# Human Eye Simulation

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**Introduction:** In developing active sensors to detect and analyze devices of interest, it is often necessary to include a human eye, or a realistic emulation of the eye, during developmental testing. Only then can an accurate assessment of the performance of the sensor be made. The possible use of eye hazardous illumination in these assessments makes the development of a human eye surrogate necessary. These surrogates are only required to have the geometrical optic and spectral reflectivity properties of a real eye, so they do not need to look like a prosthetic eye nor function as an imaging sensor.

NRL began research and development of an eye surrogate to be used in international field trials at Playas, New Mexico, in 2008. Since then, two generations of simulated eyes with the required optical characteristics have been developed. The first consists of a matched pair of opposing planoconvex lenses. The second is based on a one-inch glass sphere with a contact lens cemented onto the front surface. In both generations of eyes, a small iris was mounted near the front surface to replicate the human pupil, and the back surface was coated with a mixture of carbon and iron oxide pigments to follow the spectral reflectivity of the retina. Both generations have been employed by NRL, the Army, and research groups in the international community for a wide range of tests.

**Development:** The development of the eye simulator was divided into two basic parts, the geometric and the spectral. For the geometric part, the obvious choice was to fabricate a sphere the size of an eyeball with an index of refraction that focuses incoming light onto the back of the sphere. For the spectral part, the task was to formulate a pigment coating that closely matches the spectral reflectivity of the back of the eye.

The Navarro–Escudero eye model was the basis for the geometric optical design of the eye simulators.[1] Zemax optical design software was used to replicate the Navarro–Escudero model and determine the point spread function (PSF) at wavelengths in the visible and near-infrared. The simulated eyes were also designed in Zemax to closely match this PSF performance (see Fig. 1).

Several initial glass sphere approaches were abandoned because of cost and schedule. The cost estimates to fabricate the spheres alone were well in the $1,000 range per eye simulator, and at least a dozen eyes were needed. Additionally, the production schedule placed the delivery date beyond the start of the field trials. An alternate design based on a matched pair of BK-7 lenses with a slight separation also produced the required geometric optical performance. The arrangement had shortcomings of stray reflections from the interior planar surfaces and a poorer replication of the Navarro–Escudero model's PSF (see Fig. 1, generation I model).

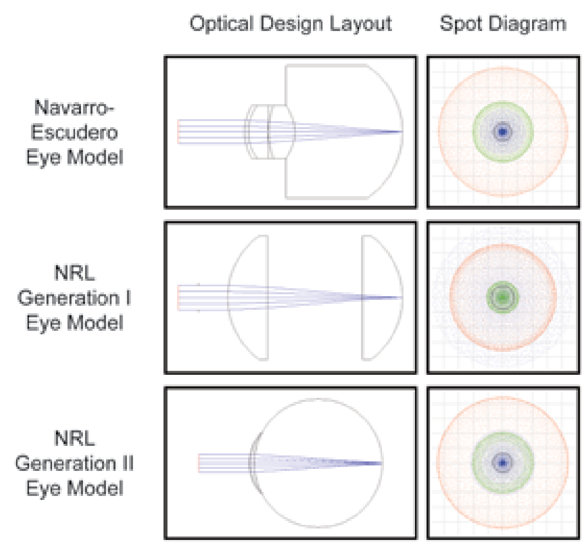


**FIGURE 1**
Zemax optical design layouts (left) and spot diagrams (right) for the Navarro–Escudero, NRL generation I, and NRL generation II eye models (top to bottom).[1] Each optical design layout shows on-axis, collimated light entering the pupil. Each spot diagram is the central 50 × 50 μm area of the image plane for wavelengths of 532 nm (blue dots), 650 nm (green dots), and 830 nm (red dots).

A major problem with the initial attempt to design the eye based on an eye-sized sphere was the custom material and fabrication costs. Zemax modeling showed that it would be possible to combine a one-inch sphere of borosilicate glass with a contact lens to produce the required geometric optical performance (see Fig. 1, generation II model). For the spheres, we bought precision glass marbles with a fine matt finish from a 300 grit abrasive polish. They were only several dollars each. About 50% of the front and back of each sphere was polished to optical quality with cerium oxide on a hard felt lap. Although the precision marbles were not advertised as optical quality, most of the spheres were free of internal defects such as bubbles and stria. An optometrist was consulted on the material and prescription of the contact lens needed and provided the prescription to obtain the contacts. The contact lens was applied to the sphere and cemented in place using an adhesive gel.

The spectral reflectivity coating was developed on a trial-and-error basis with different combinations of candidate artist oil pigments in varying proportions.

Each paint sample was measured using a spectrometer across the visible and near-infrared spectrum. The best match to an average human ocular fundus was found to be a mixture of two-thirds red iron oxide and one-third carbon black (see Fig. 2).[2,3] The coating was applied to the back surface of each eye simulator and a miniature iris diaphragm was mounted to the front at a slight angle to reduce stray reflections from the iris leaves (Fig. 3).

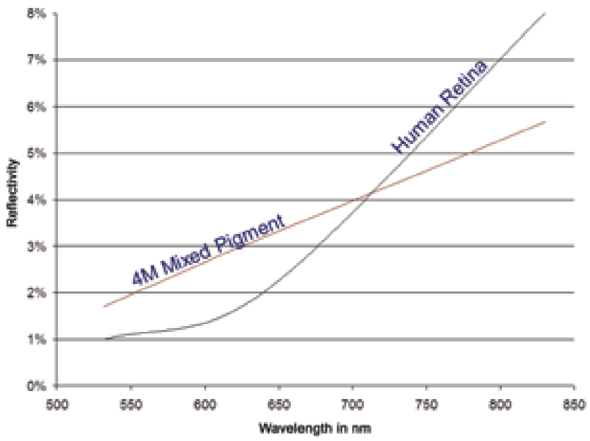


**FIGURE 2**
Spectral reflectivity curves for the mixed pigment of 2/3 red iron oxide and 1/3 carbon black (brown curve) and an average ocular fundus (black curve).[2,3]

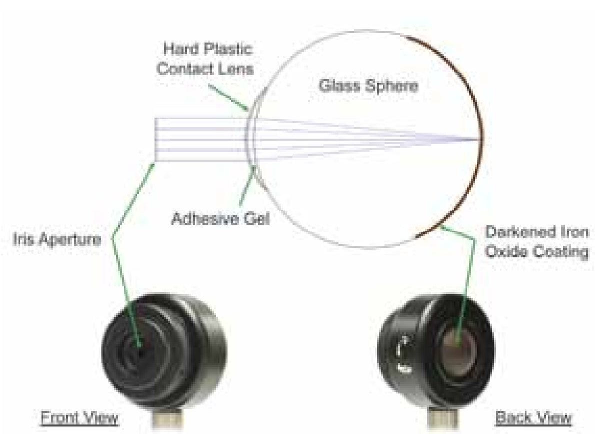


**FIGURE 3**
Zemax optical layout and pictures of the NRL generation II simulated eye in a one-inch lens holder mounted on a post.

**Performance Evaluation:** Both generations of simulated eyes have been used in development testing in the United States and abroad. They enable a safe and accurate assessment of the ability of an active sensor to detect and analyze devices without a human subject. Norman Comer at the Survivability/Lethality Analysis Directorate of the Army Research Laboratory recently analyzed the NRL simulated eyes and found that they have optical characteristics similar to those of real human eyes. However, the NRL simulated eye presents fewer aberrations than the real human eye. This is probably due to the fact that the ocular fundus has optical depth to it and presents as a semitransparent gel with suspended particles and structure, while the eye simulators have a flat surface without optical depth. Also, the iris leaves, while tilted and anodized to reduce stray reflections, still produce noticeable scatter. Refinement of the simulated eye is planned to better match the optical depth and structure of the ocular fundus.

[Sponsored by the NRL Base Program (CNR funded)]

**References**

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[2] F. Delori and K. Pflibsen, "Spectral Reflectance of the Human Ocular Fundus," *Appl. Opt.* **28**(6), 1061–1077 (1989).
[3] R. Flower, D. McLeod, and S. Pitts, "Reflection of Light by Small Areas of the Ocular Fundus," *Invest. Opthalmol. Vis. Sci.* **16**(10), 981–985 (1977).

## Towed Antiship Cruise Missile Simulator

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**Introduction:** The Fleet operates in an increasingly complex environment with many technological challenges that include a significant threat from antiship cruise missiles (ASCMs). These ASCM threats come in a wide variety of form factors with different strategies to breach ship defenses. Evaluation of antiship missile electronic warfare countermeasure performance relies on the analysis of measurements conducted with ASCM threat simulator systems. For quantifying the effectiveness of the countermeasure and the tactics, these simulators not only need to accurately replicate the potential threat seeker subsystems but also must closely match the flight profile capabilities of the ASCMs. The Naval Research Laboratory has extended its simulation capabilities from flying captive-carry simulators on a relatively slow and high flying P-3 aircraft to adding a capability for testing on a Learjet, which can fly lower and faster. Further extending NRL's growing simulator tool set for electronic warfare evaluation and assessment, NRL has developed an optical sensor–based simulator of a generic ASCM. This simulator can be reeled out and towed by a Learjet for operation down to as low as 25 ft above the water, adding to a fuller understanding of threat behaviors (Fig. 4).

**FIGURE 4**
TOWSIM reeled out during October 2010 flight testing.

**Description:** The TOWed electro-optic/infrared SIMulator (TOWSIM) was developed through advanced technologies and state-of-the-art fabrication methods (Fig. 5). The simulator makes clever use of a recoverable towed pod that is used for gunnery training. Inside the largely empty towed target body, the NRL team designed and integrated a gimbaled EO/IR sensor that met the flight restrictions for the pod.

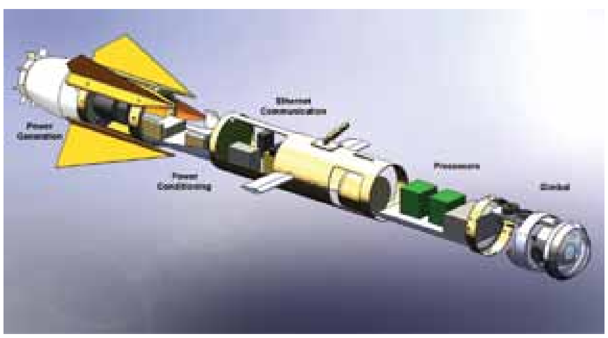


**FIGURE 5**
Interior layout of TOWSIM.

Due to the aggressive flight profiles and the risks they present, NRL used rapid prototyping methods to design and build working plastic models of a three-axis gimbal (optical pointing device) that fits inside the pod fuselage. Portions of the final design were changed from plastic to machined metal. This provides the required reliability while still allowing for easy replacement in the case of a loss at sea. The installation was designed to be adaptable to multiple simulators and has already been used successfully with two different imagers.

The simulator's embedded processor network provides mode control and data collection. Custom control software on a dedicated compact PC dynamically adjusts both the azimuth and elevation axes to inertially stabilize the sensors during fuselage movements. A separate roll axis provides for full scene stabilization and enables simulation of multiple threat capabilities. A second PC in the pod compresses the raw data for transmission via Ethernet from the towed simulator pod to the operator station in the Learjet.

**Impact:** Flight tests with the TOWSIM (Fig. 6) have provided a more accurate simulation of several aspects of threat system capabilities. Since the sensor subsystem can be towed at high speed down to 25 ft above the water, the electronic warfare responses properly incorporate the environmental effects of the low-altitude propagation path. The TOWSIM gimbal's roll axis stabilization keeps the sensor aligned with the horizon in the presence of crosswinds. The scene and mode data collected by the TOWSIM are stored in their entirety for later analysis of the threat processing and countermeasure interactions.

With the TOWSIM's capability to be reeled out to distances significantly separating it from the aircraft, the simulator can be used for testing a wide variety of shipboard countermeasure systems without compromising flight crew safety. The separation distance also improves the accuracy of threat signature representation, allowing better examination of the ship's detection and tracking capabilities.

NRL designed the TOWSIM to be modifiable so that different threat sensors can be installed, making it useful for multiple simulations. Changing sensors normally requires a new gimbal mount (readily made with rapid prototyping equipment), wiring changes, and software modifications — all of these parameters are readily accessible for modification. NRL is currently planning to build an additional TOWSIM.

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**FIGURE 6**
TOWSIM held captive before being reeled out from the Learjet during August 2011 flight testing.