Underwater Optical Beam Tracking

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Introduction

The use of blue-green laser frequencies for establishing an air ocean underwater communication channel has been well accepted. However any attempt to initialize or maintain such a link will invariably require some method of accurately spatially pointing and tracking the penetrating beam. In this paper we present results of a study concerned with determining the ability to spatially track an optical after undergoing underwater propagation. By invoking the concept of modulation transfer theory and substituting established propagation models for underwater coherence functions, the focal plane intensity patterns generated in wide angle optical lensing systems can be determined, as a function of the link characteristics (e.g. sea state, depth into the ocean, turbulence, etc.).With the intensity pattern modeled, the behavior of various forms of optical trackers can be analyzed by the application of standard tracking loop theory. Of particular interest here is the application of well known mathematical tools, such as Kolmogorov theory, which allows generalized statistical analysis to be performed on both linear and nonlinear dynamical systems. The result of such an approach is the development of a differential equation whose solution yields the statistics of the tracking error. Theoretical studies of this type have been examined previously for generalized scattered optical fields [1]. With these basic approaches as a guide, mean squared tracking errors can be derived, which assesses the perfomance of the beam tracker in relation to the channel characteristics.

Underwater Optical Scattering

Scatter channels have been studied from several viewpoints, including variations in refractive index, point scattering, and radiation transport theory. The basic analysis method is to determine the scattering effect of a single particle of a given size within the medium (in this case the water).The scattering solution is then obtained by finding electromagnetic boundary valued solutions, and then averaging over the statistics of the scatterer size and location distribution. This has been used successfully to determine point source coherence functions for the water medium, assumed to be both isotropic and homogeneous. Analytical solutions of this type have conformed well with measured data, and give insight into the behavior of light scattering in water. The fact that coherence functions have been well modeled is extremely fortunate for the beam tracking problem, since cohrence functions are all that is necessary to analyze energy detecting beam trackers.

The established cohrence function for underwater point sources is given by

$$M(x) = e^{-c_a L} \exp(-c_s L(1-B(x))) \tag{1}$$

where L is the distance from the point source on the water surface to normal observation plane immersed down into the water, and x is the distance between two points in the plane. the parameters c_a and c_s are the absorption and scattering coefficients of the water, respectively, and give the power loss per unit distance due to these effects. The function B(x) indicates the variation in water cohrence as a function of x. Limiting forms to the coherence function in (1) can be obtained for large and small x by properly modeling B(x). This leads to

$$M(x) = e^{-c_a L} e^{-(x/r_0)^2}, \qquad x \ll \frac{r_0}{(c_s L)^{1/2}} \tag{2}$$

$$M(x) = e^{-(c_a + c_s)L}, \qquad x \gg \frac{r_0}{(c_s L)^{1/2}} \tag{3}$$

where

$$r_0 = \frac{\lambda}{(c_s L)^{1/2} \theta_{rms}} \tag{4}$$

and θ_{rms} is the root mean squared forward scatter angle, having a value of a few degrees for water. The parameter r_o is the coherence distance of the medium, and is generally on the order of microns.

The point source coherence function describes the the random field at a distance L into the water from the surface. An optical lensing system converts this to the field intensity pattern in its focal plane through its operating transfer function(OTF). Mathematically the intensity requires a convolution type of integration, but in general the intensity follows the form of the coherence function at its aperture plane. Once this focal plane intensity is known, the performance of subsequent focal plane processors, such as optical beam trackers can be analyzed.

Beam Trackers

Optical beam tracking is achived by converting off axis beam pointing errors into voltage signals that can be used to correct (aim) the receiving lens so as to reduce the error. A typical spatial tracking subsystem is shown in Figure 1. An error voltage is obtained in both azimuth and elevation by a quadrant photodetector using sum and difference field energy values. The error voltages are then filtered and used in a feeedback arrangement to control azimuth and elevation pointing. The dynamics of this feedback system keep the tracking lens oriented so as to position the intensity pattern centered on the error detector in the focal plane. Knowledge of the intensity pattern allows computation of the tracking error statistics, and some degree of solution concerning the tracking behavior. Once the components of the feedback loop (loop filters, loop gain, etc.) are known the system differential equations for the tracking error in both azimuth and elevation can be written. The response charactistics of the error sensing quadrant detector can be derived by integrating the field intensity distribution over the detectors of the quadrant array,taking into account any offset pointing error.

Kolmogorov Theory

Analysis of optical trackers can be carried out by using the Equations of Kolmogorov. According to this theory the variable of a differential equation forced by a random field has a steady state probability density that satisfies a known infinite order differential equation. These equations have coefficients obtained by averaging differential changes in the equation variable with respect tothe statistics of the random field. Although these computations are often lengthy suitable approximations and truncations can be applied to yield fairly accurate solutions.

In the presentation here,the results of the preceding analysis applied to the optical beam tracking problem, when focused on an underwater beam, will be discussed. An interpretation of these results will be made. The mannner in which the tracking error density “spreads” with depth into the water is shown. The possibility of azimuth and elevation crosscoupling is also considered.

References

(1) Sheikh, M “A Statistical Analysis of Optical Beam Tracking With Quadrant Detectors” PHD Dissertation, Univ. of Southern California, Dept of Electrical Engineering, 1977, (to be published)

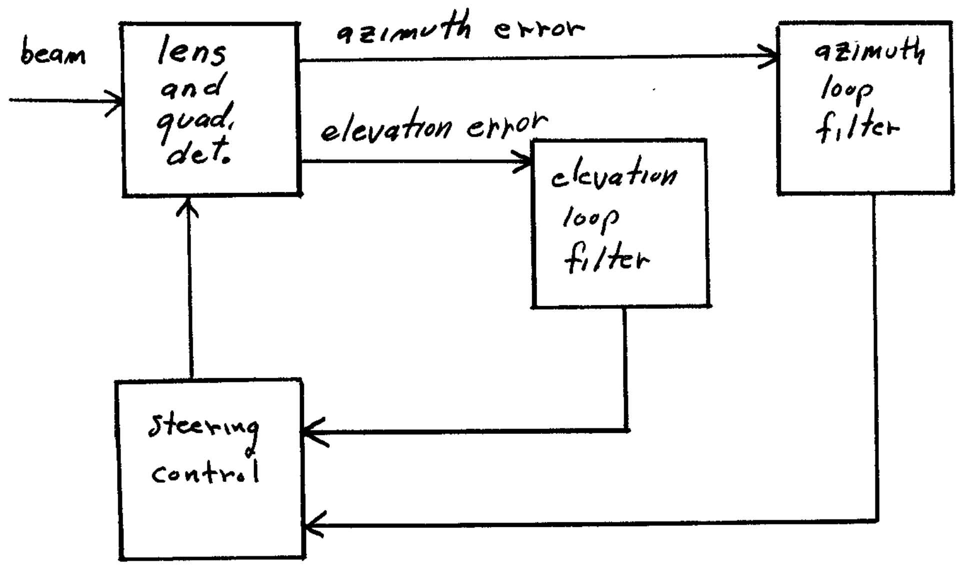
beam
lens and quad. det.
azimuth error
elevation error
elevation loop filter
azimuth loop filter
steering control

Figure 1