TERRY J. HARRIS

OPTICAL DESIGN AT APL

Computer-aided optical design and analysis are proving to be quite valuable in efforts to design, construct, and use greater numbers and varieties of optical systems. As several recent APL systems illustrate, currently used tools allow design and performance analyses of optical systems operating in any portion of the spectrum from ultraviolet through infrared wavelengths.

INTRODUCTION

Optical designers encounter interesting challenges in both hardware development programs and technology studies. For example, optical systems developed for missile and space applications require high performance and lightweight, compact packaging, with cost and scheduling considerations weighing heavily in the design process. Other applications require less attention to weight, volume, and construction details than to complex performance requirements.

In a typical space application, the optical section is built as a prototype flight unit, one that must be fully functional and reliable the first time (debugging optical systems can be time-consuming and very costly). In many respects, optical design governs the sensor performance and fixes the requirements of nonoptical elements; therefore, the optical design must be comprehensive, and its properties must be fully modeled and understood.

Many applications require a particularly intensive look at some aspect of an optics problem. Polarization sensitivity, spectral band pass, stray-light rejection, or a specific geometric aberration may be critical to an optical system's performance and require more elaborate analysis.

OPTICAL DESIGN AND LAYOUT

The first task of the optical designer is to select the basic design needed to meet the performance requirements. Components are then laid out in an appropriate geometric configuration that is the starting point for optical-component design and system-performance calculation. The optical layout is also the basis for the mechanical design of the sensor or instrument, and the optical and mechanical designers work closely during the early stages of design. For example, space and weight constraints may require a folded optical path or an even more unusual design.

REFLECTING TELESCOPES

Reflecting systems are highly desirable for many instruments because of the absence of chromatic aberration and good efficiency over wide spectral bands; in addition, there is a lack of adequate refracting materials in the ultraviolet and infrared bands. The compact, folded nature of reflecting telescopes makes them especially attractive for space missions. APL has designed several telescopes that take advantage of the characteristics of reflecting systems.

Because the degrees of freedom are limited, practical two-mirror systems are limited in correction to only two geometric aberrations, usually spherical aberration and coma. The correction is further limited if the mirror surfaces are constrained to a spherical shape (spherical mir-

THE ROLE OF THE OPTICAL DESIGNER

The computer has largely revolutionized the field of optical design, providing the computational speed and power that has long limited the optical designer's productivity. Ray tracing remains the primary method of evaluating optical systems, and computers can now quickly perform this task, which in the past was the most tedious part of the lens designer's job. Ray-intercept plots, spot diagrams, and other graphical data obtained by computerized ray tracing provide much more lens performance information than could be obtained previously.

Even with the widespread use of sophisticated optical design software in high-speed computers, the old-fashioned lens designer has not been rendered obsolescent. Computer tools for the optical designer have advanced so that exact ray tracing, aberration analysis, and lens characterizations such as modulation-transfer functions or point-spread functions can be calculated quickly and accurately. Although some progress has been made in developing expert systems for computer lens design and new optimization methods, a computer cannot independently design a useful system.[4,5]

Currently, most commercial lens-design programs use a damped least-squares method of minimizing a merit function, which is typically the sum of important aberrations and image defects. The computer's task is to find the system configuration with the minimum value of the merit function. An optical system of any complexity has many minima. A damped least-squares optimization will locate the nearest minimum, but there is no guarantee that it is best or even adequate. Without intelligent choices as to the number of elements, glasses, powers, and spacings, the computer is usually predisposed to design a poor optical system. Successful use of an optimization program depends on the optical designer not only generating a proper merit function, but beginning with a design near an acceptable minimum.

rors are less expensive and easier to manufacture and test than paraboloids, for example). For spherical mirrors, only the two mirror curvatures and the spacing between the mirrors are available to locate the focal plane, establish the focal length and image size, correct aberrations, flatten the image field, and adjust the obscuration ratio.

Figures 1 and 2 show two basic two-mirror systems; the spherical surfaces are optimized to application-specific requirements by using a commercial optical-design software package. This program uses a damped least-squares method of optimization on a user-defined merit function. The designer constructs the merit function from system requirements, optical design rules, and correction preferences. The *f*/5.0 system (Fig. 1) is a multipurpose small reflector specified for infrared wavelengths. The *f*/10.5 system (Fig. 2) was flown in a space-based ultraviolet imager.[1] Both systems have narrow fields of view (less than 3.0° full field) and modest, aberration-limited resolution (resolution across the full field was better than 400 μrad for the *f*/5.0 telescope and better than 100 μrad for the *f*/10.5 system). Measurements of focused spot size on the *f*/5.0 system and resolution chart tests on the *f*/10.5 system showed that, in both systems, the actual performance was accurately predicted by the computer code.

Three-mirror systems provide additional degrees of freedom for aberration correction; the degrees of freedom include three curvatures, three conic constants, and two spacings to correct eight conditions (typically, image location, focal length, spherical aberration, coma, astigmatism, field curvature, and two higher-order aberrations). Unfortunately, three-mirror systems have difficult layout problems, resulting in inaccessibility to the image plane, large obscurations, overly fast *f*-numbers, or largely asymmetric configurations. By using software to assist in scaling and layout, a three-mirror, wide-angle design (Fig. 3) was developed as an objective for an imaging spectrograph proposed for the satellite platform of the planned, polar-orbiting Earth-Observing System. The telescope is unobscured and uses two spherical surfaces and one elliptical surface. Spherical aberration and coma are fully corrected, although some residual astigmatism occurs as well as quite a bit of barrel distortion—about 10%. Fortunately, the distortion is manageable in this particular spectrograph system.

INFRARED DESIGNS

Optical design for infrared wavelengths is a challenge primarily because of the limited choice of transmitting materials. Widespread interest in infrared optical design

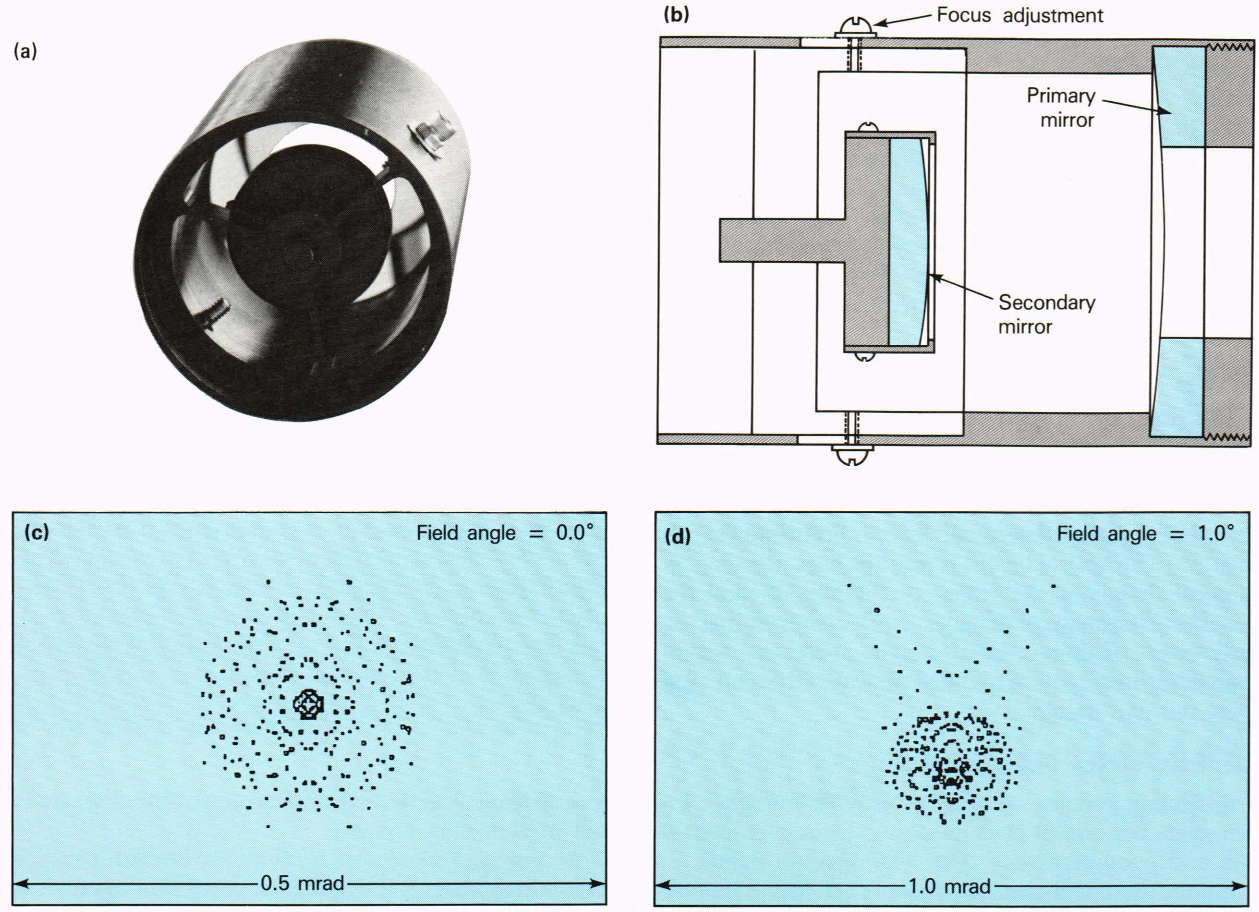

Figure 1—Photograph (a) and schematic diagram (b) of a multipurpose *f*/5.0 reflecting telescope specified for infrared wavelengths. The clear aperture is 50 mm, and the mirror surfaces are spherical. Spot diagrams (c and d) show predicted resolution over a ±1.0° field.

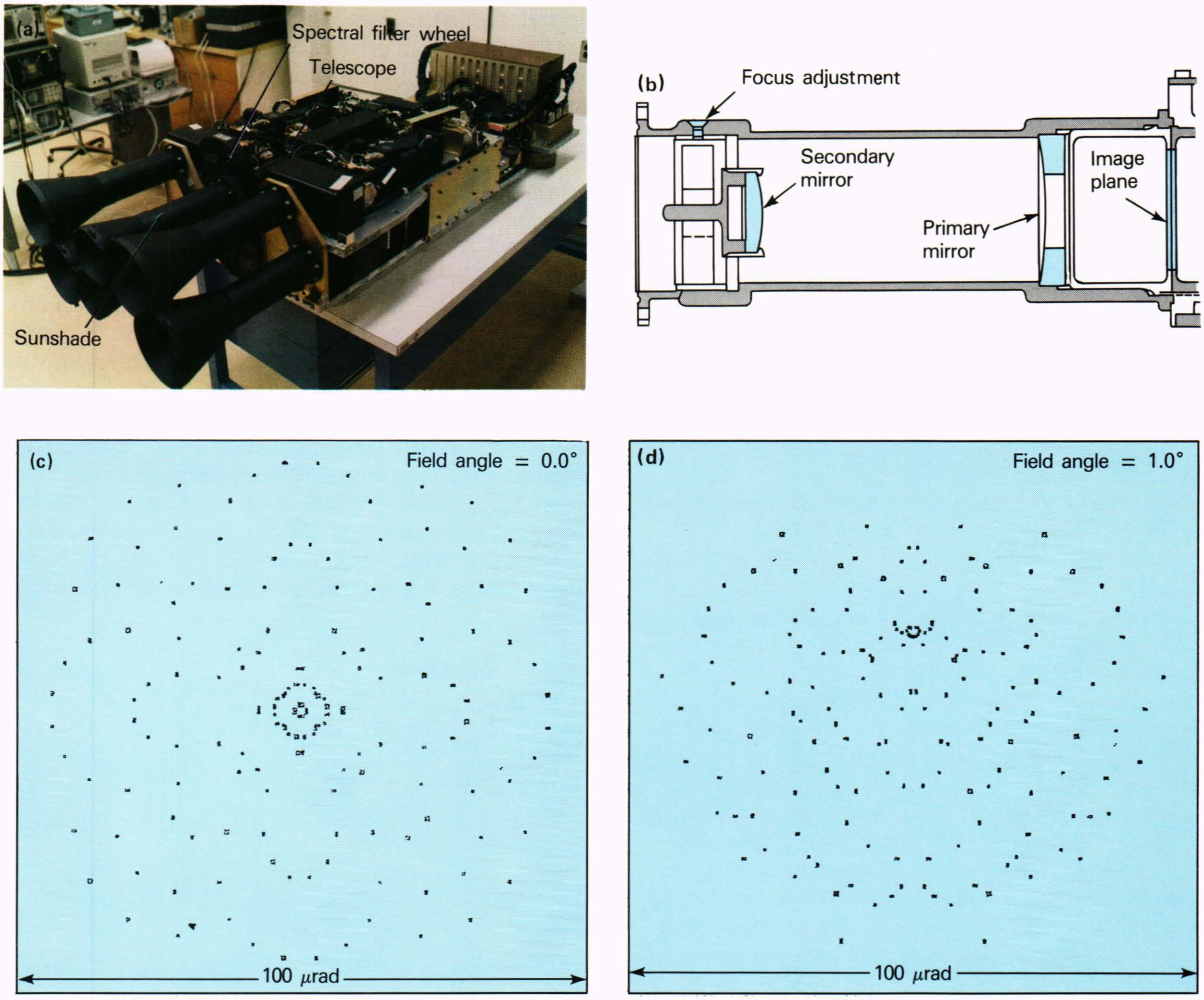

Figure 2—Photograph (a) and schematic diagram (b) of an *f*/10.5 reflecting telescope designed for an ultraviolet imaging system for a space application. The telescope is shown in the instrument assembly with associated intensifier, fiber-optic reducing bundle, detector, detector electronics, power supplies, and other instruments on the platform. The telescope entrance aperture is 46 mm, and the mirror surfaces are spherical. Spot diagrams (c and d) show predicted resolution over the full ±1.5° field.

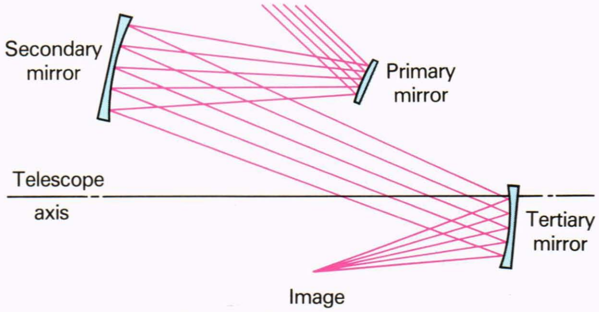

Figure 3—Three-mirror, unobscured, wide-angle telescope proposed as an objective for a space-based imaging spectrograph system. Two spherical mirrors and one ellipsoidal mirror are used. Resolution better than 0.37° is kept over a field of view of ±5.92° at a focal ratio of *f*/3.0.

has occurred because of the importance of infrared guidance in advanced missile systems. By using an optical design code, candidate optical designs for infrared seekers were evaluated for performance in a parametric study relating field of view, resolution, and sensitivity of the optical system to overall seeker performance.

Other infrared optical design projects include the layout and design of instrumentation for aerothermal testing of infrared domes and windows that have been proposed for advanced infrared-guided missile systems. In tests at APL's Propulsion Research Laboratory,[2] the windows are subjected to flow conditions (speed, temperature, and pressure) similar to those expected in high-speed flight. A small infrared optical system was developed to investigate aerothermal effects by focusing a laser transmitted through the flow field and window onto a linear detector array.

Another infrared design project involved an infrared target-source generator and projector. In this system, an actual infrared seeker can be tested against realistic targets and backgrounds. The target is generated with a thermal source that spatially and spectrally resembles an

GLOSSARY

Achromat: A lens corrected for chromatic aberration in which two wavelengths have been united at a common image point.

Anamorphic: A difference in magnification in perpendicular meridians. With focusing in only one plane, a cylindrical lens is an example of an anamorphic element.

Apochromat: A lens corrected for chromatic aberration in which three wavelengths have been united at a common image point.

Astigmatism: A geometric aberration in which the image of an off-axis point appears as a pair of focal lines, one radial to the field and one tangential to it; the lines are separated longitudinally along the optical axis.

Chromatic Aberration: The variation of an axial image-point location with wavelength.

Coma: A geometric aberration describing the variation of image height with particular zones of the aperture.

Dispersion: The variation of index of refraction with wavelength.

Distortion: A geometric aberration where the magnification varies across the field of view (the height of the image is not proportional to the height of the object).

Field Curvature: A geometric aberration where the image of a plane object perpendicular to the axis does not lie in a plane perpendicular to the axis (the image is formed on a curved surface).

***f*-Number**: A measure of the cone angle of rays exiting an optical system. For an object at infinity, the *f*-number is the focal length divided by the clear aperture diameter.

Lateral Color: An aberration related to chromatic aberration but that describes the variation with wavelength of the height of an image point. Also called transverse chromatic aberration.

Obscuration Ratio: The ratio of the area of the secondary-mirror obstruction to that of the primary mirror in a Cassegrain-type two-mirror reflecting telescope.

Spherical Aberration: A geometric aberration describing variation in position of an axial image with a particular zone of the aperture.

Spot Diagram: A plot of the image-plane intersection location of rays traced through an optical system. A spot diagram usually includes a large number of rays traced from a single object point through all areas of the aperture. The size of the spot diagram is directly related to the actual blur in the image of a point-source object (the blur can usually be measured directly).

actual target. The simulated target's image is transmitted along an optical path that is mounted on a large translation-stage assembly. The stage is computer controlled to move the target in two dimensions. The target is then folded into the main optical path where a realistic background is projected into the seeker being tested. The challenge of the optical design was to get a wide field of regard over which the seeker could search and track while maintaining high-resolution targets. The result is an optical path containing several very large infrared elements. Two 16.3-cm-diameter zinc sulfide lenses, an 11.4-cm germanium lens, a 12.7-cm germanium lens, and a 15.2-cm variable attenuator on a silicon substrate are among the optical elements needed.

SPECTROMETER DESIGNS

The ray-tracing code can model holographic and other dispersive elements used in spectrometer and spectrograph designs. In several recent space missions,[3] Ebert–Fastie designs based on a plane grating (Fig. 4a) were employed for spectrographs covering the vacuum-ultraviolet band to the near-infrared band. Figure 5 shows the Ebert–Fastie spectrograph flown recently as part of an APL space instrument. For better spectral resolution, better efficiency, and additional spatial information, concave-grating imaging spectrographs have been proposed for several new space applications. Until recently, concave gratings were used in the classical Rowland circle mounting (finite conjugate shown in Fig. 4b) or the Wadsworth mounting (infinite conjugate shown in Fig. 4c), and the grating rulings were construct-

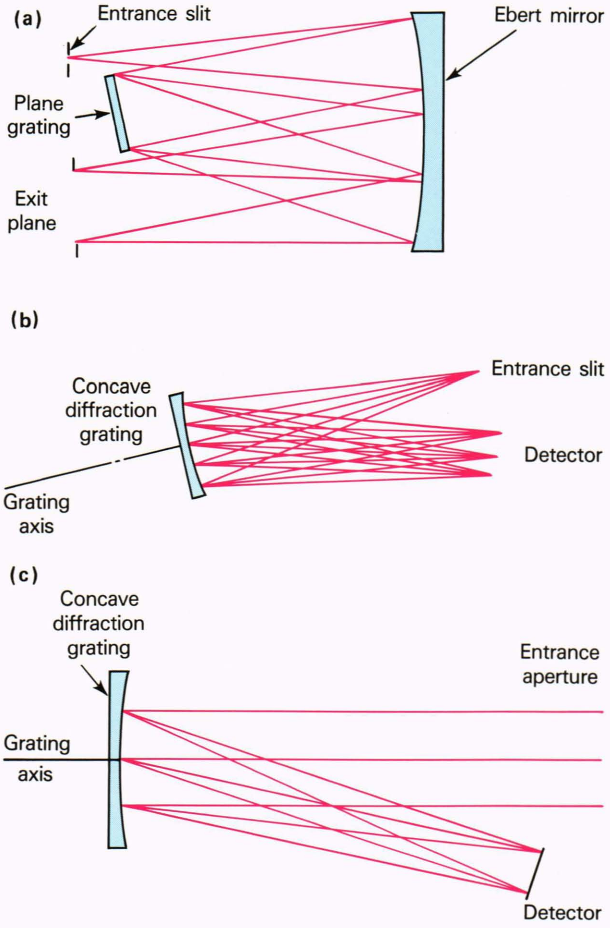

Figure 4—Spectrograph designs: (a) the Ebert–Fastie plane-grating spectrograph using a spherical collimating/refocusing mirror and a plane diffraction grating; (b) an *f*/3.0, aberration-corrected, Rowland-type spectrograph system using a single concave grating for spectral dispersion and spatial imaging; and (c) a concave grating used in a Wadsworth (infinite conjugate) mounting.

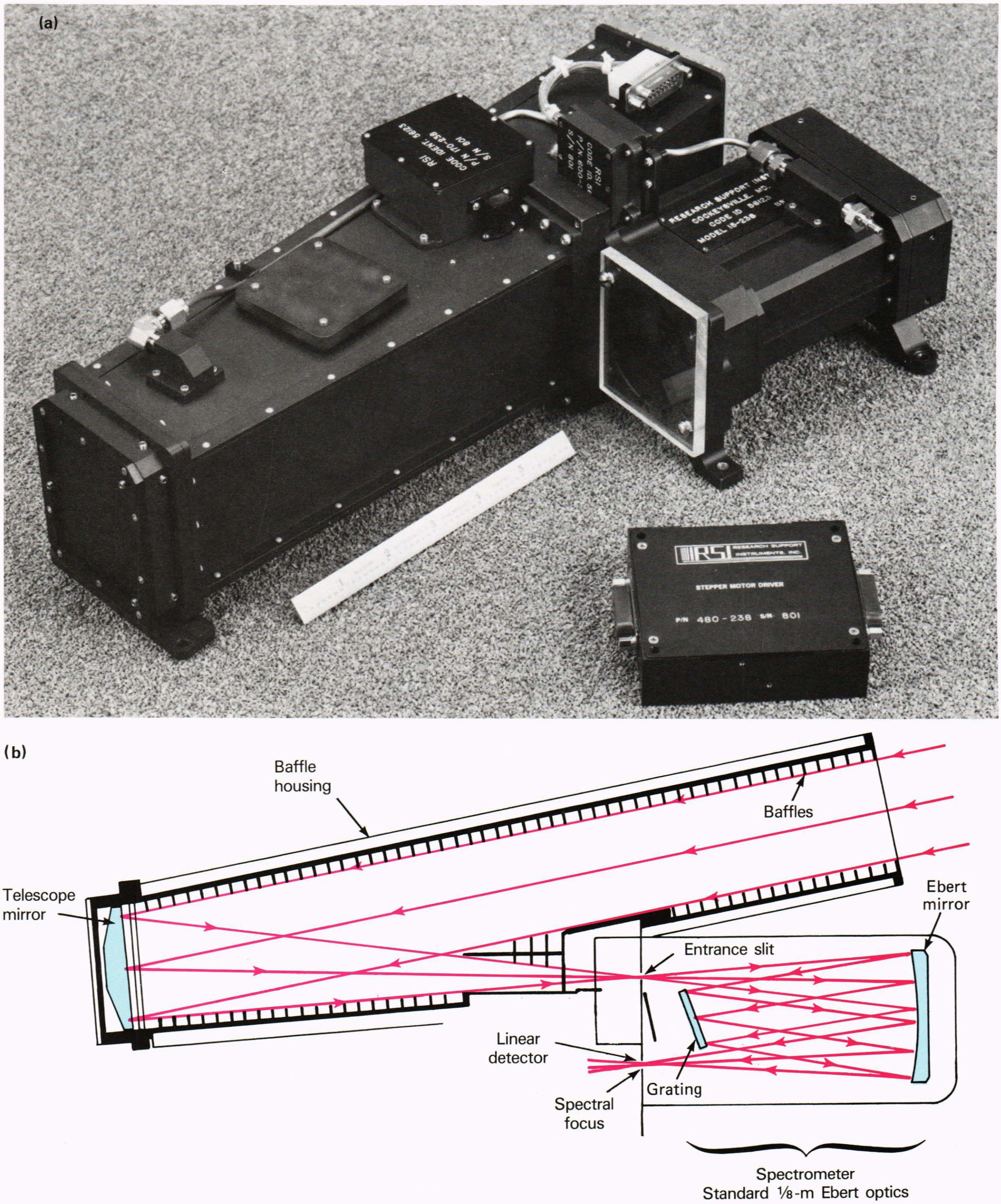

Figure 5—Photograph (a) and schematic diagram (b) of an Ebert-Fastie plane-grating spectrograph unit that was flown as part of a recent space experiment, with several units covering both visible and ultraviolet wavelengths. The spectrograph is shown in the mechanical assembly, which also houses a parabolic mirror objective.

ed to appear as straight rulings along a chord of the concave surface. These mounts, however, are limited by astigmatism and the associated curvature of the spectral focal field. By using holographic techniques, hyperbolic rulings can be generated on concave substrates that correct geometric aberrations over a wide portion of the spectral focal field. APL recently proposed an aberration-corrected, $f/3.0$, concave-grating spectrograph design for an instrument on the Earth-Observing System satellite.

SPECIFYING OPTICS

As with everything else, so it is with optics; you get what you pay for. Knowing what to pay for is the challenge of specifying optical elements.

An optical system is characterized very simply by describing the locations and shapes of its refracting or reflecting surfaces. One of the more difficult areas of optical engineering is determining the tolerances to be applied to the specification of the optical system. Loose tolerances can destroy the performance of an otherwise well-designed system, whereas overly tight tolerances can greatly increase costs and waste time (in custom fabrication).

A lens element is characterized by its diameter, radii of curvature of the surfaces, thickness of the element, and material. The material choice requires either acceptance or specification of wavelength region of interest, index of refraction, dispersion (Abbe V number for visible elements), partial dispersions, coefficient of thermal expansion, temperature coefficients of refraction and dispersion, thermal conductivity, strain characteristics, radiation hardness, homogeneity (index variations), striae, stress-optical coefficient, limits on bubbles and inclusions, and birefringence. A surface specification requires a tolerance on the radius of curvature as well as any asphericity, surface accuracy and regularity (measured in fractions of a wavelength), surface quality (scratches, pits, and digs), smoothness (measured in root-mean-squared surface roughness), and concentricity or wedge geometry specifications. Other specifications for the element include edge finish, chamfers, bevels, chip tolerances, and characteristics for any cement required. Further, element coatings require specification of spectral performance for transmission and/or reflection, angle of incidence, polarization characteristics, absorption/scatter characteristics, power-damage resistance, abrasion, adherence, and environmental requirements (temperature and humidity responses).

The application establishes the specification of the optical elements. High-resolution (near-diffraction-limited) imaging systems require special attention to surface accuracy and figure, as well as to tight dimensional tolerances. The article on the solar vector magnetograph by Rust et al. elsewhere in this issue describes one example where a loosely specified lens element destroyed otherwise very good image quality. A different application will likely require a different emphasis; for example, applications with stray-light problems need special attention to surface quality, finish, and regularity. Systems in difficult thermal environments require special attention to thermal characteristics. In the high-performance, special-purpose optical systems developed at APL, the application and system requirements must be fully understood so that the optical components can be specified sensibly.

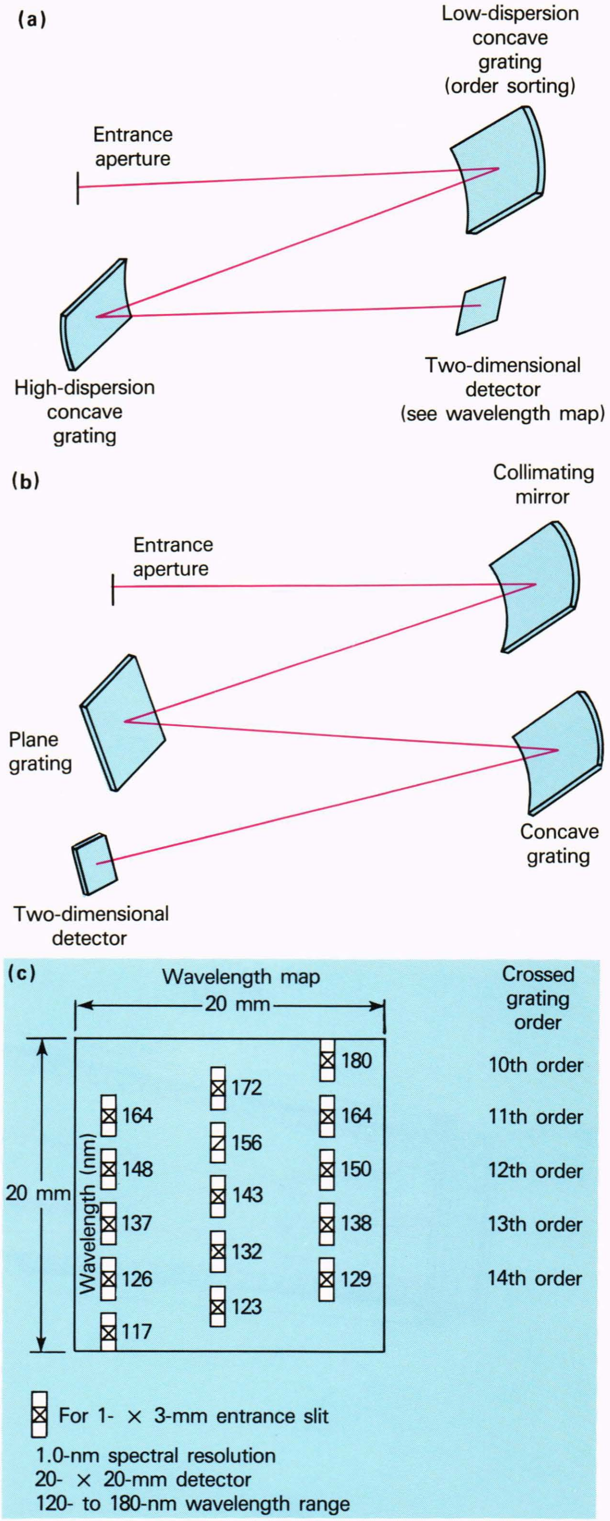

Figure 6—Two versions of a cross-dispersing spectrograph. The first (a) uses two concave gratings, and the other (b) uses a collimating mirror and a plane grating. A wavelength map for an ultraviolet spectrograph (c) shows that the first, lower dispersion grating acts to separate vertically the diffraction orders of the second, more strongly dispersive grating whose role is to spread the spectrum in each order horizontally.

A two-grating, cross-dispersing, spectrograph system was examined with the ray-tracing code for possible integration with a charge-coupled-device detector for very large spectral coverage. Two versions of the spectrograph are shown in Figs. 6a and 6b. One grating is used to disperse the wavelengths horizontally, and the other is used to disperse them vertically. With the proper choice of grating rulings, many diffraction orders of the second grating can be separated by the first grating so that a large spectral range is covered with high spectral resolution. A ray-tracing code was used to map the spectrum at the image plane for different grating combinations (Fig. 6c).

ACHROMAT DESIGNS

Longitudinal chromatic aberration and lateral color are controlled in a refractive optical system by the power, index of refraction, and relative dispersions of individual elements; two lens elements are needed to correct exactly the focus at two wavelengths (i.e., an achromat consists of a minimum of two elements).

Achromatic doublets are very useful in optical system layouts requiring high performance over a small field of view. The solar vector magnetograph, for example, uses cemented doublets for several beam expander and focusing elements within the system. Various achromats are supplied as stock items from several manufacturers. Because lens performance varies with design, companies now commonly provide design details for their lines of lenses, often on computer disks. Using several computer programs that convert manufacturers' design data to a convenient format, APL developed a database with the design information for entire achromat catalogs from several manufacturers. From the database, an achromat design can be downloaded into the optical design code for evaluation in a particular optical layout. This feature is extremely valuable in quickly assessing standard optics whose use can reduce costs and save time.

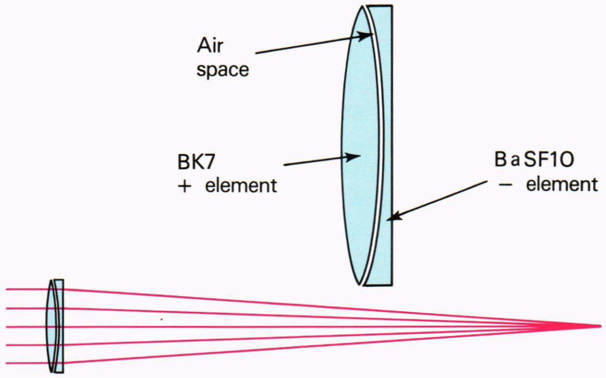

Figure 7—Custom air-spaced doublet for the final-focusing optic of the solar vector magnetograph. Designed for good correction in the red wavelength region, the two elements of the achromat are a positive crown element (BK7 glass) and a negative flint element (BaSF10 glass).

Specialized or demanding applications require custom achromat designs. A personal-computer-based optical design code was used recently to assist in a special air-spaced achromat design for a final imaging lens in the optical system of a ground-based solar vector magnetograph (Fig. 7) (see the article by Rust et al. elsewhere in this issue). The lens is highly corrected in the red wavelength region where the magnetograph will be examining spectral lines.

STRAY-LIGHT ANALYSIS

In an optical system, stray radiation is any unwanted source of power on the detector that blurs, reduces contrast, or reduces image quality. In many cases, stray light

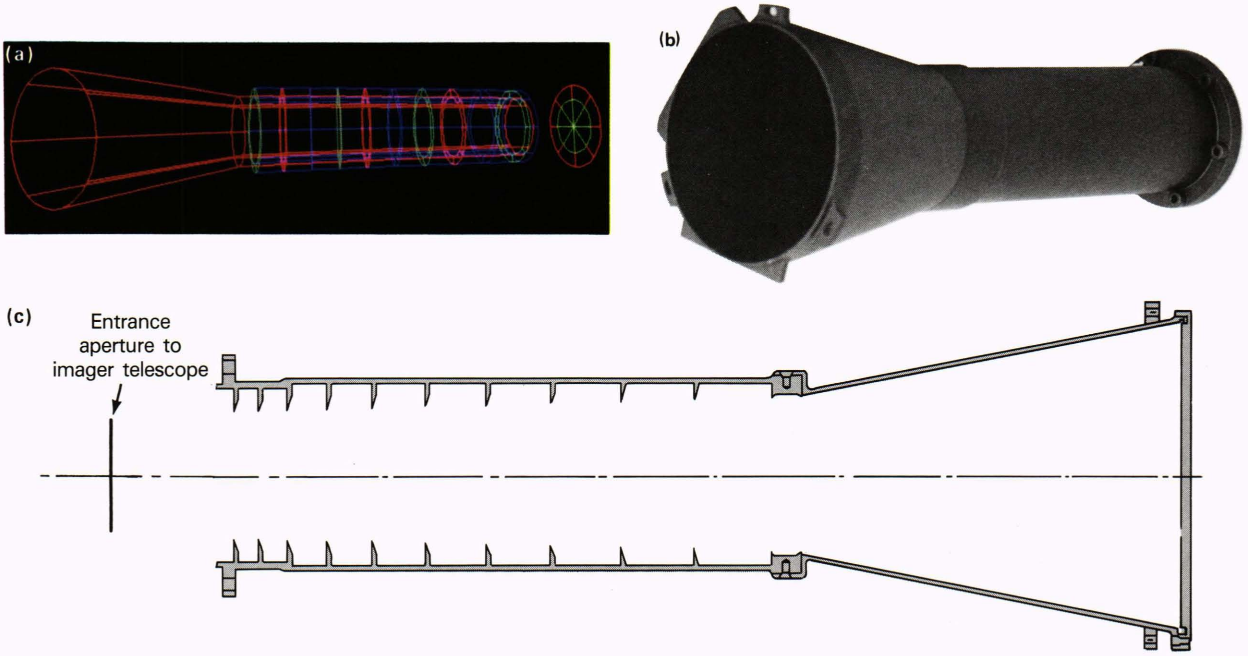

Figure 8—Two-stage sunshade assembly used with an ultraviolet imager system for a space application. The stray-light analysis code version (a), the actual flight version (b), and a schematic diagram (c) are shown. Stray-radiation sources more than 32.5° from the optical axis are attenuated an estimated nine orders of magnitude by the mechanical sunshade system.

from an intense, out-of-field source that is forward-scattered from mechanical and optical components of a system is the major source of noise. Especially in space applications, where dim objects must be imaged along a line of sight near that of bright celestial objects (Sun, Earth, and Moon, in particular), stray-light suppression is critical to instrument performance.

A large computer-based stray-radiation analysis code is used to evaluate complete optical and baffle systems for stray radiation. Being a deterministic code, it calculates the amount of out-of-field optical power that ultimately reaches the detector and affects the overall signal-to-noise ratio. The code predicts surface scattering from polished and diffuse optical surfaces by using the bidirectional reflectance distribution function; it also maintains a library of function models. The library includes bidirectional reflectance distribution functions for many black-absorbing surfaces, such as the Martin Black surface coating and common flat black paints used in baffles and shades.

Figure 8 shows a set of two-stage sunshades designed for an imaging system flown on a recent space mission.[1] The first (conical) stage shades the second (cylindrical) stage from any direct illumination from objects beyond 32.5° from the optical axis of the instrument. The cylindrical section is designed with interior baffle vanes located such that the input aperture of the optical system cannot be illuminated directly by anything but the tips of the vanes. All other paths to the input aperture require more than one scatter from the highly diffuse and highly absorbing black coating on the baffle walls. Using an analysis code to estimate the rejection, this two-stage system provides approximately nine orders of magnitude of rejection of a source of radiation greater than 32.5° off the optical axis. In this application, the mechanical baffle system is used with a reflecting-telescope optical system; the stray light reaching the detector is reduced twelve orders of magnitude over the source power entering the system. A similar baffle is necessary for the spectrograph systems aboard the platform, and Fig. 9 shows the sunshades attached to the four spectrographs and two imagers.

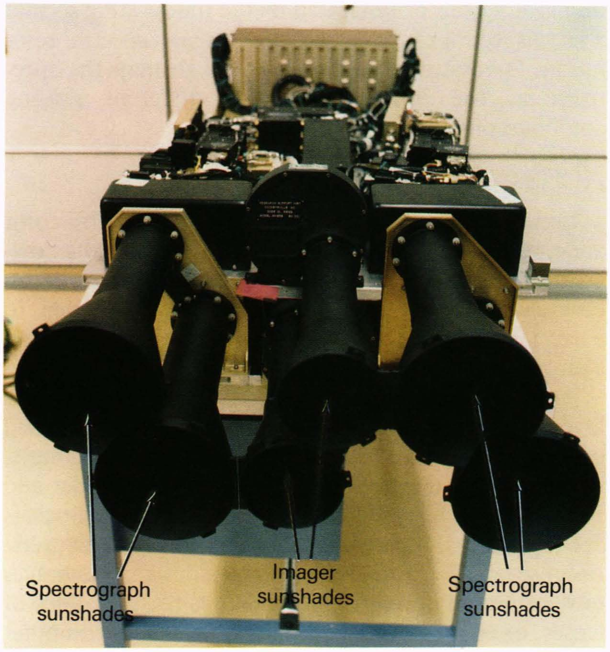

Figure 9—Sunshade assemblies shown attached to imaging and spectrograph systems flown on a recent space experiment.

CONCLUSION

Like mechanical or electronics designs, an optical system is developed by proposing a design, determining its properties, checking the properties with the requirements for the real system, and modifying the design for improvements. As higher performance optical systems are being specified, optical design experience and ability are becoming more valuable in system engineering at APL. Sophisticated software tools are now available to provide numerical support for these increasingly complex optical design and analysis tasks. These tools have been successfully applied to a variety of applications, and the resulting instruments have achieved predicted performance.

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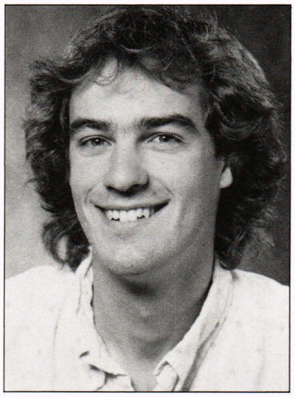
THE AUTHOR



TERRY J. HARRIS graduated in 1982 from the University of Colorado with a B.S. degree in engineering physics. He is a member of the Electro-Optical Systems Group, where where he specializes in geometric optics, lens and optical system design, and ray-trace analysis. He is a member of the Society of Photo-Optical Instrumentation Engineers. Mr. Harris has designed optical systems for ground and space instruments, as well as the optics for target projection systems and optical measurements in hypersonic flow.