Beyond spot diagrams: End-user oriented optical design

Pantazis Mouroulis*

Jet Propulsion Laboratory, California Institute of Technology

ABSTRACT

In this talk, two examples are given of the process of translating user requirements into optimization and assessment tools. In the first place, recent work on the effects of aberrations on the perceived image quality of visual instruments is reviewed. This allows the assessment of a visual system in terms of expected loss of contrast and resolution as a function of aberration, and also the formulation of an image quality metric suitable for automatic optimization. The second example concerns the extraction of accurate spectroscopic information from pushbroom imaging spectrometers. It is shown how the user requirements for calibration translate into spectral and spatial uniformity of response, and further to the complete absence of spectral and spatial distortion, as well as to the minimization of the variation of the LSF width in both directions, spatial and spectral. Techniques for accomplishing this in practice, both in terms of merit function and in terms of fabrication and assembly, are also discussed.

Keywords: Optical systems design, Image quality assessment, imaging spectroscopy

1. INTRODUCTION

There is, by now, a wealth of starting designs available in the literature to satisfy almost any conceivable requirement. With the addition of the powerful software that is now in wide use, optical designers have a formidable arsenal at their disposal. With the help of global optimization routines, one can now concoct solutions that would have needed a lot more knowledge and imagination in the past, or one can extract the last ounce of performance from a given design form. Yet, while it may seem that much of the creative aspect of optical design has been surrendered to the mind-numbing, number crunching machine, there is still an area of research that promises to be fruitful for a while to come. That area is the proper understanding of user requirements and their translation into optimization operands or design assessment tools. This ultimately means that the designer must understand more than just ray tracing, and be able to extend into other disciplines as needed. One often finds that end users do not have a complete understanding of their own requirements, and that an exchange with a knowledgeable designer can help both sides to specify the problem properly. Two examples of this process are provided below: visual instrumentation, and imaging spectrometry.

2. ASSESSMENT OF THE IMAGE QUALITY OF VISUAL INSTRUMENTATION

There is a dearth of psychophysical studies on the perceived image quality of visual instrumentation. The effects that have not been thoroughly investigated outnumber those that have. The situation is complicated by the difficulty of performing such experiments, with the result that a single psychophysical study of a particular effect is rarely adequate, and any two studies rarely come to the same conclusion. But at least one area, the examination of the effects of primary aberrations, has benefited from a number of relatively recent studies.[1] The results from these studies can be used in two ways: in raw form, as a means of assessing the net resolution or contrast loss for a given amount of aberration, or by seeking an image quality metric that can summarize them and that can be turned into a form suitable for automatic optimization.

Use of the raw data can be useful but it is limited because one cannot readily estimate the effect of arbitrary aberration combinations from data on individual aberrations. The image quality metric that emerged from

* 4800 Oak Grove Drive, Pasadena, CA 91109, USA. email: pantazis.mouroulis@jpl.nasa.gov

these studies is a limited integral of the MTF, extending from 5 to 20 c/deg in the eye space, which has been shown to correlate well with available data sets. This integral is best thought of as a volume, that is, over all azimuths, in which case it is denoted as MTFv. However, specific conditions of use or testing with one-dimensional targets, may permit simplification to only two dimensions, in which case it is designated as MTFa (area).

All image quality metrics are strongly focus-dependent, so the most critical question that needs to be answered is at what focal plane to perform the computation of the metric. The best metric is that which has a maximum or minimum at the same focal plane as the eye would choose through accommodation under the prevailing aberration conditions. In the case where the instrument aberrations are generally larger than those of the eye, the evidence points to the conclusion that for the purposes of optimization and testing and at pupil diameters <~ 3 mm, the eye can be simplified as a diffraction-limited focusing mechanism that chooses the focus by maximizing the MTFv (or MTFa). This also allows competing designs to be compared in terms of their effect on the MTFv.

At large pupil size, the eye's aberrations show considerable inter- and intra-observer variability, and thus cannot be taken into account in any systematic manner during optimization. Therefore, if an instrument possesses a large exit pupil but is also to be used at photopic light levels, it is still profitable to optimize for the smaller pupil sizes encountered in that case.

A recommended optimization method has been developed. According to the method, one first obtains a preliminary design using a rapid means of assessment based on geometric optics or spot diagrams, which is advantageous because MTF computations can slow down the optimization considerably. One then constructs the MTF-based merit function for final design optimization. In so doing, one can also set limits for the maximum allowed field curvature, chromatic aberrations and distortion, as follows.

- An F=17mm perfect lens can serve as the diffraction-limited eye, and allow all computations to be performed on a finite focal plane, instead of in angular space.
- Various field positions are separated as different configurations, thus allowing separate optimum focus for each without restricting the shape of the focal surface. Of course, in very wide field systems, one needs to check that an adequate number of field points have been selected.
- The preferred focus setting (typically ~-1D) must be set for the middle of the field, and the focus for other fields must not stray beyond ±1D.
- Transverse chromatic aberration can be controlled through the C and F chief ray intercepts (or spot centroids), by setting this difference to correspond to no more than 2.5 arc min for a well-corrected system, or 1.5 arc min for an essentially perfect system.
- Longitudinal chromatic aberration is controlled within the limits +0.7/-1D for a well-corrected system. The larger tolerance is in the direction of correcting the eye's own aberration.
- Distortion can be set to any tolerable value. Other specific requirements are added as needed.
- The MTFv can be approximated by the T and S MTF values at 5, 10, 15, and 20 c/deg, with the targets set to the corresponding diffraction-limited values.

It is noted that no benefit has been demonstrated by the use of the polychromatic MTF under the conditions described. Also, the use of a few frequencies to approximate the MTFv is strictly a convenience and does not imply that the actual MTFv value is well approximated. Rather, the design resulting from optimizing the individual MTF values will likely be substantially the same as the one resulting from optimizing the MTFv.

Application of this procedure demonstrated substantial improvement in image quality beyond the optimum spot diagram solution, using the above MTF-based merit function. In other cases it was possible to obtain an improved solution by simply switching to a wavefront-based merit function. However, the importance of the present procedure is not so much that it will produce designs that cannot be found with other optimization methods, but rather that it provides an assurance that the best possible design has been obtained, based on solid psychophysical experiments about expected observer resolution and contrast sensitivity performance.

Tolerancing can also be performed through the same methods. It has been shown that a 7% drop in MTFv corresponds to the just noticeable difference in image quality[1]. Therefore, the designer may use a tolerancing criterion that has a firm basis in psychophysical experiments. It is noted that the 7% drop applies to well-corrected systems, or typically, the on-axis image quality. If there is substantial aberration, or at off-axis points, the same criterion can be justified on the basis of simplicity. Chromatic aberration tolerances must be established separately by using the graphs showing the expected drop in performance as a function of chromatic aberration (shown in ref. 1).

It should be clear that the requirements for visual instrumentation are not exhausted by the above considerations. Indeed in many cases, small amounts of aberration are entirely secondary to other effects such as binocular disparity, or display resolution for electro-optical display systems. It is up to the designer to understand these effects and provide a design tailored to the circumstances.

3. SPECTROSCOPIC DATA FIDELITY OF PUSHBROOM IMAGING SPECTROMETERS

Pushbroom imaging spectrometers, in which the image of a slit is dispersed and imaged on an area array, suffer from potential artifacts relating to the lack of perfect registration between aerial image and detector, as well as the variation of the PSF characteristics in the spatial and spectral directions. The impact of those effects on sensor data fidelity has only recently been fully appreciated.[2,3]

This is a classic case where the instinct of the designer as well as the tendency of automatic optimization routines to reduce spot size need to be tempered by an understanding of the application requirements. Accurate spectral information is normally more crucial than high spatial resolution. This is because the existence of a target can be inferred from its spectral signature, even if it is not spatially resolved. Thus it may be advantageous to increase the amount of aberration in the system, if doing so will result in other desirable characteristics.

As a result of these considerations, two more requirements were added, beyond the original user requirement for lack of distortion that enables proper spectrum registration. Those were the constancy of the spectral response function with field, and the constancy of the spatial response function with wavelength. The spectral response function is defined as the convolution of the spectral LSF with the slit, the grating, and the detector response functions. The spatial response function is the convolution of the complete system spatial LSF with the detector response function. Assuming an ideal detector, that is, one with constant pixel response characteristics, those additional requirements translate into constancy of the LSF along the spectral and spatial directions. Since diffraction spread can be very different from one end of the spectrum to the other (typically a factor of 2.5), this means that the short wavelength LSF must be degraded by some amount to match that of the longer wavelength.

To accomplish these ends, an MTF-based optimization procedure was developed that relies on equalizing the MTF through field or wavelength as needed at the Nyquist and twice Nyquist spatial frequencies, in addition to controlling distortion at the submicron level through the chief ray or centroid coordinates. The process was tested at first on spectrometer systems that could not be characterized as very demanding in terms of the field and dispersion characteristics – it was only the response uniformity requirements that made them extraordinary. Such systems tend to have a slit height of ~15 mm and a spectral sampling of ~10 nm. The merit function performed very well, producing systems with almost zero undesired variation. A more demanding case was a slit of 54 mm, and a stated user requirement of no more than 10% total spectral nonuniformity. Despite the tremendous size of the slit, the optimization method was still able to produce the desired result by adjusting only the weighting factors. Figure 1 shows the spectral response function variation for the first-pass design in which only distortion and spot size were corrected, and the same case with the full merit function.

It is instructive to see the spot diagrams for the two solutions in order to appreciate why image quality measures, whether ray- or wavefront-based, are not adequate for this case. Figure 2 shows the spot diagrams corresponding to the first-pass solution.

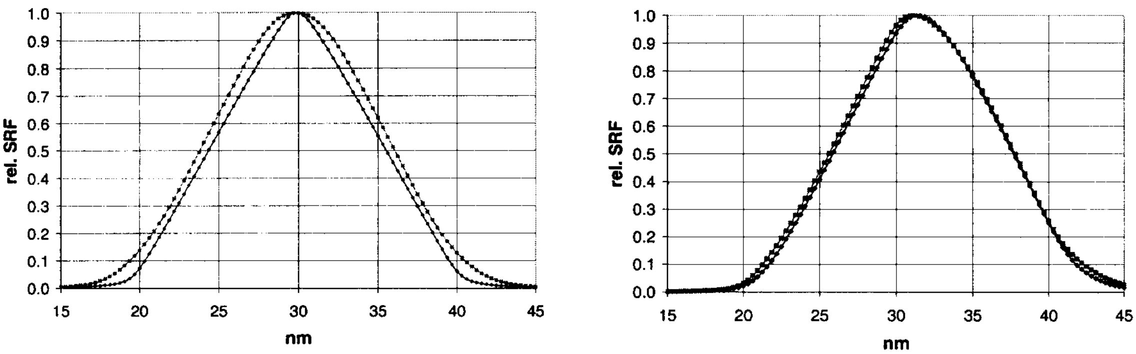

Figure 1: Maximum variation in the spectral response function of an imaging spectrometer system with a 54 mm slit, optimized for lack of distortion and optimum wavefront (left), or for spectral and spatial response uniformity (right). The slight asymmetry in the response to the right is due to the deliberate introduction of coma in the design. The increased uniformity comes at a small cost in MTF or ensquared energy: 91% instead of 95%.

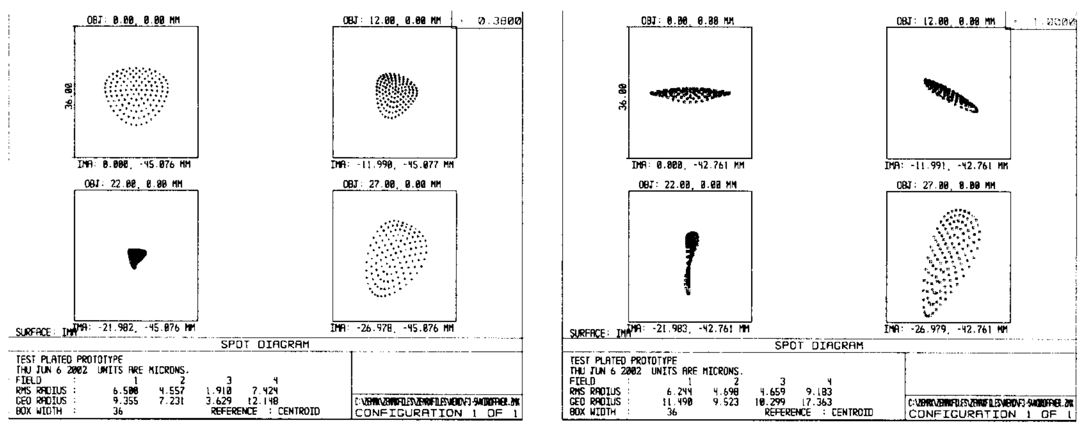

Figure 2: Spot diagrams for a spectrometer optimized for lack of distortion and optimum wavefront. Left: 380 nm wavelength, right: 1000 nm. The box size is equal to the detector pixel. The middle of the slit is on top left. The other three diagrams correspond to increasing field values. The bottom half of the slit is symmetric with the top, so it is not presented.

The spot diagrams for the system optimized for response uniformity are shown in Fig. 3. A comparison of figures 2 and 3 reveals that the optimization method allowed a reduction in image quality to achieve higher uniformity. However, the resulting image quality is still perfectly acceptable, since the spots are well contained within the pixel. In these two figures, the spectral direction is up. It can be seen that the various PSFs have very similar heights, leading to spectral uniformity. Similarly, comparison of the corresponding field points for the two wavelengths shows that the spots are almost invariant with wavelength, leading to high spatial uniformity. Of course, a quantitative comparison would need to consider the diffraction-based PSF or LSF, which is what is used to produce the curves of Fig. 1.

Further work was performed in order to realize these high uniformity values in practice. This resulted in the development of alignment and tolerancing methods that inform and constrain the design process.[4] Thus, for example, if the same spatial information is shared spectrally by two different spectrometer modules, then fabrication and alignment techniques need to be developed that would allow the two modules to have the same magnification within a small fraction of pixel size. Concentric spectrometer forms[5] are advantageous in this respect because of their inherent lack of distortion as well as utilization of all spherical surfaces that can be manufactured to high accuracy.

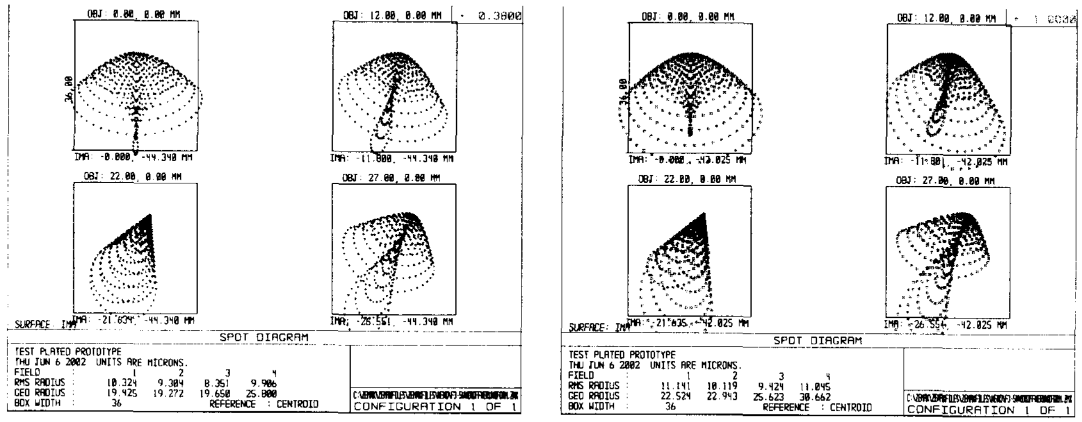

Figure 3: Spot diagrams for a system optimized for uniformity of response. Field and wavelength values are the same as those of figure 2.

4. ACKNOWLEDGMENTS

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5. REFERENCES

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