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IN-WATER PHOTOGRAMMETRY

Abstract

This paper summarizes the various degradations introduced by the water path and shows various methods of predicting imaging system performance. Several techniques for extending the useful imaging ranges are reviewed and evaluated.

Introduction

Photography in the sea is a difficult and complex task. In most applications we try to simplify the problems by getting very close to the subject and thereby eliminating as much as possible the various degradations introduced by the water path. Unfortunately for most underwater photogrammetry applications we would like to work over long water paths, so we must look for other solutions. This paper summarizes the various degradations introduced by the water path and shows various methods of predicting imaging system performance. Several techniques for extending the useful imaging ranges are reviewed and evaluated.

In order to optimize data acquisition for photogrammetric applications we need to discard many of the old rules of thumb of underwater photography and apply a thorough system approach using accurate propagation data for the operating area.

Limits of Vision in Water

The quality of an image is governed to a considerable degree by the optical properties of the water path. It is convenient to consider several basic (although somewhat arbitrary) types of image degradation.

1. Image Contrast Loss Due to Wide-angle Scattering of Light from the Illumination Source

Suspended particulate matter (both organic and inorganic) produces most of this type of scattering. However, in very clear oceanic water the Rayleigh scattering due to the water molecules is not insignificant. Figure 1 shows typical particle size distribution data for clear subtropical ocean water. This type of data has been used to predict with good accuracy both the wide-angle and the narrow-angle scattering of sea water. Unfortunately, the "Mie" equations involved in these calculations are difficult to evaluate without a large computer, and the input data on particle size distribution and indices of refraction are seldom available.

This type of contrast loss generally limits the useful visibility range to less than four attenuation lengths with ambient light fields and to considerably less distance than that when the dominant illumination source is close to the camera (or receiver, eye, etc.). Figure 3 shows typical loss of contrast for horizontal paths in ambient light. Range-gating and volume-scanning techniques are useful in reducing the wide-angle backscatter.

2. Narrow-angle Forward Scattering of Light from the Target

This type of scattering is produced by both suspended particles and refractive inhomogeneities in the water. Diffraction theory tells us that very narrow-angle scattering is produced predominantly by relatively large suspended particles (which normally have indices of refraction relatively close to that of sea water). A small fraction of the image-forming light will pass through the water without interacting with the suspended particles. This fraction is commonly referred to as the "direct light" component. It too will be slightly deviated in direction due to refractive inhomogeneities along its path. These refractive inhomogeneities are produced by temperature and/or salinity fluctuations. Temperature fluctuation can be very large where warm and cold layers of water are mixing near a thermocline. Under good conditions, however, sea water often has rms temperature fluctuations of less than 0.001° Celsius. For these cases, image details subtending less than one milliradian can be recorded even over long propagation paths. The optical effects of inhomogeneities in water can be roughly predicted using theories originally developed for astronomical viewing through the earth's atmosphere. Unfortunately, there exists little data on the temperature and salinity microstructure of sea water. Figures 4 and 5 illustrate the loss of resolution as a function of path length for clear coastal water.

3. Light Loss Due to Absorption and Scattering

Sufficient photons must be available in each resolution element in order to be able to record useful images. In many cases insufficient light will be the fundamental operating limit. Light loss in water is, in general, governed by exponential type relations. Light in the blue-green wavelength region propagates best in most types of relatively clear water. The color selectivity of water is principally due to the characteristics of the water molecule. Most of the dissolved and suspended substances in sea water have little additional spectral effect. One exception is the so-called "yellow substance", which occurs frequently in coastal waters. It shifts the best propagation wavelengths toward the green region. Whenever long light paths in water are involved, it is very important to use a light source which emits significant energy at the best propagating wavelengths. This seems very obvious but unfortunately can easily be overlooked. For example, it is generally conceded that mercury vapor lamps provide illumination superior to incandescent lamps for many long-range underwater viewing applications. This is due to the very large component of incandescent long-wavelength light, which is heavily absorbed by the water. The mercury arc emission lines are closer to the water's passband, so the average attenuation over the water path is less. However, if we use systems with very low light level capability over very long range in water, we find the incandescent lamp to be superior (i.e. provides more light through the path). The reason for this is that the incandescent lamp emits a continuum of wavelengths, some of which are in the best propagating region. Even though only a very small fraction of the incandescent lamp's emission is at these wavelengths, the propagation improvement is a much more important factor.

Significant light can also be lost due to particulate scattering. This scattered light is not always harmful and, depending on the specific situation, may be useful.

4. Local Effects of the Water

Differences in index of refraction, temperature, and pressure between the interior and exterior of the water light housings can cause harmful effects unless suitably compensated. Some of the more dominant effects include optical aberrations at the port, physical distortion of the port, and thermal expansion or contraction which changes critical dimensions in the lenses and camera.

Analytical Techniques for Predicting Performance and Designing Systems

Various models and analytical techniques have been developed which permit us to evaluate the limits on imaging which were outlined in the preceding section. In some areas, such as the optical performance of ports, the analysis is quite accurate. In other areas the accuracy is relatively poor. A prediction accurate to 20 or 30 percent might be the best possible. One of the fundamental difficulties frequently is the lack of good data concerning the water properties. Another difficulty is the complexity of certain computations and the lack of easily visualized or intuitive approaches.

Most available optical propagation data for water is based on "point" or very short path measurements. The accuracy degradation is obvious when we use, for example, attenuation data based on 1-meter path measurements to predict light losses for a 30- or a 100-meter path.

The Volume Scattering Function (VSF) is the most frequently used approach for describing the directional scattering properties of water. The major problem in using the VSF for imaging system analyses is that it has seldom been measured for angles less than 1 degree, whereas for imaging systems we are critically interested in angles which are smaller by orders of magnitude. Furthermore, the VSF basically describes single scattering, and propagation over long distances is dominated by higher order scattering. Use of the VSF in multiple scattering problems is quite possible, but the mathematics becomes very complex.

A little over a decade ago, the concept of Modulation Transfer Function (MTF) for the water path was introduced. A simple relation was developed so that MTF's measured for one water path length could be used to determine the MTF for any other path length. Accuracy loss would still occur, of course, if short path data were extrapolated to great distances. More recently, long path measurements of the spreading of narrow light beams (called Beam Spread Functions) have been made. The BSF and a related function, the Point Spread Function (PSF), have been shown to have a direct relation to the MTF. Measurements at one range can thus be extrapolated for use at other ranges. By employing two-dimensional Fourier Transform techniques (or a basically equivalent convolution technique) we can relatively conveniently and accurately model and analyze long-path imaging systems. For systems with shorter paths, the multiple-scattering aspects can sometimes be approximated, and further simplification in the analysis becomes feasible.

Techniques for Extending Image System Range

It is difficult and hazardous to make broad generalizations of long-range imaging system performance. However, in order to place some of the imaging system techniques in perspective, some performance generalizations will be offered here.

When not limited by light level we can see and record images of high-contrast targets up to about four attenuation lengths* by using ambient light. This range is influenced by the viewing direction (relative to the zenith). Spectral filtering can provide some contrast improvement if the dominant components of scattered light have significantly shorter paths than direct-image light. Methods for increasing recorded image contrast, such as high-contrast film, high-contrast development, image processing, etc., can also be helpful but can seldom extend the maximum useful range by more than one attenuation length. (See figure 3.)

When the dominant illumination source is near the receiver, the maximum useful ranges will be substantially reduced. Ranges of one to two attenuation lengths are not unreasonable. There have been built several systems which use a very large separation between the light source and the camera. Depending on the system, the source may be placed either to the side, in front, or behind the camera. Each approach offers its own advantages and disadvantages with respect to mechanical simplicity, uniformity of illumination, light loss, etc. An improvement of one attenuation length or perhaps slightly more can be realized over more conventional systems, depending on the specific geometry. Any of these approaches will not normally exceed the performance of the ambient light system.

If it is practical to polarize the source light, a "crossed" polarizer at the receiver can reject a large portion of the contrast-reducing light which is scattered by the suspended particulate matter. It is feasible to reduce this unwanted scattered light by a factor up to about eight, but at the expense of considerable light loss and the possibility of also rejecting specular-type targets. (See figure 6.) Circular and linear polarization seem to provide about the same cancellation performance, but circular techniques have practical advantage in not requiring careful alignment.

Scattered-light components can be minimized by using narrow-angle illumination and a corresponding narrow-receiver field of view. Viewing ranges of five attenuation lengths have been achieved with a low-light TV

(*) An attenuation length is $1/c$, where c is the volume attenuation coefficient.

using 1-meter source-camera separation and a field of view of only a few degrees. Carrying this narrow-angle approach to an extreme produces the so-called synchronous-scanning or volume-scanning systems. In these systems we use light source and receiver fields of view on the order of a milliradian and scan them together in systematic fashion over the desired picture area. Imaging ranges of up to eight attenuation lengths have been demonstrated for source-receiver separation of 1 meter and image resolution of about 1 milliradian.

Another version of the synchronous scanning system achieved a viewing range of four attenuation lengths using the same port for both the source and receiver. The effective source-receiver separation for this system was only a few centimeters. Very-narrow source and receiver beamwidths helped reject the large, unwanted scattered-light components. Synchronous scanning system design involves a compromise between source-receiver separation, resolution, received signal-to-noise level, and practical scanning problems.

Range gating using very short (nanosecond) light source pulses is a very effective way of rejecting back scattering. Unfortunately the presently available laser light sources are very expensive, large, and inefficient. At the present state of the art, range-gated systems may reach a light level (photon) limit long before they reach a contrast limit. When suitable pulsed light sources become available, wide-angle viewing systems for up to about eight attenuation lengths will be possible. However, as we try to image much further than this we will find that forward scattering of image light from the target will become troublesome. Rejection of unwanted forward-scattered light by range gating is not practical due to the very small path length and hence time differences. The forward-scattered component can be minimized by reducing the area of the target which is illuminated at any one time. Thus systems of very-long-range and wide viewing angle will need to incorporate both range-gating and synchronous-scanning techniques.

The ultimate limitation on visual range for in-water systems not employing ambient light is the light loss over the propagation path. With the techniques available to-day we can solve the contrast loss problem using increased separation, polarization discrimination, range gating, synchronous scanning, etc. Unfortunately, relatively small improvements in visual range involve exponentially increasing difficulty (i.e. cost, complexity, etc.). Careful system analysis and engineering is required to match performance to cost and other factors.

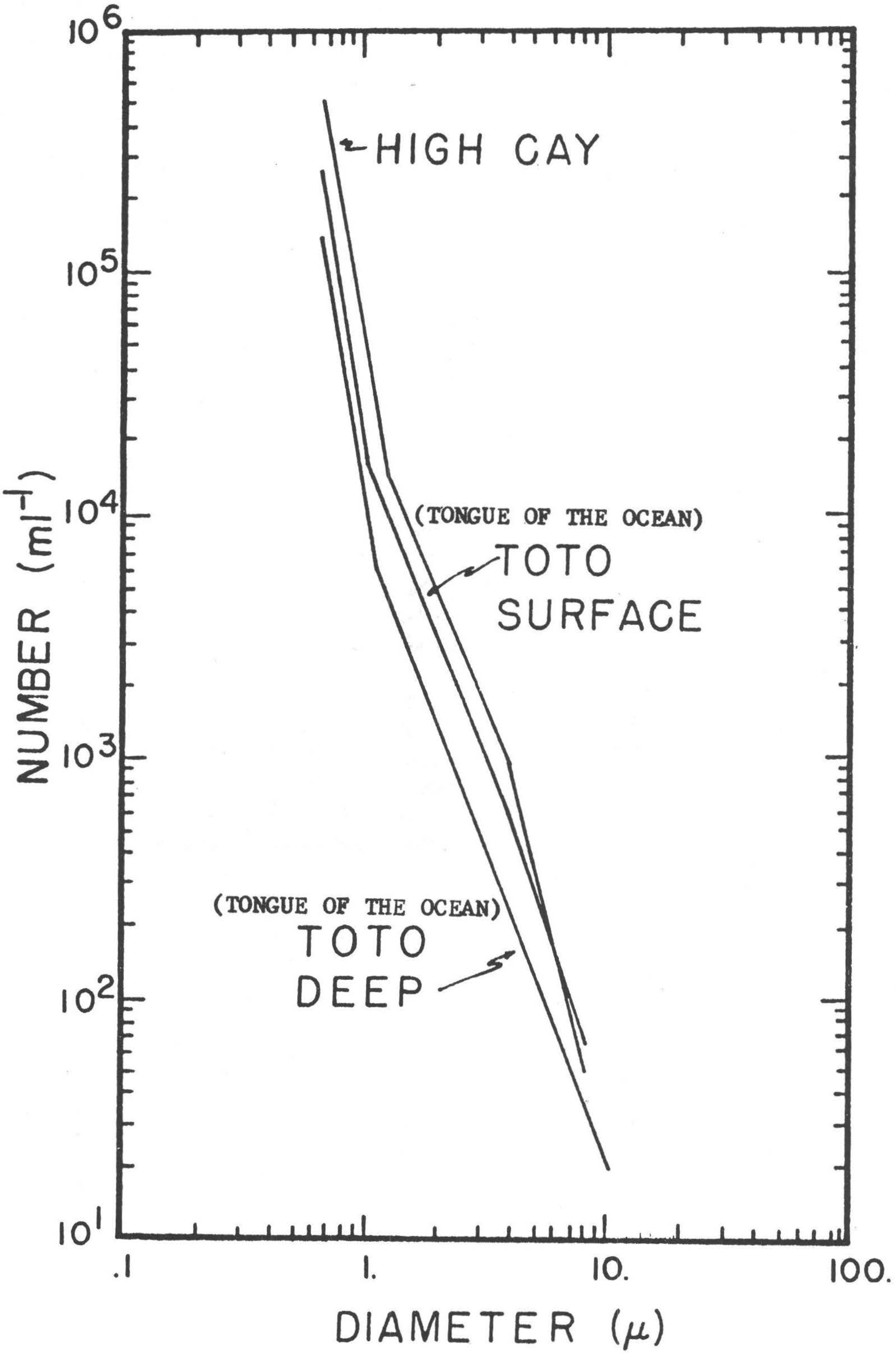


FIGURE 1 Particle size distributions for coastal and sea water near Andros Island, Bahamas, measured with a Coulter counter by H. Gordon, H. Bader, O. Brown of the University of Miami. Graph shows number of particles per ml greater in diameter than shown on the abscissa.

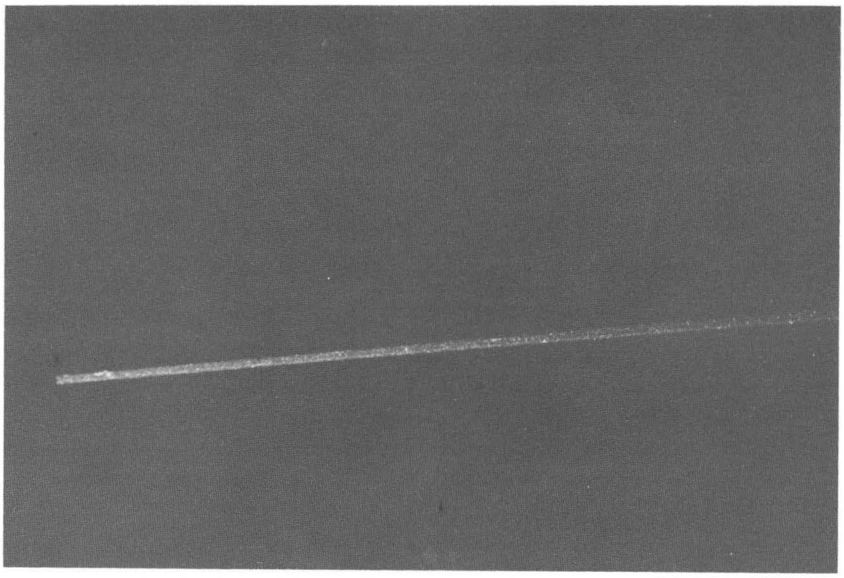


FIGURE 2 Photograph of a pulsed laser beam showing particulate scattering. Beam was nearly collimated, and the coastal sea water had a volume attenuation coefficient of .2 m^{-1}. Camera had a 35mm (focal length) lens and was approximately 1.3 m from the beam.

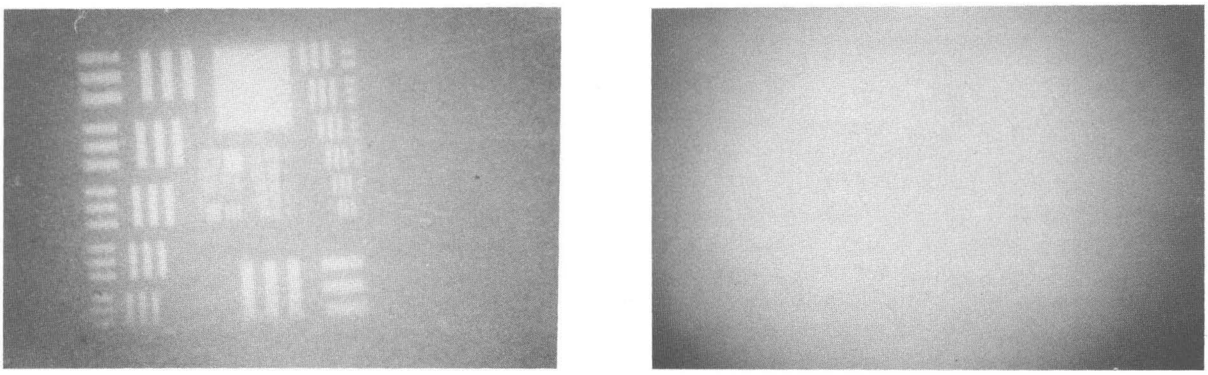


FIGURE 5 Photographs illustrating loss of resolution due to large refractive inhomogenieties in the water path. Camera was 45 meters from a backlit 10 x USAF resolution target. The volume attenuation coefficient of the coastal sea water was approximately .20m^{-1} for both photographs. Temperature fluctuations were approximately 10 times greater for the photograph on the right.

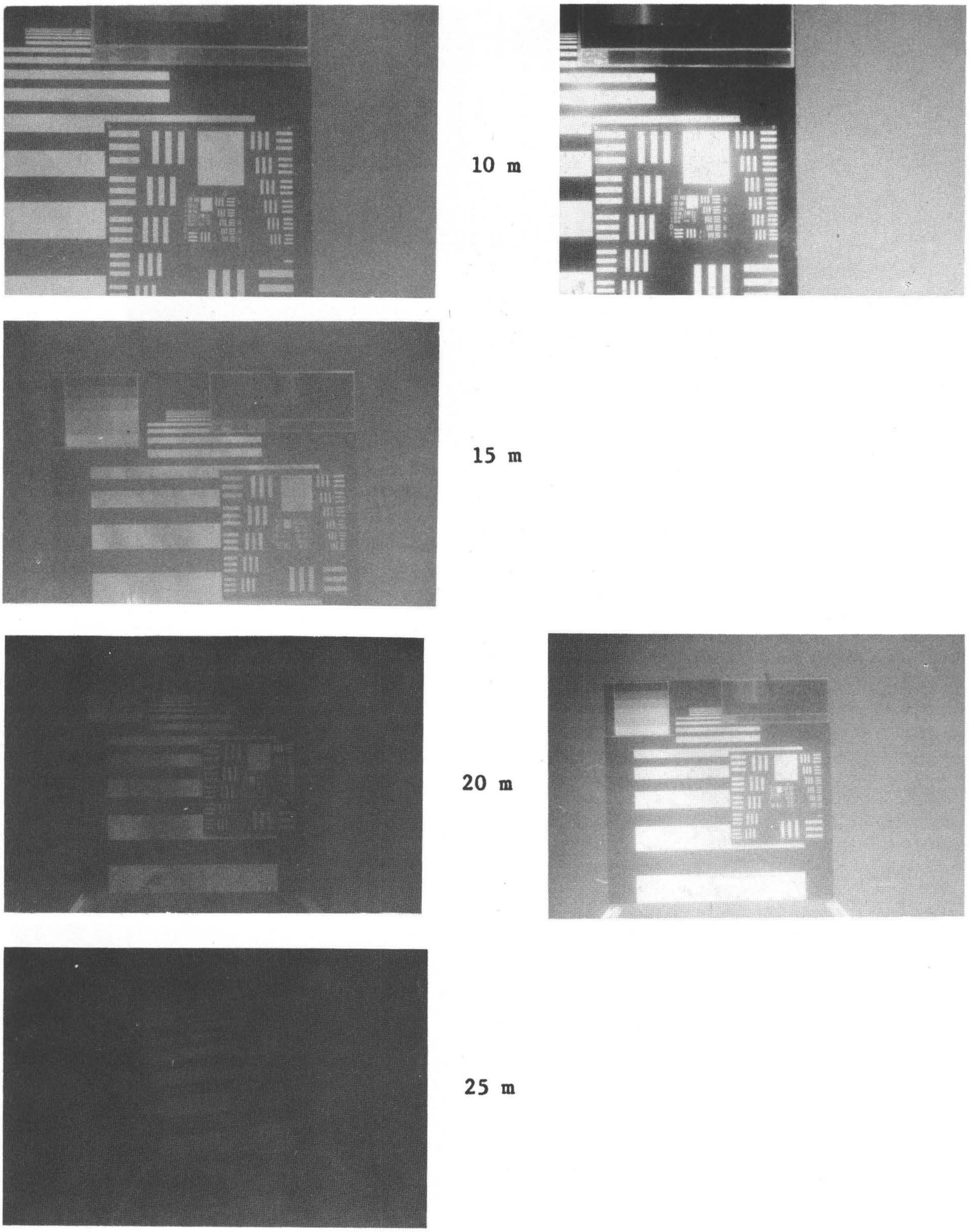
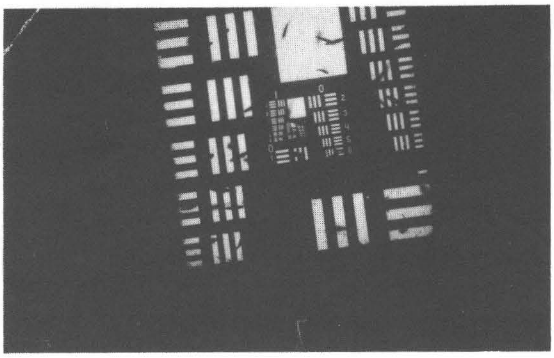
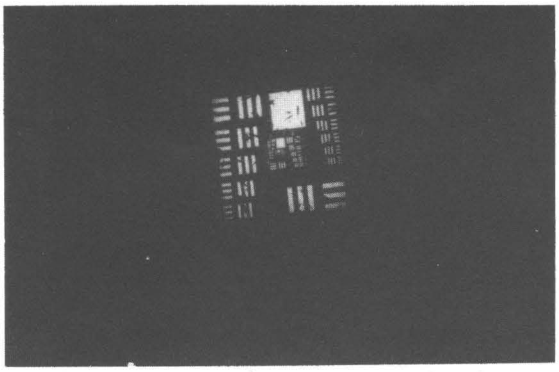


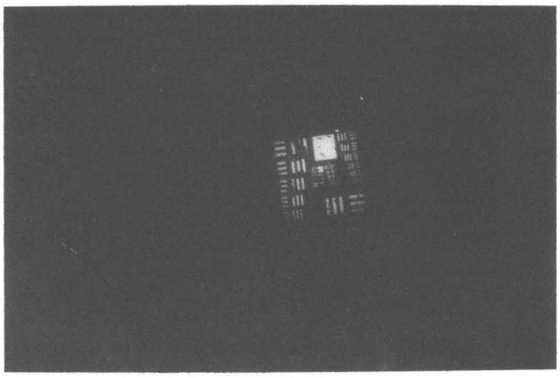
FIGURE 3 Photographs of a 10 x USAF resolution chart, large logarithmic bar chart, and grey scale in ambient light. Camera to target ranges are indicated. Water was 5 meters deep and had an attenuation coefficient of .13 m^{-1}. Photographs in left column used Panatomic X film, those in the right column used a high contrast film ($\gamma = 4.7$).



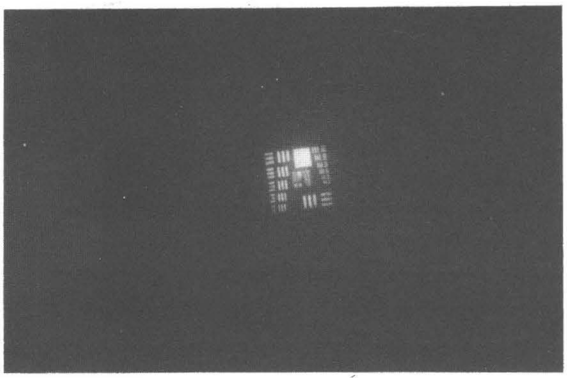
10 m



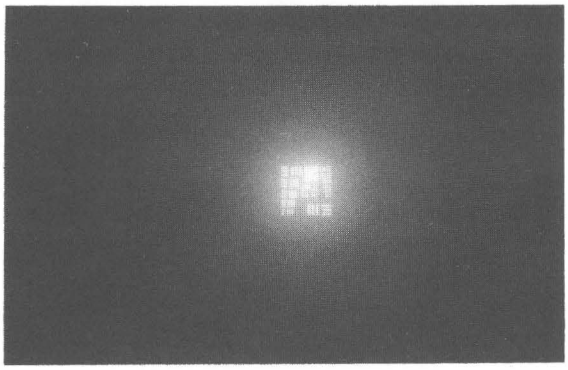
20 m



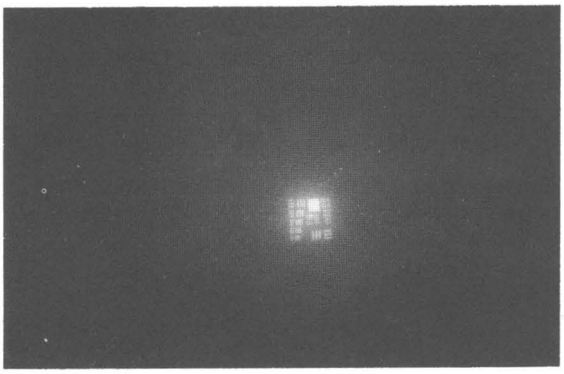
30 m



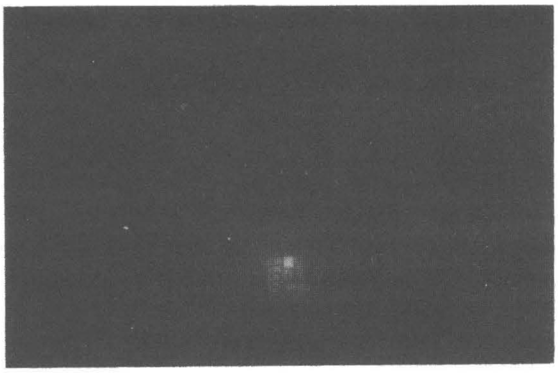
40 m



50 m



60 m



70 m

FIGURE 4 Photographs of a backlit 10 x USAF resolution target at ranges from 10 to 70 meters. Ambient light was negligible and the coastal sea water attenuation coefficient was 0.21 m^{-1}. The standard deviation of the water's temperature fluctuations was about .002°C when the longer ranges photographs were taken.

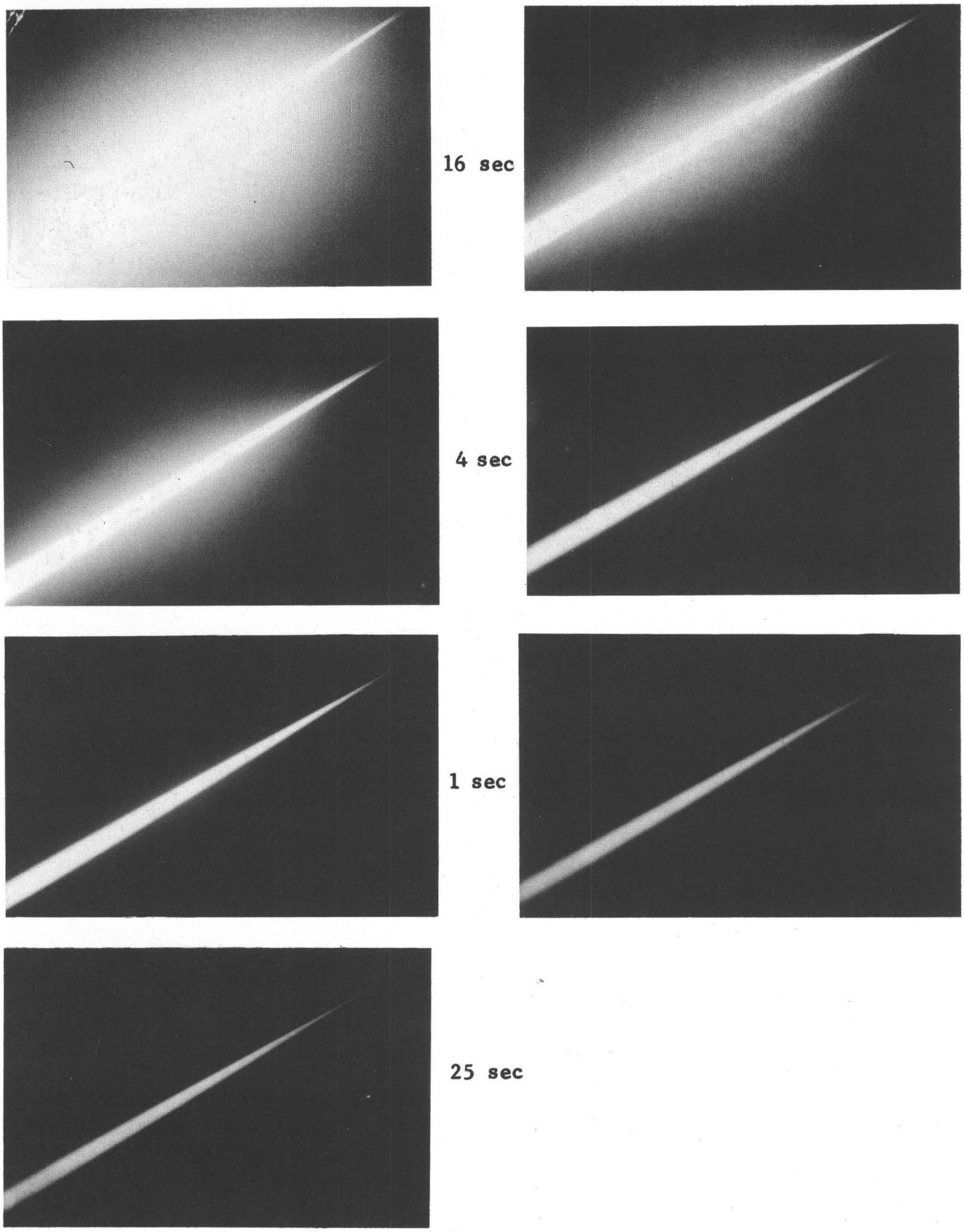


FIGURE 6 Cancellation of single and multiple scattered light using crossed linear polarizer. Camera was aimed along a collimated 488 mm laser beam with a .6 m lateral separation. Photographs on left had the linear polarizer parallel to the laser polarization axis. Photographs on the right the polarizer crossed. Exposures were f/4.0 for the indicated times.