

SEEC

*Photography at the Speed of Light*ENAR DE DIOS RODRÍGUEZ, BRANNON B. KLOPFER,
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ABSTRACT

SEEC photography is a project at the intersection of art and science. It uses modern technology to record the motion of light, to see c , that is, the universal physical constant for the speed of light and the inspiration for the project name SEEC. In order to familiarize the general public with this physical phenomenon, SEEC records light moving across familiar objects, with visual scenes paying homage to iconic images from the history of photography. Exposure times shorter than 0.3 nanoseconds allow the authors to capture light (Greek: *phos*) in the process of writing (Greek: *graphein*) an image.

Light travels at a fast but finite speed of 299,792,458 meters per second. It takes only 3 billionths of a second (3 nanoseconds) for light to travel the distance of about 1 meter. This speed makes it impossible for us to see the movement of light; our visual perception is too slow. A successful initial experimental measurement of the speed of light was done almost 400 years ago, when Ole Rømer observed Jupiter's lunar system [1]. Ever since, the movement of light has remained a topic of intense scientific investigation. Today, light can be controlled on attosecond timescales (a billionth of a second) [2] and is at the heart of modern communication technology.

Previous cases exist in which a photograph captured the movement of light. In 1979, at Bell Laboratories, the development of an ultrafast shutter based on the optical Kerr effect succeeded in imaging a light pulse in a scattering fluid [3]. Most recently, MIT Media Lab researchers released several

videos that visualized the propagation of light over small objects by using “femtophotography” (femtosecond pulsed laser illumination, picosecond-accurate detectors and mathematical reconstruction techniques) [4].

The SEEC photography project creates movies [5] made from sequential photographs that reveal the movement of light (and the movement of the shadow that light casts), slowed down by a factor of about one billion, across a wide variety of everyday objects and scenes. These images of familiar objects are shown as a temporal sequence of light being scattered and reflected off of the objects. It thus places femtophotography within the tradition of photography.

Our setup is illustrated in Fig. 1. The scene is illuminated using pulsed lasers, either a titanium sapphire laser (Ventec, wavelength 780 nm, pulse duration ~ 10 femtoseconds, repetition rate 80 MHz) or a pulsed and compact laser diode for a mobile version of the apparatus (TEEM photonics, wavelength 532 nm, pulse duration ~ 1 nanosecond, repetition rate 5 kHz).

We use a short-focal-length lens to diverge the laser beam, effectively creating an expanding half-sphere of light, whose thickness is determined by the product of the laser pulse du-

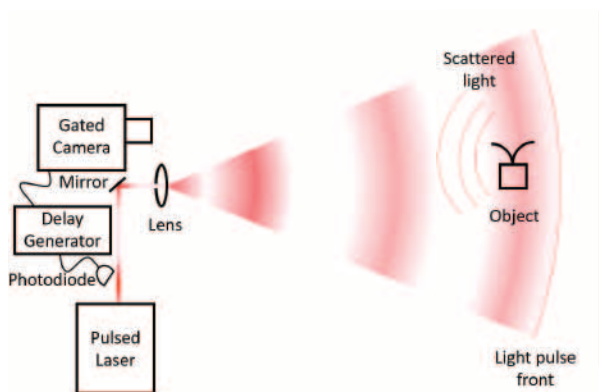


Fig. 1. SEEC Photography setup. (© SEEC Photography) Laser pulses are focused by a lens to spread out the light over the object. The gated camera is triggered to capture the light scattered back from the object at a certain delay in relation to the laser trigger.

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Fig. 2. *Still life (plant)*, video stills, 2016. (© SEEC Photography)

ration and the speed of light. For the Venteon laser, it is only 3 microns thick; for the TEEM laser the sheet of light is 30 cm thick. This light then illuminates the object, typically placed in front of a screen. Light scattered off the object (or the screen) is collected by a lens and detected using a gated and intensified charge-coupled device (CCD) camera (LaVision PicoStar). The camera is able to detect single photons—the quanta of light—and allows for exposure times shorter than 0.3 nanoseconds, a time span in which light moves by less than 10 centimeters. For synchronization of the laser and the camera, a pick-off of each individual laser pulse is detected using a fast photodiode, whose signal is amplified, delayed by the desired interval and connected to and triggering the camera. Typical averaged power levels were kept below 1 mW for laser safety reasons.

It is the total distance between the laser light source, the object and the camera that determines the time at which the scattered light reaches the camera. In most of our videos, the light source and detector are next to each other, and the object is placed in front of them (as sketched in Fig. 1). The parts of the object or scene that are closer to the camera are illuminated and photographed first. Light scattered from a more distant part of the object will reach the camera later. Finally, the light that did not hit the object reaches the screen behind it. Light scattered from the screen reveals the shadow of the object. Because the laser pulse diverges strongly due to the short-focal-length lens, the pulse first reaches the center of the screen (Fig. 1) and then seems to grow outward with time.

Figure 2 shows four images of a plant taken at different delay times between the laser trigger and the gated detection. One can see how different parts of the plant are illuminated at different times and also how the shadow grows outward. Note that the plant and its shadow are not imaged at the same time. One frame shows the plant without its shadow, and one frame shows the shadow without the plant. This challenges our normal understanding that object and shadow are intrinsically connected. The contrary is the case: Only the light that has not interacted with the object will reach the screen to form a shadow. The reason why the plant appears twice in the shadow (Fig. 2, right) is that the light first has to travel from the light source past the plant to the screen and then back from the screen to the camera. If the laser light pathway

is not precisely in line with the camera detector, the plant blocks the light bouncing back off the screen to the camera, creating what looks like a second shadow.

The frames depicted in Fig. 2 are part of a series of movies depicting classic still life scenarios such as plants or fruit.

For typical laser intensities, and a beam widened to 2×2 meters, the illumination intensity is ~ 1000 photons/cm²/pulse when using the titanium sapphire laser ($\sim 10^7$ photons/cm²/pulse for the laser diode). The total collection efficiency is on the order of $\sim 10^{-5}$, given a typical lens diameter (~ 3 cm), object distance (~ 3 m) and detection efficiency (~ 0.1), which necessitates integration over multiple laser pulses for a given delay between the laser trigger and the gated detection. In practice, for each frame of a movie, i.e. for each delay time, the signal from multiple images is integrated on a CCD chip. For the next frame, the delay is slightly changed, and again an image is integrated over multiple laser pulses. The resulting movies depict the movement of light across different objects and scenes. They are composed of frames that differ in delay by a few tens of picoseconds, as indicated at the bottom of each frame. The process described requires integration times of seconds to minutes. These long exposure times are reminiscent of the exposure times that had to be used by the pioneers of early photography to overcome the low light sensitivity of the technology at the time.

In the Victorian era, several breakthroughs in the technology of chronophotography were made that allowed scientific studies of motion that revolutionized human perception of movement [6–8]. Our project pays homage to some of the most iconic images from this photographic period. Our recording of the motion of light across a horse head mask (Fig. 3, top) is an homage to the renowned photographs of a galloping horse by Eadweard Muybridge, who, at the end of the nineteenth century, developed fast shutters and film emulsions in order to study animal locomotion. As in Fig. 2, we see that different parts of the object are illuminated at different times. Note that while Muybridge used light in order to study the motion of a horse, we use a horse to study the motion of light. While Muybridge developed photography with millisecond exposure times, we now use nanosecond and picosecond exposure times at the forefront of today's fast photography.

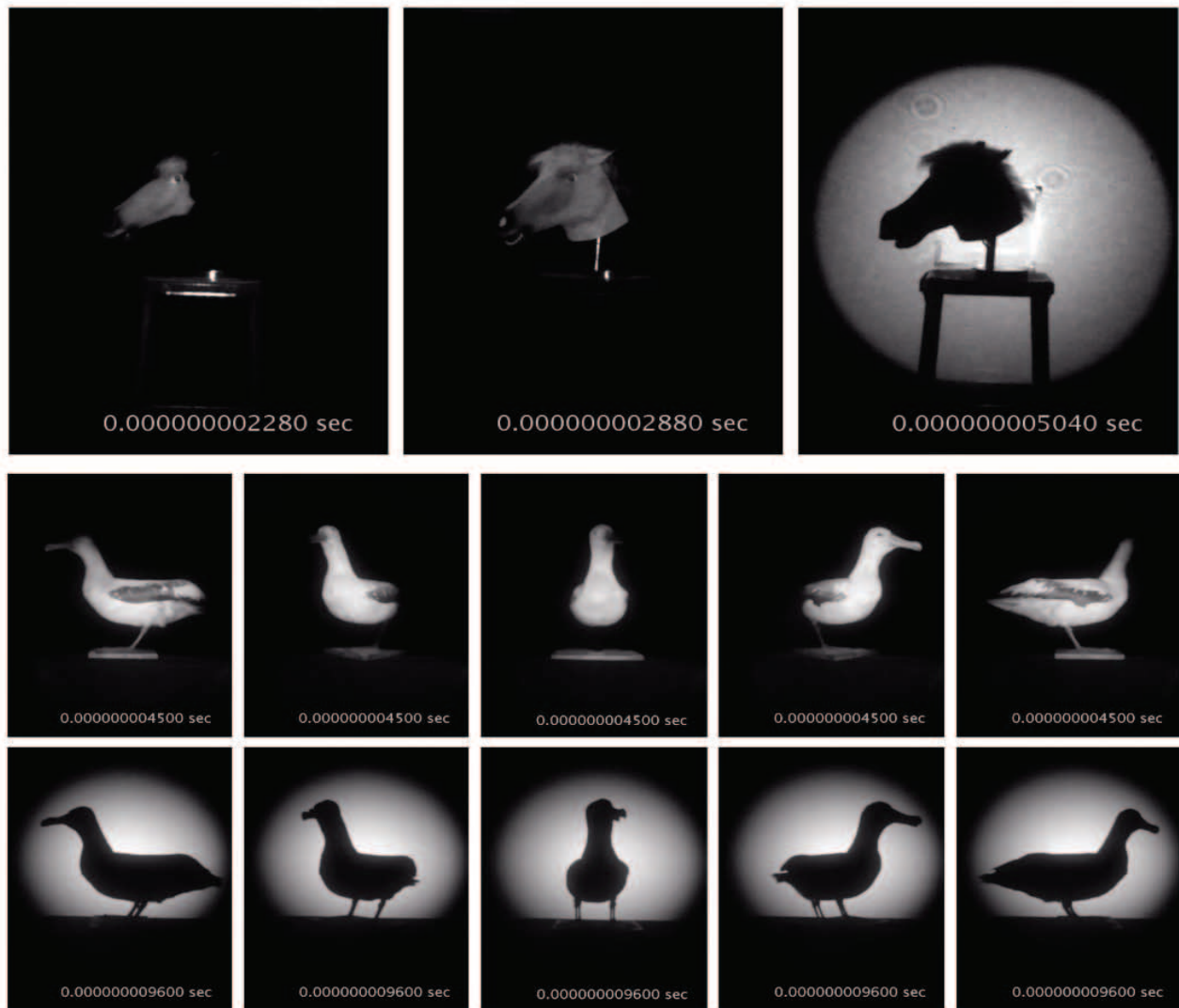


Fig. 3. *After Muybridge* (top) and *After Marey* (center, bottom), video stills, 2017. (© SEEC Photography)

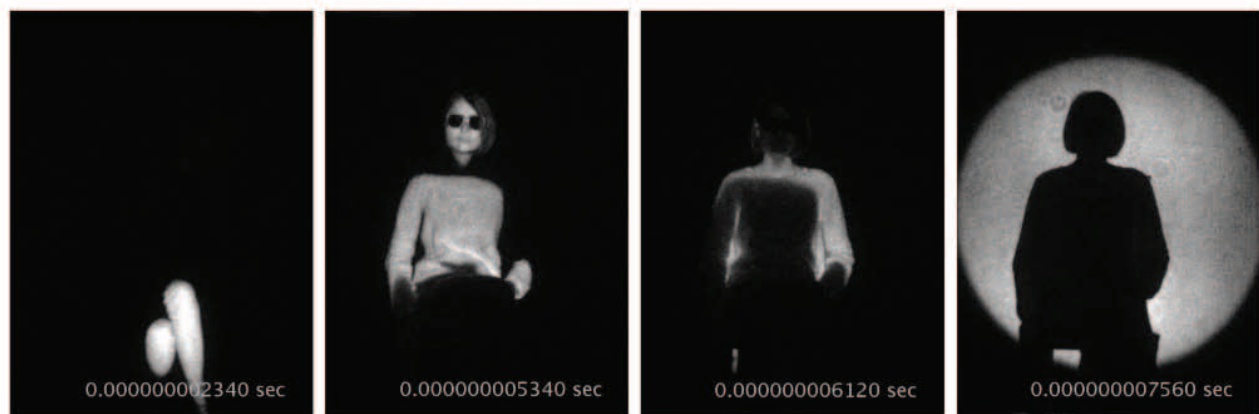


Fig. 4. *Portrait (Enar)*, video stills, 2017. (© SEEC Photography)

In another example that refers to the historic photographic study of birds' flight by Étienne-Jules Marey, we recorded movies of a taxidermied stuffed albatross from different viewpoints at the Museum of Vertebrate Zoology in Berkeley (Fig. 3, center, bottom). Once more, the reference here is both thematic (capturing motion) and aesthetic (using the subject of a bird).

Another photographic theme that we have addressed for our project was the self-portrait, conceivably the most taken and published type of amateur photograph today. Figure 4 shows images of one of us, again at different times. When recording these movies, we further decreased illumination intensity for laser safety reasons. This resulted in longer data acquisition and integration times (several minutes), requiring the subjects to remain still. It is for this reason that some of the movies from the portrait series show the slight motion of the model. The necessity of laser safety goggles resembling sunglasses is reminiscent of leisure, which is characteristic of the selfie. The separation of subject and shadow is perhaps most dramatic in this series of images, as it is now our own shadow that is being detached. Metaphorically speaking, the shadow appears after our disappearance and fades quickly.

Today, technology based on the propagation of light is everywhere (e.g. data transmission or the 3D reconstruction of our surroundings in self-driving cars). And yet we are often not aware of it, as our vision is not able to sense light in motion—nothing moves faster than the speed of light. To us, it is this close connection between time, distance and perception

that makes photography at the speed of light appealing for artistic expression. Showing the movement of light across familiar subjects and in ultra-slow motion requires us to re-think common paradigms of photography.

Any image we perceive, even of a still life (static objects), is the result of a highly dynamic process created by myriad speeding photons—the quanta of light—that transport information about the object toward our eyes.

Any image we perceive is necessarily an image from the past, as it takes time for the light to reach our eyes. Photography (and visual perception) does not capture the moment; it captures a moment from the past, the precise timing of which depends on the distance to the camera (or the eye of the observer). The positioning of the camera with respect to the scattering objects determines which object is imaged first. These notions are very familiar to astronomers; however, hardly anyone thinks about the nanosecond delays that occur when we see ourselves in a mirror.

An object and its shadow do not coexist. They are separated in time.

SEEC photography opens a new avenue for arts and photography, touching upon fundamental questions about our visual perception, image sensing enabled by technology and the nature of light itself. Light is the protagonist of our photographs, taking *photo-* (the Greek word *phos* means light) *-graphy* (the Greek *graphein* means to write) back to its literal meaning.

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References and Notes

- 1 O. Rømer, "A Demonstration Concerning the Motion of Light," *Philosophical Transactions of the Royal Society* **12**, No. 136, 893–894 (25 March 1677).
- 2 F. Krausz, "The Birth of Attosecond Physics and Its Coming of Age," *Physica Scripta* **91**, No. 6, 063011 (2016).
- 3 M.A. Duguay, "The Ultrafast Optical Kerr Shutter," *Progress in Optics* **14** (1977) pp. 161–193.
- 4 "Femto-Photography: Visualizing Photons in Motion at a Trillion Frames Per Second," Camera Culture, MIT Media Lab: <http://web.media.mit.edu/~raskar/trillionfps> (accessed 1 December 2019).
- 5 One can see selected movies at www.seecphotography.com (accessed 1 December 2019).
- 6 E. Muybridge, *Sallie Gardner at a Gallop*, film (1878).
- 7 E.-J. Marey, "Instantaneous Photography of Birds in Flight," *Nature* **26** (1882) pp. 84–86.
- 8 E. Mach and P. Salcher, "Photographische Fixierung der durch Projectile in der Luft eingeleiteten Vorgänge," *Annalen der Physik und Chemie* **268** (1887) pp. 277–291.

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