Constrained Optimization with User-Specified Functions

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Introduction

Optical thin film optimization is typically based on a merit function calculated from a target list. The list includes wavelengths and corresponding transmittance, reflectance, and/or phase values. In the wider field of optimization[1] we are introduced to the idea of an *objective* subject to *constraints*.

While the target editor is well-suited to inputting spectral shapes, a more general approach is required when such shapes are unknown[2]. This enables designers to model performance without specifying an expected spectrum. A familiar example is the design of color filters.

Spreadsheet Programming Model

Designers can achieve ultimate flexibility by defining their own objectives and constraints. This is not the same as filling in one or more dialog boxes; users must be given access to a programming environment.

This flexibility can be achieved in several ways: source-code modification, dynamic-linked libraries, etc. Eliminating the need for compilers and any additional software, we have implemented a programmable spreadsheet within the FilmStar design program. Special defined names provide links to calculation and optimization engines. The spreadsheet includes familiar Excel-compatible syntax. Spectra are automatically transferred to the spreadsheet where users have access to formulas such as *AVERAGE*, *MIN*, *MAX*, *STDEV*, etc. Special defined names include *Constraint*, *DataType*, *Design*, *Macro*, *Objective*.

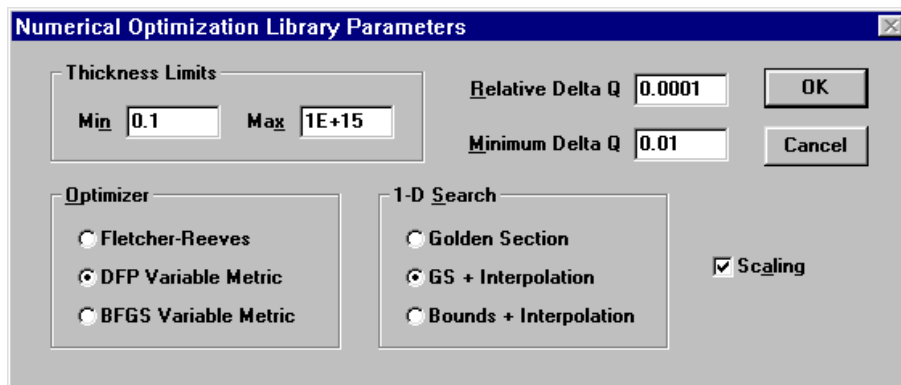## Numerical Optimization Library

Figure 1. Optimization library parameters

The Numerical Optimization Library (NOL) is a proprietary Fortran code containing a variety of algorithms for solving nonlinear optimization problems. Within FilmStar it is accessed as a Windows DLL (dynamic linked library). The library includes a number of gradient methods accessed via the following dialog box. The problems which can be considered are varied. We offer two examples:

Example 1 - AR Coating with Thickness Constraints

Converting four layer AR starting design .1H .1L .5H .25L to nanometers, we have 23.91H 37.67L 119.57H 94.18L (total thickness 275.33 nm). An AR coating is designed with the following constraints: the thickness of the first two layers is equal and the thickness of the last two layers is equal. Total thickness cannot exceed 225 nm. The objective is average reflectance. Running the optimization we obtain 19.57H 19.57L 92.68H 92.69L (total thickness 224.51 nm).
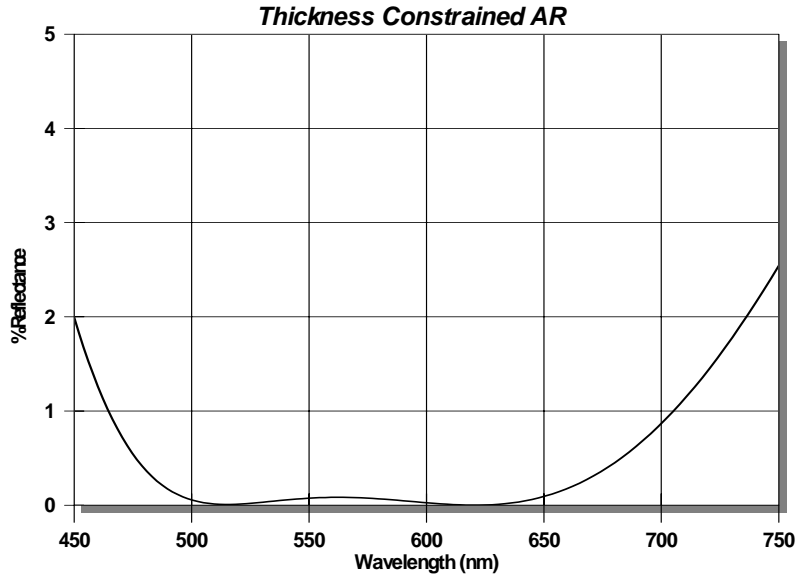

Figure 2 – Four layer AR with multiple thickness constraints

Example 2 – Color Correcting Mirror with Reflectance Constraint

Our next example is a tilted color correcting mirror with reflectance constraint at one wavelength. The starting design is a 14 layer stack. The requirements are CIE coordinates x = .35, y = .35 for Illuminant A and $R_{632.8}$ = 20%. The initial design gives x = .4375, y = .4411 and $R_{632.8}$ = 72.5%.

Figure 3. Setup for optimizing constrained color reflector

We treat CIE x, y and $R_{632.8}$ as equality (strict) constraints. We maximize photopic response Y with objective function 1-Y (cell D10). During each iteration CIE values are pasted into cells D7, D8 and D12 while $R_{632.8}$ is pasted into cell B4.

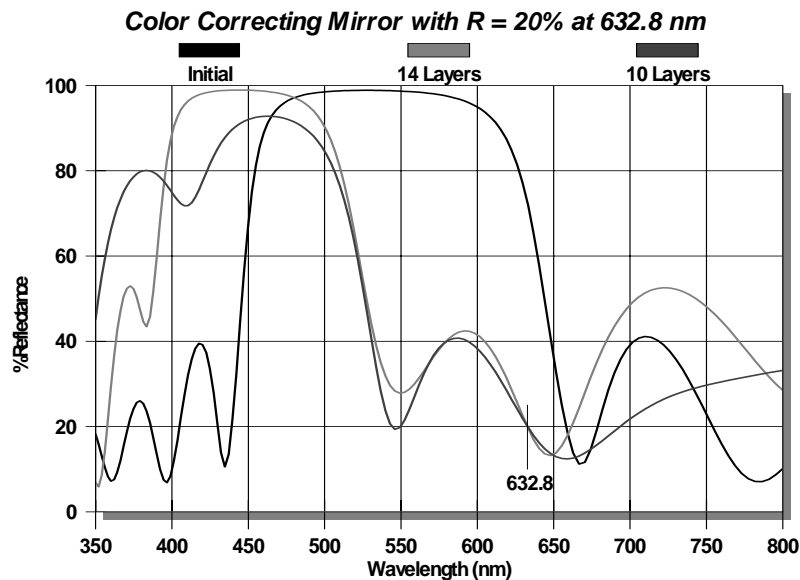**Color Correcting Mirror with R = 20% at 632.8 nm**

Figure 4. Initial and optimized constrained color reflectors

Optimization produces 14 layer design .21779H .57731L .25793H .22665L .22502H .21382L .20031H .21852L .22327H .23615L .18329H .16732L .13829H .51206L, L 1.46, H 2.3, Sub 1.52, 30 deg R pol, 1 QWOT = .25 at 550 nm. Here x = .3501, y = .3501, $R_{632.8}$ = 19.92%, Y = 39.8%. An alternative 10 layer design is .21921H .7309L .24798H .2396L .20742H .17061L .1421H .2357L .20583H .47009L gives x = .3500, y = .3500, $R_{632.8}$ = 20.05%, Y = 36.6%.

Photopic response Y can be improved by using inequality constraints to more loosely specifiy the required values of x, y, $R_{632.8}$.

Discussion

We have demonstrated a simple user-programmable interface for setting up complex problems in off-the-shelf optical thin film software. While the idea of a merit function with functional constraints is unfamiliar in optical films, it appears to be a potentially powerful approach.

Our spreadsheet model provides an alternative function-based program interface for optical thin film design software. For that reason we have duplicated many of the menu commands (opening files, editing designs, etc.) available when the main FilmStar graphics screen is displayed.

Thin film manufacturers often serve their customers better if designers can ask "What does the coating do?" rather than "What does the curve look like?"

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[1] C. A. Floudas and P. M. Pardalos, *Recent Advances in Global Optimization*, Princeton University Press, 1992.

[2] J. A. Dobrowolski, F. C. Ho, A. Belkind, and V. A. Koss, Appl. Opt. **28**, 2824-2831 (1989).