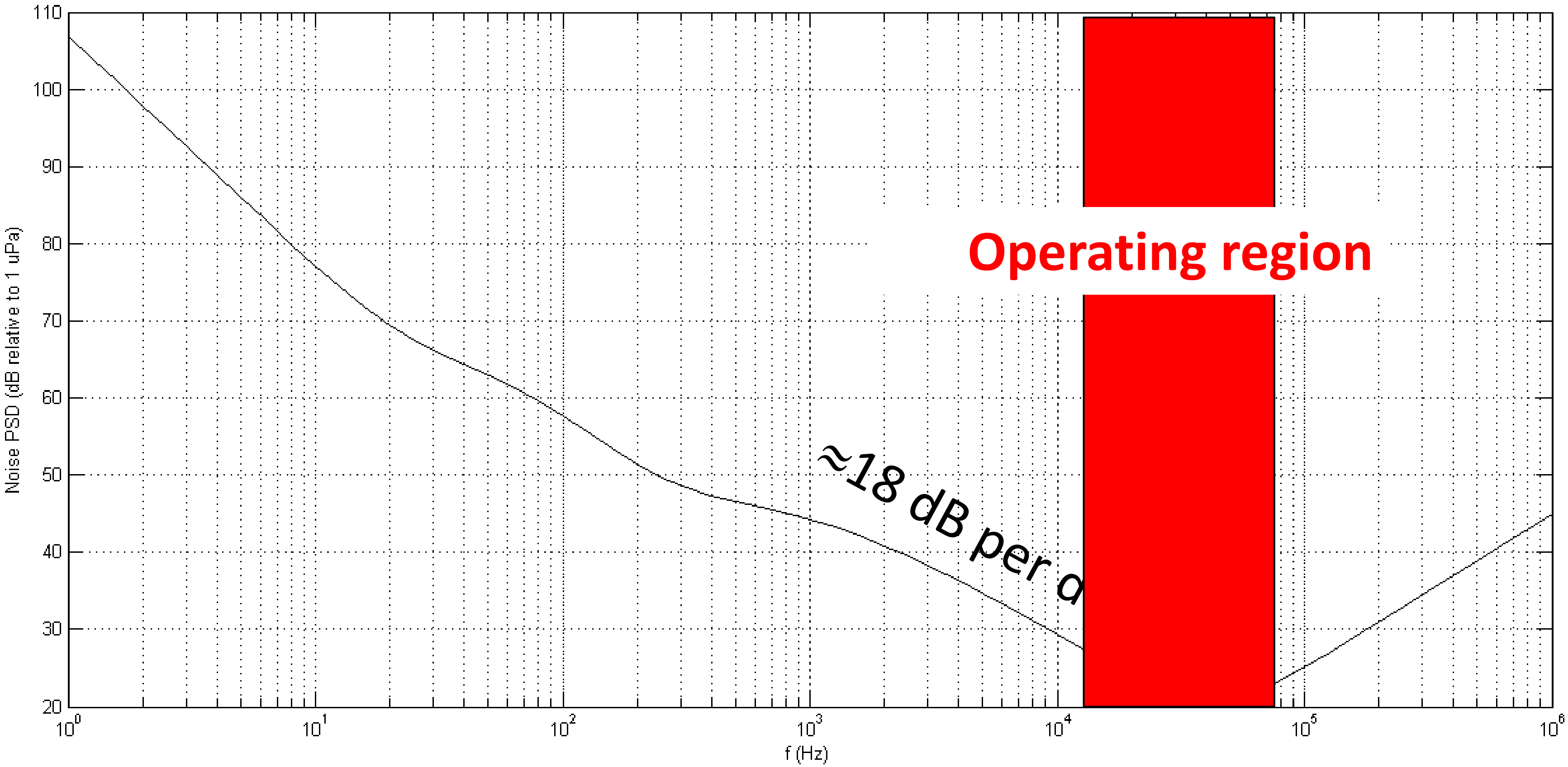
Shallow water, $k = 1$ (cylindrical spreading)

Deep water, $k = 2$ (spherical spreading)

Practical compromise $k = 1.5$

Noise

From turbulence, shipping, wind and heat

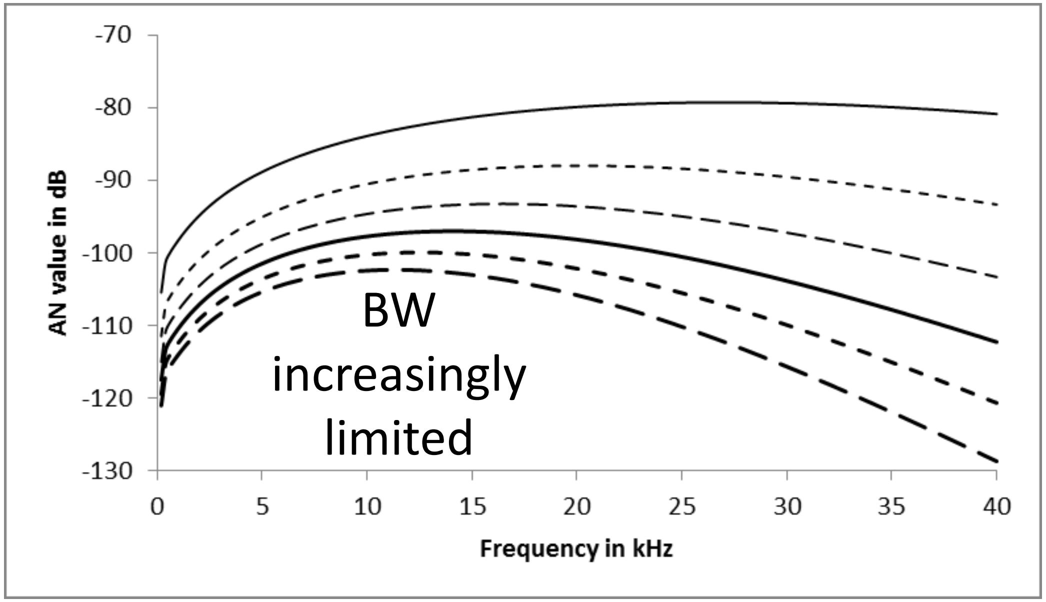


Attenuation Noise (AN) Factor

Consider a narrow band of frequencies Δf about some centre frequency f_c

$$SNR = S(f)/[A\{l,f\}N(f)\Delta f]$$

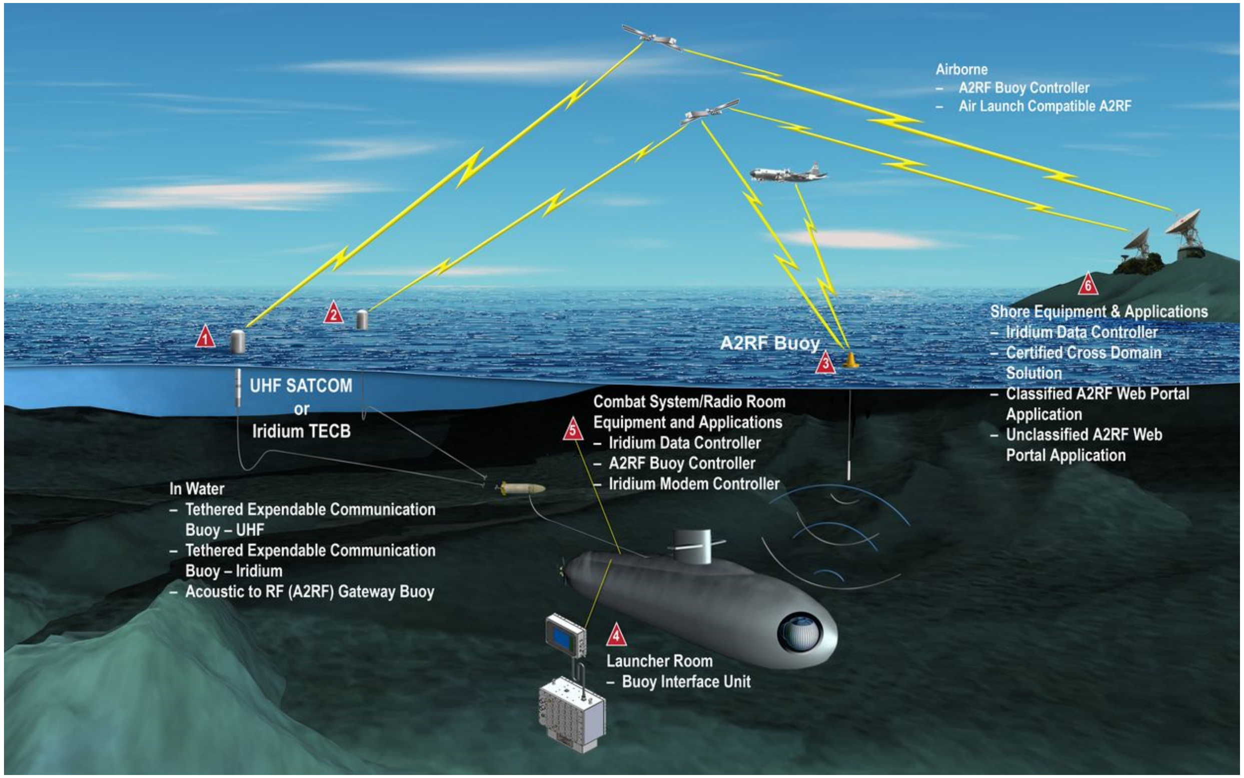
The quantity $A\{l,f\}N(f)$ is known as the attenuation noise (AN) factor



BW increasingly limited

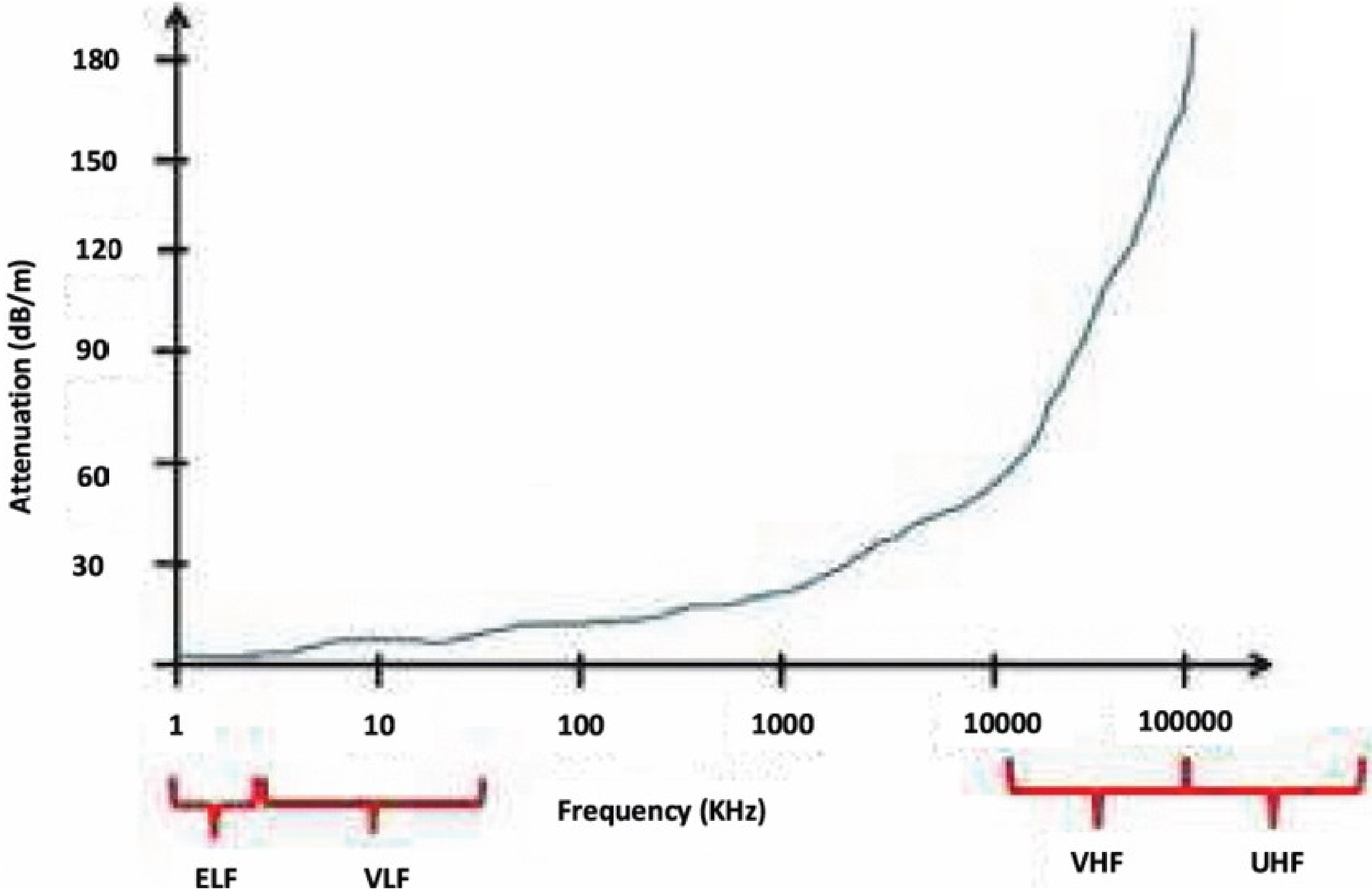
0.5 km ⇩ 3 km

RF is also established



Typical application from Edwards, New buoys enable submerged subs to communicate https://phys.org/news/2010-07-buoys-enable-submerged-subs.html

RF Attenuation in Sea Water



(Lanzagorta, Underwater Communications, Morgan & Claypool, 2013)

RF Implementations vs. Acoustic

Technology	Frequency	Modulation	Distance	Data Rate
RF	100 kHz	BPSK	6 m	1 kbps
RF	10 kHz	BPSK	16 m	1 kbps
RF	1 kHz	BPSK	2 m	1 kbps
Acoustic	800 kHz	BPSK	1 m	80 kbps
Acoustic	24 kHz	QPSK	2500 m	30 kbps
Acoustic	70 kHz	ASK	70 m	200 bps
RF	2.4 GHz	QPSK	0.17 m	2 Mbps
RF	2.4 GHz	CCK	0.16 m	11 Mbps

(Adapted from Lloret et al., Sensors, 2012)

Future Technology

Goals

- Higher bandwidth
- Communication through the air/water interface
- Secure/covert

Optical wireless is a possible solution:

transmission of a modulated light beam through an open environment to obtain broadband communication

UOWC Performance Results

Distance	Power	Source	Data Rate
20 - 30 m	500 mW	Blue LED	Few kbps
200 m	5 W	LED	1.2 Mbps
30 m (pool) 3 m (ocean)	5 W	Laser	1.2 Mbps 0.6 Mbps
2 m	10 mW	Laser	1 Gbps
30 - 50 m	1 W	Laser	1 Gbps
31 m (deep sea) 18 m (clean ocean) 11 m (coastal)	100 mW	LED	1 Gbps
64 m (clear ocean) 8 m (turbid harbour)	3 W	Laser	5 Gbps 1 Gbps
7 m (coastal)	12 mW	Laser	2.3 Gbps
5.4 m	15 mW	Laser	4.8 Gbps

Types of lasers operating in blue-green spectrum

Comparison of Technologies

Parameter	**Acoustic**	**RF**	**Optical**
Attenuation	Distance and frequency dependent (0.1 - 4 dB/km)	Frequency and conductivity dependent (3.5 - 5 dB/m)	0.39 dB/m (ocean) 11 dB/m (turbid)
Speed	$1500\ \mathrm{ms}^{-1}$	$2.3 \times 10^{8}\ \mathrm{ms}^{-1}$	$2.3 \times 10^{8}\ \mathrm{ms}^{-1}$
Data Rate	$\approx$ kbps	$\approx$ Mbps	$\approx$ Gbps
Latency	High	Moderate	Low
Distance	$\approx$ km	≤ 10 m	$\approx 10 - 100$ m
Bandwidth	1 kHz $-$ 100 kHz	$\approx$ MHz	≤ 150 MHz
Frequency Band	$10 - 15$ kHz	$30 - 300$ Hz	$\approx 5 \times 10^{14}$ Hz
Transmission Power	> 10 W	mW $-$ W	mW $-$ W

(Adapted from Kaushal & Kaddoum, IEEE Access, 2016)

Underwater Technology Comparison

- Acoustic: long range (km); low bandwidth (kHz); low efficiency (~100 bits J^{-1} – 10000 $\mu J\ bit^{-1}$)[*]

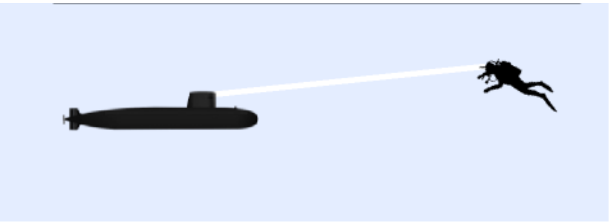
- Radio frequency: short range (<10m); low bandwidth (kHz); energy efficient (~6kbits J^{-1} – 166 $\mu J\ bit^{-1}$)[+]

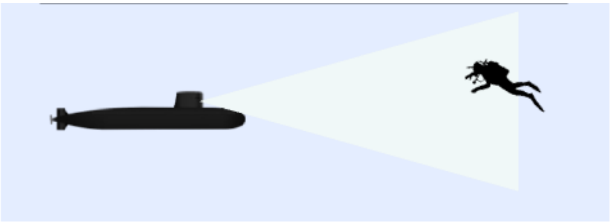
- Optical wireless: short-mid range (up to 100s of m); high bandwidth (GHz); very energy efficient (30k bits J^{-1} – 33 $\mu J\ bit^{-1}$)[*]

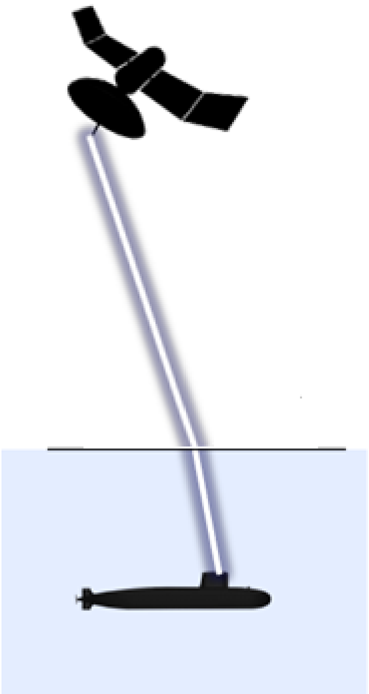
[*] e.g. Farr et al., OCEANS 2010 IEEE, Sydney, 24-27 May 2010; [+] e.g. O'Rourke et al., WUWNet, Los Angeles, California, 2012.

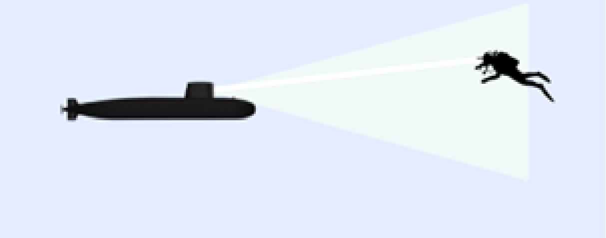
Underwater Optical Wireless Links

Configurations


LOS point-to-point


LOS diffuse


LOS boundary


Retroreflector diffuse


Non-LOS diffuse

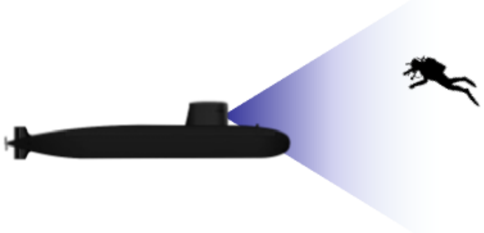
Underwater Scenarios

Atlantic Ocean

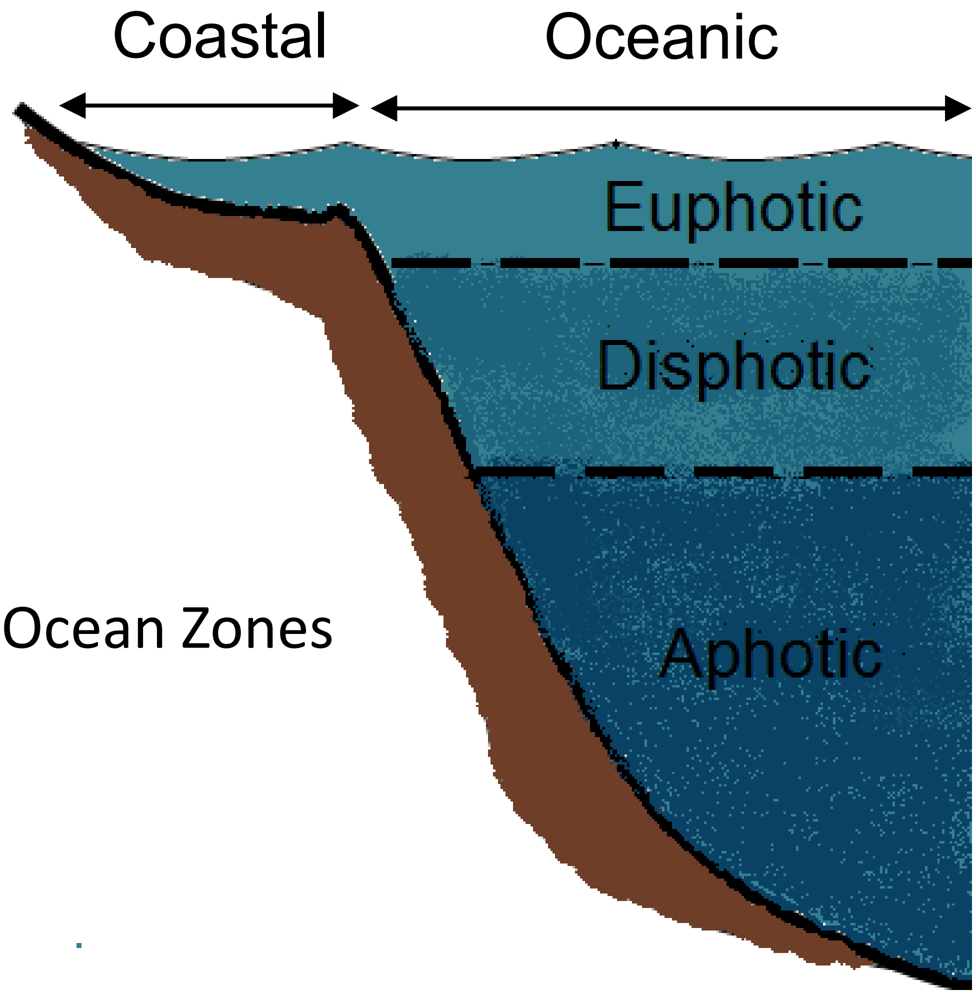
- Laser likely
- Longer range
- Tracking

Thames, UK

- LED likely
- Shorter range
- Multipath



The Underwater Channel



Photosynthetic life

Light too faint to support photosynthesis

No light passes

Ocean Zones

Jerlov Water Types

Water types divided into two categories:

oceanic (blue water) with 3 subdivisions

Type I: extremely pure ocean water

Type II: tropical-subtropical water

Type III: mid-latitude water

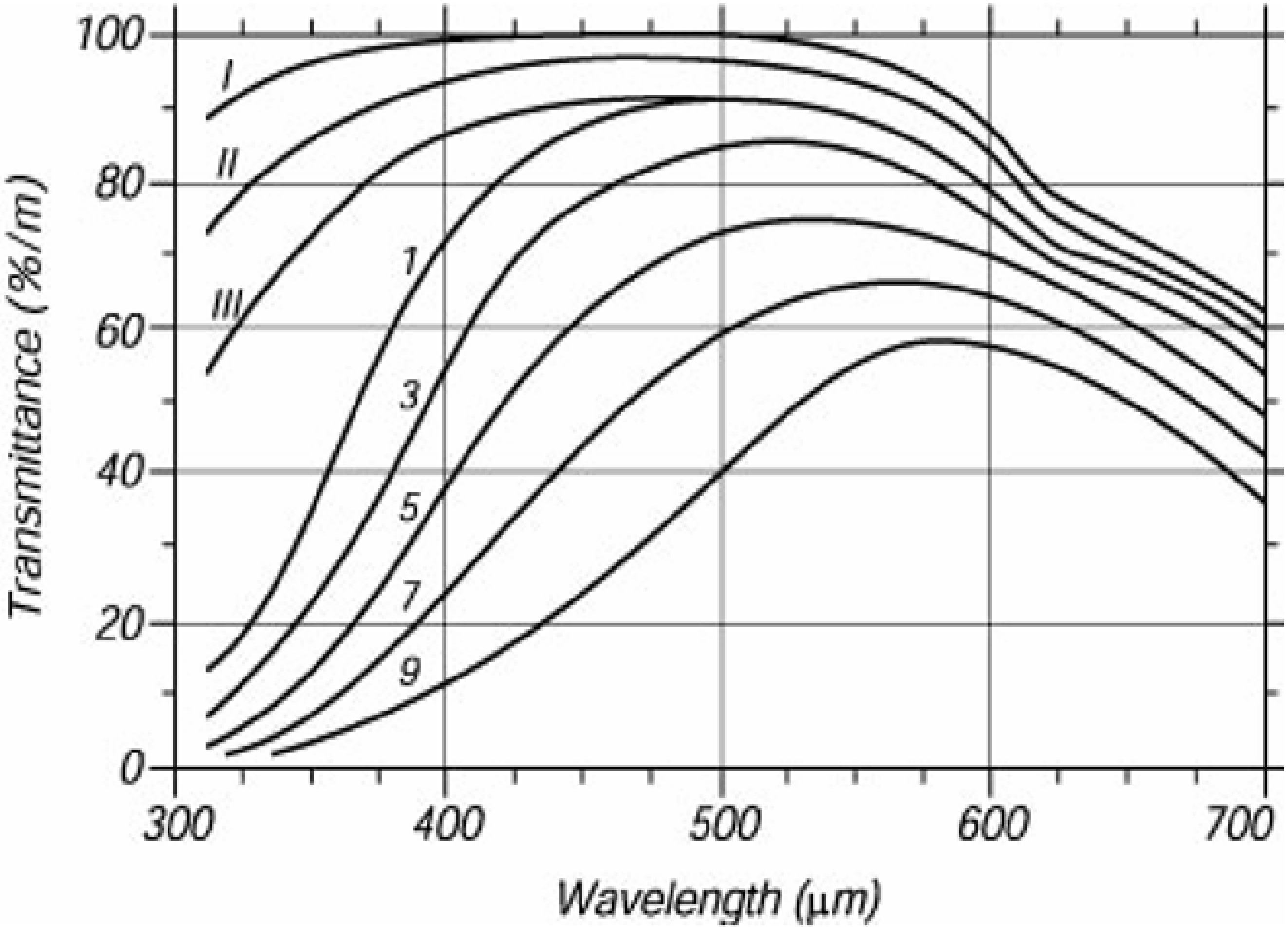
coastal (littoral zone) subdivided into nine types

Type 1 – least turbid

…

Type 9 – most turbid

Transmittance of Water Types



Jerlov, 1976

Channel Variation

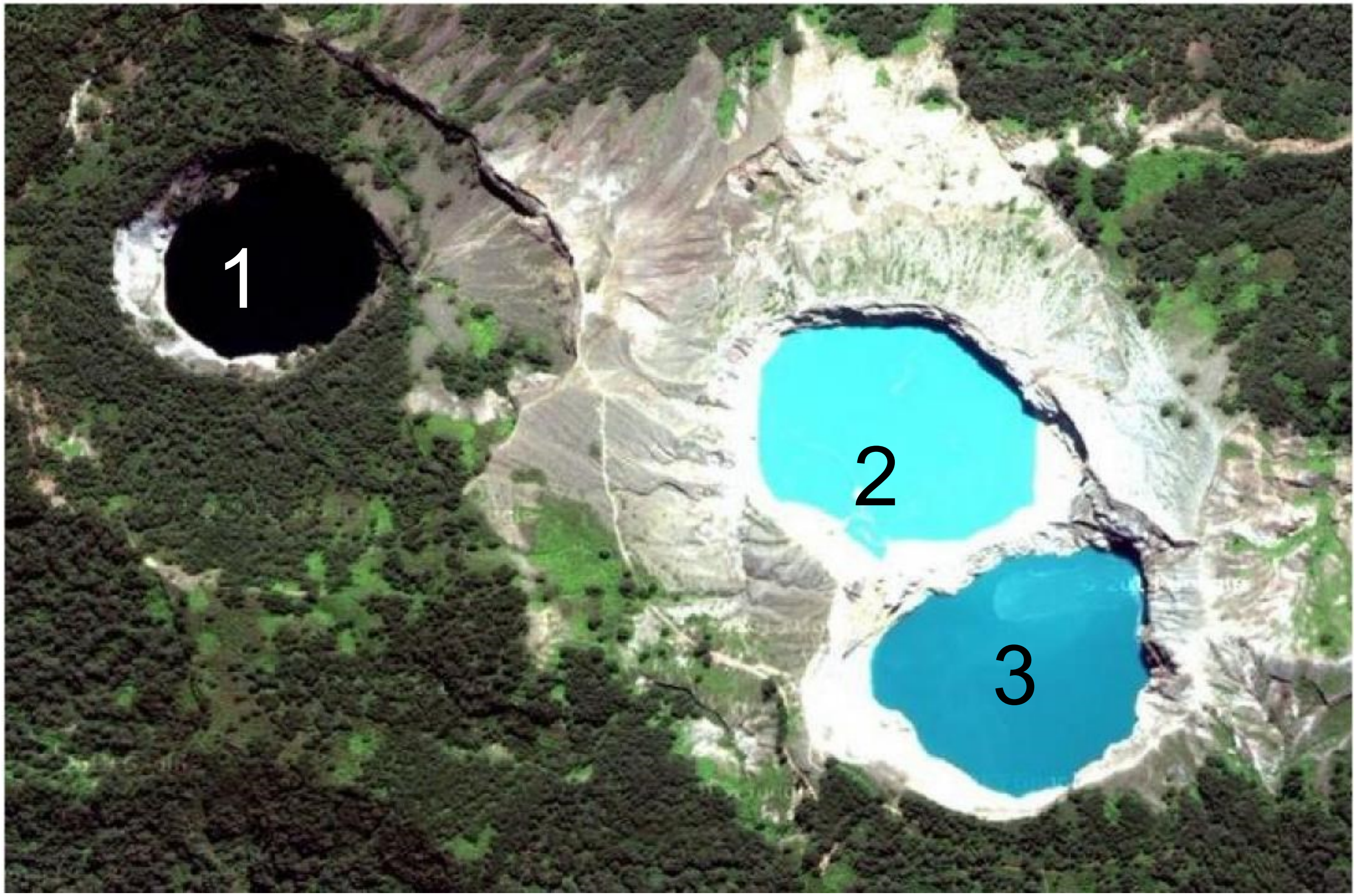
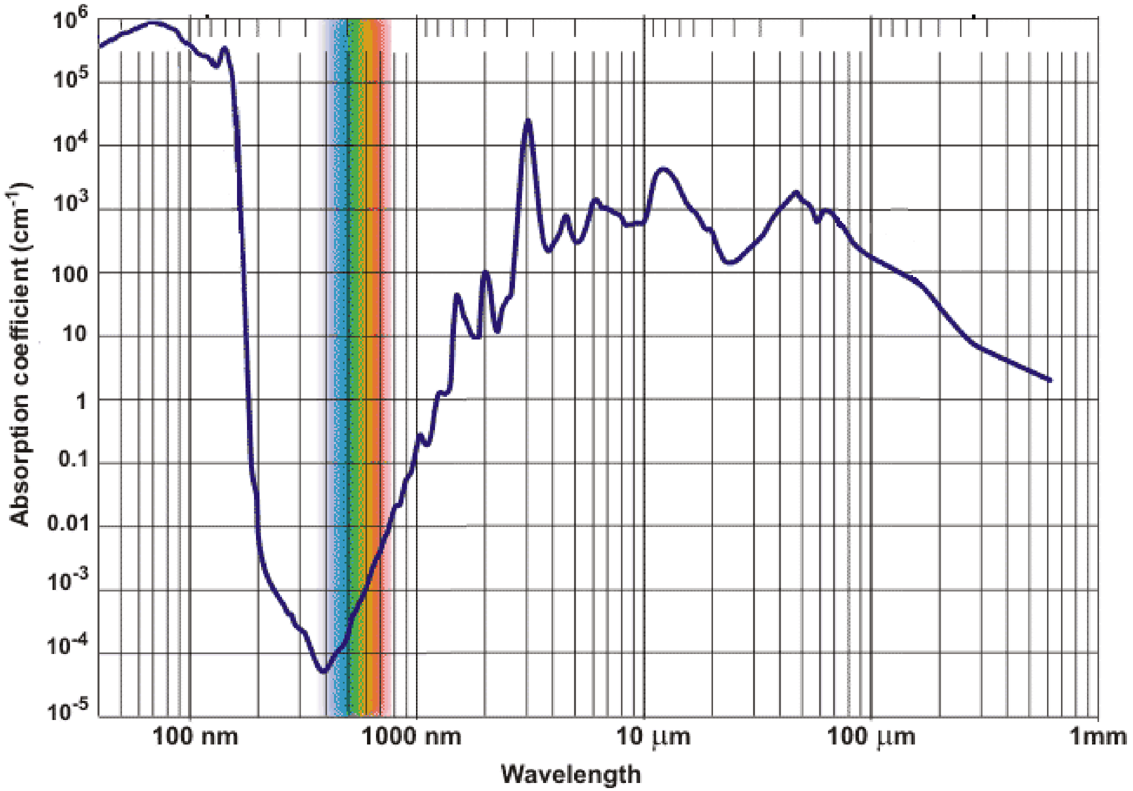


Image: Google Earth (accessed 03/03/13)

Absorption Variation

Transmission Window

Electromagnetic attenuation in water



Adapted from http://www1.lsbu.ac.uk/water/water_vibrational_spectrum.html

Light Sources: Lasers

Type	Wavelength	Advantages	Disadvantages
Argon-ion	455-529 nm	High output	- Low efficiency; needs high input power; needs cooling
Nd:YAG	532 nm (green) 473 nm (blue)	Very high output power; long life time; compact	Variable efficiency; costly; can be hard to modulate
Ti: Sapphire	455 nm	Ultra fast output; tunable	Costly; sensitive to vibrations
Metal vapour	441.6 nm, 570 nm and 578 nm	High power; long life time	Requires cooling
Dye	450 nm - 530 nm	Very high power ; tunable; high data rate	Costly; requires cooling arrangements
Semiconductor	405 nm & 450 - 470 nm (InGaN) 375 nm to 473 nm (GaN)	Highly efficient; compact	Costly; easily damaged due to over current

(Adapted from Kaushal & Kaddoum, IEEE Access, 2016)

Light Sources: LEDs

Manufacturer	Wavelength (nm)	Luminous Flux (lm)
Lamina Atlas NT-42C1-0484	460 - 470	63
AOP LED Corp PU-5WAS	455 - 475	54
Kingbright AAD1-9090QB11ZC/3	460	35.7
Ligitek LGLB-313E	460 - 475	30.6
Toshiba TL12B01(T30)	460	6
Lumex SML-LX1610USBC	470	5

(Adapted from Kaushal & Kaddoum, IEEE Access, 2016)

Channel Modelling

Beer's Law: At a depth z and a wavelength λ, the optical path loss as a function of distance L may be approximated by: $e^{-c(\lambda,z)L}$

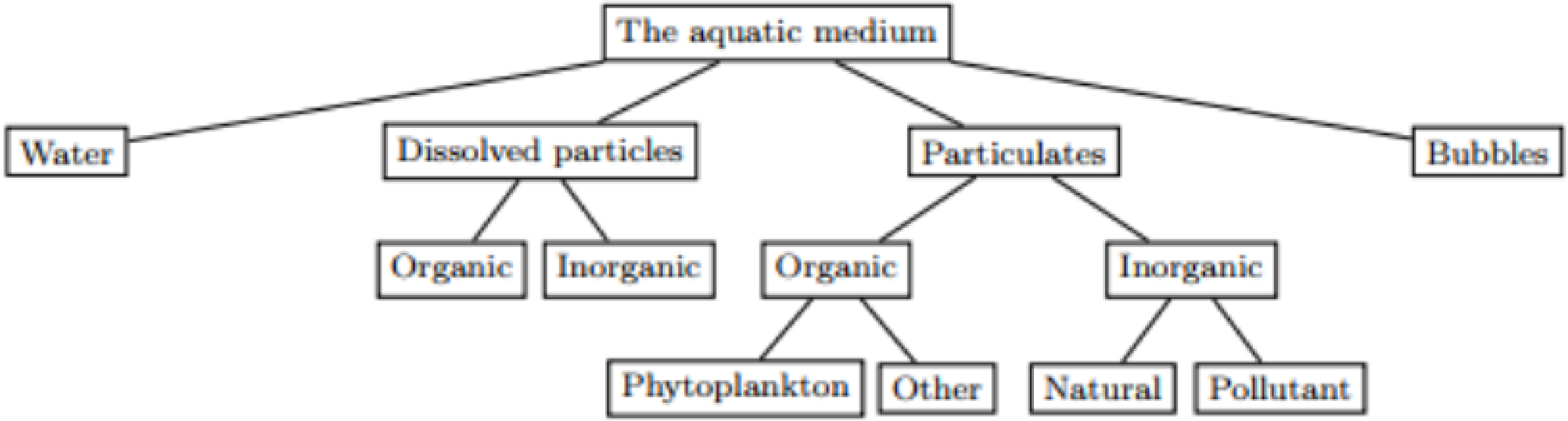
The attenuation coefficient is made up of:

$$c(\lambda, z) \quad = \quad a(\lambda, z) \; + \quad b(\lambda)$$

Attenuation = absorption + scattering

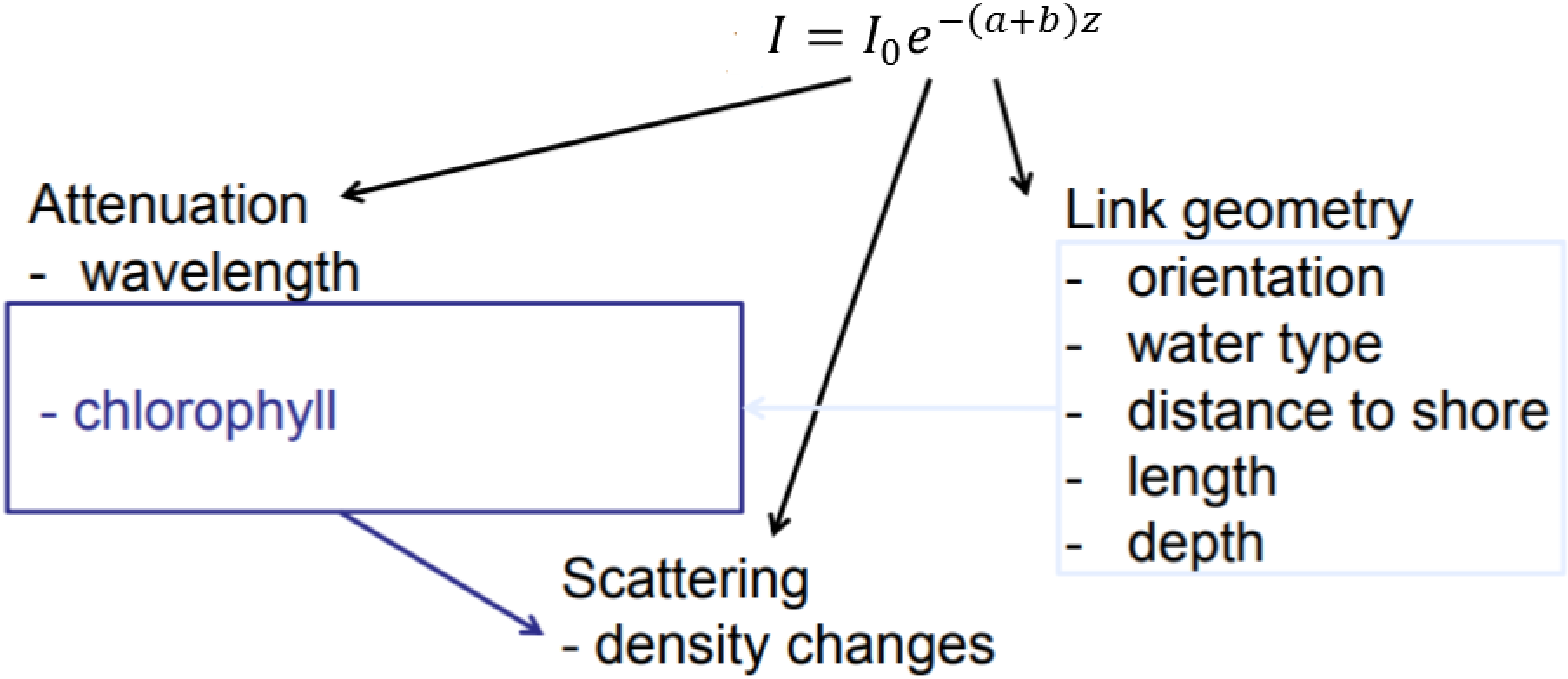
Typical Ballpark Values		
Water type	$a(m^{-1})$	$b(m^{-1})$
Clean water	0.114	0.037
Turbid water	0.226	1.824

Optically Significant Components of Aquatic Media



- The aquatic medium
  - Water
  - Dissolved particles
    - Organic
    - Inorganic
  - Particulates
    - Organic
      - Phytoplankton
      - Other
    - Inorganic
      - Natural
      - Pollutant
  - Bubbles

Channel Variation



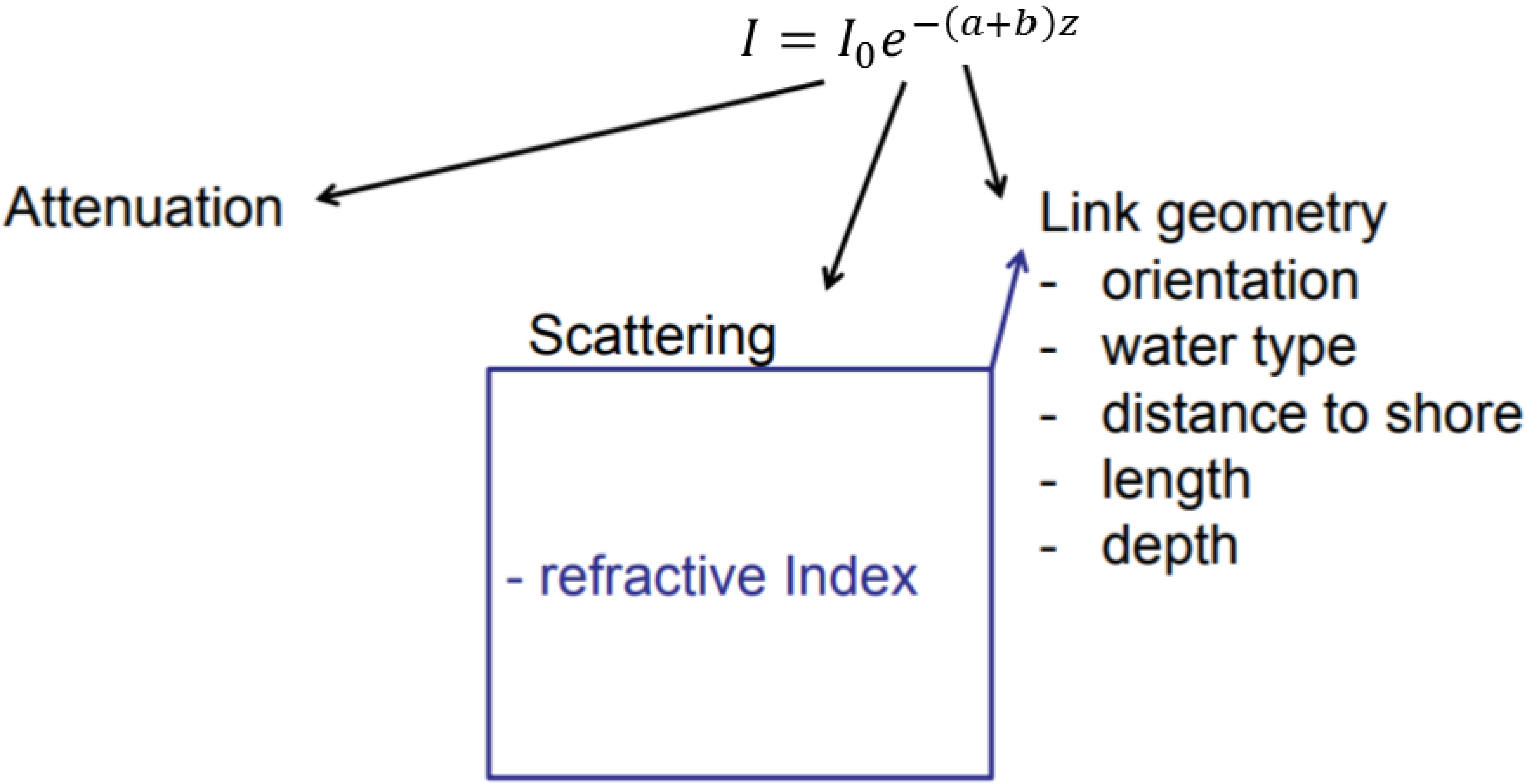
$$I = I_0 e^{-(a+b)z}$$

Attenuation
- wavelength
- chlorophyll

Scattering
- density changes

Link geometry
- orientation
- water type
- distance to shore
- length
- depth

Channel Variation



$$I = I_0 e^{-(a+b)z}$$

Attenuation

Scattering

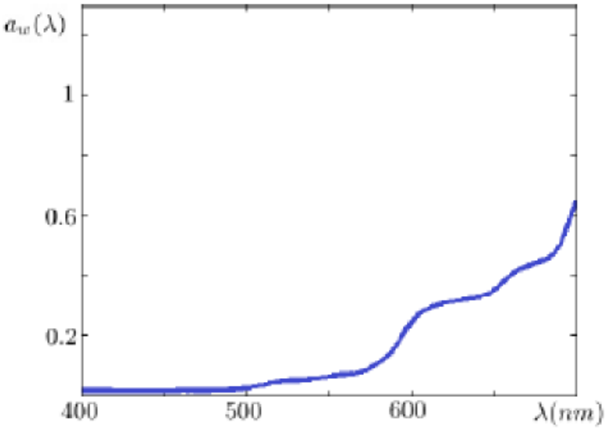
- refractive Index

Link geometry

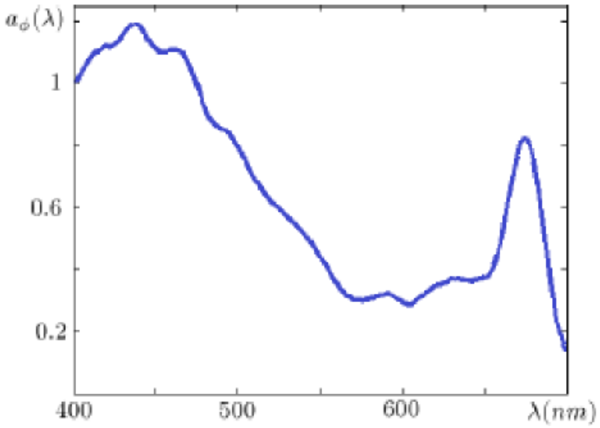
- orientation
- water type
- distance to shore
- length
- depth

Attenuation from Components

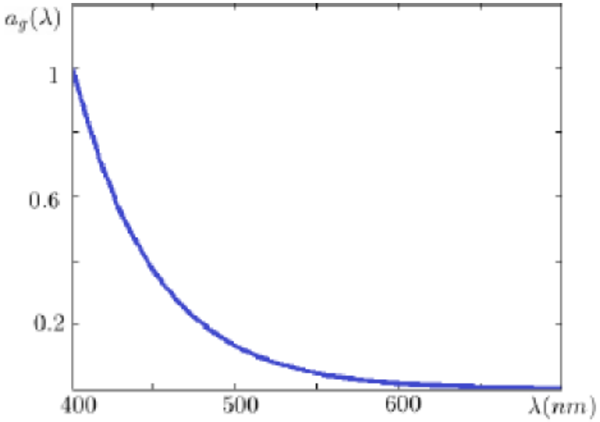
Pure water



Phytoplankton

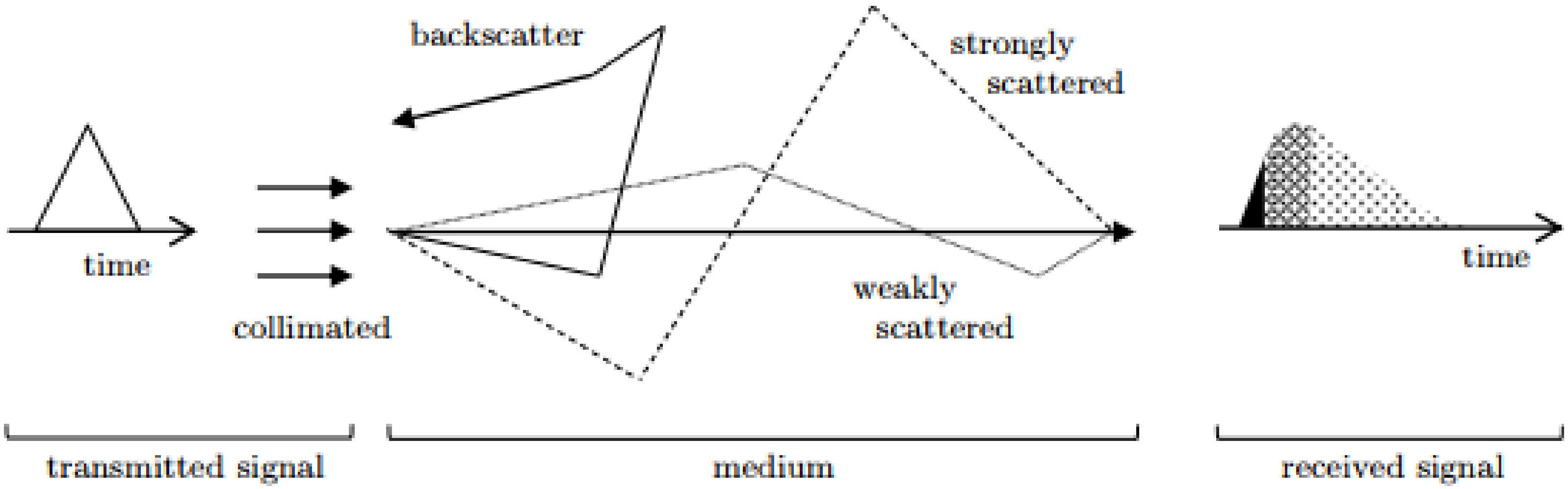


CDOM*



*colour dissolved organic material -dead & decaying organic matter

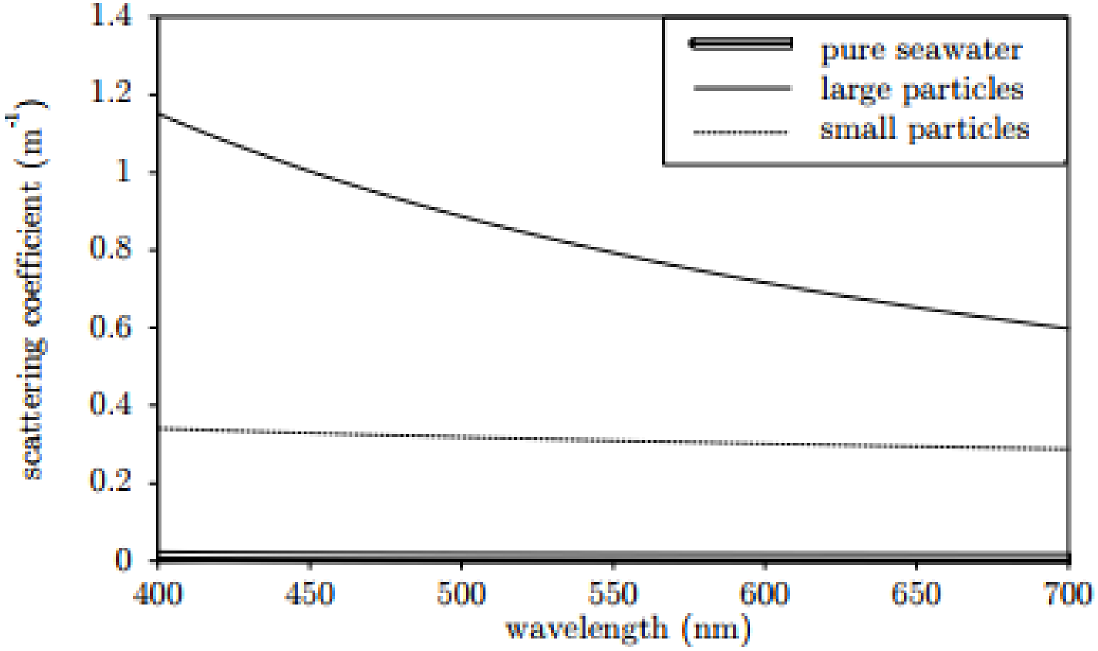
Scattering



Process causing changes in the direction of electromagnetic energy in an optical beam due to localised nonuniformities

- from different particles within the medium
- medium state variations resulting in varying refractive index

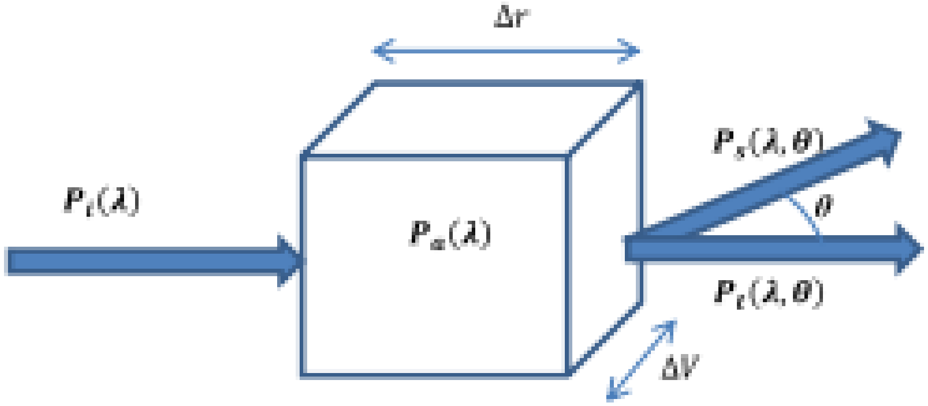
Scattering



Pure seawater and particulate scattering spectra, where small particles are defined as having a diameter < 1 μm. (data from Haltrin, 1999)

Modelling Scattering

Define volume scattering function (VSF), $\beta(\theta, \lambda)$ to describe angular distribution of scattered light to the incident irradiance per unit volume.



Inherent optical property geometry (Mobley, 1994)

For unpolarised incident light and isotropic water, the scattering becomes angular dependent and VSF for an angle θ into a solid angle ΔΩ is:

$$\beta(\theta, \lambda) = \lim_{\Delta r \to 0} \lim_{\Delta \Omega \to 0} \frac{\Delta B(\theta, \lambda)}{\Delta r \Delta \Omega}$$

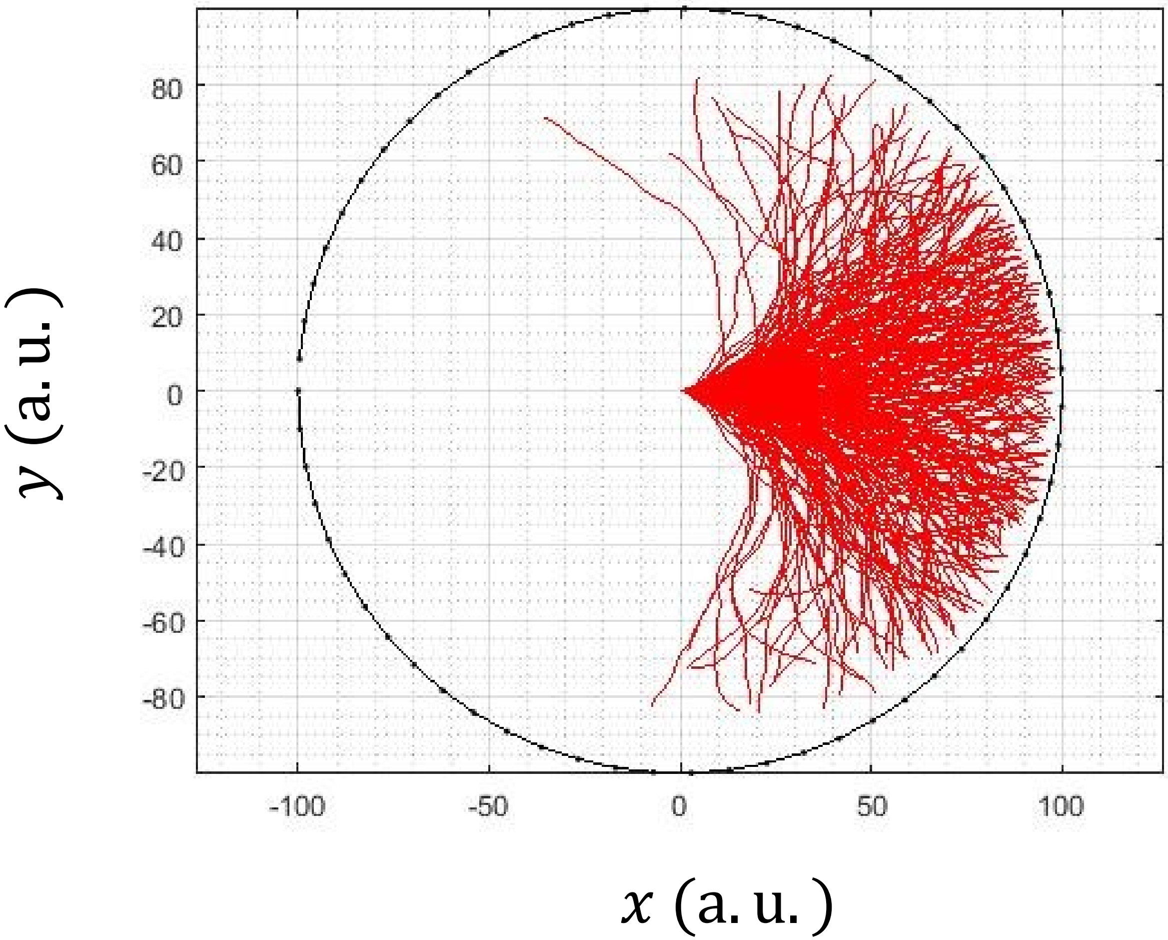
Modelling Scattering

Alternatively, use the angle between the direction vector of the incoming light $\mathbf{n}$ and the direction vector of the scattered light $\boldsymbol{n}'$ and relate it to scattering phase function $\tilde{\beta}(\boldsymbol{r},\theta)$ (that describes the angular distribution of the scattered photons) by $\beta(\mathbf{r},\mathbf{n},\mathbf{n}') = b\tilde{\beta}(\boldsymbol{r},\theta)$, where θ is defined as the scattering angle between $\boldsymbol{n}$ and $\boldsymbol{n}'$, i.e. $\boldsymbol{n}.\boldsymbol{n}' = \cos\theta$.

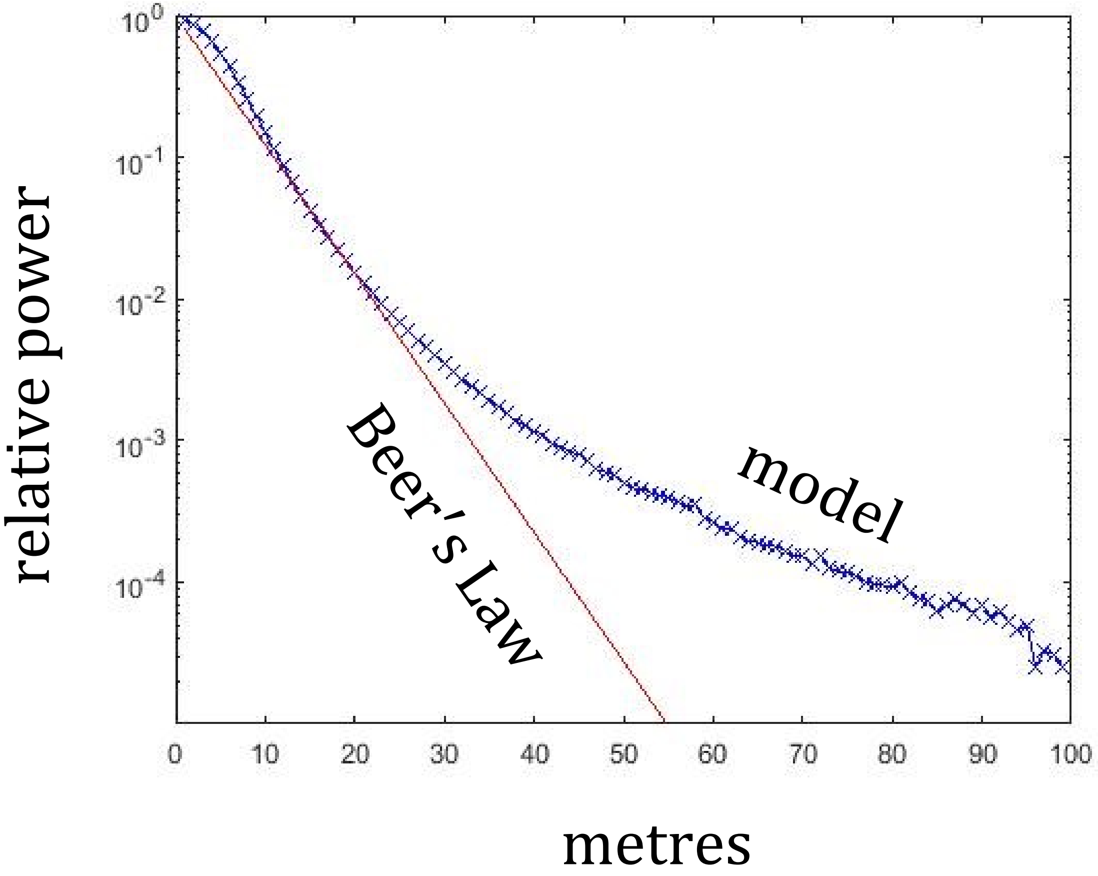
Form of $\tilde{\beta}(\boldsymbol{r},\theta)$ is a subject of ongoing work, the historical versions such as Henyey-Greenstein (HG) are old and not up to the job.

3D Simulation Model

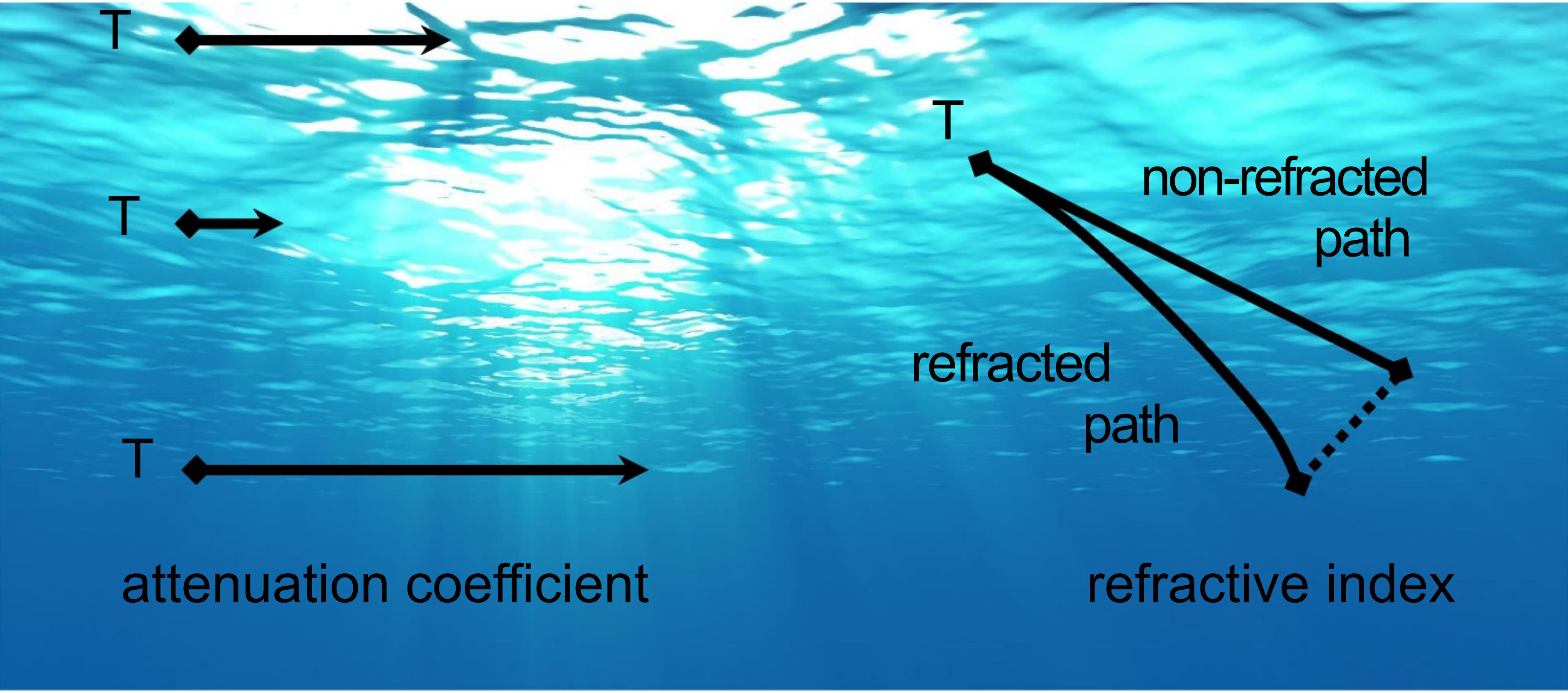
Cross-section through output



3D Model: Scattering Effect



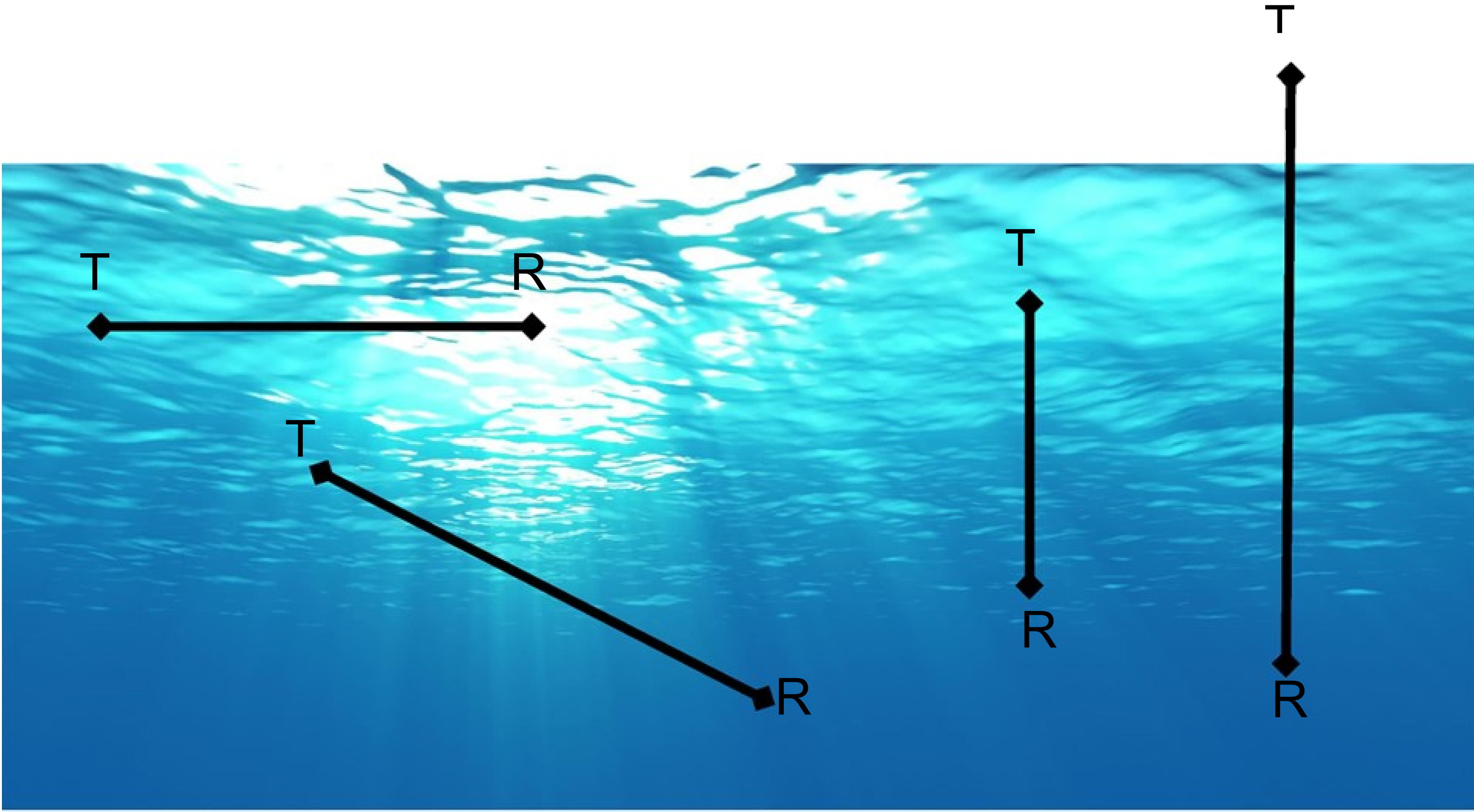
Impact of Link Orientation



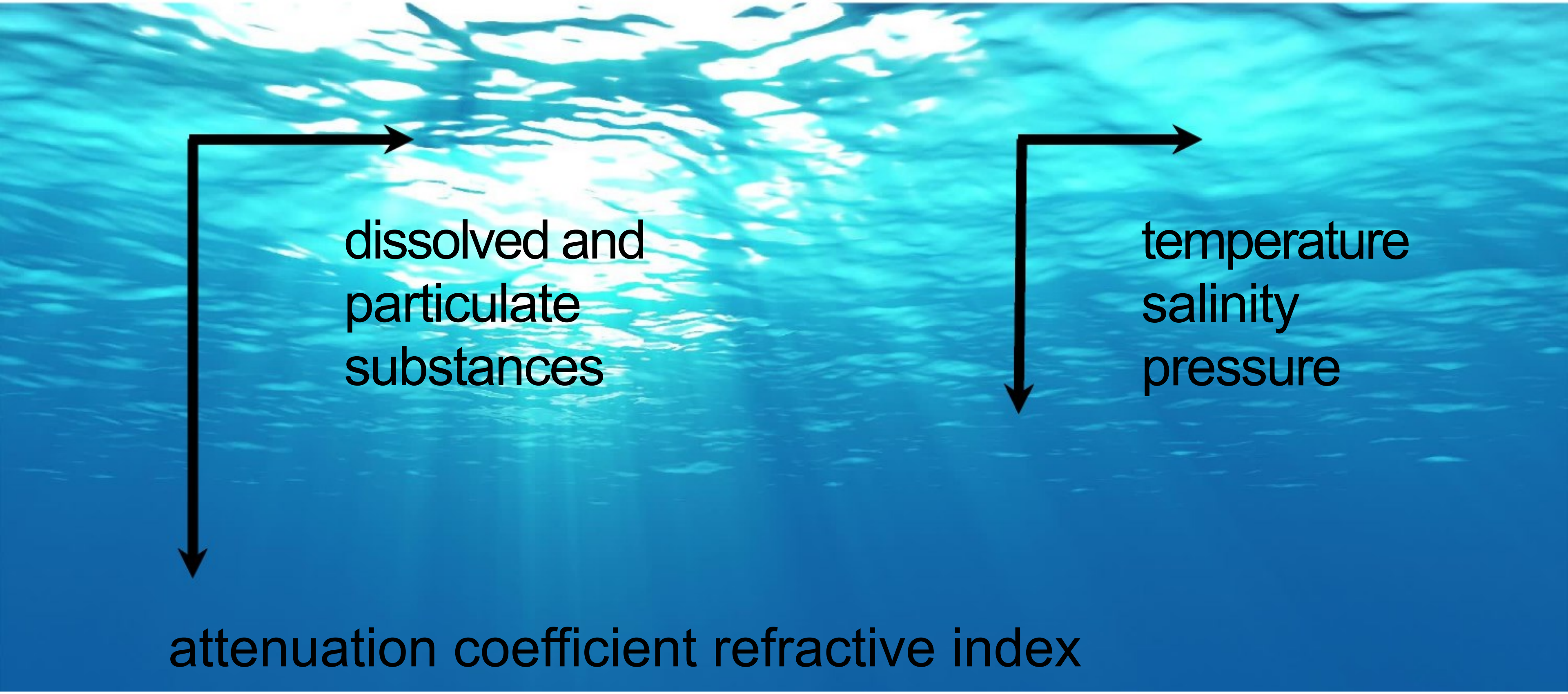
attenuation coefficient

refractive index

Link Orientation: Why it Matters



Link Orientation: Causes of Variation



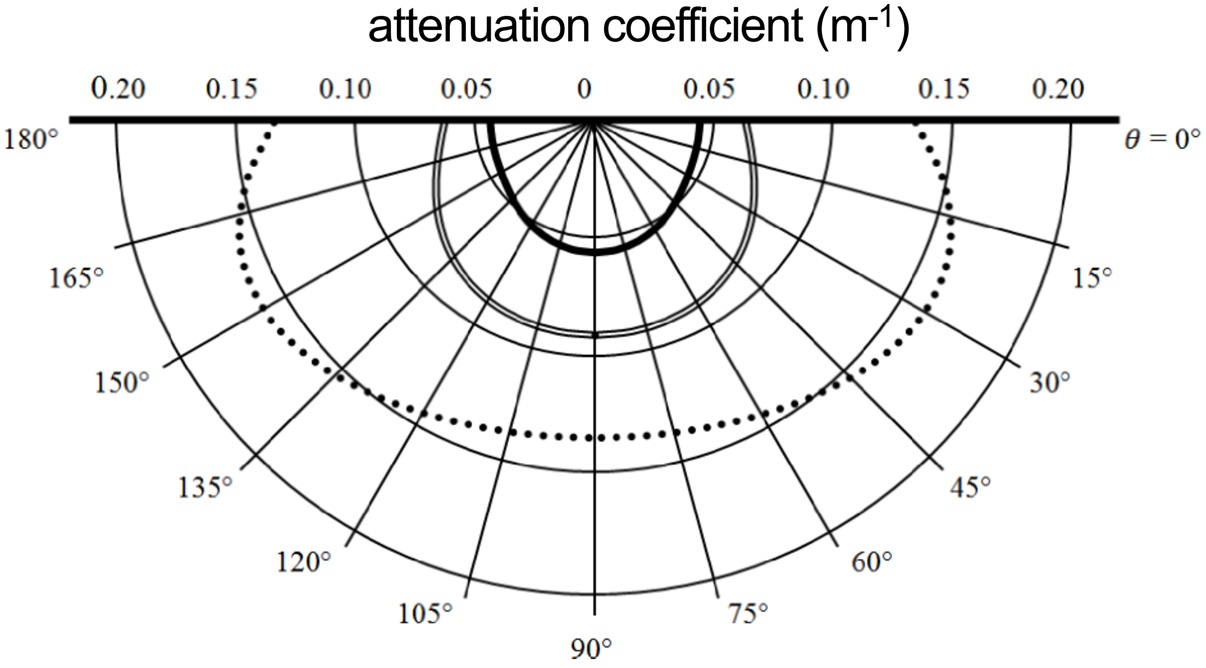
dissolved and particulate substances

temperature
salinity
pressure

attenuation coefficient refractive index

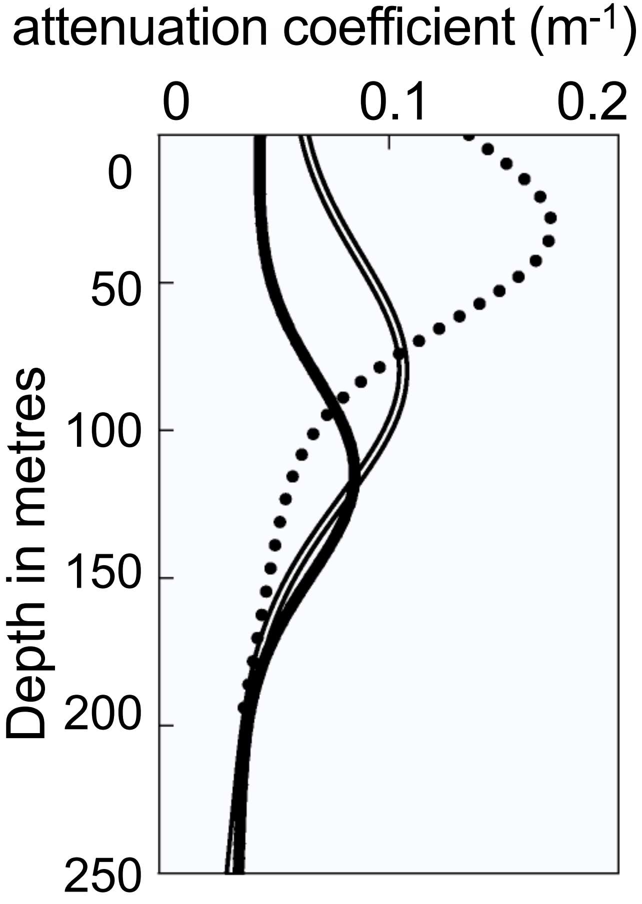
Attenuation Variation

Simulation of 200m links from a fixed starting position with average attenuation for each angle recorded



Attenuation Variation

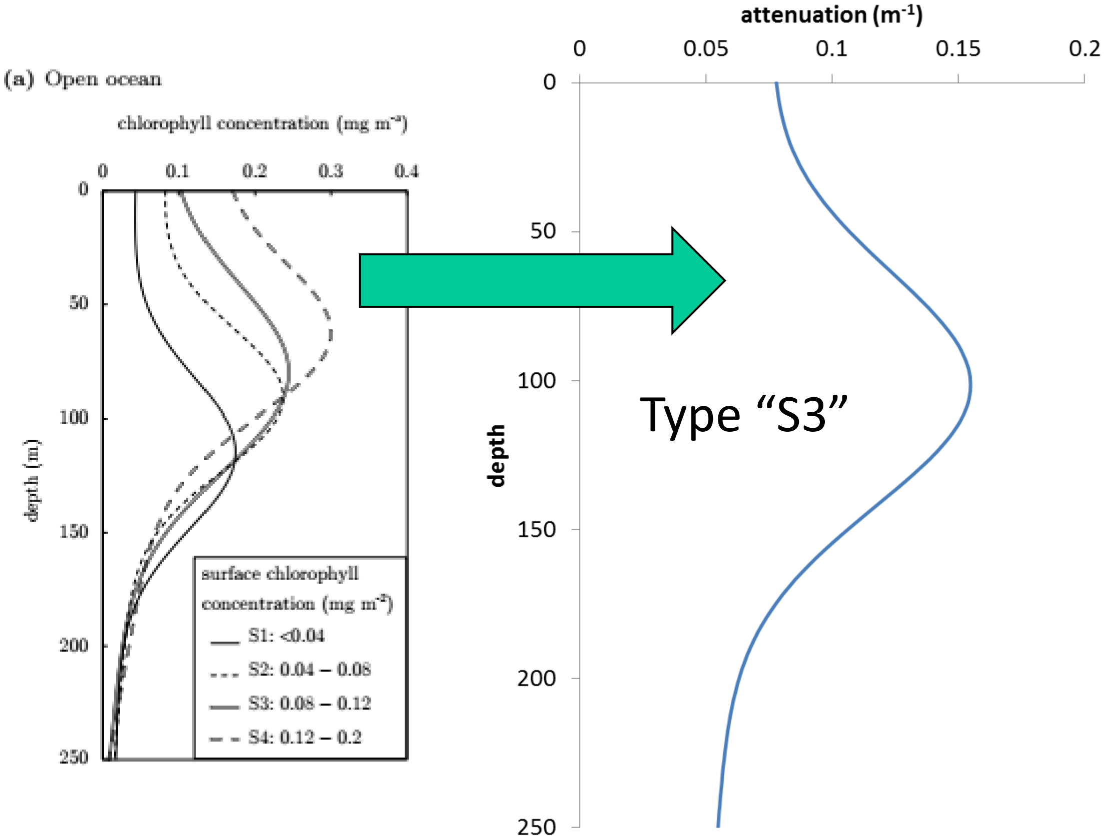
Attenuation with depth is found using bio-optical models of phytoplankton with depth and relations between constituent concentrations



Johnson, Green and Leeson, App. Opt. 52(33), 2013

Attenuation Variation

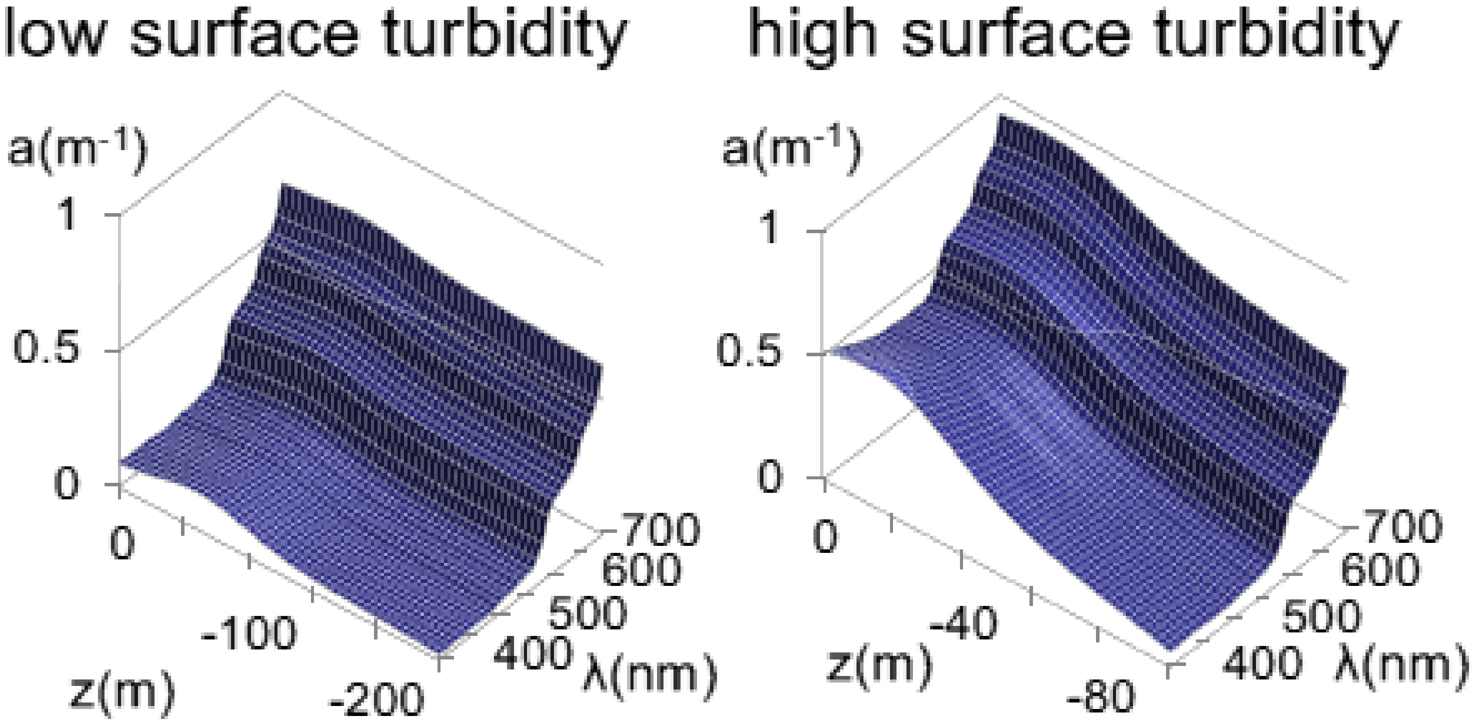
Specific case for illustration purposes



Type “S3”

Johnson, Green and Leeson, App. Opt. 52(33), 2013

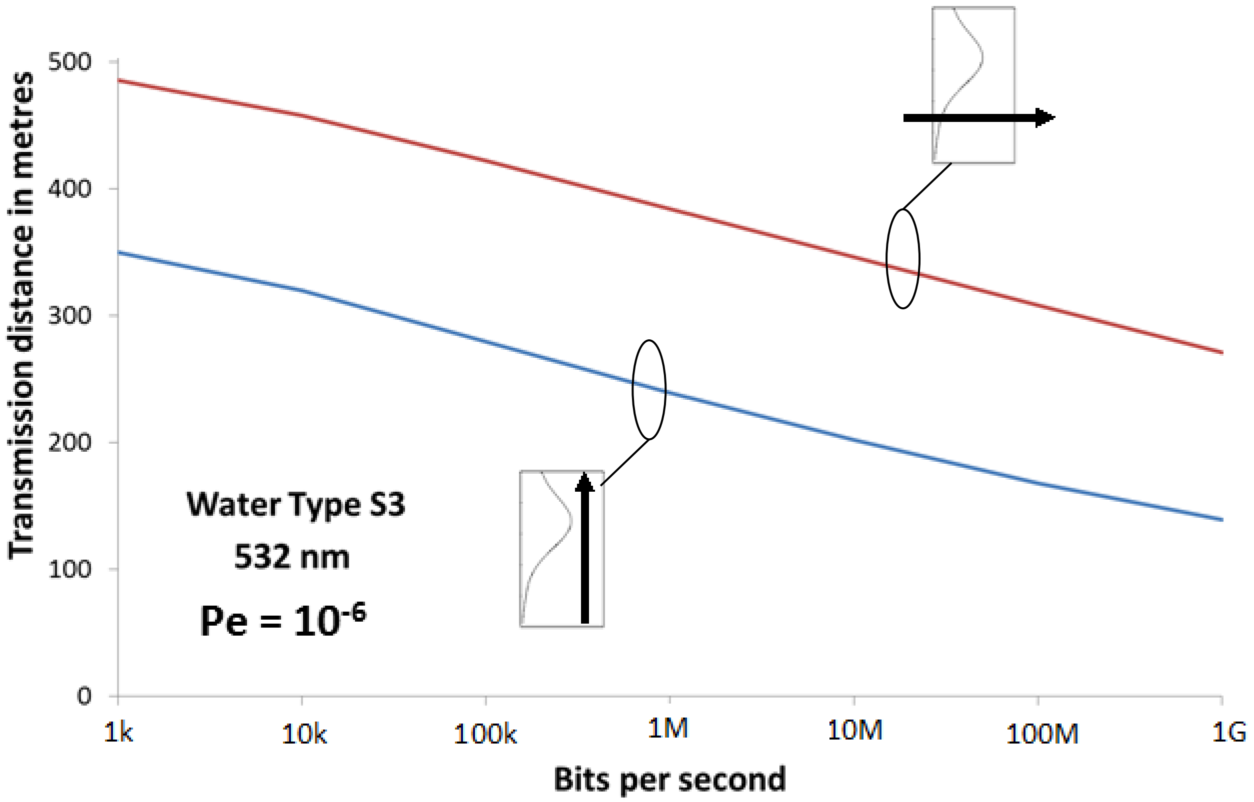
Absorption with Depth



low surface turbidity

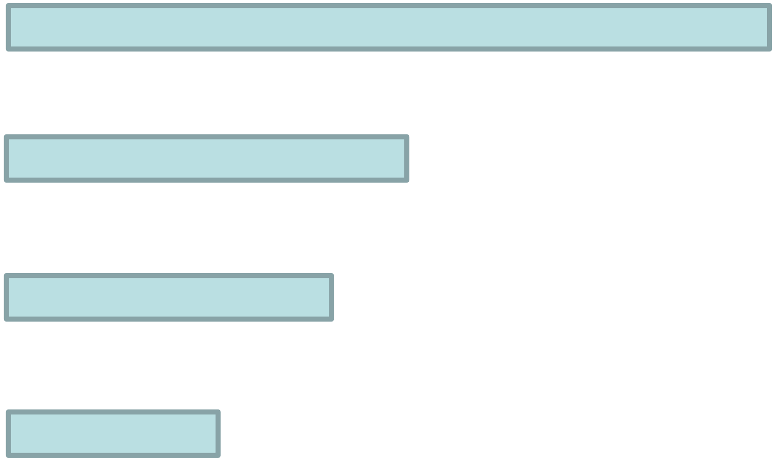
high surface turbidity

Maximum Link Distance



Attenuation Variation

Significant implications for link distance.
For example, the distances become...



100 m, minimum attenuation

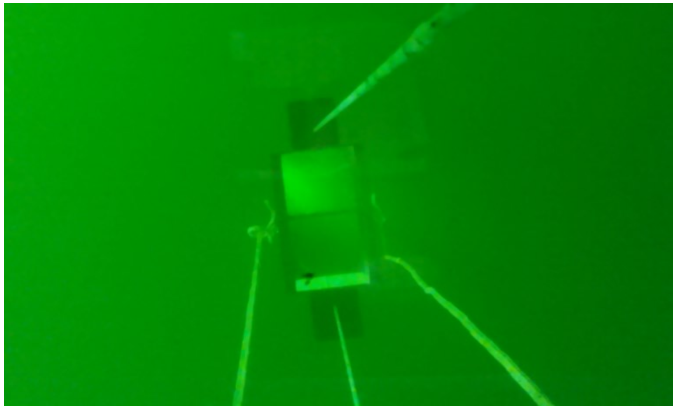
52 m, surface attenuation

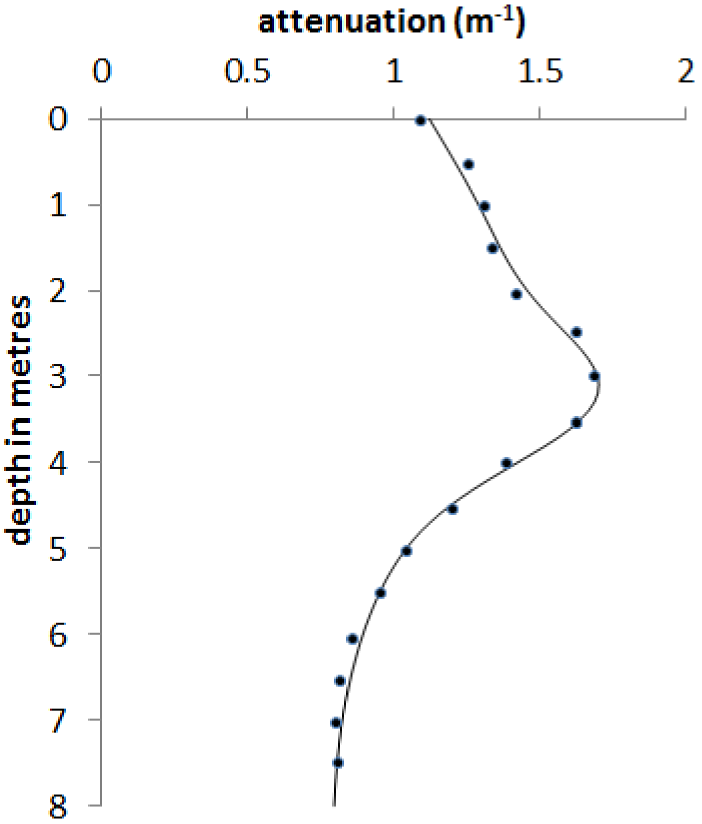
42 m, average attenuation

27 m, peak attenuation

Practical Attenuation Variation

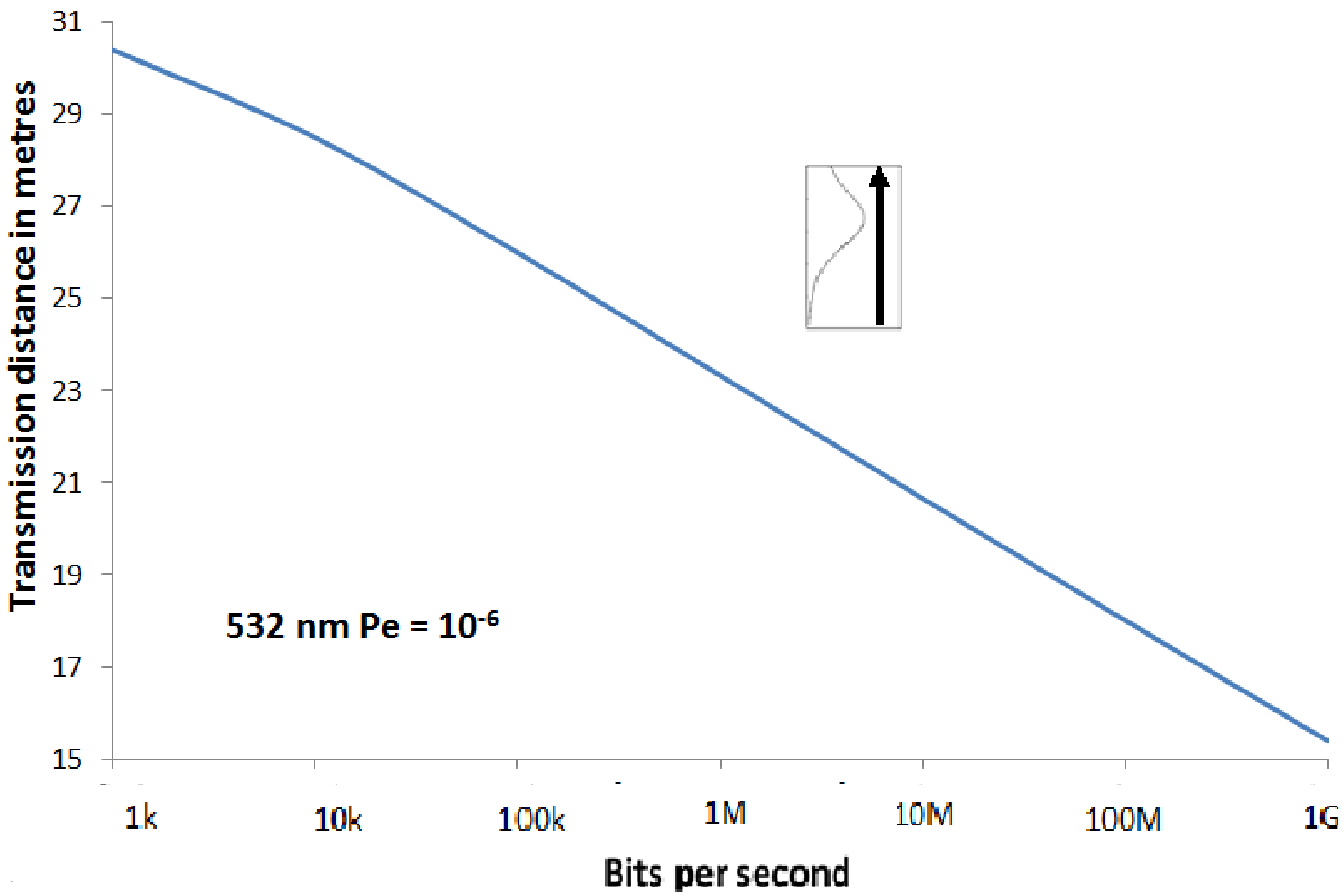
"The murky depths!"



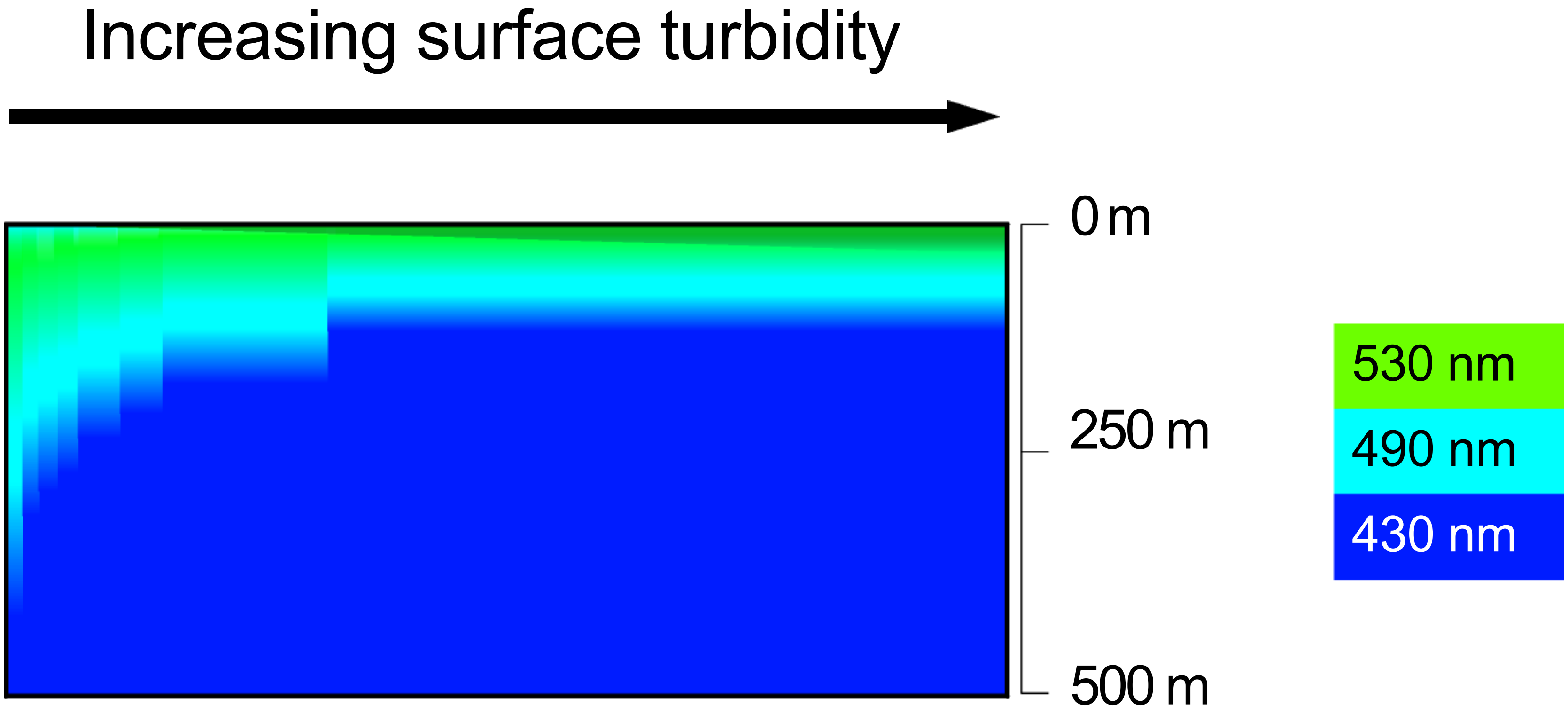


Measured data are shown by the circles with a MATLAB fit (solid line)

Practical Link Distance Prediction



Optimal Transmission Wavelengths



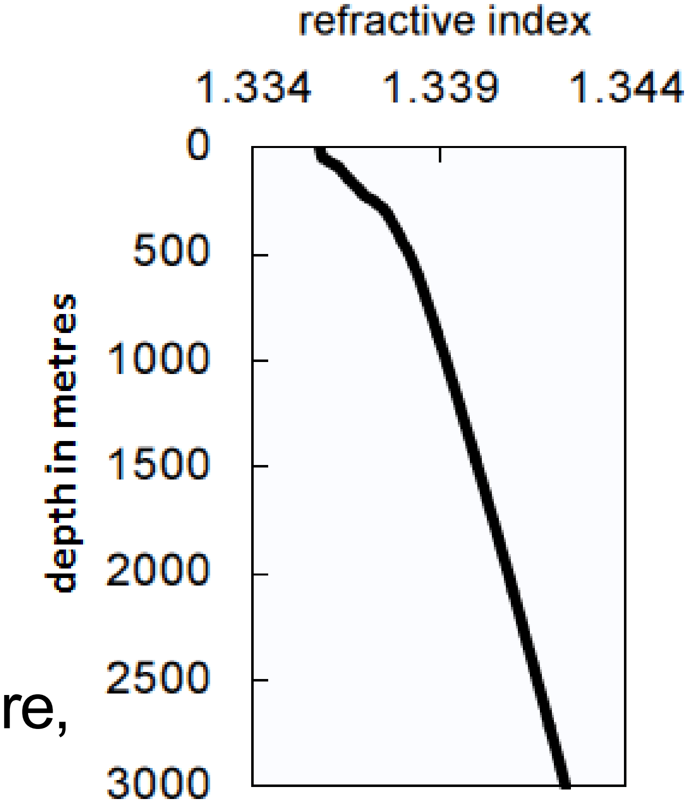
Refractive Index Variation

Changes grouped by scale

- Small scale, scattering
- Medium scale, turbulence
- Large scale, global gradients

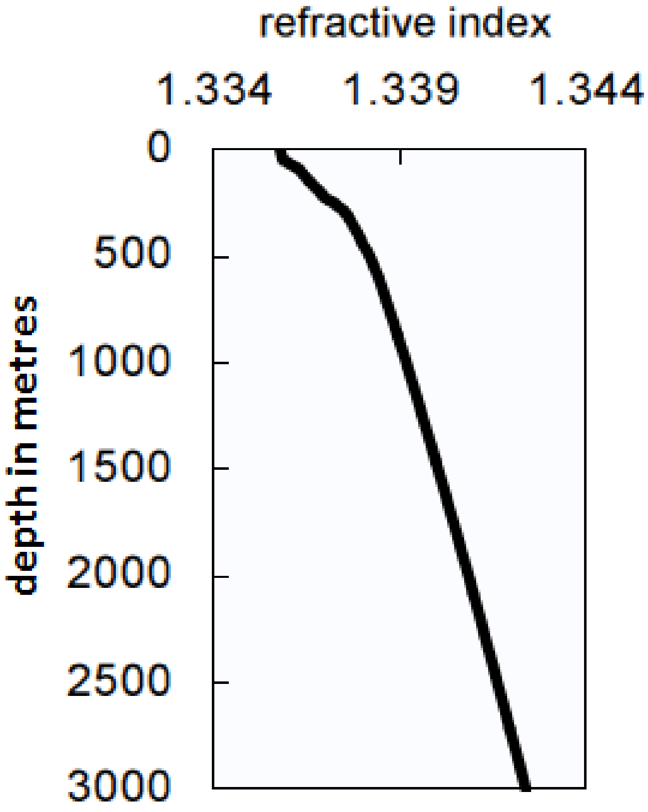
Causes

- Salinity, pressure, temperature, density



Refractive Index Variation

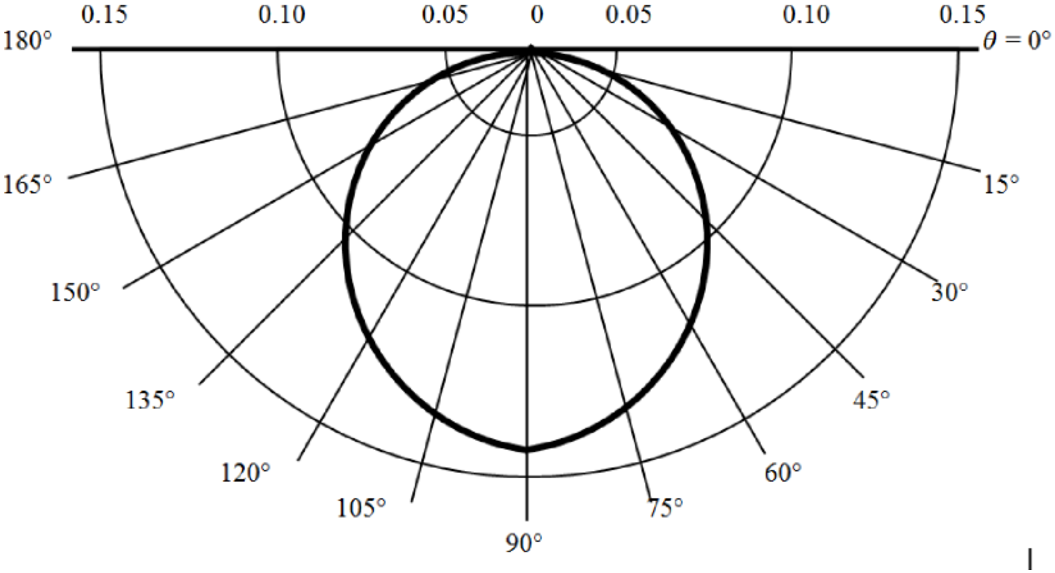
Refractive index gradients found using data available for research using an algorithm which calculates refractive indices, based on the values of temperature, wavelength, salinity and pressure



Refractive Index Variation

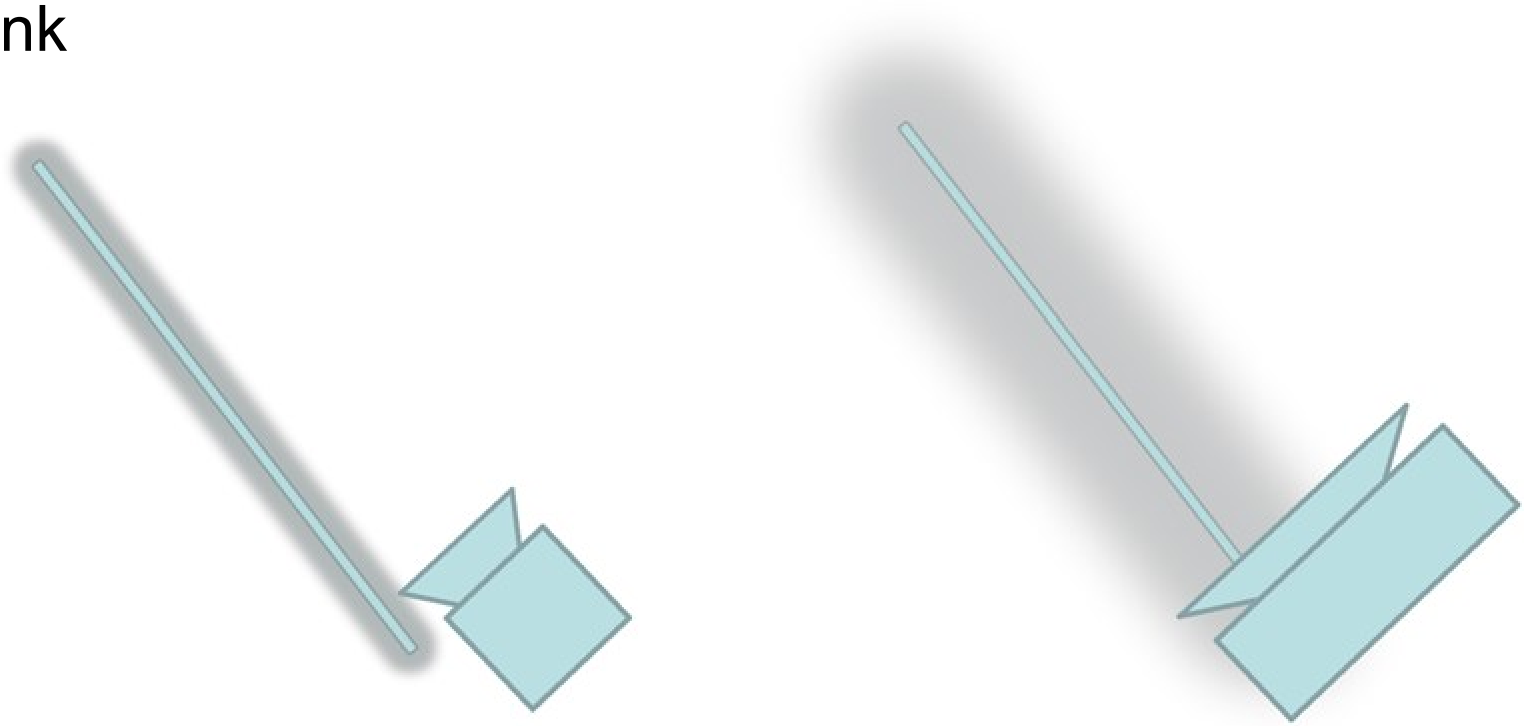
Ray tracing used to plot 200m link paths, which had different starting angles and depths, and measure size of the deviation created by refraction

magnitude of deviation (m)



Refractive Index Variation

Significance of the findings significant depends on beam angle, transmitter FOV, the magnitude of deviation (m) and the amount of scattering in the link



A Fuller Treatment

We have to employ the Radiative Transfer Equation (RTE)

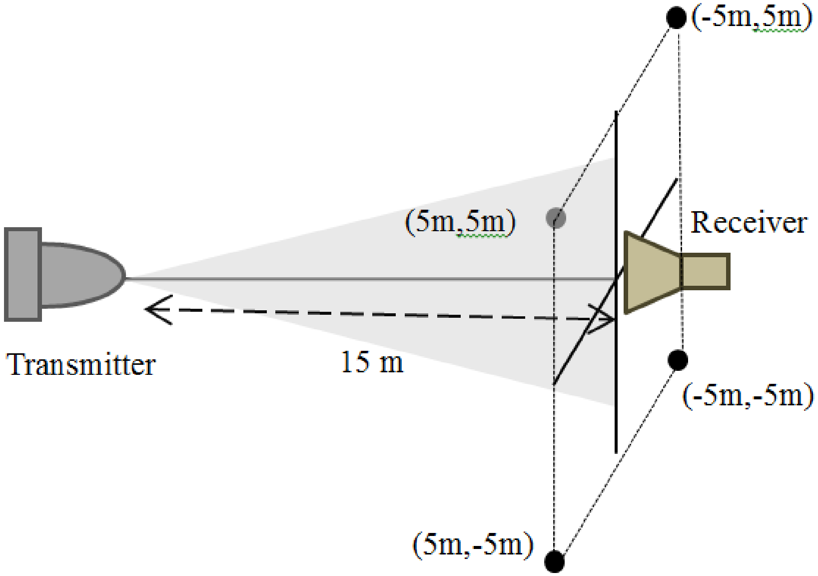
$$\left[\frac{1}{\nu}\frac{\partial}{\partial \mathrm{t}} + \mathbf{n}\,.\,\boldsymbol{\nabla}_{\mathbf{r}}\right]\mathrm{I}(\mathrm{t},\mathbf{r},\mathbf{n}) = \int_{4\pi} \beta(\mathbf{r},\mathbf{n},\mathbf{n}')\mathrm{I}(\mathrm{t},\mathbf{r},\mathbf{n}')\mathrm{d}\mathbf{n}' - \mathrm{cI}(\mathrm{t},\mathbf{r},\mathbf{n}) + \mathrm{E}(\mathrm{t},\mathbf{r},\mathbf{n})$$

No analytical solutions for useful scenarios

Approximate analytical solutions possible for transmitter field of view (FOV) less than 10° but loses the temporal information as scattered and non-scattered photons are considered to travel the same distance in the same time.

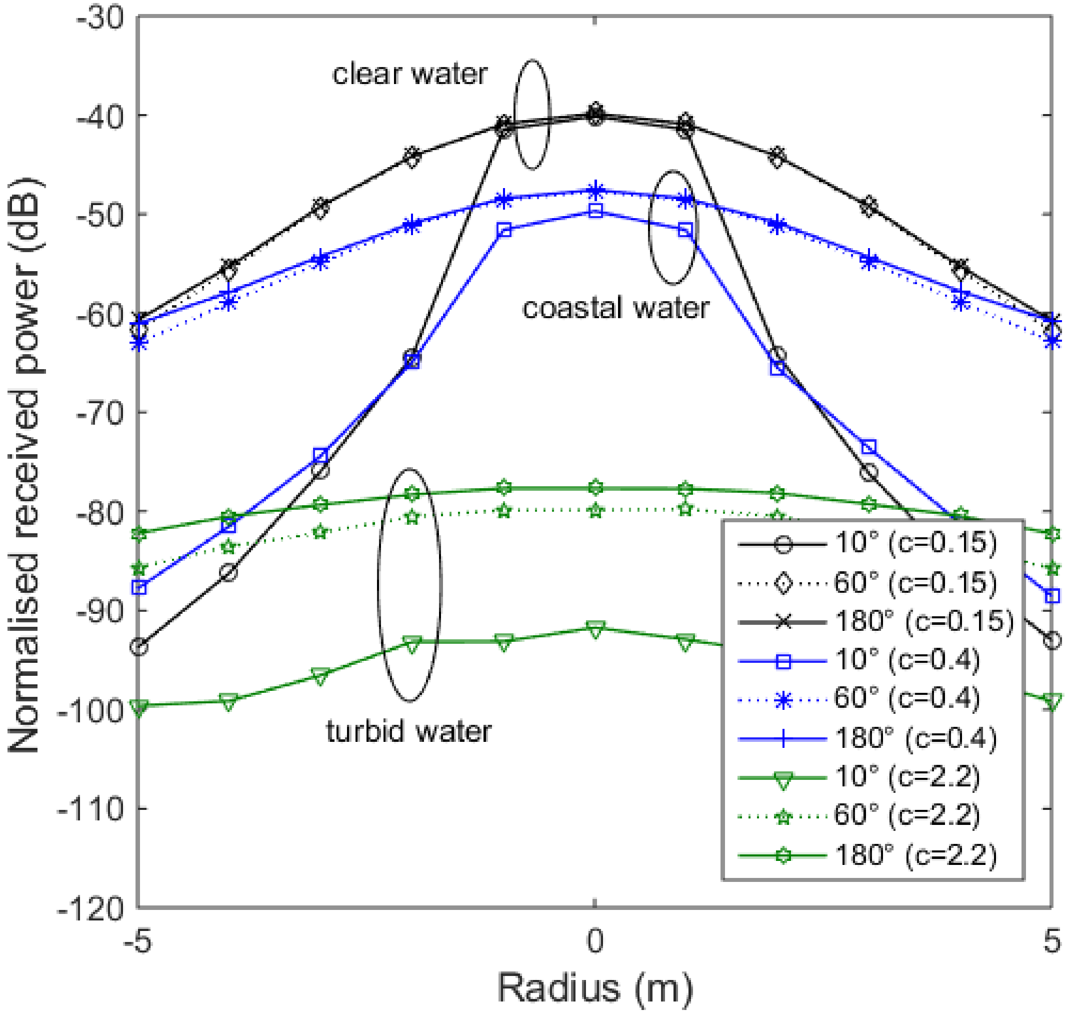
Numerical solutions – Monte Carlo

FOV Simulation: Diffuse LOS Link

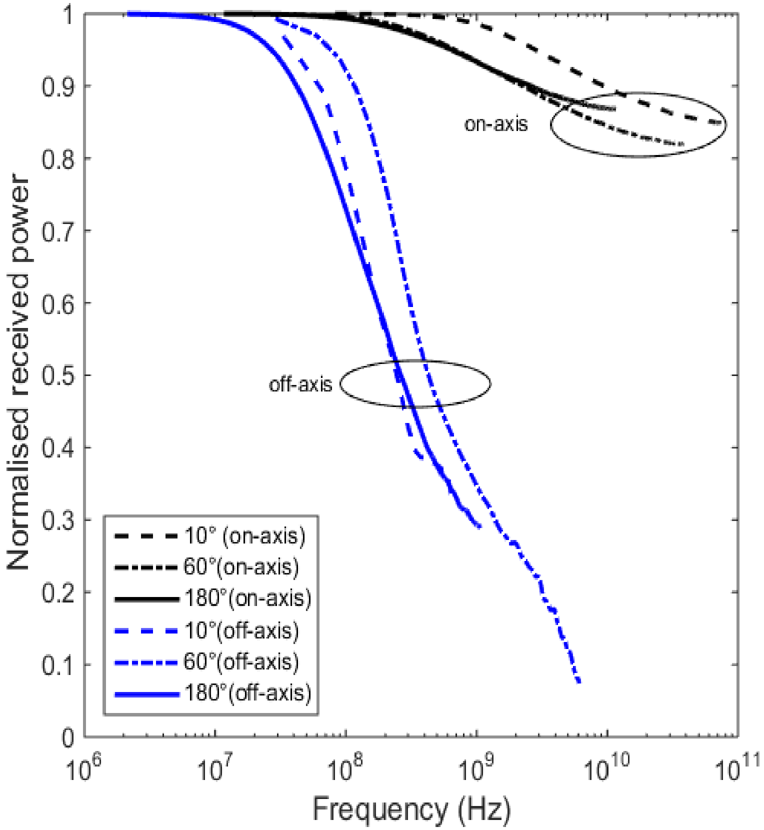


Jasman, Green and Leeson, Microwave and Optical Technology Letters, 59(4) 837-840, 2017.

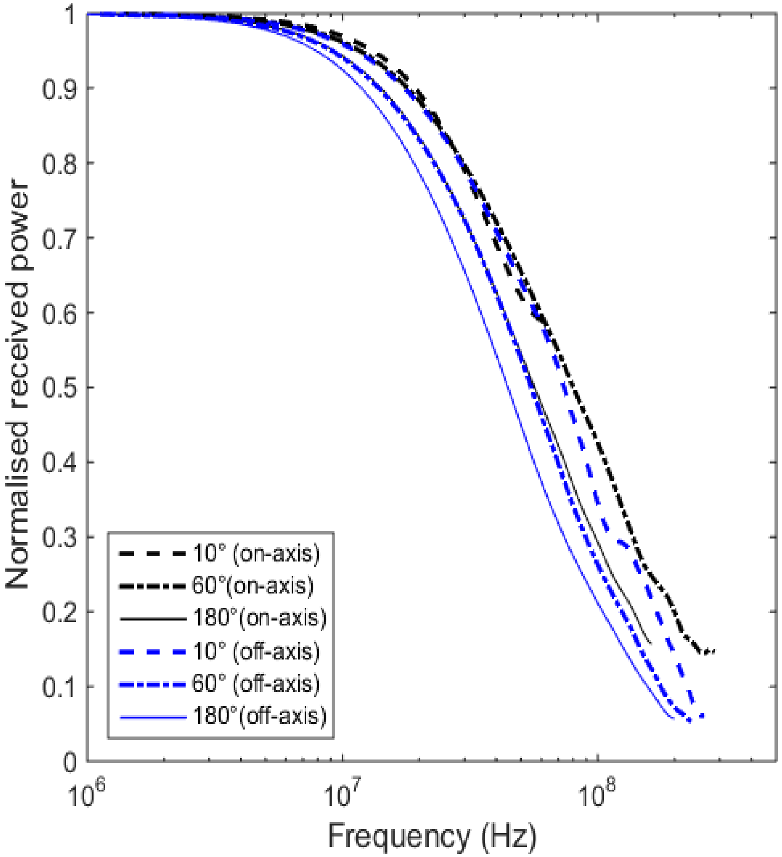
FOV Simulation: Power Distribution



FOV Simulation: Frequency Response

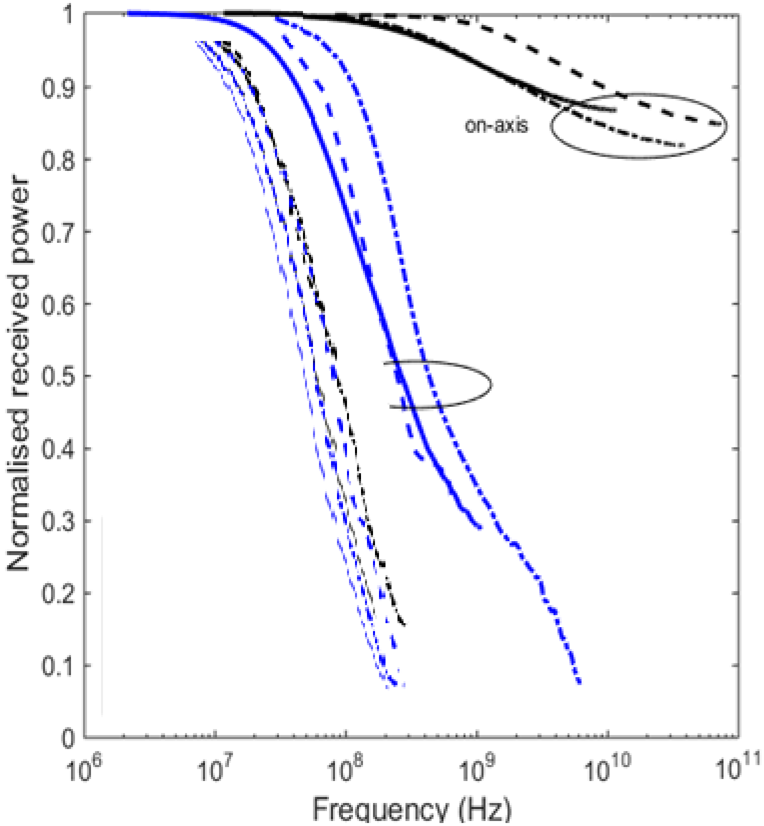


Clear water



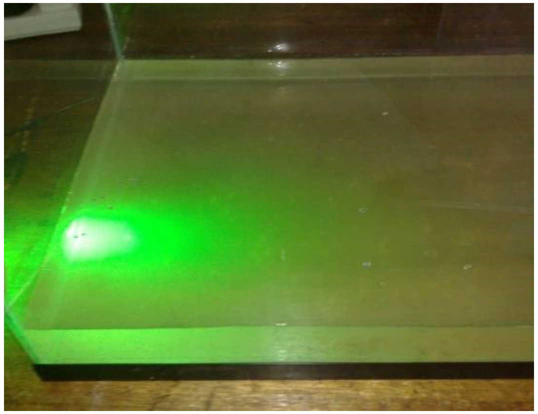
Turbid water

FOV Simulation: Frequency Response



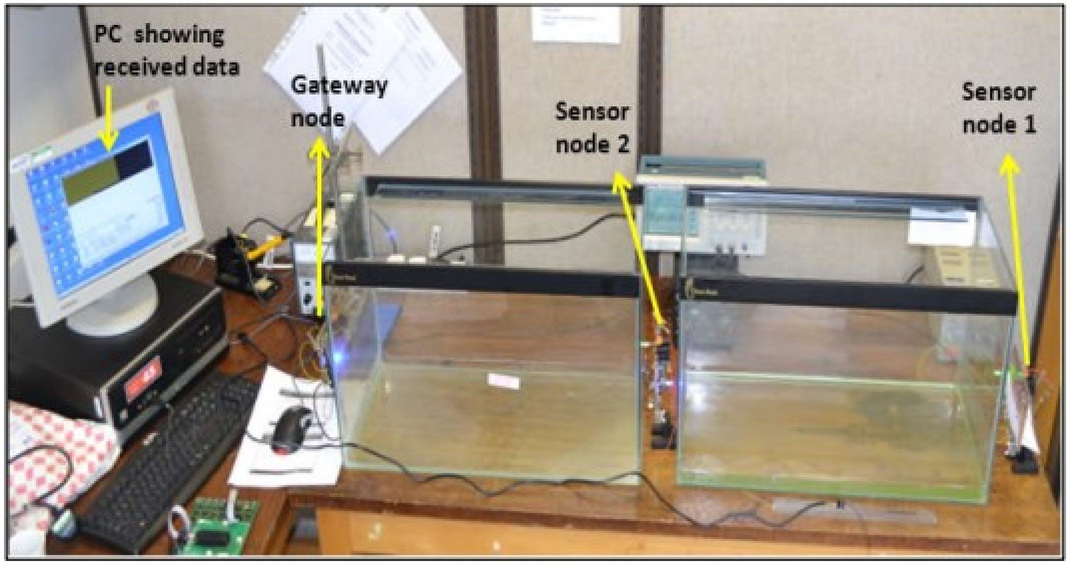
On the same scale – much reduced in turbid water

Practical Work



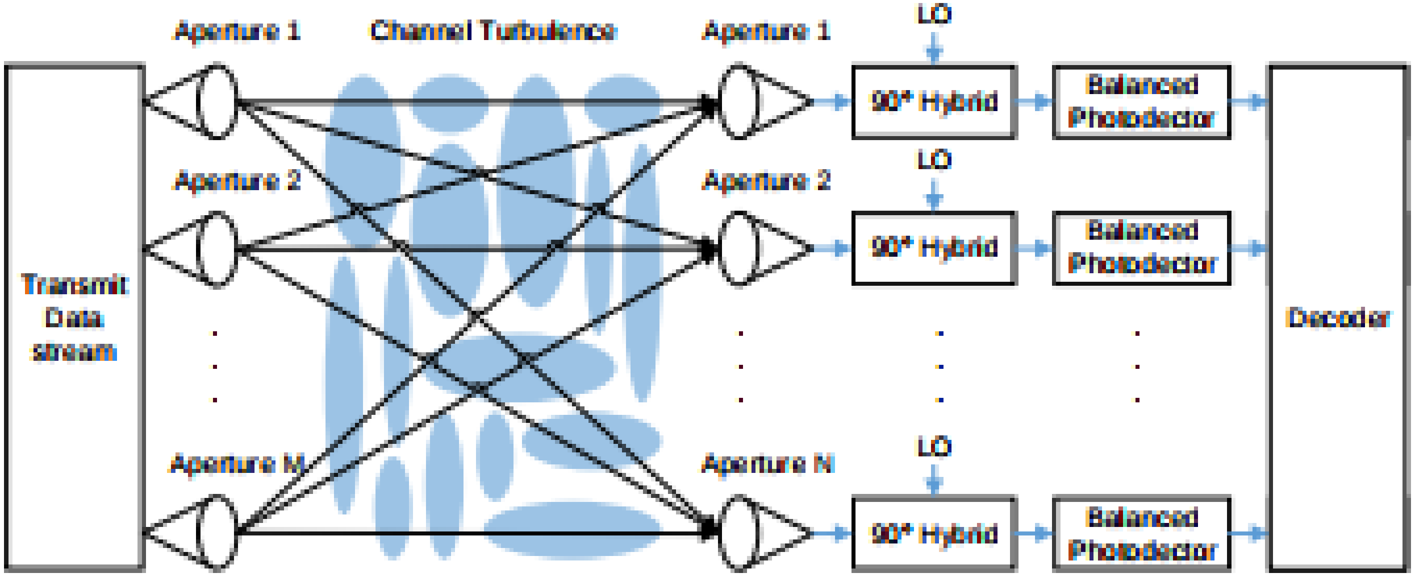
Transmission of data using IRDA protocol 8 Mbps

Some Practical Results



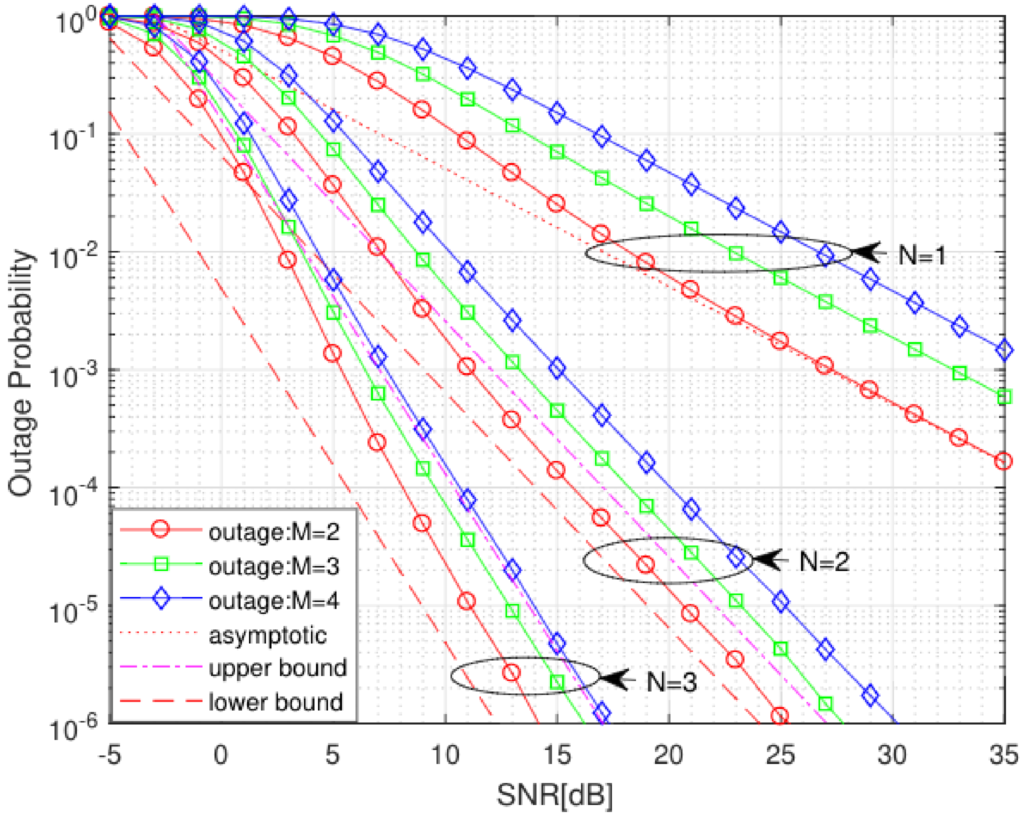
Multiple hop arrangement

Diversity



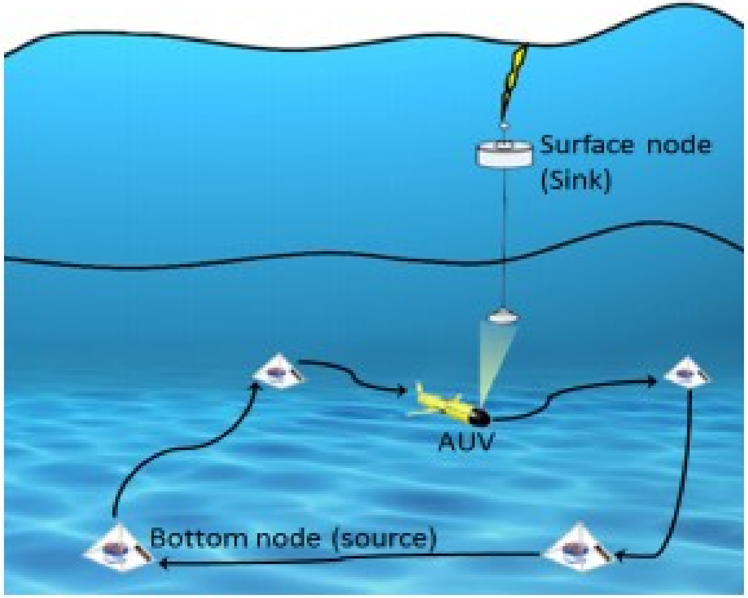
UOWC Multiple Input Multiple Output (MIMO) transmission through turbulence

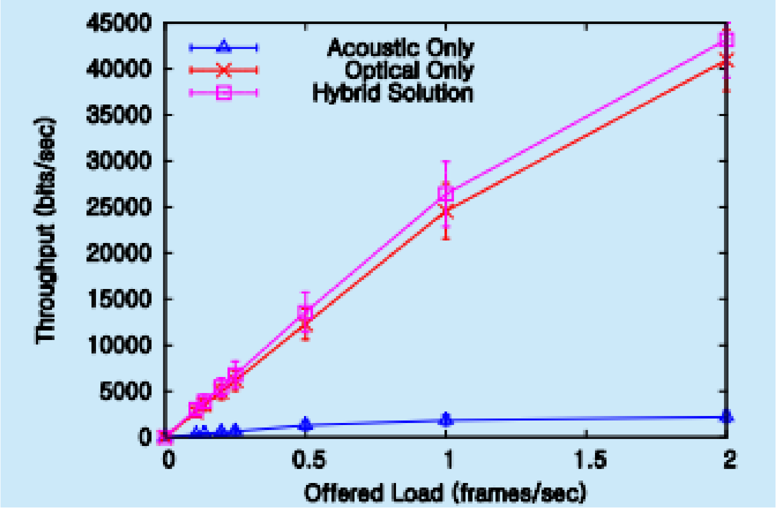
Diversity: Outage Performance



Gamma-Gamma turbulence

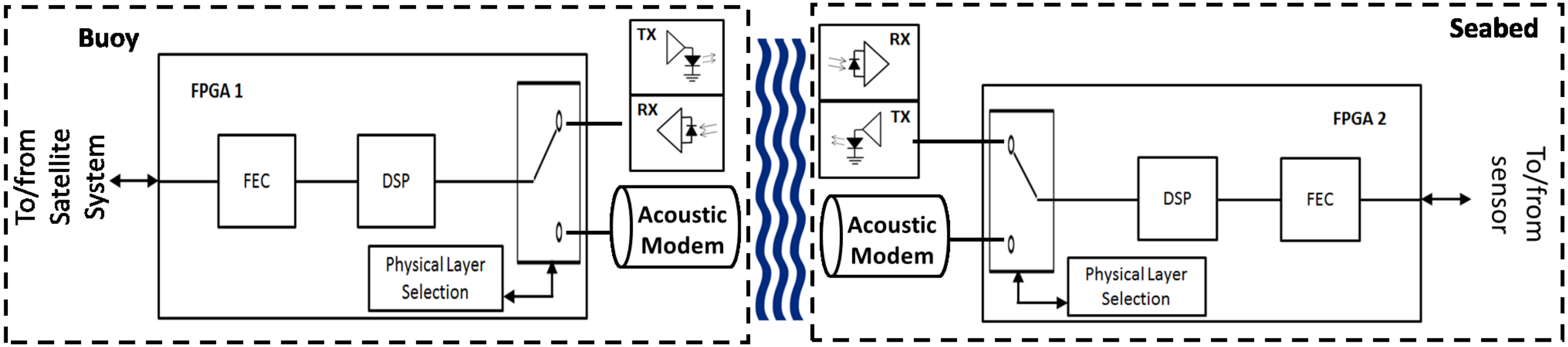
Hybrid System





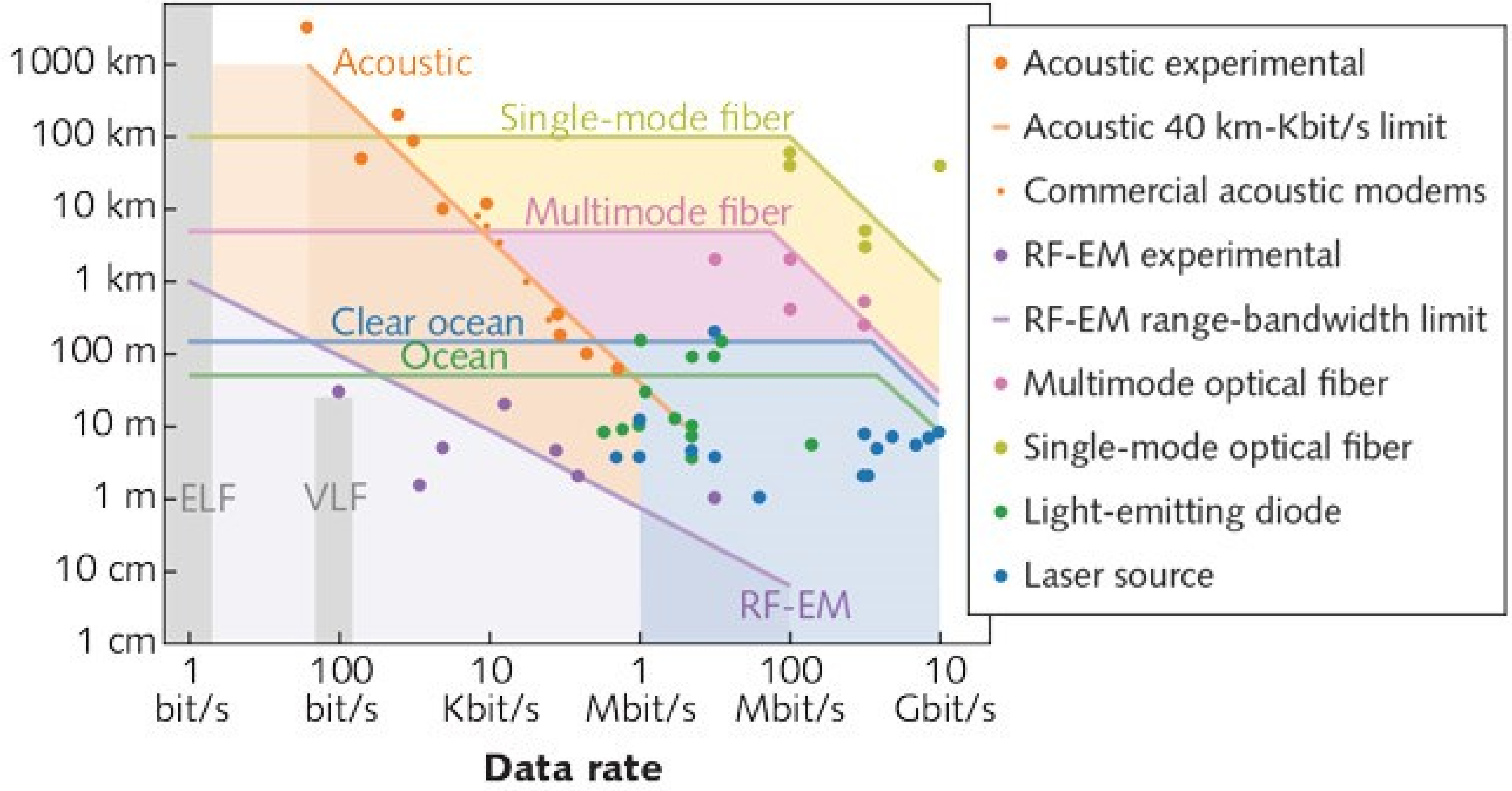
Han et al., China Communications, 11(5), 49–59, 2014

Hybrid Systems



Work needed on implementing protocols and functions in FPGAs or similar

Latest Comparison



Muth, Laser Focus World, 53(5), 2017

Conclusions

The incumbent technologies have major limitations

Optical wireless shows promise underwater

Visible light is essential

Understanding of water properties needed

Link orientation is important

High bit rates are possible in

- clearer water or
- over short distances

There are many subtleties in absorption and refraction

Future Directions

Improved channel modelling

Coding and error correction

Modulation methods

Improved practical arrangement

Receiver enhancements

  - Optical preamplifiers
  - More on Coherent transmission

Questions

Thank you for your attention.