Non-visible Light Underwater Optical Communications

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***Abstract*— One look at the absorption curve for light in water suggests that the best possible window for underwater optical transmission is at the blue-green end of the visible light spectrum, centered at roughly 450 nm for clear, deep water, and shifted more towards green for coastal water [1]. While this holds true for signal transmission in the optical communications channel, it is also true for the solar spectrum, which presents as in-band white noise near the ocean surface. The greatest signal loss and interference is in the 0 to 40 meter depth range, but solar irradiance is still present to a depth of 300 meters and in some cases to a depth of 500 meters.**

Because solar radiation shares the same spectral band as the communications signal, solar light is very difficult to reject without the loss of transmitted communications signal. For wide-angle transmitters and receivers, dielectric, thin-film (TF) filters are not effective due to the wavelength dependence on angle of incidence, thus making narrow-angle band pass filters for underwater use very difficult to design. Absorptive filters can be used to reject large portions of the visible spectrum, but the problem of in-band noise still remains since absorptive filters do not exhibit the sharp cutoff of interference filters.

Sources in the range of 350 to 400 nm present a viable means to work at, or just beyond, the edge of the visible spectrum where a majority of sunlight can be rejected. Until recently, efficient, inexpensive, near ultraviolet (NUV) sources have not been readily available; but the demand for new, high power NUV light-emitting diodes (LEDs) for commercial applications has made their use in underwater applications possible. These wavelengths are not visible to the human eye thus making them good candidates for non-visible communications.

The Woods Hole Oceanographic Institution's (WHOI's) Optical Communications Group has performed many field and lab experiments with short wavelengths for the purpose of wavelength division multiplexing (WDM), enhanced daylight performance, and non-visible underwater communications. Initially 405 nm LEDs were used for WDM in shallow water and then for long-range transmission tests in deep water at the Axial Seamount of the Juan de Fuca Ridge (JDR). Additional tests were performed using 405 nm and 385 nm near the surface at JDR to assess ambient daylight rejection. Recently, work has been done in very shallow water in Cape Cod Bay to assess range with high ambient light in very turbid water.

Keywords—communications, optical, underwater, daylight

For the development of the optical modem, we gratefully acknowledge the support of the National Science Foundation under award OCE-0942835 with additional funding from OCE-0926849 and OCE-1036843, among others.

I. Introduction

The challenges to using non-visible light to create an out-of-visible-band communications channel are significant. The optical absorption spectrum of water aligns with the greatest magnitude of the solar spectrum (Fig. 1), thus eliminating most of the visible light spectrum as a viable communications band near the surface in daylight. We desire a non-aimed optical link with large usable extent for ease of vehicle mobility. This combined with scattering from high turbidity, creates a wide field of view for a receiver, making the most efficient optical filters—i.e., thin-film (TF) dielectric interference filters—ineffective. The sharp cutoff wavelength for TF filters shifts with high angle of incidence (AOI) as much as 20 nm with a 30-degree change in AOI [2]. The wide field of view (FOV) of the communications channel makes it difficult to design a TF filter for this application. Wide-angle band pass filters are typically absorptive glass, and their selection is limited to what is available from the few manufacturers that produce them.

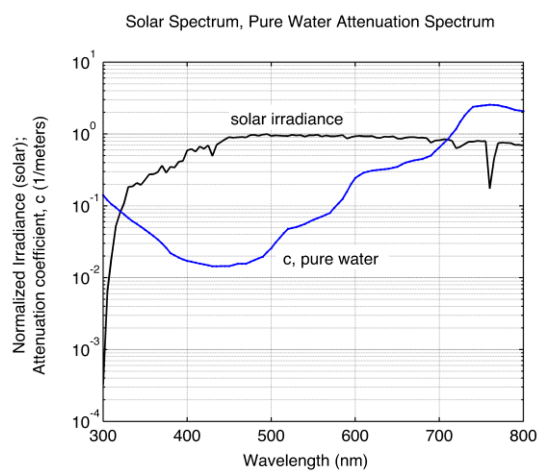

Fig. 1. Solar irradiance and pure water abortion curves show that the optical absorption spectrum of water (blue line) aligns with the greatest magnitude of the solar spectrum (black line), posing a challenge to using the visable light spectrum as a communications band. The system under test uses non-visable light (385 nm and 405 nm wavelengths) as a viable communication band.

The choices of source and receiver types are also limited after considering requirements such as bandwidth, output power, sensitivity, and wavelength. For this study we consider an array of light-emitting diodes (LEDs) as a source and a photomultiplier tube (PMT) as a receiver, and short-pass absorptive colored glass filters to block ambient light. Fig. 2 shows emission spectra of a few LED sources overlaid on transmittance spectra of several short-pass filters. Fig. 3 shows the spectral response of the receiver (PMT combined with optical short-pass filter).

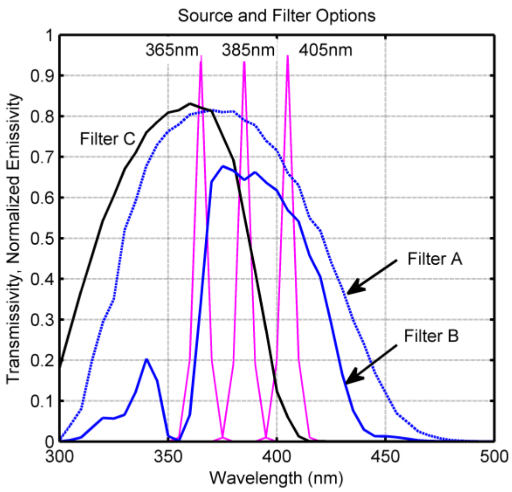

Fig. 2. Absorptive glass filter spectral transmission with LED emitter overlay. Filter A was used in early WDM testing with 405 nm communications wavelength; filters B and C were used with 385 nm for daylight testing in oceanic and littoral waters. 365 nm was considered for use with filter C but was removed from consideration due to seawater attenuation at 365 nm.

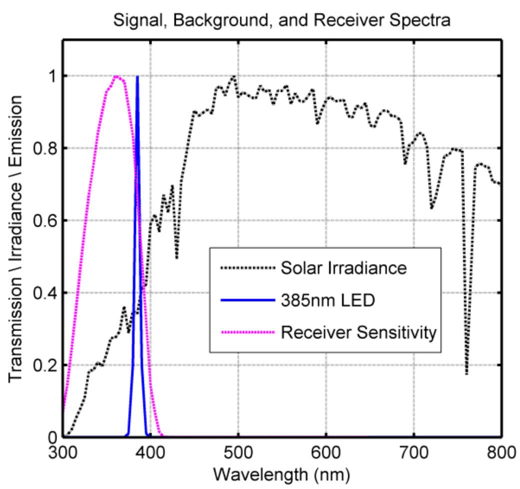

Fig. 3. Solar spectrum (linear plot) overlaid with a typical 385 nm LED source (blue) and the filtered receiver sensitivity (pink).

II. Design and Testing to Date

A. Bi-directional comms. testing from WHOI dock (405 nm)

During initial testing from Woods Hole Oceanographic Institution's (WHOI's) dock, we selected absorptive optical filters (colored glass) and two wavelengths of LEDs (405 nm and 505 nm) to attempt a bidirectional, wavelength division multiplexing (WDM) optical link (Fig. 4). Given the LED emission and filter transmittance spectra, the channel separation provided by our selected components should have been seven orders of magnitude. In practice, the long-pass filter fluoresced when excited by the violet LED that it was meant to block. This fluorescence was in the middle of the visible spectrum and reduced the channel separation to three orders of magnitude. Fluorescence of colored glass filters, and optical glasses in general, is a well-understood phenomenon where some of the energy absorbed by the materials in the glass is "dissipated" as radiated emission at longer, less energetic wavelengths. This re-emission can amount to as much as 10 percent of the absorbed energy depending on the excitation spectrum and filter glass in question [2]. Since we require >6 decades of rejection to maintain an optical link over long ranges, we abandoned the approach of using long-pass colored glass filters to block short wavelengths (>450 nm).

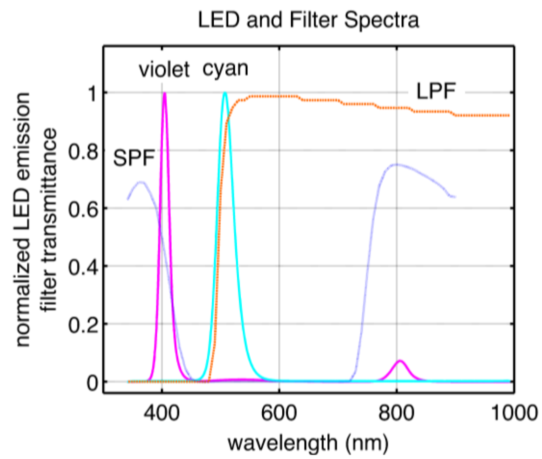

Fig. 4. Source and filter spectra of a first, failed try at WDM. Fluorescence of some colored glass filters led to rethinking the approach taken and ultimately to developing a time domain modulated (TDM) system.

B. Daylight testing at Juan de Fuca Ridge (385 nm)

Testing at the Juan de Fuca Ridge (JDR) in 2010 established the effectiveness of near ultraviolet (NUV) sources (405 nm) for optical communications in the open ocean. Deployments in the same conditions in 2014 utilized shorter wavelength filter and LED combinations for blocking sunlight from a violet-only optical channel. In order to operate in daylight, 385 nm wavelength LEDs were selected along with absorptive glass optical filters for the receiver. These absorptive filters were chosen to block most of the visible spectrum while passing much of the 385 nm emitter signal.

Prior performance from field trials at JDR using 450 nm and 405 nm sources, along with spectral beam attenuation data from Mobley [3] and others, was used to predict the range performance at ~60 meters using 385 nm LED sources in deep ocean water, as shown by the pink line in Fig. 5; purple and blue represent measured data from field trials using 405nm and 450 nm LEDs, respectively. Maximum optical link range was reduced from ~130 meters by using 385 nm vs 450 nm. Short-pass filtering at 385 nm reduced the solar background 10 dB and 15 dB more than short-pass filtering at 405 nm and 450 nm, respectively. For shallow water applications, optical signal must overcome solar background, requiring optical link ranges of < 50 meters (Fig. 7). At these ranges, operating at a 385 nm communications wavelength allows additional 10-15 dB of sunlight rejection over other blue and violet options, allowing operation at significantly shallower depths.

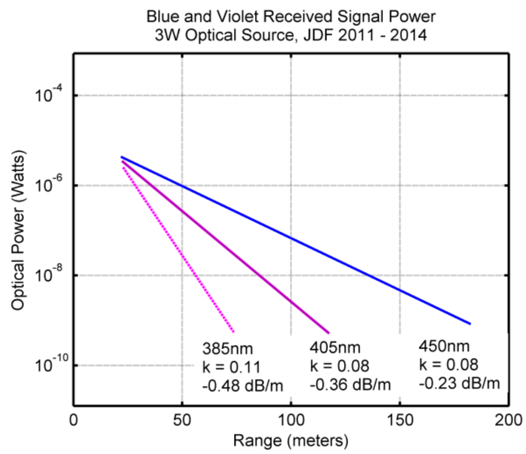

Fig. 5. Transmitted optical power in clear water (JDR) for three wavelengths, showing derived value of diffuse attenuation coefficient (k).

The R/V *Atlantis's* conductivity, temperature, and depth (CTD) carousel, which is a convenient cabled platform that is standard equipment on all oceanographic vessels, was used for testing daylight operation of the bi-directional optical modem. Vertical link separation ranges of 15 m and 25 m were tested. Since the upward-facing system was exposed to more solar background (Fig. 6), the more aggressive optical filter was used on the upward-facing receiver rather than on the downward-facing receiver. Fig. 2 shows LED emitter and optical filter spectra. Filters A and B were used in these tests.

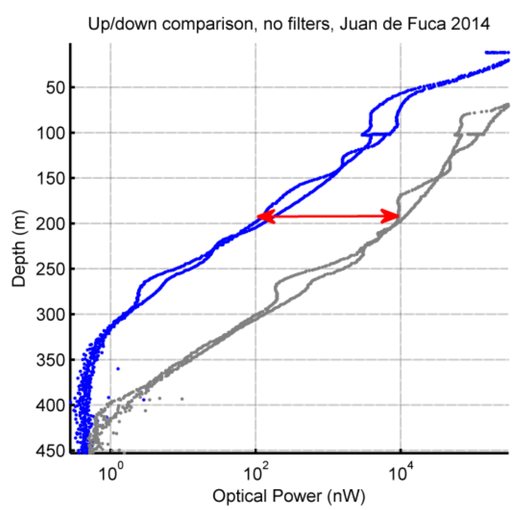

Fig. 6. Measured optical power at upward-facing and downward-facing receiver, no optical filters. Both receivers measure solar background attenuation of 1 decade per 50 meters (-2 dB per 10 meters). At any given depth, the upward-facing receiver gathers two orders of magnitude more light than the downward-facing receiver.

Even with more aggressive filtering on the upward-facing receiver, solar radiation was always the limiting factor in establishing the optical link due to the 100-fold difference in background light seen by the upward-facing receiver compared with the downward-facing one (Fig. 6). For both 15 m and 25 m separations, the minimum signal level at the receiver had to be 10 times the solar background level (after filtering): 85 m depth for the 15 m link, and 125 m depth for the 25 m link (Fig. 7). Comparing depth-for-depth the filtered solar background in Fig. 7 with the unfiltered solar background in Fig. 6, optical filter C (Fig. 2) provides ~4 decades of sunlight rejection. This level of sunlight rejection allows an optical link to be established at 80 – 100 meter water depth vs greater than 300 meter water depth for the unfiltered (blue) condition.

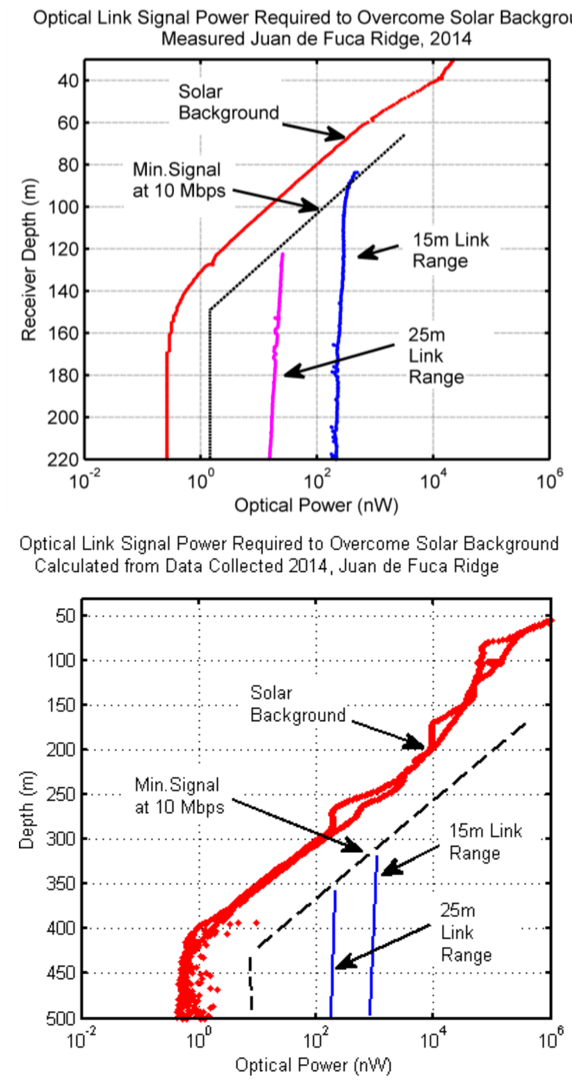

Fig. 7. Top: Measured optical power at upward-facing receiver with short-pass filter vs. depth: signal at 15 m, signal at 25 m, solar background. Bottom: Calculated optical signal required for a blue (450nm) link with no optical filter on an upward-facing reciver. Optical link requires 1 order of magnitude signal power over background. The filtered link operates at depths ~ 200m shallower than the un-filtered link.

For a receiver equipped with filter C, the measured solar background attenuates at roughly 1 decade (-10 dB) per 25 meters, or -4 dB per 10 meters, compared with unfiltered solar background attenuation of only -2 dB per 10 meters. This additional -2 dB of attenuation can be reasoned by referencing the pass band of filter C (Fig. 2). Since the filter blocks light in the blue-green part of the visible spectrum, the remaining solar irradiance is composed of shorter wavelengths that attenuate more strongly in seawater (Fig 1.)

Consider the communication signal (385nm), which attenuates at roughly 1.17 decade per 25 meters, or -10.7 dB per

10 meters (compare optical power between the 15 m and 25 m casts). This additional -6.7 dB in attenuation between the 385 nm signal and filtered sunlight is mostly explained by the combined effects of spreading and 1/e losses from a point source vs. only 1/e losses from the planar solar radiation. For the nearly hemispherical FOV of the communications system in question, $1/r^2$ spreading losses contribute significantly to signal attenuation for source-receiver separations on the order of one attenuation length (near field). Computing signal spreading resulting from an increase from 15 m to 25 m separation yields losses as high as 4.4 dB, accounting for most of the observed difference between filtered solar background attenuation and communication signal attenuation (diffuse attenuation in both signal and background).

C. Daylight coastal testing in Cape Cod Bay (385 nm)

For a shallow-as-possible daylight optical communications solution, a 385 nm optical channel wavelength was tested. Due to the ultra-high ambient light conditions imposed by shallow water, the 385 nm LED signal power was increased four-fold, and the PMT receiver was equipped with a thicker, more aggressive daylight blocking filter. The spectral sensitivity of the PMT receiver acts as a band pass filter from 300-550 nm. Fig. 3 shows the solar background, signal band, and spectral sensitivity of the PMT with the absorptive daylight filter.

Tests at the WHOI dock reveal daylight operation of a 20 Mbps optical link at a range of 10 meters in near-surface waters (Fig. 8). For reference, measured beam attenuation at 470 nm was 1.2 m^{-1}. Due to high levels of scattering, the beam attenuation measurement under-predicts the performance of a non-aimed optical communications link, particularly in turbid water. In these high scattering instances, the diffuse attenuation coefficient k is a better predictor of attenuation.

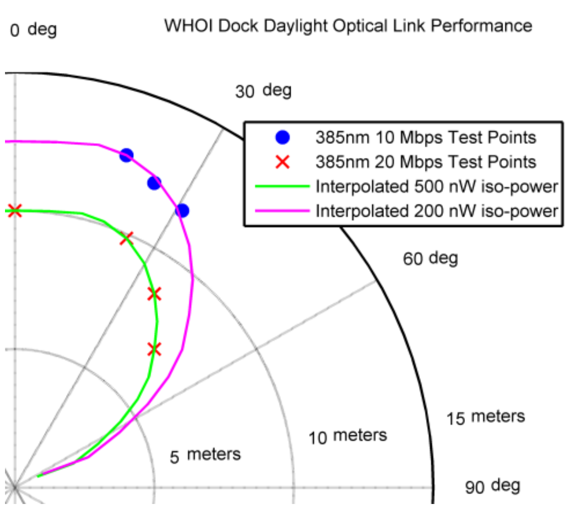

Fig. 8. Optical link performance at WHOI dock in full daylight and very high turbidity. Geometry is somewhat limited by the water depth and width of the well through the dock.

An effective diffuse attenuation coefficient was determined by using measurements of transmitted power at several ranges. At 385 nm this $k_d = 0.2\ m^{-1}$, indicating Type 1 water: the clear end of the coastal water types.

Operations in Cape Cod Bay verified optical performance observations at the WHOI dock. Optical data transfer at 10 Mbps was sustained between an autonomous underwater vehicle (AUV) and a towed platform at ranges of 11-12 meters, while 20 Mbps transfer was sustained at separations of 9-10 meters. Beam attenuation measured at 470 nm was similar to the WHOI dock (1.1 m^{-1}). This testing was conducted during the day in full sun with light cloud cover. Due to diffusion by clouds, this represents a worst case [5].

III. Summary

Extensive in situ testing of the NUV and visible underwater communications channel in littoral and deep-ocean conditions has yielded a daylight-capable high bandwidth wireless communications solution for underwater data transfer. Although not all naturally occurring ocean types were represented here, the endpoints of very high turbidity and very clear water were tested as were the extents of ambient light, from full sun at the surface to full dark at night. For the case of high angle wide-beam signals, absorptive filters performed well to reject sunlight while passing the slightly shorter signal wavelengths. Many wavelengths were considered and tested resulting in several good solutions for varying degrees of ambient light. For the near surface/full sunlight condition, a filter set resulting in -40 dB of sunlight rejection and a pass band rejection of -5 dB was developed. This yielded a signal to noise ratio of 10 dB at a receiver depth of 14 meters and an optical range of 12 meters in full sun. The range in darker water is dependent on the source power.

Diffuse attenuation, k, was calculated at several wavelengths from measured transmitted optical signal. K is a better predictor of wide angle system operation in turbid water than is the more readily available measurement of beam attenuation, or c.

Operation at the very edge of the seawater transmission window, a 385 nm light source, and the associated absorptive filter set strike a balance between ultimate optical link extent and tolerance to daylight.

Acknowledgments

We thank the captains and crews of the many research vessels and AUV teams for their field operations support. We also would like to thank our many colleagues at WHOI who provided logistical, and operational support and advice. We would like to thank Greg Mooradian, and Emmanuel Boss for sharing their knowledge of optical propagation in water.

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