Yuri Denisyuk: An appreciation

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1. Introduction

When Yuri Denisyuk began his investigations on what he dubbed "wave photography" some 48 years ago, connections with Dennis Gabor's "wavefront reconstruction" were not evident, and the field of holography did not exist. The originality of his early research impeded Denisyuk's early recognition, but from the mid 1960s he was almost continuously involved in the subject and made further major contributions to modern holography. This brief account summarizes his early career and rising recognition in the Western world [1].

Yuri Nicholaevich Denisyuk was born in 1927 in Sotchi, on the Black Sea, and grew up in Leningrad. He obtained his first degree from the Department of Physical Engineering at the Leningrad Institute of Fine Mechanics and Optics in May 1954. Rather than fulfilling his boyhood hopes of pursuing fundamental physics, however, he began work at the Vavilov State Optical Institute that year, where he was to continue working for the following thirty-four years.

The State Optical Institute (known by its Russian acronym, GOI) had been founded in 1918 and later renamed after one of its most prominent researchers, N.I. Vavilov. As the principal Soviet center for optical research and development, its work ranged from pure research to mundane applications for the armed forces. During his first seven years at the Vavilov, Yuri Denisyuk's activities were on this lower rung: working under Alexander E. Elkin in the field of optical instrumentation for the Soviet Navy, he was occupied, he later recalled, "with very dull work relating to the development of conventional optical devices consisting of lenses and prisms" [2]. His later work at the Vavilov, however, pioneered fresh, if initially unappreciated, directions.

2. *Kandidat* research

Like many of his Russian contemporaries among the large wave of post-war technical workers, Denisyuk decided to pursue an advanced degree. From 1958, Elkin, who did not possess a scientific degree himself, provided time for Denisyuk to do research for a *kandidat* thesis (roughly equivalent to the Western PhD) and recommended another colleague at the Institute, Dr Eugenii Iudin, as supervisor. Although Iudin died not long afterwards, Denisyuk was able

Fig. 1. Yuri Denisyuk at the Vavilov State Optical Institute, 1966 [courtesy Academician Yu.N. Denisyuk].

to begin and continue his studies without formal supervision, although overseen and supported by Elkin, over the following two and a half years (December 1958–June 1961). He was supported by a small stipend and well supplied with material resources purchased for the ongoing submarine research at the Vavilov Institute.

Denisyuk set out to study the problem of general imaging, beginning, in 1958, with "some investigations to develop image display devices which could reproduce an absolute illusion of the presence of the objects displayed" [3]. Initially he explored the ideas of Gabriel Lippmann, the turn-of-the-century French physicist who had developed a Nobel Prize winning process of color photography based on optical interference, and who also had proposed a form of three-dimensional photography based on a special aperture system consisting of small lenses [4].

The fly's eye arrangement of these "integral photographs" had theoretical shortcomings, however: in order to obtain high-quality near-continuous shifts of parallax as the observer moved, the lenses would have to be made as

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small as possible; but, as lenses were made smaller, their individual resolution diminished, thereby constraining image quality. The fly's eye arrangement could only ever yield a compromise three-dimensional imaging system, trading off three-dimensionality for spatial resolution.

Through 1958 and into 1959, Denisyuk studied the theoretical problem at a more fundamental level. He began to reason that the full optical information about a complex object could be recorded by combining its light with that from a reference wave. From the outset, Denisyuk focused his thinking on standing waves in space, a situation in which the phase and amplitude of the wave field was constant with time and position. Such a condition could be produced via two counter-propagating waves. Where the two waves overlapped, the result would be a standing wave – an unchanging field having fixed intensity and phase at every point – which he hoped to record as a two-dimensional slice on photographic emulsion.

Initially Denisyuk envisaged trying, like Dennis Gabor before him, to record a cross-section of this wave field of light as an interference pattern in a thin emulsion of photographic film. But unlike Gabor, he arranged the reference wave to be transmitted toward the object wave, instead of coming from the same direction. This configuration imposed a serious practical constraint: instead of the relatively large interference fringes that Gabor had recorded, Denisyuk's fringes would form surfaces nearly parallel to the emulsion. He initially considered a photographic emulsion considerably *thinner* than a wavelength to avoid recording merely a muddy smear, but this would be much thinner than any available emulsion [5]. Unaware of Gabor's work, Denisyuk did not consider other arrangements of the two interfering beams of light that would have produced a more practicable spacing of the interference fringes. Another practical worry was whether variations in the emulsion would disturb the phase and amplitude of the wave traveling through it, and prevent reconstruction of the wave field [6].

Denisyuk conceived a solution by generalizing Lippmann's concept of interference photography. This was a close analog of the Lippmann color process, but highly simplified: he was using monochromatic light (a mercury arc lamp) instead of sunlight, a curved mirror instead of a liquid mercury mirror, and a parallel (collimated) beam instead of a focused image. Light from the mercury lamp passed through the emulsion (thus serving as the reference wave) and then reflected from the convex mirror back to the emulsion (becoming the object wave). The resulting spherical standing wave interference pattern was recorded through the depth of the thick emulsion. As he initially conceived his new method, Denisyuk concluded that it would create a structure in the emulsion that was identical to the optical properties of the original curved reflecting object. This passive structure would be an unusually thick photographic emulsion that would record interference layers that modeled the surface of a shallow reflecting object. This notion, at least in its original theoretical and practical characteristics, was almost unrecognizable to Dennis Gabor's conception of "wavefront reconstruction" or "diffraction microscopy".

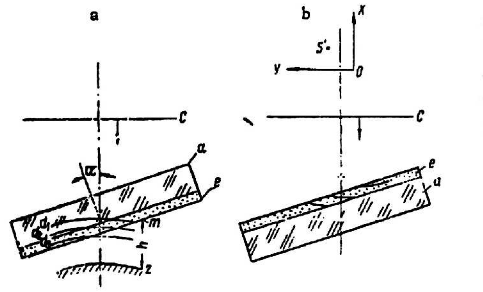

Fig. 3. (a) Diagram of the production of wave photograph of convex mirror. c—Wave surface of incident radiation, a—photo-plate, e—emulsion layer of photo-plate, d_1, d_2, d_3—antinode surfaces of the standing waves, Z—convex mirror with outer aluminizing. (b) Diagram of measurement of optical characteristics of wave photograph of convex mirror. S′—image of monochromator slit or hatched globe, formed by wave photograph. XOY is the coordinate system in which the position of the image is measured.

Fig. 2. Denisyuk recording geometry in English translation ["On the reproduction of the optical properties of an object by the wave field of its scattered radiation", *Optics and Spectroscopy* **15** (1963) 279–284].

Denisyuk began to prepare optical equipment and the necessary processing chemistry from mid 1958, even studying French to read Lippmann's original papers. By December 1958, he had begun his first experiments to test the ideas. He recalls that, although the suppliers of Navy funds for submarine research "did not count money", he was undemanding: "My experimental set-up was so simple that I could do it using my stipend and friendly connections in the Institute".[1]

Despite a seemingly straightforward experimental extension of Lippmann's method, Denisyuk's initial work until early 1959 was discouraging. He had looked to Lippmann's writings to recreate or further develop the chemistry to develop these special plates, but found that the high-resolution plates needed to record the very closely spaced fringe patterns of the standing waves were far too insensitive to record the fringe pattern. Where Lippmann had been able to make his exposures in bright sunlight, Denisyuk was restricted to a dim, highly filtered emission lamp. He collaborated with Dr Rebekka R. Protas, a specialist in silver halide emulsions at the Vavilov Institute, to improve the sensitivity of the plates a thousand-fold. Together, they experimented with some 200 emulsion formulas, adjusting the chemistry and processing to alter silver content, size of the silver halide grains and emulsion thickness to further optimize and hypersensitize

[1] He added that, several years later, financial support from the Navy and other sources made possible very large reflection holograms, but "it was not a science. Science developed in a very small room with help from [an unskilled assistant], Vera Rongonen" [7].

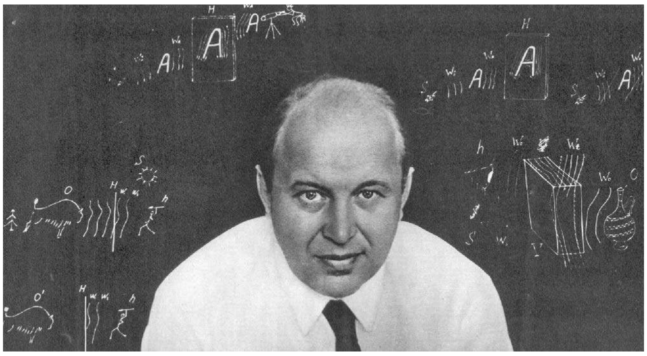

Fig. 3. Denisyuk as famous scientist [*Soviet Union* **9** (1970) 12–14].

the emulsion. There were subtle requirements of the emulsion far beyond those of regular photography: it had to maintain a nearly unchanged thickness after it was developed, so as to avoid shifting the color of the reproduced image, and the size of photosensitive grains was crucial to the recording of the standing waves and to the resulting fringe quality. They later discovered that the additional chemical steps of gold sensitization and triethanolamine hyper-sensitization made the emulsion faster while leaving its resolution unaffected [8]. The photochemical expertise at the Vavilov Institute was therefore crucial to his project.

During 1959, Denisyuk began using the improved emulsion to record standing wave patterns from his shallow mirrors, and found that his scheme did, in fact, work. Once the photographic plate was processed, it reflected collimated mercury light just as the original spherical mirror had done, producing divergent light. His small flat plates acted just like the original convex mirrors, showing that "a spatial photograph of the standing wave pattern does in fact provide a surprisingly complete reproduction of the recorded wave field" [9]. And Denisyuk verified the characteristics of his own holograms, which did indeed act as convex mirrors, but a peculiar kind of mirror that changed its focal length with wavelength. This was, in effect, the first reflective holographic optical element.[2]

Denisyuk learned of Gabor's prior work tardily, as he was completing his dissertation. His first publications correspondingly made efforts to relate the earlier work to his own.

3. Wave photographs

Denisyuk's first paper was published in 1962. Two other papers (bearing the same title, but expanded content) were published in 1962 and 1965. In his first three-page paper, Denisyuk announced "a phenomenon discovered by the author, wherein the reflecting properties of an object are manifested with extraordinary fidelity" [11]. Citing the work of Lippmann and Gabor, Denisyuk described how objects scatter light falling on them back towards the original source. The result is interference between the original wave and the scattered wave, yielding a standing-wave pattern that can be photographed [1]. Denisyuk described his "wave photograph" as "a unique kind of optical equivalent of the object":

> If radiation from the same source that illuminated the object during exposure is allowed to impinge on this structure, it will reflect this radiation in such fashion that the wave field of the reflected radiation will be identical to the wave field of the radiation reflected by the object.

Months later Denisyuk submitted a much longer paper with the same title to *Optika i Spectroskopija* (*Optics & Spectroscopy*) [12]. In it, Denisyuk observed that diffraction gratings and wavelength-dependent optical elements could be recorded in this way, but noted that the technique was limited by the brightness of the mercury source and by the monochromaticity of its light.

Table 1
Awards

1970: Lenin Prize
1970: Corresponding member, Soviet Academy of Sciences
1975: Soviet Badge of Honour
1982: National Prize of the Soviet Union
1983: Dennis Gabor Award, SPIE
1987: Progress Medal, Royal Photographic Society, UK
1988: Order of the Red Banner of Labour
1989: National Prize of the Soviet Union
1992: Academician of the Soviet Academy of Sciences
1992: R. W. Wood Prize, Optical Society of America
1992: Hood Medal, Institute of Physics (UK)

4. Initial reception

The publication of his work – a requirement for the completion of his *kandidat* research – proved difficult. When Denisyuk approached one Academician at the Vavilov for a recommendation, he was rebuffed, and was asked to provide letters of reference from other researchers. Having worked in near isolation, Denisyuk found supportive sponsors hard to find, but eventually another Academician from the Institute, Vladimir Linnik read the paper before the Academy of Sciences.

Nevertheless, once published the work gained little attention either at home or abroad. His publications had not suggested a compelling application for wave photography, and it was clear that the limited coherence of mercury sources constrained the depth of any three-dimensional objects to trivial dimensions. Denisyuk's *kandidat* degree was not granted until 1964.

At the end of 1961, with dissertation work finished, Denisyuk became director of a Vavilov laboratory responsible for infrared, sonar and especially imaging radar research for the Navy; indeed, work very similar to that being con-

[2] A different variety of holographic optical element had been invented earlier, as tardily recognised by Gordon Rogers in England: Dennis Gabor's method creates a generalized zone plate, and the hologram of a point source acts as a diffractive lens [10].

Fig. 4. Denisyuk (right) at his home with Dmitri Staselko, Eugenia Brui and Maria Serebryakova [H. Bjelkhagen photo].

ducted by Emmett Leith's small group at the Willow Run Laboratories in Michigan.[3]

5. From obscurity to recognition

Until 1965, further research on wave photography was limited to only one or two graduate students in Denisyuk's lab. That year, the laboratory began using helium–neon lasers and, more importantly, international interest in wavefront reconstruction was being dramatically awakened by the results obtained by Leith and Upatnieks in America. The connection with Denisyuk's research was only gradually understood: during the autumn of 1965, three separate American groups rediscovered that Denisyuk's geometry permitted white-light reconstruction of holographic images. The link with Denisyuk was not emphasized; an American patent was granted to the Battelle Memorial Institute in the USA, and most holographers in the West knew the technique as "Lippmann", "Lippmann–Bragg", "volume" or "reflection" holography until the 1970s.

Nevertheless, rising attention from abroad brought recognition at home. From 1965, Denisyuk and his co-workers were able to turn their attention back to the new merged subjects of "wavefront reconstruction", "lensless photography" and "wave photography", which was becoming known as "holography". He found further vocal support within the Soviet Union. Petr Kapitsa, the renowned Russian physicist who had worked with Lord Rutherford during the 1930s, had quietly provided patronage in the early 1960s but later used his influence to greater effect, ensuring that positive reviews were written of Denisyuk's work. And Mstislav V. Keldysh, President of the Soviet Academy of Sciences and theoretician of the Soviet space program, discovered on visiting America in 1969 that Denisyuk was better known in the West than in his native country.

In 1970, nearly a decade after the completion of his original work on wave photography, Denisyuk had a rising reputation in the Soviet Union. That year he was awarded the Lenin Prize and made a Corresponding Member of the Soviet Academy of Sciences.

The prizes rehabilitated Denisyuk's work in the Soviet Union, and signaled a growing public awareness of holography there. Journalists on the most important newspapers, such as *Isvestia* and *Pravda*, described his work for the first time in popular terms [13,14]. But fame had its price, as Denisyuk later recalled:

> My struggles with conservative colleagues and my subsequent triumph had a bad influence on my investigations in the field of holography. During these long years, I was bombarded by journalists and numerous beginners who wished to become involved with holography. These were not my best years [15].

6. Foreign exposure

Even so, Yuri Denisyuk was still only recognized peripherally in the west; as his reputation grew internationally, Russian activities remained tantalizingly obscure, and Denisyuk attained a near mythical status. He made his first trip abroad in 1970, visiting Besançon, France, for a holography conference. American connections remained weak for a further decade. Emmett Leith and Denisyuk had first come into contact at the Novosibirsk meeting on holography in the winter of 1973, but Leith, presumably for security reasons, did not meet many Russians. Six years later, Leith was invited to visit the Soviet Union as the guest of the A.F. Ioffe Physico-Technical Institute in Leningrad, and the two developed a close friendship, renewed during increasingly frequent visits made by Denisyuk to Western Europe and North America from the late 1980s, especially following the end of the Soviet Union. Denisyuk spent extended periods as a visiting researcher in several countries, including Canada, Italy, America and Colombia. In fact, Denisyuk met his third wife while spending a year at the Universita degli Studi dell' Insubia in Como, Italy during 1998–1999. Denisyuk himself moved to the Ioffe Institute

[3] See "Emmett Leith: early work and influence", this volume.

Fig. 5. At De Montfort University, Leicester, to receive an honorary DSc, 1999 [H. Bjelkhagen photo].

in 1988, having spent the bulk of his career, like Leith, in a single city (Leningrad, now St. Petersburg). His final foreign conference was in Varna, Bulgaria in 2005.

The increasing mingling of Western and Russian scientists at conferences during the 1970s revealed more about what had been a little known and overlooked research effort for Western eyes. Dmitri Staselko of Denisyuk's lab had developed pulsed lasers for human portraits during the late 1960s [16]. And with the availability of improved lasers and the continuing Soviet development of high-quality emulsions, the holograms made by Denisyuk and his co-workers began to gain surprised Western attention during the mid 1970s, becoming objects of envy for leading researchers such as Stephen Benton in America and Nick Phillips in the UK. For over a decade, large Denisyuk-type holograms of high dynamic range – the firm favorite of Soviet investigators – remained unequalled in the West, and spurred intense research efforts to improve processing chemistry and alternate optical geometries. So just as Denisyuk's career in holography was triggered by Western successes, researchers in the West were later sustained by their goals to surpass Russian accomplishments.

Denisyuk himself contributed to every branch of the developing field. In 1969 he conceived a technique of recording a wave train of light in flight [17], and during the late 1970s developed holograms based on traveling intensity waves [18]. A decade later he described how "pseudo-deep" holograms could be recorded for a special class of objects [19]. During the 1990s, Denisyuk devised "selectograms", a means of recording three-dimensional images without a reference beam, a concept closely akin to the Lippmann photography that had begun his research decades earlier [20]. Along the way were publications on holographic memories, holographic cinema, recording media and more. Such innovations made him a seminal researcher for forty years.

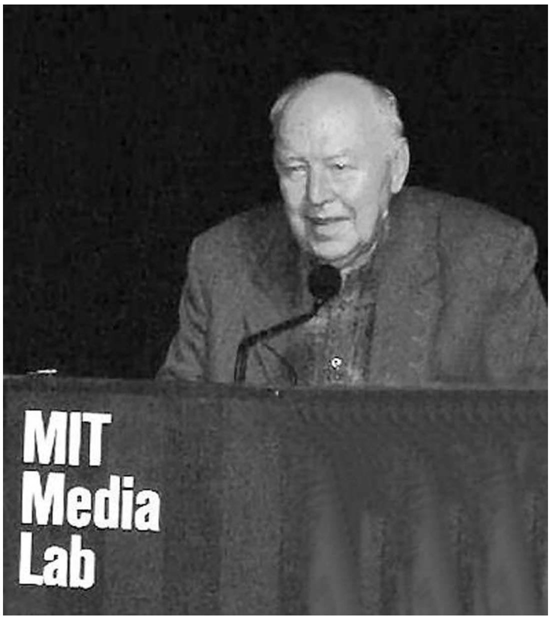

Fig. 6. Denisyuk at the Stephen Benton memorial conference, November 2003 [H. Bjelkhagen photo].

7. Status as a founding father

Yuri Denisyuk was more than merely a source of fertile ideas for scientific holographers, however; he also became an almost mythical character in the wider field, and even a prototypical example of the senior scientist. Part of that mythology had to do with his rare sightings in the West. Denisyuk first visited the UK in 1987 to receive an award from the Royal Photographic Society, and attended the International Symposium on Display Holography in the USA in 1989, over a quarter-century after his first paper appeared in English translation. Denisyuk's growing reputation as a senior figurehead of the field suited his generous and affable character very well indeed.

Practitioners of any field feel an understandable desire to define their identity by identifying key ideas and decisive individuals who shaped the subject. Since the mid 1970s, when holographers began to acquire awareness of their historical roots, Yuri Denisyuk and Emmett Leith, along with Dennis Gabor, have understandably been categorized as three such founders. For both Denisyuk and Leith, that status took time to develop, but both enjoyed enviable recognition and appreciation from their peers during the latter half of their professional careers. That reputation was further buttressed by their dedication to the subject throughout their working lives, regular conference contributions, similar demeanors and continuing creativity well beyond normal retirement age. It is a curious coincidence that the career parallels of Yuri Denisyuk and Emmett Leith extended even to their life-spans:

the two survived to within a week of the same age: 78 years, 10 months and 18 and 11 days, respectively.[4]

References

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