**TECHNICAL UNIVERSITY of CRETE**

Department of Electronic and Computer Engineering

# Development of an Underwater Vision Improving System

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Chania, Crete 2015

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Dedicated to my mother,

who has been very supportive through all these years, which were not few.

## Abstract

Underwater imaging is important for scientific research and technology, as well as for popular activities. This paper describes a method to overcome limitations in underwater imaging using colour correction and polarizing filters. Scattering and colour absorption are two major problems of distortion for imaging, especially in underwater environment. Scattering is caused by large suspended particles, like fog or turbid water. Colour degradation corresponds to the varying degrees of attenuation encountered by light travelling in the water with different wavelengths, rendering ambient underwater environments dominated by a bluish tone. Our key target was to create a simple and cost efficient method eliminating satisfactorily image blurring and increase colour intensity and visual acuity in natural an artificial lighting source. We demonstrated light as a signal with scattering and backscattering distorting images and also analyzed the function of the human eye contributing to the constraints of vision especially in underwater environment. We researched various different approaches encounter the same topic and made a comparative study and developed an underwater vision system which improves contrast and visual image quality and explained the physical effects of visibility degradation.

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# Water World

Figure 1 - Underwater life of Klein Bonaire (a small uninhabited islet off the west coast of the Caribbean)

The sea is the connected body of salty water that covers 70.8% of the Earth's surface **[1]**, the 97% of the water on the Earth is salt water and only three percent is fresh water and slightly over two thirds of this is frozen in glaciers and polar ice caps **[2]**. The sea moderates the Earth's climate and has important roles in the water cycle, carbon cycle, and nitrogen cycle. Without water, our planet would be just one of billions of lifeless rocks floating endlessly in the vastness of the inky-black void **[3]**. The sea has been travelled and explored since prehistory and the modern scientific study of the sea is called oceanography. The sea is conventionally divided into four or five large sections, such as the Pacific, called oceans while smaller sections, such as the Mediterranean, are known as seas **[4]**.

The Earth's oceans are the central engine of the energy and chemical balance that sustains humankind. They provide warmth and power. They moderate the weather so food can be grown on land to feed the Earth's population. Their living resources also supply food. Understanding them is one of humanity's most important challenges **[5]**.

The existence of underwater food reserves was the first reason for human activities expansion to the water world. Great civilization progress was triggered by this transgression of human, terrestrially bounded specifications. For centuries, explorers and scientists have taken to the high seas or journeyed into the ocean’s depths to view, measure, and study its wonders. The methods they use range from a simple bucket swung overboard to a highly sophisticated, remotely operated vehicle towed miles beneath the surface **[6]**.

Ship construction and overseas navigation changed forever the human interaction with nature. Underwater natural resources, such as fossil fuels along with the exploration efforts for the vast ocean biodiversity, were the basic reasons to promote marine activities and research during last century **[5]**. Man was always interested going underwater with the curiosity for the underwater world trying to find his limits. Man has designed underwater futuristic colonies with the ambition to live underwater.

Figure 2 - Fabian Cousteau after a 31 day underwater mission

One of the most famous undersea explorers and oceanographers of the 20th century is Jacques Cousteau. Jacques Cousteau (1910 – 1997) was a French undersea explorer, researcher, photographer and documentary host who invented diving and scuba devices, including the Aqua-Lung. He also conducted underwater expeditions and produced films and television series, including the Undersea World of Jacques Cousteau **[7]**.

Figure 3 - Jacques Cousteau 1910-1997 - Print by Granger

In 1964 he presents a new documentary called World without Sun, where he and his specialized diving team also called oceanauts, design, build and live in an underwater station where they lived in a star-fish shaped house for 30 days in 10 meters deep. The undersea living experiment also had two other structures, one a submarine hangar that housed a small, two man submarine referred to as the "diving saucer" for its resemblance to a science fiction flying saucer, and a smaller "deep cabin" where two oceanauts lived at a depth of 30 meters for a week. The undersea colony was supported with air, water, food, power, all essentials of life, from a large support team above. Men on the bottom performed a number of experiments intended to determine the practicality of working on the sea floor and were subjected to continual medical examinations.

The years of World War II were decisive for the history of diving. After the armistice of 1940, the family of Simone and Jacques-Yves Cousteau took refuge in Megève (south-eastern France), where he became a friend of the Ichac family who also lived there. Jacques-Yves Cousteau and Marcel Ichac shared the same desire to reveal to the general public unknown and inaccessible places — for Cousteau the underwater world and for Ichac the high mountains. The two neighbors took the first ex-aequo prize of the Congress of Documentary Film in 1943, for the first French underwater film: Par dix-huit mètres de fond (18 meters deep), made without breathing apparatus the previous year in the Embiez islands with Philippe Tailliez and Frédéric Dumas, using a depth-pressure-proof camera case developed by mechanical engineer Léon Vèche (engineer of Arts and Métiers and the Naval College).


Figure 4 - Cousteau's submarine near Oceanographic Museum in Monaco

In 1943, they made the film Épaves (Shipwrecks), in which they used two of the very first Aqua-Lung prototypes. These prototypes were made in Boulogne-Billancourt by the Air Liquide company, following instructions from Cousteau and Émile Gagnan **[8]**. When making Épaves, Cousteau could not find the necessary blank reels of movie film, but had to buy hundreds of small still camera film reels the same width, intended for a maker of child's camera, and cemented them together to make long reels **[9]**.

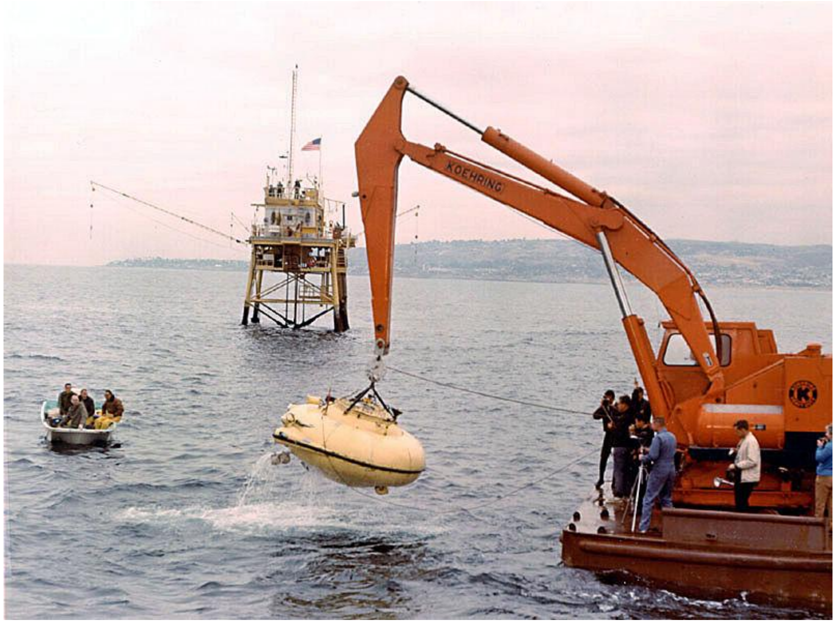



Figure 5 - “Diving saucer,” an experimental underwater vehicle that could reach a depth of 350 meters

Having kept bonds with the English speakers (he spent part of his childhood in the United States and usually spoke English) and with French soldiers in North Africa, Jacques-Yves Cousteau helped the French Navy to join again with the Allies. During the 1940s, Cousteau is credited with improving the aqua-lung design which gave birth to the open-circuit scuba technology used today. According to his first book, The Silent World: A Story of Undersea Discovery and Adventure (1953), Cousteau started diving with Fernez goggles in 1936, and in 1939 used the self-contained underwater breathing apparatus invented in 1926 by Commander Yves le Prieur **[9]**. Cousteau was not satisfied with the length of time he could spend underwater with the Le Prieur apparatus so he improved it to extend underwater duration by adding a demand regulator, invented in 1942 by Émile Gagnan **[9]**. In 1943 Cousteau tried out the first prototype aqua-lung which finally made extended underwater exploration possible.

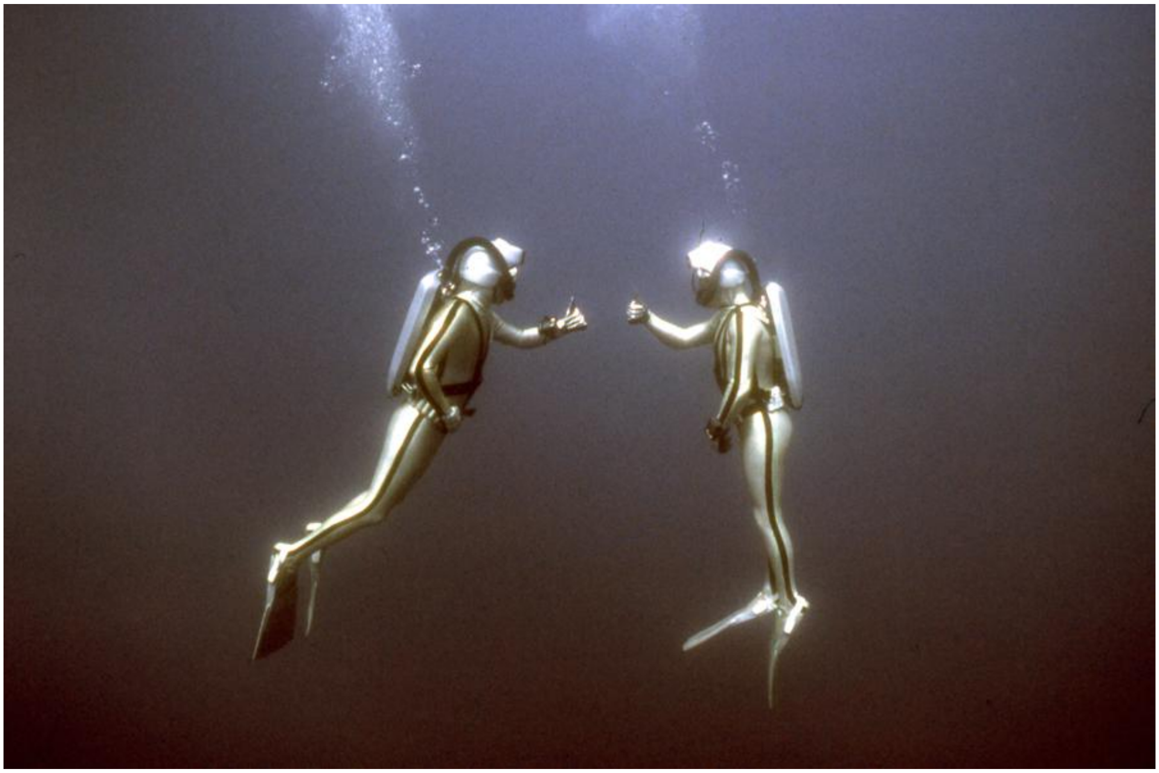


Figure 6 - Cousteau and his team using Aqua-lung

## Underwater Photography

Figure 7 - M. Edge-The underwater photographer-Celestial Light (2010) [6]

The underwater photography is a recreational diving activity and photographic practice of taking photographs underwater. It is characterized by the constraints of diving, optical physical (refraction, colour loss with depth, blurring and others as mentioning in detail below). It therefore requires specific equipment, resistant to pressure, corrections distance settings, and compensation for the loss of the colour spectrum by the extra lighting (flash).From the late of the $19^{th}$ century for many sports and hobbies like scuba diving, visiting shipwrecks with submarine tours and off course taking pictures, Photography was a leader of all the technology revolution gaining real momentum. Many other uses force man underwater like building underwater vehicles to survey the ocean floor.

Underwater photography can also be categorized as an art form and a method for recording data. Successful underwater imaging is usually done with specialized equipment and techniques. However, it offers exciting and rare photographic opportunities. Animals such as fish and marine mammals are common subjects, but photographers also pursue shipwrecks, submerged cave systems, underwater "landscapes", invertebrates, seaweeds, geological features, and portraits of fellow divers.

This is usually done while scuba diving, but can be done while diving on surface supply, snorkeling, swimming, from a submersible or remotely operated underwater vehicle, or from automated cameras lowered from the surface.

Figure 8 - Underwater Photography using macro lens

## The Evolution of Underwater Photography

For more than 150 years, the method for recording the underwater world was with silver halide crystals, otherwise known as film. Then, around the turn of the twenty-first century, the whole photo industry took a dramatic turn with the introduction of digital. It wasn’t long before digital cameras moved from topside photography into underwater housings so they could be used to document the wonders of the sea. No single technology has had more impact on underwater photography. Change in the film world moved slowly. New advancements in film, cameras, lenses, and flash systems took years to become fully accepted as tools for underwater photography. In fact, when a new film camera was introduced, it was conceivably two to three years before a compatible housing would be introduced. Then, that camera and housing combination would be in the mainstream for years. The digital world, on the other hand, moves ahead at such a clip that it is often difficult to stay ahead of it all. Digital point & shoot camera models are commonly replaced within a year and the life span of digital SLR camera models isn’t more than two to three years. For this reason, we now find that underwater housings are being introduced within weeks of the announcement of their corresponding digital cameras (if not simultaneously!). Even photographic terminology has changed. We are now starting to see manufacturers refer to film shooting as “analog” photography. In the year 2000, we also started to see a definite reduction of new film emulsions introduced by film manufacturers.

Simultaneously, these same manufacturers started to introduce an expansive offering of digital cameras. The Kodak slide projector disappeared, and E-6 processing was harder to find as it dropped below 1 percent of the images processed. The inkjet printer quality quickly surpassed photographic quality, and now photographers could even print their own images at home. Does this mean the end to the film camera? Not really, it just means that the film camera is no longer the dominant method used for taking pictures topside or underwater. Even so, many underwater photographers are reluctant to make the transition to digital. They have made a considerable investment in their underwater film-camera systems and are satisfied, since they have worked well for many years. Some feel that investing in a new underwater digital camera system may not be very practical because of the added cost and time required to master the new systems. This causes the field of underwater digital photography to be divided into two groups. You have underwater photographers who willingly sell their film camera systems and embrace digital with open arms. These digital camera users are now the predominant group, and the numbers continue to steadily grow. The second group consists of film photographers who have converted to digital via the film scanner. They have the advantage of using film's wide exposure latitude[1], yet they can still become a part of the digital world. Properly exposed, scanned-film images can equal or better their digital counterparts and best of all, you still have the tangible images. At the present time almost all underwater photographers are digital photographers. In both digital cameras and scanned film, when it comes right down to it, backscatter is backscatter, and a lighting ratio is a lighting ratio, no matter what medium you use to capture the image **[10]**.

[1] Exposure latitude is the extent to which a light-sensitive material can be overexposed or underexposed and still achieve an acceptable result.

## History of underwater photography

### Timeline

- 1856 - William Thompson takes the first underwater pictures using a camera mounted on a pole.
- 1893 - Louis Boutan takes underwater pictures while diving using a surface supplied hard hat diving gear.
- 1914 - John Ernest Williamson shoots the first underwater motion picture in the Bahamas **[11]**.
- 1926 - William Harding Longley and Charles Martin take the first underwater colour photos using a magnesium-powered flash.
- 1940 - Bruce Mozert begins to photograph at Silver Springs, Florida
- 1957 - The CALYPSO-PHOT camera is designed by Jean de Wouters and promoted by Jacques-Yves Cousteau. It is first released in Australia in 1963. It features a maximum 1/1000 second shutter speed. A similar version is later produced by Nikon as the Nikonos, with a maximum 1/500 second shutter speed and becomes the best-selling underwater camera series.
- 1961 — The San Diego Underwater Photographic Society is established, one of the earliest organizations dedicated to the advancement of underwater photography.

Figure 9 - World’s first underwater photograph © Louis Boutan

The image above is known as the world’s first underwater photograph – it is said that the model was so excited that he held the identification plate upside down! It was made in 1893 by the French zoologist Louis Boutan by using a magnesium flash.

Yet little is known that the Frenchman Louis Boutan didn't actually take the first underwater photograph. According to John F. Brown (British Journal of Photography, 9th August, 1985) the incredible achievement goes to Dorset solicitor and natural historian William Thompson, who took the first underwater photograph in 1856! In February that year, Thompson, assisted by his friend Mr. Kenyon rowed out a short distance into Weymouth bay **(**Dorset, England) and lowered a box containing a 5′ x 4′ (12.7cm x 10.16cm), plate camera into the sea and operated the shutter from a boat to expose the plate to create the first ever underwater photograph.

Thompson's box had a plate glass front and a wooden shutter operated from the surface with a length of string. The camera was prefocused at 10 yards (9.144meters) a distance Thompson later acknowledged was too great. A portable darkroom tent, on shore, was used to prepare the glass plate negative. The film holder was then put into the camera, the dark slide withdrawn, the lens uncapped and placed in the box with the shutter closed. Next the whole contraption was attached to an iron tripod and taken out by boat to be lowered to the seabed. On his second attempt, using an exposure of ten minutes, an image was obtained.

The next problem concerned the camera itself. Thompson's camera took a plate measuring 5 by 4 inches, which he prepared using the collodion process[2]. This meant that the liquid chemical had to be poured on to the plate, and be exposed and developed all within a matter of an hour or so. Following the procedure usual at the time, Thompson set up a small tent, on Weymouth beach, and inside it prepared a plate and put it in his camera. He then, under cover of a black cloth, placed the camera in the box, making sure that its lens was against the plate glass, and screwed on the back, to then lower it into the sea.

For the site of his experiment Thompson chose what he described as "a nook in the bay of Weymouth which is bounded by a ridge of rocks (where the area within is of sand and boulders and thickly clothed with many species of seaweeds". Thompson and his friend Kenyon, having rowed out a sufficient distance from the beach, lowered the box into 18 feet of water.

**2** The collodion process is an early photographic process, invented by Frederick Scott Archer. It was introduced in the 1850s and by the end of that decade it had almost entirely replaced the first practical photographic process, the daguerreotype **[80]**. During the 1880s the collodion process, in turn, was largely replaced by gelatin dry plates—glass plates with a photographic emulsion of silver halides suspended in gelatin. The dry gelatin emulsion was not only more convenient but could be made much more sensitive, greatly reducing exposure times **[81]**.

When he was sure that the apparatus was standing upright on the bottom, he pulled the string that raised the hinged shutter. Thompson made two attempts that day. For the first he allowed an exposure time of five minutes but found that the plate having been developed registered nothing.

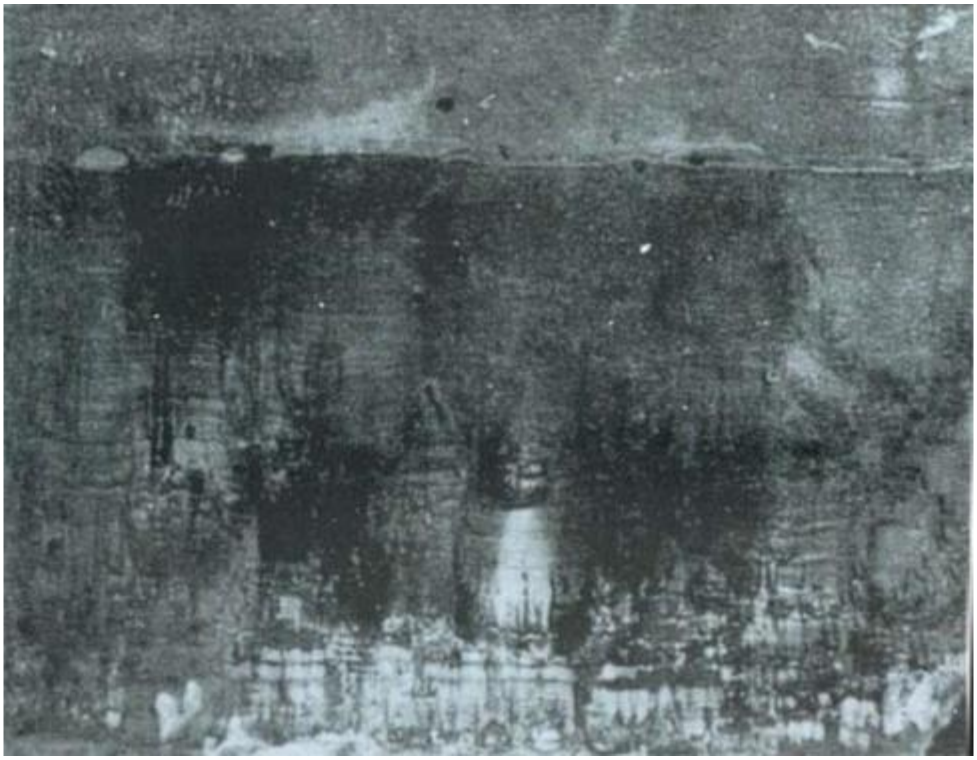


Figure 10 - Thompson's wet-plate Photograph in 1856!

Even though the depth was estimated to be no more than eighteen feet, the pressure was such that water forced its way through the joints and into the box. Thompson despaired of obtaining an image. After washing the plate in fresh water and developing it, he was, however, pleased to note that seawater was not as injurious as he feared. The seawater left only a line at the height which it had reached during the exposure. John Brown considers Thompson’s photograph a “gallant and innovative failure, it being difficult to decipher”. But it was the first, and beat Boutan by thirty seven years.

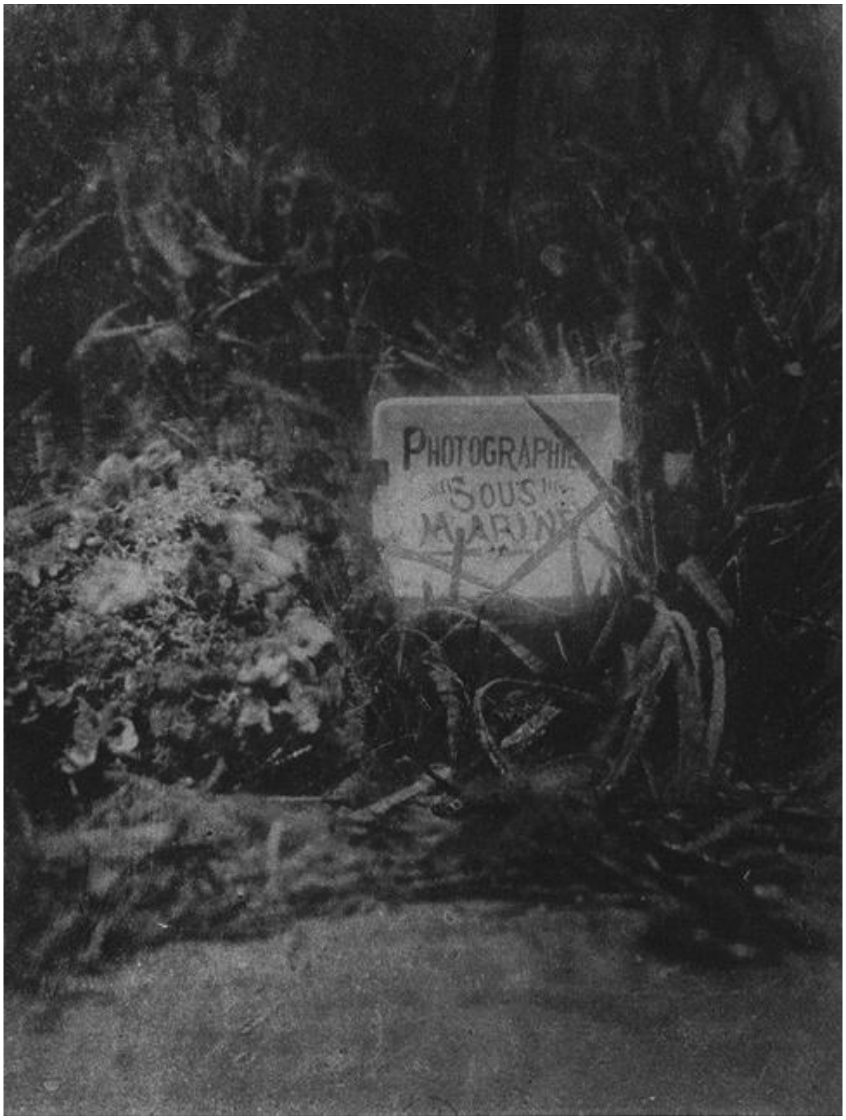



Figure 11 - Photographe sous Marin (Underwater Photographer)

For his second attempt he doubled the exposure time. Although by then the light had deteriorated, he obtained a reasonable satisfactory negative, from which he made a print on which it was possible faintly to discern the outlines of boulders and seaweed. Water had leaked into the camera but this, Thompson was pleased to see, had not seriously affected the quality of the picture. He also noted with surprise that the image had not been inverted, and came to the conclusion that the thick plate glass in front of the lens must have acted as a reversing mirror.

Thompson later designed a better apparatus, but he then lost interest and pursued the matter no further. His friend William Penney of Poole, who was a chemist, and a naturalist of some note, persuaded him to send an account of his experiment to be printed in the Journal of the Society of Arts, otherwise there would probably have been no record of it in existence today **[12] [13]**.

Louis Boutan for most people known as the world's first photographer began his work in 1893 and developed underwater cameras and wrote a substantial book on underwater photography that would inspire generations.

Figure 12 The World's First Underwater Photographer: Louis Boutan

Boutan was first interested in biology, graduating in 1879 with a Doctorate of Science from the University of Paris. Shortly after, in 1893, he became a professor at the University's marine biology lab: Arago Laboratories at Banyuls-sur-Mer. His work at the Arago Laboratory gave a new perspective on what lay beneath the waves of the ocean, including opportunities to use their diving suits. After experiencing the underwater landscapes first-hand, Boutan was inspired to find a method of photographing them.

To create underwater photographs, he had to contact his brother Auguste who was an engineer. Auguste drafted a plan for an underwater camera that allowed for underwater adjustments to the diaphragm, plates, and shutter. The first design even included a method of changing the buoyancy of the camera through an air-filled balloon. In the same year, he had the camera built and began his experiments.

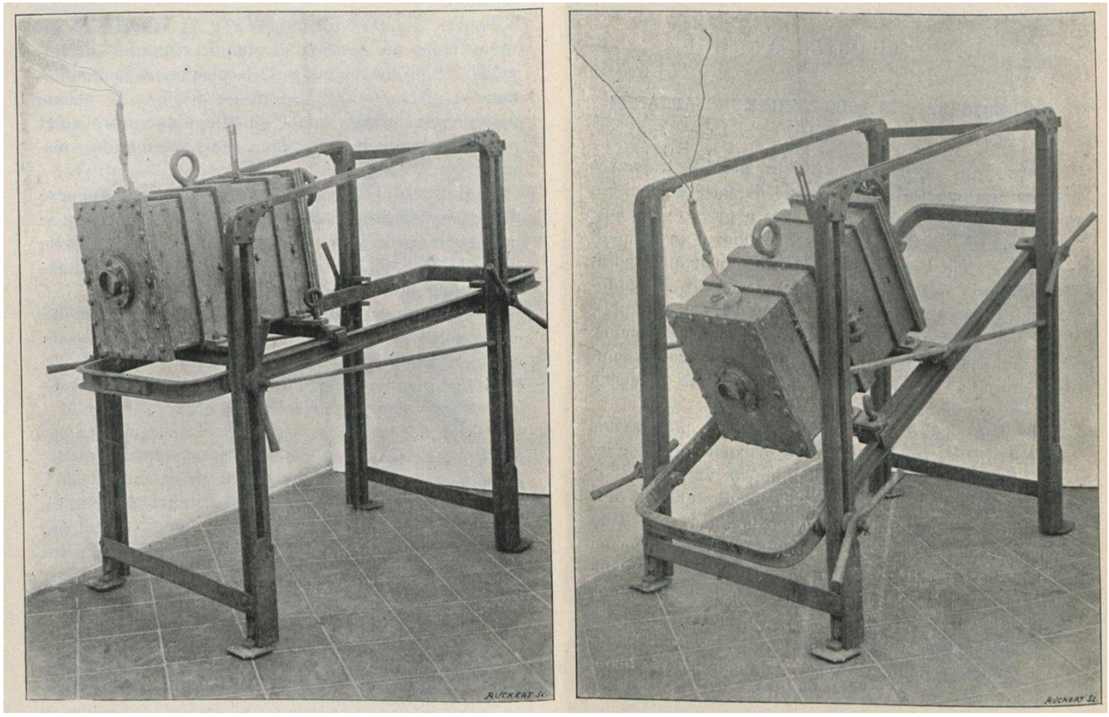


Figure 13 - Boutan's underwater camera (adjusted for a 2 meter shot at right)

Early experiments with lighting left Boutan disappointed. Until this point, flash photography required oxygen, typically utilizing burning magnesium or a mixture thereof. Still, within the same year, electrical engineer M. Chaffour helped Boutan create a bulb to house a magnesium ribbon. The bulb was filled with pure oxygen and the magnesium ribbon was lit using an electric current. Unfortunately, the burning magnesium led to a thick smoke of magnesium oxide which coated the inside of the bulb making the images dim. The heat that the bulbs produced also became a problem, as a majority of the bulbs would explode when used.

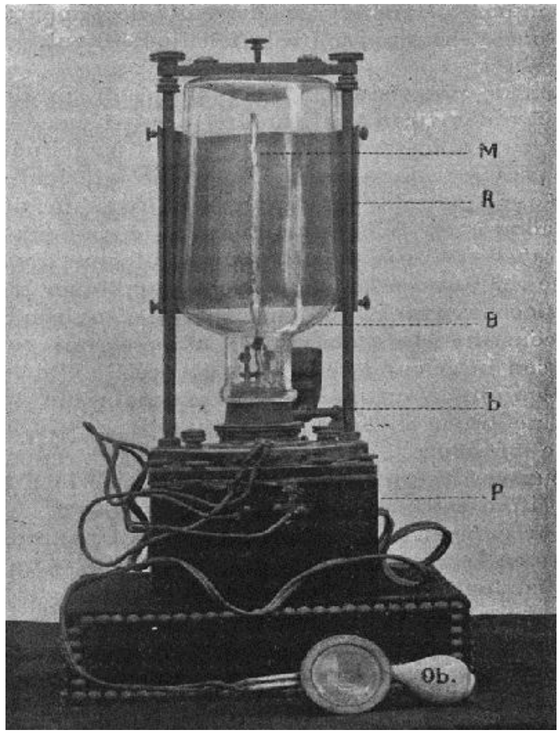



Figure 14 – An early underwater magnesium flash

With the non-success of the first bulb, Boutan’s assistant, Joseph David, helped create a more reliable flashbulb. This new flash used a rubber bulb that blew magnesium powder into a burning alcohol lamp. While this was a much more reliable method, it was attached to a wooden barrel and therefore fairly inconvenient. Boutan was required to dive without the photography equipment and have it sent down after he determined his shot. However, it was around the same time that the camera’s design had been reduced in size, allowing for a little extra maneuverability.

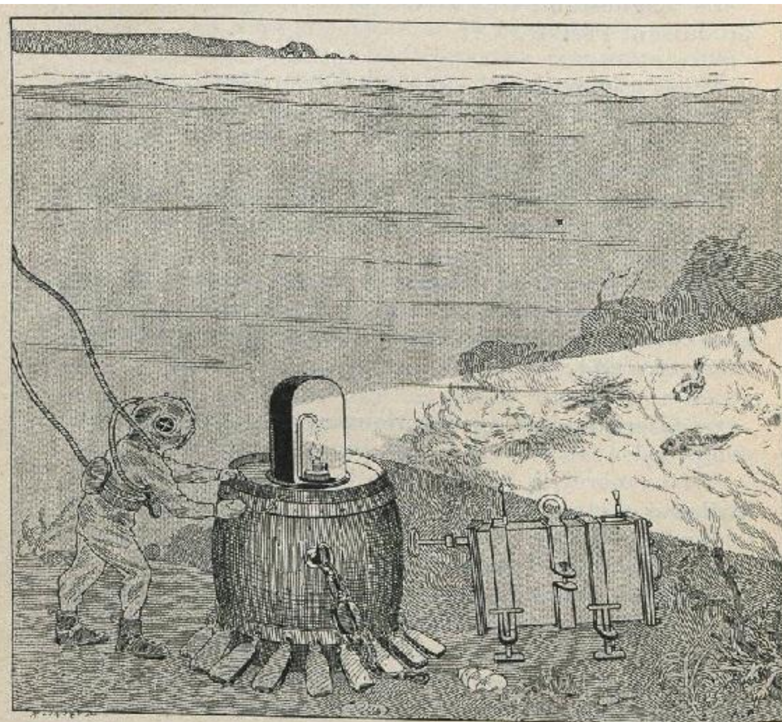


FIG. 33. — Figure théorique montrant comment ont été prises les vues sous-marines à la lumière du magnésium.

Figure 15 – An illustration (from Boutan's book) of the barrel-flash

Very quickly, Boutan developed more reliable methods of photography. More compact and portable flashes, smaller camera boxes, and better lenses. Eventually, the camera box was small enough to be brought to the seafloor by hand; the process was much quicker at that point. In addition to easier maneuverability of the camera, Boutan began to use a system of dual, carbon-arc (electricity) lamps.

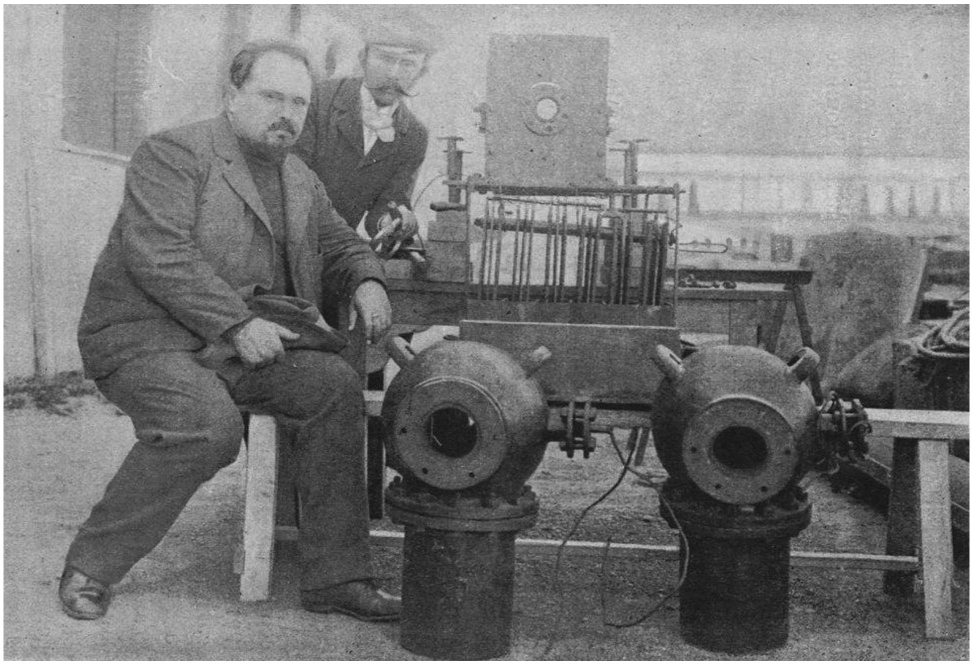


Figure 16 - Boutan (seen at left) and his dual, electric lamps (his camera is seen at top and center)

After more experimentation, Louis Boutan became the principal underwater photographer of his time. In 1898 he published a book detailing his work with underwater photography titled La Photographie Sous-Marine (**Figure 11**). Included in the book are several illustrations of his work, plus many more photos that he had taken in the years prior **[14]**.

Figure 17 - "Within the Wave's Intenser Day" – 6 July 1914, The Independent

Underwater colour photography was born with this shot of a hogfish, photographed off the Florida Keys in the Gulf of Mexico by Dr. William Longley and National Geographic staff photographer Charles Martin in 1926. Equipped with cameras encased in waterproof housing and pounds of highly explosive magnesium flash powder for underwater illumination, the pair pioneered underwater photography.

Figure 18 - First Underwater Colour Photo © National Geographic

In 1926 Dr. William Longley and National Geographic’s Charles Martin took this photo of a hogfish off the Florida Keys, and brought in a new generation of underwater photography — this time in colour. They needed extremely specialized gear to take the shot, and were faced with a major problems in order to get enough light to properly expose. So, how did they manage to produce a great burst of light projected into the ocean?

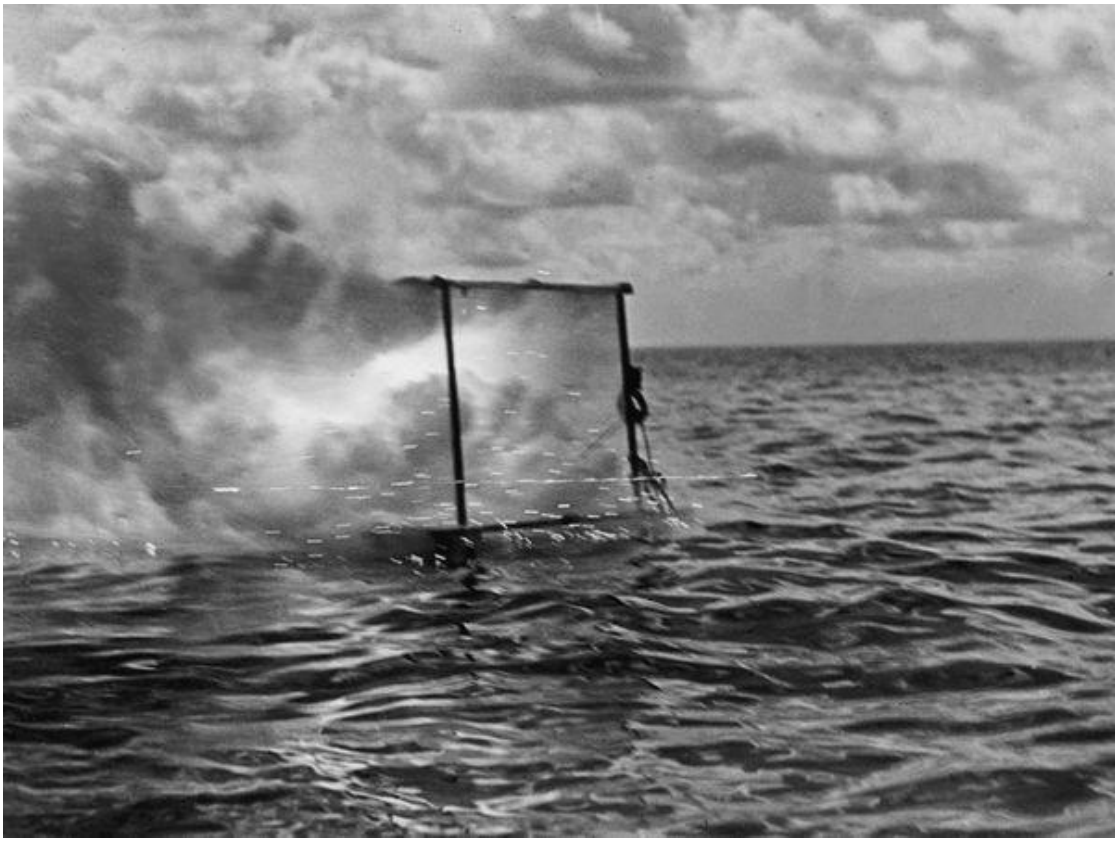


Figure 19 - Flashlight Explosion © National Geographic

They ended up relying on pounds of magnesium flash powder, floating in a boat on the surface.

## Underwater Vision

Just about every aspect of vision appears to be altered underwater. The appearance of objects underwater differs from that in air. Radiant energy[3] changes when it travels through water when compared to air. Water transmits less total energy than air. Visibility during dives varies and may differ from one site to another. The purpose of this paragraph is to describe how vision under water is altered under different conditions. The transmission of energy through water and air depends on what is known as Beer's law:

where is the radiant energy or power at a distance into the medium, is the radiant energy or power at the initial point, is the base of natural logarithms, is the attenuation or absorption coefficient that is wavelength dependent. A large value of a means a rapid attenuation of light with depth. For example, if 90% of incident energy (light) is transmitted through 1 m of clear water, 81% will be transmitted through 2 m and only 37% through 10 m.

The magnitude of depends on two components, (a) the absorption energy of the water and (b), the loss of energy caused by scattering of the energy due to small particles suspended in the water. **Figure 20** shows two independent measurements of absorption coefficient **[15] [16]** of pure clear water plotted against wavelength.

[3] Radiant energy is the energy of electromagnetic radiation. The SI unit of radiant energy is the joule (J). **[90]**

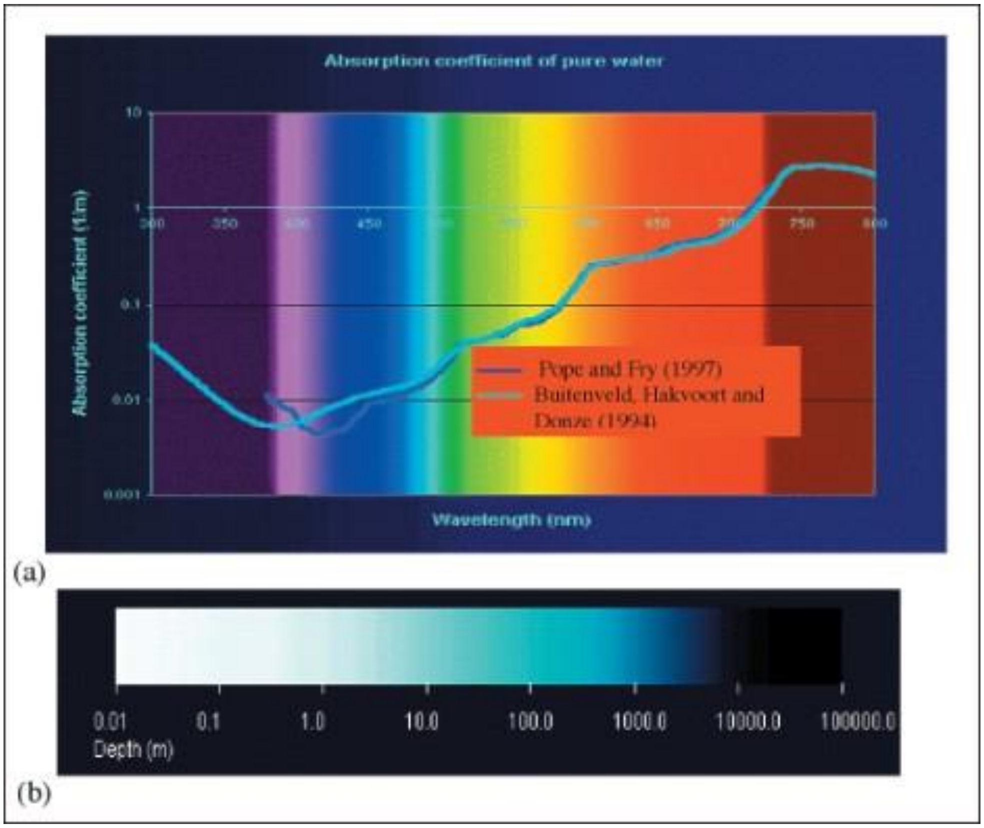



Figure 20 - **(a)** shows two independent measurements of absorption coefficient[4] of pure clear water plotted against wavelength. The absorption coefficient is plotted on a logarithmic scale. The two curves differ only slightly in the blue/violet region of the visible spectrum. As can be seen the largest absorption is in the red region and the least in the violet/blue region. **(b)** Shows the colour of pure clear water versus depth. Coefficient is about 0.01 m -1 for blue, 0.02 m -1 for green and 0.5 m for red[5].

The absorption coefficient is plotted on a logarithmic scale. The measurements differ only slightly in the blue/violet region of the visible spectrum.

As can be seen the largest absorption is in the red region and the least in the violet/blue region. **Figure 20**(b) shows the colour of pure clear water versus depth. For blue coefficient is about 0.01, for green it is about 0.02 and for red about 0.5. Another important factor controlling water visibility is phytoplankton. Phytoplankton is microscopic organism less than two microns in size that float in the water. It forms the base of the oceanic food chain and is the main supply of food and energy for oceanic ecosystem.

[4] Buitenveld, Hakvoort and Donze, 1994; Pope and Fry, 1997

[5] Reproduced from Deep ocean diving. Underwater vision. http://www.deepocean.net

Phytoplankton grows by converting nutrients, sunlight and carbon dioxide into plant material. This is performed by photosynthesis using chlorophyll. Chlorophyll, also found within plants, absorbs sunlight, whereas phytoplankton itself also scatters light. This changes the colour of the water. Chlorophyll comes in two types: chlorophyll **a** and chlorophyll **b.** Chlorophyll **a** absorbs **blue**, **violet** and **red** light and reflects **green**. Chlorophyll **b** mainly absorbs **blue** and **orange** and reflects **yellow-green** light. Satellites like SeaWiFS[6] was a satellite-borne sensor that was designed to collect global ocean biological data. Its primary mission was to quantify chlorophyll produced by marine phytoplankton (microscopic plants) measure the ocean colours in several wavelength bands. From this the phytoplankton concentration can be calculated as it is illustrated in **Figure 21**.

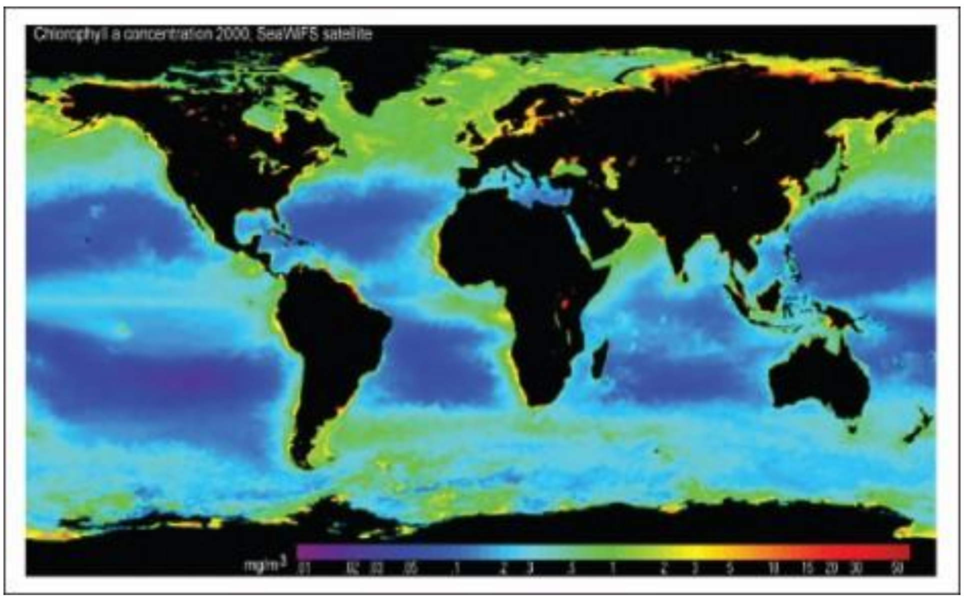



Figure 21 - Image of the earth taken from the SeaWiFS satellite showing the ocean colours in several wavelength bands. From this phytoplankton concentrations can be calculated [7]

[6] SeaWiFS (Sea-Viewing Wide Field-of-View Sensor) **[91]**

[7] Reproduced from Deep ocean diving. Underwater vision. www deepocean.net

Both of these components have visual consequences underwater. **Scattering** causes a loss of energy from the line of sight (LOS) between the object and the eye and thus causes blurring of the outline of the object and decreases the contrast between an object and its surroundings. As a rule of thumb the luminance contrast between an object and its surroundings must be at least 2 percent in order for the object to be just visible.

The loss of energy due to absorption as previously mentioned varies with wavelength and the type of water involved. **Figure 22** shows transmission curves measured through a 1 m of water for four different bodies of water. At the top is fresh water from Morrison Springs, Florida, famous for its clarity. A fairly even absorption rate (less than 10%) up to approximately 580 nm and then a sudden increase up to 700 nm. Water from the Gulf of Mexico has a higher absorption rate for the shorter (violet and blue) and longer (red and orange) wavelengths respectively. This is probably due to the absorption of these wavelengths by plankton.

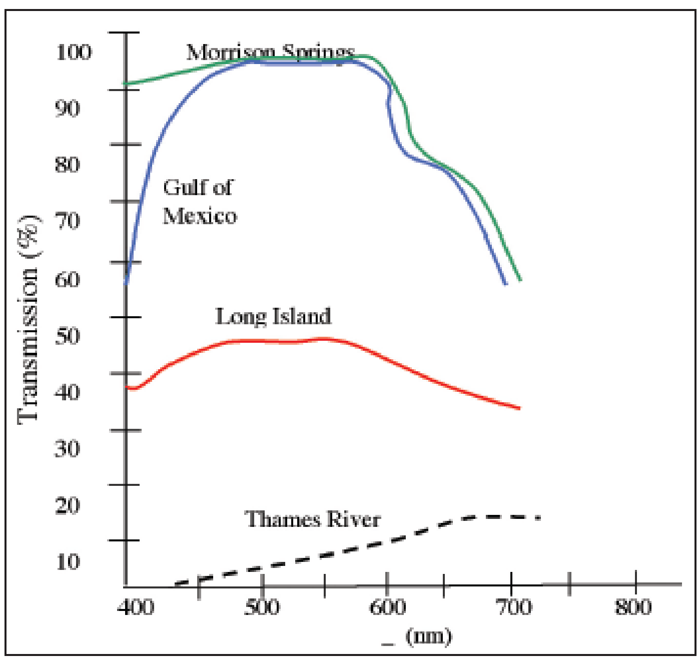



Figure 22 - Transmission curves of various wavelengths of visible light through a distance of 1 m of various bodies of water.

The transmission of light varies from clear water in Morrison Springs to murky polluted water in the Thames River in Connecticut. (Reproduced with modification [17])

The water from Long Island Sound is sea water and more absorption is occurring across the whole spectrum. Finally, the Thames River in Connecticut provides a fine example of murky polluted water. Almost no violet (nearly 100% absorption) and very little blue light is transmitted with the greatest transmittance being the longer wavelengths (red light approximately 13%).

As a result of these differences, both the absolute and relative visibility of colours differ greatly under at different distances and in different bodies of water.

Of all the different types of photography, taking pictures underwater is one of the most difficult. Photography itself is difficult enough, as you must contend with achieving correct exposure, accurate focus, controlling subject movement, attaining pleasing colour balance, and dealing with varying light levels. When you also cross the line from photographing in the "air" environment to that of the "water" world, it becomes even more difficult. The line that divides the wet and dry environments brings with it a whole new set of parameters that affect your picture. This is why underwater photographers are a rare breed.

**Light Loss.** Let's explore a couple of the challenges involved in underwater photography, star ting with light itself. When sunlight passes through the surface of water, much of it is reflected back upwards, thus the amount of light that continues underwater is reduced. The lower the sun is in the sky, the more light is reflected off the water's surface. In order to achieve the maximum light level for your underwater photography, the best shooting times are between 10 AM and 2 PM.As you descend below the waves into the abyss, the light level decreases at an exponential rate. Even at a depth of 100 feet (≃30m), the light is at an extremely low level. The **Figure 23** illustrates the different wavelengths and the depths they are absorbed in pure water.

| Color | Average wavelength | Approximate depth of total absorption |
|---|---|---|
| Ultraviolet | 300 nm | 25 m |
| Violet | 400 nm | 100 m |
| Blue | 475 nm | 275 m |
| Green | 525 nm | 110 m |
| Yellow | 575 nm | 50 m |
| Orange | 600 nm | 20 m |
| Red | 685 nm | 5 m |
| Infra-red | 800 nm | 3 m |

Figure 23 - Table of Light Absorption in **pure water**

In addition to this problem, the colours that make up the spectrum of light decrease at varying rates. Red is lost first, and disappears in as little as 15 feet (≃4,5m). It is closely followed by orange, yellow, green, and finally blue. This imbalance in the colour spectrum [**Figure 52 - Colour Spectrum**] causes havoc with images taken underwater using available light. That is why so many underwater images are taken using electronic flash. Even when a photographer uses a large flash, though, the colour and intensity of the flash fall off drastically with distance. Usually, the strobe's impact dissipates if the flash-to-subject distance is more than eight feet. In addition to the loss of colour and intensity, there is also a contrast and colour-saturation loss as the subject's distance increases from the camera and flash.

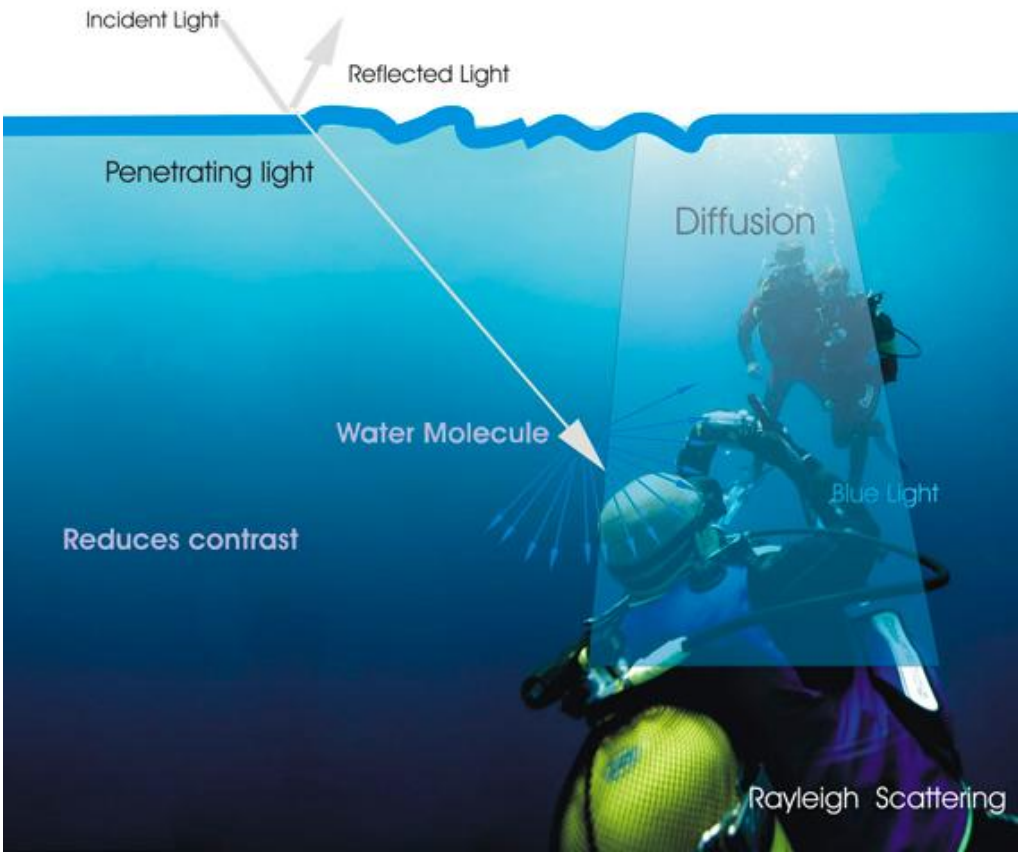



Figure 24 - Rayleigh scattering [18]

**Backscatter**. If all of that were not discouraging enough, the underwater world also has its own unique problem. As particulate matter floats through the water with the currents, it takes on the appearance of snow in a snowstorm when illuminated by a flash or other bright light source. This unique effect is called backscatter and is one of the biggest issues plaguing underwater photographers.

Figure 25 – By including the flash in the photo, the highlighted backscatter is very evident. You can see that it decreases in intensity as the flash distance increases and beam angle widens.

Some of the most striking underwater photos showing the vastness of the underwater world are made using only available light. Available-light photography is usually the best choice when the water is very dirty, since it helps to avoid backscatter. It also best when the underwater subjects are very large or your dive is deep enough that the light level and colours are reduced.

Figure 26 - Digital image with a test chart designed to measure the different levels of colour falloff at various depths

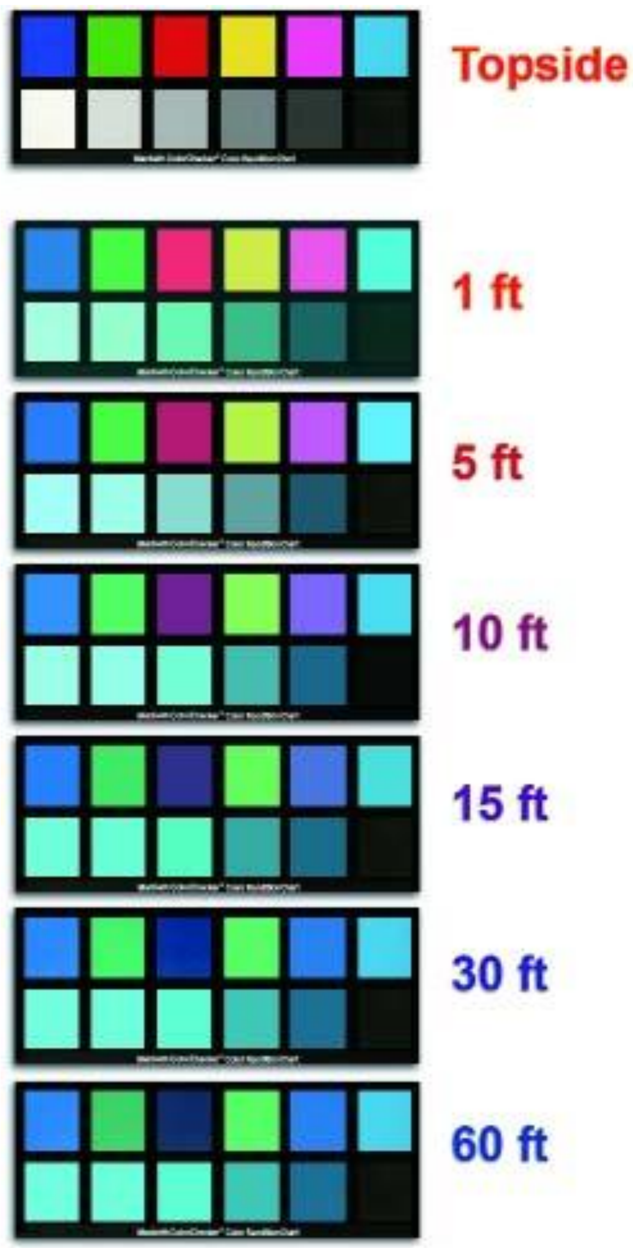



Figure 27 - This chart shows the final results of all colour tests. You will see that when the chart is placed even just one foot underwater, the colour loss begins. At 15 feet, red is almost gone, and the colour changes from 30 feet to 60 feet are barely noticeable.

The behavior of light underwater is unlike the behavior of light on land. For a start, the density of water is 800 times that of air. Such is the density of water, in fact, that people compare a picture taken in 0.5 m of water with a picture on land taken at 800 m away. As soon as light enters the water it also interacts with suspended particles, resulting in a loss of both colour and contrast.

It often comes as a huge shock for non-divers to discover that colour also decreases with the depth of water. Particulates and water molecules react with the light entering the sea, and it immediately begins to be absorbed. Red goes first, then orange and yellow, until only green and blue are left. The loss of red is so rapid that within half a meter of the surface those red swimming shorts are muted and dull! Even in the best imaginable visibility, particulates are suspended in the water column.

In a typical tropical diving destination with good visibility, these particulates tend to reflect and scatter light as they move through the water. You can reduce their effects, but never eliminate them entirely. Beginners to underwater photography often forget that horizontal distance also reduces light. If you are 7 m deep and 2 m from your subject, the total light path is actually equivalent to 9 m. It is also important for the underwater photographer to recognize that the conditions on the surface of the water have an effect on how light passes through the water. Calm seas generally allow more light to pass through, whilst a choppy sea reflects more light.

**Underwater imaging** is widely used in scientific research and technology, as well as for popular activities. Underwater cable tracking, inspection of underwater power and telecommunication cables, pipelines, nuclear reactors, and columns of offshore platforms

In addition, underwater imaging is used for research in marine biology, archaeology and mapping.

Moreover, underwater photography is becoming more accessible to the wider public **[19]**.

Digital cameras weren't initially developed for underwater use but nowadays digital cameras are built water resistant and with underwater mode witch which will automatically help you capture the distinct colours of the sea. Also because underwater lighting differs dramatically from above-water lighting the underwater mode some digital cameras have developed can automatically set the illumination settings for better results when going underwater.

What makes underwater imaging so problematic? To understand the challenge, consider **Figure 28**, which shows an archaeological site 2.5m under the water surface. It is easy to see that **visibility degradation** effects vary as **distances** to the objects **increase**.

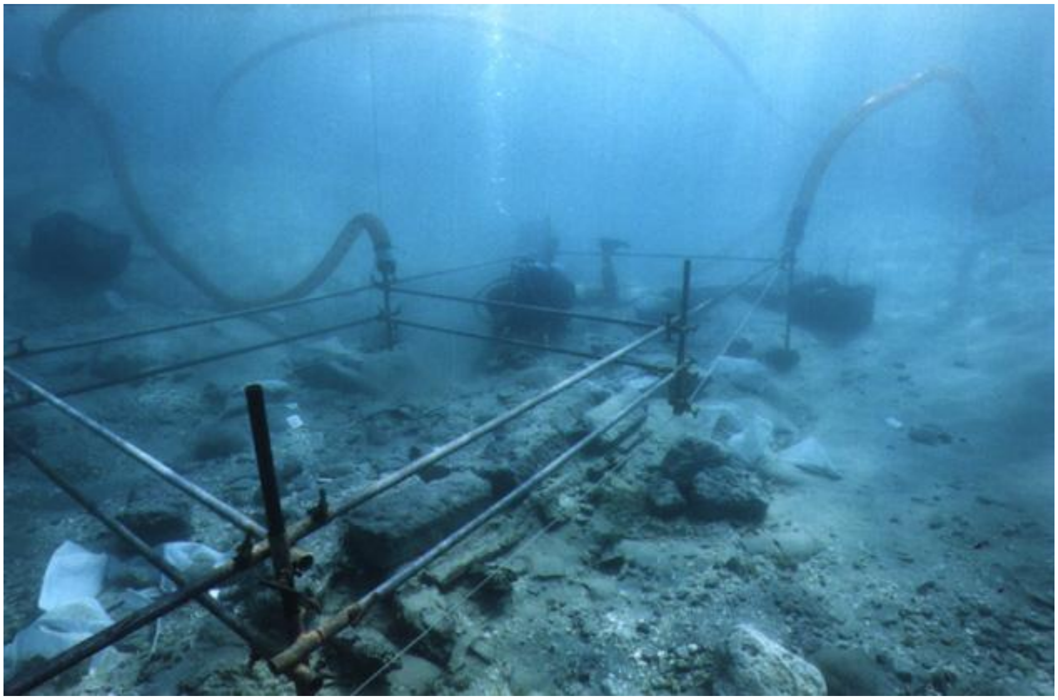


Figure 28 - An underwater Mediterranean archaeological site.

Since objects in the field of view are at different distances from the camera, the causes for image degradation are spatially varying.

This situation is analogous to open-air vision in bad weather (fog or haze).Contrary to this fact, traditional image enhancement tools, e.g., high pass filtering and histogram equalization are typically spatially invariant. Since they do not model the spatially varying distance dependencies, traditional methods are of limited utility in countering visibility problems, as has been demonstrated in experiments.

Imaging conditions underwater are quite different than in the open air. In the open air, on clear days the sun is a dominant source, which lies low in mornings and afternoons. It lies low throughout the day in high geographic latitudes. Alternatively, on a cloudy day natural lighting may come from the entire hemisphere. In contrast, underwater natural lighting comes from a limited cone above the scene, as depicted in **Figure 29 - The optical manhole. Due to refraction at the water surface,.**

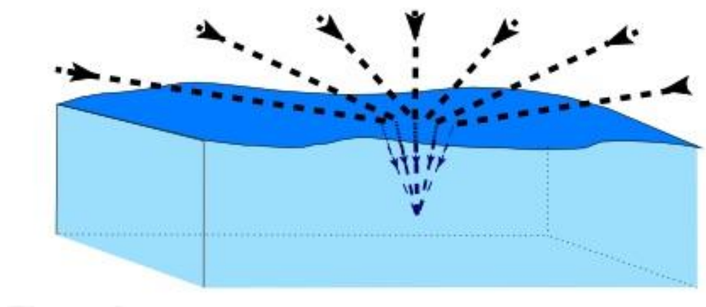


Figure 29 - The optical manhole. Due to refraction at the water surface,

Natural underwater lighting comes from above.

This phenomenon is caused by refraction of the illuminating rays through the water surface, and is termed the optical manhole or **Snell's window**.

Once in the water, the natural illumination undergoes strong colour dependent attenuation. As a result, it typically becomes predominantly green-blue **[19]**, resulting in images having this hue. Then, part of this light interacts in the viewed scene.

## Snell's window

Snell's window is a phenomenon by which an underwater viewer sees everything above the surface through a cone of light of width of about 96 degrees. This phenomenon is caused by refraction of light entering water, and is governed by Snell's Law. The area outside Snell's window will either be completely dark or show a reflection of underwater objects.

Underwater photographers sometimes compose photographs from below such that their subjects fall inside Snell's window, which backlights and focuses attention on the subjects.

Snell's window is also called 'Snell's circle or optical man-hole.

Figure 30 - The optical manhole or Snell's window

Under ideal conditions, an observer looking up at the water surface from underneath sees a perfectly circular image of the entire above-water hemisphere - from horizon to horizon. Due to refraction at the air/water boundary, Snell's window compresses a 180° angle of view above water to a 97° angle of view below water, similar to the effect of **Fisheye Lens effect**. The brightness of this image falls off to nothing at the circumference/horizon because more of the incident light at low grazing angles is reflected rather than refracted (Fresnel equations)[8]. Refraction is very sensitive to any irregularities in the flatness of the surface (such as ripples or waves), which will cause local distortions or complete disintegration of the image. Turbidity in the water will veil the image behind a cloud of scattered light.

## Snell's Law – Refraction

Snell's law (also known as the law of refraction) is a formula used to describe the relationship between the angles of incidence and refraction, when referring to light or other waves passing through a boundary between two different isotropic media, such as water, glass and air.

In *optics*, the law is used in ray tracing to compute the angles of incidence or refraction, and in experimental optics to find the refractive index of a material. The law is also satisfied in metamaterials, which allow light to be bent "backward" at a negative angle of refraction with a negative refractive index **[20]**.

Although named after Dutch astronomer Willebrord Snellius (1580–1626), the law was first accurately described by the scientist Ibn Sahl at the Baghdad court in 1984. In the manuscript *On Burning Mirrors and Lenses*, Sahl used the law to derive lens shapes that focus light with no geometric aberrations **[21] [22]**.

[8] The Fresnel equations describe the behavior of light (reflection and refraction of light) when moving between media (uniform planar interfaces) of differing refractive indices. The reflection of light that the equations predict is known as Fresnel reflection **[89]**.

Snell's law states that the ratio of the sines of the angles of incidence and refraction is equivalent to the ratio of phase velocities in the two media, or equivalent to the reciprocal of the ratio of the indices of refraction:

,with each as the angle measured from the normal of the boundary, as the velocity of light in the respective medium (SI m/s) and *n* as the refractive index (which is unit less) of the respective medium.

The law follows from Fermat's principle **[23]** of least time, which in turn follows from the propagation of light as waves.

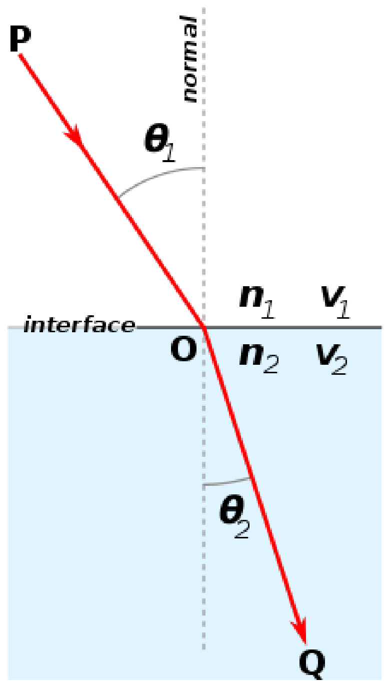



Figure 31 - Refraction of light at the interface between two media of different refractive indices, with n2 > n1. Since the velocity is lower in the second medium (v2 < v1), the angle of refraction θ2 is less than the angle of incidence θ1; that is, the ray in the higher-index medium is closer to the normal

In optics, Fermat's principle is the principle that the path taken between two points by a ray of light is the path that can be traversed in the least time. Fermat's principle can be used to describe the properties of light rays reflected off mirrors, refracted through different media, or undergoing total internal reflection **[23]**.

Once in the water, the natural illumination undergoes a strong colour-dependent attenuation. As a result, it typically becomes predominantly green-blue, resulting in images having this hue. Then, part of this light interacts the viewed scene **[24]**.

We should also mention the Beer–Lambert law **[25]**. The Beer–Lambert law, also known as Beer's law, relates the attenuation of light to the properties of the material through which the light is traveling **[25]**.

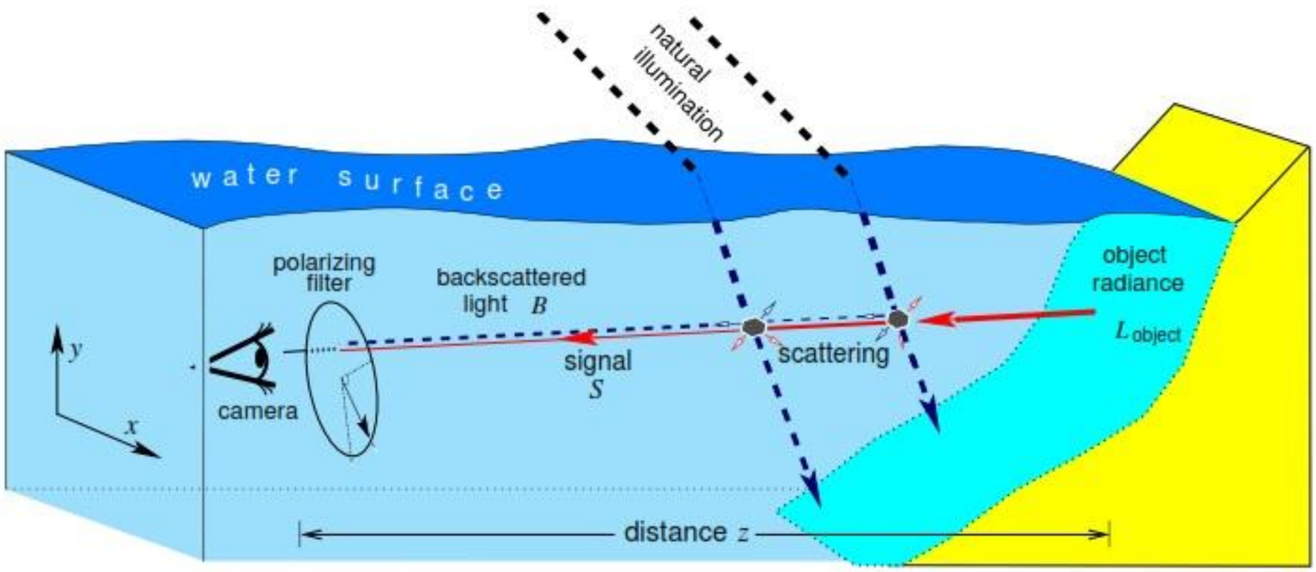



Figure 32 - Underwater imaging of a scene, e.g., a reef, through a polarizing filter. [Dashed rays] Light coming from a source is backscattered towards the camera by particles in the water. The backscatter increases with the distance z to the object. [Solid ray] Signal: Light emanating from the object is attenuated and somewhat blurred as z increases, leading to the signal S. Without scattering and absorption along the line of sight (LOS), the object radiance would have been Lobject.

As depicted in **Figure 32**, when imaging underwater we sense two sources. The first source is the scene object at distance *z*, whose radiance is attenuated by absorption and scattering in the water. It is also somewhat blurred. The image corresponding to this degraded source is the *signal*. The second source is the ambient illumination. Part of that light is scattered towards the camera by the particles in the water. It is termed *backscattered light* **[26] [27] [28]**.

## The Signal

### *Direct Transmission*

The signal is composed of two components, termed direct transmission and forward scattering **[26] [27] [28]**. As a light ray progresses from the object towards the camera, part of its energy is lost due to scattering and absorption. The fraction reaching the camera is the direct transmission[9]

$$D = L_{object}\, e^{-\eta z} \quad (1)$$

, where $\eta$ is the attenuation coefficient. Here $L_{object}$ is the object radiance we would have sensed, had there been no scattering and absorption along the line of sight (LOS).

The attenuation coefficient is given by $\eta = a + \beta$, where $a$ is the absorption coefficient and $\beta$ is the total scattering coefficient of the water. The scattering coefficient $\beta$ expresses the ability of an infinitesimal water volume to scatter flux in all directions. Integrating over all solid angles ,

(2)

, where $\theta$ is the scattering angle relative to the propagation direction, and $(\theta)$ is the angular scattering coefficient. The variables a, $(\theta)$, $\eta$ and $L_{object}$ are all functions of the wavelength .

[9] There is a proportion factor between the scene radiance and image irradiance that depends on the imaging system, but does not depend on the medium and its characteristics. Thus this factor is left out.

## Forward Scattering

The forward scattering component is similar to the direct transmission. However, it represents light scattered forward at small angles relative to LOS. This creates image blur given by the convolution,

$$F = D*\qquad (3)$$

where D is given by (1) and is a point spread function (PSF). The PSF is parameterized by the distance *z*, since the farther the object, the wider the support of the blur kernel. There are several models in the literature for the form of the underwater PSF **[27] [29]**. Since the PSF depends on the hydrosols[10] suspended in the water, the models are typically parameterized by various empirical constants. For example, the model in Ref. **[26] [27]**is of the form

(4)

, where (5)

, while $K>0$ and $\gamma$ are empirical constants, is the inverse Fourier transform, and $\omega$ is the spatial frequency in the image plane. The filter $G_z$ is a low pass. Its effective frequency "width" is inversely proportional to *z*. This expresses the increase of spatial blur for distant objects. The constant $\gamma$ is limited to **[27]**. Note that the models of the PSF obtained empirically and through numerical simulations **[27] [29]** do not conserve energy as light propagates in *z*.

This is clearly the case in Eq.(4), (5). Thus forward scattering is a blurred and attenuated version D.

Accounting for both the direct transmission (1) and the forward scattering (3)**,** the signal is defined as **[19]**

$$S = D + F \qquad (6)$$

[10] Hydrosols, also known as floral waters, hydroflorates.

An effective object radiance is defined as

(7)

It is a somewhat blurred version of . From Eqs. (1),(3),(6) the signal is

(8)

## Backscattering

In physics, backscatter (or backscattering) is the reflection of waves, particles, or signals back to the direction from which they came. It is a diffuse reflection due to scattering, as opposed to specular reflection like a mirror. Backscattering has important applications in astronomy, photography and medical ultrasonography **[30]**.

The term backscatter in photography refers to light from a flash or strobe reflecting back from particles in the lens's field of view causing specks of light to appear in the photo. This gives rise to what are sometimes referred to as orb artifacts. Backscatter can result from snowflakes, rain or mist, or airborne dust and is particularly a problem in underwater video and photography, where particulate matter can be very dense and include plankton which would otherwise be near transparent.

Backscatter can be reduced by offsetting the direction of the light source as far from the angle of the lens as possible. If possible this can be done by placing the light source high and to one side on an extendable arm. This is the reason why underwater photographers are using strobes to minimize backscattering and enables you to try different lighting options when using artificial lighting.

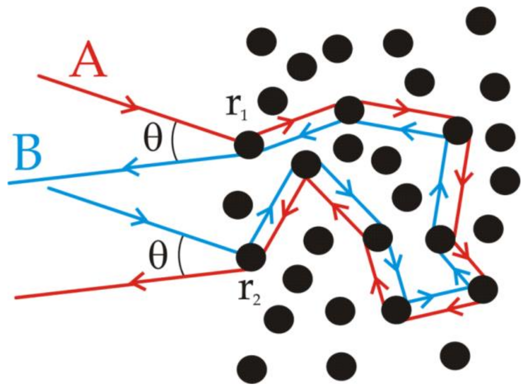



Figure 33 - Backscattering A is light source and B is the backscattered light with θ the angle between them

Figure 34 - Underwater strobe light kit[11]

[11] Strobes, also known as flashes or flashguns, are very important in underwater photography. One, two, and sometimes even 3 or 4 strobes underwater are used to light subjects. Strobes can be places in different positions for different effects.

By having the light come from the side, the reflected light is primarily in the direction of the light source instead of the camera lens. This is similar to comparing a full moon to a half moon. The full moon is when the moon is lit from almost behind the earth, creating reflection off the whole surface facing the earth. A half moon is when the moon is being lit from one side, making the reflection half the size and the light intensity much less. In photography, the side lighting minimizes the backscatter light **[31]**.

Backscatter does not originate from the object on the LOS (line of sight)**Figure 32**. Rather, light coming from ambient illumination sources is scattered into the LOS and towards the camera by suspended particles (**Figure 32**). Before integrating all the contributions to the illumination of the LOS, let's first analyze the effect of a single distant source.

The source illuminates the particles on the LOS from direction relative to the LOS, with intensity .

Following Refs. **[26] [27]**, the contribution of this source to the backscatter is:

(9)

where is the focal length of the camera and is the distance between the lens and the underwater housing window. These integral accounts for scattering into the LOS at some distance , followed by attenuation until reaching the camera. It also accounts for geometric projection of the irradiance on the detector, via the ratio .

The exponent in Eq. (9) sets a typical attenuation distance of in the water. We exploit this observation to make a practical simplification of Eq.(9):

typically , making the effect of the term very small. Consider typical ranges of values as ∈ [3m, 10m] (according to **[32]**), f ∈ [20mm, 50mm], 80mm, and object distance in the order of meters. Assessing the integrals numerically. It can be shown that to an accuracy of 99%, we can write Eq. (9) as:

(10)

Where, is s a constant parameterized by the focal length of the camera lens. A focal length of f =20mm corresponds to =1.06. Eq. (10)

is solved as:

(11)

Where,

(12)

I

s the backscatter in a LOS which extends to infinity in the water. Summing up the contribution from light sources at all directions, the total backscatter is

(13)

Where

(14)

, is a scalar which depends on λ.

## Human Eye

Light rays bend when they travel from one medium to another; the amount of bending is determined by the refractive indices of the two media. If one medium has a particular curved shape, it functions as a lens.

The retina (from Latin rēte, meaning "net") is a light-sensitive layer of tissue, lining the inner surface of the eye. The optics of the eye create an image of the visual world on the retina (through the cornea and lens), which serves much the same function as the film in a camera. **[33]**

The response of cones[12] to various wavelengths of light is called their spectral sensitivity. In normal human vision, the spectral sensitivity of a cone falls into one of three subgroups. These are often called blue, green, and red cones but more accurately are short, medium, and long wavelength sensitive cone subgroups.

The Purkinje effect **[34]** (sometimes called the Purkinje shift, or dark adaptation and named after the Czech anatomist Jan Evangelista Purkyně) is the tendency for the peak luminance sensitivity of the human eye to shift toward the blue end of the colour spectrum at low illumination levels.

The effect occurs because the colour-sensitive cones in the retina are most sensitive to green light, whereas the rods[13], which are more light-sensitive (and thus more important in low light) but which do not distinguish colours, respond best to green-blue light.[4] This is why humans become virtually colour-blind under low levels of illumination, for instance moonlight.

---

**12** Cone cells, or cones, are one of the two types of photoreceptor cells that are in the retina of the eye.

**13** Rod cells, or rods, are photoreceptor cells in the retina of the eye that can function in less intense light than the other type of visual photoreceptor, cone cells.

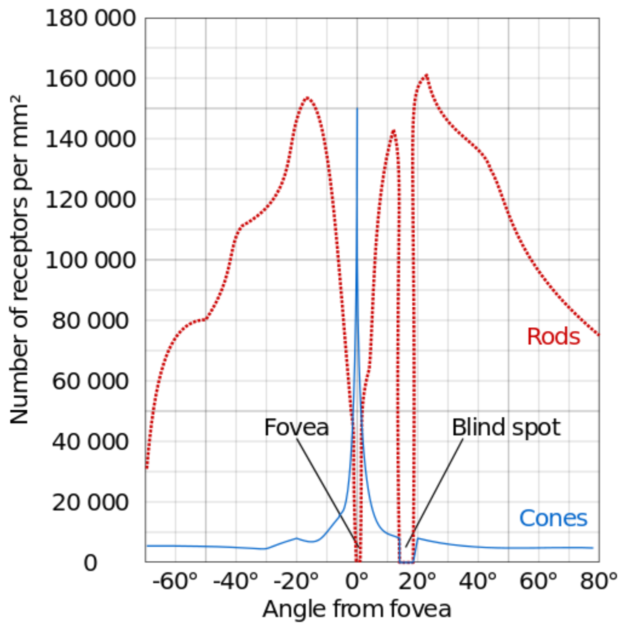



Figure 35 - Distribution of rods and cones along a line passing through the fovea and the blind spot of a human eye

The Purkinje **[34]** effect occurs at the transition between primary use of the photopic (cone-based) and scotopic (rod-based) systems, that is, in the mesopic state: as intensity dims, the rods take over, and before colour disappears completely, it shifts towards the rods' top sensitivity.

The insensitivity of rods to long-wavelength light has led to the use of red lights under certain special circumstances – for example, in the control rooms of submarines, in research laboratories, aircraft, during naked-eye astronomy or at the navigation instruments of a sailing boat when sailing at night.

Under conditions where it is desirable to have both the photopic and scotopic systems active, red lights provide a solution. Submarines are dimly lit to preserve the night vision of the crew members working there, but the control room must be lit to allow crew members to read instrument panels. By using red lights, or wearing red goggles, the cones can receive enough light to provide photopic vision (namely the high-acuity vision required for reading). The rods are not saturated by the bright red light because they are not sensitive to long-wavelength light, so the crew members remain dark adapted. Similarly, sailing boat cockpits use red light on their instruments so sailors can read their instruments and maps while maintaining night vision to see outside the boat.

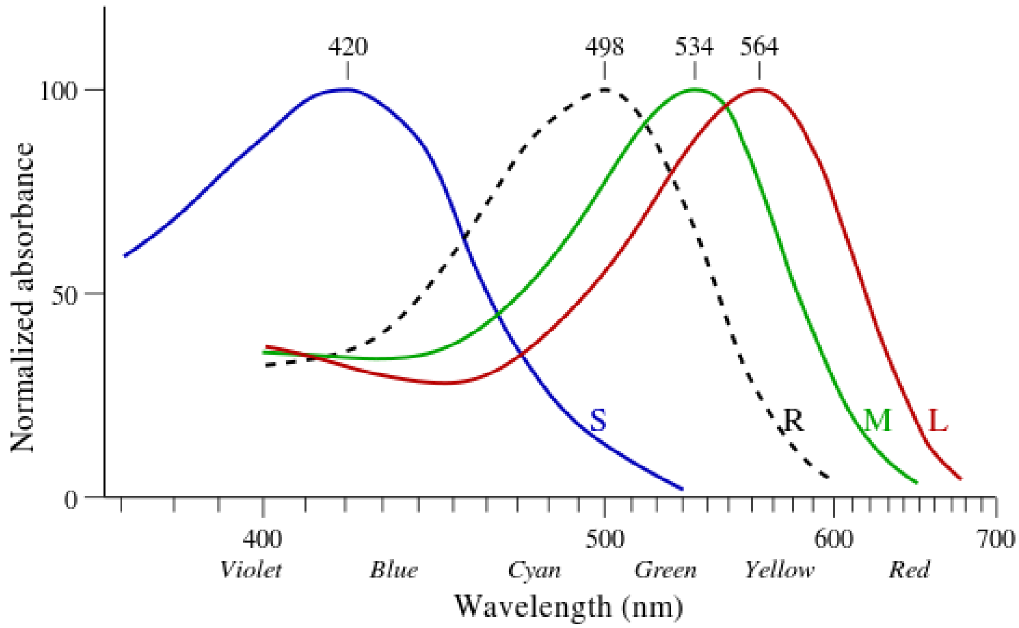



Figure 36 - Spectral absorption curves of the short (S), medium (M) and long (L),

Wavelength pigments in human cone and rod (R) cells.

The cornea, humours, and crystalline lens of the eye together form a lens that focuses images on the retina. Our eyes are adapted for viewing in air. Water, however, has approximately the same refractive index as the cornea (both about 1.33), effectively eliminating the cornea's focusing properties. Water has a significantly different refractive index to air, and this affects the focusing of the eye. Most animals' eyes are adapted to either underwater or air vision, and do not focus properly when in the other environment. When our eyes are in water, instead of focusing images on the retina, they now focus them far behind the retina, resulting in an extremely blurred image from hypermetropia.

**Hyperopia** or **hypermetropia**, from the Greek word "hyper-metropia : ὑ περ-μετρωπία" commonly known as being **farsighted** (American English) or **longsighted** (British English), is a defect of vision caused by an imperfection in the eye (often when the eyeball is too short or the lens cannot become round enough), causing difficulty focusing on near objects, and in extreme cases causing a sufferer to be unable to focus on objects at any distance. As an object moves toward the eye, the eye must increase its optical power to keep the image in focus on the retina. If the power of the cornea and lens is insufficient, as in hyperopia, the image will appear blurred.

People with hyperopia can experience blurred vision, asthenopia, accommodative disfunction, binocular disfunction, amblyopia, and strabismus, another condition that frequently causes blurry near vision.[2] Presbyopes who report good far vision typically experience blurry near vision because of a reduced accommodative amplitude brought about by natural aging changes with the crystalline lens. It is also sometimes referred to as farsightedness, since in otherwise normally-sighted persons it makes it more difficult to focus on near objects than on far objects.

The causes of hyperopia are typically genetic and involve an eye that is too short or a cornea that is too flat, so that images focus at a point behind the retina. The opposite of hyperopia is myopia.

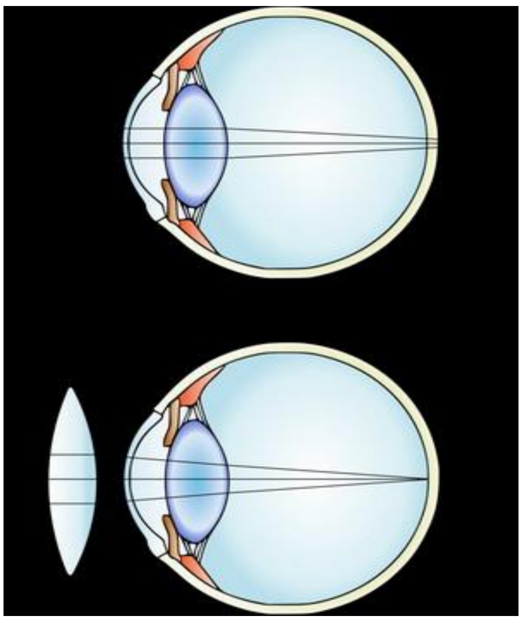


Figure 37 - Hyperopia

It is well known that about two-thirds of the refraction of light in the normal human eye takes place at the surface of the cornea, only about one-third being supplied by the two surfaces of the so-called "crystalline lens." Now since the index of refraction of the aqueous humour[14] of

[14] The aqueous humour is a transparent, gelatinous fluid similar to plasma, but containing low protein concentrations. It is secreted from the ciliary epithelium, a structure supporting the lens. It is located in the anterior and posterior chambers of the eye, the space between the lens and the cornea.

the eye is nearly the same as that of water, it is evident that a naked diver has lost two-thirds of the refracting power of his eyes while under water. Swimmers know that while large objects may be roughly seen while swimming under water, the vision is very indistinct.

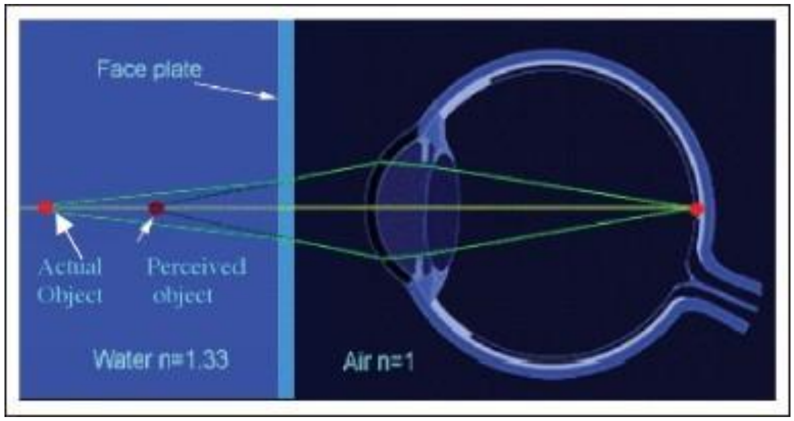



Figure 38 - Refraction of light through a diving mask. Light travelling in water towards a flat diving mask with air on the other side is refracted away from the normal in the air and the object appears closer than it actually is. The object appears slightly closer and magnified. (Reproduced from Deep ocean diving. Underwater vision. www deepocean.net)

The radius of curvature of the human cornea is approximately 7.6 mm. In air the power can be calculated by means of the equation:

— (10)

where F is the power of the refracting surface, n' is the refractive index of the cornea and n is the refractive index of the surrounding medium. The refractive index of the cornea is 1.376 as we find from Equation 10 that the power of the cornea against air is 44.20 D. Under water with a refractive index of about 4/3 calculation shows the power of the cornea is approximately 5.60 D. Very little refraction takes place at the cornea under water, thus leaving the eye hyperopic(see human eye below). This is the reason why vision is not clear underwater with the naked eye.

As a result of this magnification one would expect the resolution and stereoacuity[15] to be better underwater than in air. However, this is only true for resolution acuity under ideal

[15] Stereoscopic acuity, also stereoacuity, is the smallest detectable depth difference that can be seen in binocular vision **[92]**.

conditions where the water is absolutely clear and the viewing distances are short. Since these conditions are very rare it is more common to expect acuity to be poorer underwater.

Studies done by Luria et al [35] have shown that, with distance increasing, the estimations varied according to distance and clarity of the water. Two experiments were conducted under different conditions. Subjects were asked to estimate distances in different bodies of water: one was in clear water (50 to 85% transmission per meter of water) and the other murky (30 to 38% transmission per meter). Target distances were underestimated at very short distances (below 1.2 m) and overestimated beyond it (up to 4.2 m). Moreover, the median estimates of distance was invariably greater under the murky conditions. This was probably due to the lack of contrast due to scattering effects and murkiness of the water. Similar effects have been reported in low contrast conditions in air. However, overestimation of distance does occur under water at greater distances in clear water and in conditions of high contrast.

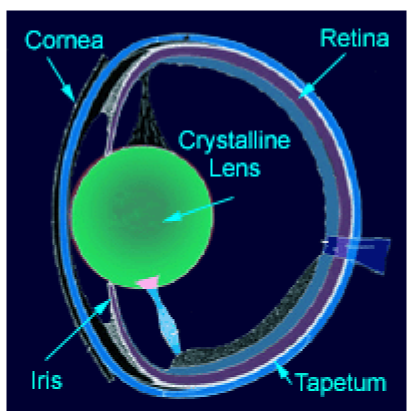



Figure 39 - A fish eye. The crystalline lens of a fish eye has a high refracting power and is of a relatively high refractive index, ranging up to 1.65. The lens itself is placed close to the cornea, bulging through the iris. (Reproduced from Deepocean diving. Underwater vision. www.deepocean.net)

By contrast with the human eye, fish can see under water without any problems. Interestingly, note that marine animals use polarization for improved vision. Nature has provided a solution for the problems humans cope with under water. Since refraction at the water-cornea surface is significant for humans, in the fish eye the crystalline lens performs most of the refraction needed for focusing. The crystalline lens of a fish eye has a high refracting power and also has a relatively high refractive index, ranging up to 1.65. This is illustrated in Figure 39. The lens itself is placed close to the cornea, bulging through the iris. The reason for this placement is twofold: firstly, more light enters the lens since due to lack of refraction at the cornea, the cornea does not concentrate the light on the lens; secondly, the lens produces a wide field of view. This is advantageous since a fish cannot turn its neck to look behind it. Since the lens bulges through the iris, the iris cannot close. The iris cannot be used to regulate light. Besides that, the fish cannot close its eye. So it is not advisable to shine a bright diving light right into the eyes of a fish. The fish uses synchronized movement of the light sensitive cells (rods, cones and pigment granules) in the retina to control the amount of light that is processed **[36]**.

By wearing a flat diving mask, humans can see clearly under water. The scuba mask's flat window separates the eyes from the surrounding water by a layer of air. Light rays entering from water into the flat parallel window change their direction minimally within the window material itself. But when these rays exit the window into the air space between the flat window and the eye, the refraction is quite noticeable. The view paths refract (bend) in a manner similar to viewing fish kept in an aquarium. Linear polarizing filters decrease visibility underwater by limiting ambient light and dimming artificial light sources.

While wearing a flat scuba mask or goggles, objects underwater will appear 33% bigger (34% bigger in salt water) and 25% closer than they actually are. Also pincushion distortion and lateral chromatic aberration are noticeable. Double-dome masks restore natural sized underwater vision and field of view, with certain limitations [37] [38].

Diving masks can be fitted with lenses for divers needing optical correction to improve vision. Corrective lenses are ground flat on one side and optically cemented to the inside face of the mask lens. This provides the same amount of correction above and below the surface of the water. Bifocal lenses are also available for this application [39].

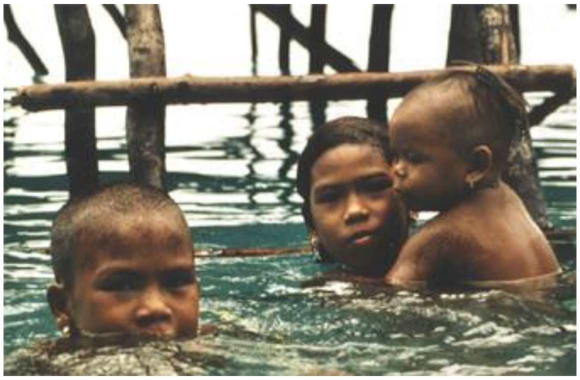


Figure 40 - Moken children spend much of their lives on the water

Another reason that has been hypothesized is that, unlike the air world, the underwater world appears hazy, lacks definition and approaches what is known in psychology as a Ganzfeld that is an unstructured homogeneous field of view. A Ganzfeld distorts many visual functions, impairs target detection and degrades other processes which are considered to be basically foveal, such as reading. We can understand better now the many effects that affect the human vision and perception underwater that some are based except the physical also in psychological factors. The Ganzfeld effect[16] (from German for "complete field") or perceptual deprivation, is a phenomenon of perception caused by exposure to an unstructured, uniform stimulation field. The effect is the result of the brain amplifying neural noise in order to look for the missing visual signals. The noise is interpreted in the higher visual cortex, and gives rise to hallucinations. **[40]**

**16** There is also the Ganzfeld experiment which is a technique used in parapsychology which claims to be able to test individuals for extrasensory perception (ESP). The Ganzfeld experiments are among the most recent in parapsychology for testing telepathy **[93]**.

## Fisheye Lens effect

A fisheye lens is an ultra wide-angle lens that produces strong visual distortion intended to create a wide panoramic or hemispherical image. Fisheye lenses achieve extremely wide angles of view by forgoing producing images with straight lines of perspective (rectilinear images), opting instead for a special mapping, which gives images a characteristic convex non-rectilinear appearance.

Figure 41 - Fisheye Lens

The term fisheye was coined in 1906 by American physicist and inventor Robert W. Wood **[41]** based on how a fish would see an ultra-wide hemispherical view from beneath the water (Snell's window). Their first practical use was in the 1920s for use in meteorology to study cloud formation giving them the name "whole-sky lenses". The angle of view of a fisheye lens is usually between 100 and 180 degrees while the focal lengths depend on the film format they are designed for mass-produced fisheye lenses for photography first appeared in the early 1960s and are generally used for their unique, distorted appearance. For the popular 35 mm film format, typical focal lengths of fisheye lenses are between 8 mm and 10 mm for circular images, and 15–16 mm for full-frame images. For digital cameras using smaller electronic imagers such as 1/4" and 1/3" format CCD or CMOS sensors, the focal length of "miniature" fisheye lenses can be as short as 1 to 2mm.

These types of lenses also have other applications such as re-projecting images filmed through a fisheye lens, or created via computer generated graphics, onto hemispherical screens. Fisheye lenses are also used for scientific photography such as recording of aurora and meteors, and to study plant canopy geometry and to calculate near-ground solar radiation. They are also used as peephole door viewers to give the user a wide field of view.

In a circular fisheye lens, the image circle is inscribed in the film or sensor area; in a full-frame fisheye lens the image circle is circumscribed around the film or sensor area. Further, different fisheye lenses distort images differently, and the manner of distortion is referred to as their mapping function. A common type for consumer use is equisolid angle[17]. Although there are digital fisheye effects available both in-camera and as computer software they can't extend the angle of view of the original images to the very large one of a true fisheye lens **[42]**.

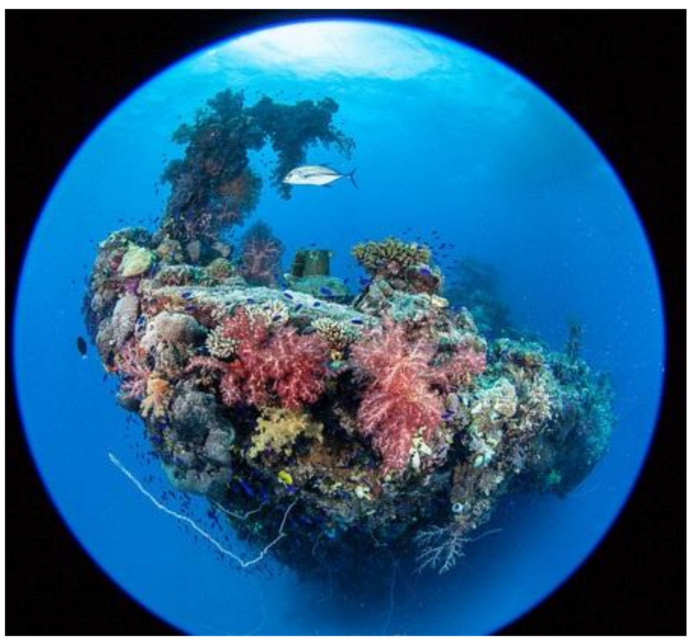


Figure 42 - Fisheye lens http://www.underwaterreflections.com/Underwater

[17] Equisolid angle (equal area): – maintains surface relations. Every pixel subtends an equal solid angle, or an equal area on the unit sphere. Looks like a mirror image on a ball, best special effect (unsophisticated distances), suitable for area comparison (clouds grade determination). This type is popular but it compresses marginal objects.

## Polarized filters

*Reduces glare and reflection*

A polarizing filter is placed in front of the camera lens in photography in order to manage reflections, or suppress glare from the sea or objects underwater. Since reflections tend to be at least partially linearly-polarized, a linear polarizer can be used to change the balance of the light in the photograph. The rotational orientation of the filter is adjusted for the preferred artistic effect. Usually, a circular polarizer is typically used, this comprises firstly a linear polarizer which performs the artistic function just described, followed by a quarter-wave plate which further filters the now-linearly polarized light into circularly-polarized light before entering the camera. This additional step avoids problems with auto-focus and light-metering sensors within some cameras, which otherwise may not function reliably with a simple linear polarizer **[43]**.

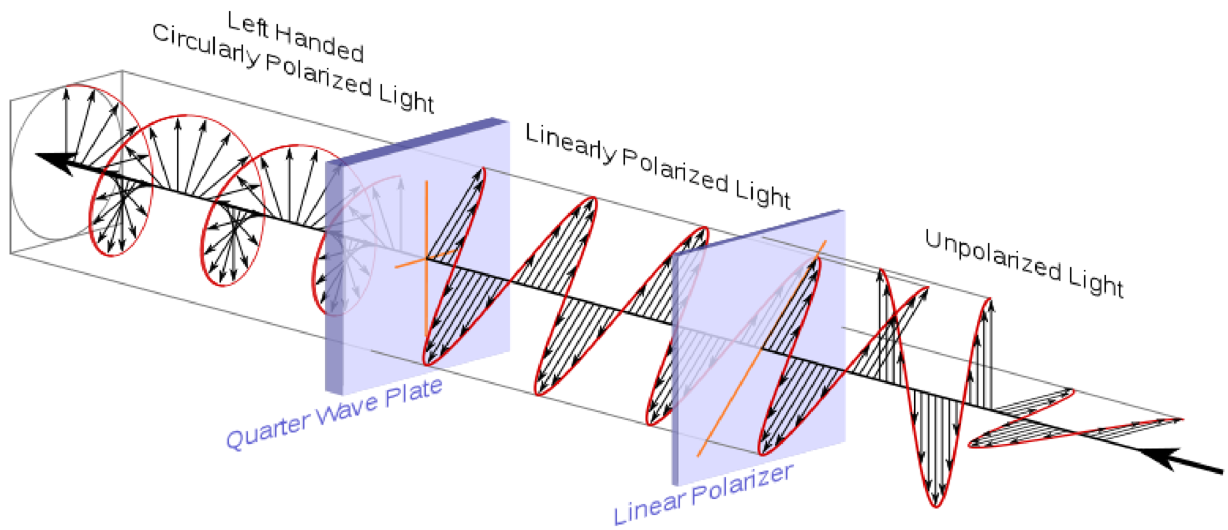



Figure 43 - Circular polarizer/linear analyzer filtering unpolarized light and then circularly polarizing the result. [43]

Polarizing filters can increase colour saturation and decrease reflections — and are one of the only lens filters which cannot be replicated using digital photo editing. While software post-processing can simulate many other types of filter, a photograph does not record the light polarization, so the effects of controlling polarization at the time of exposure cannot be replicated in software. Polarizers work by filtering out sunlight which has been directly reflected toward the camera at specific angles. This is beneficial because the remaining light is often more diffuse and colourful, but it also requires a longer exposure time (since light has been discarded).

Polarizing filters can be rotated to maximize or minimize admission of polarized light. They are mounted in a rotating collar for this purpose. Rotating the polarizing filter will make reflections, and other polarized light stand out or nearly disappear depending on how much of the light is polarized and the angle of polarization, and the strength of this effect can be controlled by changing the camera's line of sight relative to the sun. **[44]**

Figure 44 - A glass squid photographed without (left) and with a polarizing filter (right) [43]

How polarized light is distributed throughout the overall underwater light field is highly variable, even at a single geographical location at a single time of day. Unlike the situation in air, where the celestial polarization field is reasonably constant with small changes in height or altitude, underwater, the polarization fields at depths separated by only a few meters or tens of meters can be extremely different. In part, this is a consequence of vertical variations in the amount and the quality of suspended material.

A much more significant effect, however, is produced at shallow depths by variations in the relative contributions of the aerial polarization field, transmitted into water but refracted at the water's surface, and the internal submarine light field produced by scattering within the water itself. The refractive index [**Figure 31**] change between air and water restricts the view of the sky to a conical viewport (called Snell's window in deference to Snell's law of refraction **Snell's Law – Refraction**) about 96° in diameter, within which the aerial polarization field may be visualized **[45]**. Outside Snell's window, polarized light is produced by scattering of down welling sunlight.

Near the surface, especially when the water is calm and clear, and there are few waves or ripples, polarization in the sky is readily observed [**Figure 45**]. As depth increases, multiple-path scattering destroys the remnants of the celestial pattern, and only in-water scattering, produced relatively near the observer, creates the polarization field.

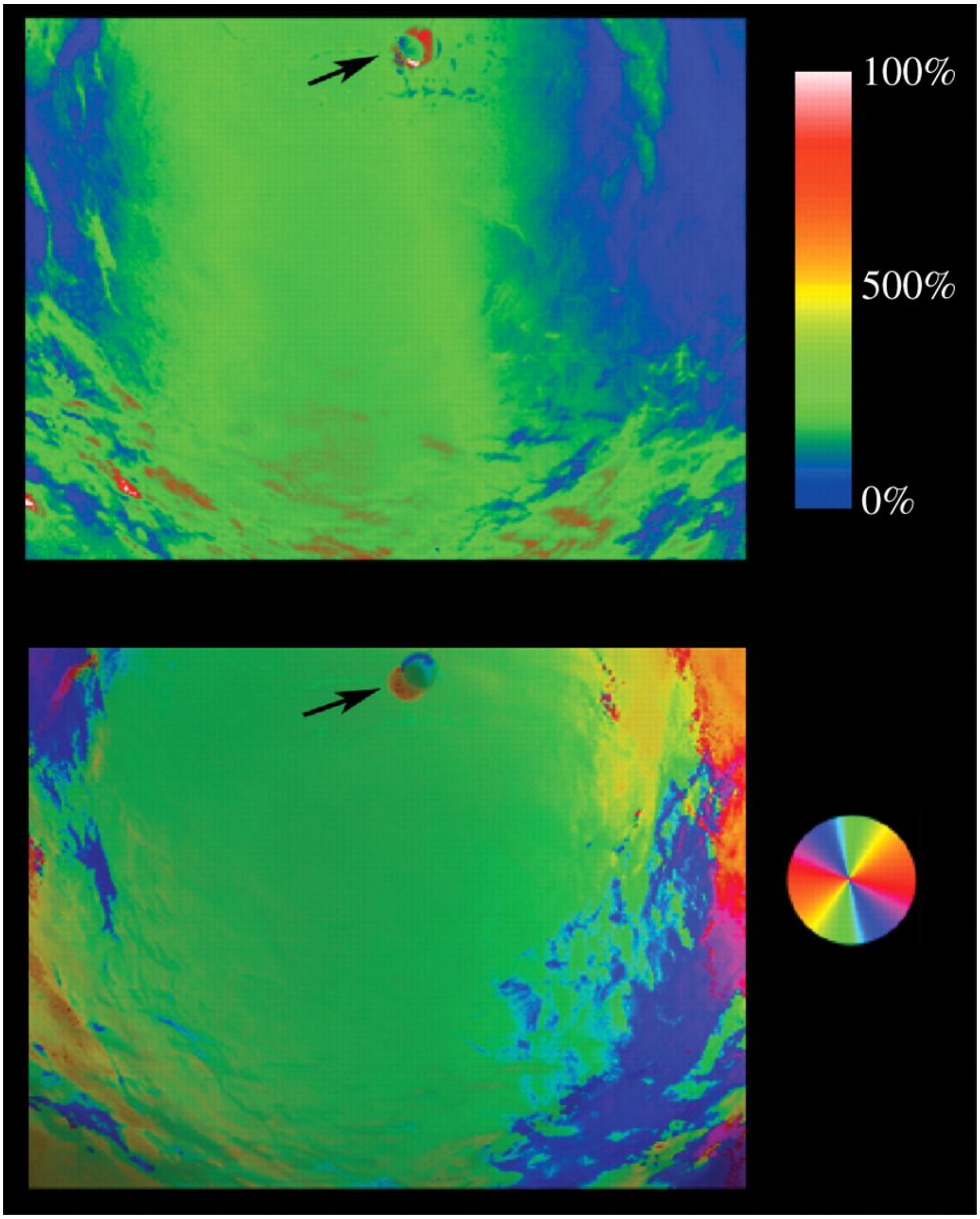



Figure 45

Polarization visible through the air–water interface at a depth of approximately 5 m in a coral-reef habitat at Horseshoe Reef, Lizard Island, Australia. Images were collected using a digital camera in a submersible housing fitted with a rotatable linear polarizer, and series of three sets of images were analyzed for degree and angle of polarization. The camera was angled upward so as to image the zenith (indicated by a tethered float at the position of the arrow in each image); south is to the bottom of the image and west is to the right. The edges of Snell's window (where the image of the sky terminates) lie near the arc of rippled water near the bottom of each panel. The top panel shows the degree of polarization in false colour, while the bottom panel shows the angle of polarization (e-vector angle); colour keys are provided to the right. Note that the skylight pattern of polarization is visible underwater at this depth to the edge of Snell's window. Below Snell's window, polarization was oriented horizontally (not shown), but the band of overhead polarization is vertically polarized in the image, being oriented north/south. The small patches of random false colour near the margins of Snell's window are owing to differences in the three photographic frames used for the analysis (mostly caused by ripples at the surface); the float also drifted slightly between photographs and thus is multi-coloured in these images. [46]

The first detailed examination of the overall pattern of polarized light in natural water was initiated by Waterman, **[47]** who used a visual polarization analyzer (an axis-finder) to estimate the polarization distribution in shallow marine water (approx. 2–3 m depth) at different times of the day.

At this relatively shallow location, the features of the aerial polarized-light distribution were obvious. The development of a submersible spectropolarimeter permitted Cronin & Shashar **[48]** to continue from this pioneering work, making spectral measurements of polarization at 25 points throughout the upper hemisphere at a depth of 15 m in marine waters. This second set of measurements differed from Waterman's **[47]** set in that the greater distance between the instrument and the water's surface was sufficient to obliterate the aerial pattern (**Figure 46**). Shashar et al. **[48]** showed that even in clear natural water, polarization is reduced by 50 per cent due to multiple-path scattering as light passes through each 2–4 m of water, so at 15 m depth there would be little to no trace remaining of celestial polarization. Instead, scattering of incident sunlight, arriving at its refracted angle after transiting the water's surface, is entirely responsible for the observed polarization at this depth. Consequently, the distribution of polarization is centered on the refracted position of the Sun, which is easily observed in the panels of **Figure 46** as the Sun moves from east to west in the refracted sky.

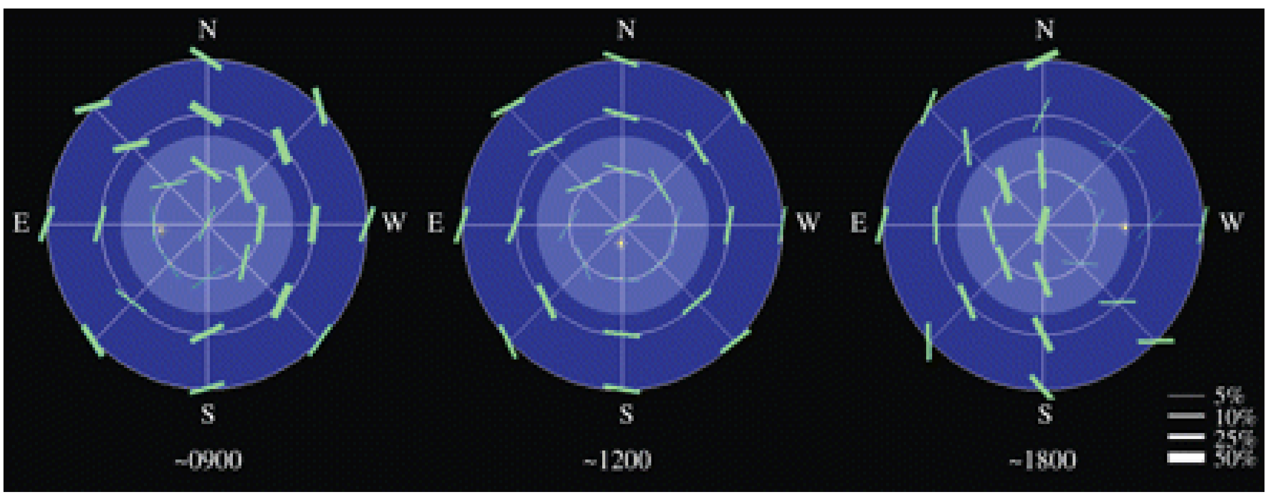



Figure 46

Polarization underwater at a wavelength of 500 nm throughout the day Times given are Eastern Standard Time. Each part of the figure shows the polarization pattern looking upwards (this is why east and west are reversed from their positions on a compass card). The margin of each panel represents horizontal, and the concentric circles show elevations at 30° intervals. The lighter inner circle indicates the region within Snell's window, where skylight is visible through the sea's surface. At each location of measurement, the e-vector angle is plotted as the angle between a tangent to the elevation circle, and the degree of polarization is coded by the thickness of the plotted line (see the key at the lower right). The estimated position of the Sun at the midpoint of each series of measurements is indicated by the yellow symbol within Snell's window.

While the Sun's position in the sky continues to strongly influence the underwater polarization pattern at moderate depths, sunlight is increasingly diffused at greater depths owing to continuous scattering. In addition, absorption of sunlight oriented away from the zenith, owing to the large paths through water at depth, gradually creates a stable, or asymptotic, light field centered on the zenith that varies little if at all in its radiance distribution throughout the day **[49] [50]**.

Thus, throughout most of the ocean's depths where sunlight is able to penetrate (to approx. 1000 m in the clearest water), the polarization pattern is stable, with the e-vector oriented within a few degrees of horizontal. Even near the surface, refraction confines the apparent position of the Sun to the bounds of Snell's window, limiting angular variation in e-vector orientation (**Figure 46**).

Because underwater polarization originates locally by scattering, the observed degree of polarization in a scene varies strongly with the brightness of the background. Reflection of light by background objects is rarely strongly polarized (as it can be in air) because of the relatively greater refractive index of water, but even if it were polarized, the rapid attenuation of polarization state with distance removes the original signal at viewing distances of only a few meters. Thus, polarization tends to be relatively stronger against dark parts of an underwater scene (or from the water background) than bright regions, because most of the light reaching the viewer from these regions has been scattered by water itself. This is obvious in the example illustrated in **Figure 47**, showing the appearance of an underwater reef scene photographed through horizontal, 45°, and vertical linear polarizers. From these images, the degree and angle of linear polarization can be computed and displayed for each pixel, (**Figure 47**, bottom panels). Note that in this scene, which is typical, polarization is close to horizontal throughout much of the field of view, although there are variations related to surface orientation of nearby objects (most of the blue and green spots are artifacts caused by wave ripple or fish motion between frames). Note that the degree of polarization correlates well with the background darkness and also that the open water region, on the right margin of the image, is evenly polarized with a uniformly horizontal axis.

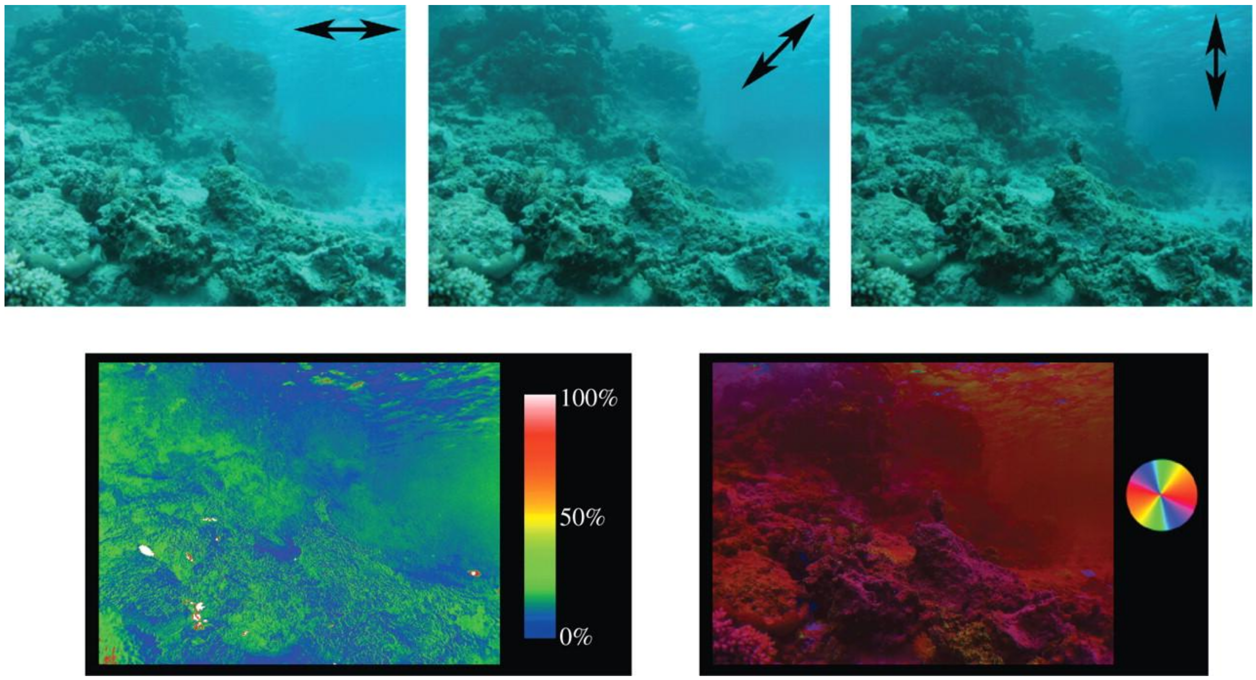



Figure 47

Underwater images of polarization, taken at a site on the Great Barrier Reef, Australia, near the Lizard Island Research Station using a calibrated digital camera in a submersible housing fitted with a rotating linear polarizer. The top set of three images shows the raw images captured with the polarizer rotated to three positions, transmitting the e-vector indicated by the double-headed arrow in the upper right corner of each image. Note that the image with the polarizer horizontal is distinctly hazier than the image taken with the polarizer oriented vertically. The bottom panels show the data analyzed for degree of polarization and angle of polarization (e-vector angle), plotted in false colour with the appropriate colour key to the right of each image. Note that polarization is generally greater against darker regions of the background, as well as in the open water view on the right margin of the image. The angle of polarization is near horizontal throughout the image, with some small variations visible on the substrate owing to reflection (although the reflected polarization is very weak). Small patches of random colour in the analyzed images are owing to motions of the water's surface or to movements of fishes swimming over the reef.

Close inspection of the images in the top row of **Figure 47** reveals subtle differences in contrast and clarity. In particular, since most underwater scatter creates polarization that is near horizontal in orientation, images taken using a horizontal polarizer are notably hazier than images using a vertically oriented filter. This simple means of image enhancement can extend visual range and object detection in water by at least 20 per cent and up to 80 per cent **[51] [52]**, a fact that has been discovered by some midwater predators that use polarization vision to detect prey **[53]**. The significant, if marginal, gains available simply by using polarization filters have encouraged more complex instrumental or computational approaches to enhancing underwater vision and image quality.

Several techniques have taken advantage of the natural polarization properties of underwater light, following the observation that the polarization originates in water, and that submerged objects reflect relatively little polarized light, especially when viewed from some distance away.

Schechner & Karpel **[19]** described a particularly effective approach that relies on subtle differences between image pairs acquired through polarizers oriented orthogonally. Their idea is based on the recognition that generation of veiling light in water is closely related to polarization, since both processes result from scattering of naturally incident light. Furthermore, loss of object visibility also results in part from scattering, as light originally reflected from objects becomes scattered away and mixed with haze produced between the object and the viewer. If the haze can be removed, and the original intensity and colour of the object restored by estimating its original reflectance, compensating for scattering and absorption of light by the intervening water, the scene can be restored to the view that would be available in a clear, non-scattering medium.

Schechner & Karpel's **[19]** approach uses the relationship between polarization and the quantity of intervening haze, which is backscatter (**Backscatter**). Lythgoe **[54]** termed this light, when it appears in front of viewed objects, ‘veiling light’.

If the backscatter is polarized, but light coming from the object is not, it is possible to estimate the backscattering light by comparing two polarization images. An additional benefit of this approach is that the distance to an object can be estimated by the quantity of backscatter between it and the observer. The quantity of backscatter at effective infinity, and the degree of polarization created by scattering, can both be estimated from portions of the image that include only the background water. The method is very sensitive to small variations in these estimates, which might arise from inhomogeneity in lighting or from different amounts of scattering along different visual axes (particularly away from the horizontal), but it can be extremely effective in both removing haze and restoring object radiance. If the correction is done independently for different colour channels in an image, the resulting image is largely colour-corrected as well. See examples in **Figure 48Figure 48**, where the Schechner & Karpel approach produces very satisfying colour and haze correction.

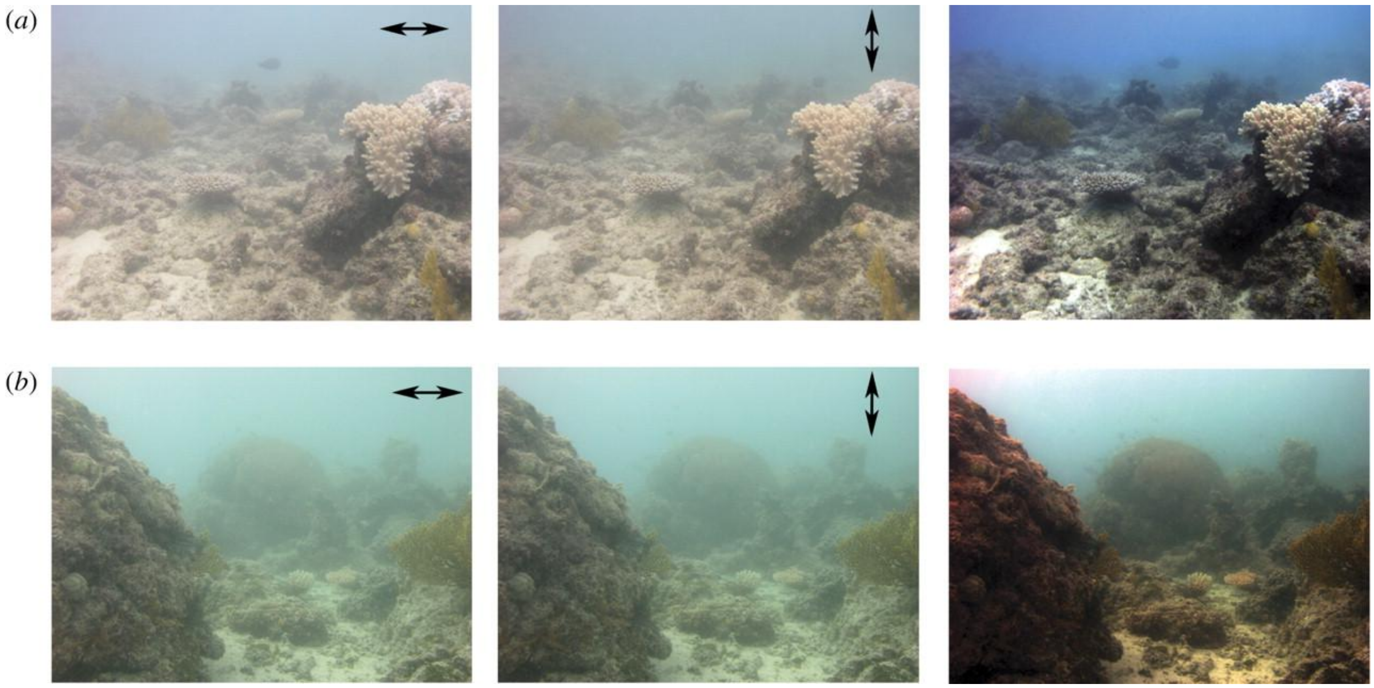



Figure 48

Image enhancement via polarization processing using the approach of Schechner & Karpel [19] on two sets of underwater images. The original input images are illustrated at the left, taken as pairs with polarizing filters horizontal or vertical as shown by the double-headed arrows. None of the images, either original or analyzed, has been altered in any way. Note that the input images differ only subtly, and neither has much contrast nor much colour saturation. Also, the colour tends towards hazy blue with increasing distance into the scene. After analysis for backscatter and degree of polarization at each pixel, the analyzed image recaptures much of the inherent contrast in the scene and restores colour. Note how the objects deeper into the scene in particular recover their contrast and their inherent colour.

So far we have included only linear polarization (partial polarization). Light can also be circularly polarized; in fact, a complete description of light's polarization requires knowing intensity, orientation and degree of linear polarization and handedness and degree of circular polarization.

Polarized light is abundant in natural scenes, and has the special attribute in such scenes of having been produced locally, almost always either by scattering or reflection. Thus, the patterns of polarized light visible to animals with polarization vision or to artificial instruments sensitive to light's polarization provide abundant information about objects in the scene, location of the Sun and time of day. Furthermore, natural polarization distributions can be used to enhance information indirectly, either simply by minimizing the contribution of scattered polarized light, or possibly more elaborately by processing polarization signals for visual enhancement. Technological approaches to polarization analysis are also attractive, for communication, object discrimination, object recognition and image enhancement.

In addition to the natural features of polarized-light distributions in scenes, animals themselves produce polarization signals (in some cases, circularly polarized ones), the study of which is still in its early phases. It is also possible that animals may manipulate polarized light in ways that decrease their visibility, creating ‘polarization camouflage’. While the importance of light's polarization for animals has been recognized for over half a century, recent research emphasizes how this property of light, of which humans are only dimly aware, plays many roles in biology. As is revealed by the papers throughout this special issue, our understanding of the roles that polarized light plays in the lives of animals continually evolves, and many questions concerning polarization vision, polarization signaling and the mechanisms by which living photoreceptors detect and analyze light's polarization remain unanswered **[46]**.

## MTF - (Modulation Transfer Function)

The modulation transfer function (MTF) is a fundamental tool for assessing the performance of imaging systems and the most widely used scientific method of describing an optical system's performance. Particularly, MTF is a commonly used metric for defining the spatial resolution characteristics of imaging systems. It has been applied to a range of capture and output devices, including photographic optics, photolithographic optics, contact lenses, video systems, fax, copy optics, printers and even the media itself are included in the list of such optical systems.

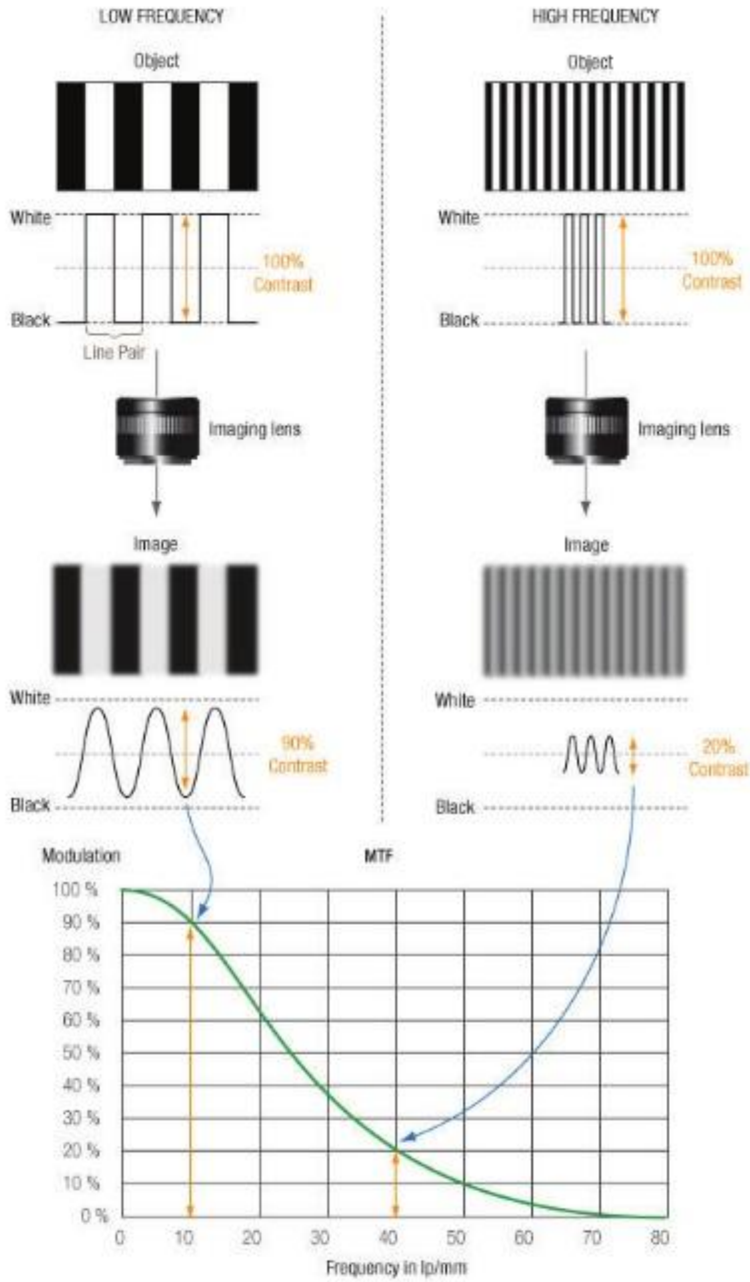
The modulation transfer function is, as the name suggests, a measure of the transfer of modulation (or contrast/sharpness) from the subject to the image. MTF is a function of Spatial Resolution. It is generally expressed as the ratio of the relative image contrast divided by the relative object contrast:

As it has been previously mentioned, it is necessary to first define two terms regarding MTF, which are required in order to truly characterize image performance:

i. resolution

ii. contrast

**Resolution** is an imaging system's ability to distinguish object detail. It is often expressed in terms of line-pairs per millimeter (where a line-pair is a sequence of one black line and one white line). This measure of linepairs per millimeter (lp/mm) is also known as frequency. The inverse of the frequency yields the spacing in millimeters between two resolved lines. Bar targets with a series of equally spaced, alternating white and black bars are ideal for testing system performance. For all imaging optics, when imaging such a pattern, perfect line edges become blurred to a degree. High-resolution images are those which exhibit a large amount of detail as a result of minimal blurring. Conversely, low-resolution images lack fine detail.



A MTF curve is represented above. The x-axis represents the spatial frequency in line pairs per mm (here on the image sensor). The maximum attainable frequency on the sensor is called the Nyquist frequency and corresponds to alternating dark and bright lines one pixel wide. The y-axis (MTF value) represents the contrast restitution for the corresponding spatial frequency. This value is between 0 and 100%, meaning complete obliteration or perfect restitution of the frequency, respectively. The value of the MTF at frequency 0 is always 100% since a flat field is considered to have been reproduced perfectly, with no intensity loss. Attenuation due to lens transmission is measured separately.

**Contrast/Modulation**

Consider normalizing the intensity of a bar target by assigning a maximum value to the white bars and zero value to the black bars. Plotting these values results in a square wave, from which the notion of contrast can be more easily seen in **Figure 49**. Mathematically, contrast is calculated with equation (9), which is known as Michelson contrast equation:

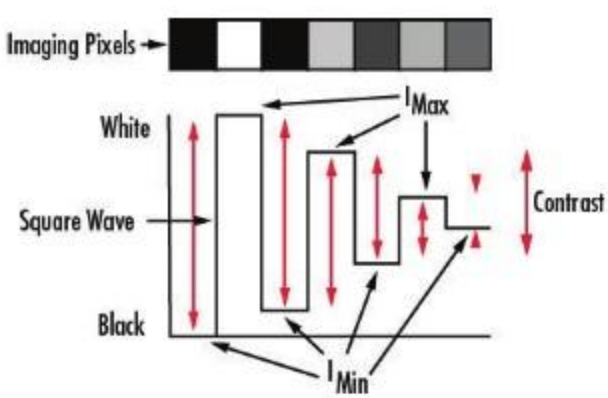



Figure 49 - Contrast expressed as a square wave at different levels of resolution.

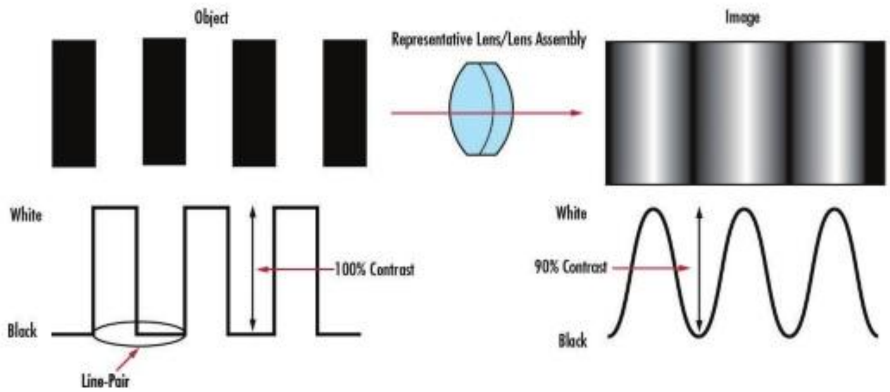



*Figure 7.4:* *Contrast of a low-frequency bar target.*

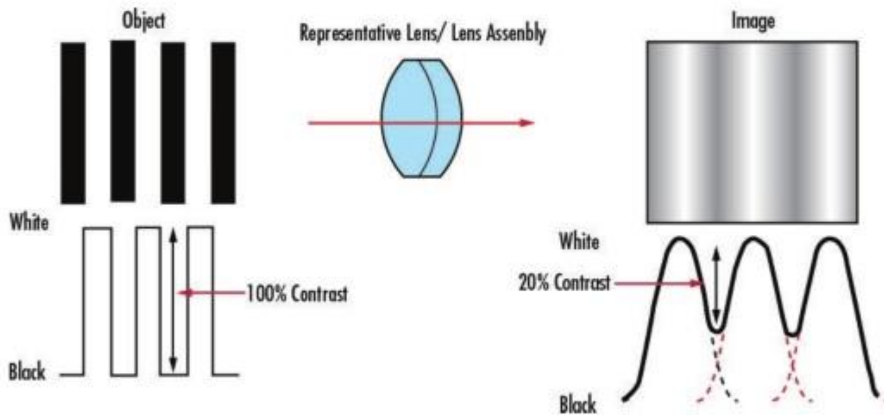



Figure 50 - Contrast of a high-frequency bar target

## Spatial Resolution

The spatial frequency in an MTF figure X-axis is described in line pairs/mm. This refers to the density of black and white stripes that can be resolved from the system from a bar test target. Also can be described in cycles/mm when it has to do with sine wave test targets.

As described in the equation above the MTF represents the contrast of an image in a specific resolution. Michelson contrast **[55]** is described as **[56]**

with $I_{max}$ and $I_{min}$ representing the highest and lowest luminance of the image respectively.

Considering the above, MTF is defined as where $M_{captured}$ and $M_{original}$ are the modulations of the captured and the original image target respectively.

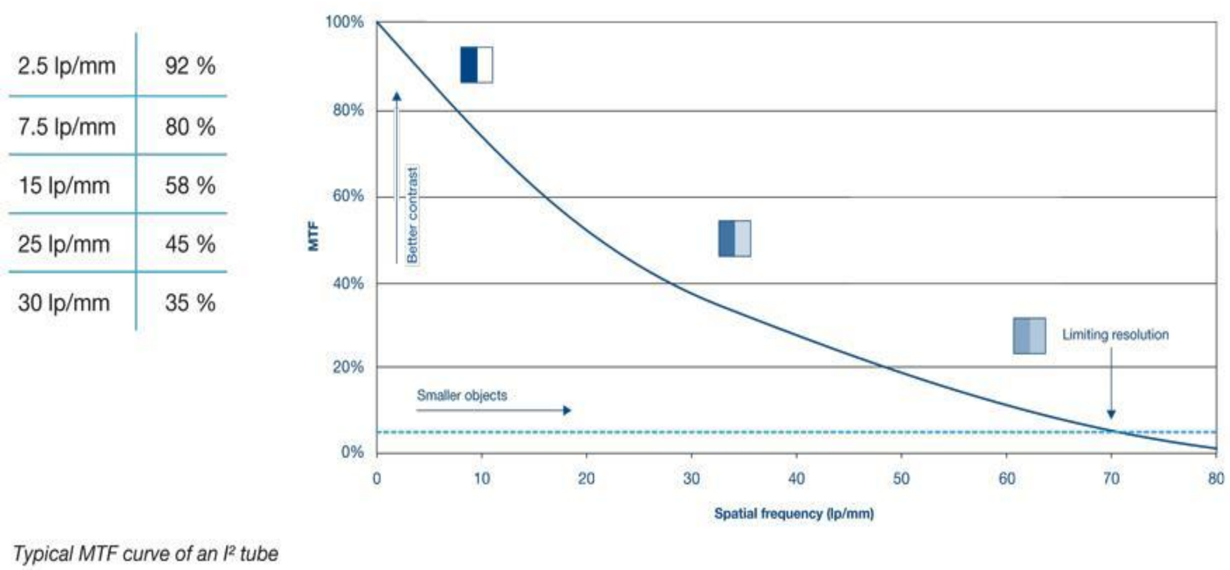



Figure 51 - MTF - Spatial frequency (line pair/mm)

## Underwater Improving Vision Filter

One of the major parameters in the quality of the underwater photography in colour absorption as previously mentioned. Colours are nothing more than different wavelengths reflected by an object. As we previously mentioned, water absorbs different wavelengths of light to different degrees. The longest wavelengths, with the lowest energy, are absorbed first. Red (650nm-780nm) is the first to be absorbed, followed by orange (585nm-650nm) & yellow (575nm-585nm).As we already have mentioned the colour absorption depends also from the clearness and the quality of the water. The colours disappear underwater in the **same order as they appear** in the colour spectrum (clear water) [**Figure 52 - Colour Spectrum**].


Figure 52 - Colour Spectrum

Every diver has noticed that the underwater environment is one of monochromatic hues rather than distinct colours. Depending on your location, objects will take on a blue or green cast at the expense of all things yellow, orange, red, etc. This is because water acts as a filter of red light. The deeper you dive the more the red spectrum is filtered from the ambient light **[57]**.

Even water at 5ft depth will have a noticeable loss of red. Green stays longer and Blue the longest, which is why things look bluer the deeper you go. As long as the water is clear, that is. In murky water there is less light penetration and things tend to look greenish-yellow **[58] [59]**. For this reason, we are trying to find the best suitable filter for the equivalent depth and colour absorption. Filters can either be made of glass, acrylic or optical quality polyester gels.

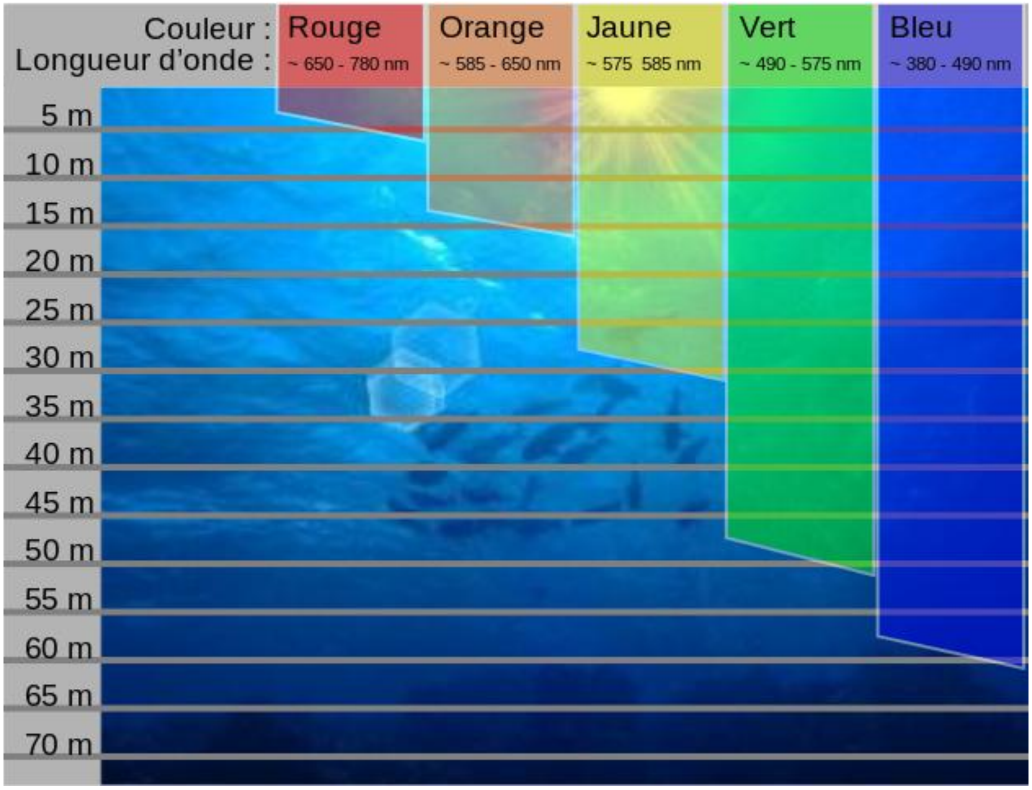



Figure 53 - Colour absorption to water depth

We notice from the **Figure 53** in which depths the colours disappear, and also colour absorption depending on the quality of the water as **Figure 54** illustrates the depth at which different colours of light penetrate ocean waters **[60]**.

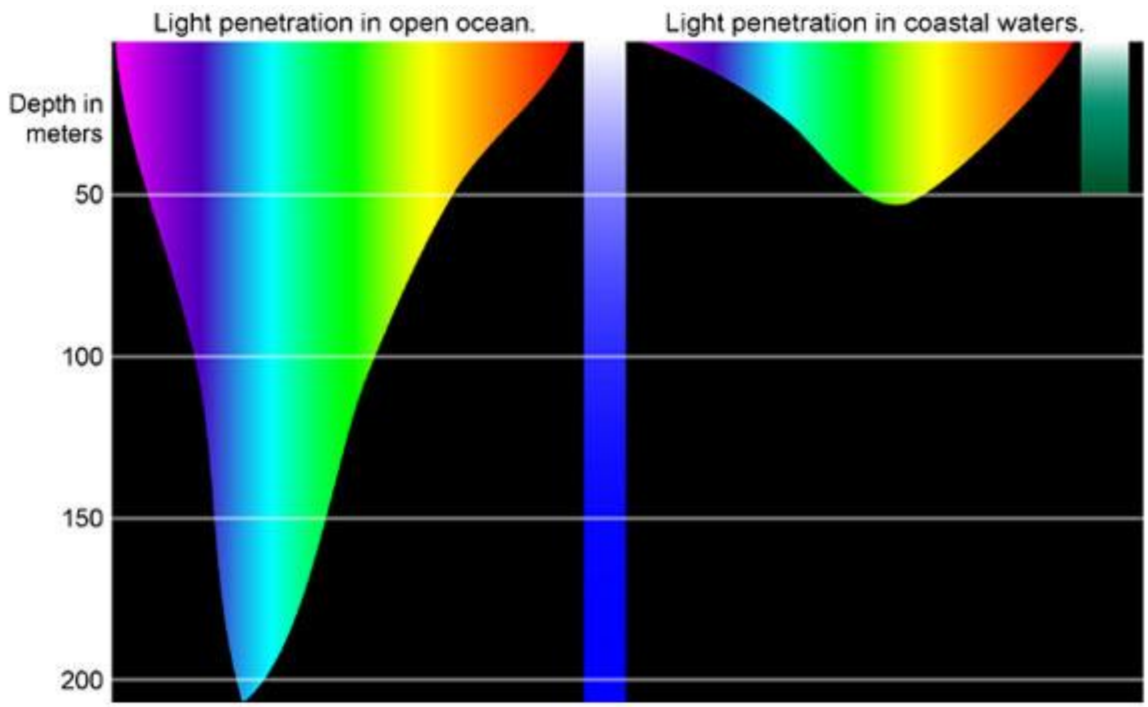



Figure 54 - Comparison of penetration of light of different wavelengths in the Open Ocean and coastal waters

NOAA - National Oceanic and Atmospheric Administration

Filters work by transmitting light of similar colour to that of the filter and holding back complementary colours and the intention of which is to alter the overall colour of the light. In shallow waters until the depth of 5-6m the absence of red is noticeable. A colour compensation (CC) filter, for colour correction, controls light by attenuating principally one or two of the red, blue, or green parts of the visible spectrum, and include the cyan series and magenta series. Broadly, these are filters that affect the balance and the shift of the light that passes through them **[61] [62]**.

The technique we used to restore colour balance is the use of a colour correction filter. Comparing the spectral characteristics of each filter and transmission spectrum, provided by the manufacturer, at the specific (ex. Red 650nm) wavelength that is absorbed underwater we were able to make a match and decide which filter is suitable for attenuating missing colour. We used two colour filters with dimensions 50mm square x 2.5mm thick, from HOYA optics, one from 0 m to 6 m – Red and the other from 5- 20 m – Orange from and a third circular photographic polarizing filter which allows you to adjust how it impacts simply rotating the front element of the filter as described in the polarizing section. The colour filters are suitable to add colour back to subjects, the colours missing from our underwater world. The polarizing filter increases colour Saturation and decrease reflections.

Figure 55 - An example of a red (650nm) colour filter

Figure 56 - HOYA monolithic colour glass filters

Here are HOYA filter graphs and their characteristics, helping us to choose the right filter.

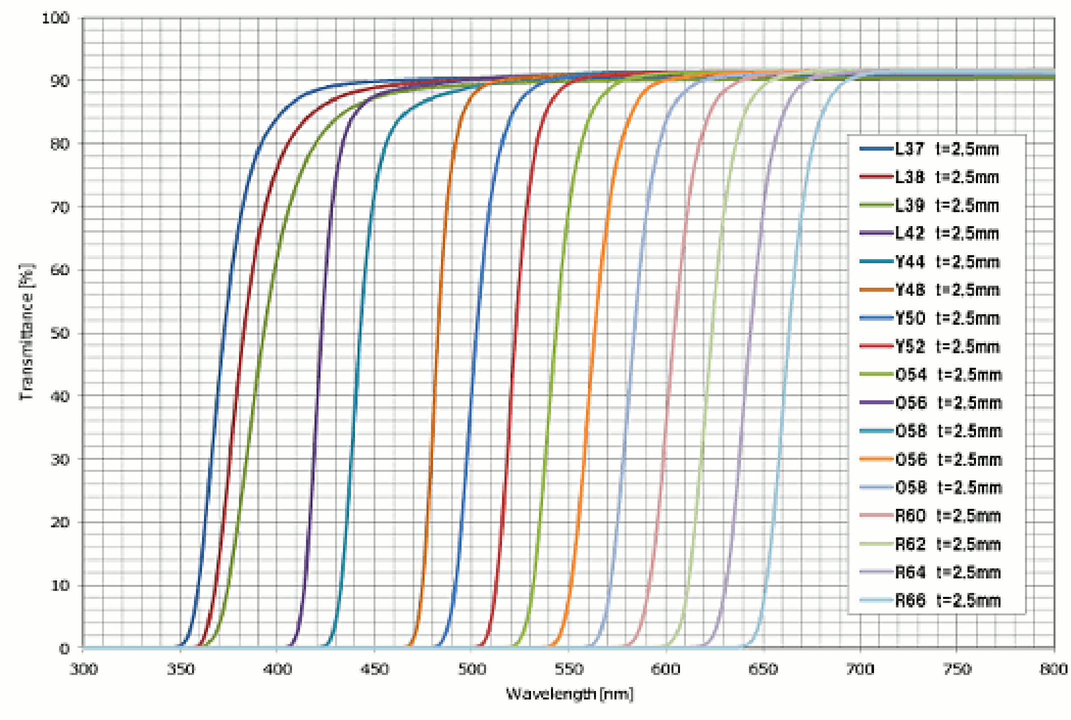



Figure 57 - Sharp Cut Filters HOYA Corporation USA

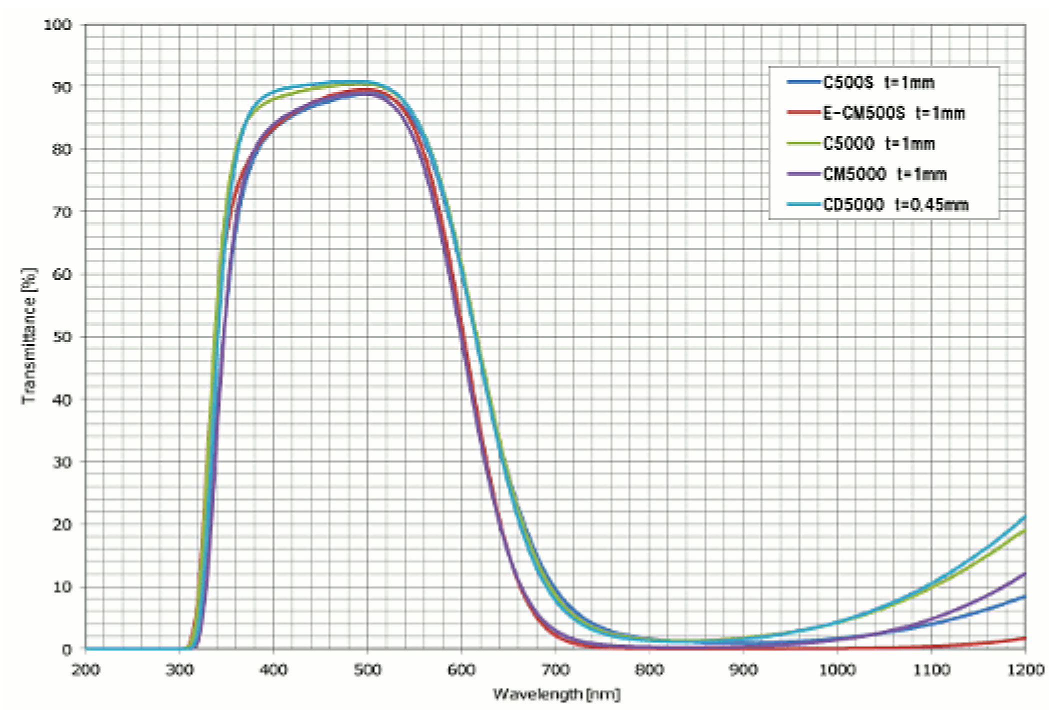



Figure 58 - Colour Compensating Filters (Cyan) HOYA Corporation USA

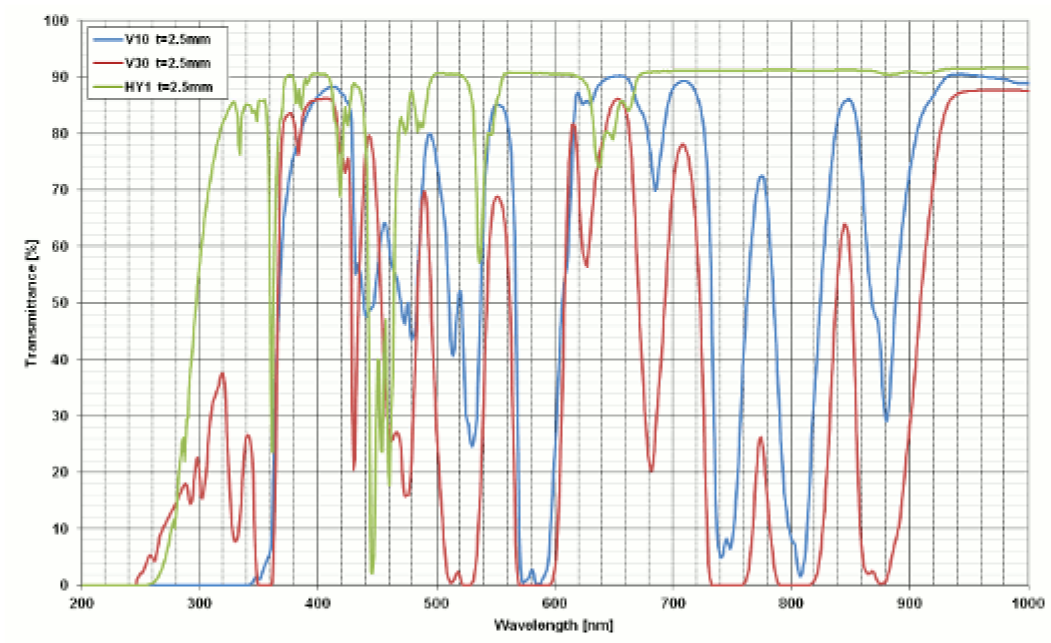



Figure 59 - Multiband Calibration Filters HOYA Corporation USA

Subsequently we tested our lenses filters using the previous described MTF (69) measurement, to quantify the overall filters performance of the system in terms of resolution and contrast. We used the bar patterns shown in **Figure 60** and **Figure 61**(bar pattern numbers 1-9), presenting the MTF curves in **Figure 62** and **Figure 63**, for both filters in 590nm and 620nm respectively.

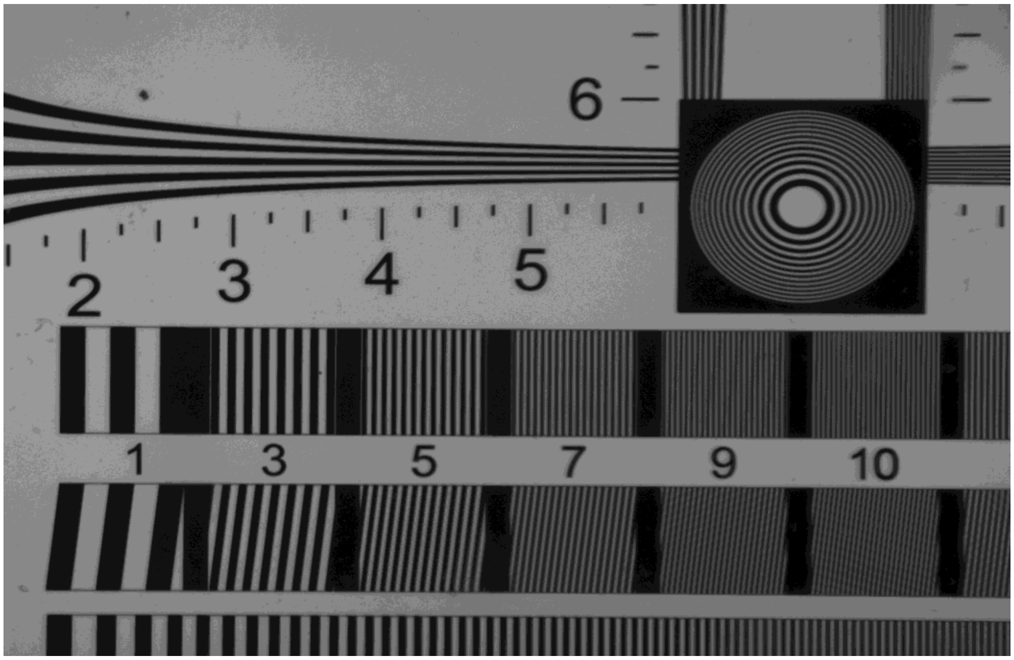



Figure 60 - 590nm (Orange) bar pattern

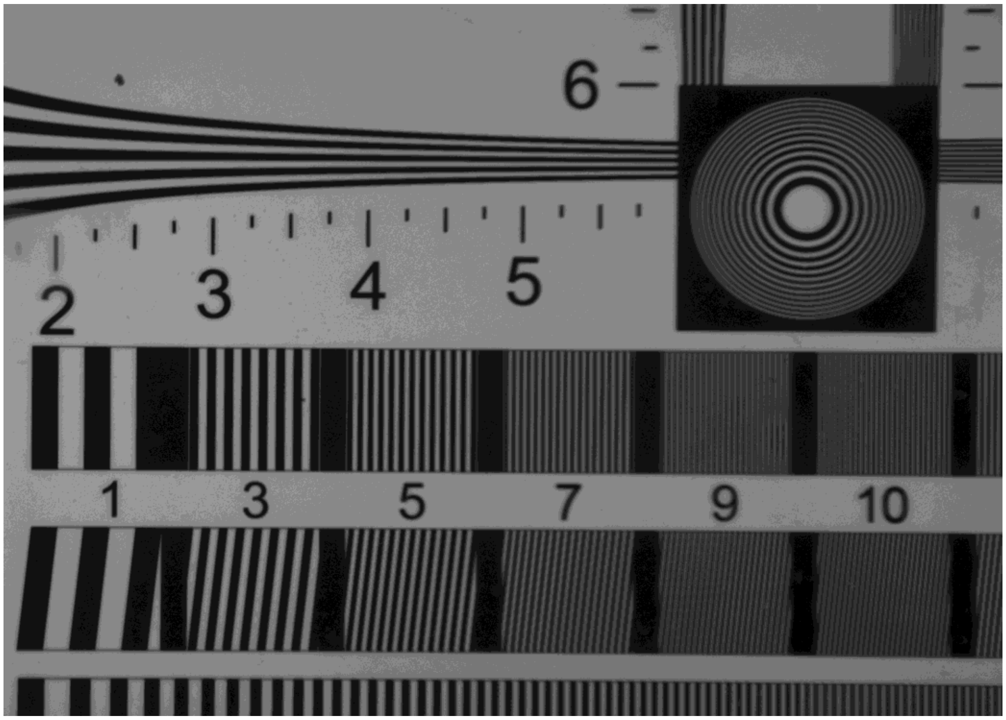



Figure 61 - 650nm (Red) bar pattern

The depicted numbers indicate the line pairs per millimeter (lp/mm).

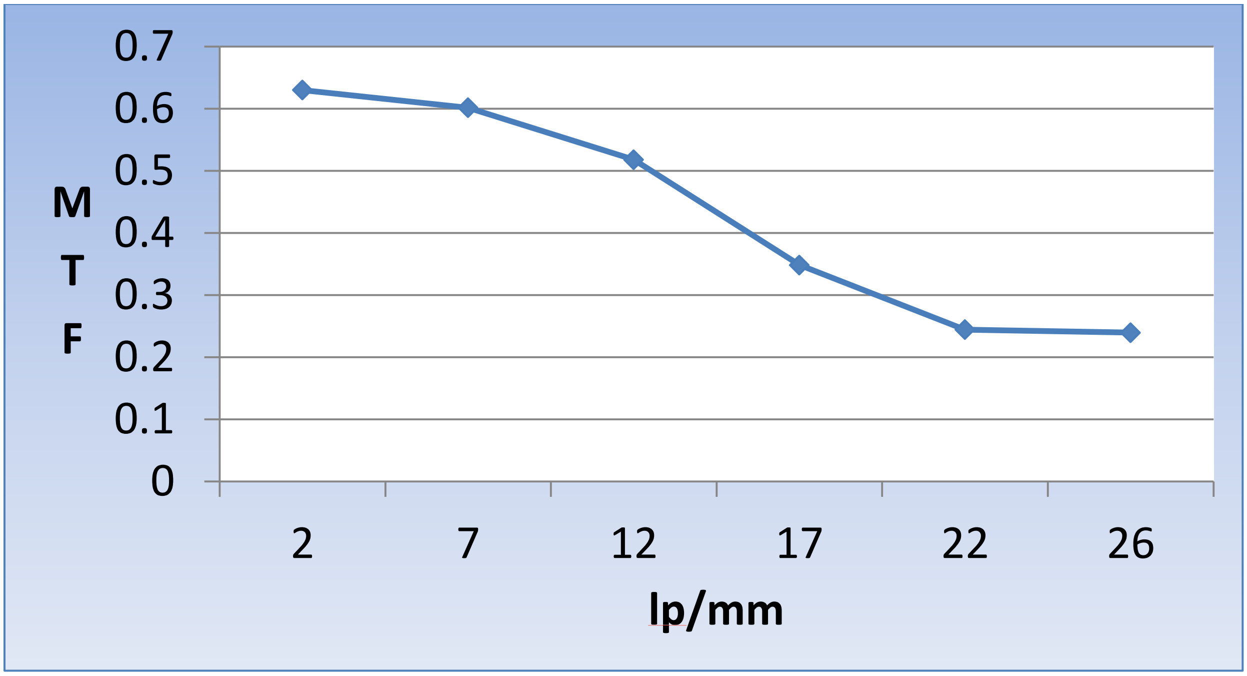



Figure 62 - 590nm Orange filter MTF curve and spatial Frequency

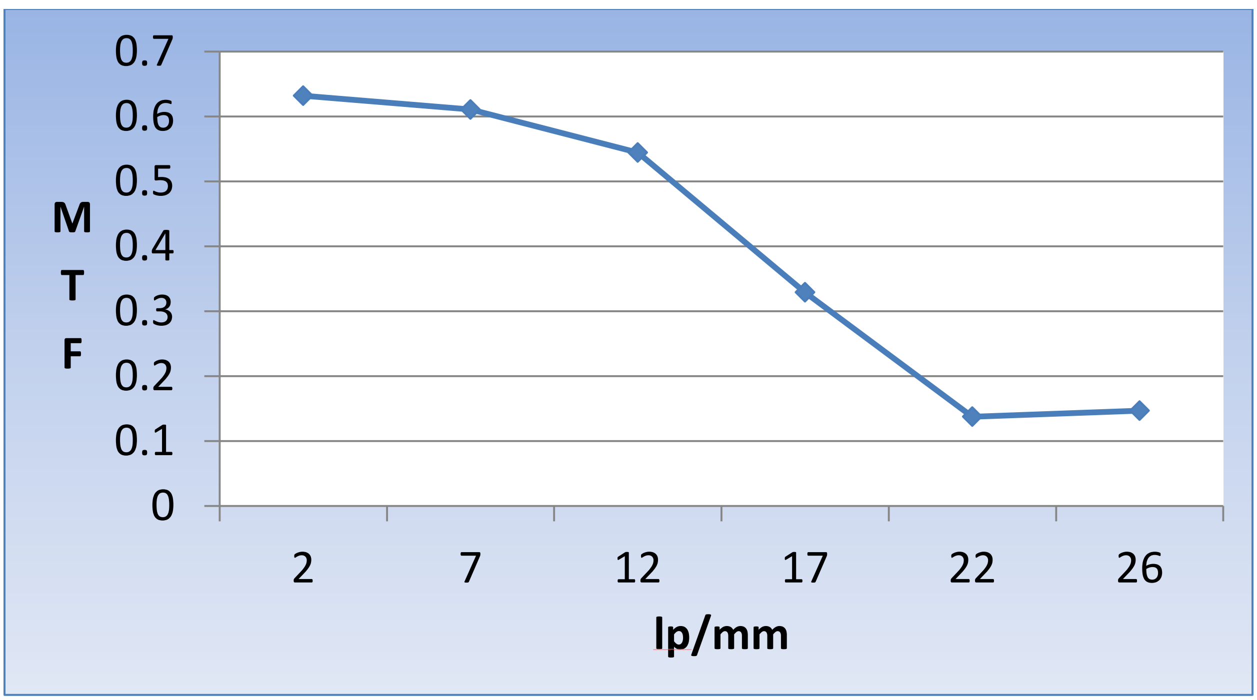



Figure 63 - 620 nm Red filter MTF curve and spatial Frequency

Generally, MTF needs to be >0.5 in order to have a higher contrast. This means that in **Figure 62** almost half of the contrast is reproduced in frequency of 12 line pairs every millimeter. We can observe that in **Figure 63** we achieve better contrast (  0.55) at the same frequency of 12 lp/mm also having a much better resolution in higher frequencies. The 590nm filter shows better MTF performance.

## Various Implementations and different approaches

- Enhanced underwater imaging **[63]**
- Colour Correction for Underwater Photography **[64]**
- A novel application of range-gated underwater laser imaging, elimination of backscattered effect **[65]**
- Flooded mask for underwater and above-water vision **[66]**
- Improving underwater vision using confocal imaging **[67]**
- A vision system for an underwater cable tracker **[68]**
- An Image Based Technique For Enhancement Of Underwater Images **[69]**
- Adaptive Background Estimation of Underwater Using Kalman-Filtering **[70]**
- Detection and Tracking Objects in Underwater Video **[71]**

- Underwater image dehazing using joint trilateral filter **[72]**

In this paper it is explored and successfully implemented a simple and effectiveness image dehazing techniques for underwater imaging system. They propose a simple prior based on the difference in attenuation among the different colour channels, which estimate the transmission depth map through red colour channel in underwater images. Another contribution is to compensate the attenuation discrepancy along the propagation path, and to take the joint trilateral filter for filtering the transmission depth map. The trilateral filter utilizes the reflectivity in addition to the spatial and intensity information so that geometrical features such as jump and edges are preserved while smoothing. Beside of this, the trilateral filter can achieve edge-preserving smoothing with a narrow spatial window in only a few iterations. Moreover, the proposed joint trilateral filter can remove the overly dark field of the underwater images by refining the transmission depth map through trilateral filtered source image and estimated transmission depth map. The experiments also demonstrate this algorithm is faster than the-state-of-the-art algorithms. That is suitable for real-time underwater imaging system in practice from the image processing effects and computation complex.

The proposed algorithm also contains some problems, such as the influence of the possible presence of an artificial lighting source is not considering, and the quality assessment may be unsuitable for underwater images.

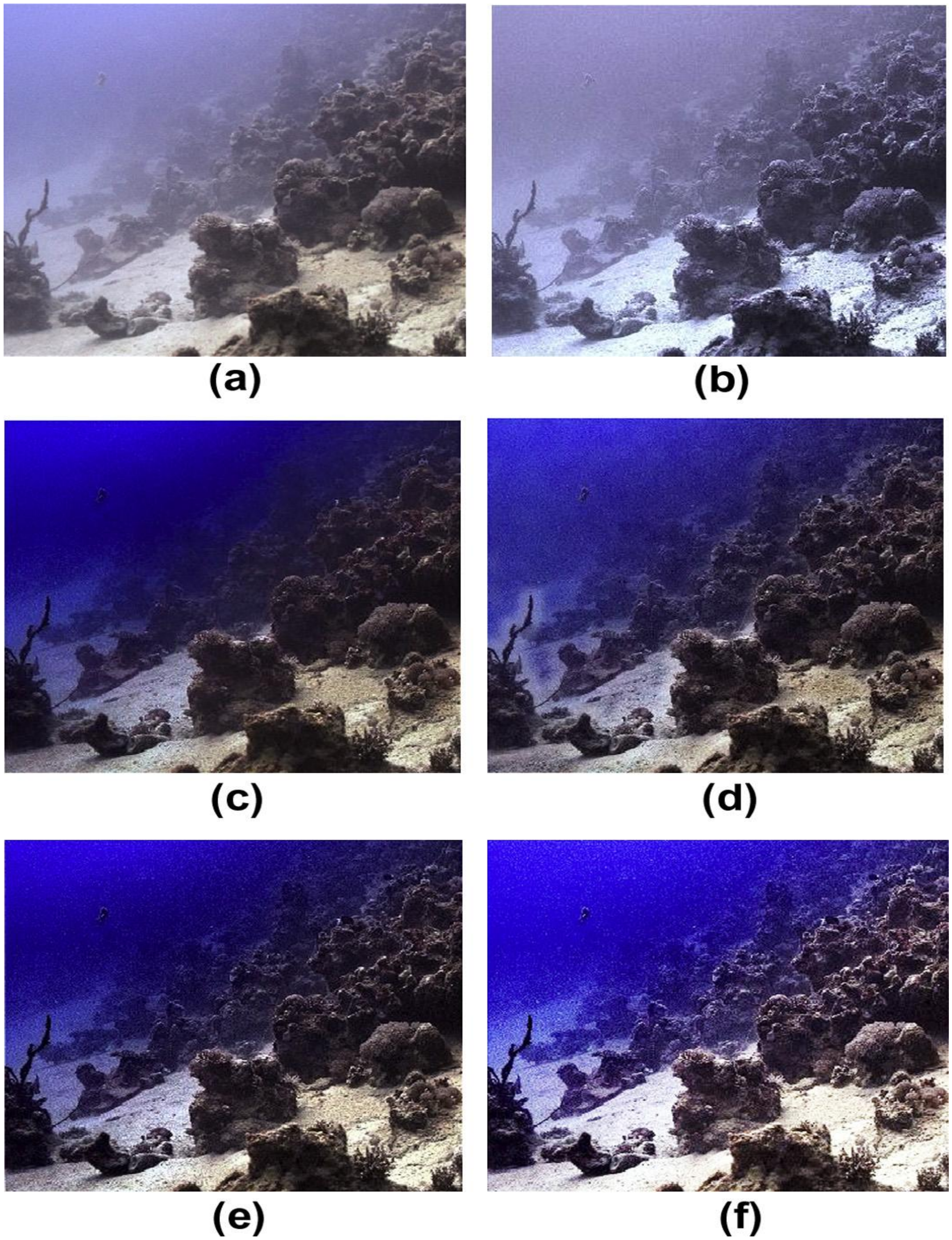



Figure 64- Different models for underwater image dehazing. (a) Input image. (b) Fattal's model. (c) He's model. (d) Xiao's model. (e) Our proposed model. (f)

### Pre-processing:

- Novel depth cues from light scattering **[73]**(exploring ways to extract depth information from images by exploiting the phenomenon of interaction between light and the medium through which it travels)

- Underwater Image Enhancement using adaptive filtering for enhanced shift-based image matching **[74]**.

In this paper it is presented a novel underwater pre-processing algorithm. This algorithm is automatic and requires no parameter adjustment and no a priori knowledge of the acquisition conditions. This is because functions evaluate their parameters or use pre-adjusted defaults values. The algorithm is fast and can be improved with a translation in C language. It is shown that the filter greatly enhances edge detection and also often increase image visual quality. It is illustrated those enhancements on edge detection comparing gradient magnitude histograms and using a robustness criterion.

Figure 65 - Images with additional underwater noise

(Average blur, Gaussian white noise, spot effect and colour range reduced) on the left and the same images after pre-processing on the right.

- Automatic Underwater Image Pre-Processing **[75]**

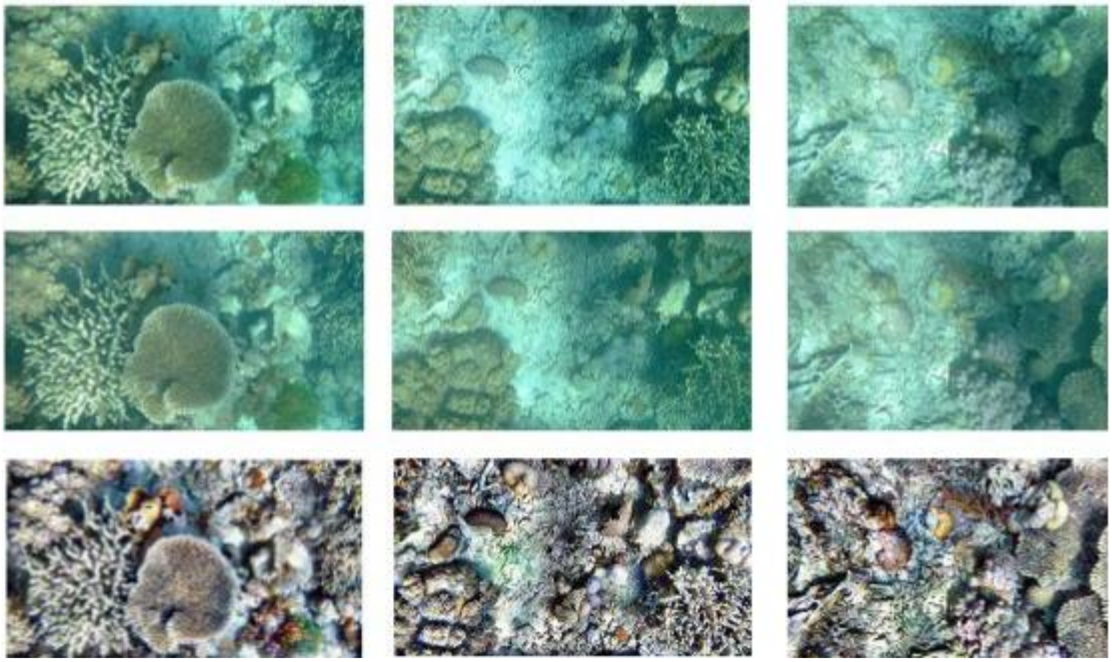


Figure 66 - Comparison of image quality before and after enhancement. First Row: without image enhancement. Second Row: Image enhancement using contrast stretching. Third Row: Image enhancement using CLAHE with Rayleigh

- Adaptive Cross Image Filters for Underwater Image Enhancement **[76]**.

Some methods improve underwater visibility by using specialized active radiation hardware. In contrast, we deal with a passive computer vision approach, exploiting both natural and artificial illumination. Other prior methods are based either on a simple subtraction of images that are differently polarization filtered, or display the degree of polarization (DOP). They assume that polarization is associated with the object radiation, rather than the causes which degrade this signal. However, this assumption becomes invalid as distances increase.

According to Ref, most computer vision methods (e.g., those based on stereo triangulation or on structure from motion) cannot be employed directly underwater. This is due to the particularly challenging environmental conditions, which complicate image matching and analysis. It is therefore important to improve these visibility problems.

# Summary

In this thesis we explored the limitations of underwater vision and we presented a simple and cost effective solution to overcome the limitations of colour absorption and decrease reflections in underwater imaging. We described and explained how vision under water is altered under different conditions and which are the causes affecting the image quality. We also researched various different approaches encounter the same topic and made a comparative study and developed an underwater vision system which improves contrast and visual image quality and explained the physical effects of visibility degradation.

## Uses and future work

There are many usages of the colour correction filter, also including in consideration the small cost price and the ease of use, practically making it suitable for every underwater camera or any underwater equipment using camera with the respective modifications for each. At first the everyday diver with a camera and also in numerous applications, like video surveillance of swimming underwater in swimming pools, detection and tracking of objects in underwater imaging or realtime video, in autonomous underwater vehicles (AUV's) and many other.

Underwater droids – Drones possibly in future will develop for everyone having his own (considering the price drop and wireless communications) and with cooperation with smart phones with the latest news being manufacturing drones that keep tracking and flying constantly to a close distance from its operator. Taking this idea underwater with an underwater drone following his operator diver and constantly filming – tracking

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