Trans-Interface Optical Communication (TIOC)

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LONG-TERM GOALS

The goal of our work is to develop a system for optical communications through the sea-air interface and to provide a predictive performance model for the system for different environmental conditions, source power levels, receiver range, etc.

OBJECTIVES

The scientific objectives of the project involve understanding the spectral and temporal effects of water constituents and surface characteristics on trans-interface communication. This involves the development of a system that utilizes several, separated, redundant, sources to reduce the data drop-out rate due to wave refraction. Engineering objectives of the project are the design and development of an intelligent optical receiver that can identify the positions of redundant sources within video imagery and control a micro electro-mechanical system (MEMS) device to direct radiance from only those sources to a high-speed sensor for demodulation. This spatial filtering should reduce interference from surface reflection of skylight.

APPROACH

Wave refraction of light rays passing through the sea-air interface causes a perturbation in the path of the ray relative to its position and direction for a flat sea surface. While gravity waves range in slopes up to about 15^o (e.g. Lighthill 1980), these slopes can be augmented near the crests by parasitic capillary waves (Martin 2004). According to the Cox-Munk (Cox and Munk 1954) wave-slope relationship to wind speed, a wind of 10m/s results in a mean wave slope of about 0.19. Wu (1990) suggests a more rapid increase of slope with wind speed, however. Past experience in trying to avoid sun glint when performing remote sensing operations indicates that slopes of 0.6 are not unusual for individual waves.

For capillary waves, the disruption in directionality of an optical beam or ray that results in information dropouts can be significant. This is corroborated by an experiment made in Bayboro Harbor (St. Petersburg, FL) where the continuity of signal from a single LED was contrasted against that from up to four LEDs, where four LEDs were separated by four feet at the corners of a square frame approximately 1 foot below the interface. Generating capillary waves with 2 air jets provides enough capillary wave activity to provide significant signal drop-outs. Redundant, spatially separated sources are used with digital signal processing (DSP) of video imagery to identify the positions of

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redundant sources within the imagery (areas of interest, AOIs). Radiance from these dispersed sources it then collected onto a common intensified receiver to reduce interference from surface reflection of skylight while increasing the signal for high-rate data reception.

BACKGROUND

In this concept for optical communication through the air-sea interface, multiple emitters are placed beneath the water's surface and imaged from above. These emitters appear as small points of light in a video image of the area. In a project funded by Blackbird Technologies, we have demonstrated the ability to process video in real-time and identify our emitters within the video. For this work, we designed optical emitters using LEDs that transmit data using on/off keying. Since standard video rates are used, data bandwidth is limited to 5 baud and only short messages containing emitter ID information is transmitted.

Utilizing digital signal processing (DSP) hardware, we developed a system that processes NTSC video, identifies sources within the video matching search criteria, decodes data transmitted by those sources, and outputs the input video signal with graphical overlays highlighting the detected signals and displaying received data. Fig. 1 shows the prototype electronics (left) and a screen capture from a video clip (right). The screen capture shows several sources of light imaged through a narrow band-pass filter. For the case shown, only one point of light is actually a device (ID 399) communicating data. The other points are street and car lamps with energy in the pass band of the optical filter. Without our DSP approach, these other points would not only decrease S/N but could be identified as spurious targets. We have demonstrated the ability to maintain detection of signal sources under a wide range of environmental conditions, have demonstrated tracking of moving signal sources, and proven our ability to distinguish our devices from sources that may appear similar in nature.

This extension of the basic system involves the use of a spatial modulator to optically direct only the portions of the image containing signal sources to high-speed detectors for data reception. This concept is illustrated below in Fig. 2. Any camera outputting NTSC video is used to image the scene of interest. The video signal is processed by the DSP electronics to determine the coordinates of signal sources. These coordinates are used to control an active modulator to direct only the portions of the image containing signal sources to a high-speed detector, reducing background noise and raising the signal-to-noise ratio.

MEMS 2-D imaging arrays are commercially available and widely used in TV and data projection systems [eg. Texas Instruments Digital Mirror Device (DMD)]. The DMD is designed to tilt each of several million mirrors into 1 of 2 positions according to a video image received by the coupled electronics module. In the first (default) position the mirrors are turned off and are all coplanar. Incoming radiation is simply reflected at the same angle as the incoming beam (relative to the surface normal).

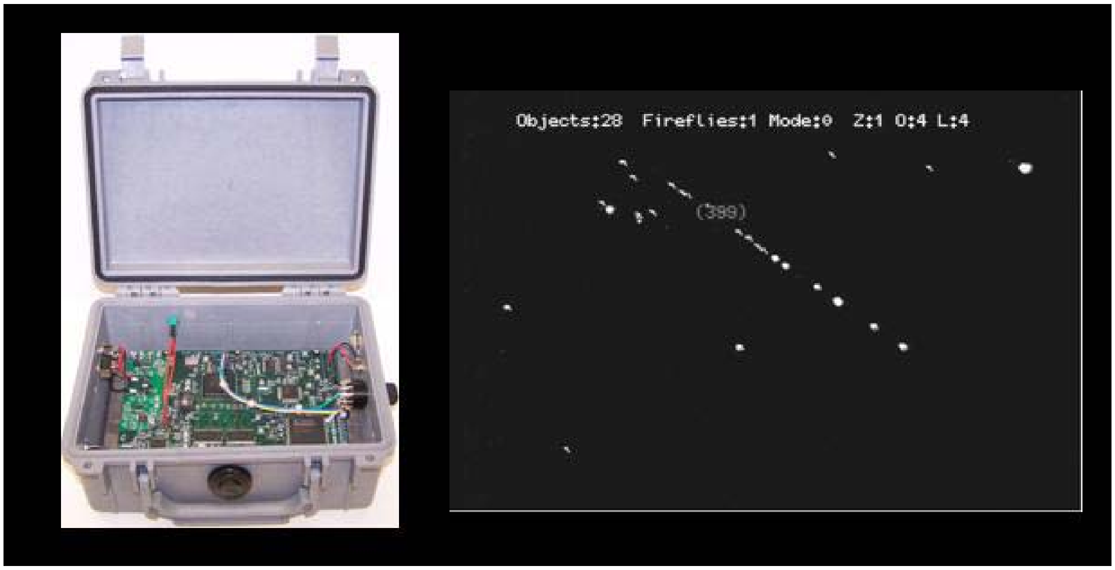


Fig. 1: Prototype electronics used to process video signals to locate and decode optical signals, and a representative screen capture showing the detection of a signal source placed near many noise sources.

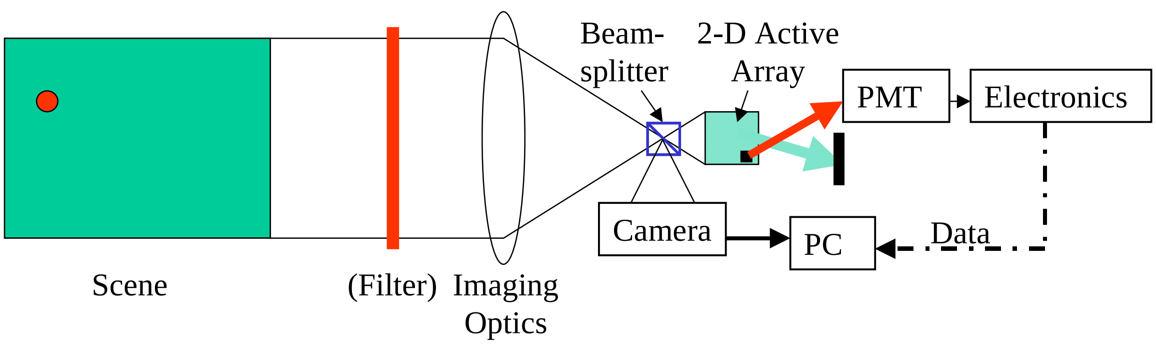


Fig. 2: Actively-steered high-speed, high sensitivity detector. 2-D Active Array (Eg. TI DLP) is used to actively project only areas of the scene of interest onto a high speed, highly-sensitive PMT detector.

In the second position, the mirrors are tilted by approximately 7 degrees. Depending on the orientation of the DMD, the reflected beam can either be at a larger or smaller angle (by 14 degrees) than the beam reflecting off the mirrors in the first position. By turning the appropriate mirrors on or off, light from specific portions of the image can be separated from other regions. It is proposed that such a 2D DMD array be utilized within a custom optical system to allow simultaneous targeting of each of the individual sources that comprise the underwater transmitter. Only those mirror elements corresponding to the locations of the signals will be energized to redirect the signals to the high-speed detector. As wave action and other factors interfere with the reception of an individual source, the corresponding mirror elements will be turned off and only light from the other valid sources will continue to the high-speed detector. In the best case, all individual sources will be present and their combined energy will be directed to the detector for maximum signal to noise. Note that by rejecting residual background image noise due to reflected skylight or sun glint, the gain on the high-speed detector can be increased.

WORK COMPLETED

Scientific A single-wavelength (525 nm), 4-source, LED array was constructed and deployed in both day and night field tests. Analysis of the data acquired during these deployments indicates that the basic hypothesis is correct and that our envisioned approach is viable (Carder et al. 2007). Redundant sources increased transmission efficiency in both daytime and nocturnal field tests. We utilized only narrow-band-pass and polarization filters on the camera. Compared to losses with one LED, data drop-outs for the redundant sources were reduced by factors of 6-14 (see Fig. 3).

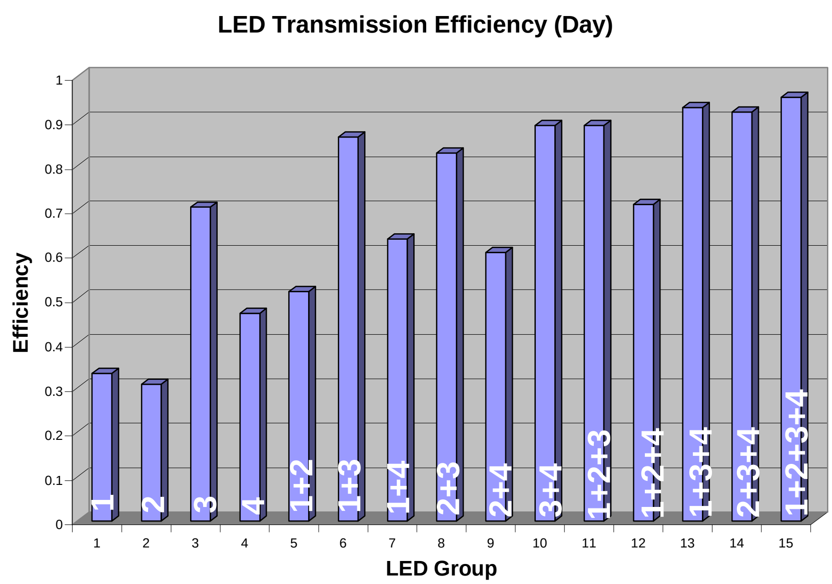


Fig. 3. Statistical analysis of the various permutations of the four, redundant, LED sources. Transmission efficiency increased to 95% utilizing all four sources versus 30% utilizing a single LED.

When completed, spatial filtering is expected to increase the signal-to-noise, and thus range and/or data rate, by a factor equivalent to the ratio of the total image area divided by the sum of the LED-neighborhood areas of the images (e.g. > 20X).

Engineering Engineering activities have focused on construction and testing of prototype hardware to demonstrate proof-of-concept. We completed construction of the prototype receiving hardware as shown below in Fig. 4. The main lens views the target and produces an image on a beam splitter. One path from this beam splitter is directed towards a video camera for image display and processing. In the second path, an enlarging lens relays the primary image onto the spatial modulator (DMD). To compensate for the different sizes of the camera sensor and the spatial modulator, the relayed image is magnified by a factor of 1.6. Light reflecting off the spatial modulator is collected and focused onto the data detector for subsequent analysis.

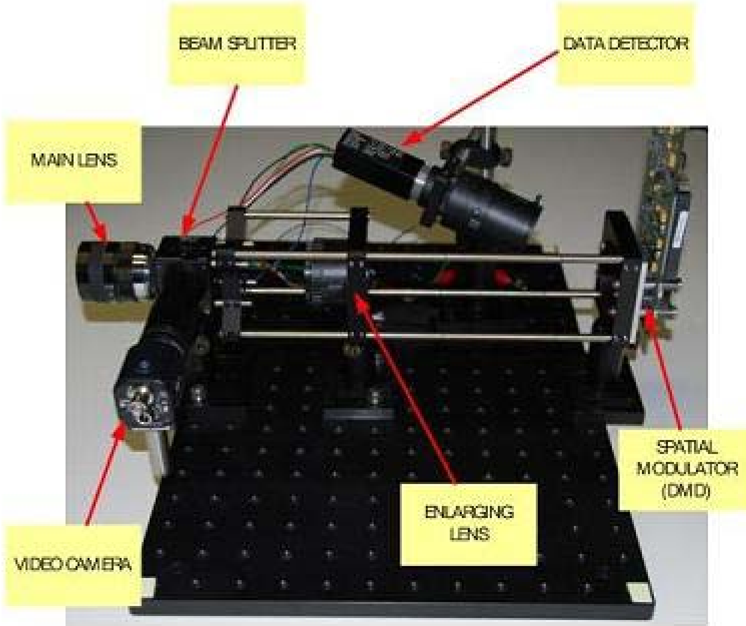


Figure 4: A photo of the prototype optical receiving hardware.

Not shown in the figure are the electronics used to process images and control the spatial modulator (refer to Fig. 2). In our concept, optical transmitters will appear as small dots in the images. These transmitters will modulate data at a high rate (> 100 Khz) within a much slower modulating envelope (< 10 Hz) that can be detected with a standard video camera. Image processing will detect the slow modulation and activate only those elements of the spatial modulator upon which the modulating signal is incident. The active elements reflect the incident light to the data (high-speed) detector for analysis. The goal of this approach is to increase the system's signal-to-noise ratio by filtering out ambient scene light and ultimately detecting only that light received from the close neighborhood of the transmitter(s).

To increase gain, we replaced the photodiode initially chosen for the data detector with a photomultiplier tube (PMT). These detectors offer excellent sensitivity and frequency response at the cost of complexity.

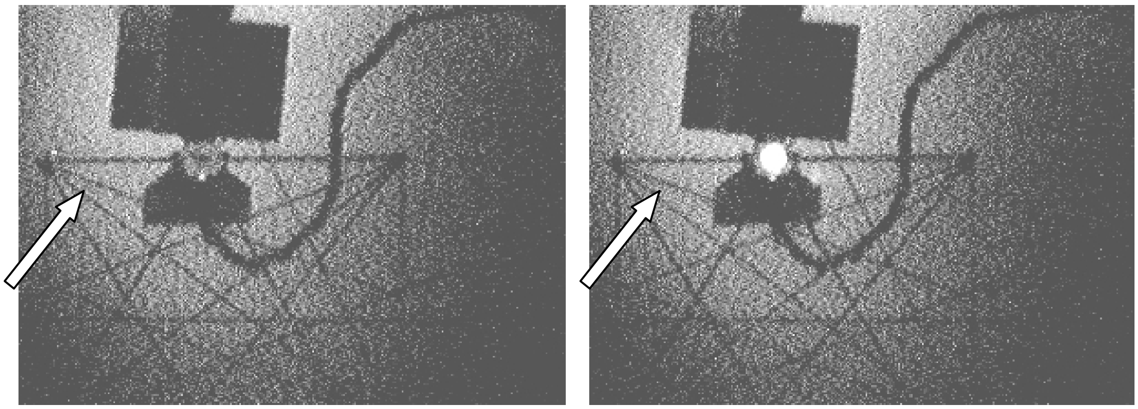
Spatial Filter This experiment demonstrates the effectiveness of using a Digital Micro-Mirror Device (DMD), from Texas Instruments, as an active, digital, spatial filter, allowing optical communication in conditions not otherwise possible.

The DMD is an array of tiny mirrors, each corresponding to one pixel, which tilt +- 12 degrees along a 45 degree axis (lower-left to upper-right). Using an optical geometry very similar to that used in video projectors, we were able to use the DMD to reflect light from specific parts of the image onto a Photo-Multiplier Tube (PMT) for signal detection, or reflect light away from the PMT. This is called a "mask" because it masks-off most of the image, only passing the parts of the image which correspond to the LED transmitting the signal. The light that is reflected away from the PMT is called the "reject" light. This light can be viewed with a camera, and we call that the “reject image”. By observing the reject image, we can verify that the mask corresponds to the correct part of the image because the hole in the mask should make the LED invisible. We can also invert the mask to allow our camera to see the light that should be reaching the PMT. All of the grayscale images below were captured from the reject image camera.

TIOC test results from the optics lab are shown in Figure 5. Equipment was in a light-tight box. Fluorescent room lights were on. Incandescent lamps were off. The LED emitted 850 nm, high-power, light, but it was operated using a large, current-limiting resistor to reduce output power. No optical band-pass filter was used, allowing more background light as “noise” in the image. Imaging was performed with a 3”, 400mm spherical mirror directly onto the DMD. The data were transmitted from a standard computer, RS-232, serial port at 115200N81 (115,200 bits/second, no parity bit, 8 data bits, one stop bit) through an IrDA encoder chip, which converts each bit into the presence (0) or absence (1) of 1uS pulses. After reception by the voltage-output PMT, the signal passed through a single-pole 100 kHz band-pass filter with a gain of 6. After this, the signal was passed through a Schmitt trigger and a 555 chip to ensure that the incoming pulses were of the proper width. They were then passed into an IrDA decoder chip, which output RS-232 signals to the serial port of the receiving PC.

The lower image of Figure 5 shows the received signal on the oscilloscope. The unfiltered PMT signal (pink) is off the screen due to the ambient light (noise). Note that the ambient light is not simply a DC offset, or else it would be filtered-out by the 100 kHz high-pass analog filter (yellow), leaving our data signal. The oscilloscope is set to trigger on the yellow trace, on any positive pulse shorter than 3.8 uS and as tall as the yellow arrow on the left. One may observe that near the trigger point there appears to be a tendency for a corresponding square wave on the RS-232 output (green is darker on the upper line and darker on the lower line), however noise is causing too many false square waves to differentiate the data signal from the noise. Despite adjusting the oscilloscope viewing and triggering parameters, and adjusting the PMT gain, no usable data could be extracted from the noise.

In the two images in Figure 5 the image is focused upon the DMD. Without using the DMD as a spatial filter, all light energy in this image reached the PMT. Although the image of the LED appears obvious, it comprises only a fraction of the total light energy in the image, resulting in a signal-to-noise ratio much less than 1. The resulting signal is indecipherable.



LED “off” **LED “on”**

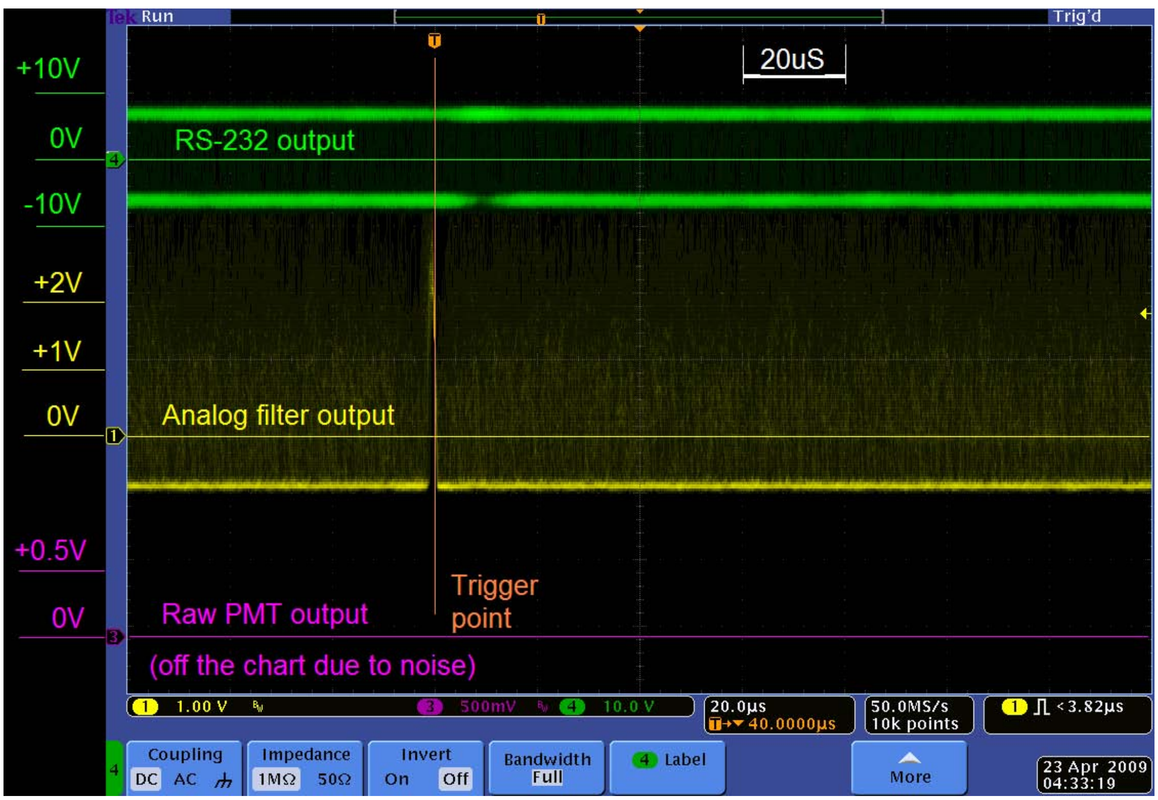
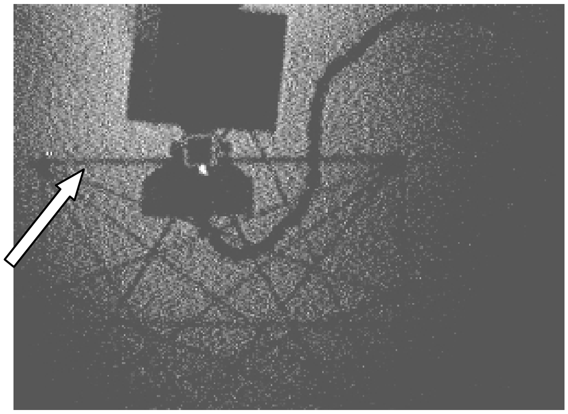
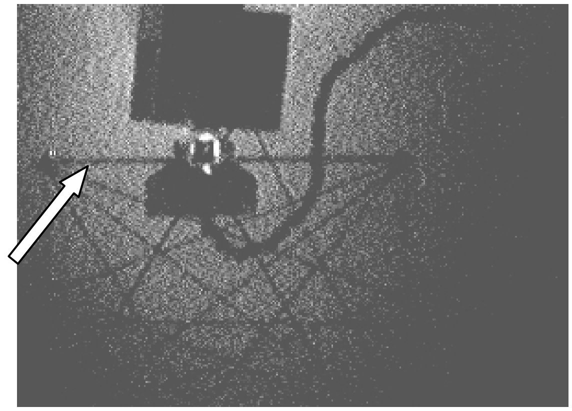


Figure 5. Source image with LED “off” (top left) and “on” (top right); oscilloscope traces for various test configurations (bottom).





LED “off” and masked by the DMD **LED “on” and masked by the DMD**

LED “off” through the DMD mask **LED “on” through the DMD mask**

Figure 6. Mask effects on the images rejected by the DMD.

In the upper two images of Figure 6, we can see the “reject” image of the mask. The black square over the LED corresponds to the DMD mirrors that are tilted toward the PMT and away from the camera. The remaining mirrors are tilted toward the camera. This allows us to view the image on the actual DMD and verify the alignment of the active digital spatial filter (mirrors tilted toward the PMT) with the signal source (LED). The lower two images show an inverted filter. This allows us to view the spatially filtered light that should be striking the PMT. The other light areas in the image (not pointed-to by the arrow) are noise, possibly due to glare off the edges of the mirrors or a smudge on an optic.

The effectiveness of this technique is confirmed in the oscilloscope image (Fig. 7) showing a high signal-to-noise ratio (approximately 3:1 in the raw PMT signal, and about 7:1 after the 100kHz high-pass filter). The IrDA-encoded pulses are easily decoded and converted back into RS-232 data, as used in a standard computer serial port. This is shown in the green trace. The character received here is the RS-232, ASCII encoded letter “f”, as when the user on the transmitting computer types an f on the keyboard in HyperTerminal. In this encoding, the ASCII code for “f” is 01100110, and RS-232 specifies a start bit (0) and stop bit (1), where 1 is -7V and 0 is +7V. IrDA encoding (yellow) is similar, but it uses a single pulse of 1.6uS for each transmitted 0 and the absence of a pulse implies a 1. There is a slight time delay in the decoding from IrDA (yellow) to RS-232 (green).

Figure 7: Oscilloscope showing the reception of the letter "f". Pink = raw PMT signal. Yellow = output of 100kHz high-pass filter with a gain of 6. Green = RS-232 output.

This experiment showed the active digital spatial filter to be very effective at increasing the signal to noise ratio. It dropped the unfiltered bias in the image due to background light (noise) from more than 5V to about 0.2 volts after spatial filtration, or more than 25X. This spatial filtration reduced background light enough to permit the system to transceive data nearly flawlessly at the high data rate of 112 kBaud. Data rates were mostly limited by the slew rate of the trans-impedance amplifier built into the PMT. Additional signal-to-noise improvements will surely be seen with the use of an optical, narrow band-pass filter, matched to the wavelength of the transmitting LED. For use outside, both the band-pass filter and a “full-power” LED would be used to obtain more range under daylight conditions.

CONCLUSIONS

Redundant LED sources at the corners of a 1-m square used for optical communication from below-water to above water reduced the data drop-out rate by 6- to 14-fold because wave facets rarely directed the radiance from all four LEDs away from the receiver.

Laboratory tests of elements of optical communication in a light-rich environment (e.g. reflected skylight) were also performed. Because narrow-band-pass (NBP) optical filters are well-understood in terms of suppressing out-of-band background light, NBPs were not used in the laboratory. Instead, tests were of a spatial-filter to restrict the field of view of a high-gain receiver to the neighborhood about the light source. This approach reduced the background light 25-fold, enabling the PMT to be operated at a much higher gain. The resulting signal-to-noise ratio was about 3:1. After passing the spatially filtered PMT signal through a high-pass electronic filter, the signal-to-noise ratio was increased to 7:1. This was sufficient to allow optical communication at 112 kBaud. In transitioning outside during daylight, the LED emitter will be returned to full power, and a narrow band-pass filter will be added to contend with the brighter environment.

IMPACT/APPLICATIONS

There are many scenarios where communication between a submerged asset and an airborne asset would be very desirable. However, communication through the air/sea interface is, at best, problematic, and any high-bandwidth communication strategy remains elusive. Tests of our basic approach (redundant, separated sources with a spatial filter of the image field of view) have shown that our hypotheses were sound. Data dropouts were reduced by factors from 6X to 14X, and background light rejection was about 25X. This provides enough signal to noise to permit optical data transmission rates up to 112 kBaud. Additional, brighter LED sources will further reduce data drop-outs.

RELATED PROJECTS

- USF College of Marine Science Center for Underwater Observability and Optical Communication – Utilization of the ROSEBUD ROV and the TOPO-13 air platform

- Eric Kaltenbacher, SRI International – Optical tagging and 3D underwater imaging.

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