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# Photothermoplastic-based airborne camera for remote sensing applications

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## ABSTRACT

Photo-thermo-plastic film (PTPF) is a multi-layer structure with the resolving power up to 1000 line pairs per millimeter in the binary and/or half-tone optical data recording modes. These structures are high-sensitive in the spectral range from 400 to 800 nm which is determined by chalcogenide glassy semiconductors (CGS) layer in the PTPF. We technologically challenged the CGS by tin-doping; this allows satisfying to main requirements which high-efficient observation systems are demanding.

PTPF-based devices imply some critical elements for providing PTPF sensitization by means of the corona discharge as well as thermal development of the latent image to the form of superficial relief on the PTPF. Such PTPF-based slit camera was used for airborne monitoring of the Black Sea surface from the 9000-m-altitude. Camera resolving power is high enough for determining of waves heights and spacing as well for discovering of small sea objects and determining of their speed and drift direction. PTPF-based remote sensing seems to be even more advantageous due to the possibility to record different images multiple (up to 100) times on a single PTPF frame within the “recording – read-out – thermal erasing – re-recording” cycle.

An algorithm for automatic measurements of the sea surface conditions is proposed. The measured parameters are height and spacing of waves as well as their motion direction. Mathematical processing includes 2-D smoothing of sample data, forming 1-D profile of the waves, and calculating its Fourier transform. By introducing of the scale factors, it makes possible to obtain certain data on the waves’ characteristics. This system allows compressing of 2-D information to numerical data flow which is characterizing the rough seas and transmitting of these data through communication channels.

**Keywords:** remote sensing, image processing, photothermoplastic films, photosensitivity, resolving power

## 1 INTRODUCTION

Photo-thermo-plastic films (PTPF) are non-silver two-layered structures for optical data recording [1]. Semiconductor-thermoplastic configuration provides recording of photographic, holographic, and other types of optical data without a wet chemical development, giving ones the better radiation resistance. Optical data recorded on photothermoplastic (PTP) media is characterized by simplicity of development and erasing processes. The property of radiation resistance makes these systems particularly useful for remote sensing of different objects from Space. This paper presents some experience in fabrication and practical use of PTP recording structures. Most importantly, PTP-recording devices have resolving power that exceeds its values in comparable photographic systems.

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The main idea of the data processing algorithm is based on an assumption that physical parameters of the sea surface mostly have one-directed undulating character. Ideally, the sea surface might be approximated by periodic function, e.g. as it is shown in Figure 1. Despite it is not a real image of the sea surface (this is an image formed by the interference of two laser beams and recorded on the PTPF), we could use it for algorithm explanation purposes. The presence of intensity maximums and minimums in the image and their quasi-periodically distribution brings the information about the height and length of waves and their direction of motion. Data processing could be performed by determining of 2-D scalar function and describing of its distribution in gray scale. If this procedure can be realized in an effective programmed manner, it can be considered as a base for remote sensing of sea surface conditions and transmitting them in a real-time scale.

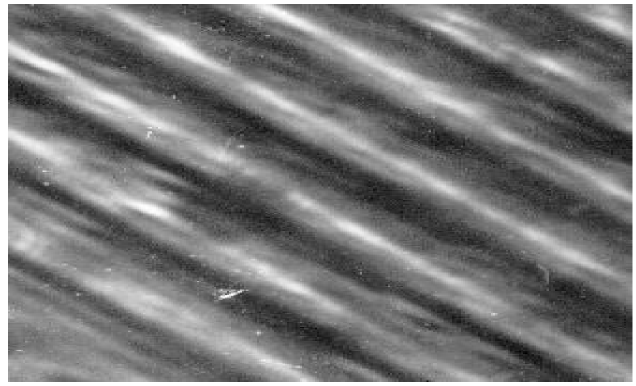


Figure 1: Simulated one-directed undulating process

## 2 PARAMETERS OF GLASSY CHALCOGENIDE LAYERS

A number of requirements have to be met in the process of fabrication of PTPF based on chalcogenide glasses. Among them are high specific resistance ($10^{13}$-$10^{14}$ Ohm·cm), dark conductivity is of less importance), mechanical durability, thermal stability of electro-physical parameters and recycling of the used materials. The basic requirements to the photosensitive semiconductor layers affiliated to the PTPF structure are their high resistance and large multiplication ratio of resistance change under the electromagnetic irradiation exposure. In spite of the successes in development of electrophotography and PTP recording on the base of the materials mentioned above, currently there are remained the actual tasks of photosensitivity increasing, widening of spectral range for recording, and realization of new properties of media for information recording. For its successful application in two-layer PTPF photosensitive semiconductor layer should have dark resistivity about $\rho_d$~$10^{12}$-$10^{14}$ Ohm·cm at the multiplication ratio of photo-response at the level of 10 at the minimal illumination of 5-10 Lx. Modification of composition allows purposeful changing of the properties of thin films and obtaining the layers, satisfying the requirements of any practical needs. Also, one of the important tasks in the field of recording of optical information from space is the search of the materials of recording media, possessing high photosensitivity and transparency for polychromatic light including monochromic light of definite wavelength.

Measurement of the drift mobility of charge carriers was carried out through the time-flight method [2] on “sandwich” type samples with deposited chromic top electrode. The values of band gap width determined from the curves of adsorption in coordinates $(h\nu K)^{1/2}=f(h\nu)$ and from the spectral characteristics of photoconductivity (by the wavelength of monochromic light at which photocurrent decreases up to 50% of maximal value) are coincided. Width of the bandgap is linearly decreased with the composition alteration from $E_g$=2.4 eV ($As_2S_3$) to the value 1.75 eV ($As_2Se_3$). We determined that $E_g$ values are practically congruent with values presented in Refs [3,4]. Dependence of the coefficients of adsorption of thin films $(As_2S_3)_x(As_2Se_3)_{1-x}$ on the photons energy of incident irradiation in the field of weak adsorption ($h\nu<E_g$), for the following x: 1 – 1.0; 2 – 0.7; 3 – 0.5; 4 – 0.3; 5 – 0, is presented in Figure 2.

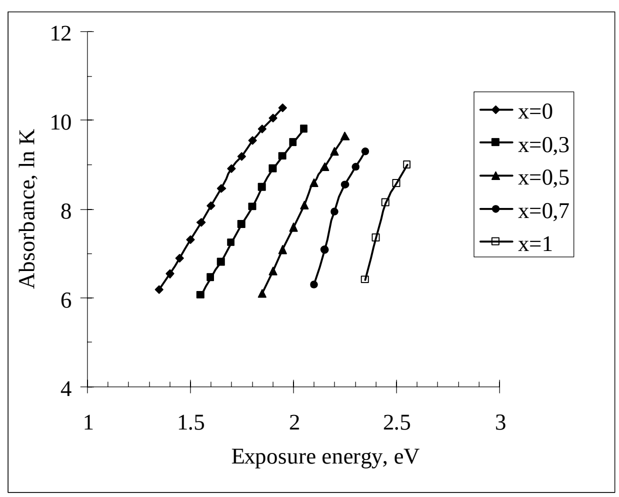



Fig.2. Dependence of the $(As_2S_3)_x(As_2Se_3)_{1-x}$ system absorption on photon energy of incident irradiation.

Figure 2 shows that in the field of weak adsorption ($h\nu<E_g$) all compositions there have exponential dependence of

adsorption coefficient on the energy of descending phonons as an evidence of Urbach's law feasibility: $K=K_0\exp[(h\nu-E_g)/\Delta]$. Feasibility of this rule, generally speaking, points to the presence of "tail" of state's density in bandgap. Charge carriers possess the greatest mobility in the layers $As_2Se_3$ ($\mu\sim10^{-7}$ $cm^2/V{\cdot}c$). As the arsenic sulfide content growths the drift mobility of carriers is decreased and achieved the value of $\mu\sim10^{-10}$ $cm^2/V{\cdot}c$ in the case of $(As_2S_3)_{0.7}(As_2Se_3)_{0.3}$. Temperature dependence of the drift mobility has the exponent form: $\mu\sim\exp(-E_a/kT)$, where $E_a$ is energy of activation of mobility. Dependence $\lg\mu=f(10^3/T)$ allows to find out the energy of trap's activation which are participating in the charge transfer. Determined value of the activation energy $E_a$ for arsenic selenide is 0.1 eV; for solid solutions $E_a$ is increased up to 0.18 eV for the $(As_2S_3)_{0.7}(As_2Se_3)_{0.3}$ composition. The sensitivity spectra of the PTPF on base chalcogenide glass semiconductors are presented in Figure 3.

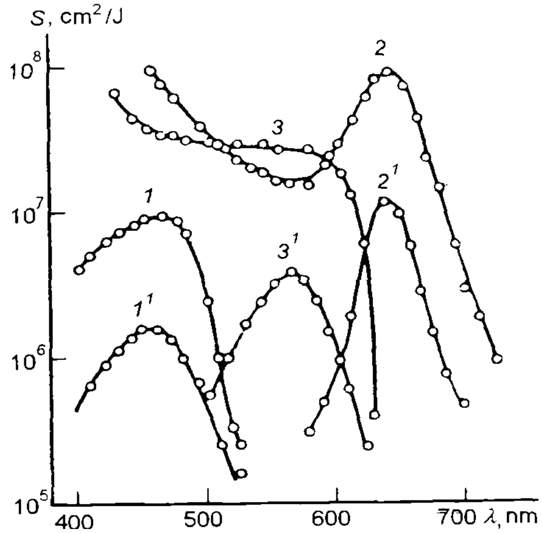


Fig.3. Spectral sensitivity of PTPF based on: $As_2S_3$ (1,1'); $As_2Se_3$ (2, 2');$(As_2S_3)_{0.3}\cdot(As_2Se_3)_{0.7}$ (3, 3').

These results were successfully applied for creation of PTPF from $(As_2S_3)_{0.5}(As_2Se_3)_{0.5}$ layers and heterojunctions on their base; however, the high speed of the relaxation of the dark surface potential limits their application in simultaneous recording procedure. The performed investigations allow determining the composition in doped As-S-Se systems with different percentage of containing component, possessing high exploiting parameters. Studying of optical, photoelectrical, and electrophotographical properties of As-S-Se-Sn compounds shows that these layers possess darkish specific resistance of $3\text{-}5\cdot10^{14}$ Ohm·cm at T=30°C, and the changing brevity of resistance is $K=10^2$ at E=10 lx. When the temperature rises up to the values used during PTP recording (~70°C), an insignificant deterioration of chalcogenide semiconductor parameters occurs. Maximum of spectral sensitivity of such layers is dependent on the layer composition and located within the range 460-480 nm in which multiplicity of the photo-response $(1.8\text{-}11)\text{-}10^3$ is ensured. These results allow ones to conclude that these layers can be successfully used for preparation of two-layer PTPF capable to register optical information in diapason 400-700 nm. Studying of influence of electric field polarity on photocurrent and on light response showed that maximum values reach when negative potential applied to alight surface of thin CGS layers.

CGS-based PTPFs have spectral sensitivity which covers X-rays, visible, and near-IR ranges. Also, one can select a wavelength range with a width of about 0.1 μm in which some of PTPFs are able to ensure photographing of objects in these spectral zones. Technologically, these CGS layers were created on flexible 40-m-long and 190-mm-wide films with thickness accuracy of better than 0.2 nm and electric parameters deviations not more than ±5%.

## 3 PARAMETERS OF THERMOPLASTIC LAYERS

Novel thermoplastic materials with improved deformation capabilities and high compatibility with CGS layers were created. We have synthesized and studied a number of copolymers of carbazolyl-N-alkylmethacrylates (CAM) with octylmethacrylates (OMA) and with cetylmethacrylates (CMA) with composition of CAM parts from 50 to 80 mole%. Two types of thermoplastic layers: copolymer CAM:OMA 60:40 mole% - type **I**, and copolymer CAM:CMA 60:40 mole % - type **II**, were studied. It was established that replacement of OMA-parts with CMA-parts in copolymers significantly increases the deformation characteristics of the layers due to better plasticization of polymer by cetylmethacrylate parts. It was found that for attainment of maximal deformation and resolution capability the optimal temperature for type I copolymer makes up 85-87˚C but for copolymer of type II it amounts 70-73˚C. The dark specific resistance $\rho_{dark}$ is equal to $2{\cdot}10^{15}$ Ohm·cm for copolymer I and $5{\cdot}10^{14}$ Ohm·cm for copolymer II at 21˚C temperature. With the temperature growing up to ~71˚C which is the recording temperature of PTP process, the $\rho_{dark}$ value for is decreased both copolymers by one order of magnitude and became within the same order of magnitude as studied photosensitive semiconductor layers as it was described above. The last is being the optimal combination for creation of two-layer PTPF with improved exploitation characteristics.

Also, thermoplastic materials BMA-50 (copolymer of styrene with butylmethacrylate, 50:50 mole%) and CEM-CMA (copolymer of the carbazolylethylmethacrylate with cetylmetacrylate) in conjunction with photosensitive CGS thin layers were studied. For estimation of quality of an image recorded on PTPF, procedure and experimental setup developed by Laboratory for Photothermoplastic Recording of Moldova State University were used. One can precisely determine all photographic characteristics for different conditions and modes of the PTP recording within the single test. This procedure consists in several steps. Firstly, standard transmission gray scale test (TGST) was projected on PTPF and recorded on it. Then TGST was read-out by means of visualizing optical system and its image was characterized by the corresponding ratio of the photodetector currents $I_b/I_d$ measured in bright and dark fringes of reproduced test. Value $\lg(I_b/I_d)$ was accepted as a criterion for estimation of the reproduced image quality in accordance with the Weber-Fechner law. Therefore, $\lg(I_b/I_d)=f[\lg(Et)]$ dependence serves as a characteristic curve for PTP recording. It allows calculate contrast coefficient as a characteristic curve slope $\gamma=\tan(\alpha)$,photographic width $L=\lg(Et)_2-\lg(Et)_1$, and photographic sensitivity $S=1/Et$. Coefficient of transformation for this read-out setup was assumed as unity. The $(Et)_{min}$ value was determined at the 0.2 level above the background value. A set of curves for surface potential relaxation for elaborated PTPF is shown in Figure 5.

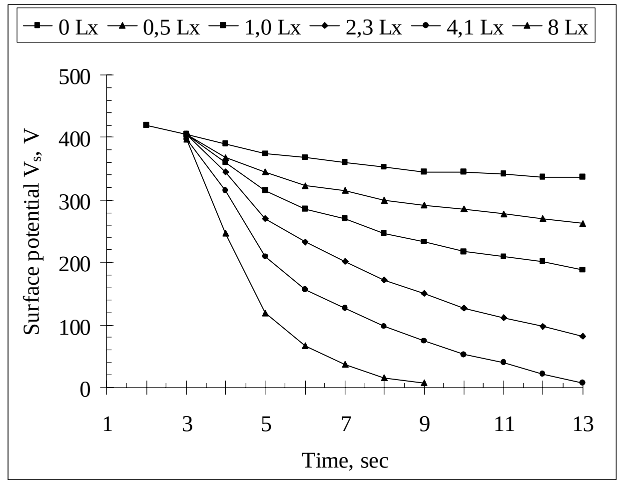



Fig.5. Surface potential relaxation for different levels of PTPF illumination.

Superficial dimples and craters appear nearly of the same size onto PTPF. It is known that resolution capability especially influences on the quality of recorded PTP image. Maximal resolution during recording of GOI test pattern on PTPF samples was about 350 $mm^{-1}$ with "Industar-70" objective. However, the last one does not limit the PTPF resolution because resolving power is more than 3,000 $mm^{-1}$ for holographic recording. Obtained results were adequately described by means of mathematical model on kinetic processes in PTPF.

## 4 ALGORITHM AND METHODS FOR OPTICAL DATA PROCESSING

An algorithm for automatic measurements of the sea surface conditions is proposed. The measured parameters are height and spacing of waves as well as their motion direction. In real situation, a single-directed process is not so pronounced, but still there is a hope that we could determine the motion direction firstly and all other parameters after that. Indeed, the distribution of the illumination intensity on gray scale image can be treated as a scalar function of two variables and its gradient in every point will be directed along the direction of waves' motion aside to wave ascent. Furthermore, because the wave profile is asymmetric (Figure 6), the number of nodes of discrimination on windward wave slope will be more than on the leeward slope. So we can calculate the resulting vector ***D*** of all elementary unit vectors along with the function gradient in regularly network nodes. Thus, one can obtain not only the direction of motion, but the sense of this direction, too. The wave profile along this direction will be quasi-periodic and spatial frequencies (i.e. wavelengths) could be determined by using of the Fourier transform. It should be noted again that the profile amplitude is proportional to a modeled wave height.

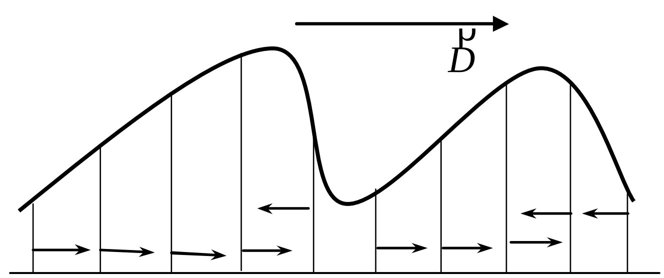
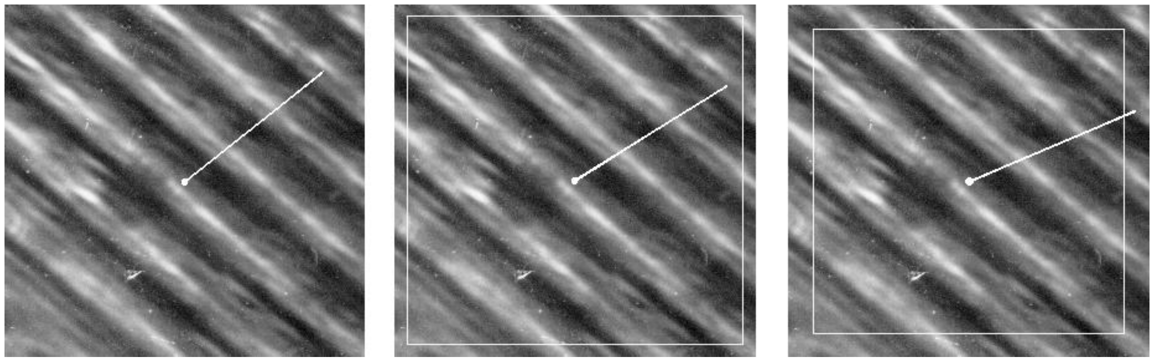



Fig. 6. Asymmetric wave profile and resulting vector $\vec{D}$ of wave motion. Short arrows are the unit vectors along the gradient in network nodes.

Let us consider that the image of the sea surface is obtained and its digital sample is stored in memory as a graphical file. Therefore, the image processing becomes a stand-alone problem. As we pointed above, the key



(a) (b) (c)

Fig. 7. Calculated vector $\vec{D}$ (directed to center of image) over the testing image in Fig. 1. (a) – all pixels are considered in calculations; (b) - (c) – a band of 10 (20) pixels over the perimeter was excluded from calculation.

problem is construction of mathematical representation of this sample. We use for it a variant of B-spline fitting to construct $C^2$ smooth scalar functions of two variables. This approach is ideal for fast computation of function gradients. Proposed algorithm consists of the following steps:

- Construction of B-spline scalar function of two variables fitting the image sample;
- Construction of vector field of gradients in 2D points over the image sample;
- Computation the resulting vector of wave motion direction;
- Construction the function of waves profile along the direction of motion;
- Construction the fitting B-spline of profile function;
- Computation Fourier transform of profile function to find the spectra of spatial frequencies and determine the length of main wave.

The basic characteristic of undulating process have to be fond is the direction ***D*** of the wave motion. Figure 7 shows the vector ***D*** over the testing image which is shown in Figure 1. Despite of pronounced trend of waves in this image, the calculated vector manifests instability. It depends on chosen frame limits, pixels of which are taken into account. Three major trends are related with this instability:

- Border influence. This influence is caused by the fact, that the windward and leeward areas of wave inequality take part in calculations. This effect is manifested as much as less waves are there on image and it seems, we can't avoid it at all, but can minimize by special choice of border form, circular, for example;
- Constant intensity areas. These are areas of maximums and minimums of intensity, where the computing instability occurs, when unity vector along gradient is calculated. This difficulty can be avoided by excluding such areas, using small gradient criteria;
- Noisy areas. These are the image areas of bad quality, which must by excluded by more accurate focusing of optical system.

Figure 8 shows the calculation results for a real image of the sea surface area which was recorded onto PTPF and reconstructed in a visualization system. Taking into account the direction of calculated vector ***D*** from picture (b), we could obtain additional data only by variation the frame limits of image despite the original image was very noisy.

Figures 9 (a) and (b) shows the wave profiles along with directions of ***D*** from Figures 7 (a) and 8 (b), correspondingly. The periodicity of function (a) is pronounced and its Fourier transform gives us a certain wave periodicity (spacing) expressed in number of pixels as per length unit. The periodicity of graph (b) is slightly lower than (a), and because Fourier analysis gives us a diffuse peak, we can determine the wave spacing very approximately only. However, these results fairly corresponded to the testing ones.

## 5 PTPF-BASED RECORDING DEVICE FOR REMOTE SENSING

For a couple of decades, PTPF seems to be smart material for large area of technical applications [5]. However, a strong scattering circle appears around the central maximum formed by the spectrum of chaotic deformations [6]. It determines

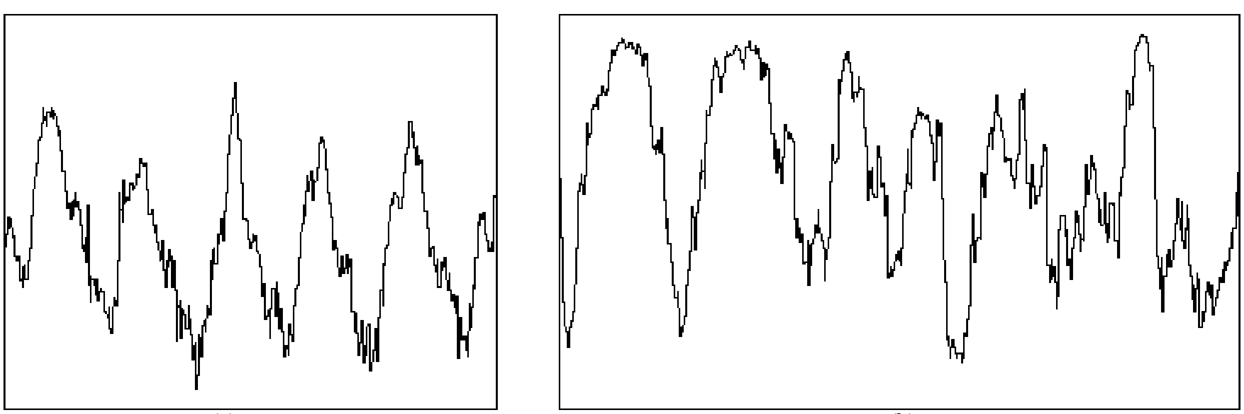
(a) (b) (c)

Fig. 8. Calculated vector $\vec{D}$ (directed to center of image) over the real image of a sea area. (a) – all pixels are considered in calculations; (b) - (c) – a band of 10 (20) pixels over the perimeter was excluded from calculations.

the resonant frequency, at which the maximum scattering of read-out light occurs. As a matter of this fact, the resonant frequency determines the resolving power. Let us note that correlation between the thermoplastic layer thickness and resonant frequency is considered constant and does not depend on the recording conditions.

A tendency to wide the photographic recording diapason towards the minimal luminous flux from the space objects requires creation of photo-recording devices used special lenses. We used one of such lenses with the following parameters: focal length f=99.3 mm; numerical aperture D/f=1:1.12; resolving power R=960 $mm^{-1}$, the field of view 8°. All PTPF-based devices imply some critical elements for providing PTPF sensitization by means of the corona discharge as well as thermal development of the latent image to the form of superficial relief on the PTPF. PTPF-based device for airborne and satellite imaging, PARUS, was described previously in Ref. [7]. Let us briefly repeat the main operation features of the PARUS. The lens provides the exposure of the PTPF photosensitive layer through the slit and the PTPF base. Synchronization of the PTPF movement and image run was performed; this allows controlling both the quality of the image on the thermoplastic surface and its erasure during rewinding. The weight of the PARUS device is about 16 kg comprising the 7-kg-weight of the lens with the diaphragm. To avoid overheating under the zero-gravity condition the suitable radiators at the energy-consuming components were taken off the closed cassette space to cool them outside by the air fan. The film-pulling device for these practical PARUS modifications was produced in two modifications providing the synchronization of the PTPF movement from 1.5 to 2.5 mm/s or from 2.6 to 4.3 mm/s providing optimal exposure time about 0.15 s.

Figure 10 shows the Black Sea surface picture made from the 9000-m-altitude and its area magnified by instant reproducing system. A small moving shipboard could be easily detected on it. Camera resolving power is high enough



(a) (b)

Fig. 9. Wave profiles along the directions $\vec{D}$ in Figures 7 (a) and 8 (b).

for determining of waves heights and spacing as well for discovering of small sea objects and determining of their speed and drift direction. PTPF-based remote sensing seems to be even more advantageous due to the possibility to record different images multiple (up to 100) times on a single PTPF frame within the "recording → read-out → thermal erasing → re-recording" cycle.

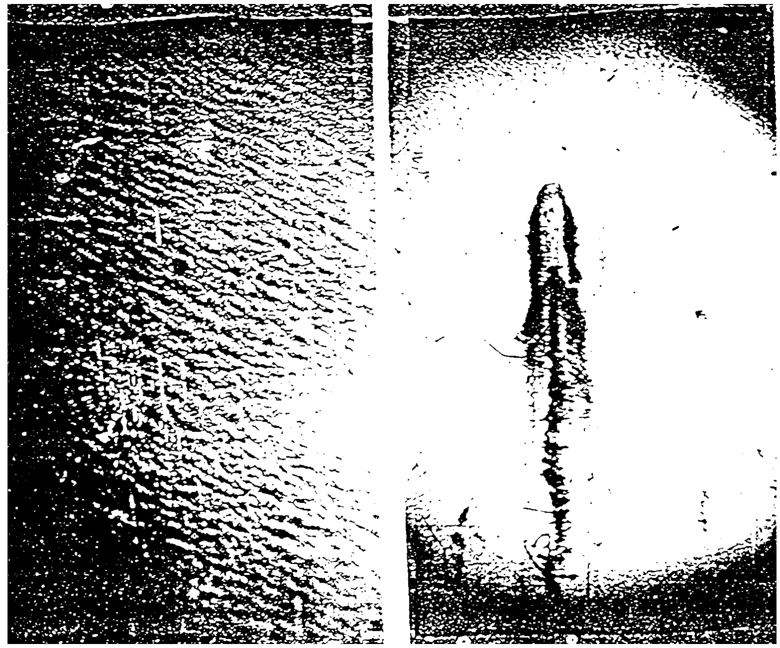


Fig. 10. Black Sea surface from the 9000-m-altitude and small moving shipboard magnified by instant reproducing system.

## 6 CONCLUSIONS

- PTPF-based devices allow optical data recording with photosensitivity from 0.13 to 4 $lx^{-1} \cdot s^{-1}$ while average contrast value was not less than 2.

- Optical image processing allows input-output exchange of the information blocks and their archiving for further processing. These parameters include direction of the waves' motion, and their spacing and height.

- Increasing of PTPF sensitivity through the utilization of multi-component CGS and novel polymeric compositions allows increasing the rate of information accumulation and processing.

- Such slit camera was tested in on-flight and in-ground operating regimes for panoramic photography. Resolving power was about 220 $mm^{-1}$ for the OSL-100 objective which allowed efficient detection of small objects on the sea surface.

## ACKNOWLEDGMENT

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