curves. Note that aberration data has been calculated at the final image plane, located 254 mm from the borescope's exit pupil. Examination of the aberration curves indicates a design that is well balanced, with uniform image quality across the entire field of view. Both field curvature and distortion are well corrected for a design of this type. While the example presented deals only with the visual mode, it is quite reasonable to assume that a solid-state TV camera could be inserted near the eyepiece to provide video output for both viewing and recording.

7.15 The Head-Up Display (HUD)*

The head-up display is a sophisticated optical system found in most high-performance military fighter aircraft. The function of the HUD is to present a display of critical information to the pilot, with that display appearing superimposed on his view of the outside world through the plane's canopy.

While several more sophisticated HUD systems have been developed in recent years, the example presented here will deal with a conventional design, with very good image quality. This is a prototype design that was first generated for use in the A-10 fighter-bomber. Having been designed for close-support, relatively slow-speed missions, the A-10 is not nearly as sleek and streamlined as many other modern aircraft (thus its affectionate nickname, the "Warthog"). This results in a considerable increase in available space within the cockpit, which made the HUD design task somewhat easier. The HUD concept calls for the projection of data to the pilot's eyes from the face of a CRT that is located in the vicinity of his knees.

Projected data may involve flight instrumentation information, such as speed, altitude, and bearing, or it may involve data relating to targets and weapon delivery systems. In either case, the data is displayed on the CRT face; is collimated (projected to infinity) by a high-quality lens system; and then is reflected to the pilot's eyes via a beam-splitting plate called a *combining glass.* This combining glass will have a dichroic coating on one surface, designed specifically to reflect the wavelength (generally quite monochromatic) of the CRT. This eliminates the need for correction of chromatic aberrations in the HUD lens design.

Unique to the HUD optics is the fact that the exit pupil of the lens is located at the pilot's head, a considerable distance from the projection

* Original design work for the optics described in this section was done by the Kollmorgen Corporation (Electro Optical Division), Northampton, Massachusetts.

lens itself. Also unique is the fact that, while the HUD lens will generally be quite large, with a very fast f-number, the actual system pupil size is determined by the size, spacing, and location of the pilot's eyes. This factor has a significant impact on the philosophies employed in the design and evaluation of the HUD lens. While all aberrations must be given consideration, it is particularly important to control spherical aberration and coma, to prevent apparent motion (swimming) of the projected image as the eye moves about the exit pupil.

Figure 7.33 describes the optical system of the A-10 prototype HUD lens, with a complete set of aberration and lens prescription data. This is basically a high-speed, 5-element, compact Petzval lens, with a field flattener. The piano components near the field flattener are spectral filters, which fine-tune the output of the CRT. Aberration curves indicate good levels of correction for spherical aberration, coma, astigmatism, distortion, and color. The ray-trace analysis has been done over the full (= 7-inch) exit pupil diameter. Further detailed analysis, not to be included here, would involve the effects of these aberrations as viewed with two eyes located within this pupil.

7.16 Summary and Conclusions

This chapter has dealt with the specifics of the lens design process, as it applies to the design of systems intended for use in visual applications. The first part of this presentation has been dedicated to a general discussion of primary factors, including visual resolution and magnification. A model of the human eye has been generated, to serve several purposes. First, it is essential that the reader have a clear understanding of the way in which the human eye functions, in terms of its basic optical characteristics and parameters.

The second purpose for generating this model has been to make possible the valid comparison of relative optical performance between numerous visual systems in a meaningful manner. The model of the eye created and presented here has been, by necessity, simplified relative to what is actually the case. However, this model is functionally correct and has been specified such that its image quality is essentially equal to that of the *typical* eye.

The remainder of the chapter contains a variety of basic lens designs, dealing with an assortment of optical systems intended for use in visual applications. Data presented for each design contain detailed lens prescription data, along with basic design parameters and performance data. While all of the designs presented here are real, and will perform as indicated, their major value will be found when they are used to improve the reader's basic understanding of the design, and then as a