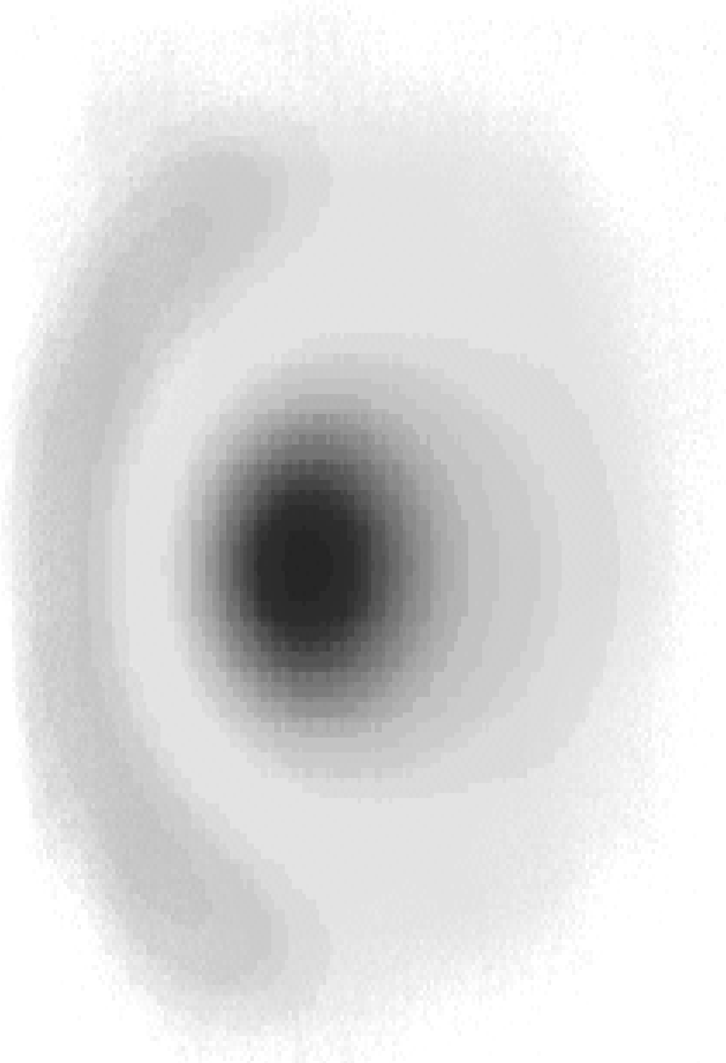
Chapter 1



Introduction

1.1 Overview

The Optical Readout Channel Analysis Model (Optical Readout Model) has been written primarily as a tool for modeling the readout mechanism in a variety of optical storage systems. The basis of this analysis extends from modeling theory developed to simulate the readout signal in scanning laser microscopes. This approach has been extended to model the readout signal from the magneto-optic scanning laser microscope and to simulate the signals produced in optical storage systems. The modeling theory will be presented briefly in §1.2.

The optical readout model software uses the MATLAB™ graphical user interface (GUI) environment and a collection of simulation routines written specifically for MATLAB™. These features allow the user to easily investigate the operation of the optical readout channel and produce theoretical readout waveforms.

The features of the optical readout model include the following:

- Signal generation for an arbitrary resolution

- Arbitrary illumination
    - Uniform
    - Gaussian
    - Arbitrary polarisation angle

- Focused spot simulation for any arbitrary aperture pupil

- Signal generation for both reflectance and magneto-optic objects using
    - Scalar diffraction or
    - Pseudo-vector diffraction

- Generation of arbitrary 2-D objects
    - reflectance (e.g. DVD-RAM), phase (e.g. CD-ROM and DVD-ROM), and magneto-optic objects
    - land/groove
    - arbitrary track width, reflectance and/or Kerr rotation
    - arbitrary bit width, length, shape, reflectance and/or Kerr rotation
    - arbitrary data patterns (used defined)
    - simulation of up to three tracks of data (scan made along the central track)

- Generation of readout waveforms
    - Multiple signal calculations
    - Arbitrary quadrant photodetector configurations (2 in total)
    - Track scanning
    - Across track scanning
    - Introduction of a constant tracking error

- Generation of the optical transfer function
    - 2-D
    - 1-D

- Channel optimisation investigations using the optical transfer function

- Full compatibility with the recording and channel simulation models

- Investigation of the effects of aberrations
    - Astigmatism
    - Defocus
    - Coma
    - Spherical
    - Tilt

- Investigation of apodization techniques
    - Horizontal shading bands, objective and collector pupils
    - Vertical shading bands, objective and collector pupils
    - Annular shading band, objective and collector pupils

- Signal generation for near-field imaging using a Solid Immersion lens
    - Hemispherical SILs
    - Superspheres (Stigmatic SILs)
    - Single phase approximation (using Seidel aberrations)
    - Fresnel transmission

- Propagating field analysis (using movies)
    - Field distribution at object, x and y polarised
    - Field distribution at the detectors, x and y polarised

This user guide has been produced to provide all the relevant information necessary to understand the operation and applications of the optical readout model, and is organized as follows:

Chapter 1 provides a brief introduction to the optical readout model, it's operating theory and installation.

Chapter 2 provides an overview of the operations accessed through the program interface File menu.

Chapter 3 provides an overview of the operations accessed through the program interface Preferences menu.

Chapter 4 provides an overview of the operations accessed through the program interface Pupil Settings menu.

Chapter 5 provides an overview of the operations accessed through the program interface Object Specification menu.

Chapter 6 provides an overview of the operations accessed through the program interface Analysis menu.

1.2 Modeling Theory

The signal from an optical readout channel is calculated using a theoretical approach that has its origins in scanning optical microscopy[1,2]. Using this approach the field distribution at the focal point of a lens, the Fraunhofer or far-field diffraction pattern, is calculated using scalar diffraction theory[3]. Simply stated, the field distribution at the focal point of a lens, $y(x,y)$, is calculated by taking the Fourier transform of the field distribution, $y(s_x, s_y)$, at the exit pupil of the lens[3],

$$y(x,y) = FT\{y(s_x, s_y)\}. \qquad \text{Eqn. (1.2.1)}$$

In the optical storage channel the focused field distribution interacts with the disc and then propagates back to the objective lens by the diffraction process, where it is collimated and continues to propagate to the detection arm of the channel. In the case of the reflectance type arrangement, the reflectance properties of the disc modify the focused field distribution and the resulting change in reflectance is measured as a change of field intensity at a single photodetector. In the case of the magneto-optic arrangement, the plane of polarization of the focused field distribution is rotated by the polar Kerr properties of the disc and is measured using a differential detection strategy using two photodetectors.

Two modeling approaches are used successively to predict the readout signal in both reflectance and magneto-optic optical readout channels; these are referred to as the ‘transfer function’ and ‘direct calculation’ approaches. In the direct calculation approach the form of the optical field through the readout channel is calculated as the disc is scanned beneath the focused spot. In the transfer function approach the signal from the readout channel is expressed in such a form where the spatial frequency properties of the optical channel are distinct from those of the sample, thus enabling the quantitative comparison of the imaging performance of various imaging configurations.

The maximum attainable storage density of the optical channel is governed by the cut-off spatial frequency of the optical channel, given by $l/(2\times\mathrm{NA})$, where l is the wavelength of the incident illumination and NA is the numerical aperture of the lens. To increase the data storage density of the optical channel it is necessary to increase its spatial cut-off frequency, which requires either increasing the NA of the lens or reducing the wavelength of the source. The minimum wavelength of solid state lasers is currently limited by the technology available; hence, modern optical storage systems employ an objective lens with high NA.

A major disadvantage of the scalar diffraction approach is that it does not allow the affects of diffraction on polarization to be determined. The lens introduces a curvature phase factor across the incident plane wave such that it is brought to focus at the focal point of the lens. However, across the aperture of the lens the rays are bent towards the focal point by an amount depending upon the numerical aperture (NA) of the lens and their position of incidence relative to the radius of the lens. The marginal rays, which are incident around the circumference of the lens, are bent most severely by an angle given by *asin*(NA); this bending being reduced for rays incident closer to the center of the lens. The result of this bending of the rays is that the incident field distribution will no longer maintain its polarization state upon propagation through the lens. This is of little consequence in low NA applications where the angle of rotation is small. However, in large NA systems this problem needs to be addressed if the polarization state of the focused field is to be accurately determined and the imaging of smaller objects is to more accurately predicted.

The scalar diffraction model has been improved by introducing a pseudo-vector diffraction model to take into account the severe bending of the rays upon propagation through a high NA lens. If a linearly polarized plane wave, which has components of polarization, y_x and y_y, in the x and y planes respectively, is bent along a vector s = (s_x, s_y, s_z) upon propagation through a lens, then it can be shown that the resulting field distribution at the focal point of the lens is given by [4,5],

$$\begin{bmatrix} y_x(x,y) \\ y_y(x,y) \\ y_z(x,y) \end{bmatrix} = FT\left\{ \frac{1}{\sqrt{s_z}} \begin{bmatrix} 1-\frac{s_x^2}{1+s_z} & \frac{-s_x s_y}{1+s_z} \\ \frac{-s_x s_y}{1+s_z} & 1-\frac{s_y^2}{1+s_z} \\ -s_x & -s_y \end{bmatrix} \begin{bmatrix} y_x(s_x, s_y) \\ y_y(s_x, s_y) \end{bmatrix} \right\} \qquad \text{Eqn. (1.2.2)}$$

which has components of polarization, y_x, y_y *and* y_z, in the *x*, *y* and *z* planes respectively.

This is the approach used to accurately predict the form of the propagating optical wavefront in the Optical Readout Model.

[1] *Theory and practice of scanning optical microscopy*, T. Wilson and C. Sheppard, Academic Press Inc.

[2] “A theoretical model of magneto optic scanning laser microscope”, C. D. Wright, P. W. Nutter and P. W. M. Filbrandt, IEE Trans. Mag., Vol. 32, No. 4, pp. 3154-3164, 1996.

[3] *Introduction to Fourier Optics*, J. W. Goodman, McGraw-Hill Inc.

[4] “Distribution of light at and near the focus of high-numerical-aperture objectives”, M. Mansuripur, J. Opt. Soc. Am. A., Vol. 3, No. 12, pp. 2086-2093, 1986.

[5] “High density optical recording using a solid immersion lens”, Isao Ichimura, Shinichi Hayashi. and G. S. Kino, Applied Optics, Vol. 36, No. 19, pp.4339-4348, 1997.

1.3 *Installation*

The Optical Readout Model has been written specifically for operation under the MATLAB™ technical computing environment, ver. 5.2 and above. Hence, the model may be executed in any operating system that supports MATLAB. However, the software has only been rigorously tested when running under Microsoft Windows95, 98 and NT4.

The minimum specification when running on a PC is as set out for MATLAB Ver. 5.2. However, for more demanding applications an Intel PII 400MHz or better with 256MB of RAM and 100MB of free disc space is recommended.

The zip file containing the source files for the Optical Readout Model need to be extracted to a directory on your hard disc. Create a suitable directory and extract the files to this directory.

Start the MATLAB environment.

At the MATLAB prompt change to the directory where the optical readout model source files are located (note: you do not have to enter this directory into the MATLAB path); however, do not change the MATLAB operating directory whilst the optical readout model is running.
To start the optical readout model type "startup" at the MATLAB command prompt, as illustrated in Figure 1.3.1.

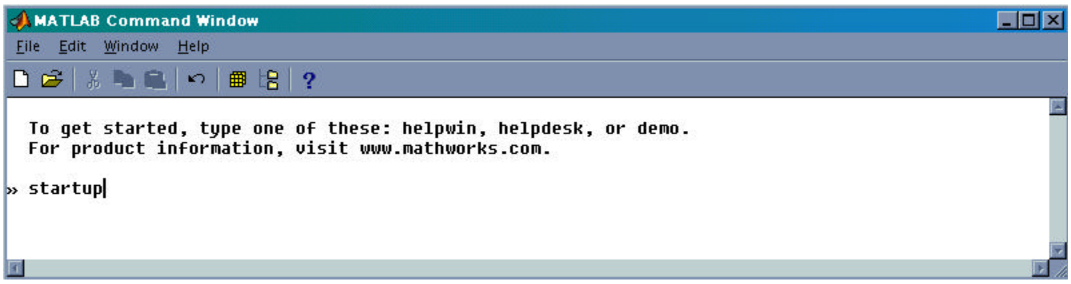


Figure 1.3.1: Starting the optical readout model

When the program is being executed for the first time, you will be required to enter the location of a temporary directory where temporary files created during the simulation process can be stored, as illustrated in Fig. 1.3.2.

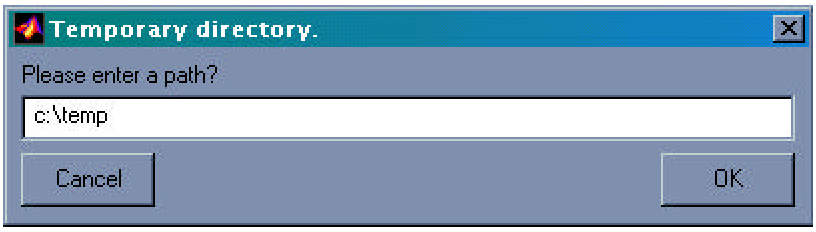


Figure 1.3.2: Enter the location of the temporary directory.

The temporary files have the format ~orm_*.mat, and must not be deleted whilst the optical readout model is running. However, on exiting the model the temporary files will be automatically deleted.

The program will continue to request a temporary directory location until a valid directory is entered, the program will then generate the initialization file "default_startups.mat" and continue to execute the program. If "Cancel" is selected then the program will fail to start.

Note: Each time the program is executed the location of the temporary directory is checked, if it no longer exists then the program will prompt you for a new location and re-generate the default_startups.mat file.

On starting the program the splash screen illustrated in Fig. 1.3.3 will be displayed for a few seconds. The main program interface will then appear at the top of the screen, as illustrated in Fig. 1.3.4.

From the program interface all program actions are controlled.

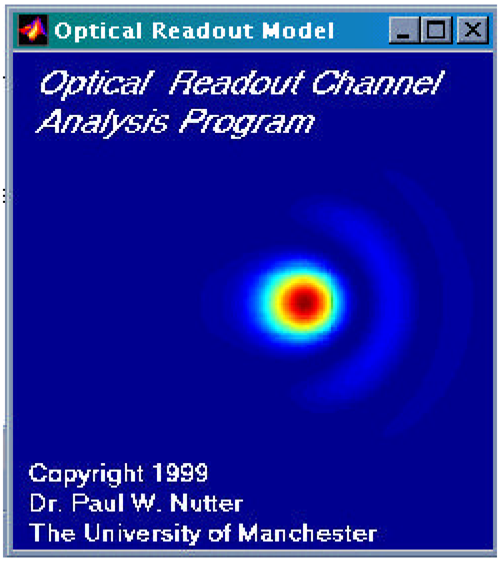


Figure 1.3.3:Initial splash screen

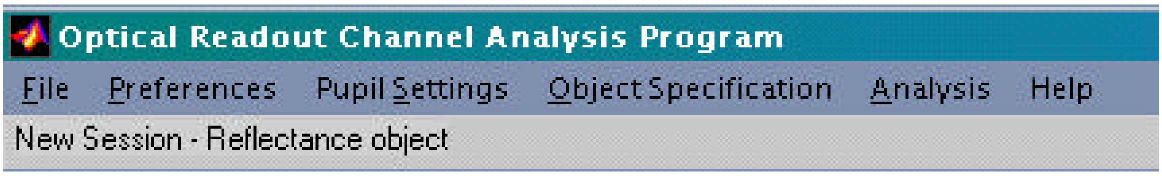


Figure 1.3.4: Optical Readout Model program interface.

1.4 Operation

The following section will present a brief summary of the simulation process used in the optical readout model for generting the readout signal from an optical storage system.

1.4.1 Generating the Focused Spot

The focused spot profiles are calculated by taking the 2-D FFT of the field distribution at the exit pupil of the objective lens. The process is illustrated diagramitically in Fig. 1.4.1.

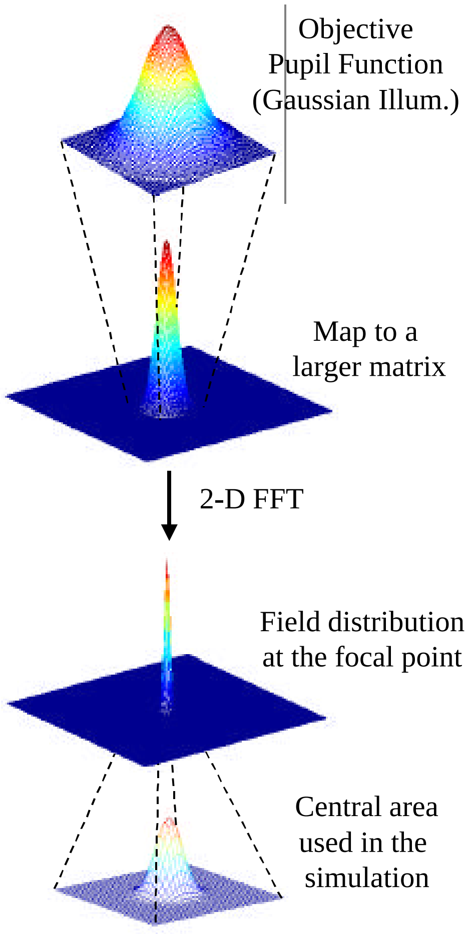


Figure 1.4.1: The focused spot calculation process

1.4.2 Generating the Readout Signal

The readout signal is calculated by scanning the focused spot along the object to be imaged. At each scan position the field distribution after interaction with the object is calculated. The field distribution is then mapped onto a larger matrix, and the 2D FFT is taken to produce the collimated field distribution in the plane of the collector lens. The field distribution incident on the detector is then formed by modifying the field distribution by the collector aperture pupil function. The signal is calculated as the squared modulus of the field distribution incident on the detector. This procedure is illustrated diagramatically in Fig. 1.4.2.

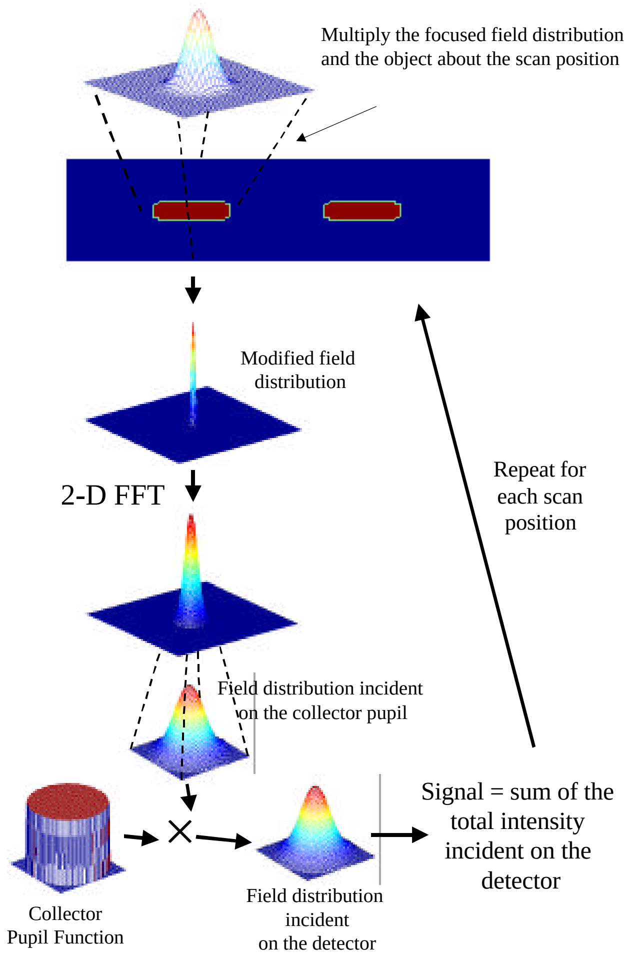
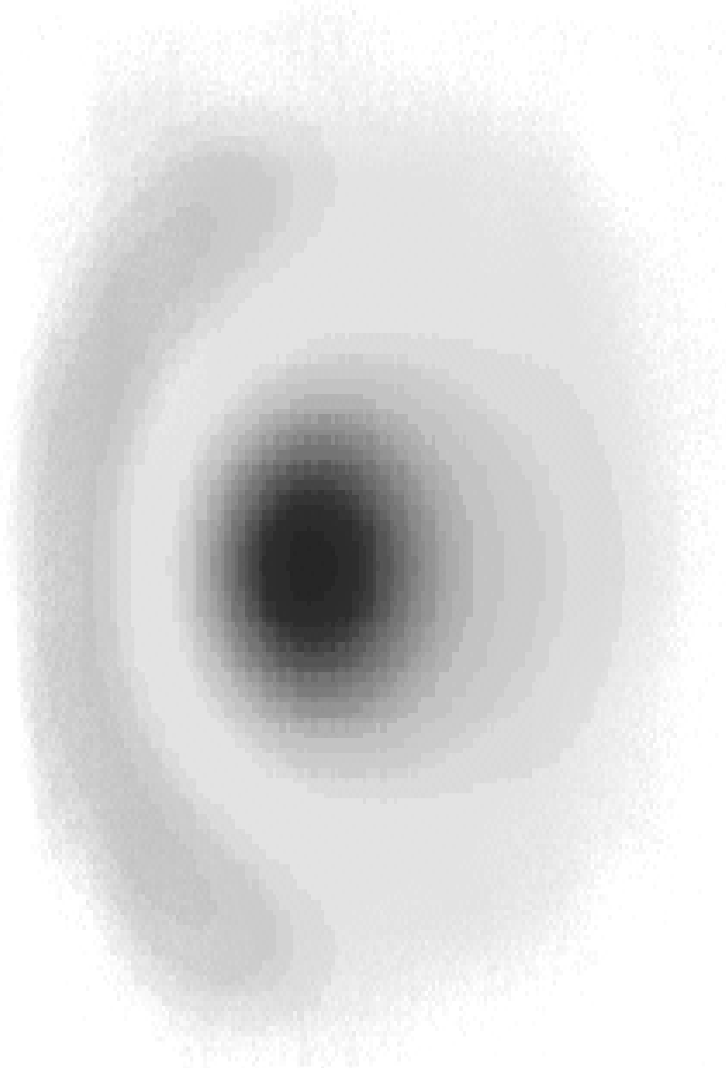


Figure 1.4.2: The signal calculation process

Chapter 2



The File menu

2.1 Introduction

The following chapter describes options available from Program Interface File menu options, illustrated in Fig. 2.1.1.

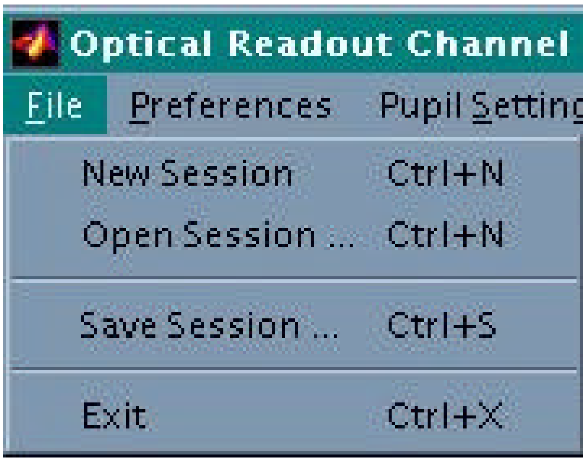


Figure 2.1.1: File menu options

Table 2.1.1 summarizes the menu options.

Menu shortcut: Alt+F

Menu options:	**Action:**	**see §**
New Session	Create a new session	2.2
Open Session…	Open a previously saved session	2.3
Save Session…	Save the current session	2.4
Exit	Close all figure windows and exit the optical readout model	2.5

Table 2.1.1: File menu options

2.2 Creating a Session

The optical readout model program has been designed so that the user can save the current operating parameters and GUI view to a MATLAB mat format file, a session file. The application of session filed allows any modeling configuration to be saved and re-opened at a later date without having to re-enter all the modeling parameters.

The session file includes the following information:

1. the current model settings,
2. which windows are currently open and where they are located on the screen, and
3. any information entered by the user regarding the current session, see §2.3.

Any data generated by the program, such as aperture pupil functions, focused spot profiles, objects, readout signals and movies are not saved, some of these are re-generated when a session is opened. (Externally imported objects are not saved).

By default, the program starts with only the Program Interface open and all the program options set to default values. If at any time you wish to revert to this configuration then simply select “New Session…” from the File menu.

2.3 Opening a Session

To open a previously saved session select “Open Session…” from the File menu. This will open an open file dialog box. Select the path and file that contains the session to open and select OK. The program will then configure itself to the settings stored in the session file. The session information contained in the session file will displayed on the program interface, as illustrated in Fig. 2.3.1.

If an attempt is made to open a mat file that does not contain any session information then the error dialog box illustrated in Fig. 2.3.2 will be displayed and the program will revert to the previous settings.

Figure 2.3.1: Displaying session information.

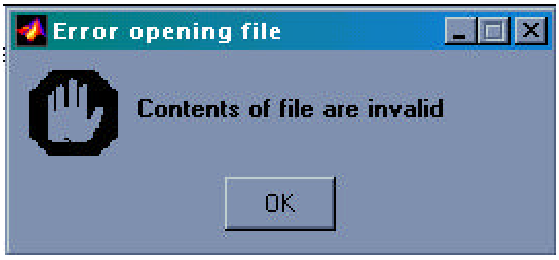


Figure 2.3.2: Invalid Session file

2.4 Saving a Session

To save the current session, select "Save Session…" from the File menu. The program will request you to enter some information regarding the current session using the dialog box illustrated in Fig. 2.4.1.

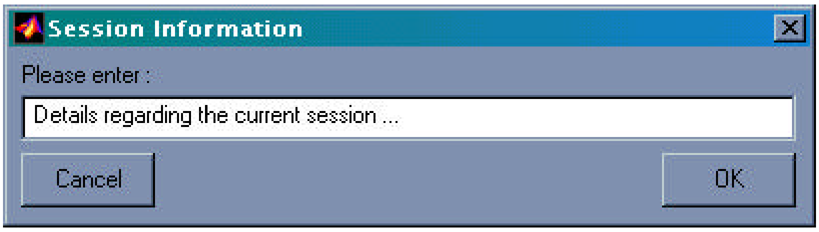


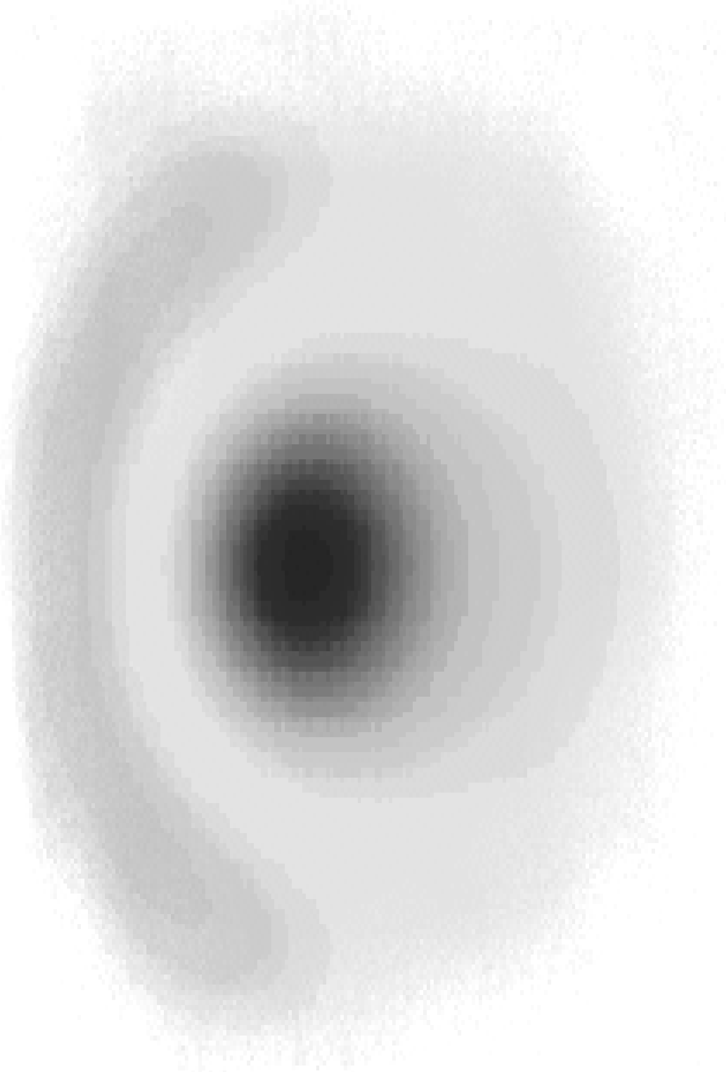
Figure 2.4.1: Enter Session Information

Selecting OK will open a save file dialog box, select the path and enter the filename to which you wish to save the current session. If cancel is selected then no session information will be saved.

2.5 Exiting the Program

To exit the program simply select “Exit” from the File menu, this will close all windows and exit to the MATLAB prompt.

Chapter 3



The Preferences Menu

3.1 Introduction

The following chapter describes options available from the Program Interface Preferences menu, illustrated in Fig. 3.1.1.

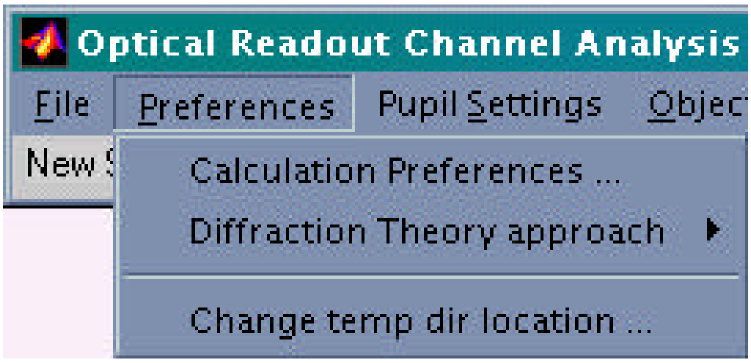


Figure 3.1.1: The Preferences menu options

Table 3.1.1 summarizes the menu options.

Menu shortcut: Alt+P

Menu options:	**Action:**	**see §**
Calculation Preferences…	Opens the calculation preferences dialog box	3.2
Diffraction Theory approach	Select the diffraction theory approach	3.3
Change temp dir location…	Change the location of the temporary directory	3.4

Table 3.1.1: Preferences menu options

3.2 Changing the Calculation Parameters

The calculation parameters are set using the Calculation Parameters dialog box, illustrated in Fig. 3.2.1, which is opened by selecting “Calculation Preferences…” from the program interface Preferences menu.

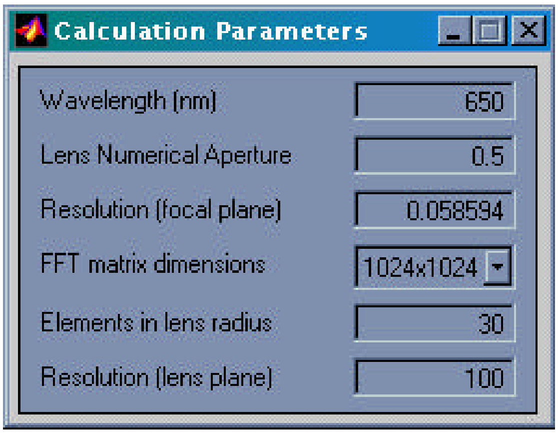


Figure 3.2.1: The Calculation Parameters dialog box.

The calculation preferences dialog is used to set important modeling parameters that determine the speed of simulation and resolution, such as wavelength, NA and FFT matrix dimensions.

In the optical readout model the propagation of the optical wavefront is calculated using a Fourier transform operation, the focused spot profile is given by the Fourier transform of the objective aperture pupil function. The relationship between the size of the FFT matrix, n_{FFT}, the number of elements in the radius of the objective pupil, n_p, and the resolution of the focused spot, Δ_f, is given by

$$\Delta_f = \frac{n_p}{n_{FFT}} . \frac{l}{\mathrm{NA}} \qquad \text{Eqn. (3.2.1)}$$

where l is the wavelength of illumination and NA is the numerical aperture of the lens. Invariably the wavelength, l, and numerical aperture, NA, are determined by the application, i.e. CDROM, DVDRAM etc, hence, the resolution of the resulting signal is determined primarily by varying the parameters n_{FFT} and n_p.

If any calculation parameters are changed then the aperture pupil functions, focused spot matrices and objects need to be re-generated to take into account the change in the resolution.

3.2.1 Selecting the Wavelength of Illumination (l)

The wavelength of incident illumination determines the resolution of the imaging system, the size of the focused spot being directly proportional to λ. However, the wavelength is typically set by the application, i.e. in the CDROM system λ=780nm, in the DVDROM system λ=650nm.

The wavelength of the incident illumination is entered into the wavelength edit box and its value must be in nanometers and within the range 450-850nm. If an invalid value is entered then the error dialog illustrated in Fig. 3.2.2 will be displayed and the value of wavelength will revert to its previous value.

Figure 3.2.2: Invalid wavelength error dialog

3.2.2 Entering the Objective Lens Numerical Aperture (NA)

The objective lens NA primarily determines the resolution of the imaging system, the size of the focused spot being inversely proportional to the NA. However, the NA is typically set by the application, i.e. in the CDROM system NA=0.45, in the DVDROM system NA=0.6.

The objective lens NA is entered into the Lens Numerical Aperture edit box and must be positive and less than 1; this limit is imposed since the maximum angle subtended by the cone of converging light from a lens is given by *asin*(NA).

If an invalid value for the NA is entered then the dialog box illustrated in Fig. 3.2.3 will be displayed and the value of NA will revert to its previous value.

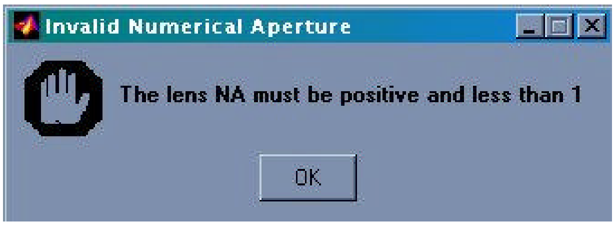


Figure 3.2.3: Invalid NA error dialog

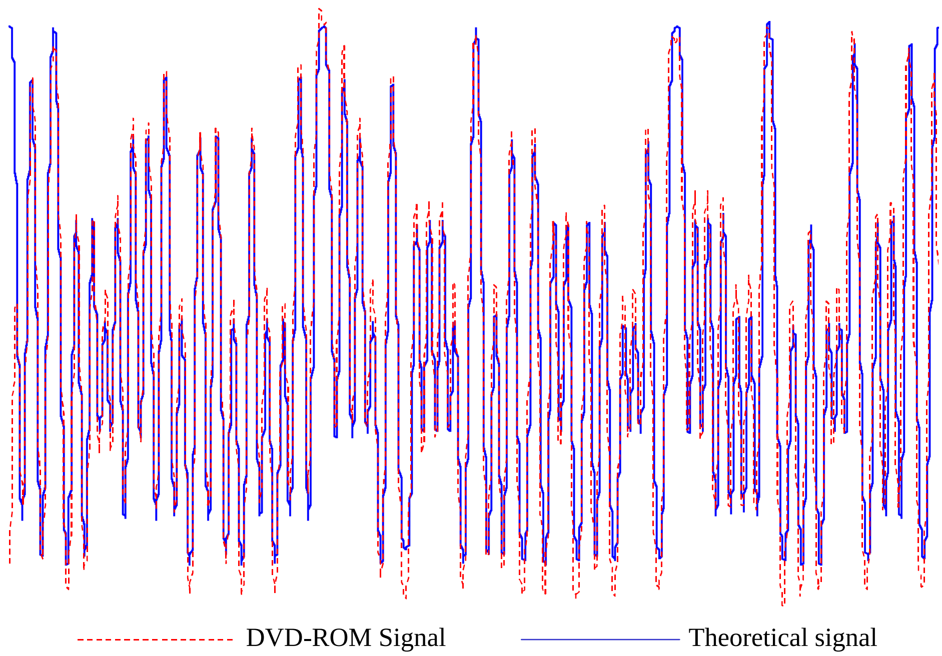


Figure 3.2.4: Comparison of theoretical and experimental DVDROM waveforms

Since the program uses a paraxial approximation (scalar diffraction) then values of NA > 0.5 produce approximate results. However, it has been found that for large NA values (up to 0.7) the theoretical results produced by the model agree extremely closely to experimental waveforms. Figure 3.2.4 compares an experimental waveform obtained from a DVDROM system and a theoretical waveform generated using this model using the same data stream, the NA=0.6.

If a value of NA greater than 0.5 is entered then the warning dialog illustrated in Fig. 3.2.5 will be displayed.

Figure 3.2.5: NA warning dialog

When the value of NA is changed the values of resolution in both the focal and lens planes, which are in units of wavelength, will be updated automatically.

3.2.3 Selecting the FFT Matrix Dimensions (n_{FFT})

The FFT matrix is used in the simulation process to generate the field distribution at the focal point of the lens. The matrix representing the objective aperture pupil function is mapped to the center of the FFT matrix and then the 2-D FFT is performed to calculate the field distribution at the focal point (scalar diffraction). The ratio between the size of the matrices representing the aperture pupil function and the FFT matrix determines the resolution in the focal plane. The allowed values for the size of the FFT matrix are restricted to 256x256, 512x512 and 1024x1024 due to the optimization restrictions of the MATLAB FFT routine. The size of the FFT matrix is selected from the FFT matrix dimensions pull down menu illustrated in Fig. 3.2.6.

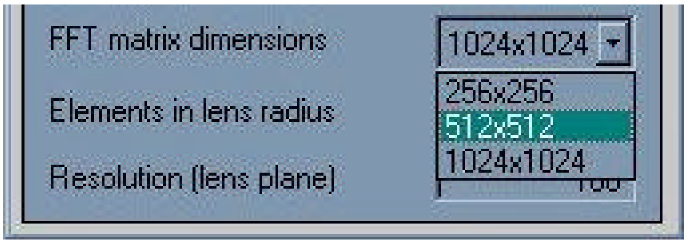


Figure 3.2.6: FFT matrix dimensions pull down menu

The greater the number of elements in the FFT matrix compared with the number of elements in the aperture pupil function matrix, the greater the resolution; however, the slower the calculation. The selected number of elements used in the simulation process is usually a trade off between speed and resolution. By default, a FFT matrix of size 1024x1024 is selected; however, it is recommended that your PC be of a high specification when using this setting.

Once the FFT matrix dimensions have been selected the values of resolution (focal plane) and resolution (lens plane) will be automatically updated.

3.2.4 Entering the Number of Elements in the Lens Radius (n_p)

As discussed in §3.2.3, the ratio between the number of elements in the objective aperture pupil function matrix and that in the FFT matrix determines the resolution in the focal plane. The size of the aperture pupil function matrix is selected by changing the value of the number of elements in the lens radius. Ideally, for a high resolution in the output signal we require very few elements in the lens plane; however, it is necessary to increase the number of elements in the lens radius when investigating aberrations or apodization techniques.

The number of elements in the lens radius is entered into the Elements in lens radius edit box, the value must be positive and is limited to half the number of elements in the FFT matrix. If an invalid value is entered then the error dialog illustrated in Fig. 3.2.7 will be displayed and the value will revert to its previous value.

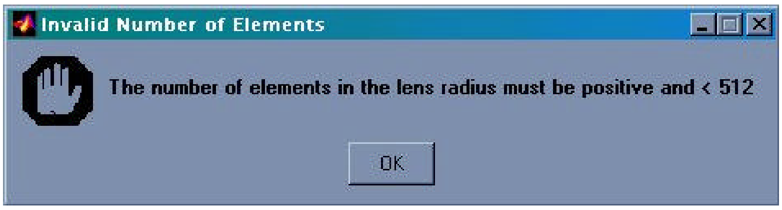


Figure 3.2.7: Invalid number of elements in the lens radius entered

Equation (3.1) illustrates the relationship between the number of elements in the lens radius, n_p, the size of the FFT matrix, n_{FFT}, and the resolution of the focused spot, Δ_f. Table 3.2.1 illustrates the effect on the resolution, in units of wavelength, due to changing n_r. The NA of the objective lens is assumed to be 0.5.

N.B. the number of elements in the lens diameter will always be odd and given by $(2n_r)+1$.

n_{FFT}	n_r	Δ_f (*l*)
256x256	60	0.469
256x256	30	0.234
512x512	60	0.234
512x512	30	0.117
1024x1024	60	0.117
1024x1024	30	0.059

Table 3.2.1: The relationship between the number of elements in the lens radius, the FFT matrix dimensions and the resolution of the focused spot

3.3 Selecting the Diffraction Theory Approach

As discussed in §1, the mathematical approach used in the optical readout model is based upon scalar diffraction analysis. This analysis has been modified to take into account the bending of light by the objective lens – this is often referred to as vector diffraction, although strictly speaking it is pseudo-vector diffraction. For an incident beam linearly polarized in one plane, the result of the bending of the rays is to introduce components of polarization in x, y, and z planes.

The diffraction theory approach is selected from the Preferences pull down menu from the main menubar illustrated in Fig. 3.2.8.

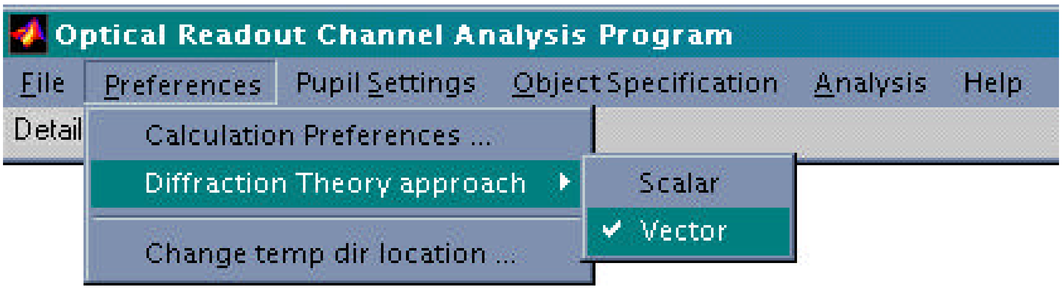


Figure 3.2.8: Scalar or vector diffraction

The choice of scalar or vector diffraction depends upon the speed and accuracy required.

Scalar diffraction is quicker, since the model only takes into account the propagation of a single field component, compared to three for the vector approach. However, vector diffraction is more accurate, especially when modeling a MO system, due to the more accurate representation of the polarized field components. The selection of scalar or vector diffraction will change the operation of the Aperture Pupil and Focused Spot generation windows, see §4.4 and §6.2 respectively. If the diffraction theory approach is changed then the aperture pupil functions and focused spot matrices need to be re-generated.

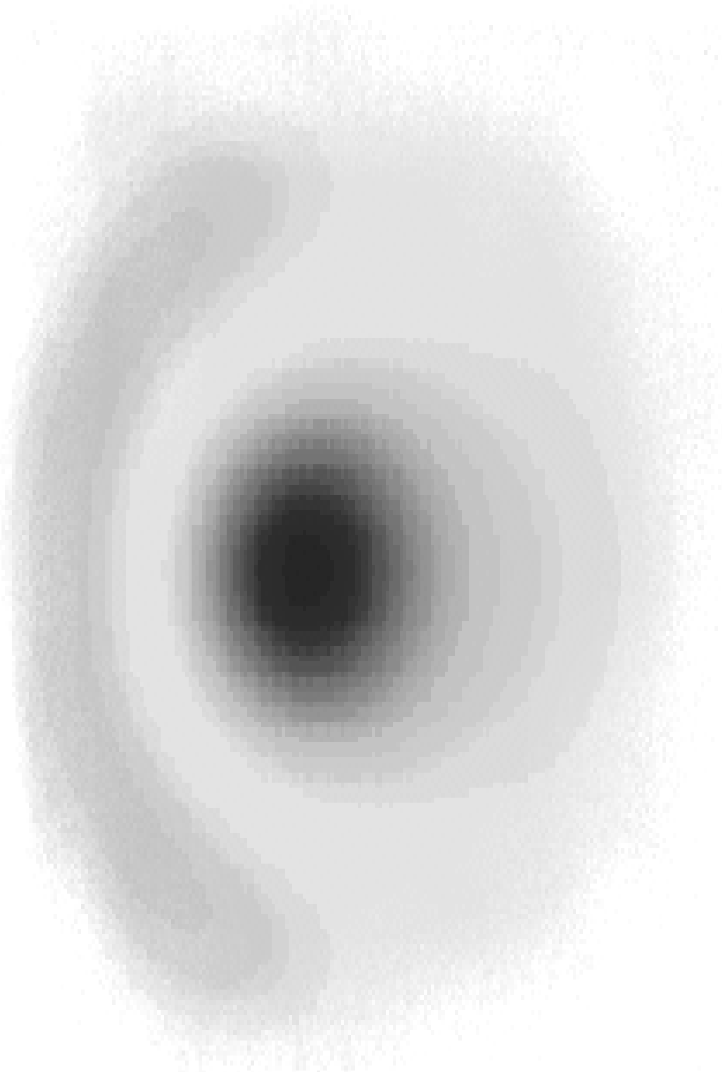
3.4 Changing the Location of the Temp Dir.

The temporary directory is used to store data generated by the optical readout model; these temporary files have a filename of format ~orm*.mat. When the main program is closed or when the windows that generated the temporary files are closed any files in the temporary directory of this format will be deleted.

The location of the temporary directory is entered when the program is executed for the first time. If the program is executed and the temporary directory has been removed or cannot be accessed by the MATLAB environment then the program will request a new location for the temporary files to be stored.

Currently, the option to change the location from the Preferences menu is unavailable. Hence, to change the location of the temporary directory you will have to either delete the temporary directory or delete the file default_startups.mat (NOT default_startups.m) from the source files directory, in both cases the optical readout model will need to be restarted.

Chapter 4



The Pupil Settings Menu

4.1 Introduction

The following chapter describes options available from the Program Interface Pupil Settings menu, illustrated in Fig. 4.1.1.

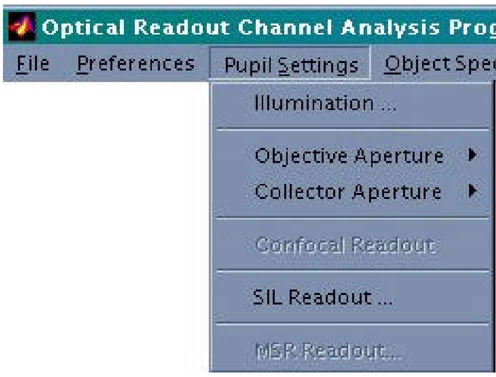


Figure 4.1.1: The Pupil Settings menu options

Table 4.1.1 summarizes the menu options.

Menu shortcut: Alt+S

Menu options:	**Action:**	**see §**
Illumination…	Set the form of the incident illumination	4.2
Objective aperture	Set the objective aperture pupil function options	
	⇒ Set objective aperture aberrations	4.3
	⇒ Set objective aperture apodization	4.4
	⇒ Plot the objective aperture pupil function	4.5
Collector aperture	Set the collector aperture pupil function options	
	⇒ Set collector aperture aberrations	4.3
	⇒ Set collector aperture apodization	4.4
	⇒ Plot the collector aperture pupil function	4.5
Confocal Readout	Select confocal readout	4.6
SIL Readout…	Select SIL readout and set SIL options	4.7
MSR Readout…	Select MSR readout and set MSR options	4.8

Table 4.1.1: Pupil Settings menu options

4.2 Selecting the Incident Illumination

The form of the incident illumination incident on the objective pupil determines the form of the objective aperture pupil function and hence, the shape and resolution of the focused spot. For example, a Gaussian distribution across the objective lens results in a Gaussian distribution in the focused spot; however, a uniform distribution across the objective lens results in a much sharper Airy disc profile focused spot. Figure 4.1.2 illustrates the difference in the width of the focused spot due to the form of the incident filed distribution.

The Illumination settings dialog, illustrated in Fig. 4.2.2, is opened by selecting "Illumination…" from the program interface Pupil Settings menu.

The form of the incident illumination is selected from the Illumination pull down menu; the choices are Uniform or Gaussian, as illustrated in Fig. 4.2.3.

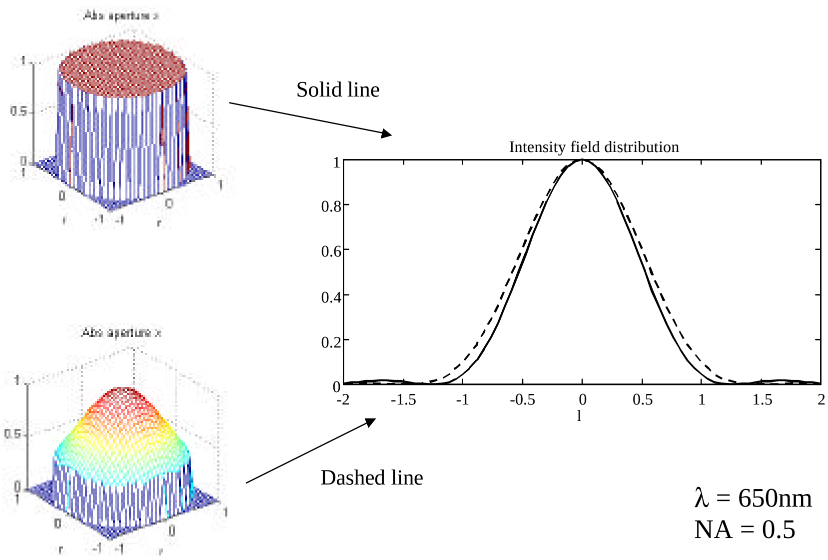


Figure 4.1.2: Focused field profile for uniform and Gaussian (*w*=1) incident illumination

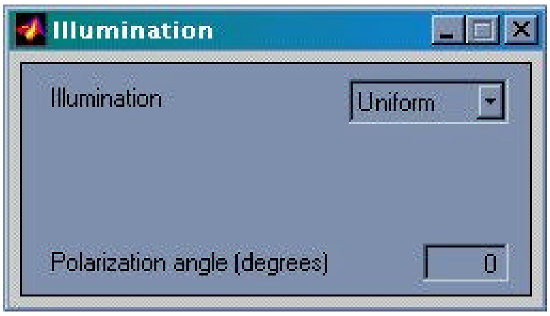


Figure 4.2.2: Illumination settings dialog

Figure 4.2.3: Choice of incident illumination

On selecting Gaussian illumination settings dialog changes, as illustrated in Fig. 4.2.4 and the width of the Gaussian in both *x* (tangential) and *y* (radial) directions can be specified.

The Gaussian width parameter is entered as the position of the e^{-2} intensity point of the resulting Gaussian profile as a function of the aperture radius. For example, a width of 1 produces a Gaussian intensity distribution with a value of e^{-2} (0.135) the peak intensity at the rim of the aperture; a value of 0.5 produces the same value at half the aperture radius.

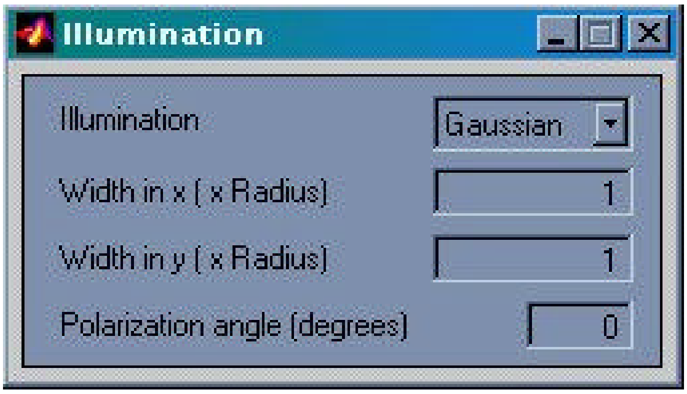


Figure 4.2.4: Gaussian illumination selected

If an invalid value is entered (greater than 20 or less than 0) then the error dialog illustrated in Fig. 4.2.5 will displayed and the value will revert to its previous value. A value greater than 20 is assumed to produce a uniform distribution across the aperture.

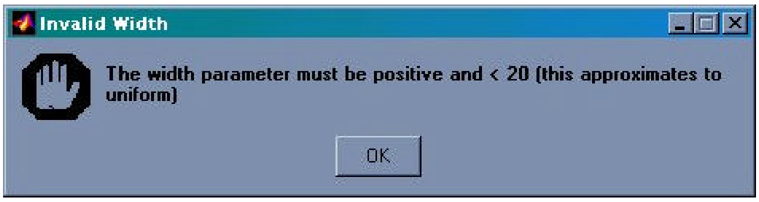


Figure 4.2.5: Invalid Gaussian width entered.

The angle of polarization determines the proportion of the incident field distribution that is polarized in *x* and *y*, and is entered in the Polarization angle edit box (0 being the *x*-axis); the range of values is between -90° and 90°. If an invalid value is entered then the error dialog illustrated in Fig. 4.2.6 will be displayed and the value will revert to its previous setting.

Figure 4.2.6: Invalid polarization angle error dialog

If the incident illumination characteristics are changed then the program warns that the aperture pupil functions, focused spot matrices need to be re-generated for the settings to take effect using the warning dialog illustrated in Fig. 4.2.7.

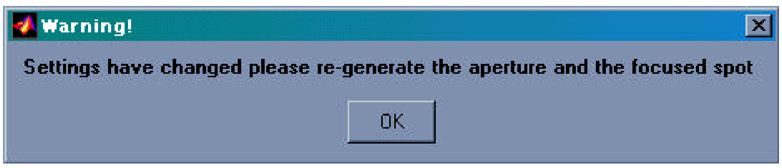


Figure 4.2.7: Settings have changed warning dialog

4.3 Aberrations

The optical readout model may be used to model the effect of aberrations on the optical readout channel. To a first approximation aberrations are modeled as phase modifications to the objective and collector aperture pupil functions.

Aberrations are inserted into the optical path using the Aberrations dialog illustrated in Fig. 4.3.1, for objective aberrations.

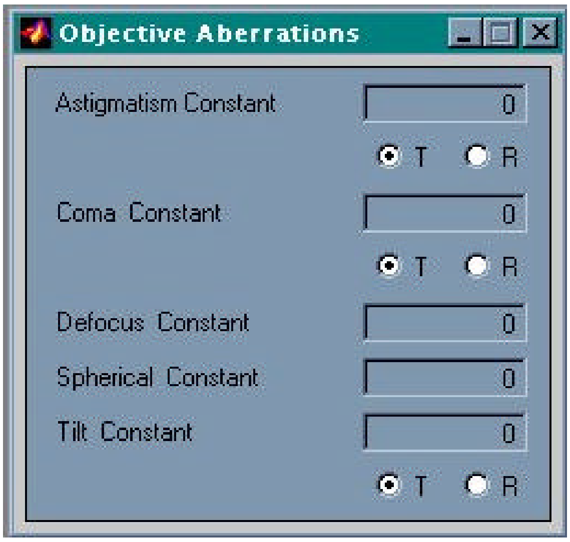


Figure 4.3.1: Aberrations dialog

An aberrations dialog is opened for both Objective and Collector aberrations by selecting “Objective Aperture->Aberrations…” and “Collector Aperture->Aberrations…” from the program interface Pupil Settings menu, as illustrated in Fig. 4.3.2 and Fig. 4.3.3 respectively.

There are 5 types of Seidel aberrations that can be modeled using the optical readout model; these are astigmatism, coma, defocus, spherical aberrations and tilt.

If any form of aberration is introduced then the aperture pupil functions will need to be re-generated. If the aberration is introduced into the objective aperture then the focused spot will also need to be re-generated.

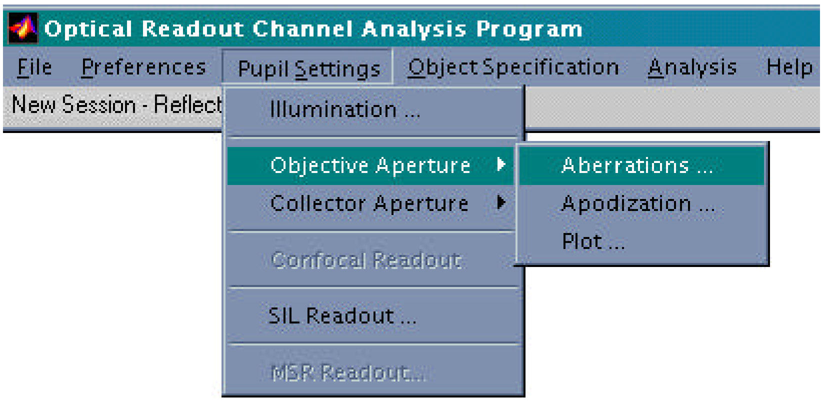


Figure 4.3.2: Selecting the objective aberrations

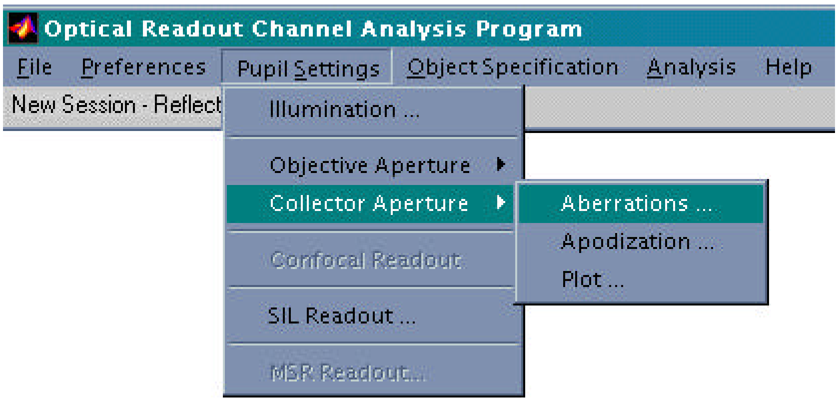


Figure 4.3.3: Selecting the collector aberrations

4.3.1 Selecting Astigmatism

Astigmatism in optical storage systems arises due to the anisotropic birefringent properties of polycarbonate substrates. As a first-order approximation, the phase error introduced by astigmatism, *W*(~), is modeled using the aberration function

$$W(r,f)=\exp\{2pjC_A r^2\cos(f)^2\} \qquad \text{Eqn. (4.3.1)}$$

where $\{r, f\}$ are polar coordinates and C_A is the coefficient of astigmatism in units of wavelength (l). If the astigmatism is in the tangential direction, x, then f=0, whereas if the astigmatism in the radial direction, y, then f=90°.

Astigmatism is selected by entering an amount of astigmatism, in units of wavelength (l), into the Astigmatism Constant edit box. A value of zero indicates no astigmatism. The direction of the astigmatism, tangential (T) or radial (R) is determined by selecting the appropriate checkbox.

Fig. 4.3.4 illustrates the effect of astigmatism on the focused spot.

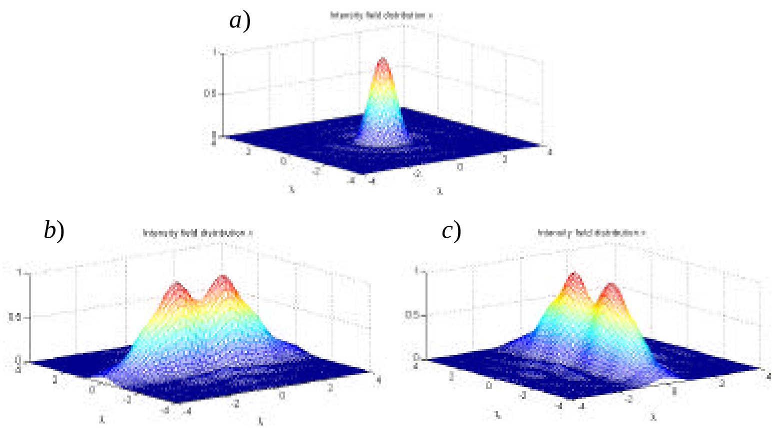


Figure 4.3.4: The effect of astigmatism *a*) the unaberrated focused spot, *b*) the focused spot with 1 unit of astigmatism (λ) in the tangential direction, and *c*) the focused spot with 1 unit of astigmatism in the radial direction.

The sign of the coefficient of astigmatism has no effect.

4.3.2 Selecting Coma

Coma in optical storage systems arises due to the propagation of a non-collimated beam through a titled plate, lens or beamsplitter. Since, the beam is invariable collimated in an optical storage system there is often little evidence of coma. As a first-order approximation, the phase error introduced by coma, $W(\sim)$, is modeled using the aberration function

$$W(r,f)=\exp\{2pjC_C r^3\cos(f)\} \qquad \text{Eqn. (4.3.2)}$$

where $\{r,f\}$ are polar coordinates and C_C is the coefficient of coma in units of wavelength (l). If the coma is in the tangential direction, x, then f=0, whereas if the coma in the radial direction, y, then f=90°.

Coma is selected by entering an amount of coma, in units of wavelength (l), into the Coma Constant edit box. A value of zero indicates no coma. The direction of the coma, tangential (T) or radial (R) is determined by selecting the appropriate checkbox.

Fig. 4.3.5 illustrates the effect of coma on the focused spot.

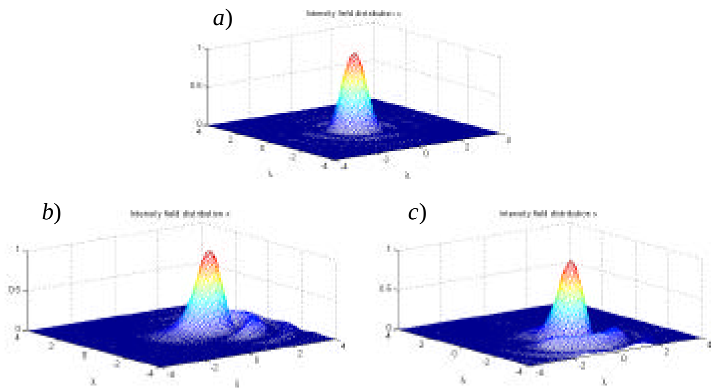


Figure 4.3.5: The effect of coma, *a*) the unaberrated focused spot, *b*) the focused spot with 1 unit of coma (λ) in the tangential direction, and *c*) the focused spot with 1 unit of coma in the radial direction.

The sign of the coefficient of coma causes the skewing of the focused spot to appear in the opposite direction.

4.3.3 Selecting Defocus

Defocus in optical storage systems arises due to the storage layer of a disc not lying within the focal range of the lens. As a first-order approximation, the phase error introduced by defocus, $W(\sim)$, is modeled using the aberration function

$$W(r, f) = \exp\{2pjC_D \cos(r)\} \qquad \text{Eqn. (4.3.3)}$$

where $\{r, f\}$ are polar coordinates, C_C is the coefficient of coma in units of wavelength. Defocus is symmetrical about the optic axis.

Defocus is selected by entering an amount of defocus, in units of lambda, into the Defocus Constant edit box. A value of zero indicates no defocus.

Fig. 4.3.6 illustrates the effect of defocus on the focused spot.

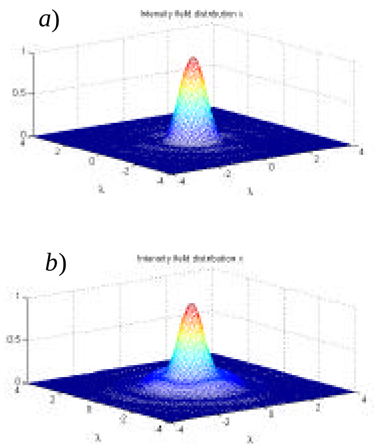


Figure 4.3.6: The effect of defocus, *a*) the unaberrated focused spot, and *b*) the focused spot with 1 unit of defocus (λ).

The sign of the coefficient of defocus has no effect.

4.3.4 Selecting Spherical Aberration

Spherical aberration in optical storage systems arises due to the propagation of a non-collimated beam through a parallel plate, such as a substrate. As a first-order approximation, the phase error introduced by spherical aberration, *W*(~), is modeled using the aberration function

$$W(r,f)=\exp\{2pjC_S r^4\} \qquad \text{Eqn. (4.3.4)}$$

where $\{r,f\}$ are polar coordinates, C_S is the coefficient of spherical aberration in units of wavelength. Spherical aberrations are symmetrical about the optic axis.

Spherical aberration is selected by entering an amount of astigmatism, in units of lambda, into the Spherical Constant edit box. A value of zero indicates no spherical aberration.

Fig. 4.3.7 illustrates the effect of spherical aberration on the focused spot.

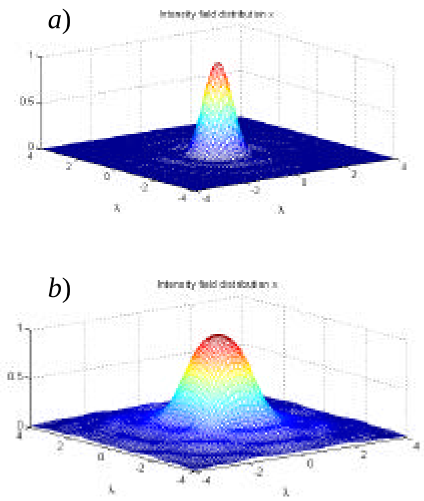


Figure 4.3.7: The effect of spherical aberration, *a*) the unaberrated focused spot, and *b*) the focused spot with 1 unit of spherical aberration (λ).

The sign of the coefficient of spherical aberration has no effect.

4.3.5 Selecting Tilt

Tilt (distortion) in optical storage systems arises due to non-normal incidence of a collimated wavefront and an optical component, such as a lens. As a first-order approximation, the phase error introduced by tilt, *W*(~), is modeled using the aberration function

$$W(r,f)=\exp\{2pjC_T r\cos(f)\} \qquad \text{Eqn. (4.3.5)}$$

where $\{r,f\}$ are polar coordinates, C_T is the coefficient of tilt in units of wavelength. If the tilt is in the tangential direction, *x*, then f=0, whereas if the tilt in the radial direction, *y*, then f=90°. The effect of tilt is to produce a shift the position of the focused spot on the surface of the object.

Tilt is selected by entering an amount of tilt, in units of lambda, into the Tilt Constant edit box. A value of zero indicates no tilt. The direction of the tilt, tangential (T) or radial (R), is determined by selecting the appropriate checkbox.

Fig. 4.3.8 illustrates the effect of tilt on the focused spot.

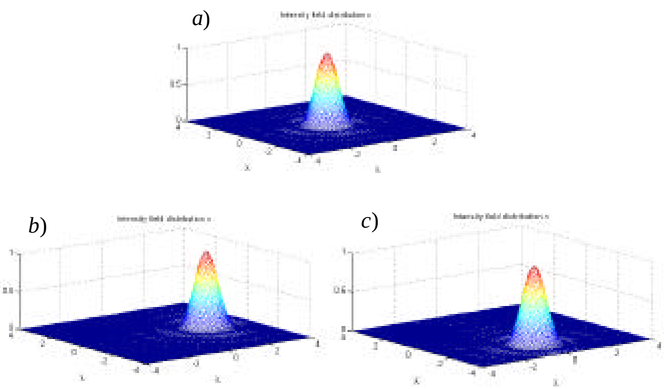


Figure 4.3.8: The effect of tilt, *a*) the unaberrated focused spot, *b*) the focused spot with 1 unit of tilt (λ) in the tangential direction, and *c*) the focused spot with 1 unit of tilt in the radial direction.

The sign of the coefficient of tilt causes the shifting of the focused spot to occur in the opposite direction.

4.4 Apodization

The placement of obscuring apertures into the illumination or collector paths of the optical channel can be used to change the spatial frequency characteristics and hence, the imaging characteristics of the readout system. These obscurations are modeled as modifications to the objective and collector aperture pupil functions and is termed apodization. If the obscuration is placed in the illumination path then it will affect the form of the focused spot. If the obscuration is placed in the collector path then it will affect the field distribution across the photodetector(s). In both cases the readout signal will be effected. The modification of the optical path using obscuring apertures is termed apodization.

Figure 4.4.1 illustrates the resulting focused spot due to the placement of an annular aperture in the illumination path. The illumination is assumed to be uniform, λ=650nm, NA=0.5 and the radius of the inner radius is half the aperture radius.

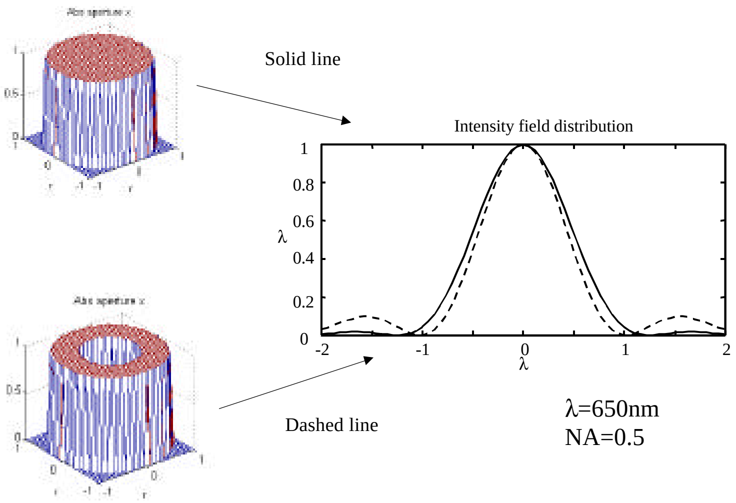


Figure 4.4.1: The resulting focused spot due to an annular aperture in the illumination path.

The resulting Airy disc focused spot has a narrower central spot, leading to increased resolution, but suffers from an increase in the intensity of the sidelobes.

Obscuring apertures are inserted into the optical path using the Apodization dialog illustrated in Fig. 4.4.2, for objective apodization.

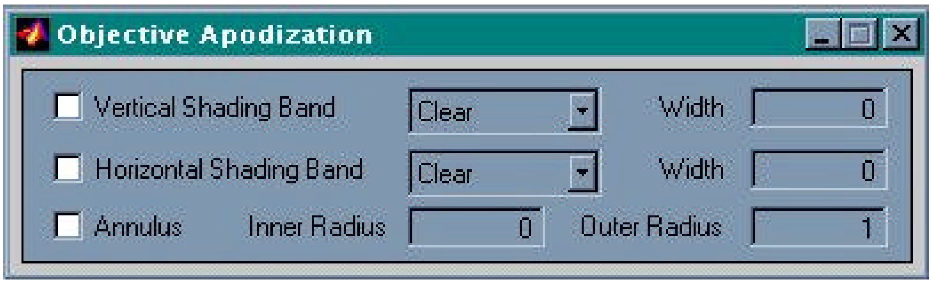


Figure 4.4.2: Apodization dialog

An apodization dialog is opened for both Objective and Collector apodization by selecting "Objective Aperture->Apodization…" and "Collector Aperture->Apodization…" from the program interface Pupil Settings menu, as illustrated in Fig. 4.4.3 and Fig. 4.4.4 respectively.

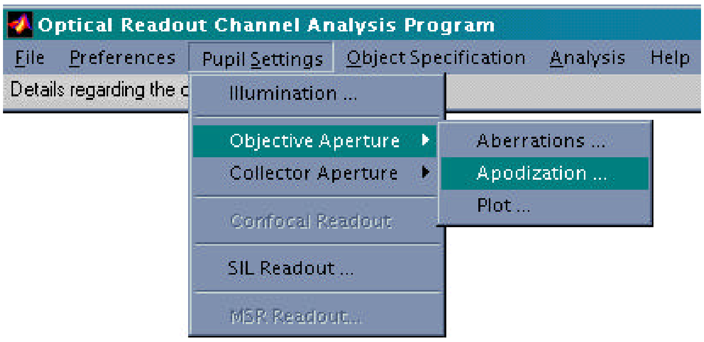


Figure 4.4.3: Selecting Objective apodization

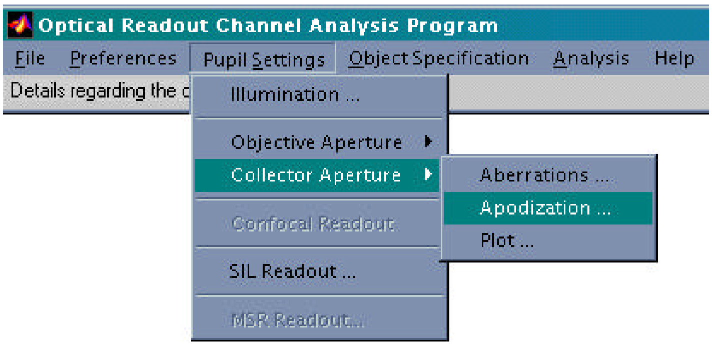


Figure 4.4.4: Selecting Collector apodization

The optical readout model can be used to investigate two apodization schemes, rectangular and annular shading bands.

If any form of obscuration is introduced then the aperture pupil functions will need to be re-generated and the focused spot matrices also if the apodization is placed in the objective aperture.

4.4.1 Selecting a Rectangular Shading Band

A rectangular shading band can be placed either horizontally (*x*, tangential direction) or vertically (*y*, radial direction) in the aperture, or both, by selecting the appropriate checkbox. The form of the rectangular shading band, clear or obscured, is selected using the popup menu from the apodization dialog, as illustrated in Fig. 4.4.5.

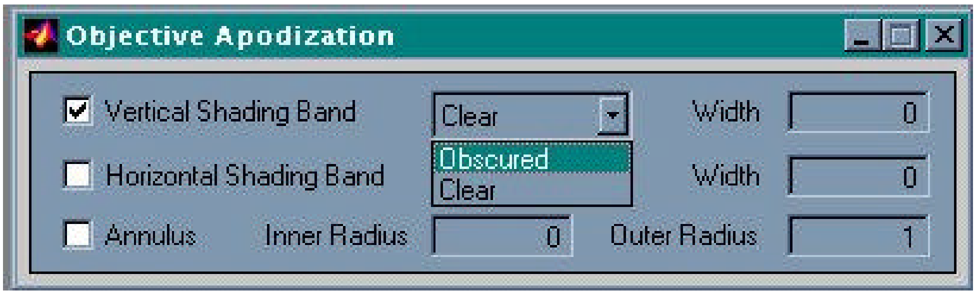


Figure 4.4.5: Selecting an obscured vertical shading band

The width of the shading band is specified in units of the aperture radius and is entered into the appropriate Width edit box; a width of 1 represents a shading band of width equal to the aperture radius placed centrally in the aperture. The minimum width value is 0 and the maximum 2. (Note: there is no method to offset the shading band in this version of the software). If an invalid value is entered then the error dialog illustrated in Fig. 4.4.6 will be displayed and the width will revert to its previous value.

Figure 4.4.7 illustrates a circular aperture pupil function with various forms of rectangular shading bands.

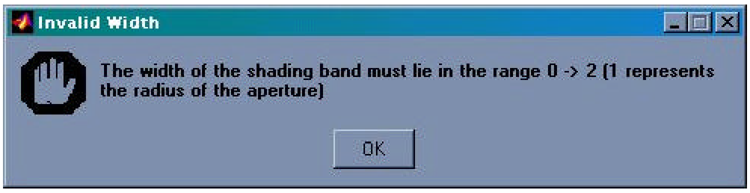


Figure 4.4.6: Invalid width entered

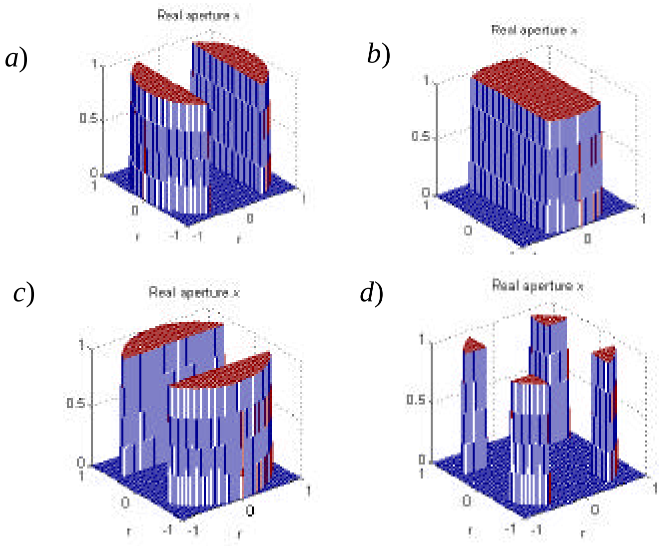


Figure 4.4.7: An example of rectangular shading bands, *a*) an obscured vertical shading band of width *a* (where *a* is the radius of the aperture), *b*) a clear vertical shading band of width *a*, *c*) an obscured horizontal shading band of width *a*, and *d*) an obscured horizontal and vertical shading band both of width *a*.

4.4.2 Selecting an Annular Shading Band

An annular shading band is inserted by selecting the annulus checkbox. The inner and outer radii values define the inside and outside radii of the annulus respectively. The radius value is a function of the aperture radius, therefore, the minimum value is 0 and the maximum value is 1. Checks are made to ensure that entered values are within the correct range and that the inner radius is less than the outer radius. If an invalid inner radius is entered the error dialog illustrated in Fig. 4.48 is displayed and the value will revert to its previous value, a similar dialog will be displayed, as illustrated in Fig. 4.4.9, if an invalid outer radius is entered.

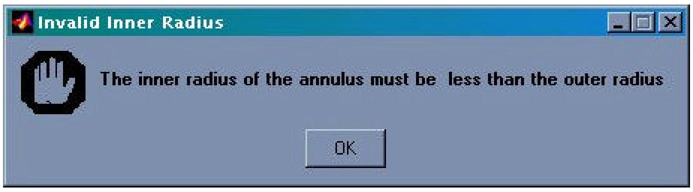


Figure 4.4.8: Invalid inner radius error dialog

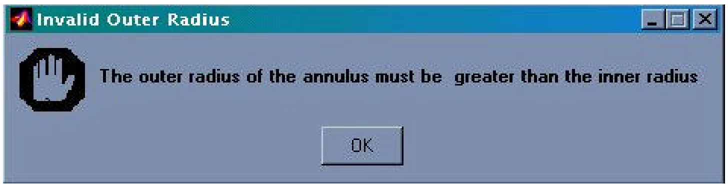


Figure 4.4.9: Invalid outer radius error dialog

To reduce the outer radius less than the inner radius it is necessary to first change the inner radius.

Figure 4.4.10 illustrates a circular aperture pupil function with various forms of annular shading bands.

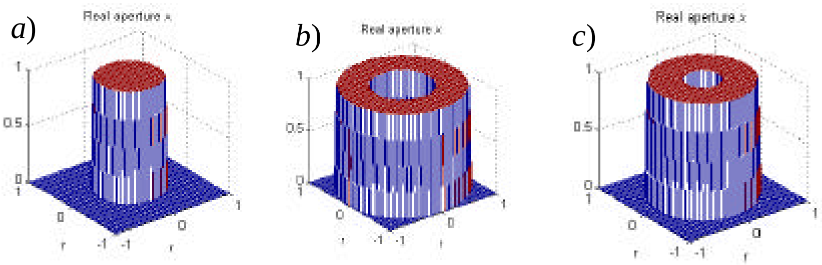


Figure 3.33: An example of annular apertures, *a*) inner radius 0, outer radius *a*/2, (where *a* is the radius of the aperture), *b*) inner radius *a*/2, outer radius *a*, and *c*) inner radius *a*/4, outer radius 3*a*/4.

4.5 Generating the Aperture Pupil Functions

The objective and collector aperture pupil functions are generated and displayed using the Pupil Function window, illustrated in Fig. 4.5.1, which is opened by selecting "Objective Aperture -> Plot…", or "Collector Aperture -> Plot…" from the program interface Pupil Settings menu, or alternatively "Pupil Function…" from the program interface Analysis menu, as illustrated in Figs. 4.5.2, 4.5.3 and 4.5.4 respectively.

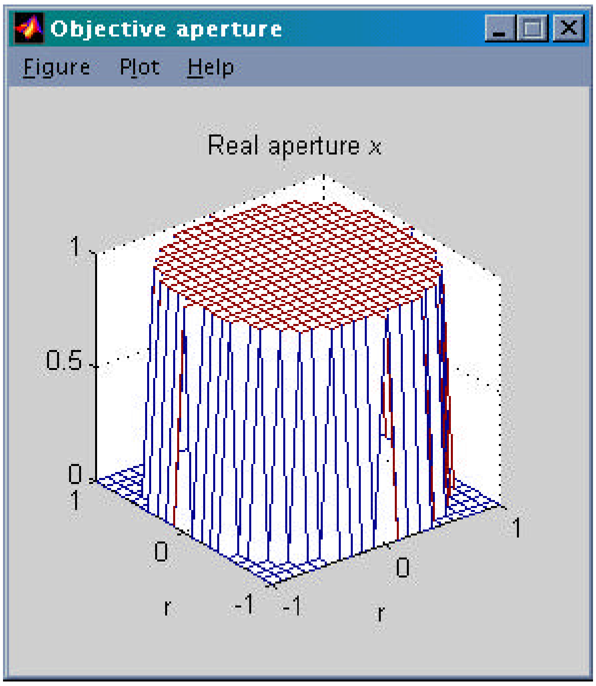


Figure 4.5.1: The Pupil Function window.

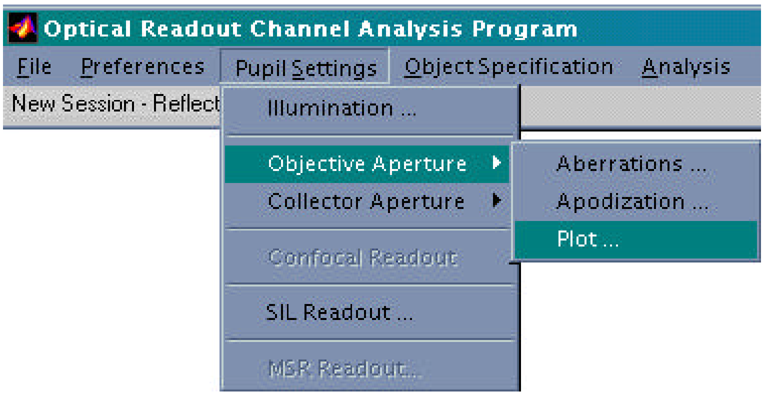


Figure 4.5.2: Opening the Pupil Function window, option 1

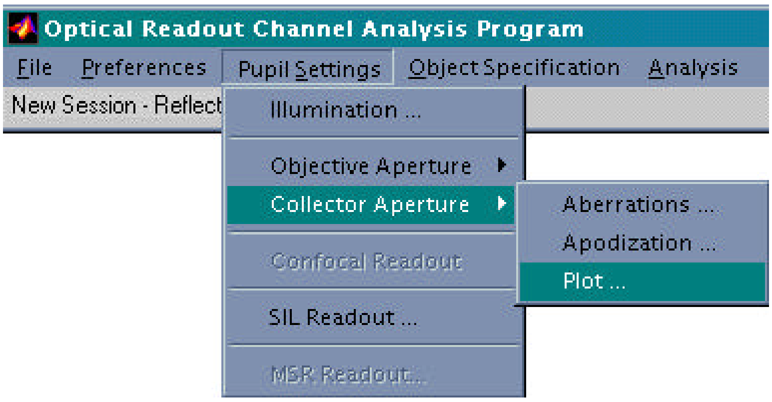


Figure 4.5.3: Opening the Pupil Function window, option 2

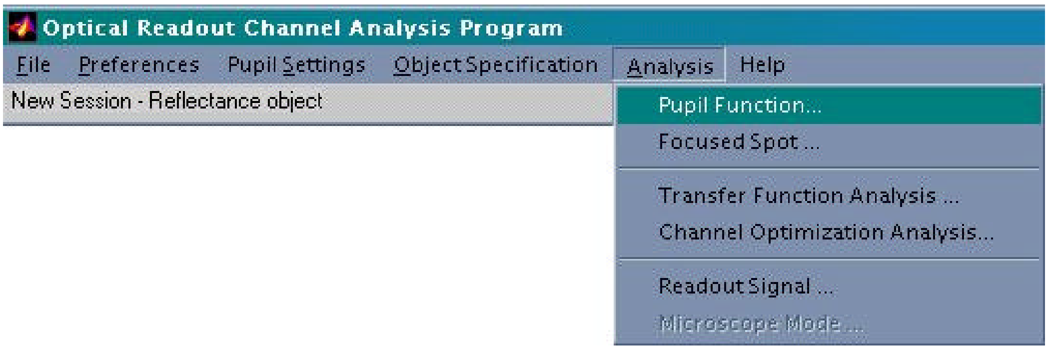


Figure 4.5.4: Opening the Pupil Function window, option 3

Actions regarding the Pupil Function window are accessed using the Figure and Plot menus.

The Pupil Function window generates temporary files to store the objective and collector aperture pupil functions; these are required before other windows, such as the Focused Spot window, may be opened.

4.5.1 The Figure Menu

The Pupil Function window File menu, illustrated in Fig. 4.5.5, is used to Print, Copy, Load and Save the pupil functions and also to close the window.

Figure 4.5.5: Pupil Function window File menu

The menu options are summarized in Table 4.5.1.

Menu Option	**Action**
Print …	Print the displayed pupil function to the current system printer
Copy …	Copy the displayed pupil function to the clipboard
Load …	Load previously saved pupil function settings from a standard *.mat format file. This will overwrite all current settings.
Save …	Save the current pupil function settings to a standard *.mat format file.
Exit	Close the Pupil Function window.

Table 4.5.1: Pupil Function window File menu options

4.5.2 The Plot Menu

The Pupil Function window Plot menu, illustrated in Fig. 4.5.6, is used to change the format of the displayed pupil function.

The menu options are summarized in Table 4.5.2.

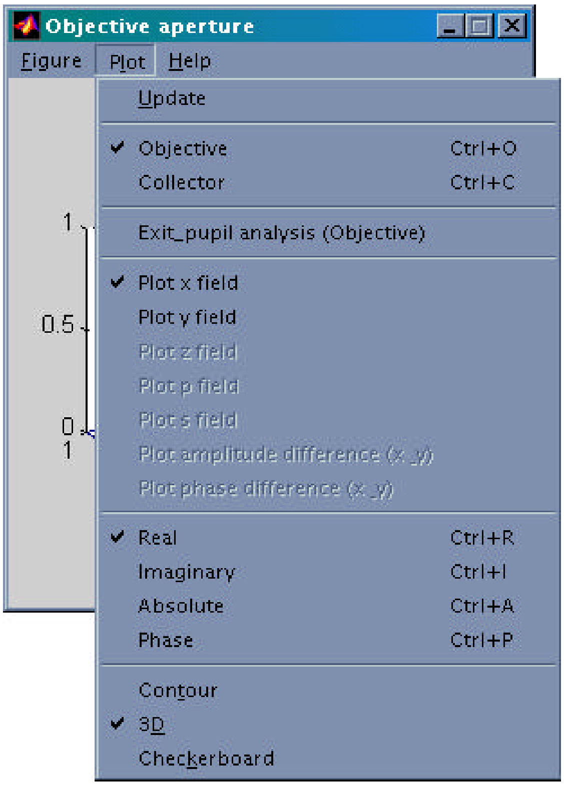


Figure 4.5.6: Pupil Function window Plot menu

Menu Option	**Action**
Update	Re-generate the aperture pupil functions. A statusbar will be displayed to illustrate the progress of the calculation.
Objective	Display the objective aperture pupil function. Menu shortcut Ctrl+O.
Collector	Display the collector aperture pupil function. Menu shortcut Ctrl+C.
Exit pupil analysis	Display the wavefronts at the exit pupil of the objective lens (objective pupil plot only). Menu options Plot x field, Plot p field, Plot s field, Plot amplitude difference and Plot phase difference become available when Exit pupil analysis is selected.

Table 4.5.2: Pupil Function window Plot menu options

Plot x field	Display the collimated *x* polarized field component, or the *x* polarized field component at the exit pupil when Exit pupil analysis is selected.
Plot y field	Display the collimated *y* polarized field component, or the *y* polarized field component at the exit pupil when Exit pupil analysis is selected.
Plot z field	Display the *z* polarized field component at the exit pupil when Exit pupil analysis is selected (only available for when displaying the objective pupil function).
Plot p field	Display the *p* polarized field component at the exit pupil when Exit pupil analysis is selected (only available for when displaying the objective pupil function).
Plot s field	Display the *s* polarized field component at the exit pupil when Exit pupil analysis is selected (only available for when displaying the objective pupil function).
Plot amplitude difference	Display the amplitude difference, i.e. *x*-*y*, at the exit pupil when Exit pupil analysis is selected (only available for when displaying the objective pupil function).
Plot phase difference	Display the phase difference, i.e. *x*-*y*, at the exit pupil when Exit pupil analysis is selected (only available for when displaying the objective pupil function).
Real	Display the real component of the aperture pupil function. Menu shortcut Ctrl+R.
Imaginary	Display the imaginary component of the aperture pupil function. Menu shortcut Ctrl+I.
Absolute	Display the absolute component of the aperture pupil function. Menu shortcut Ctrl+A.
Phase	Display the phase component of the aperture pupil function. Menu shortcut Ctrl+P.

Table 4.5.2: Pupil Function window Plot menu options cont.

Contour	Contour plot of the aperture pupil function.
3D	3D mesh plot of the aperture pupil function.
Checkerboard	Checkerboard plot of the aperture pupil function.

Table 4.5.2: Pupil Function window Plot menu options cont.

Figure 4.5.7 illustrates the different plot options available when displaying the objective aperture pupil function.

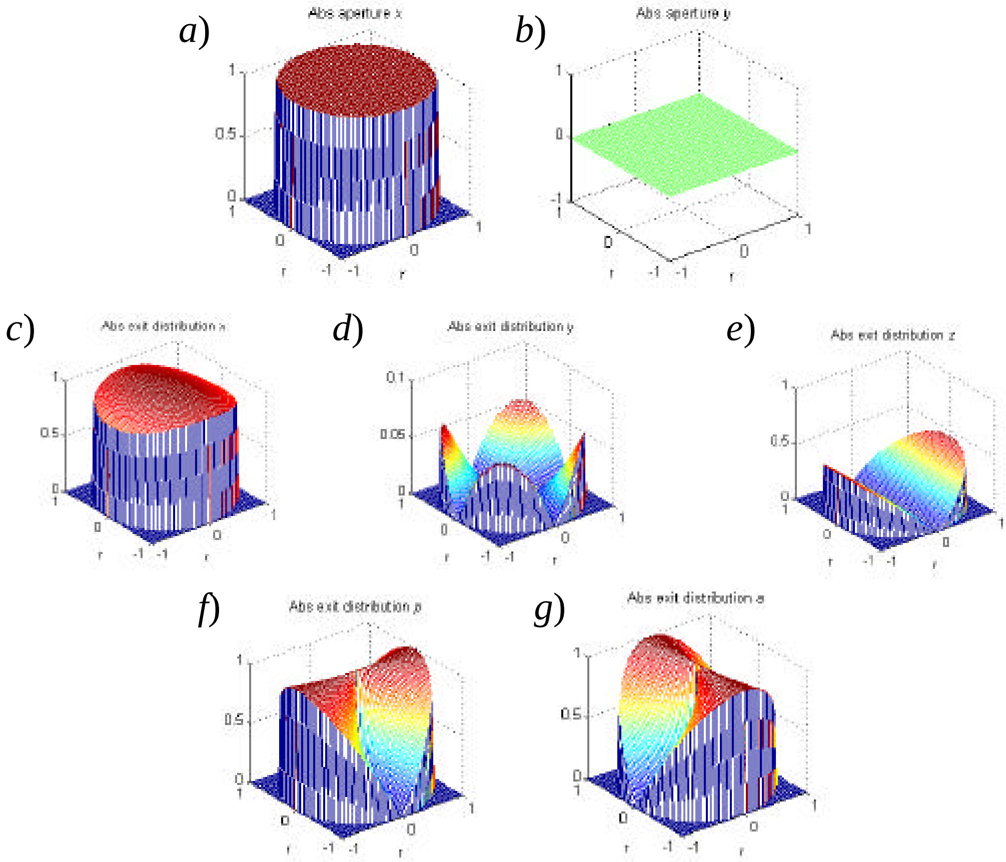


Figure 4.5.7: Plots of objective aperture pupil function, for a circular aperture under uniform illumination linearly polarized in *x*. *a*) *x* polarized field component, *b*) *y* polarized field component, *c*) *x* polarized field component in the exit pupil (Exit Pupil Analysis selected), *d*) *y* polarized field component in the exit pupil, *e*) *p* polarized field component in the exit pupil, and *f*) *s* polarized field component in the exit pupil of the objective lens.

4.6 Selecting Confocal Detection

Used to select confocal readout and set the size of the confocal pinhole, currently not available.

4.7 Selecting SIL Imaging

A Solid Immersion Lens (SIL) is used to increase the spatial resolution of an optical system, and operates in a similar to the oil immersion microscope. Typically, the SIL is a hemisphere of high refractive index material, n_{sil}, with its flat bottom surface placed such that it is coincident with the focal point of a lens. Due to the reduction in wavelength in the SIL compared to that in air, the size of the focused spot is reduced by a factor n_{sil} over that attainable in air. An alternative SIL, the supersphere or stigmatic SIL, is a sphere of high refractive index material that has been truncated to a depth $a(1+1/n_{sil})$, where a is the radius of the sphere. In this case the size of the focused spot is reduced by a factor n_{sil}^2 over that attainable in air. The application of SILs to optical storage is an exciting prospect due to the obvious increase in the resolution of the optical stylus.

If the flat bottom surface of the SIL is held in close contact with the surface of the object to be imaged, then the evanescent fields at the SIL/object interface can be effected by the reflectance properties of the object, resulting in a signal change at the photodetector(s). If there is not close contact between the SIL and object, then an air-gap will exist between the SIL and the object, leading to a reduction in the resolution of the optical system.

The SIL is modeled as a transmittance and phase modification of the objective aperture pupil function, which can be viewed using the Pupil Function window (Exit Pupil Analysis selected).

The SIL dialog box, illustrated in Figure 4.7.1, is opened by selecting “SIL Readout…” from the program interface Pupil Settings menu.

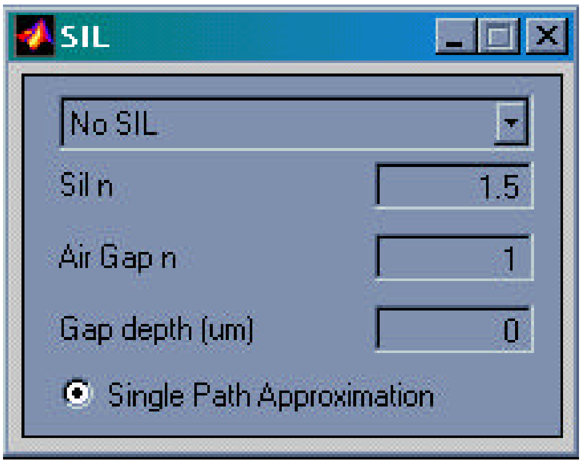


Figure 4.7.1: The SIL dialog

To select the type of SIL use the pull-down menu illustrated in Fig. 4.7.2, by default No SIL is selected.

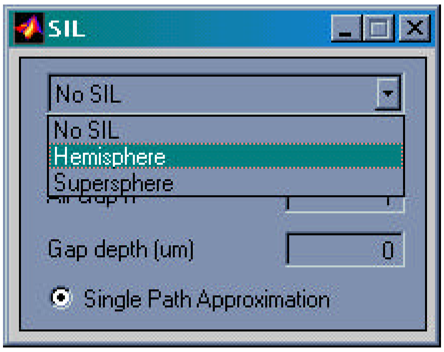


Figure 4.7.2: Selecting the type of SIL

Once a SIL has been selected, the calculation parameters will be changed due to the increase in the resolution due to the SIL.

The “SIL n” edit box is used to enter the refractive index of the SIL material, and is only available when a SIL has been selected. The valid range of SIL refractive index is greater than 0 and less than 2, if an invalid value is entered then the error dialog illustrated in Fig. 4.7.3 will be displayed and the value will revert to its previous value.

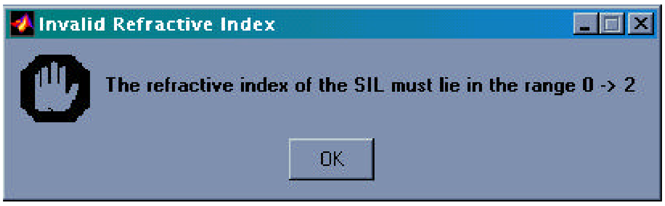


Figure 4.7.3: Invalid SIL refractive index.

The default value of the refractive index of the air-gap is 1. However, this may be changed, using the "Air Gap n" edit box, to take into account any other material or fluid that can be placed between the SIL and object. Again valid values are in the range 0 to 2.

The depth of the air-gap can be set using the "Gap depth" edit box, and is entered in μm. If the depth of the air-gap is set to zero, then the modeling procedure will simply change the resolution at the focal plane of the lens. However, if the depth of the air-gap is set to any other value then the aberration introduced by the air-gap will be modeled as a phase modification of the aperture pupil function. The valid range for the depth of the air-gap is between 0 and 200um. If an invalid value is entered then the error dialog illustrated in Fig. 4.7.4 will be displayed and the value will revert to its previous value.

Figure 4.7.4: Invalid depth of air-gap.

There are two methods of modeling the aberrations introduced by the air-gap between the SIL and the object. The first is by using Fresnel reflection coefficients to calculate the transmission and phase properties of the SIL/air-gap/object interface across the aperture of the optical system. This approach is more applicable to the case where the effective NA, i.e. n_{sil}.NA, is greater than or equal to 1, since the this leads to an attenuation of the propagating optical field across the aperture. The other approach is to calculate the phase error introduced by the SIL/air-gap/object interface, the single path approximation. This approach is more applicable to the case where the effective NA is less than 1, since very little attenuation of the optical field will occur across the aperture. Hence, to select between the two modeling methods, you must check the Single Path Approximation radiobutton to select the single path approximation, and uncheck it to select modeling using Fresnel transmission coefficients.

Figure 4.7.5 illustrates the focused spot profile when including a hemispherical SIL and supersphere.

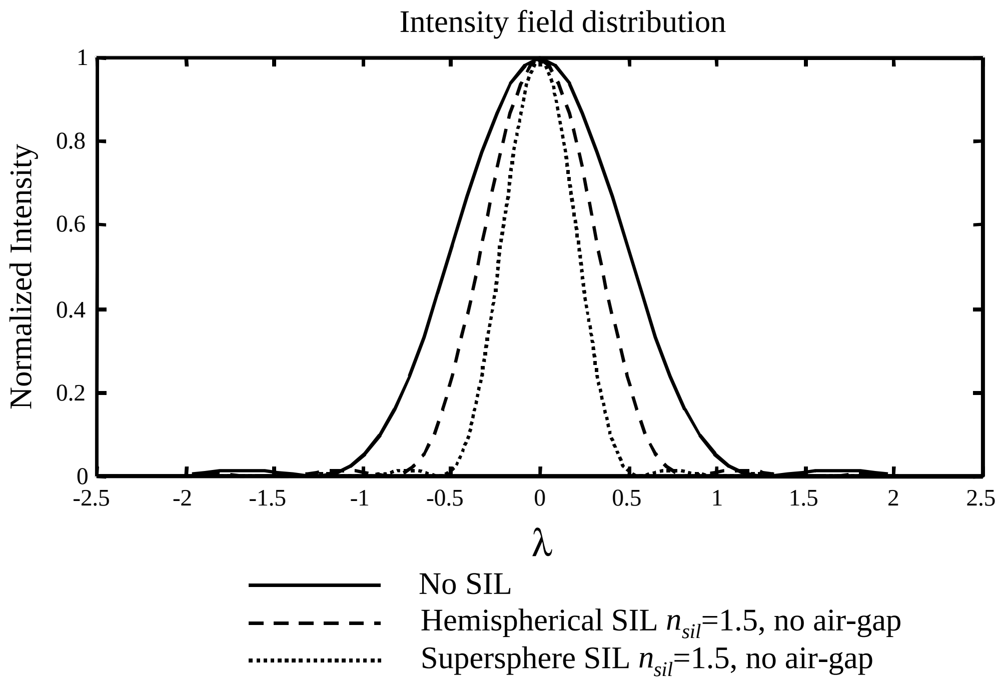


Figure 4.7.5: Focused spot profiles, with and without a SIL.

If the SIL is included or changed, then the aperture pupil functions and focused spots need to be re-generated. If the object generation window is open then the object will need to be re-generated due to the change in resolution.

4.8 Selecting Magnetic Super-Resolution

The MSR option is only available when a magneto-optic object type is selected, see §5.2. The MSR window, illustrated in Fig. 4.8.1, is opened by selecting "MSR Readout…" from the program interface Pupil Settings menu.

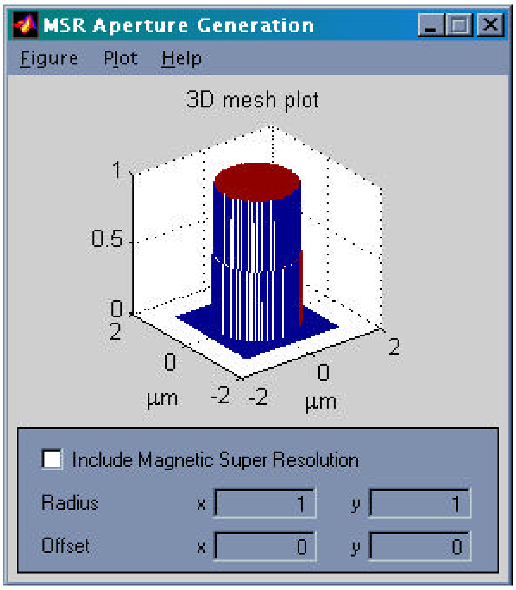


Figure 4.8.1: The MSR window

Magnetic super-resolution is a masking technique used to effectively increase the resolution of the magneto-optic readout channel. During readout a "magnetic mask" is created at the surface of the disk that effectively masks off a small proportion of the recorded data, this small area is the only information detected by the scanning spot. The "magnetic mask" is modeled as a focal plane pupil function, applied to the focused spot, which outside the mask sets the Kerr rotation to zero; i.e. no magnetic information is detected.

The MSR window is used to specify and display the MSR mask. To include MSR you must check the Include Magnetic Super Resolution checkbox. The radius and offset edit boxes are then used to specify the radius in x and y, and the offset in x and y. All values are entered in µm.

Since the MSR aperture is mapped to the aperture representing the focused spot, the matrix representing the MSR aperture must not be greater in size. For example, if the focused spot matrix is ±4λ (5.2µm for λ=650nm) and we choose a MSR mask of radius 3µm, the resulting mask will be 6µm in size, i.e. greater than the focused spot matrix. In this case the error dialog illustrated in Fig. 4.8.2 will be displayed, and the values will revert to their previous values. In this case you will have to increase the size of the focused spot matrix, see §6.2. A similar error dialog will be observed if an offset value entered causes the resulting mask size to be greater than the focused spot matrix.

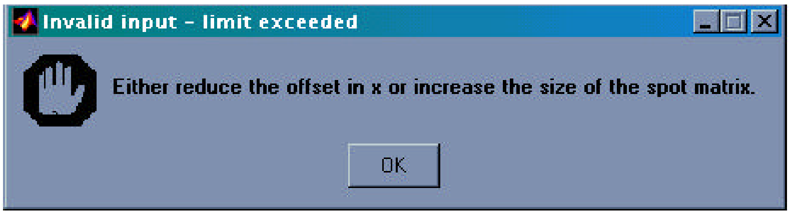
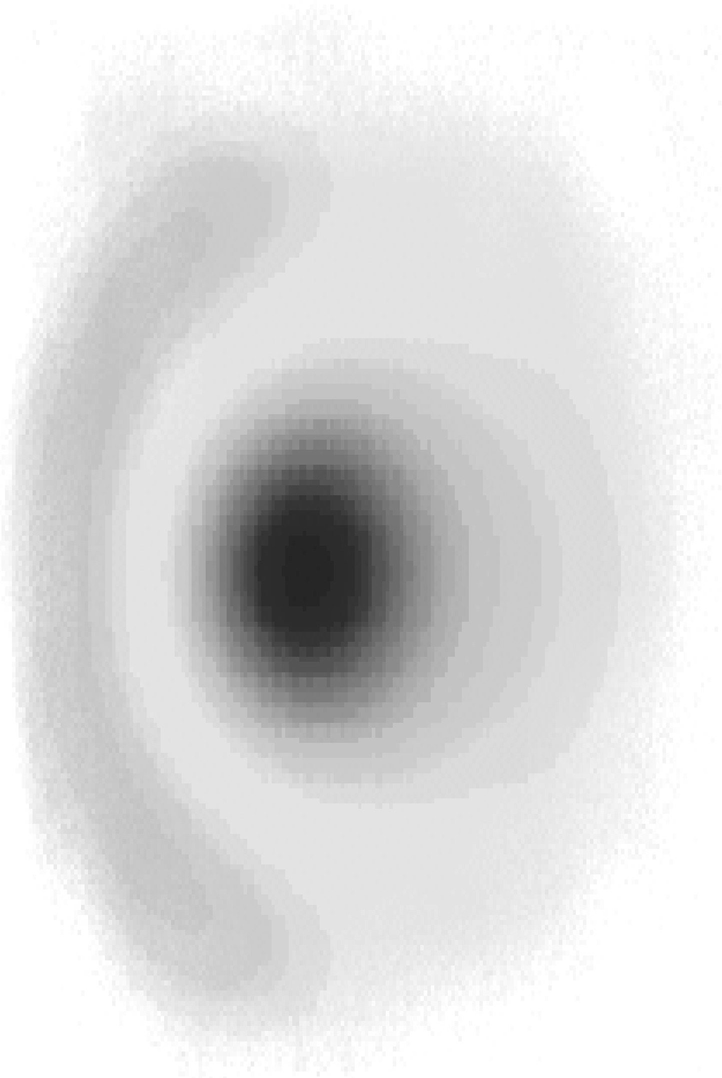


Figure 4.8.2: Invalid value entered

The File menu is used to Print and Copy to the clipboard the current MSR mask and to close the window. The Plot menu is used to Update the MSR mask, and to change the plot style.

Chapter 5



The Object Specification Menu

5.1 Introduction

The following chapter describes the options available from the Program Interface Object Specification menu illustrated in Fig. 5.1.1.

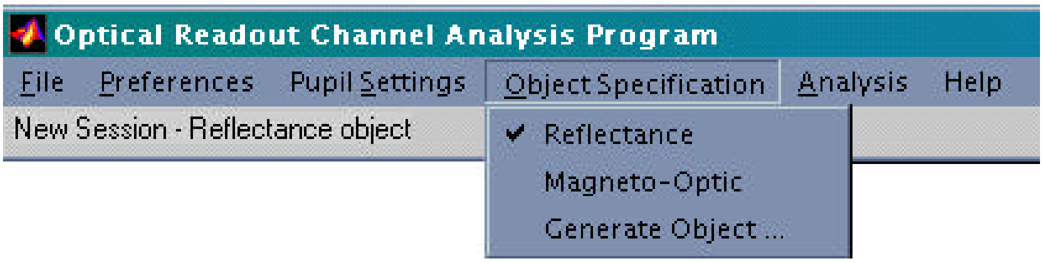


Figure 5.1.1: The Object Specification menu

Table 5.1.1 summarizes the menu options.

Menu shortcut: Alt+O

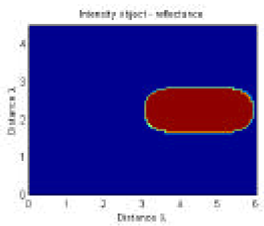
Menu options:	**Action:**	**see §**
Reflectance	Select reflectance type object and readout	5.2
Magneto-Optic	Select magneto-optic type object and readout	5.3
Generate Object…	Open the object generation window	5.4

Table 5.1.1: Object Specification menu options

The object specification menu is used to select the type of object to be imaged, reflectance/phase or magneto-optic, and to open the object generation window that is used to generate the object. The type of object selected also defines the detection scheme used in the signal simulation process. If a reflectance object is selected then the program assumes a single quadrant photodetector detection scheme. If a magneto-optic object is selected then the program assumes a differential quadrant photodetector detection scheme.

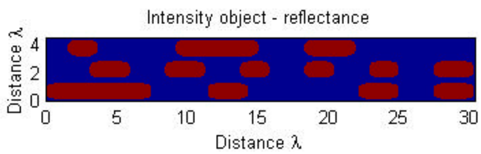
The object generation window can be used to generate any arbitrary object for imaging. The object can consists of up to three tracks where the signal is recorded along the central track. The track width, reflectance, phase and if applicable Kerr rotation, is easy specified using the window menus, along with the recorded data pattern, bit width, length, end shape, reflectance, phase and if applicable Kerr rotation. Externally generated objects may also be imported into the object generation window. Note: the size of the object must be greater than the size of the matrix used in the simulation process, see §6.2.

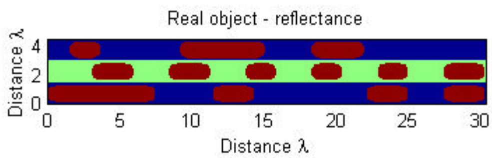
Figure 5.1.2 illustrates some example objects generated using the object generation window.



a) reflectance step object
track width 1um
bit width 0.75um
bit length 0.5um
data pattern 00001111
track ref. 0%
bit ref. 100%

b) reflectance object
track width 1um
bit width 0.75um
bit length 0.5um
data pattern arbitrary
track ref. 0%
bit ref. 100%





c) phase object
track width 1um, bit width 0.75um
bit length 0.5um, data pattern arbitrary
track ref. land 50%, track ref. Groove 50%
track phase land pi/4, track phase groove 0
bit ref. 100%land & groove

Figure 5.1.2: Sample objects generated using the Object window

5.2 Selecting Reflectance/Phase Imaging

A reflectance object is chosen by selecting “Reflectance” from the Object Specification menu, as illustrated in Fig. 5.2.1.

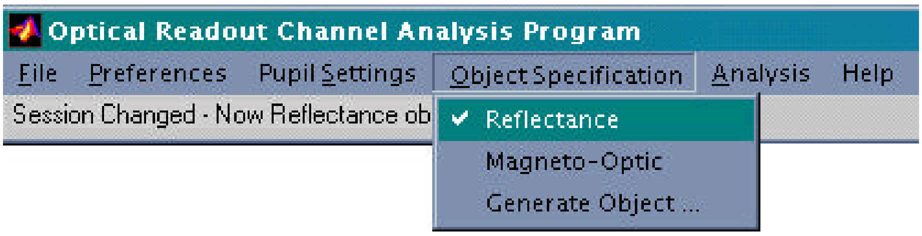


Figure 5.2.1: Selecting a reflectance object.

Changing the object type will change the simulation process, as well as the current object. Hence, before the settings are changed the program asks whether you are sure, using the warning dialog illustrated in Fig. 5.2.2.

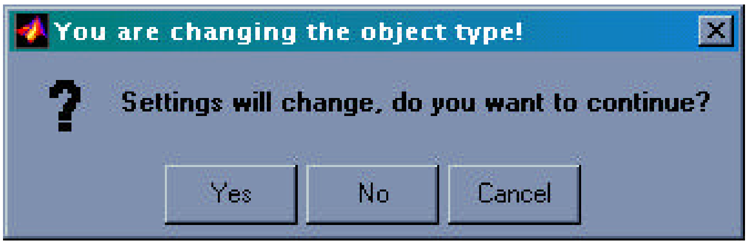


Figure 5.2.2: Do you want to change the object?

If the object generation window is open, then it will be updated upon changing the object type.

5.3 Selecting Magneto-Optic Imaging

A magneto-optic object is chosen by selecting “Magneto-Optic” from the program interface Object Specification menu, as illustrated in Fig. 5.3.1.

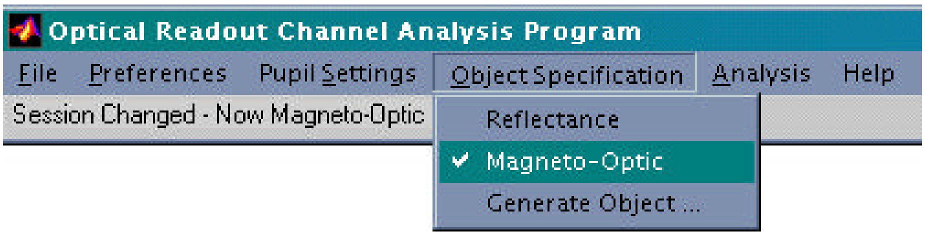


Figure 5.3.1: Selecting a magneto-optic object.

Again, you will be prompted whether you want to continue by the warning dialog illustrated in Fig. 5.2.2.

5.4 Generating the Object

The object used in the imaging process is specified and generated using the Object Generation window illustrated in Fig. 5.4.1, which is opened by selecting "Generate Object…" from the Object Specification menu, as illustrated in Fig. 5.4.2.

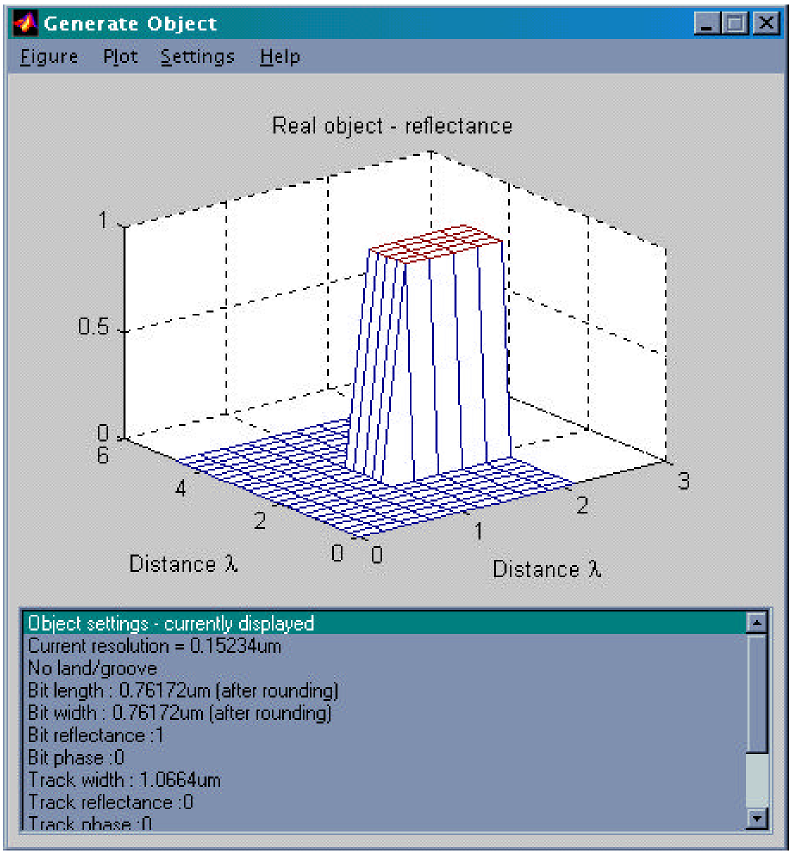


Figure 5.4.1: The Object Generation window.

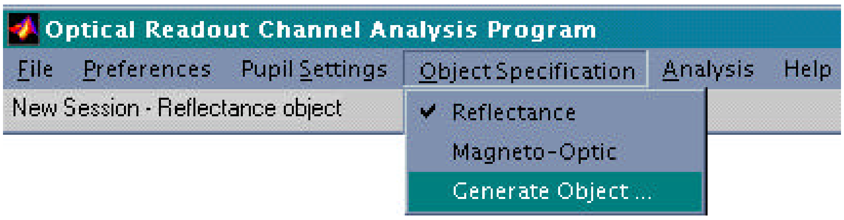


Figure 5.4.2: Opening the Object window.

The Object window displays the current object created/loaded along with the object specifications. The object characteristics are set using the Settings menu.

The Figure, Plot and Settings menus are described below.

5.4.1 The Figure Menu

The Generate Object window File menu illustrated in Fig. 5.4.3 is used to open, save, export, import, copy, and print objects, and also to close the Object window.

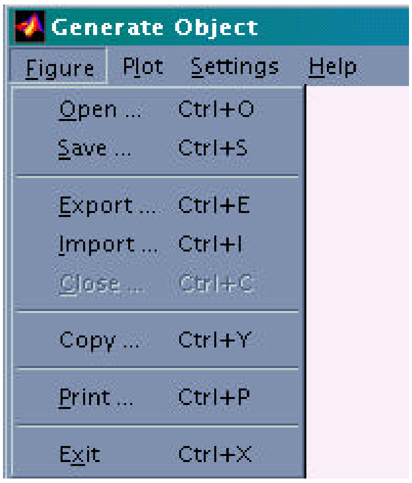


Figure 5.4.3: The Object window File menu.

The menu options are summarized in Table 5.4.1.

Menu Option	Action
Open…	Load previously saved object settings (The object will be re-generated). Menu shortcut Ctrl+O.
Save…	Save the current object settings. Menu shortcut Ctrl+S.
Export…	Save the object displayed. Menu shortcut Ctrl+E.
Import…	Import an object created either by the recording model or stored in a MATLAB mat file. Menu shortcut Ctrl+I.
Close	Close an object loaded externally (only available when an object has been successfully imported). Menu shortcut Ctrl+C.
Copy	Copy the displayed object to the clipboard. Menu shortcut Ctrl+Y.
Print…	Print the displayed object to the current system printer. Menu shortcut Ctrl+P.
Exit	Close the Generate Object window. Menu shortcut Ctrl+X.

Table 5.4.1: Object window File menu options

5.4.2 The Plot Menu

The Generate Object window Plot menu illustrated in Fig. 5.4.4 is used to change the window plotting options and to re-generate the object.

Figure 5.4.4: The Object window Plot menu.

The menu options are summarized in Table 5.4.2.

Menu Option	**Action**
Update	Generate the object using the current object settings (unavailable when an object has been imported). Menu shortcut Ctrl+U. A statusbar will indicate the progress of the calculation.
Reflectance	Display the reflectance component of the object
Kerr	Display the Kerr component of the object (only available when magneto-optic is selected)
Real	Display the real component of the object
Imaginary	Display the imaginary component of the object
Absolute	Display the absolute component of the object
Phase	Display the phase component of the object
Contour	Select contour plot
3D	Select 3D mesh plot
Checkerboard	Select checkerboard plot
Normalised	Display normalised object w.r.t abs. maximum value
Normalised Scale	Select normalised scale (in units of wavelength)

Table 5.43.2: Object window Plot menu options

5.4.3 The Settings Menu

The Object window Settings menu illustrated in Fig. 5.4.5 is used to set the object properties. The Settings menu is unavailable when an object has been imported.

The menu options are summarized in Table 5.4.3.

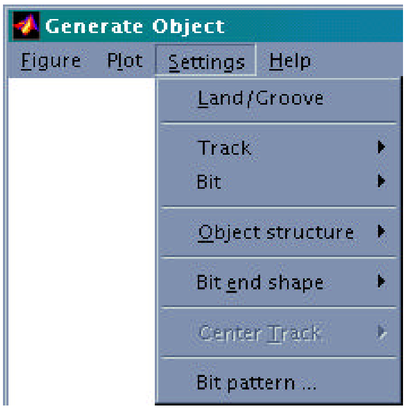


Figure 5.4.5: The Object window Settings menu.

Menu Option	**Action**
Land/Groove	Select Land/Groove object
Track	Track settings
⇒ Width …	Set track width in um.
⇒ Reflectance...	Track reflectance (range 0->1)
⇒⇒ Land …	Set track land reflectance
⇒⇒ Groove …	Set track groove reflectance (only available when Land/Groove is selected)
⇒ Phase	Track phase (range 0->pi)
⇒⇒ Land …	Set track land phase

Table 5.4.3: The Object window Settings menu options

⇒⇒ Groove …	Set track groove phase (only available when Land/Groove is selected)
⇒ Kerr Rotation	Track Kerr rotation (range –0.5 -> 0.5) (only available when magneto-optic object is selected)
⇒⇒ Land …	Set track land Kerr rotation (only available when magneto-optic object is selected)
⇒⇒ Groove …	Set track groove Kerr rotation (only available when magneto-optic object is selected and Land/Groove is selected)
Bit	Bit settings
⇒ Length …	Set bit length in um
⇒ Width …	Set bit width in um
⇒ Reflectance	Bit reflectance (range 0->1)
⇒⇒ Land …	Set bit land reflectance
⇒⇒ Groove …	Set bit groove reflectance (only available when Land/Groove is selected)
⇒ Phase	Bit phase (range 0->pi)
⇒⇒ Land …	Set bit land phase
⇒⇒ Groove …	Set bit groove phase (only available when Land/Groove is selected)
⇒ Kerr Rotation	Bit Kerr rotation (range –0.5->0.5) (only available when magneto-optic object is selected)
⇒⇒ Land …	Set bit land Kerr rotation (only available when magneto-optic object is selected)
⇒⇒ Groove …	Set bit groove Kerr rotation (only available when magneto-optic object is selected and Land/Groove is selected)
Object Structure	Object structure, single track or three tracks
⇒ Single Track	Select a single center track

Table 5.4.3: The Object window Settings menu options

⇒ Multiple Tracks	Select multiple tracks where the scan is made along the central track of three
Bit end shape	Bit end shape selection
⇒ Square	Select square end shape
⇒ Round	Select round end shape
Center Track	Select the form of the center track (only available when Land/Groove and multiple tracks are selected)
⇒ Land	Select land center track
⇒ Groove	Select groove center track
Bit Pattern …	Set the bit pattern on the object

Table 5.4.3: The Object window Settings menu options cont. (⇒ indicates a sub-menu)

5.5 Specifying the Track Characteristics

The following section describes the options available from the Settings menu for setting the object track characteristics. Note: when object settings are changed the object has to be re-generated before settings take effect, this is done by selecting "Update" (Ctrl+U) from the Plot menu. The edit box at the bottom of the Object window displays the current object settings. When the displayed object is up to date the edit box will display the message illustrated in Fig. 5.5.1, if the object is to re-generated the message illustrated in Fig. 5.5.2 will be displayed.

Figure 5.5.1: Object up to date

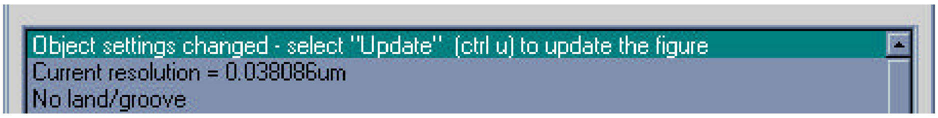


Figure 5.5.2: Object to be re-generated

5.5.1 Multiple Tracks

It has been discussed that the object generated can contain either a single track of data or multiple tracks, in both cases the main track, along which the signal is simulated, lies along the center of the object.

To specify the number of tracks on the object you select either "Single Track" or "Multiple Tracks" from the Settings->Object Structure sub menu, as illustrated in Fig. 5.5.3.

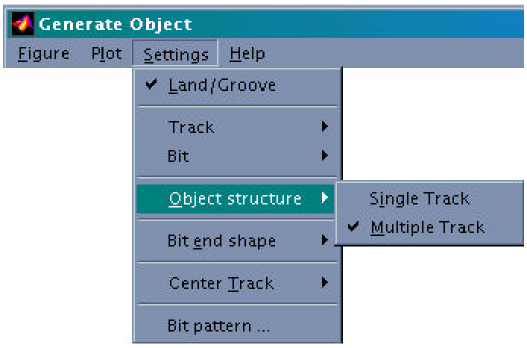


Figure 5.5.3: Object structure, single or multiple tracks

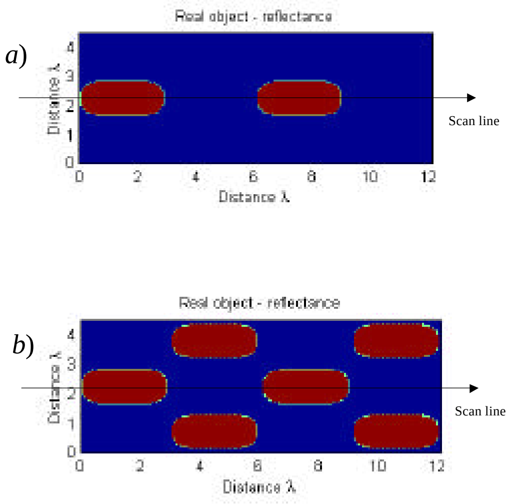


Figure 5.5.4: The effect of introducing multiple tracks, *a*) single track and *b*) multiple tracks

Figure 5.5.4 illustrates the difference between an object generated a single track and multiple tracks.

5.5.2 Land/Groove Object

The Object may be created using a land and groove structure. Here, adjacent tracks will have different phase and/or reflectance characteristics depending upon whether they are land or groove. A land/groove object is created by selecting Land/Groove from the Object window Settings menu, as illustrated in Fig. 5.5.5.

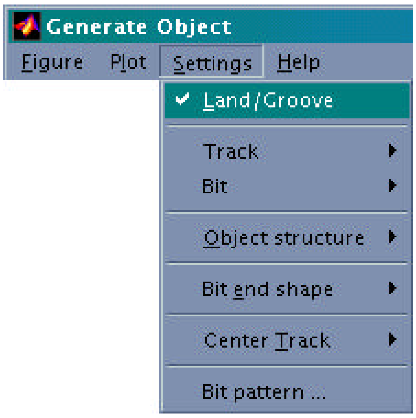


Figure 5.5.5: Selecting Land/Groove

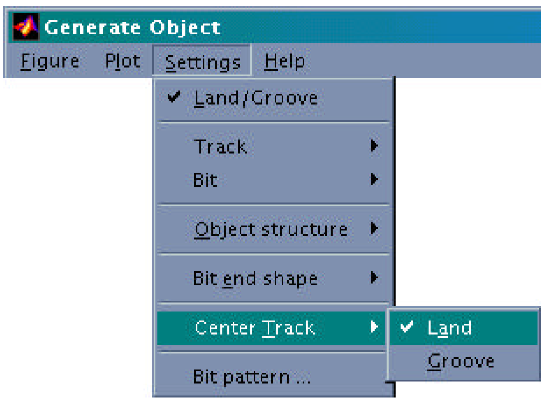


Figure 5.5.6: Center track structure

Selecting Land/Groove will make more menu options available, such as "Bit->Reflectance->Groove" and "Track->Reflectance->Groove". Also, the menu option Center Track, illustrated in Fig. 5.5.6, will become available, this allows the format of the central, main track to be specified, i.e. whether it is a land or groove structure.

Figure 5.5.7 illustrates the result of introducing a land/groove structure. Here, the land and groove have a reflectance of 70%, the groove has a phase of pi/4, and the bit reflectance is 50% with zero phase.

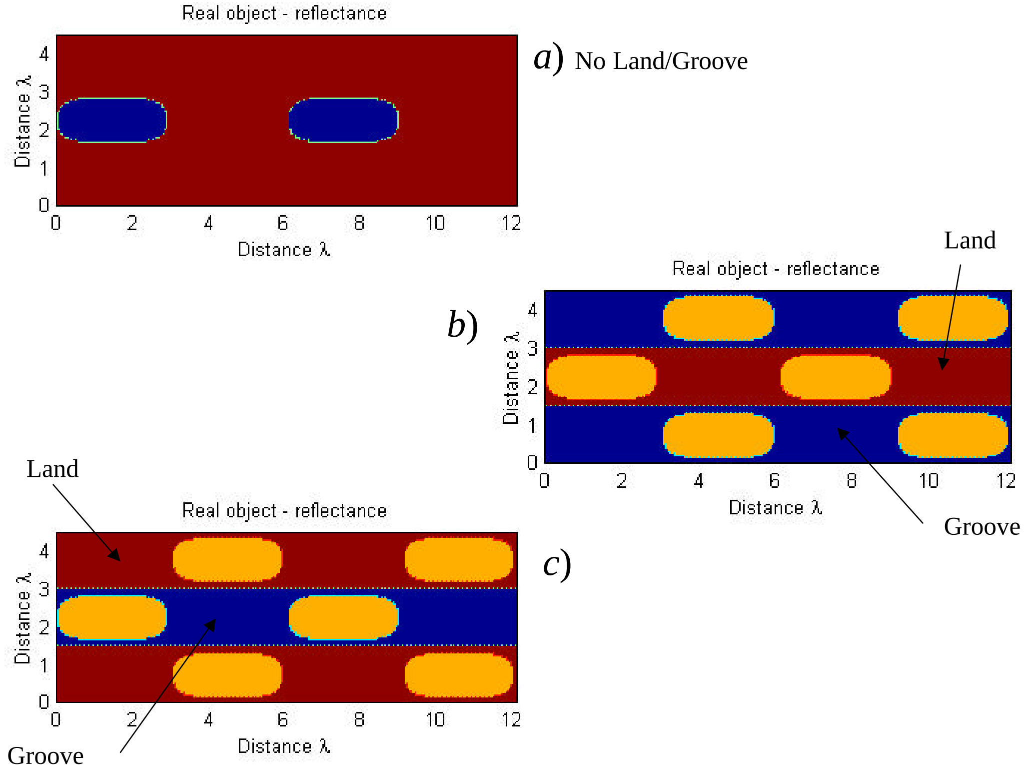


Figure 5.5.7: Examples of Land/Groove objects, *a*) No Land/Groove, *b*) Land/Groove, center track land, *c*) Land/Groove, center track groove.

5.5.3 Track Reflectance, Phase and Kerr Rotation

The track reflectance, phase and, if a magneto-optic object is selected, Kerr rotation are selected via the Object window Settings menu.

The track reflectance is set using the dialog illustrated in Fig. 5.5.8, which is opened by selecting "Track->Reflectance->Land..." from the Settings menu, as illustrated in Fig. 5.5.9.

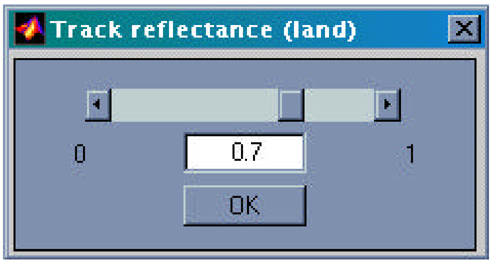


Figure 5.5.8: Track reflectance dialog

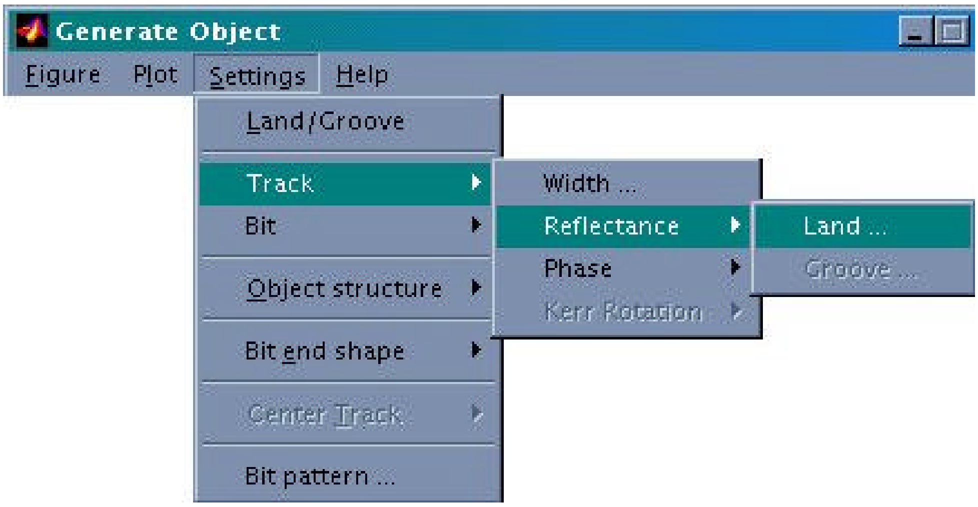


Figure 5.5.9: Selecting the Track Reflectance dialog

The track reflectance dialog is modal and so has to be closed before any other program actions may be performed. The value of reflectance, which can range from 0 to 1 (0 to

100%) is entered using either the edit box or slider. Select “OK” to confirm the track reflectance setting and close the track reflectance dialog.

The track phase is set using the dialog illustrated in Fig. 5.5.10, which is opened by selecting “Track->Phase->Land...” from the Settings menu, as illustrated in Fig. 5.5.11.

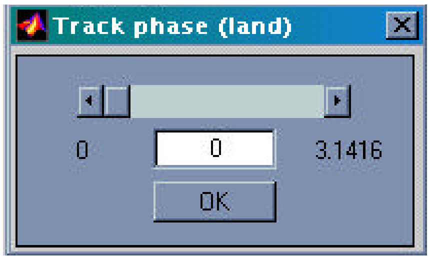


Figure 5.5.11: Track Phase dialog

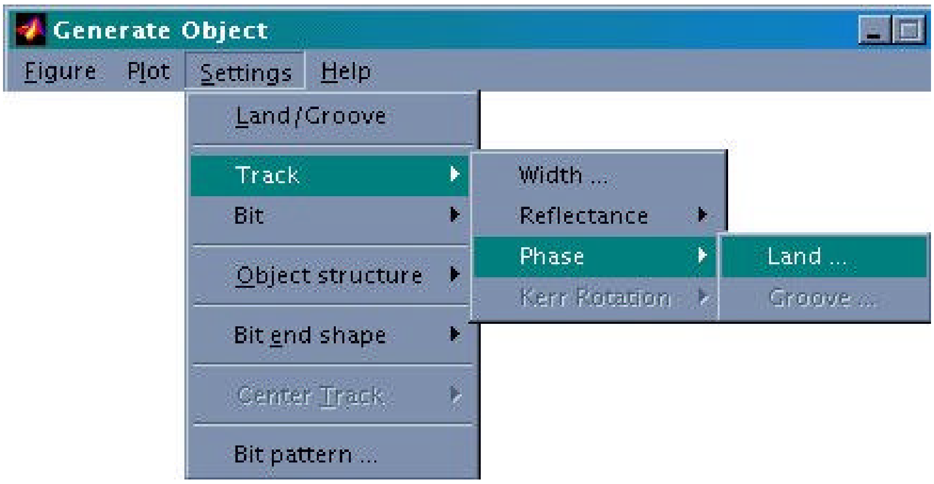


Figure 5.5.11: Selecting Track Phase

The track phase dialog is modal and so has to be closed before any other program actions may be performed. The value of phase, which can range from 0 to 3.14 (0 to π) is entered using either the edit box or slider. Select “OK” to confirm the track phase setting and close the track phase dialog.

The track Kerr rotation, magneto-optic object only, is set using the dialog illustrated in Fig. 5.5.12, which is opened by selecting "Track->Kerr Rotation->Land..." from the Settings menu, as illustrated in Fig. 5.5.13.

The track Kerr rotation dialog is modal and so has to be closed before any other program actions may be performed. The value of Kerr rotation, which can range from -0.5 to 0.5 (degrees), is entered using either the edit box or slider is updated. Select "OK" to confirm the track Kerr rotation setting and close the track Kerr rotation dialog.

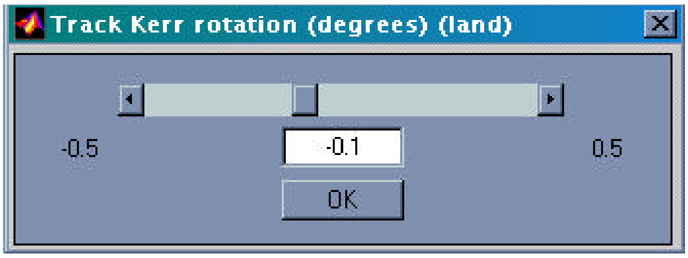


Figure 5.5.12: Track Kerr Rotation dialog (MO objects only)

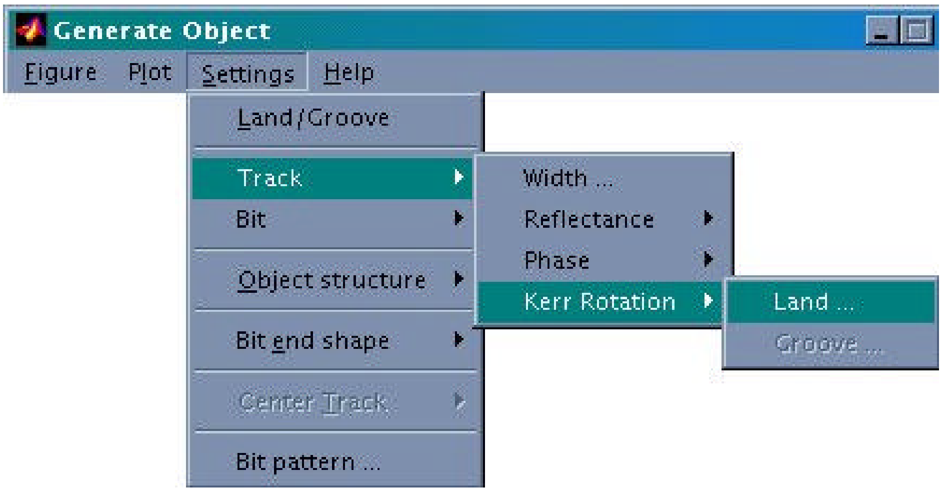


Figure 5.5.13: Selecting Track Kerr Rotation (MO objects only)

If a Land/Groove object is selected then there are extra menu options available to set the groove characteristics. To set the Land track reflectance, phase and Kerr rotation characteristics follow the same procedure outlined in the previous section. To set the Groove track characteristics follow a similar procedure but select the "Groove..." option from the menu.

5.5.4 Track Width

The track width is entered using the dialog illustrated in Fig. 5.5.14, which is opened by selecting “Track->Width...” from the Settings menu, as illustrated in Fig. 5.5.15.

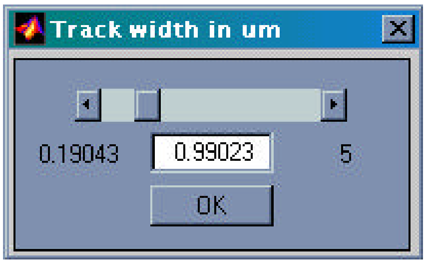


Figure 5.5.14: The Track Width dialog

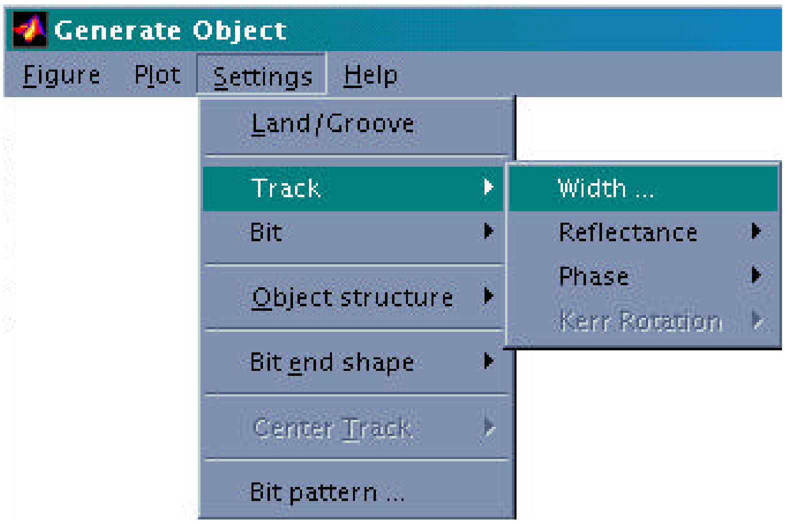


Figure 5.5.15: Opening the Track Width Dialog

The track width dialog is modal and so has to be closed before any other program actions may be performed. The width is entered, in um, using either the edit box or slider. Select “OK” to confirm the track width setting and close the track width dialog.

The minimum track width is determined by the current bit width and the default maximum track width is 5um. Note: the resolution of the track width is determined by the model resolution.

5.6 Specifying the Bit Characteristics

The following section describes the options available from the Settings menu for setting the object bit characteristics. Note: when object settings are changed the object has to be re-generated before settings take effect, this is done by selecting “Update” (Ctrl+U) from the Object window Plot menu.

5.6.1 Bit Reflectance, Phase and Kerr Rotation

The bit characteristics are set in much the same way as for the tracks. The bit reflectance, phase and, if a magneto-optic object is selected, Kerr rotation are selected via the Object window Settings menu.

The bit reflectance is set using the dialog illustrated in Fig. 5.6.1, which is opened by selecting “Bit->Reflectance->Land...” from the Settings menu, as illustrated in Fig. 5.6.2.

Figure 5.6.1: Bit reflectance dialog

The bit reflectance dialog is modal and so has to be closed before any other program actions may be performed. The value of reflectance, which can range from 0 to 1 (0 to 100%) is entered using either the edit box or slider. Select “OK” to confirm the bit reflectance setting and close the bit reflectance dialog.

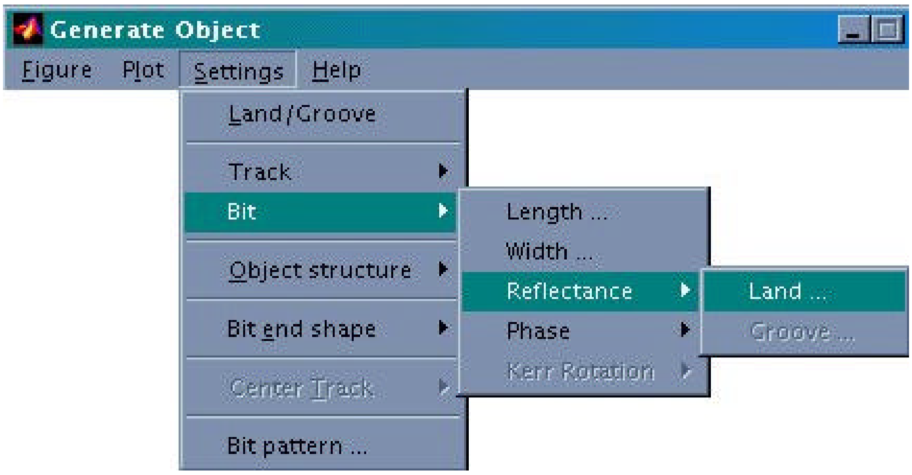


Figure 5.6.2: Selecting Bit Reflectance

The bit phase is set using the dialog box illustrated in Fig. 5.6.3, which is opened by selecting “Bit->Phase->Land...” from the Settings menu, as illustrated in Fig. 5.6.4.

Figure 5.6.3: Bit Phase dialog

The bit phase dialog is modal and so has to be closed before any other program actions may be performed. The value of phase, which can range from 0 to 3.14 (0 to π) is entered using either the edit box or slider. Select “OK” to confirm the bit phase setting and close the bit phase dialog.

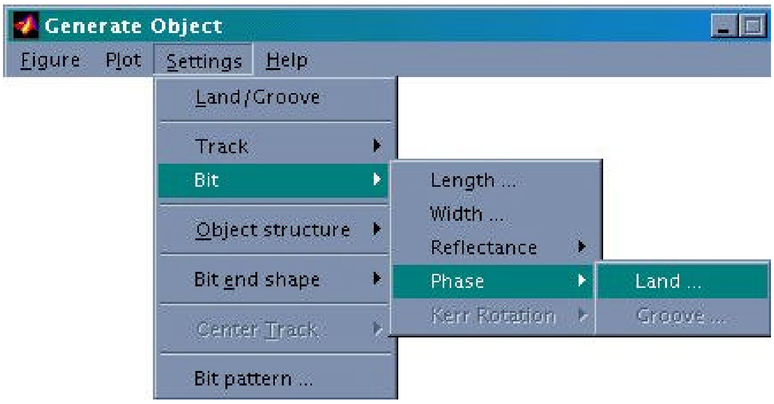


Figure 5.6.4: Selecting Bit Phase

The bit Kerr rotation, magneto-optic object only, is set using the dialog illustrated in Fig. 5.6.5, which is opened by selecting "Bit->Kerr Rotation->Land..." from the Settings menu, as illustrated in Fig. 5.6.6.

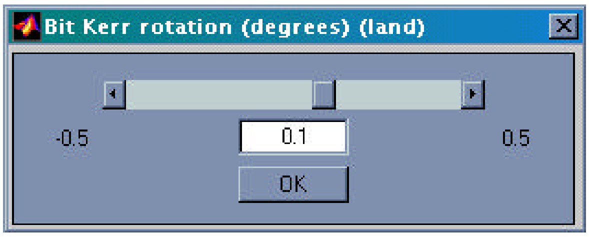


Figure 5.6.5: Bit Kerr Rotation dialog (MO objects only)

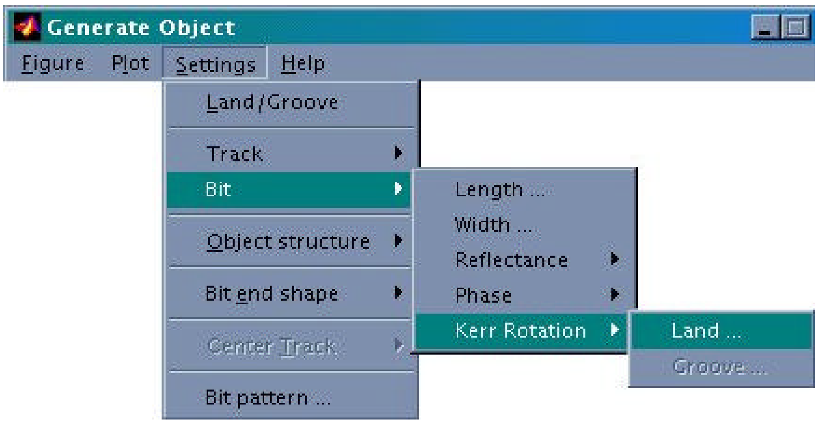


Figure 5.6.6: Selecting Bit Kerr Rotation (MO objects only)

The bit Kerr rotation dialog is modal and so has to be closed before any other program actions may be performed. The value of Kerr rotation, which can range from -0.5 to 0.5 (degrees), is entered using either the edit box or slider. Select “OK” to confirm the bit Kerr rotation setting and close the bit Kerr rotation dialog.

If a Land/Groove object is selected then there are extra menu options available to set the groove characteristics. To set the Land bit reflectance, phase and Kerr rotation characteristics follow the same procedure outlined in the previous section. To set the Groove bit characteristics follow a similar procedure but select the “Groove...” option instead of the “Land...”.

5.6.2 Bit Width

The bit width is entered using the dialog illustrated in Fig. 5.6.7, which is opened by selecting “Bit->Width...” from the Settings menu, as illustrated in Fig. 5.6.8.

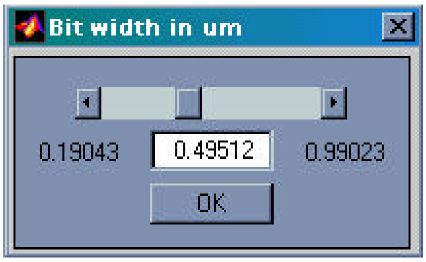


Figure 5.6.7: The Bit Width dialog

The bit width dialog is modal and so has to be closed before any other program actions may be performed. The width is entered, in um, using either the edit box or slider. Select “OK” to confirm the bit width setting and close the bit width dialog.

The minimum bit width is given by 5×resolution and the default maximum bit width is the current track width. Note: the resolution of the bit width is determined by the model resolution.

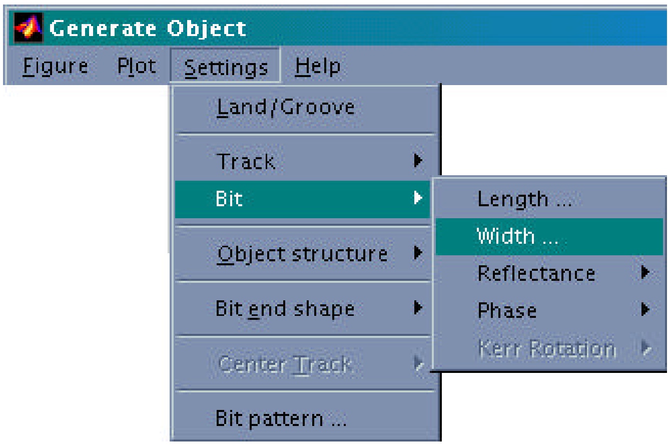


Figure 5.6.8: Opening the Bit Width Dialog

5.6.3 Bit Length

The bit length is entered using the dialog illustrated in Fig. 5.6.9, which is opened by selecting “Bit->Length...” from the Settings menu, as illustrated in Fig. 5.6.10.

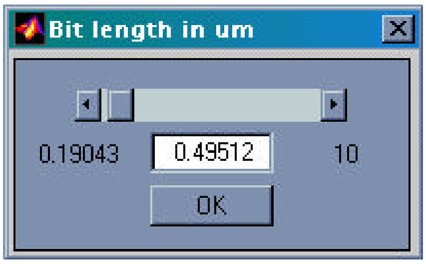


Figure 5.6.9: The Bit Length dialog

The bit length dialog is modal and so has to be closed before any other program actions may be performed. The length is entered, in um, using either the edit box or slider. Select “OK” to confirm the bit length setting and close the bit length dialog.

The minimum bit length is given by the minimum bit width and the default maximum bit width is the 10um. Note: the resolution of the bit width is determined by the model resolution.

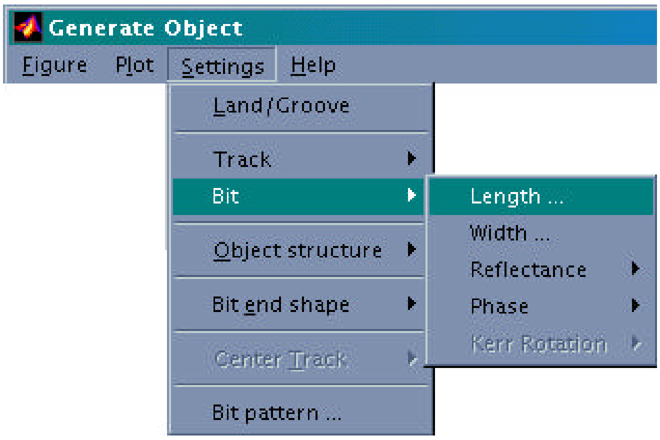


Figure 5.6.10: Opening the Bit Length Dialog

5.6.4 Bit End-Shape

The bit end shape is set from the Settings menu, as illustrated in Fig. 5.6.11.

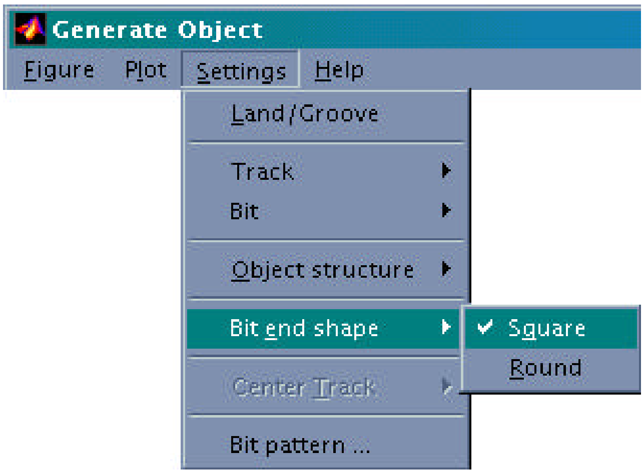


Figure 5.6.11: Selecting the bit end shape

The menu options are square and circular. If square is selected then the resulting bits will be rectangular; however, if circular is selected then the resulting bits will be cigar shaped.

Note: if a circular end shape is selected and the length of the bit, which is dependent on the bit length and data pattern, is less than the bit width, then the program will automatically revert to square ends.

5.6.5 Data

The data pattern displayed on the object is entered using the Data Pattern dialog illustrated in Fig. 5.6.12, which is opened by selecting “Bit Pattern...” from the Settings menu, as illustrated in Fig. 5.6.13.

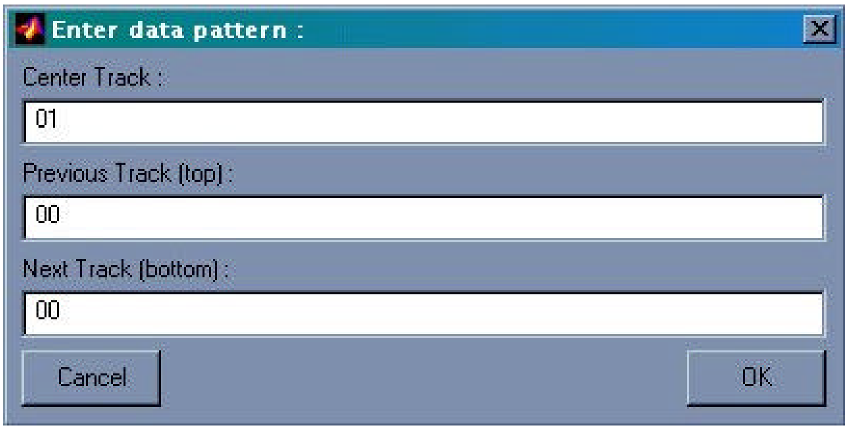


Figure 5.6.12: Data Pattern dialog

The bit pattern is entered into the bit pattern dialog as a series of 1’s and 0’s. Invalid characters are filtered out by the program upon selecting ‘OK’. An individual data bit, 1 or 0, represents one recorded channel bit of length and width specified.

All three tracks of data are entered using the data pattern dialog. The center, main track data is entered into the top edit box and the other tracks into the lower two edit boxes, if Single Track is selected then the data in these edit boxes will be ignored.

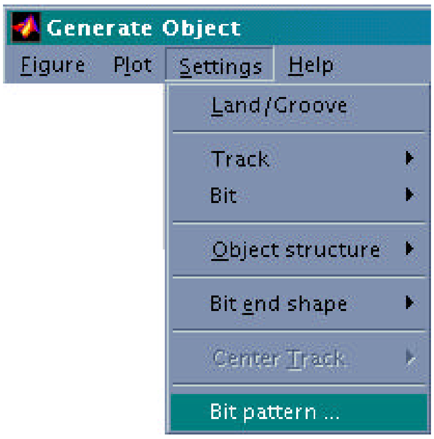


Figure 5.6.13: Selecting the Bit Pattern

The size of the object is determined by the number of bits in the data stream and the bit length. If Multiple Tracks is selected, then the size of the object depends upon the longest data pattern of the three tracks; they do not have to be the same length. The data pattern can be of any length, the only limitation is the speed of execution.

5.7 Importing an Externally Generated Object

The readout model is not restricted to simulations using objects generated using the object window, externally generated objects, such as those produced by the recording model, may be easily imported into the object window. These objects may be of any size, providing they are larger than the matrix representing the focused spot, see §6.2, and of any arbitrary resolution since they will be interpolated to match the resolution set in the program, see §3.

To import an object select "Import..." from the File menu, as illustrated in Fig. 5.7.1. It is important that the focused spot has been generated prior to importing the object since the size of the focused spot matrix must be known. If the focused spot matrix has not been generated, using the Focused Spot window, see §6.2, then the dialog illustrated in Fig.

5.7.2 will be displayed. If the focused spot matrix has been generated then the dialog illustrated in Fig. 5.7.3 will be displayed.

The source of the object needs to be selected. Selecting "Recording model object" allows data stored in the recording model format to be loaded. Selecting "Other" allows data stored in a general format to be loaded.

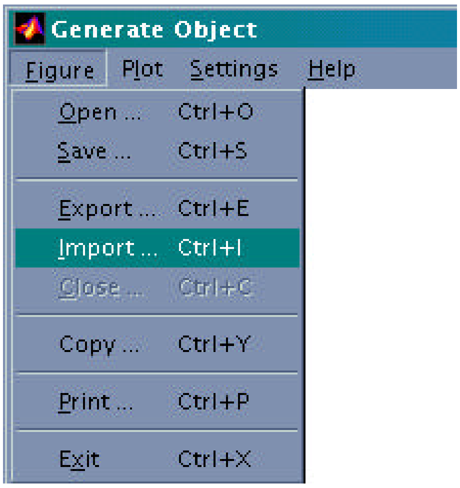


Figure 5.7.1: Selecting Import from the File menu

Figure 5.7.2: Focused spot needs to be generated error dialog

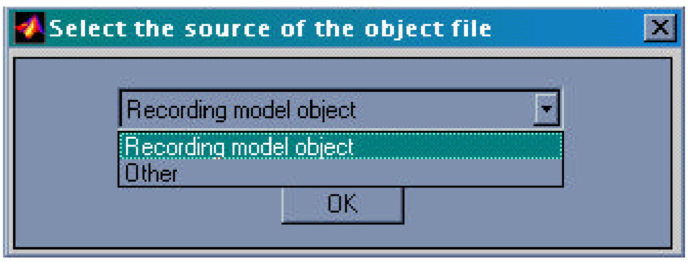


Figure 5.7.3: Which object type dialog

5.7.1 Recording Model Object

To import a recording model object select "Recording model object" from the object source dialog, an open file dialog box will be displayed.

Select the path and filename of the file containing the data. If the data contained in the file is invalid then the error dialog illustrated in Fig. 5.7.4 will be displayed and no object will be loaded.

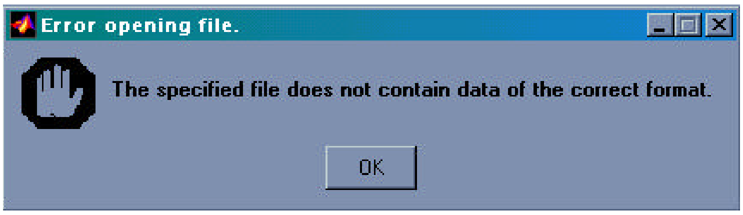


Figure 5.7.4: Invalid object file error dialog

If the file contains a valid recording model object, the program next checks the wavelength stored with the object data, if it is different from that currently set the warning dialog illustrated in Fig. 5.7.5 will be displayed and the program will continue to import the object.

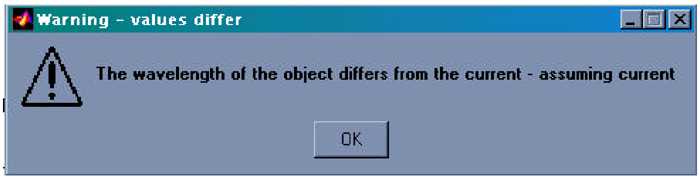


Figure 5.7.5: Recorded wavelength differs warning dialog

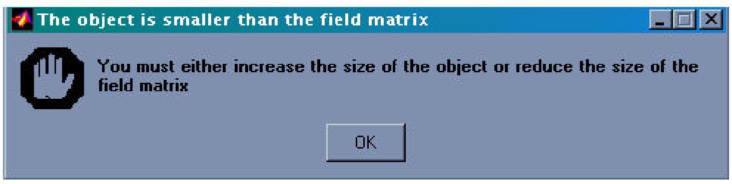


Figure 5.7.6: Object is too small error dialog

The program next checks to make sure the object is bigger than the focused spot matrix, see §6.2. If the object is too small then a readout signal cannot be generated, hence, the program requests that you either reduce the size of the focused spot matrix or increase the size of the object, as illustrated in Fig. 5.7.6.

Next the format of the data needs to be selected, since the recording model does not save the form of the object. The object type is selected using the dialog illustrated in Fig. 5.7.7.

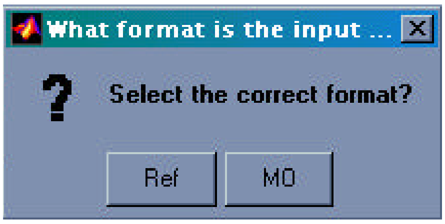


Figure 5.7.7: Select the object type

The imaging method is changed due to the object type selected. If “Ref” is selected then the maximum reflectance of the object needs to be entered using the dialog illustrated in Fig. 5.7.8.

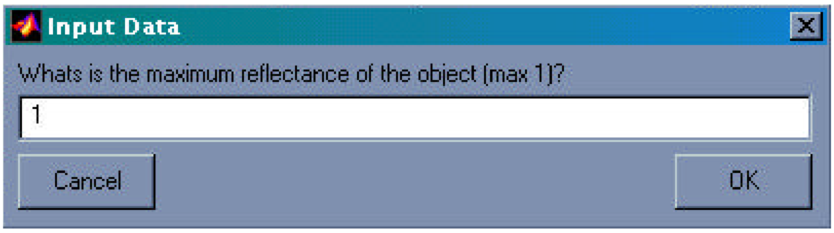


Figure 5.7.8: Enter the maximum reflectance dialog

If the resolution of the object differs from that currently set, then the interpolation dialog box illustrated in Fig. 5.7.9 will be displayed, which allows the form of interpolation to be selected.

The interpolation options are nearest, linear, cubic and spline. Select the preferred method of interpolation and the object will be interpolated and displayed in the object window, as illustrated in Fig. 5.7.10.

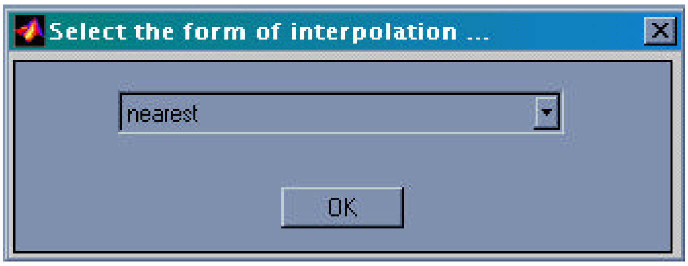


Figure 5.7.9: Interpolation dialog box

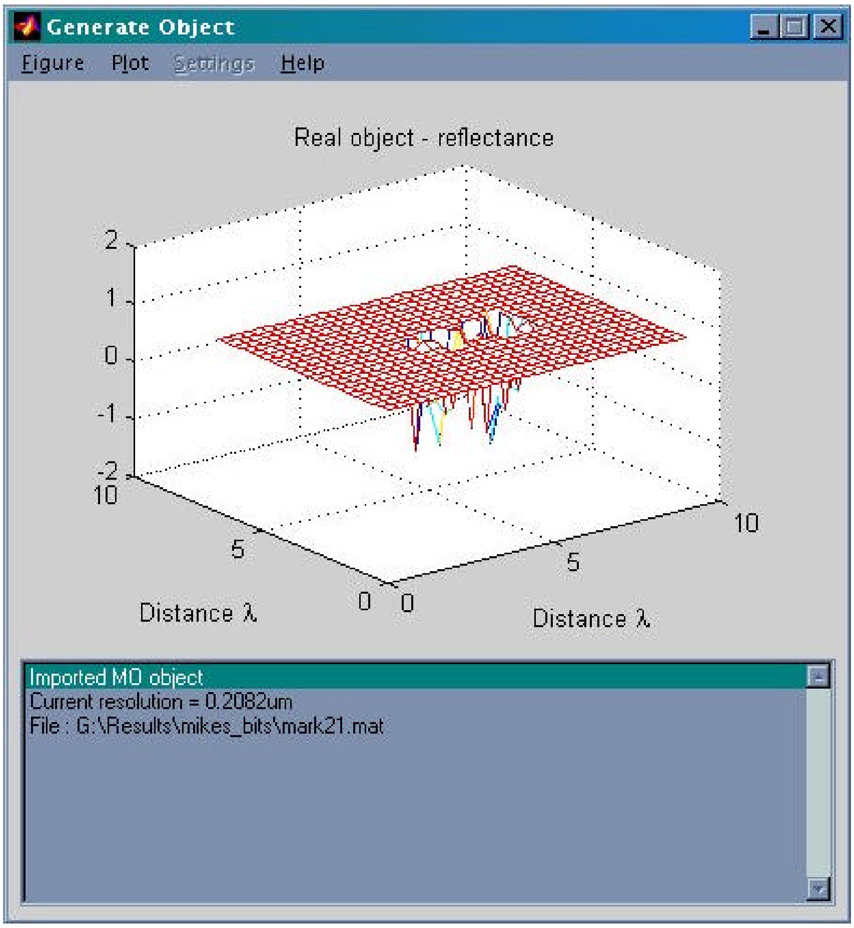


Figure 5.7.10: Imported object displayed

When an object has been successfully imported, the Plot->Update menu option and Settings menu will be disabled. Also the resolution will be fixed at the current value.

To close the imported object simply select "Close" from the File menu, as illustrated in Fig. 5.7.11.

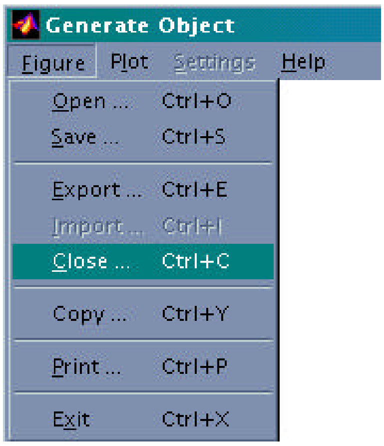


Figure 5.7.11: Close the imported object

If "MO" is selected then the maximum Kerr rotation of the object needs to be entered using a similar dialog to that for reflectance illustrated in Fig. 5.7.8. Again, if the resolution is different then the interpolation method needs to be selected from the interpolation dialog of Fig. 5.7.9. Finally, the program requests the reflectance of the object to be entered using the dialog illustrated in Fig. 5.7.8.

5.7.2 Other Object

To import an object generated in MATLAB select "Other" from the object source dialog. An object type dialog, similar to that of Fig. 5.7.7, is displayed. Again, the imaging method is changed depending upon the object type selected.

If "Ref" is selected the program will open an open file dialog, select the path and filename of the file containing the object. The file must contain a 2-D object, called ref_obj, which represents the reflectance properties of the object (real and imaginary). If the contents of the file are invalid then the error dialog illustrated in Fig. 5.7.12 will be displayed.

If “MO” is selected the program will request for two files to be selected. First, the file contain the reflectance object, ref_obj, then the file containing the Kerr rotation object, which contains the object kerr_obj. Checks will be made to ensure the two objects are the same size. In both cases if the contents of the file an invalid then a similar error dialog to that of Fig. 5.7.12 will be displayed and the object will fail to load.

Figure: 5.7.12: Invalid object file error dialog

If the contents of the files are valid, then the program next requests you to enter the resolution of the object using the dialog illustrated in Fig. 5.7.13.

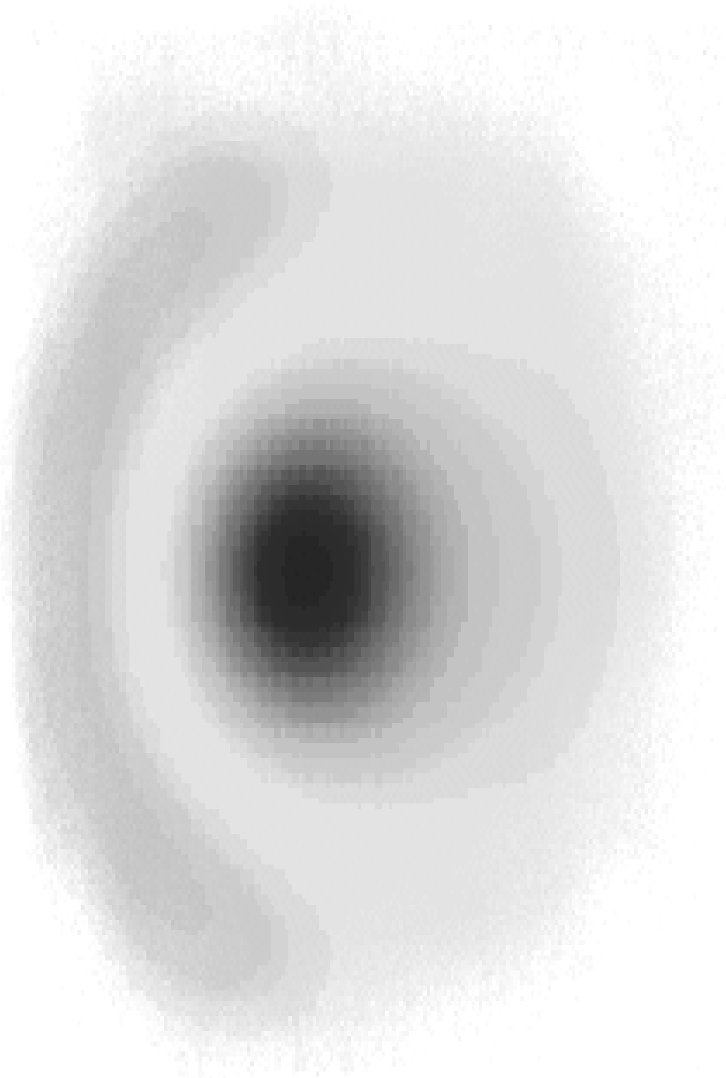
Figure 5.7.13: Enter the object resolution edit box

By default the edit dialog illustrated in Fig. 5.7.13 opens with the current resolution set, if this is selected then no object interpolation will be performed. However, if another value is entered (in normalized units of wavelength) then the interpolation method will be requested using the interpolation dialog illustrated in Fig. 5.7.9.

Again, when the object has been successfully imported, the Plot->Update menu option and Settings menu will be disabled, and the resolution will remain fixed.

To close the imported object simply select “Close” from the File menu, as illustrated in Fig. 5.7.11.

Chapter 6



The Analysis Menu

6.1 Introduction

The following chapter describes the options available from the Program Interface Analysis menu illustrated in Fig. 6.1.1.

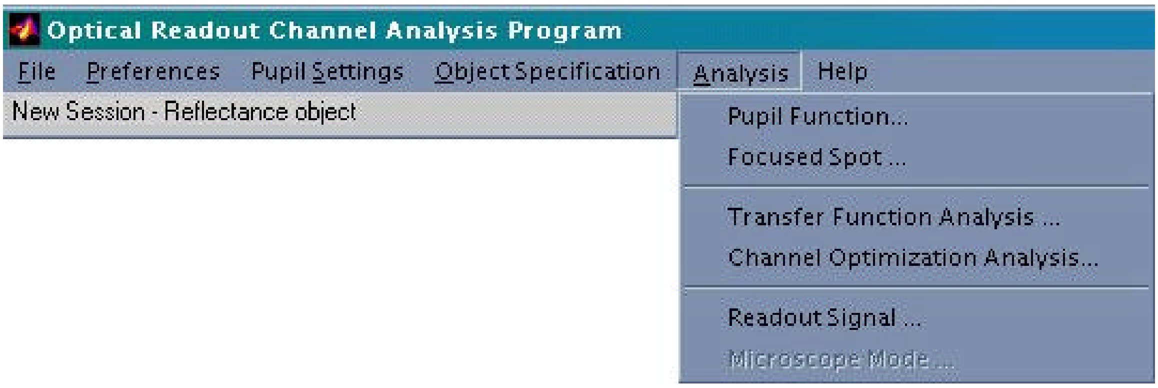


Figure 6.1.1: The Analysis menu

Table 6.1.1 summarizes the menu options.

Menu shortcut: Alt+A

Menu options:	**Action:**	**see §**
Pupil Function…	Open the pupil function generation window	4.5
Focused Spot…	Open the focused spot generation window	6.2
Transfer Function Analysis…	Open the transfer function generation window	6.4
Channel Optimization Analysis…	Open the channel optimization window	6.5
Readout Signal…	Open the readout signal generation window	6.6
Microscope Mode…	Open the microscope model readout window	6.7

Table 6.1.1: Analysis menu options

The Analysis menu is used to access the windows that perform the variety of analysis options available using the optical readout model.

Some of the analysis tools options require that other menu options have been selected. For example:

The Focused Spot window, opened when selecting “Focused Spot...”, requires that the pupil functions have been generated, by opening the Pupil Function window, see §4.5.

The Readout Signal window, opened by selecting “Readout Signal...”, requires that the focused spot profiles and object have been generated, by opening the Focused Spot window, see §6.2, and the Object window, see §5.4, respectively.

In most cases if an analysis option requires some data that has not yet been generated, the program will display a warning dialog.

6.2 Generating the Focused Spot

The focused spots are generated and displayed using the Focused Spot window, illustrated in Fig. 6.2.1, which is opened by selecting “Focused Spot...” from the Analysis menu, as illustrated in Fig. 6.2.2.

Note: the Pupil Function window needs to be opened prior to opening the Focused Spot window so that the aperture pupil functions are generated, otherwise the error dialog illustrated in Figure 6.2.3 will be displayed.

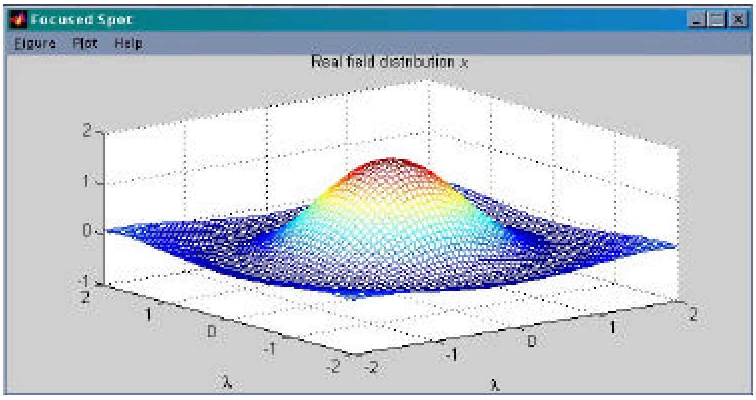


Figure 6.2.1: The Focused Spot window

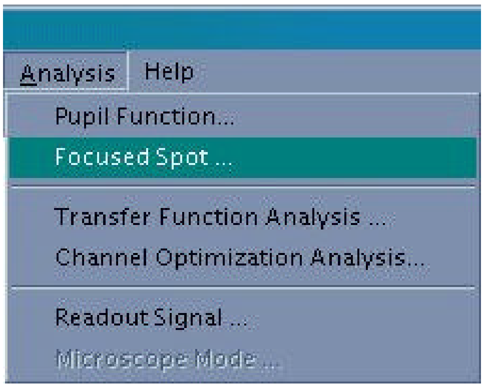


Figure 6.2.2: Opening the Focused Spot window

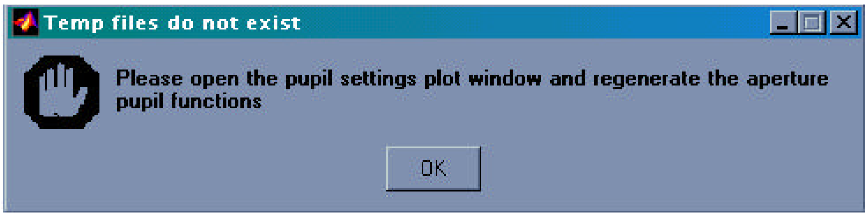


Figure 6.2.3: Pupil Functions do not exist error dialog

On opening the focused spot window the focused spots will be generated, a statusbar will indicate the process of the calculation.

Actions regarding the Focused Spot window are accessed using the Figure and Plot menus.

6.2.1 The Figure Menu

The Focused Spot window Figure menu illustrated in Fig. 6.2.4 is used to Print, Copy, Save the focused spot and to close the window.

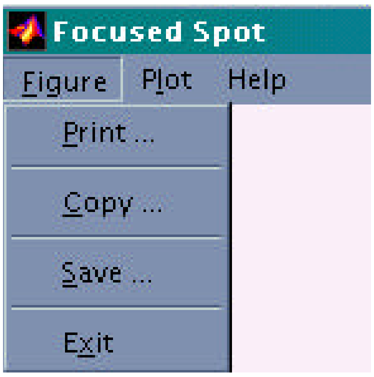


Figure 6.2.4: Focused Spot window Figure menu

The menu options are summarized in Table 6.2.1.

Menu Option	**Action**
Print	Print the displayed focused spot on the current system printer
Copy	Copy the displayed focused spot to the clipboard
Save	Save the current focused spot to a standard *.mat format file.
Exit	Close the Focused Spot window

Table 6.2.1: Focused Spot window Figure menu options

6.2.2 The Plot Menu

The Focused Spot window Plot menu, illustrated in Fig. 6.2.5, is used to change the format of the displayed focused spot profile(s).

The menu options are summarized in Table 6.2.2.

Figure 6.2.5: The Focused Spot window Plot menu.

Menu Option	**Action**
Update	Re-generate the focused spot. Menu shortcut Ctrl+U.
x field	Display the *x* polarized field component. Menu shortcut Ctrl+X.
y field	Display the *y* polarized field component. Menu shortcut Ctrl+Y.
z field	Display the z polarized field component. Menu shortcut Ctrl+Z. (only available when vector diffraction is selected)

Table 6.2.2: Focused Spot window Plot menu options

xy & z field	Display the *x*, *y* and *z* polarized field component. Menu shortcut Ctrl+F. (only available when vector diffraction is selected)
Total field	Display the total field (x^2+y^2+z^2)
Real	Display the real field component. Menu shortcut Ctrl+R.
Imaginary	Display the imaginary field component. Menu shortcut Ctrl+I.
Intensity	Display the total intensity field component. Menu shortcut Ctrl+T.
Phase	Display the phase field component. Menu shortcut Ctrl+P.
Contour	Select Contour plot.
3D	Select 3D plot.
Checkerboard	Select checkerboard plot.
Axial Plot	Axial plot.
⇒ Tangential	Select axial plot in the tangential (along track) direction.
⇒ Radial	Select axial plot in the radial (across track) direction.
Hold	Hold the displayed axial plots. (only available when an axial plot is selected, disables Contour, 3D and Checkerboard plot options)
Normalized	Display normalized field component
Normalized Scale	Display normalized scale (in units of wavelength)
Include MSR	Select to include the MSR mask in the displayed focused spot, see §4.8.
Zoom …	Zoom in and out of the field distribution. See §6.3.

Table 6.2.2: Focused Spot window Plot menu options cont. ⇒ indicates a sub-menu

6.3 Specifying the Size of the Focused Spot

Initially, the focused spot window does not display the entire matrix representing the focused field distribution, but by default, a central portion 4λ square; this is the extent of the field distribution used in the simulation, to help speed up the calculation. It is possible to zoom in or out of the field distribution, and hence, change the extent of the field distribution used in the simulation. To change the zoom value select “Zoom...” from the focused spot window plot menu, this will open the dialog illustrated in Fig. 6.3.1.

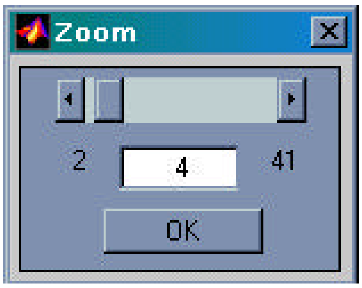
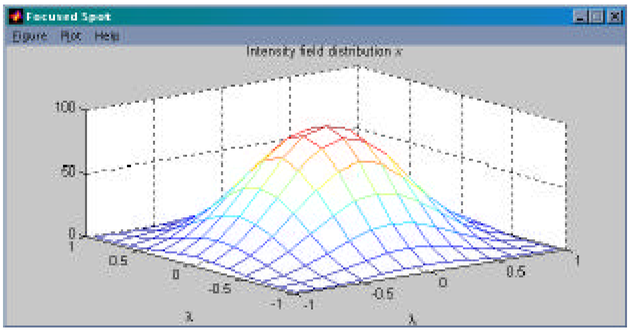


Figure 6.3.1: The Zoom dialog

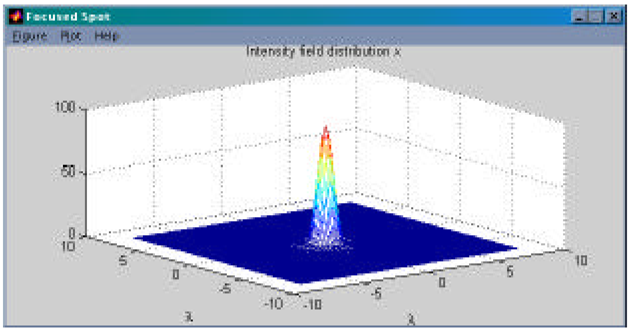
The Zoom value is given in units of wavelength, the minimum value is two and the maximum is determined by the size of the FFT matrix, see §3.2.3. The zoom value can be changed using either the edit box or slider. Select ‘OK’ to conform the zoom setting and the focused spot window will update the display with the new zoom setting.

The larger the zoom value the more accurate the simulation, since more of the focused spot will be used in the calculation; however, a large zoom value results in larger matrices that will reduce the speed of the calculation and consume more memory. Conversely, the smaller the zoom value, the less accurate the simulation; however, the calculation will be performed much quicker, and will require less memory.

Figure 6.3.2 illustrates the same field distribution but displayed at different zoom values.



a)



b)

Figure 6.3.2: The same field distribution displayed with different zoom values, *a*) a zoom value of two and *b*) a zoom value of 16.

It can be clearly seen that the distribution illustrated in Fig. 6.3.2*b*) will offer the greatest accuracy since all the field distribution will be used in the simulation process. However, the truncated distribution of Fig. 6.3.2*a*), which will be less accurate, will speed the simulation process significantly, due to the reduced number of data points in the matrix.

The zoom value is a compromise between accuracy and speed of execution.

Note: the size of the focused field matrix determines the minimum size of the object matrix.

6.4 Transfer Function Analysis

The transfer function analysis window illustrated in Fig. 6.4.1, is used to investigate the optical transfer function, sometimes referred to the Partially Coherent Transfer Function (PCTF), and is opened by selecting "Transfer Function Analysis..." from the program interface Analysis menu.

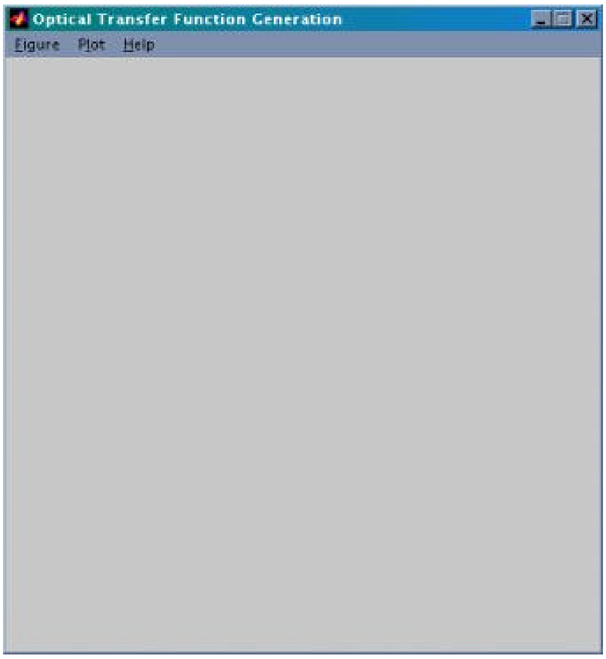


Figure 6.4.1: The Transfer Function Analysis window

Initially the transfer function analysis window is blank.

The optical transfer function, OTF, represents the spatial frequency response of the optical channel and has a cut-off spatial frequency of $2NA/\lambda$, for circular objective and collector apertures of equal radii under uniform incident illumination. The optical transfer function is calculated using a convolutional type process involving the objective aperture pupil function, its complex conjugate and the squared modulus of the collector aperture pupil function. Hence, the spatial frequency response of the optical channel is dependent upon the objective pupil characteristics and the incident illumination. The collector aperture pupil function has little effect upon the 'quality' of the imaging system. The advantage of analyzing the OTF is its independence from the properties of the object being imaged.

Since the OTF is generated using the aperture pupil functions, they need to be generated first using the pupil function window, see § 4.5.

Note: The OTF is generated using a function pre-compiled for use with an IBM AT architecture (i.e. Windows95, WindowsNT etc) and as a result will not work on any other operating system, such as UNIX.

The Transfer Function Analysis window Figure and Plot menus are described below.

6.4.1 The Figure menu

The Transfer Function Analysis window Figure menu, illustrated in Fig. 6.4.2, is used to Open, Save, Copy and Print the displayed optical transfer function and to close the window.

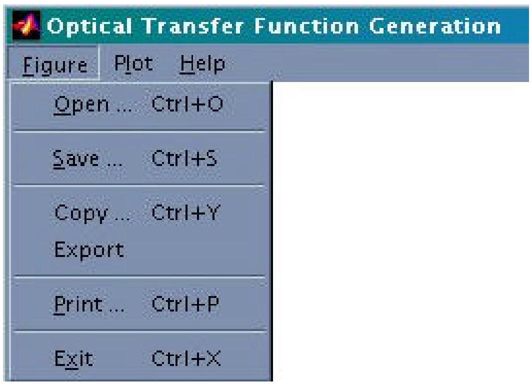


Figure 6.4.2: The Transfer Function Analysis window Figure menu.

The menu options are summarized in Table 6.4.1.

Menu Option	Action
Open…	Open a previously saved OTF. Menu shortcut Ctrl+O.
Save…	Save the currently displayed OTF. Menu shortcut Ctrl+S.
Copy…	Copy the currently displayed OTF to the clipboard. Menu shortcut Ctrl+Y.
Export	Export the currently displayed OTF to the Matlab workspace. The OTF will be named “pctf”.
Print…	Print the currently displayed PCTF on the current system printer. Menu shortcut Ctrl+P.
Exit	Close the Transfer Function Analysis window. Menu shortcut Ctrl+X.

Table 6.4.1: Transfer Function Analysis window Figure menu options

6.4.2 The Plot Menu

The Transfer Function Analysis window Plot menu, illustrated in Fig. 6.4.3, is used to generate the OTF and to change the format of the displayed OTF.

The menu options are summarized in Table 6.4.2.

Menu Option	Action
Generate	Generate the OTF. Menu shortcut Ctrl+G.
x polarized field	Use the x polarized field distribution in the objective pupil for calculating the OTF.
y polarized field	Use the y polarized field distribution in the objective pupil for calculating the OTF.

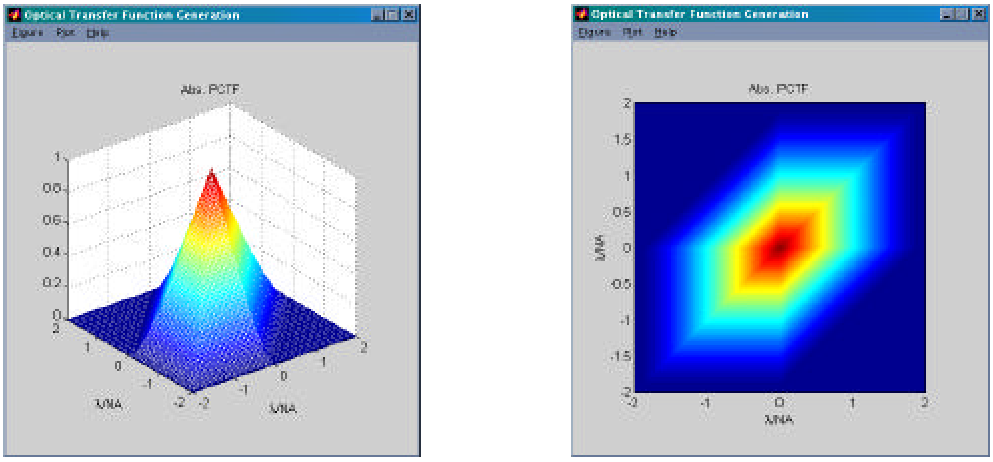
Table 6.4.2: Transfer Function Analysis window Figure menu options

Real	Display the real component of the OTF. Menu shortcut Ctrl+R.
Imaginary	Display the imaginary component of the OTF. Menu shortcut Ctrl+I.
Absolute	Display the absolute component of the OTF. Menu shortcut Ctrl+A.
Phase	Display the phase component of the OTF. Menu shortcut Ctrl+H.
Contour	Select Contour plot
3D	Select 3D Mesh plot
Checkerboard	Select Checkerboard plot
Axial Plot	Axial Plot
⇒ Tangential	Select axial plot in the tangential direction
⇒ Radial	Select axial plot in the radial direction
Hold	Hold the displayed axial plots (only available when an axial ploy is selected)
Normalized	Display the normalized OTF
Normalized Scale	Display normalized scale (in units of NA/λ)

Table 6.4.2: Transfer Function Analysis window Figure menu options cont.

Figure 6.4.3: The Transfer Function Analysis window Plot menu

Figure 6.4.4 illustrates plots of an OTF generated with circular apertures of equal radii under uniform incident illumination linearly polarized in x.



a) *b*)

Figure 6.4.4: Plots of OTF generated using the Transfer Function Analysis window, *a*) 3D plot and *b*) checkerboard plot.

Figure 6.4.5 illustrates a comparison of the axial response of the OTF for different illumination conditions; the OTF has been generated with circular apertures of equal radii.

Figure 6.4.5 clearly illustrates the effect that the form of the incident illumination has on the spatial frequency response of the optical system.

It can be seen that the OTF allows a quantitative comparison of the imaging characteristics of different imaging configurations.

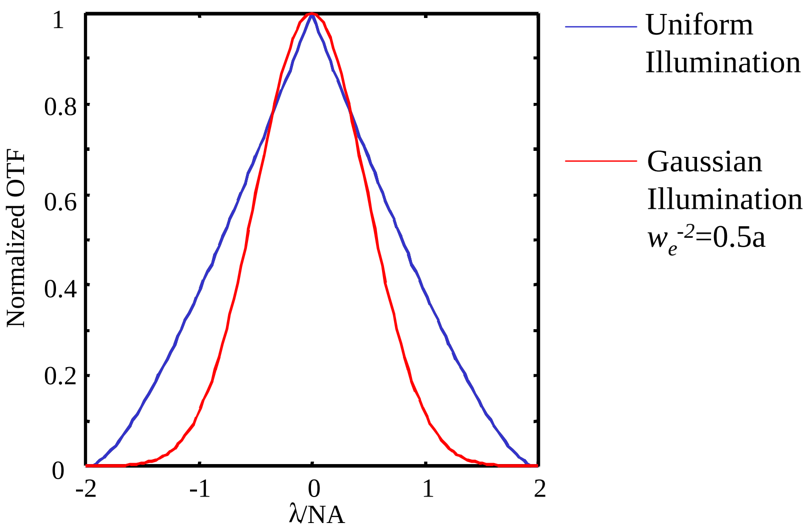


Figure 6.4.5: Axial plots of OTF, for circular apertures or equal radii under different illumination conditions

6.5 Channel Optimization Analysis

The Channel Optimization analysis window, illustrated in Fig. 6.5.1, is used to investigate methods of OTF optimization, and is opened by selecting "Channel Optimization Analysis..." from the program interface Analysis menu.

It has been discussed previously that the OTF represents the spatial frequency response of the optical readout channel, and is generated using a convolutional type operation involving the objective and collector aperture pupil functions. Any modification of the aperture pupil functions in any way, i.e. obscurations, aberrations or illumination, will result in a change in the spatial frequency response of the channel. The axial response of the OTFcan be used to understand the effects of these changes.

In many applications, it is often quite useful to tailor the response of the optical channel to suit a desired need. For example, we may require the readout channel to act as a band-pass filter; we could do this by placing a shading band in the objective aperture. The Channel Optimization window has been designed to facilitate the investigation of such filtering schemes using the tools available in the optical readout model.

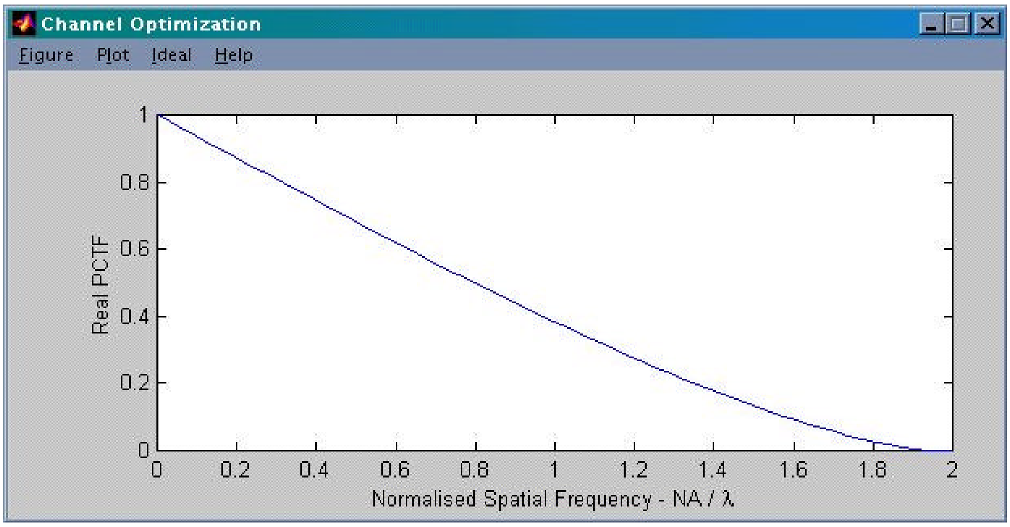


Figure 6.5.1: The Channel Optimization Analysis window.

Initially, the Channel Optimization analysis window displays the axial OTF generated from the aperture pupil functions produced and saved by the Pupil Function window, hence, the pupil function window must be open. Figure 6.5.2 illustrates how placing an obscuring shading band in the objective aperture pupil (see §4.4) produces a band-pass spatial frequency characteristic.

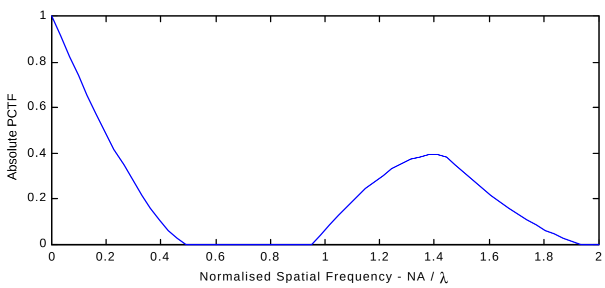


Figure 6.5.2: Modified OTF

The channel optimization analysis window is specifically aimed at investigating the application of Partial Response (PR) filtering in the optical domain rather than the electronic domain.

The channel optimization Figure, Plot and Ideal menus are described below.

6.5.1 The Figure Menu

The Channel Optimization Analysis window Figure menu illustrated in Fig. 6.5.3 is used to Print, Copy, Open and Save OTF axial responses and to close the window.

The menu options are summarized in Table 6.5.1.

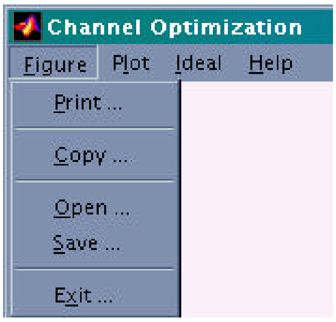


Figure 6.5.3: The Channel Optimization Analysis window Figure menu

Menu Option	**Action**
Print…	Print the displayed axial OTF to the current system printer
Copy…	Copy the displayed axial OTF to the clipboard
Open…	Open a previously saved axial OTF
Save…	Save the displayed axial OTF
Exit	Close the Channel Optimization Analysis window

Table 6.5.1: Channel Optimization Analysis window Figure menu options

6.5.2 The Plot Menu

The Channel Optimization window Plot menu, illustrated in Fig. 6.5.4, is used to change the format of the displayed axial OTF.

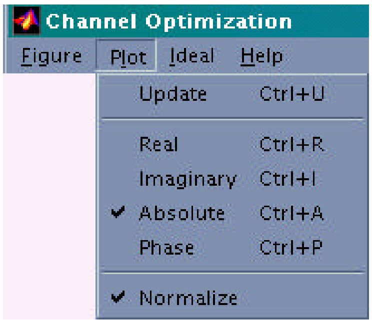


Figure 6.5.4: The Channel Optimization window Plot menu

The menu options are summarized in Table 6.5.2.

Menu Option	**Action**
Update	Generate the axial OTF. Menu shortcut Ctrl+U.
Real	Display the real axial OTF component. Menu shortcut Ctrl+R.
Imaginary	Display the imaginary axial OTF component. Menu shortcut Ctrl+I.
Absolute	Display the absolute axial OTF component. Menu shortcut Ctrl+A.
Phase	Display the phase axial OTF component. Menu shortcut Ctrl+P.
Normalized	Display normalized axial OTF

Table 6.5.2: Channel Optimization Analysis window Plot menu options

6.5.3 The Ideal menu

The Channel Optimization window Ideal menu, illustrated in Fig. 6.5.5, is to import a desired OTF or PR target to which the channel spatial frequency characteristics are to be matched.

Figure 6.5.5: The Channel Optimization window Ideal menu

The menu options are summarized in Table 6.5.3.

Menu Option	**Action**
Import…	Import an externally generated Frequency response (see §6.5.4)
PR Target…	Generate a PR target response (see §6.5.5)
Show	Select to display the ideal desired response

Table 6.5.3: Channel Optimization Analysis window Ideal menu options

6.5.4 Importing an Ideal Frequency Response

A generated ideal frequency response, to which the axial OTF is to be matched, can be loaded by selecting “Import…” from the Ideal menu, this will open a file open dialog box, select the file containing the response data.

The Matlab mat format file should contain a data structure, with the same name as the filename, which has two components, a vector f representing the frequency axis and a vector H representing the frequency response, these must be of equal length. The frequency data must already be in the same scale as the OTF, i.e. in normalized spatial frequency components of NA/λ. Once the data has been successfully loaded, the program will display the ideal response (dashed red line) along with the axial OTF of the current optical configuration.

The ideal response can be toggled on and off by selecting "Show" from the Ideal menu.

6.5.5 Generating a PR Target Response

Selecting "PR Target…" from the Channel Optimization Analysis Ideal menu opens the PR dialog box illustrated in Fig. 6.5.6.

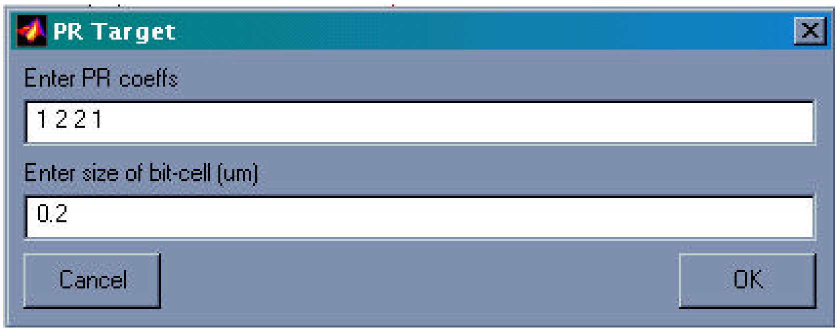


Figure 6.5.6: The PR dialog box

There are two sets of parameters that must be entered to generate the ideal PR target, these are the PR target coefficients (*a b a* or *a b b a*) and the channel bit size in um.

Once the correct data has been entered and OK is selected, the dialog box will close and the PR target will be calculated and displayed with the axial OTF.

Figure 6.5.7 illustrates the Channel Optimization Analysis window when a PR(1 2 2 1) target with a channel bit size of 0.3um (dashed red line) is displayed along with the axial OTF for clear circular apertures, of equal radii, under uniform illumination.

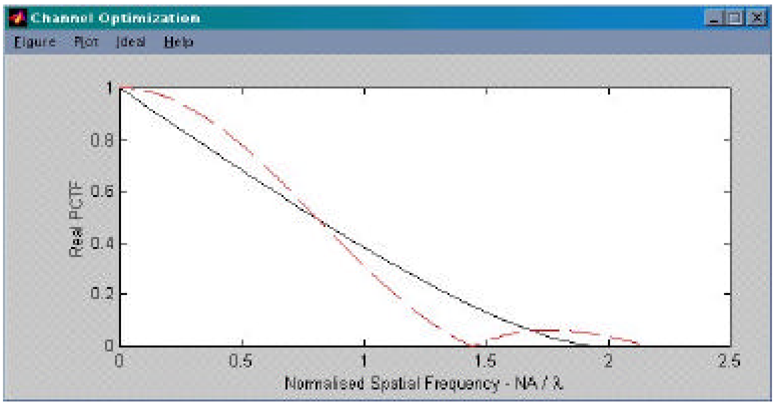


Figure 6.5.7: Channel Optimization Analysis window with a PR target displayed.

6.6 Generating the Readout Signal

The Readout Signal Generation window illustrated in Fig. 6.6.1 is used to generate readout signals using the pupil functions, focused spot profiles and object previously generated, and is opened by selecting “Readout Signal...” from the program interface Analysis menu.

Initially the readout signal window is blank.

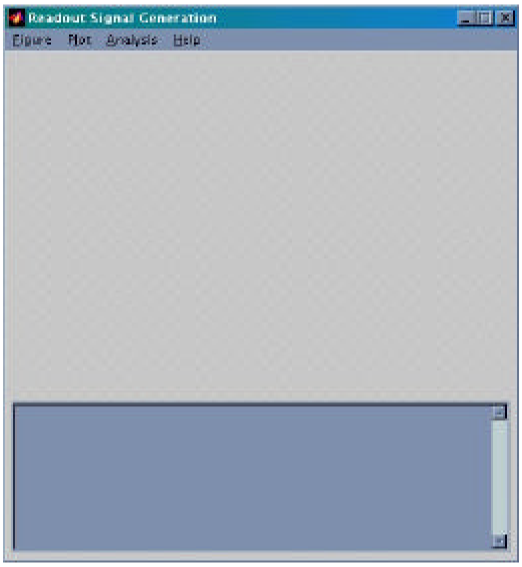


Figure 6.6.1: The Readout Signal Generation window

The readout signal window is used to generate and display readout signals and is used to set imaging options such as tracking offset, detector configuration and waveplate angle for magneto-optic imaging. Three signals may be generated using the Readout Signal window. Two signals can be specified from any quadrant photodectector configuration, whilst the third is generated from a combination of the other two signals.

The list box at the bottom of the Readout Signal window displays information regarding the signals displayed.

Actions regarding the readout signal window are accessed using the Figure and Plot menus. Actions regarding the imaging procedure are accessed using the analysis menu.

6.6.1 The Figure Menu

The Readout Signal window File menu, illustrated in Fig. 6.6.2, is used to Open, Save, Copy, Export and Print the displayed signal, and also to close the window.

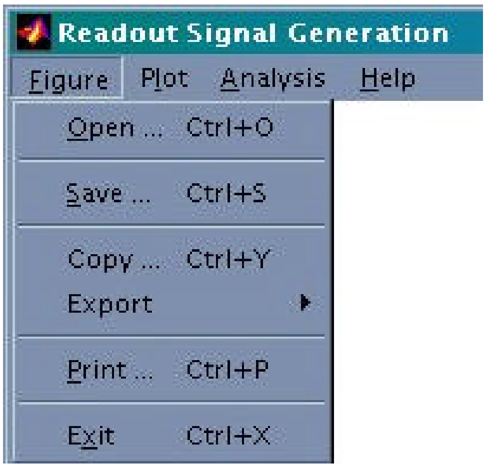


Figure 6.6.2: Readout Signal window File menu

The menu options are summarized in Table 6.6.1.

Menu Option	Action
Open...	Open a previously saved set of signals. Menu Shortcut Ctrl+O.
Save...	Save the currently displayed set of signals. Menu Shortcut Ctrl+S.
Copy…	Copy the figure window to the clipboard. Menu Shortcut Ctrl+Y.
Export	Export the displayed set of signals
⇒Chansim	Export a signal to a Channel Simulation model format file. You will be required to enter further data.
⇒Matlab	Export a signal to the MATLAB workspace. Signals will be called Signal1, Signal2 and Signalc. The object profile is also exported as Objectp.
Print	Print the figure window to the current system printer. Menu Shortcut Ctrl+P.
Exit	Close the Readout Signal window. Menu Shortcut Ctrl+X.

Table 6.6.1: Readout Signal window File menu options cont.

6.6.2 The Plot Menu

The Readout Signal window Plot menu illustrated in Fig. 6.6.3 is used to change the format of the displayed signals, and to generate the readout signals.

The menu options are summarized in Table 6.6.2.

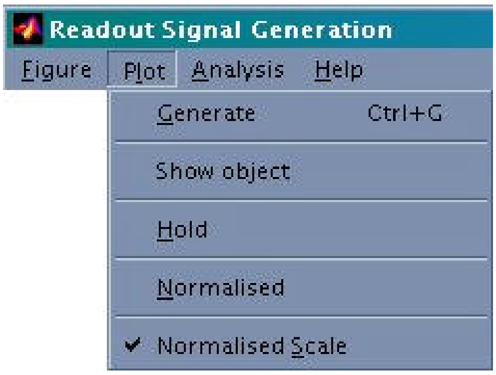


Figure 6.6.3: Readout Signal window Plot menu

Menu Option	**Action**
Generate	Generate the readout signals. The pupil functions, focused spots and objects need to be generated previously before this action can be performed. A statusbar will indicate the progress of the simulation. Menu Shortcut Ctrl+G.
Show Object	Show the object profile on the signal plot. Must be selected prior to the signal generation.
Hold	Hold the currently displayed signals.
Normalized	Display normalized signals.
Normalized Scale	Displays normalized scale (in units of wavelength).

Table 6.6.2: Readout Signal window Plot menu options

If "Generate" is selected and the temporary files required, i.e. the pupil functions, focused spot and object, have not been generated, then the error dialogs illustrated in Figs. 6.6.4, 6.6.5, and 6.6.6 will be displayed, depending upon which files have not been generated.

Figure 6.6.4: The collector pupil function needs to be generated error dialog

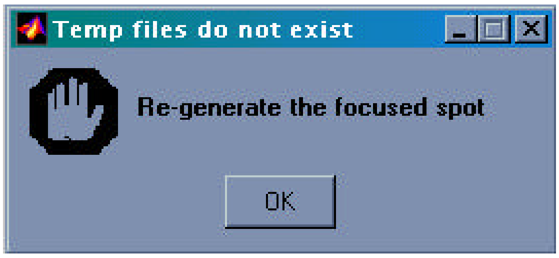


Figure 6.6.5: The focused spots need to be generated error dialog.

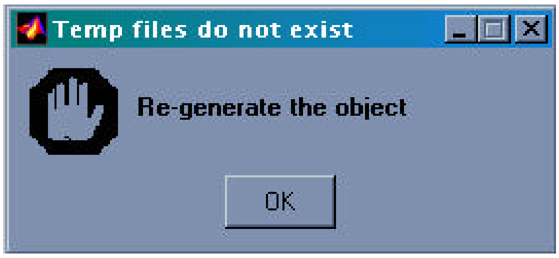


Figure 6.6.6: The object needs to be generated error dialog.

6.6.3 The Analysis Menu

The Readout Signal window Analysis menu, illustrated in Fig. 6.6.7, is used to select and configure the readout signals to be generated and to select other simulation options.

The menu options are summarized in Table 6.6.3.

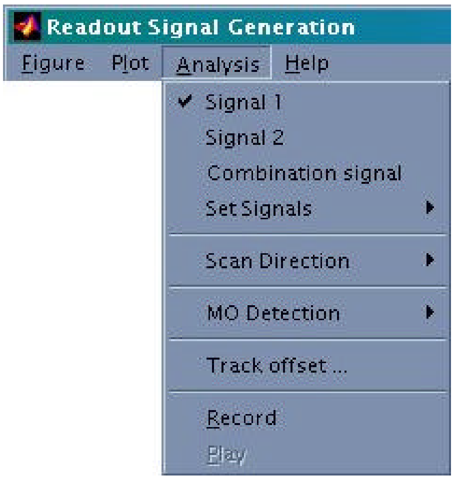


Figure 6.6.7: Readout Signal Analysis menu

Menu Option	**Action**
Signal 1	Select Signal 1 to be generated.
Signal 2	Select Signal 2 to be generated.
Combination Signal	Select the combination signal to be generated.
Set Signals	Set the signals.
⇒ Signal 1...	Set the detector combination for signal 1.
⇒ Signal 2...	Set the detector combination for signal 2.
⇒ Combination Signal ...	Set the combination of signals 1 and 2 to calculate the combination signal.
Scan Direction	Set the scan direction.
⇒ Tangential	Scan tangentially, along the track, through the center of the object.
⇒ Radial	Scan radially, across the tracks, through the center of the object.
MO Detection	Set the waveplate angle (MO detection only, available when an MO object has been selected)
⇒ Half waveplate angle...	Set the halfwave plate angle.

Table 6.6.3: Readout Signal window Analysis menu options

⇒ Quarter waveplate angle...	Set the quarter waveplate angle
Track Offset ...	Set a track offset (tangential scan only)
Record	Record the field profiles during the scan for viewing later.
Play	Opens the field profile movie viewer window (only available after the signals have been generated if "Record" has been selected).

Table 6.6.3: Readout Signal window Analysis menu options cont.

6.6.4 The Signal Configuration

The program is able to calculate two readout signals by combining signals, in any combination, from the quadrant photodetector(s). The model assumes that the detectors have an active area the same size as the collimated beam (i.e. the same as the collector aperture) and have unity responsivity over the whole area of the detector.

The signal combinations are set by selecting "Set Signals->Signal 1..." for signal 1 and "Set Signals->Signal 2..." for signal 2 from the analysis menu. In each case the dialog illustrated in Fig. 6.6.8 will be displayed for the case of reflectance imaging.

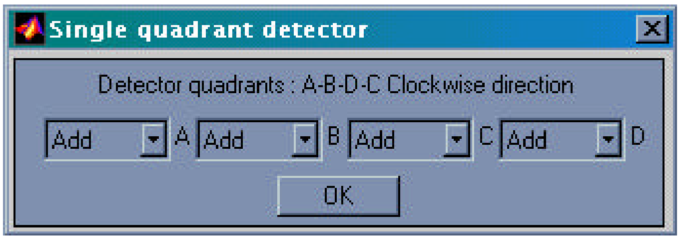


Figure 6.6.8: Signal combination dialog – reflectance/phase imaging

The detector quadrants are labeled A, B, C and D and are arranged as illustrated in Fig. 6.6.9.

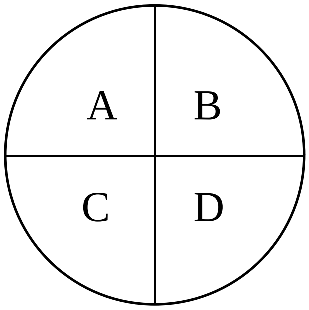


Figure 6.6.9: Photodetector quadrant arrangement

The signal contribution of each detector to the overall readout signal is set using the pull down menus in the dialog of Fig. 6.6.8; the options are summarized in Table 6.6.4.

Contribution	**Result**
Add	Add the signal to the total signal
Subtract	Subtract the signal from the total signal
Ignore	Ignore the signal, it will do not contribute to the total signal.

Table 6.6.4: Signal options

For example, if we set the signal combination Add A, Add B, Add C and Add D then the resulting signal will be a total intensity signal. However, if we set the signal combination to Add A, Subtract B, Add C and Subtract D then the resulting signal will be a split detector signal often used for tracking.

In the case of magneto-optic detection, it is possible to set the signal combination for both detectors in the differential arrangement. Selecting “Set Signals->Signal 1...” or “Set Signals->Signal 2...” will open the dialog illustrated in Fig. 6.6.10 in this case.

In this case the quadrants of one detector are labeled A, B, C, and D and arranged as previously, and the quadrants of the second detector are labeled E, F, G, and H and arranged in a similar manner. Setting the combination signal Add A, Add B, Add C, Add D, Subtract E, Subtract F, Subtract G, and Subtract H will generate the polar Kerr signal.

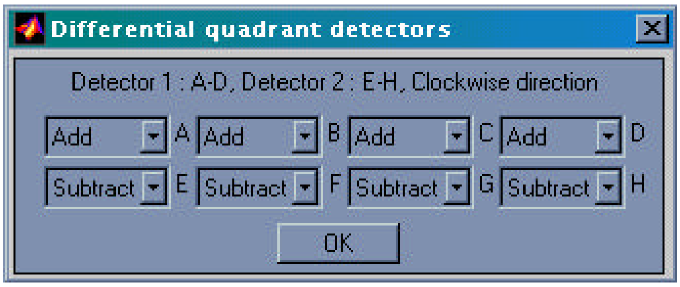


Figure 6.6.10: Signal combination dialog – magneto-optic imaging

The program can also calculate a signal that is composed of combinations of the other two signals, this is referred to as the combination signal. The combination signal is set using the dialog box illustrated in Fig. 6.6.11, which is opened by selecting “Set Signals->Combination Signal...” from the analysis menu.

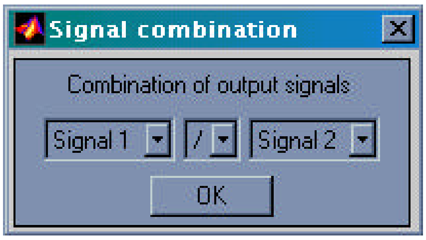


Figure 6.6.11: Combination signal dialog

In this case, the combination signal can be calculated by adding, subtracting, multiplying or dividing combinations of signals 1 and 2.

To calculate Signal 1, Signal 2 or the Combination Signal, they must be selected from the analysis menu.

6.6.5 Selecting the Scan Direction

The program is able to simulate the readout signal by scanning the focused spot across the object in two directions, tangentially and radially.

A tangential scan is selected by selecting “Scan Direction->Tangential” from the analysis menu, as illustrated in Fig. 6.6.12. A radial scan is selected by selecting “Scan Direction->Radial” from the analysis menu.

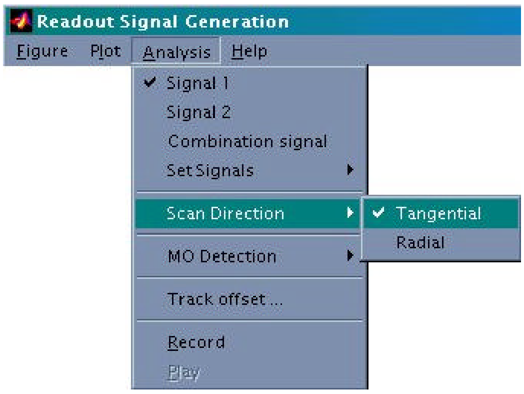


Figure 6.6.12: Selecting a tangential scan direction

Figure 6.6.13 illustrates the difference between the two possible scan directions. It can be seen that a tangential scan is made parallel to the track direction through the center of the object. A radial scan is made perpendicular to the track direction through the center of the object.

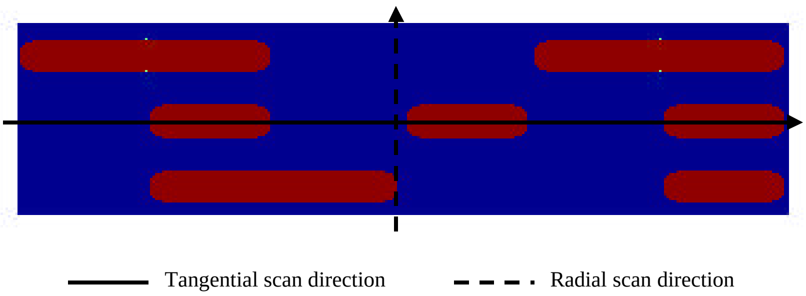


Figure 6.6.13: Scan directions

Note: the signal can only be generated in one scan direction in any one simulation.

6.6.6 Waveplate Orientation (Magneto-Optic Imaging)

In magneto-optic detection, the *x* and *y* polarized field distributions are usually rotated using a half waveplate so that the large dc signal component is removed differentially at the detectors. Also a quarter waveplate is sometimes employed to remove any ellipticity in the collimated beam. The angle of these waveplates is changed by selecting “MO Detection->Half waveplate angle...” and “MO Detection->Quarter waveplate angle...” from the analysis menu. In the case of the half waveplate orientation, this will open the dialog illustrated in Fig. 6.6.14.

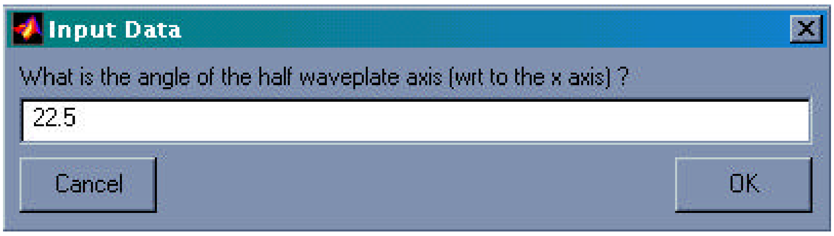


Figure 6.6.14: Half waveplate orientation dialog

The default setting is 22.5° from the *x* axis (tangential scan direction). In the case of the quarter waveplate orientation a similar dialog is observed, the default settings being 0°.

6.6.7 Track Offset

The readout signal may also be simulated for a constant tracking error (in the tangential scan direction only). The tracking offset dialog illustrated in Fig. 6.6.15, is opened by selecting “Tracking Offset...” from the analysis menu.

Note: the focused spot and object matrices need to be generated before tracking offset can be selected.

The tracking offset dialog is modal and so has to be closed before any other program actions may be performed. The offset is entered in elements, equivalent to the resolution, using either the edit box or slider. The maximum number of elements depends upon the different in the number of elements between the focused spot matrix and the object matrix.

Figure 6.6.15: Track offset dialog

6.6.8 Field Record

The simulated field distributions after interaction with the object and incident on the detectors may be saved at each scan point in the image and then viewed using the movie viewer window. To enable this option select “Record” from the analysis menu. After the scan is complete, the “Play” option will become available, which, upon selecting, will open the Movie Viewer window illustrated in Fig. 6.6.16.

The movie viewer window Figure menu is used to close the movie viewer. The movie viewer Movie window is used to set display options, such as the fields to be displayed, the format of the display and the number of iterations in the movie. To generate the movie select “Generate” from the Movie menu. To play the generated movie, select “Play Movie” from the Movie menu.

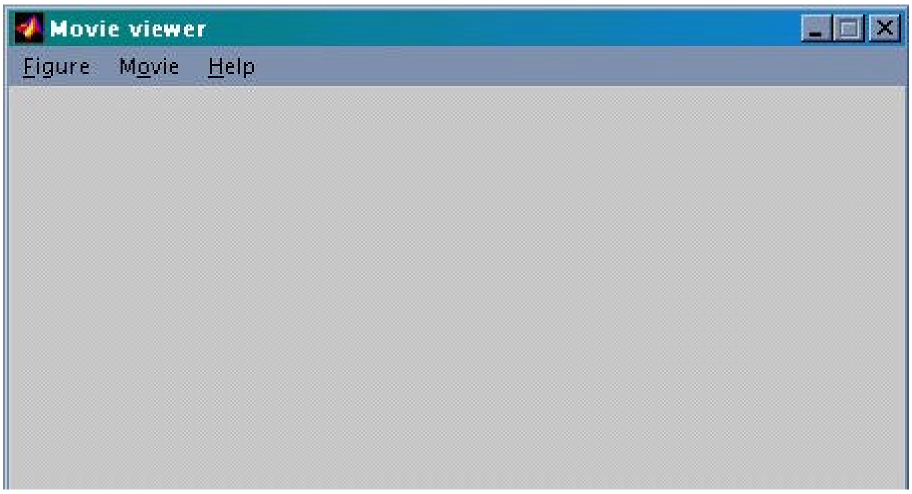


Figure 6.6.15: The Movie Viewer window

6.7 Microscope Imaging

The Microscope mode window allows you to make an image over the whole area of an object, thus imaging as in a scanning laser microscope. Currently not available in this version of the software.