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Holographically amplified interferometry with coherent fringe projection for the oil on the water remote sensing and characterization

Nickolai V. Kukhtarev, Tatiana V. Kukhtareva, Alabama A&M Univ. (United States); Arcadi Chirita, University de Stat din Moldova (Moldova)

Abstract.

We suggest combining several optical methods of remote sensing and characterization of crude oil films and emulsions: coherent fringe projection illumination (CFP), holographic in-line interferometry (HILI). Combined methods of CFP and HILI are described in the frame of coherent superposition of partial interference patterns. Moreover, we evaluated different alternative schemes of interferometry with holographic recording and preliminary holographic amplification in photorefractive crystals. Holographic amplification of weak images without phase distortions is possible in a special mode of holographic recording in photorefractive crystals.

OCIS codes: 090.0050, 090.199, 120.2880

1.INTRODUCTION

Although there are several methods of remote detection/identification of crude oil in water and/or on the solid surfaces, there is still a requirement for more efficient and reliable methods [1]. Spectroscopic methods allow characterization of oil composition [2] but give little information about spatial distribution of oil. Among the optical means, the generation of UV-induced fluorescence [3] and the change of surface reflectivity on surface oil [4] are the two existing oil-spill detection mechanisms. Unfortunately, all of the existing detection schemes have one or several disadvantages, such as poor reliability, high power consumption, high cost, difficulties in maintenance, and complexity. Digital holographic in-line interferometry (DHILI) allows determination oil film thickness [5,6] and size of oil droplets, but requires elaborate image processing. Coherent fringe projection (CFP) techniques proved to be efficient in non-contact metrology of microstructured objects [7]. We suggest combining DHILI and CFP in one set-up for improved detection/identification of oil. We propose a unified approach for modeling of both DHILI and CFP that is suitable for remote characterization of oil films (spills) in sea water. We describe two different experimental schemes of interferometry: with single beam and two beams.

2. Experiments for remote determination of oil droplets and films using fringe projection interferometry.

The methodology and experimental setup method for determining the size of the droplets of oil on the water surface is based on illumination of the oil/water surface by the interference pattern with known period ***d***. Figure 1 shows the experimental setup, which uses a DPSS laser with wavelength λ = 532 nm. The plane-wave laser beam with diameter 24 mm (1, Figure 1) illuminates glass plate (with wedge angle 1, 2") with a semi-transparent back plane. As a result, the interference pattern of reflected signals from the front and back surfaces of the plates with period d = 3mm illuminates the analyzed object (3). Since the glass plate is illuminated by the plane-wave beam, the reflected beams are also plane waves, and its period of interference pattern does not change with distance.

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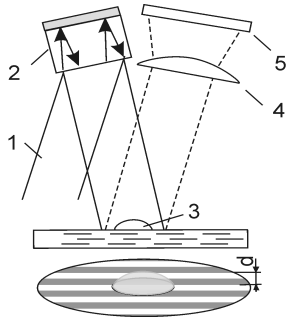


Figure1. Depicts the experimental set up: 1) Plane-parallel laser beam, 2) Wedged glass plate 3) Object, 4) Lens, 5) Screen

When the droplet of oil spreads on the water surface, there is interference over the entire surface of the object (Figure 2). Interference rings are the result of interference between the reflected beam from the front surface of the oil droplet and a plane wave reflected from the water surface.

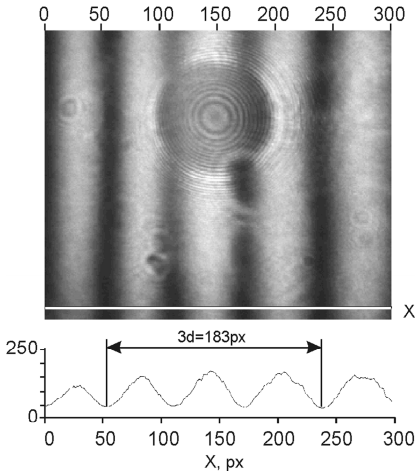


Figure.2. Interference pattern of the drop of motor oil

The image was processed by a graphical editor to determine the pixel-by-pixel distribution of the grey scale along the frame. A one-pixel-thick line (white line X, Figure 2) was chosen and scanned perpendicularly to the interference pattern along the entire image (total of 300 pixels). Fig.2 shows the pixels brightness distribution (from 0 to 255 of the grey scale) where the alternation of maxima and minima corresponds to the a priori known fringe pattern period d=3 mm. By dividing the value of the d=3 mm period by the number of pixels between the maxima (or minima), we found that 1 mm of the real object dimension corresponds to ~20 pixels of the image. This allows determination of the dimensions of motor oil drop at pixel by pixel scanning of the object in graphical editor.

3. Theory of the stripe and circular fringes formation

We will consider the interference pattern on the screen, formed by the two near-parallel waves reflected from the oil-water surface. Complex amplitude of these two fields can be written as:

$$S_l = (R_l + R_{ld}) S_{l0} \exp(-ik_l x) \quad (1)$$

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Here the reflection coefficients from water (R_l) and oil spot (R_{ld}) and input amplitudes (S_{lo}) can be presented in the form

$$R_l = r_l \exp(i\varphi_l), R_{ld} = r_{ld} \exp(i\varphi_{ld}), S_{l0} = \sqrt{I_{l0}} \exp(i\varphi_{l0})$$

where subscript l =1,2 , k_l is the x-component of the wave vector, x is a coordinate perpendicular to the lines of the fringe pattern. For near collinear propagation of two beams, we assume that the reflection coefficients for two beams are equal ($r_1 = r_2 = r$, $r_{1d} = r_{2d} = r_d$) , so the pattern on the screen may be presented as

$$I = \left|S_1 + S_2\right|^2 = I_0(r + r_d)(1 + m\cos(\varphi) + M\cos(\phi) + 0.5mM(\cos(\phi + \varphi) + \cos(\phi - \varphi))) \quad (2)$$

Here I_0 is input intensity , and phases are

$$\phi = \phi_0 + 2\pi x / d, \varphi = \varphi_0 + (\varphi_l - \varphi_{ld})$$

zero indexes means, that possible constant phase shift may be introduced during reflection from the surface. From Eq.(3) it can be seen that ϕ is phase difference between plane (reflected from the unperturbed water) waves that forms partial interference fringe patten with contrast M, while φ is phase diference in the partial interference pattern (with contrast m) formed by the plane wave and the wave diffracted from the oil spot. We will model oil film convex-type shape on the water surface as a product of two shapes :1) segment of sphere with curvature radius R that looks from above as a plano-convex lens with radius P and height h (sagitta), and 2) step-like function F. This model of oil thickness changes Z (as measured from the water level) can be written as:

$$Z(x,y) = (\frac{1}{2R})(P^2 - x^2 - y^2)(1 - \exp[\frac{b}{R^2}\{P^2 - x^2 - y^2\}])^{-1} \quad (3)$$

This shape of the oil film was dictated by an effort to simulate the experimental profile of the oil film. In this simulation parameter b is chosen as a big number (in the order of 10^5 - 10^6) in an effort to best fit the experimental shape of the boundary of the oil film on the water. The relation of phase modultion $\varphi(x,y,z)$ introduced by the oil film can be found from the general expression, known in inferferometry of reflective surfaces

$$\varphi(x,y,z) = (\frac{2\pi}{\lambda})(\vec{n}\vec{S}) = \frac{4\pi}{\lambda} Z(x,y)\cos(\theta) \quad (4)$$

here $\vec{n}$ is the unit vector of the surface deformation, $\vec{S}$ is the so-called sensitivity vector, equal to the difference between reflected and incident wave vectors, θ is the angle of incidence (measured from the z-axis).

The experimental interference pattern of the oil-on water spot on the screen (Fig. 2) is compared with the theoretical one. Choosing a set of parameters P= 0.369 cm, L= 0.7cm, λ= 532 nm, R = 170 cm, $M = m$ = 0.5, b= 8.5 10^5,

$$\varphi_0 = \phi_0 = 0$$

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we will get the density plot of intensity on the screen and plot the modelled shape of the oil film (across section in **xz** plane) (Fig.3 a,b).

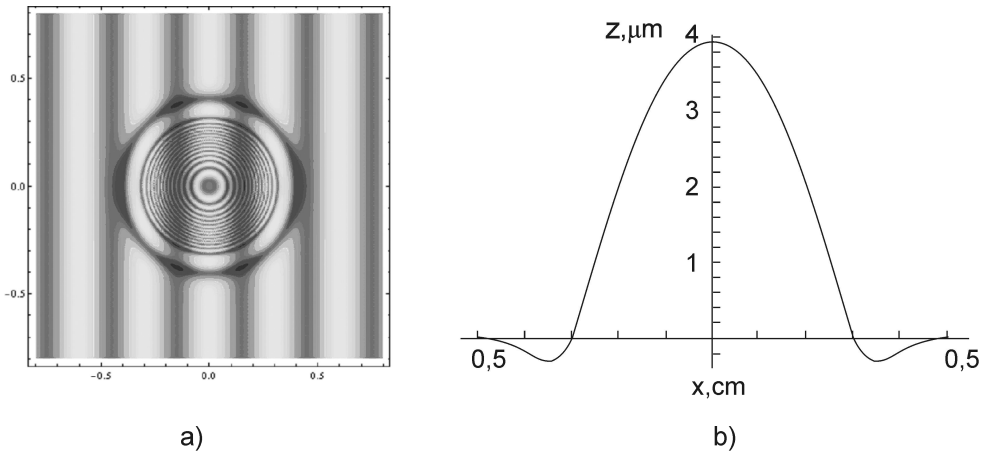


Figure 3. a) Calculated density plot of the combined intensity pattern on the screen; b) **XZ** cross section of the modeled surface profile of the oil spot. For parameters best fitted experimental density plot (m= M=0.5, P= 0.3369 cm, L=0.7cm, R =170cm, b = 8.5 10^5 and assuming no constant phase shift during reflection).

4. Comparison of experimental results with theoretical modeling.

In the presented approach for deciphering of the interference pattern from the oil spots, we used a method of probed shapes by modeling oil spot surface profile with functions, according to symmetry of spot (in our case by convolution of part of sphere with a step-function with several adjusted parameters). Some of parameters, like stripe fringe period ***d***, contrasts of partial interferograms ***m*** and ***M*** , circular symmetry are estimated and deduced from the experimental results. By varying the two remaining adjusted parameters (curvature radius ***R*** and parameter ***b*** of step-function), we achieved a best-fitting comparison between experimental and theoretical density plots. This fitting allow us to find maximal height (sagitta) of the modeled shape of the oil circular spot.

Our approach of choosing probed function for the oil spot surface with parameters, defined by best-fitting comparison with experiment may work well for the shapes allowing modeling with analytical functions (like circular, elliptical and similar shapes).

In our case of cylindrical symmetry oil film shape is defined by two parameters: radius of spot ***P*** and sagitta (height ***h***). From fringe projection pattern radius a was determined as ***P*** = .3 cm, from fitting density plots oil film maximal thickness ***h*** (sagitta) was estimated as ***h*** = 0.375 microns (see Fig.3).

4.1. Pump-probe experiments

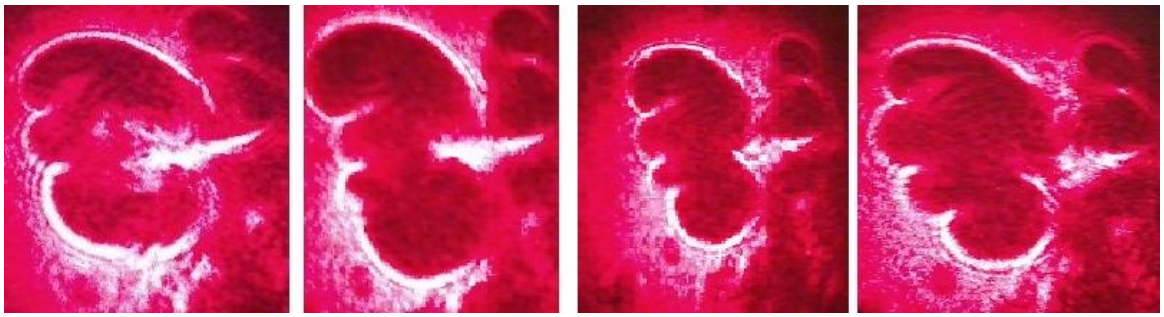
We have tested two-color method of oil film characterization using green and red lasers. Illumination of the oil-in film by a spot (diameter 1.5 cm) of expanded red laser (P = 40 mw) produce on the screen (distance ~ 3m 30 cm) spot with diameter ~ 9cm. Oil-film islands were seen as dark spots with interference fringes. When we applied unexpanded CW green beam (P = 100 mW) to the red illuminated spot on or near the oil film spot, then we saw fast rearrangement of the oil island shape. In addition, reflected green beam (observed on the distance of ~ 80 cm) showed fast changing "blooming" interference patterns

Both beams (red probe and pump green) illuminate samples on near-normal angle of incidence.

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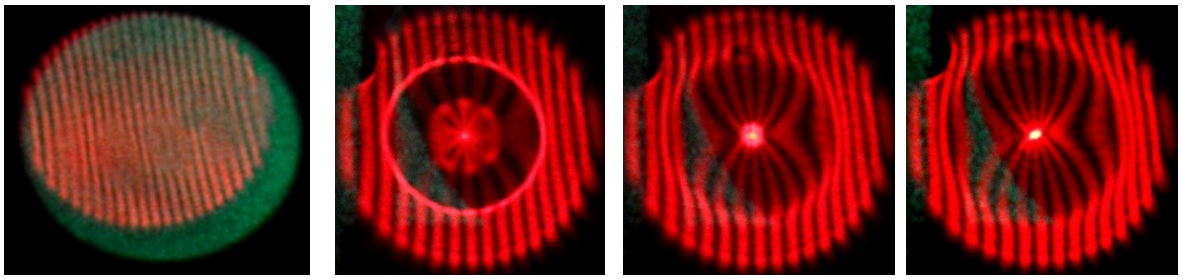
Similar experiments, when oil-in-water sample was replaced by the organic solution, shows quite different behavior: illumination by the pump green laser did not produce noticeable changes in the probe red beam reflect pattern. Also, there were not any blooming interference fringes in the reflected pump (green) beam.

These preliminary results show, that two-color, pump-probe technique is promising method for distinguishing of oil from CODM (colored organic dispersed materials)..



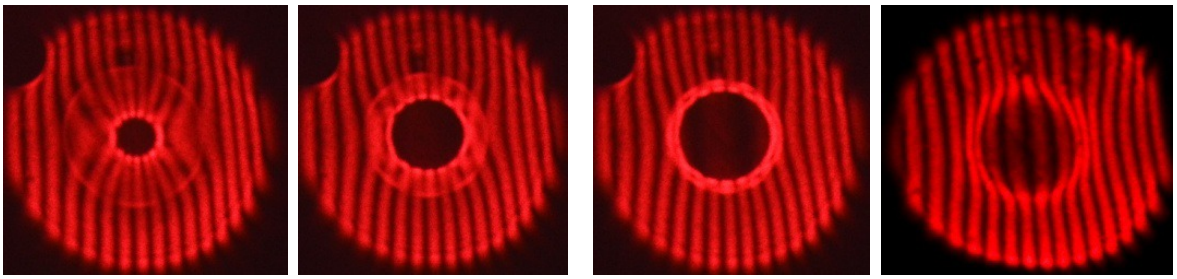
4. Kinetic of oil-film aging during green laser illumination (as seen by red laser reflection)

Additional experiments were performed using interferometric fringe projection by HeNe laser (λ =633nm) and degradation of oil film on water surface by Ar-laser (λ=514nm) with various intensity of laser beam (Fig. 5a,b,c,d) and Fig.6, a,b,c,d)



(a) (b) (c) (d)

Fig.5. Kinetic of reflection interferometric pattern changes after 5second illumination by green laser : (a) –fringe projection on water surface, (b),(c),(d) – fringe projection, laser on (60mW), time interval between pictures taken 5 sec



(a) (b) (c) (d)

Fig.6. Kinetic of reflection interferometric pattern changes, green laser off, time interval between pictures taken 5 sec

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At the same time absorption of the blue-green (λ=470nm, 514nm) was generated fluorescence, which can be used for oil detection (Fig.7.)

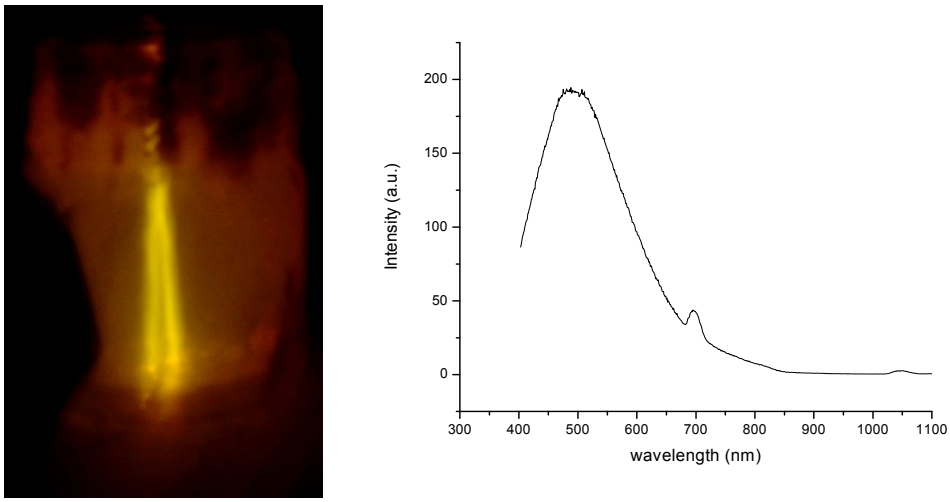


Fig. 7. (Left) Photo of fluorescence induced by the blue laser beam in the oil-water emulsion, (Right) fluorescence spectrum of oil the excited by 400 nm laser line.

5. Holographic amplification of weak reflection images.

Interferometric methods, described above are working well for the strong enough reflected signals. In real-life experiments we may expect that reflection from the oil spots on the water may be too weak for direct application of holographic interferometric methods. For dealing with these weak signals preliminary amplification of the optical signal may be required.

Traditional optical amplifiers that use gain media are not suitable in this case, since they introduce phase distortions, which make distortion of interference patterns. To solve this delicate problem of amplification of optical signal without distortion of phases we may use holographic amplification based on beam coupling in the photorefractive crystals [8]. This method of holographic amplification using photorefractive materials was successfully tested for amplifying of the weak images in the digital holography.

Physical basis of this holographic amplification is described in our previous papers [9, 10]. From the dynamic holography it follows, that holographic amplification without phase distortions is possible in the photorefractive materials with dominant diffusion mechanism of dynamic (real-time) hologram recording. There are wide ranges of materials [7, 8] with different response time, which allow dynamic hologram recording with millisecond response time, for example, semiconductor crystals of CdTe.

6. Conclusion.

We have suggested a method of remote detection and characterization of oil spills on water, based on a combination of CFP and HILI. Theoretical modeling of CFP and HILI is based on the introduction of partial interferograms (stripe/circle diagrams), that in paraxial approximations give adequate description of oil spots with near-spherical or elliptical shapes. The suggested method allows determination of the drop size and slicks of petroleum products accurately from a remote distance by illumination of an object using its plane-parallel interference pattern. Determination of oil thickness films on the sea requires pulse laser application to overcome the effect of wind and wind stress on the water. The measurements can be carried out remotely (ship and aircraft) using a parallel laser beam and semi-transparent plane-parallel plates. Structured light illumination, in addition to metrology, can be used

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for oil spill containment and as alternative means of decontamination. In addition, the fluorescence phenomenon can be used for oil detection
Our future work will be focused on using holographic amplification of weak reflected signals by photorefractive materials.

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