

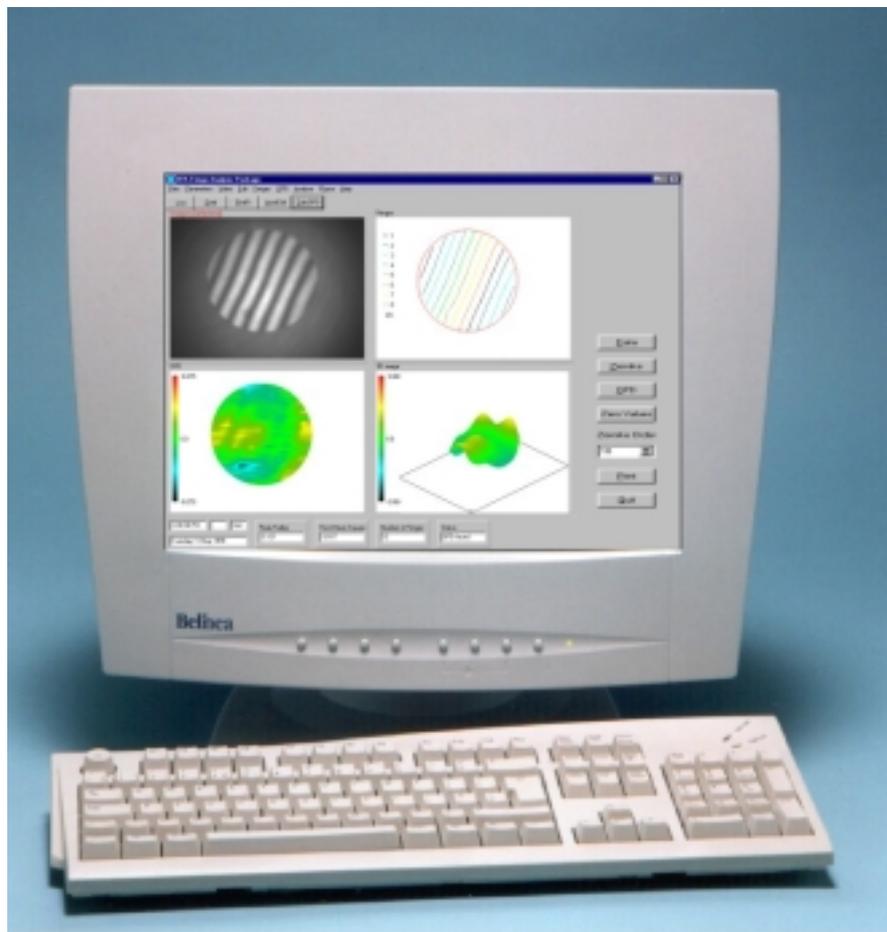
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Fringe Master for *Windows*



User Guide

(version 4.05)

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SCIENTIFIC INSTRUMENTATION for RESEARCH, EDUCATION, AND INDUSTRY

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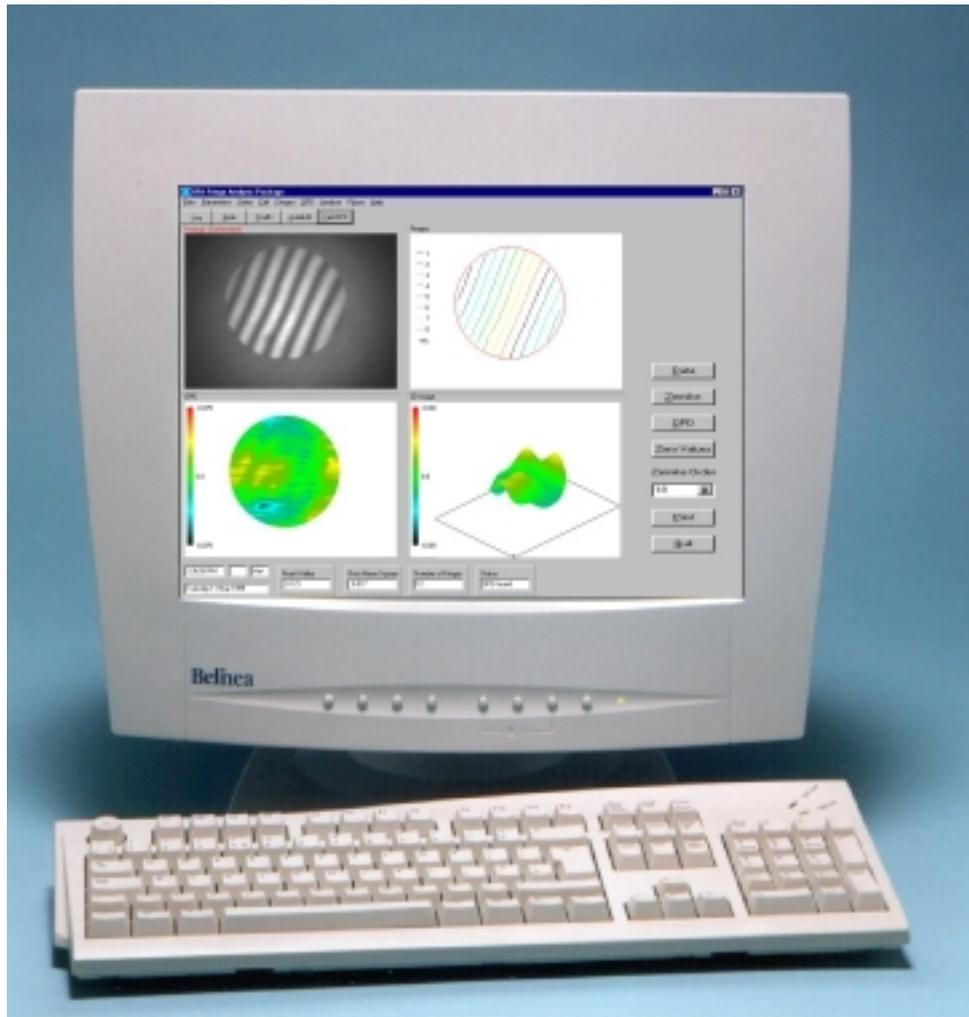
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Fringe Master™

for

Windows
(version 4.05)



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1. Introduction to Fringe-Master™

1.1 Background

Interferometry is a technique whereby the modification of a wavefront may be studied by observing the interference fringes produced by the coherent combination of the modified and unmodified waves. The disturbance to the wave may be caused by the refractivity of the medium through which the wave propagates or by the surface characteristics of a reflecting boundary. This phase information is most often used to infer characteristics of the medium causing the disturbance; thus the interferometer finds widespread application in the study of flowing or turbulent fluids, transmitting and reflecting and plasmas, in both research and production environments.

An important application in both the visible and infra-red region of the spectrum is in the testing of optical components where the technique offers an observation of an object on a scale length smaller than the wavelength of light. An important advantage of the method is that it involves no physical contact and so mechanically or thermally delicate optics are protected from damage.

1.2 Automatic fringe analysis

A requirement of all interferometric measurement is that it is dependent upon interpretation of a fringe pattern and without the aid of an automated analysis system, the obtaining of accurate quantitative results can be extremely time consuming. It is for this reason that automated fringe analysis is finding increasing applications in industry and research as optical requirements become more severe.

The OFA Fringe-Master™ system is a vital link in the numerical interpretation of fringe patterns in research and the optical manufacturing industry and as a means to standardise optical quality on a numerical basis for specification, testing, and acceptance purposes. It enables reproducible assessments of optical flatness to be obtained to an accuracy limited by the interferometer and its associated environmental control; air turbulence, vibration, and thermal effects.

1.3 Hardware requirements

Fringe-Master™ is designed to run on a standard PC computer under the Windows NT operating system. The framestore supplied requires a single PCI slot and the display requirements are for a single SVGA screen operated in 1024 x 768 resolution with greater than 256 colours.

Input to Fringe Master can be live video from an interferometer, a scanned image of a hard copy of a fringe pattern or from a PC disc file. The system is based on a 576 x 568 8-bit video format and the absolute resolution of the system when used on a typical fringe pattern of around ten fringes is of the order of one hundredth wave. Fringe Master accepts either CCIR or RS170 standard video input, configured by the supplier before delivery. The video input is via a standard BNC connection. The system supports either .RAW or .TIF digital image formats.

Output is available to any Windows supported hard copy device including laser printer, colour ink-jet, etc., and to other Windows applications, spreadsheets, databases, etc. via data export options.

To enable the software to run, the Datakey “dongle” must be connected to the PC via the 25 pin parallel printer port. The printer should be reconnected to the back of the Datakey which is “transparent” in operation and does not interfere with the operation of the printer in any

way. If the copyright notice is followed by the message "*Passkey is corrupt or missing*", the Datakey is probably misconnected. It is possible to connect the Datakey the wrong way round to the *serial port* rather than the parallel port. The correct orientation towards the computer is marked on the Datakey itself. If this does not solve the problem then check the operation of the parallel port by attempting to print. If printing is unsuccessful then the problem lies with the configuration of the parallel port.

1.4 Fringe Master™ software

Fringe-Master software is extremely simple to use. It is a Windows application, driven by the well established "point – and – click" user interface. "Speed Buttons" on the top level screen enable the user to progress quickly through a measurement sequence while drop down menus give access to more detailed analysis options.

Many of the user adjustable parameters which control the operation of Fringe Master are stored in a configuration file, *frin.dat*, which is loaded each time Fringe Master runs. An example is the position and size of the fringe analysis aperture, or window. The system boots with the setting of the window which was in operation when the system was last closed down. Each time the user adjusts the window position, the new data is written to the configuration file to ensure that an up to date record of the system configuration is maintained.

1.5 Input Image Format for the "non-framegrabber" version

A basic entry level version of Fringe-Master software is available with the full functionality of the full system but which does not support the video frame grabber. In this version, the "Live" and "Grab" software buttons are greyed out and input of images is from disc.

The required format for the images is 768 (H) x 576 (V) x 8 bits greyscale in ".raw" format without compression. Many 3rd party image manipulation utilities, such as Paint Shop Pro, are suitable for converting images to the ".raw" format.

An upgrade is available to add frame grabber support.

1.6 Principles of Interferometry

Within the interferometer, a spatially and temporally coherent wavefront is divided into two beams of equal intensity. One is passed through the optical path to be tested, either once or twice depending on the design, while the other beam is maintained as a reference. Upon recombination, the two beams interfere to produce a fringe pattern from which the optical properties of the divided path may be inferred. In the case of optical testing, it must be arranged that the component under test makes the dominant contribution to the distortion in the divided beam path. This requires that vibration and atmospheric turbulence be largely eliminated and that the optical path in air must be kept to a minimum.

Lasers are now in widespread use as the light source for interferometers. Their inherent brightness and coherence enable interferometric measurements to be made over long pathlengths and they produce high visibility in the resulting fringe pattern.

An obvious way to set up an interferometer is to arrange a coplanar recombination of two beams. By this method, a perfect test piece will produce a uniform intensity distribution across the view, the brightness being determined by the optical path difference between the measurement and the reference wavefronts. However, the use of fluffed-out fringes of this type is not generally useful for static fringe analysis. Such a fringe pattern is invariably dominated by imperfections which cause the pattern to be unstable, while the sensitivity the interferometer in this mode is too great for practical measurements.

The most readily interpreted feature of an interference pattern, both from observation by eye and by TV cameras, is the variation of intensity associated with regularly spaced black and white fringes. Such a pattern is obtained by introducing a slight tilt between the wavefronts prior to recombination. The tilt, obtained by adjustment to one of the mirrors in the measurement beam, is usually arranged in the horizontal or vertical plane, in which case the fringes will be produced in the vertical or horizontal direction respectively.

Fringe-Master currently requires fringes to be in the vertical direction. An image “Rotate” option is included in the software to enable horizontal fringes to be analysed. There is no fundamental limit on the number of fringes but for reasons relating to the resolution of the interferometric technique, it is usual to set seven or eight dark bands across the field of view for optical testing.

In the case of the nominally flat element, the fringes will be straight and equi-spaced. Deviation from straight is indicative of distortion normal to the fringes, whilst variation in the spacing of the fringes indicates distortion parallel to the fringes. Fringe Master performs quantitative evaluation of both distortions simultaneously.

A facility is included to subtract any spherical component to the OPD surface, thereby enabling focus errors to be measured, and to make the measurement of lens performance less dependent on the exact location of the reference sphere or other retro-reflector.

Subtraction of a reference OPD enables systematic errors in the interferometer optics to be removed while averaging of multiple OPD measurements can be performed to improve measurement accuracy.

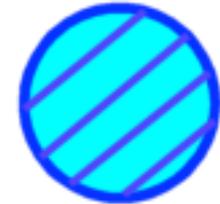
Results are expressed in terms of Root Mean Square (RMS) and Peak-to-Valley (P-V) distortion, in units of wavelength. An Optical Path Difference (OPD) map of the field is available in an isometric projection. Fringe-Master also provides decomposition of the OPD phase front into Zernike polynomials up to 45th order, calculates the Seidel aberration coefficients and performs Optical Transfer Function calculations using in-built FFT routines.

2. Using Fringe Master™ for the first time

This section gives the user a “quick tour” through the Fringe Master software, using a stored image supplied with the system as the data source. This tour introduces some of the basic capabilities of the system and points to the more sophisticated options in terms of data analysis, etc. It uses the basic set-up parameters supplied as defaults with the software, such as interferometer wavelength, OPD scale length, etc. Later sections of this manual explain how these defaults may be tailored to the user’s particular requirements.

2.1 Software operation

After installing the software, double click the Fringe Master icon which you will find on the Windows desktop. The software will load and the OFA copyright notice will appear briefly on the PC screen followed by the top level menu. The OFA “arrow” cursor should appear at the centre of the screen.



Fringe Master

Fig. 1: The Fringe Master icon

Follow the instructions from Section 2.1.1 through to 2.1.4 to load an image from disc, set the window to define the region of interest, track the fringes and analyse the O.P.D. surface for P-V and r.m.s. errors.

2.1.1 Load an image from disc

From the Fringe Master toolbar at the top left of the screen, select the **Files** menu by clicking with the mouse. Then select **Open** from the sub-menu.



Fig. 2: The Fringe Master toolbar



Fig. 3: The Open file menu

The usual Windows file and folder housekeeping menu is presented to the user. Browse the folder structure of the PC if necessary to locate the *fringes* folder. Double click and then select the *static* folder. Double click on one of the image files as shown in Fig. 3.

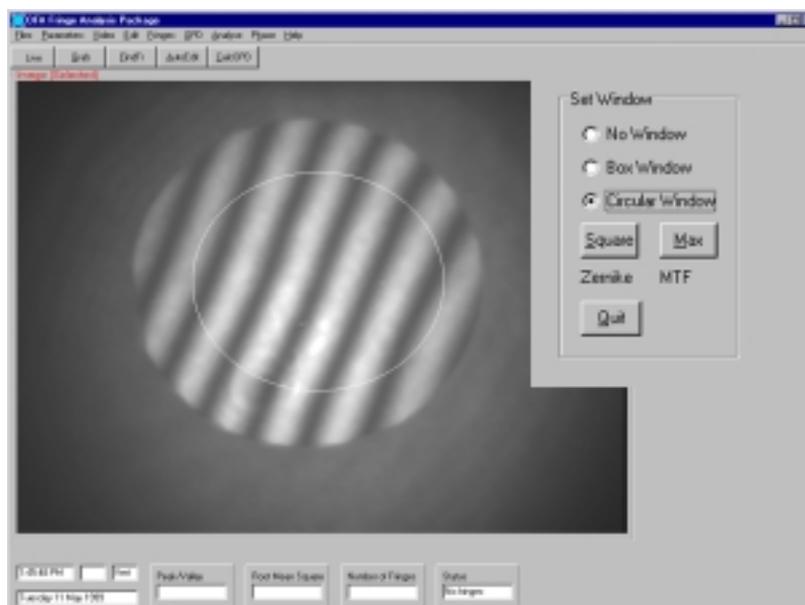
The user will notice that although there may be many files within the folder, only files of the .RAW format are shown.

[Other files names can be displayed by clicking on the small “down arrow” in the Files of type window and selecting either the Tiff [.TIF] or All files [.]* option.]*

2.1.2 Set the Window to define the aperture for analysis

Select the **V**ideo option from the Fringe Master toolbar as shown in Fig. 2. Followed by **W**indow. The video image is displayed at full resolution and the window sizing and positioning interface is presented as shown in Fig. 4.

The window shown in its previous position. This information is stored in Fringe Master's



configuration file, along with other user adjustable parameters, and is loaded each time the software is run. When the window is adjusted, the new data is written to the config. file.

The window position is adjusted by clicking *inside* the window and dragging with the mouse. The window size and shape is adjusted by clicking *outside* the window (at the top, bottom, left or right edge) and dragging with the mouse. Radio buttons are used to switch between no window (*Box*) and a circular or elliptical window (*Circular window*). It is suggested that the window is positioned around the fringe pattern, just inside the edge of the aperture.

The other two buttons are used when Zernike or MTF analysis is to be performed at a later stage in the process. Zernike polynomials can only be defined over a circular aperture. The **1:1** button adjusts the window such that the horizontal and vertical dimensions are equal. MTF analysis requires FFT calculation, which requires that the number of data points, or pixels, in the image be multiples of 2. This limits the maximum horizontal and vertical dimensions of the window to 512 pixels. The **Max** button adjusts the window appropriately if either dimension exceeds 512 pixels. If either dimension is less than 512, the image is packed with zero values outside the window.

From the window setting screen, the user retains access to the Fringe Master toolbar. This enables new images to be loaded from disc or the system to display live or grabbed images using the **L**ive or **G**rab buttons (see section 3 on page 13 of this user guide).

When the window is positioned as required, use the **Q**uit button to return to the top level screen. At this point, the Fringe Master display screen will appear as shown in Fig. 5.

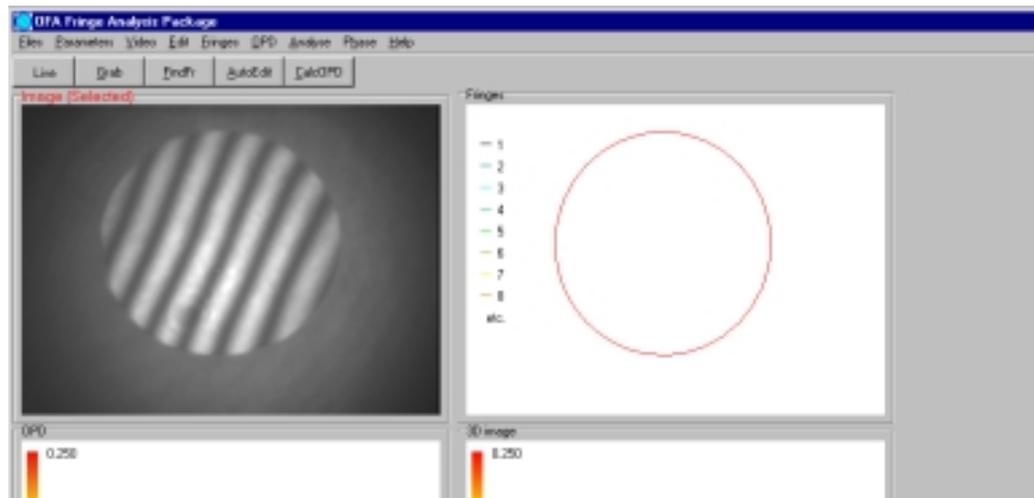


Fig. 5: The top level screen after setting the window position

The system is now ready to track the positions of the fringes and to calculate the Optical Path Difference (OPD) map.

2.1.3 Tracking and analysing fringes

Click on the **FindFr** “speed button” on the Fringe Master toolbar.

[A Speed button is a menu selectable function that is available from a sub-menu but is duplicated on the top level screen to facilitate repetitive operations.]

The fringes are tracked and their positions displayed in the top right hand quadrant of the screen. Follow this by selecting the **CalcOPD** button. The top level screen will now be redrawn as shown below in Fig. 6.

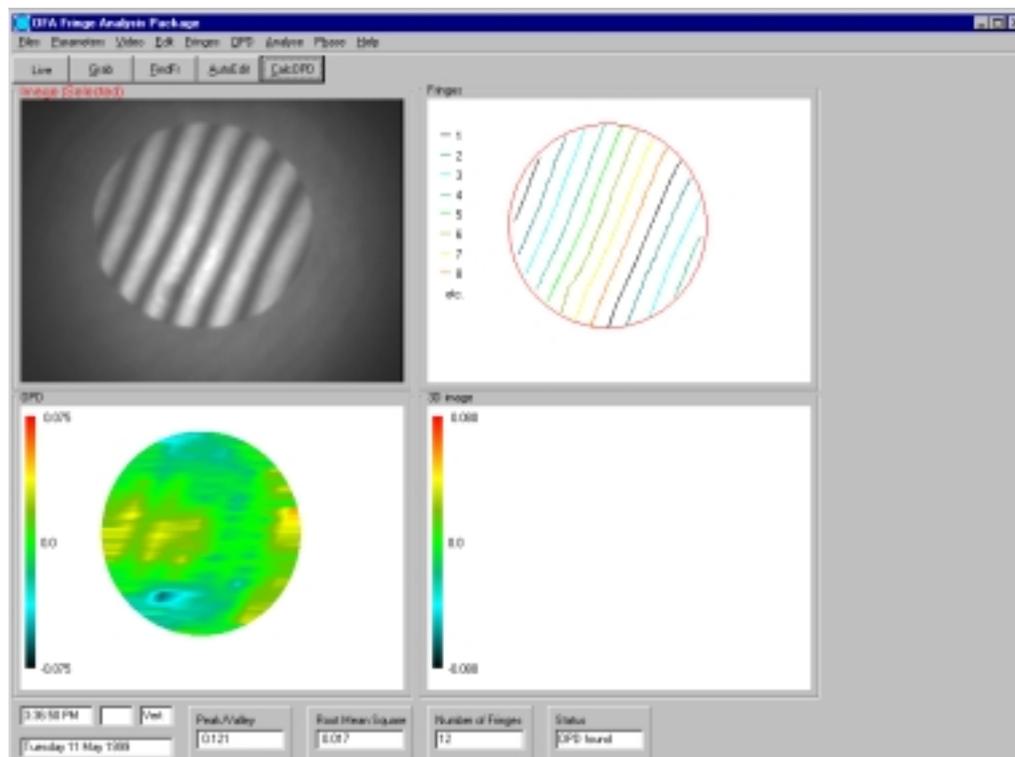


Fig. 6: Fringes analysed and the OPD calculated & plotted

The screen shown in Fig. 6 presents the basic OPD surface information in terms of P-V and r.m.s. It records the time and date of the measurement and “Vert” just above the date. This refers to the vertical orientation of the fringes in the original image. If horizontal fringes are to be analysed, the image must be rotate before the fringes are tracked. Image rotation is provided within the **V**ideo sub-menu and upon rotation, the panel on the top level screen will switch to **H**oriz (ontal).

It will be noticed in Fig. 6 that both black and white fringes have been tracked. This maximises the sampling of the image but may be undesirable if, for example, the black bands are narrower, and consequently more precisely defined in space, than the white bands. Fringe Master supports black only and white only tracking as well as “both”. This option, described in a later section of this manual, is set elsewhere in the software set-up and recorded in the configuration file.

2.1.4 3-D plot of the OPD surface

It is often helpful in visualising the OPD surface to plot it isometrically in “3-D”. This is done by selecting the **O**PD sub-menu from the top level screen followed by “3D plot” as shown in Fig. 7.

The user chooses one of 4 orthogonal projections, or "Full size" by clicking with the mouse. The chosen view is displayed in the lower right hand area of the Fringe Master main screen as shown in Fig. 8.

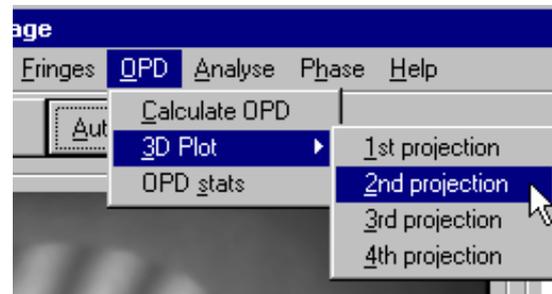


Fig. 7: Locating the 3D Plot menu

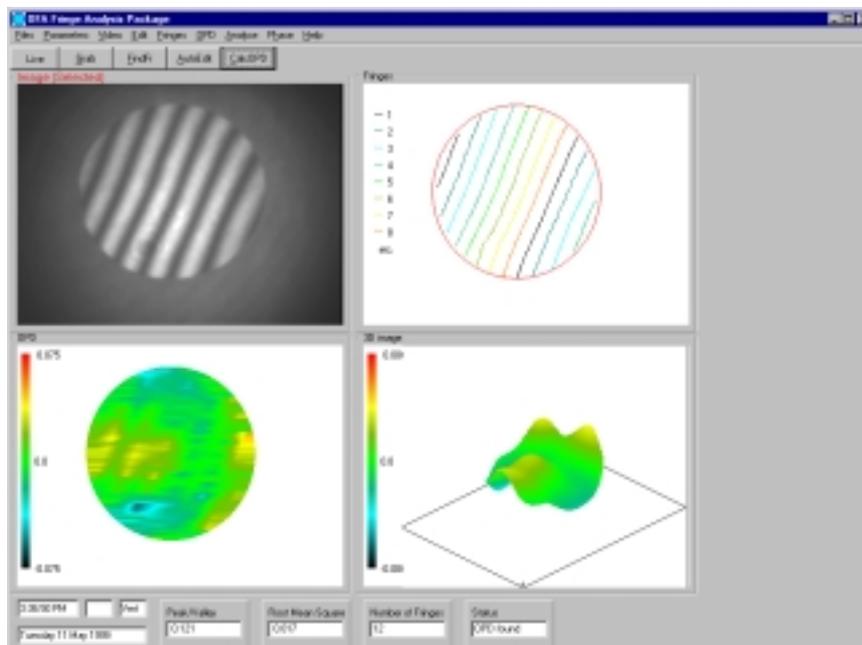


Fig. 8: The Fringe Master top level screen after OPD analysis and plotting

If "Full size" is selected, a new screen is drawn with the OPD at full resolution. In this case a check box can be used to invert the OPD, to view the surface from "underneath".

3. Image input from live video (*frame grabber versions*)

Having explored the basic features of Fringe Master using a stored digital image, the next stage is to configure the system for image input from a live video signal. First, ensure that the video signal is connected to the frame grabber board via the BNC socket on the back plane of the P.C.

3.1 Live image and single frame Grab

The system is set into live video mode by selecting the Live speed button from the top level screen as shown in Fig. 9. Alternatively, **Grab** can be used to snatch a single image.



Fig. 9: The Live and Grab image speed buttons

It will be noticed that when live operation has been selected, the caption on the Live button changes to Freeze.

The frame buffer has access to every video frame though the half resolution display on the PC screen is updated at half video rate.

If Live or Grab is selected with no video signal present, the system will wait for a predetermined timeout period and an error message will be displayed on the PC screen as shown in Fig. 10.

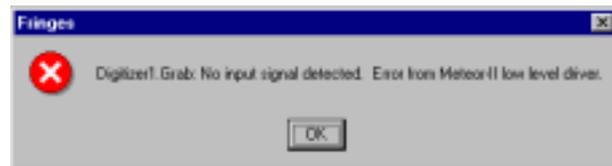


Fig. 10: Input video missing error message

In this case, select **OK** to continue.

3.2 Adjusting contrast and brightness for the optimum signal

The video digitiser is equipped with a video amplifier with variable gain and offset which are controllable in software. The set-up procedure for Fringe Master includes the proper adjustment of these settings, which are subsequently saved in the configuration file.

On selecting the Parameters sub-menu, the user is presented with a set of option menus entitled **Brightness/Contrast**, **Video**, **Fringes** and **OPD**. Select the **Brightness/Contrast** menu by clicking on the tab at the top of the menu.

As shown in Fig. 11, there are two sliders labelled Brightness and Contrast at the top of the menu screen which can be dragged with the mouse. Readout boxes show the current settings. Beneath the sliders a graph box shows an intensity cross section through the centre of the image. Fig. 11 shows the system set correctly.

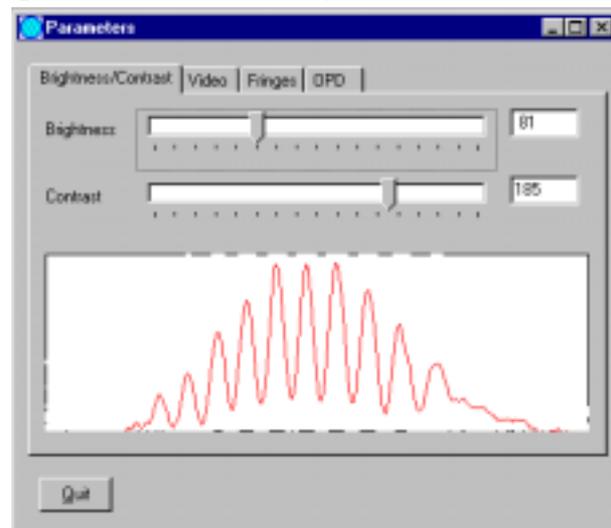


Fig. 11: Brightness/Contrast set correctly

Fig. 12 shows the brightness set incorrectly; in (a) the brightness is set too high, in (b) it is too low.

Similar effects are seen when the contrast is adjusted; in this case the amplitude of the signal is affected rather than the vertical position.

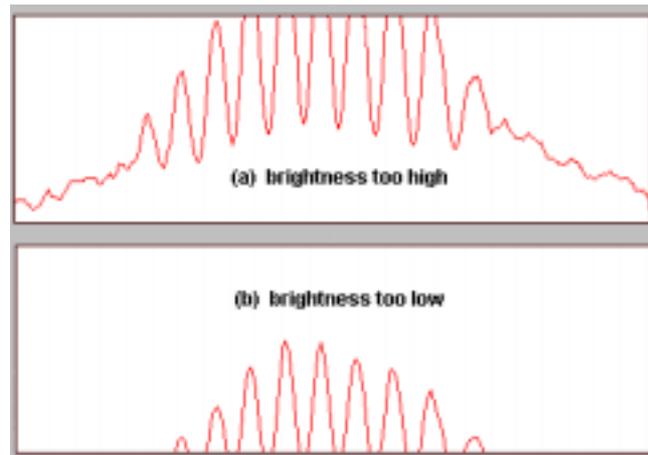


Fig. 12: Incorrect brightness settings

It is extremely important that the best quality image possible should be obtained from the interferometer, and then the Fringe Master settings adjusted in order to obtain the highest accuracy and ease of use from the system. If only low contrast, poor quality images are available, then there are image enhancement routines incorporated within Fringe Master to enable results to be obtained. Extensive image processing, however, is time consuming and has the potential to mask the fine points of detail in the data.

3.3 Saving images to disc

Section 2.1.1 described how to load an image from disc. Saving to disc is performed in a similar way. Select **F**iles and **S**ave, to open the image saving menu as shown in Fig. 13.

By clicking on the **S**ave as **t**ype arrow, the user can select raw image format (a simple array of bytes) or TIF format. TIF files can also be loaded into the system by changing the files type option in the load image menu.

The file name should be entered into the **F**ile **n**ame box. Long file names are supported in both Windows '95 and Windows NT.



Fig. 13: Save image file menu

-  The first button to the right of the **S**ave **i**n: window, tracks one level up through the directory tree structure.
-  The second button creates a new folder which can be named by typing at the keyboard.
-  The pair of buttons to the right of the new folder button toggles the level of file detail shown in the list of files.

3.4 Video set-up parameters

To control the video image acquisition, select the **Parameters** menu from the top level screen and select the **Video** tab at the top of the card index display as shown in Fig. 14.



Fig. 14: Video set-up parameters

3.5 Grab Mode

Frame mode should be selected for maximum vertical resolution. If vibration of the interferometer is a problem, selecting **Field** will minimise the problem at the expense of halving the vertical resolution.

3.6 Input

It is possible to connect up to four video inputs to the frame digitiser and to switch between inputs using the radio buttons as shown. This option is not standard and requires a special 4-channel video connection lead.

3.7 Camera Format

Fringe Master will accept either CCIR or RS-170 standard video input. This is selected in the Camera Format panel as shown in Fig. 14.

NOTE: When changed, the new setting only becomes effective when Fringe Master is next loaded. Quit from the program and re-load for the new setting to take effect.

3.8 Camera Gamma

Fringe Master applies an automatic gamma correction to the image before tracking fringe positions and making calculations of phase. Select gamma = 1.0 for a CCD camera and between 0.5 and 0.75 for a vidicon camera. Consult the camera manufacturer for the correct gamma of specific cameras.

4. Input Image Format (no framegrabber)

A basic entry level version of Fringe-Master software is available with the full functionality of the full system but which does not support the video frame grabber. In this version, the "Live" and "Grab" software buttons are greyed out and input of images is from disc.

The required format for the images is 768 (H) x 576 (V) x 8 bits greyscale in ".raw" format without compression. Many 3rd party image manipulation utilities, such as Paint Shop Pro, are suitable for converting images to the ".raw" format.

An upgrade is available to add frame grabber support.

5. X & Y Calibration of Fringe Master

Fringe Master is calibrated using the *X-Calib* and *Y-Calib* buttons on the Video tab in the Parameters menu.

A simple procedure to calibrate the system is suggested as follows. First an image of an object of known size is grabbed or loaded into Fringe Master. Next, the window is set around the border on the object.

Select the *X-Calib* and *Y-Calib* buttons in turn and enter the respective horizontal and vertical size of the object in mm in answer to the prompt as shown in Fig. 15. The system will then store the calibration in the *Frin.dat* set-up file. The display panels below the *X & Y calib* buttons show the calibration in pixels / mm; the screen also shows the current window position in pixels.

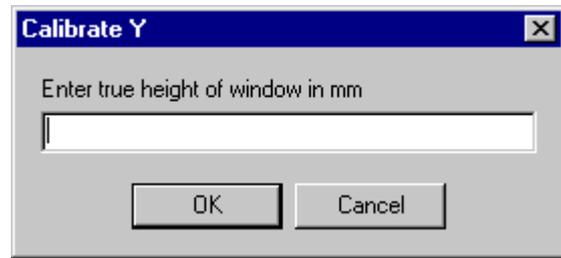


Fig. 15: Calibration dialogue

For many fringe analysis operations, calibration of the system is not necessary. It is required for the measurement of parallelism, wedge angle, and the calculation of MTF data.

Note: *In the absence of calibration data, MTF will be displayed in normalised units.*

6. Fringe tracking parameters

Automatic fringe tracking has already been described in section 2.1.3. At this stage, the software used the values of various parameters associated with fringe tracking which were loaded from the configuration file when the programme was loaded. The values may need to be changed in some cases; if this is done, the values in the configuration file will be updated.

Select the **Parameters** menu from the top level screen and select the **Fringes** tab at the top of the card index display as shown in Fig. 16.

6.1 Black/White fringe tracking

Fringe Master can be set to track black fringes, white fringes or both, selected using the "radio buttons" beside the legends.

If the fringes are of equal width, the **Black and White** option should be used in order to increase the sampling frequency of the pattern.

Often, the black fringes will be narrower than the white due to the configuration of the video camera. In this case, **Black Only** should be selected to improve the accuracy of the fringe location.



Fig. 16: Fringe tracking parameters

6.2 Smooth option

The algorithms used to detect the fringe centres use a smooth parameter which is adjusted either by using the up/down arrows or by typing a number inside the window followed by <return>. For narrow, closely spaced fringes, a value of 1 or 2 may be required. For typical fringe patterns comprised of 7 or 8 fringes, a value of 3 or 4 should prove satisfactory. Exceptionally, for the analysis of wide fringes against a noisy background, a value of 5 or higher may be required.

The optimum value is probably best determined by trial and error. Too high a value will cause the tracking algorithm to miss fringes while too small a value will cause small points of noise to be allocated erroneously to fringes.

6.3 Diffraction

The diffraction setting may be used to restrict the finding of fringes to a reduced area within the window. If the parameter is set to 10, for example, the effective window radius for fringe finding purposes is reduced by 10%. This has the effect of stopping the fringes before the window is encountered as shown in Fig. 17.

Note: a 10% reduction in radius results in reduction to 81% (0.9 x 0.9) in area of the window analysed. This may be useful when a specification calls for a performance over a reduced aperture.

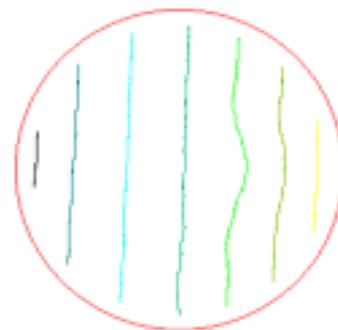


Fig. 17: Diffraction setting

6.4 Shear Option

This adjusts the width of the pixel gap which will cause a new fringe to be generated when exceeded. This setting should not be changed.

6.5 Delete Length Option

Fringe Master features an automatic fringe editing facility which can be invoked from the top level screen using a speed button as shown in Fig. 2 on page 9. If the **Delete Length** parameter is set to 50, for example, the automatic edit process removes any fringes in the image which are comprised of less than 50 points.

False fringes arising from the detection of noise in the image are most likely to be short compared with the genuine fringes due to the scale size of the noise in comparison with the fringes.

Set the **Delete Length** using the up/down arrows or type a number into the window followed by <return>.

7. OPD calculation parameters

Calculation of the Optical Path Difference map (OPD) was described in section 2.1.3. The software used the values of various parameters required for the calculation which were loaded from the configuration file when the programme was loaded. The values may need to be changed to meet the testing requirements of a particular component. If this is done, the values in the configuration file will be updated.

Select **Parameters** from the top level screen and select the **OPD** tab at the top of the card index display as shown in Fig. 18.

7.1 Number of passes

Whether the interferometer is operated in single or double pass is selected by clicking on the appropriate **Number of passes** radio button.

***NOTE:** An optical component measured in reflection will give rise to a double pass measurement because any defect will be effectively double passed.*

7.2 Interferometer Wavelength

The wavelength of the interferometer is entered in the panel followed by <cr>.



Fig. 18: OPD parameters

7.3 Measurement Wavelength

The wavelength at which the measurement is required should be entered in the panel followed by <return> in the same units as used for the Interferometer Wavelength entered in 7.2 above. This enables the flatness of an optic, for example, to be measured at the helium neon laser wavelength at 632.8nm and the measurement to be quoted in waves of distortion at 1.064μ.

7.4 Measurement Units

The measurement units can be switched between waves, fringes, microns & micro-inches. The system of units selected is displayed in an indicator panel at the bottom of the top level screen.

7.5 Full Scale on OPD

The OPD is calculated in terms of optical waves and plotted on the top level screen in false colour. The scaling of this false colour plot is controlled by the **Full Scale on OPD** parameter. The f.s.d. of the OPD plot is entered in waves.

If the OPD is an almost uniform green when plotted, the OPD scale should be reduced. The P-V measurement on the top level screen should be used to indicate a suitable value.

If the f.s.d. is too small to accommodate the OPD when plotted, a message is plotted on the screen as



Fig. 19: OPD overflow message

shown in Fig. 19. The OPD parameter should be increased progressively until a suitable plot is obtained.

7.6 Refractive Index

The Fringe Master software enables the parallelism, or wedge angle, of an optical element to be determined to high accuracy.

This measurement depends on the refractive index of the material, which is entered in the panel as shown in Fig. 18.

8. Auto setup

The fifth tab on the Parameters screen enables the user to set operations to be performed when the **Auto Run** button is selected on the top level screen.

Auto setup enables the user to select which operations should be added to the sequence which is executed during **Auto Run**. Options are shown in Fig. 20 and include image grab, fringe detection, editing and various display and analysis controls.

The use of this feature is described more fully in Section 22 of this manual.

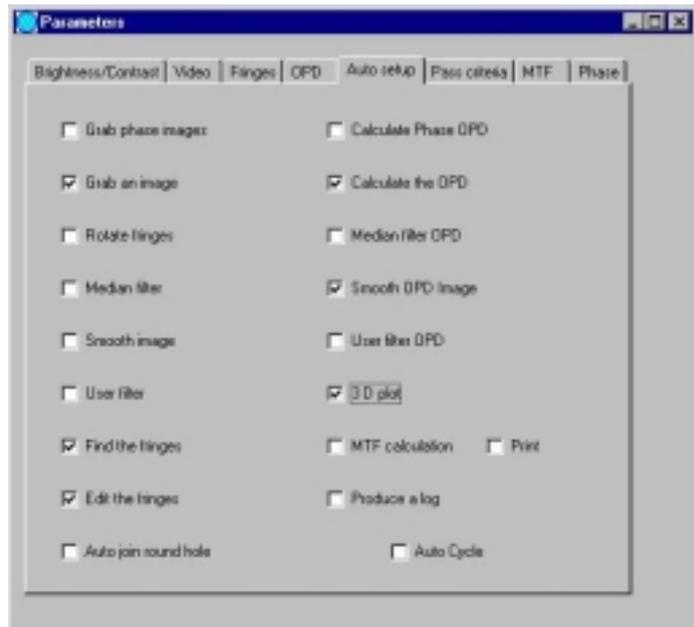


Fig. 20: Option selection for the Auto Run facility

9. Automatic OPD "Pass / Fail" test

Fringe Master can be used to compare automatically the P-V and/or rms measurement of the OPD with user entered limit values.

Select the "Pass criteria" tab from the Parameters menu and check PV, rms or both to enable the check.

Enter the limiting value of the required value of the PV and/or rms as appropriate.

Quit to the top level screen, and Fringe Master will display a Pass or Fail marker each time a new OPD is calculated.

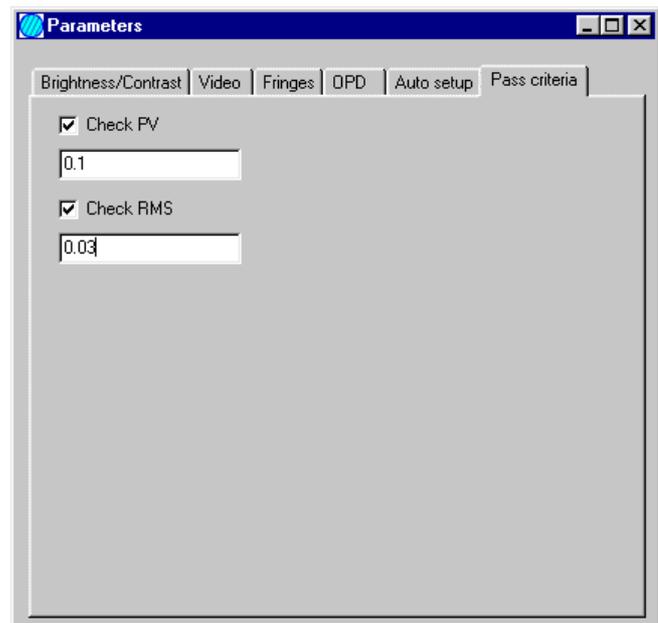


Fig. 21: Selecting PV and rms checks and entering the limiting values

10. Fringe Editing

The options within the edit menu enable the user to correct errors in the fringe location and assignment. The editing options can be very effective but should never be used as an alternative to adjusting the interferometer and camera system correctly. In general use with good quality images, there should be relatively few occasions when editing is required other than the automatic fringe clean-up described below in section 10.1.

Select **E**dit from the top level screen followed by **F**ringes. The Fringe Edit screen will be displayed as shown in Fig. 23.

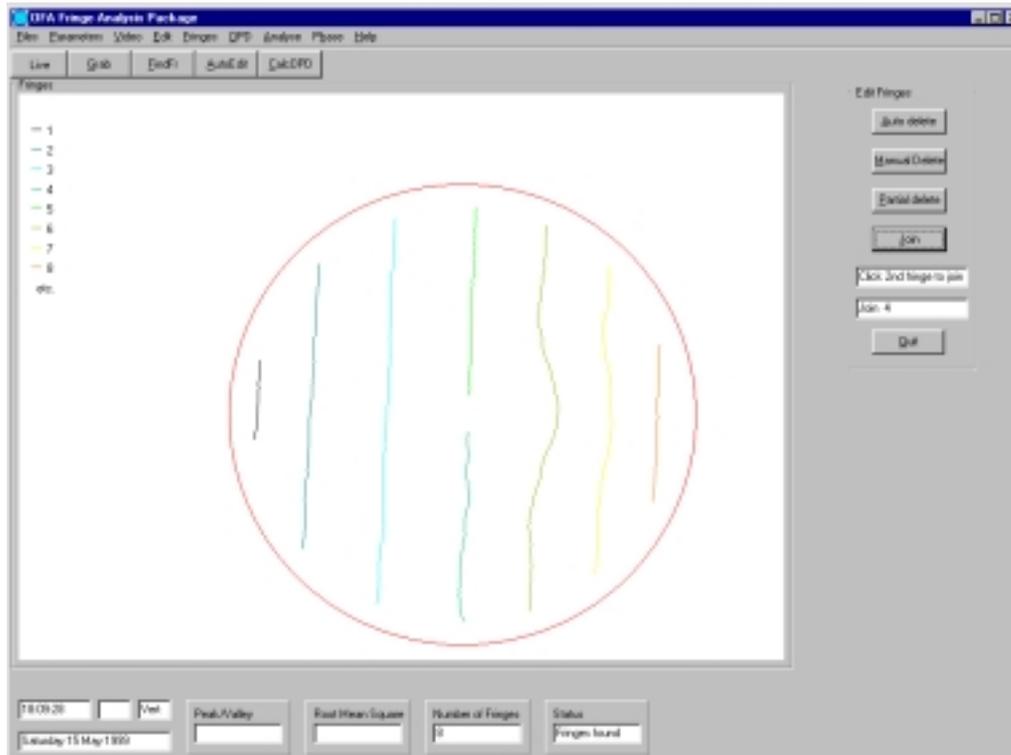


Fig. 23: Fringe editing screen

It is very important to inspect the fringe plot carefully before proceeding to the OPD analysis stage.

The use of the false colour assists in ensuring that fringes are identified correctly.

Typical errors in fringe identification include multiple small fringes arising from noise, gaps in fringes and fringes which deviate from their correct path caused again by image noise. To correct such errors, four editing operations are provided; **A**uto delete, **M**anual delete, **P**artial delete and **J**oin. All options are controlled from the fringe edit interface panel as shown in Fig. 22.

The information panels under the Join option button give context sensitive help on the editing operations. Fig. 22 shows the dialogue provided when joining fringes.



Fig. 22: Fringe edit user interface

10.1 Auto delete

Auto delete applies the minimum number of points condition to all located fringes. Any fringes which are found to have less than the defined number are deleted. The minimum number of points can be adjusted in the Parameters - Fringes menu described in section 6.5 on page 19.

NOTE: This is an extremely useful feature and can be used to remove extremely small “error” fringes which are difficult to detect. This option should be used routinely after fringe tracking before proceeding to OPD analysis. The option is duplicated as a speed button on the top level screen.

10.2 Manual delete

This option removes an entire fringe. After selecting the manual delete option, the user clicks on the fringe to be deleted which is erased from the screen.

A dialogue box (Fig. 24) prompts the user to confirm or reject the deletion of the fringe.

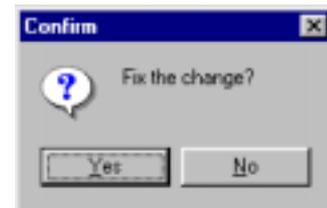


Fig. 24: Delete confirmation dialogue

10.3 Partial delete

This option is used to remove erroneous points from an otherwise correctly identified fringe. After selecting the option, the cursor is moved to the fringe to be edited. The mouse is dragged over the points to be removed using the left mouse button. The information panel displays the number of the fringe being edited.

On releasing the mouse button, the dialogue box invites the user to accept or reject the change. If accepted, the result will be that the edited fringe will be split and must be re-joined as described in section 10.4 below.

10.4 Join fringes

This option is used to join fringe points that have been allocated to separate fringes in error, possibly due to a break in the continuity of the fringe or which have been split by removing points manually using the **Partial delete** option above.

After selecting the option, the cursor is clicked on one part of the fringe to be joined. The number of the fringe in question is displayed in the information panel. The second fringe to complete the join is then identified by a second mouse click. The join is shown on the screen and the dialogue box invites the user to accept or reject the change.

If, despite the use of the fringe editing options described above, it is found that a satisfactory set of fringes can not be obtained, it will be necessary to return to the original image and to perform image editing before proceeding to the fringe tracking stage. Image editing is described in section 11 below.

11. Image Editing

Image editing functions are provided to improve the detectability of the fringes before fringe tracking is performed. Select **E**dit followed by **I**mage to bring up the image editing screen as shown in Fig. 25.

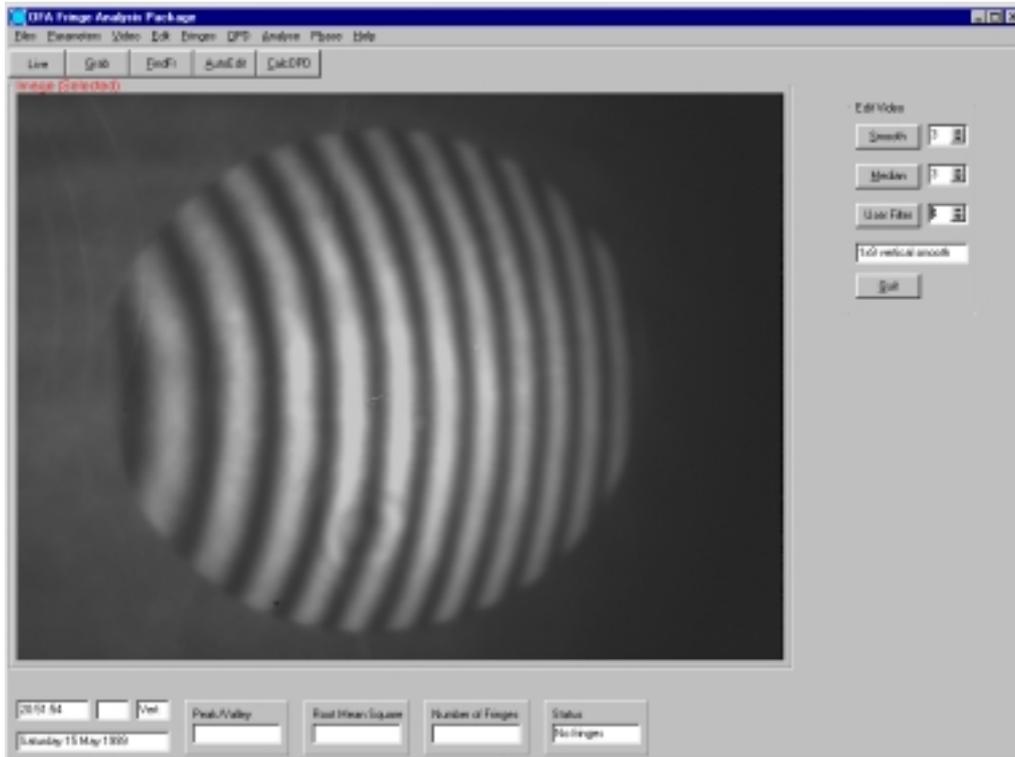


Fig. 25: The Image Edit screen

The image is displayed at full resolution and the three edit feature options are displayed in the image edit control panel shown in Fig. 26.

11.1 Smooth

The smooth option performs a two dimensional convolution on the image of the type

$$\begin{pmatrix} 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \\ 1 & 1 & 1 & 1 & 1 \end{pmatrix}$$

The order of the matrix, 5 in the case shown, is set either by typing in the panel followed by **<return>** or by incrementing/decrementing the number by clicking on the up/down arrows with the mouse.

The smooth operation is initiated by selecting the **S**mooth button with the mouse.

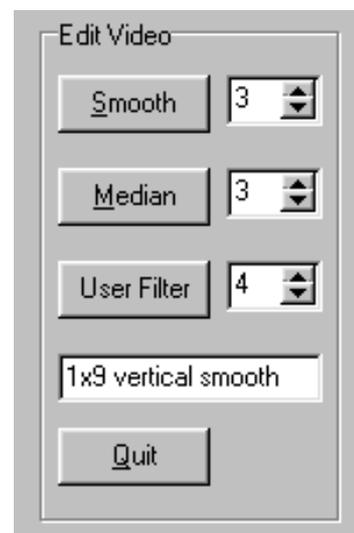


Fig. 26: Image edit control panel

11.2 Median

The rank of the median filter is set either by typing in the panel followed by <return> or by incrementing/decrementing the number by clicking on the up/down arrows with the mouse. Rank 3 is the usual choice for the median filter.

Median filtering is a powerful technique for removal of single noise in the image. The pixel in the centre of the matrix convolution is replaced by the median value of those pixels covered by the kernel of the matrix.

The median filter operation is initiated by selecting the **Median** button with the mouse.

11.3 User filter

This option convolves the image with one of the user defined matrices. Up to 99 such filters may be constructed and stored in the directory containing the Fringe Master software in files named Filter00.txt, Filter01.txt, etc. The filter is chosen either by typing in the panel followed by <return> or by incrementing/decrementing the number by clicking on the up/down arrows with the mouse. A brief description of the filter is given in the information panel. Filters can be constructed using a simple text editor such as NOTEPAD, an accessory supplied with Windows '95 and NT.

The user filter selected in Fig. 26, is number 4, described as a 1 x 9 vertical smooth. The contents of the Filter04.txt file containing this information is shown in Fig. 27. This filter will perform a relatively long range smooth along the vertical direction, i.e. the fringe direction. This is a valuable technique which improves the fringe tracking reliability without losing horizontal accuracy due to horizontal blurring.

The title to be displayed in the information panel is entered in the first line. The second line contains the number of vertical elements ("v"), the number of horizontal elements ("h") and the total sum of all elements for normalisation. The matrix elements themselves are entered in the next "v" lines.

```
1 x 9 vertical smooth
9 1 9
1
1
1
1
1
1
1
1
1
1
1
```

Fig. 27: 1 x 9 user defined "filter04.txt"

Image editing using the routines provided in Fringe Master can enable fringes to be tracked successfully in images where contrast is low and in which noise would otherwise result in the detection of many spurious fringes. In severe cases it may be found that a combination of image and fringe editing is required to give a satisfactory result. Experimentation may be required in order to achieve the best balance between the different procedures.

12. Fringe patterns with Holes

12.1 Introduction

This capability enables Fringe Master to perform automatic analysis of fringe patterns with a central obscuration, or hole, as shown for example in Fig. 28.

In some cases when dealing with particularly complex or poorly defined fringe patterns the software may prompt the user to perform manual joining of detected fringes across the hole though this is rarely necessary.

The analysis of fringe patterns with obscurations is performed in four stages. First the area of interest is defined by setting outer and inner windows. Second, the fringes are detected using the Find Fringe command. Next, the fringe pattern is edited to remove any image noise incorrectly interpreted as fringes and then the fringes are joined across the hole, either automatically or manually. Finally the OPD is calculated as usual and analysed further as required.



Fig. 28: Fringe pattern with internal obscuration

It should be noted that the joining of fringes across the hole is required to achieve proper allocation of fringe numbering around the hole. The resulting “pseudo-OPD” data generated inside the hole is excluded from the P-V and r.m.s. and other data analysis functions.

12.2 Setting Inner and Outer Windows

Select the **Window** option from the Video menu to display the fringe pattern at high resolution and the Set Window interface panel as shown in Fig. 29.

Select the **Outer window** button, **Box** or **Circular** as required, and use the mouse to set the window around the outside edge of the fringe pattern in the usual way. If Zernike analysis of the resulting OPD distribution will be required, select the **1:1** option to equalise the vertical and horizontal dimensions.

If PSF or MTF analysis is required, the maximum window size which can be accommodated is 512 x 512 pixels. Selecting **Max** will automatically set the window to this maximum size.

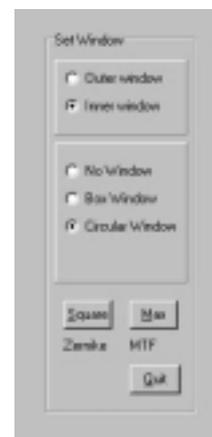


Fig. 29: Window selection panel



Fig. 30: Setting the inner window

Next, select **Inner window** followed by **Box** or **Circular** and use the mouse again to position the inner window as shown in Fig. 30.

Quit from the Set Window panel and return to the top level screen of Fringe Master.

12.3 Detecting the Fringes

Click on the **Find Fringe** button on the top-level screen, and Fringe Master will detect the fringes as normal. Select **Auto Edit** to remove small fringes associated from noise and the fringes will be displayed as shown in Fig. 31.

Fig. 31 shows that at this stage, the upper and lower portions of the split fringes are not associated, demonstrated by the different colours of the upper and lower parts. This association can be performed automatically using the fringe editing options which are available within the **Edit Fringe** menu.

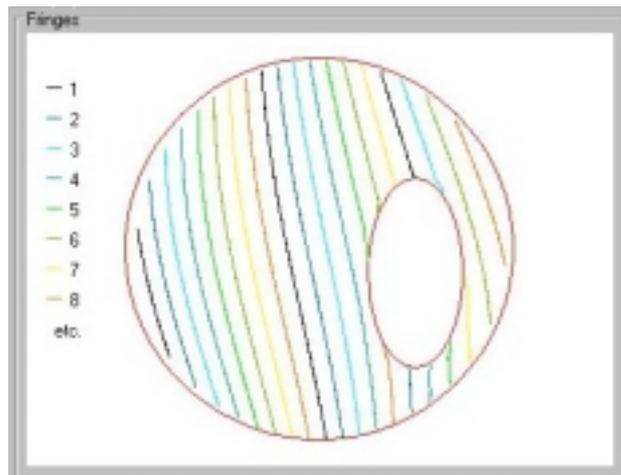


Fig. 31: Detected fringes with internal obscuration

12.4 Associating Upper and Lower Split Fringes

Select the **Edit Fringes** option from the **Edit** menu of Fringe Master as shown in Fig. 32. Select **Renumber over hole**, and the software will run algorithms to identify fringes for joining and perform the join operation automatically.

If the algorithms detect an ambiguity in the fringe pattern, for example a mismatch in the number of upper and lower split fringes, the user will be prompted to perform a manual join as shown below in Fig. 33. At this stage, the user may decide to perform a complete manual join of all split fringes as described in the user manual. Alternatively, the fringe pattern may be edited, spurious fringes removed, and the automatic joining re-selected.



Fig. 32: Fringe edit panel



Fig. 33: Manual join prompt

To assist manual verification of the joining process, the software shows the automatic joins implemented after which the user is able to perform further editing manually if required.

When the fringe joins are satisfactory, quit from the edit fringe panel and return to the top-level screen. The fringe display panel will now show a colour assignment to the split fringes which reflects their association by joining across the hole.

Renumber over hole is selectable from the Auto-Set-up panel within the **Parameters** menu, in which case renumbering will occur automatically when **Auto-run** is selected.

12.5 OPD Calculation

Once the fringes have been detected and split fringes joined, OPD calculation and any subsequent analysis proceeds in the normal way. Select the **CalcOPD** button on the top-level screen. The top-level screen will then be displayed as shown in Fig. 34.

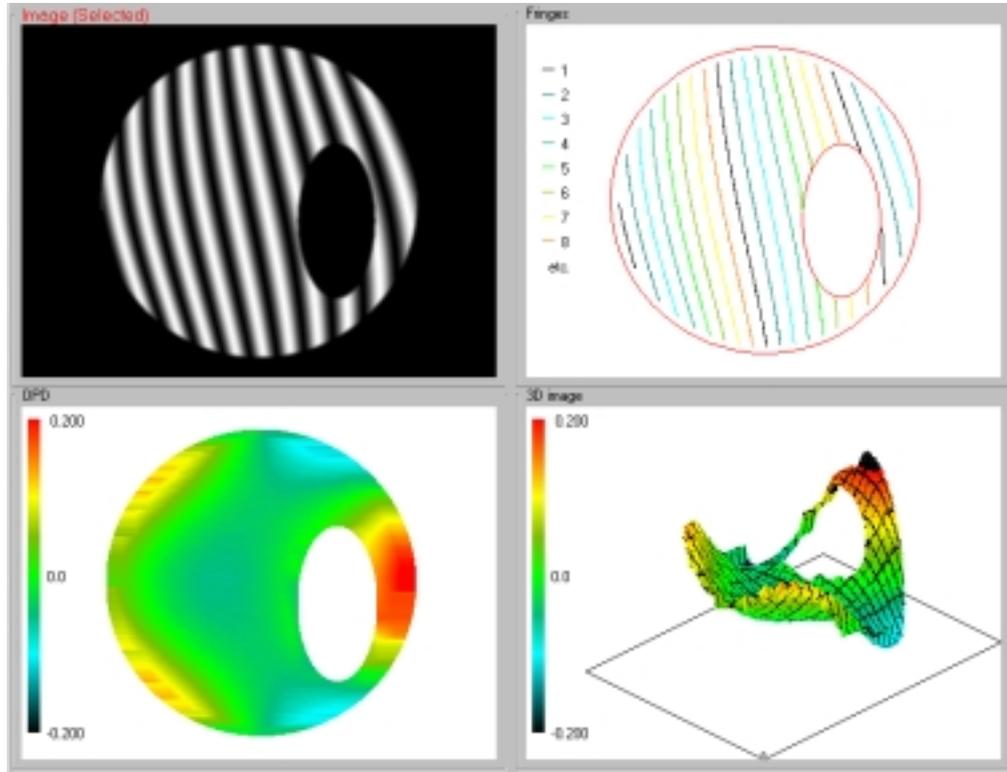


Fig. 34: Fringe Master top level screen following OPD calculation and 3-D plot

The P-V and r.m.s. calculation, OPD statistics and PSF/MTF analysis is performed only on the OPD data between the inner and outer windows.

12.6 Diffraction Limit and Interferometer Adjustment

The correct choice of diffraction limit, accessed within the **Fringes** tab of the **Parameters** menu, is very important when analysing fringe patterns with large obscurations within the outer window. This option is used to restrict the fringe tracking close to the window edge, where window edge effects may cause fringe walk-off at the edge of the region of interest. The diffraction limit selected is applied to the inner window as well as the outer. If the setting is too high, the inner and outer regions may overlap and no fringes will be detected!

Some experimentation may be required to obtain a satisfactory fringe tracking result at the boundary of the inner window, and adjustment of the diffraction limit is one possible way of improving the accuracy. Alternatively, the ends of the fringes may be edited manually by the user prior to selecting the **Renumber across hole** option.

It may also be found that setting a slightly higher number of fringes in the field of view, by adjustment of the interferometer, than in the case of non-obscured interferograms, may improve the fringe following. It is also advisable to adjust the fringe pattern to be as close to vertical orientation as possible.

13. OPD surface statistics

Fringe Master performs area based and histogram based analysis of the OPD surface based upon the aperture over which fringe tracking has been performed.

After calculating the OPD surface, select **OPD** followed by **OPD stats** to run the calculation. The analysis will be explained using the example of an astigmatic OPD surface as shown in Fig. 35

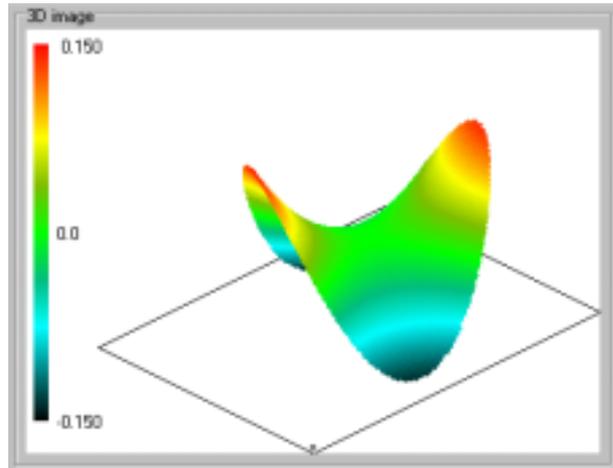


Fig. 35: Astigmatic OPD to be analysed

The output from the calculation is shown in Fig. 36.

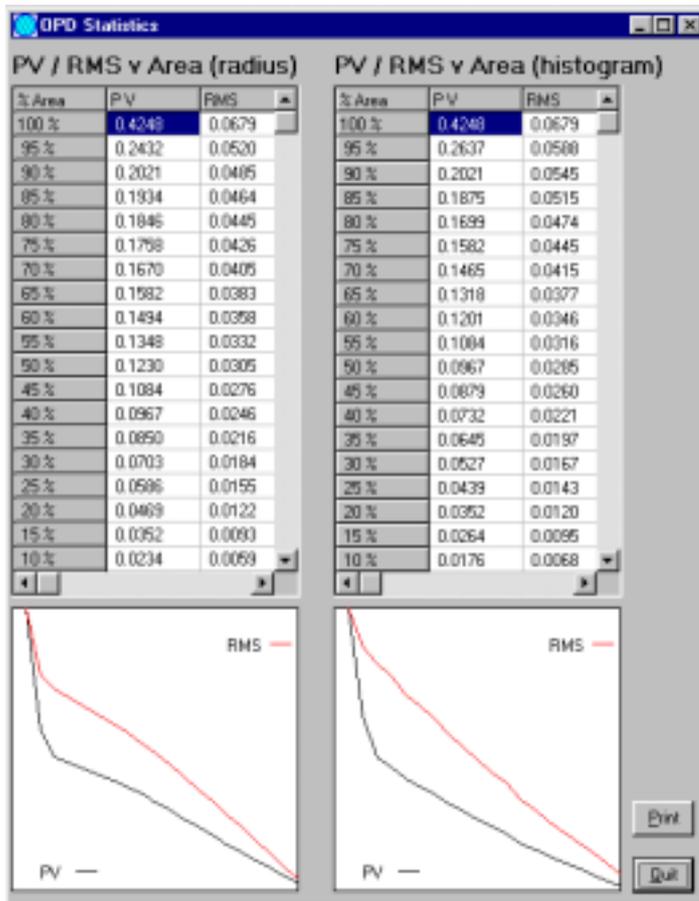


Fig. 36: Statistical analysis of the OPD surface

The table on the left of Fig. 36 shows the dependence of P-V and RMS of the surface as a function of *decreasing radius*. For example, the table shows that by removing an outer annulus equivalent to 30% of the total area, the resulting P-V falls to 0.167 waves and the RMS to 0.0405 waves. The variation with reducing radius is plotted beneath the table. This analysis can be useful in showing the diameter of a component which falls within a certain tolerance.

The table on the right is *histogram* based. The table shows that if, for example, the worst 25% of the area analysed is discarded, the P-V falls to 0.158 waves and the RMS to 0.0445 waves. This may be useful in determining component performance in a non-imaging application. The dependence is plotted below the table.

14. OPD Cross section

After calculating the OPD surface, select **OPD** followed by **X**-section as shown in Fig. 37.

The OPD map will be re-drawn at full resolution. The user will be presented with cross hairs which can be moved under mouse control. The OPD cross section under these cross hairs is plotted to the screen and updated as the cross hairs are moved or dragged.

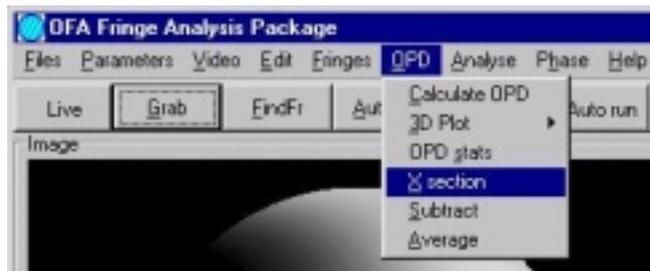


Fig. 37: OPD cross section menu

15. Operations with multiple OPD files

In some cases, the accuracy of an OPD measurement can be improved, either by the subtraction of a reference OPD, by the averaging of multiple OPD measurements or by a combination of both.

15.1 OPD reference subtraction

First a reference OPD is recorded to disc. This might be, for example, of an interferometer without the test piece to enable the residual instrument aberrations to be recorded. Analyse the fringes and determine the OPD in the usual way.

Click on the OPD image title above the OPD plot on the top level screen, and notice that the title changes to **OPD selected** in red type as shown in Fig. 38.

Next, select the **F**iles menu followed by the **S**ave option. Since the OPD is already selected, the system will prompt for an OPD file name, with the appropriate file extension.

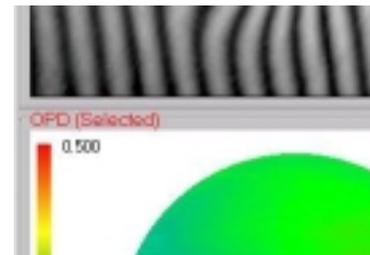


Fig. 38: Selecting the OPD for saving to disc

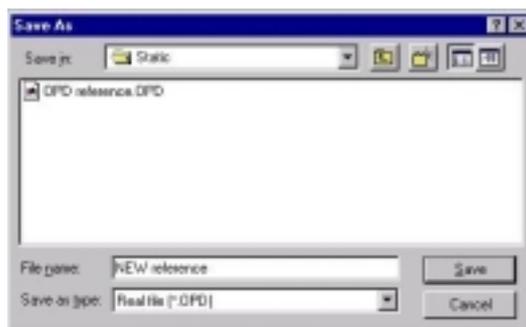


Fig. 39: Selecting the real data option

Before saving the file, it is important to select the "Real file (*.OPD) option as shown in Fig. 39. This ensures that the OPD is saved to the full numerical resolution of the system rather than as a simple image file.

Choose a suitable name and **S**ave the file. This data is now available from disc for subsequent subtraction from test data.

Obtain a new OPD of the test piece in the usual way. Select the **OPD** menu, followed by the **S**ubtract option as shown in Fig. 37 above. Use the Windows file location dialogue to select the OPD data file of your choice and select it by double clicking with the mouse. Fringe Master will calculate the difference between the two OPDs, plot the resultant to the screen and re-evaluate the P-V and rms values.

Note: OPD subtraction is performed on a point by point basis and the field of view must not be changed by adjusting the zoom setting between the two measurements.

15.2 OPD averaging

OPD averaging can be used to reduce errors arising from sources such as air turbulence in the interferometer. The way in which OPD distributions are averaged is very similar to the subtraction of an OPD reference as described in section 15.1 above.

First, a number of OPD distributions are saved to disc using the OPD save option as described above, taking care to choose the "Real file" option.

Next, select the **OPD** menu from the top level screen followed by the **Average** option. The user will be prompted to include or discard the OPD currently displayed on the screen as shown in Fig. 40.

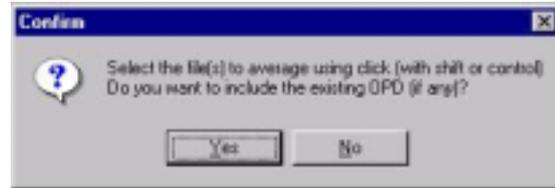


Fig. 40: OPD average dialogue

After making the appropriate choice, use the Windows file dialogue box to select the OPD files for averaging. After selecting OK, the files are loaded from disc and averaged, with the result displayed in the lower left display section of the top level screen.

16. Fringe tilt measurement

Following fringe finding, editing and OPD calculation, the fringe tilt present in the fringe field is available to the user.

Select **Fringes** from the top level screen, and **Fringe Data** from the drop-down menu. The tilt is displayed as shown in Fig. 41.

The total tilt is decomposed into horizontal and vertical components. The units are those selected for the OPD scaling; options include fringes, waves, microns and micro-inches as described in section 7.4 on page 20 above.

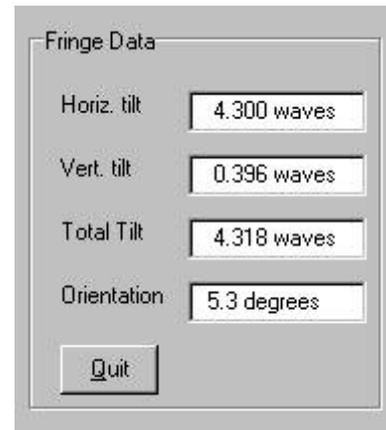


Fig. 41: Fringe tilt data

17. Removal of spherical & Cylindrical power

Fringe Master enables spherical and horizontal power to be subtracted explicitly from apertures of any shape. This can also be done using Zernike analysis of the OPD, but this approach is only valid for circular apertures.

The user is able to measure the radius of the sphere or cylinder of best fit, or to measure and subtract that shape, as shown in Fig. 42. The software reports the radius of the sphere or cylinder in appropriate units (meters or feet) depending on whether metric or Imperial units have been selected for the OPD scale (see Section 7.4).

An example of a spherical subtraction from an aberrated OPD surface generated from Zernike polynomials is shown in Fig. 43 above. The image on the left shows an OPD with 0.4 waves of spherical power and 0.1 waves of the 14th Zernike coefficient. The image on the right shows the residual 0.1 wave OPD distortion after removal of the spherical power.

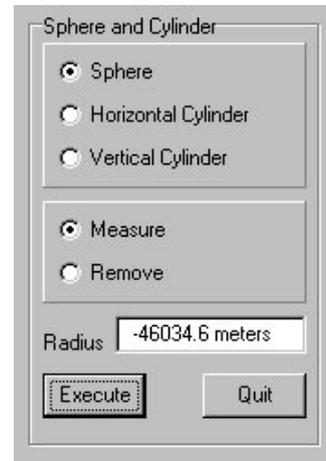


Fig. 42: User interface of power removal

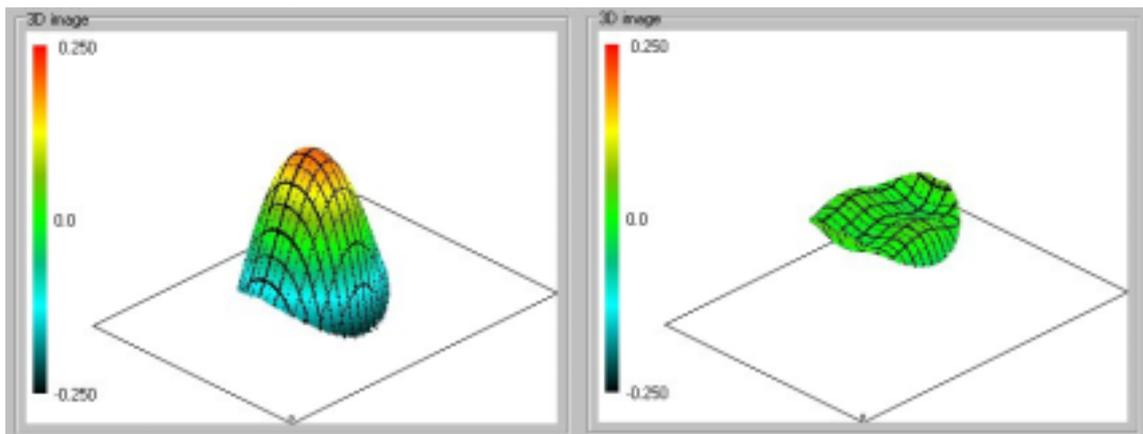


Fig. 43: OPD before and after spherical power subtraction

18. Seidel analysis

Seidel analysis of the optical aberrations induced by the OPD performance of the component under test is available within Fringe Master. Select **A**nalyse followed by **S**eidel. The calculation screen is displayed as shown in Fig. 44.

Name	Magnitude Waves	Angle Radians
Tilt	0.00000	0.80404
Power	0.00000	
Focus	-0.09997	
Astigmatism	0.19995	0.78540
Coma	0.00000	-1.65637
Spherical Aberration	0.00000	

Fig. 44: Seidel analysis using Fringe Master

The values shown in the coefficient boxes relate to the previously calculated values, so the user must click on the **C**alculate button.

NOTE: Seidel analysis is performed using a Zernike method, so the window should be set to a 1:1 aspect ratio before analysis as described in section 2.1.2 on page 9.

The **P**rint button enables the table to be printed to any connected hard copy device. **D**ata saves the numerical values to disk in a form compatible with loading into a spreadsheet as shown below in Fig. 45.

Name	Magnitude	Angle
Tilt	0.00000	0.80404
Power	-0.00000	
Focus	-0.09997	
Astigmatism	0.19995	0.78540
Coma	0.00000	-1.65637
Sph. Aberration	0.00000	

Fig. 45: Contents of the Seidel data text file

19. PSF, Strehl Ratio and MTF analysis

Calculation of the Point Spread Function (PSF), Modulation Transfer Function (MTF) and Strehl ratio is available within Fringe master.



Select **Analyse** from the top level menu as shown in Fig. 46.

If the OPD has not yet been calculated, all the analysis options will be greyed out. If the OPD has been found, select **PSF** (Point Spread Function) from the menu. The MTF (Modulation Transfer Function) will be greyed out until the PSF has been calculated.

Fig. 46: Analyse OPD sub-menu

The PSF and MTF calculations involve FFT calculations. If the window size is greater than 256 pixels in width, the data must be sampled in order to provide sufficient data buffering within memory. The user is informed with a message to the screen as shown in Fig. 47.



Fig. 47: FFT window size warning

The PSF screen will be displayed as shown in Fig. 48.

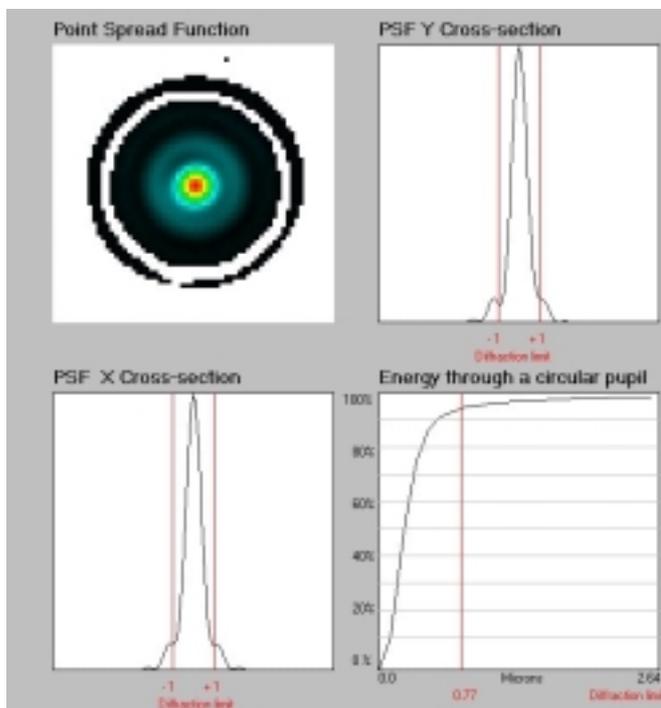


Fig. 48: PSF display screen

The point spread is shown together with X & Y cross sections. The vertical red lines correspond to the diffraction limited spot size. The units along the x-axis depend on the wavelength of the source (entered through the Parameters/OPD menu and the F number of the optical system (entered through the Parameters/MTF menu).

The diffraction limit information is only displayed when the window is set to 1:1 aspect ratio. The calculation takes account of whether the window is square or circular.

The integrated energy is also plotted in the lower right of the screen as a function of radius of a circular aperture located in the focal plane.

Along the bottom of the screen, the user has access to further display and calculation options as shown in Fig. 49.

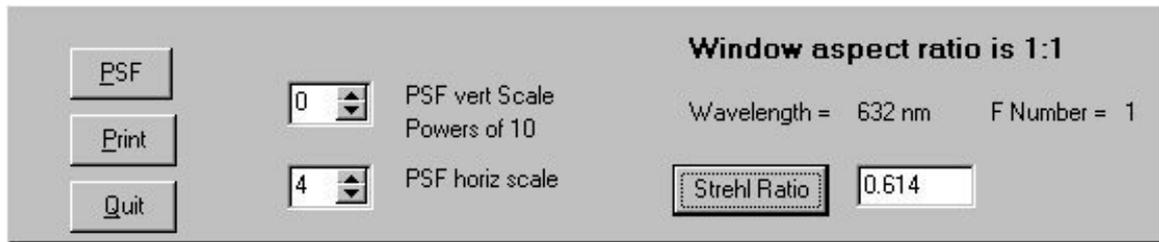


Fig. 49: Point Spread Function display controls

The panel displays the current settings of the wavelength, F-number of the imaging system and the aspect ratio of the analysis window.

The radio button labelled PSF horiz scale can be used to stretch the cross section and power transmission display. This is useful in the case of good OPD performance where the diffraction limit is extremely small.

The vertical scale ratio button stretches the PSF display vertically to show low level features in the display.

19.1 Strehl ratio

Select **Strehl ratio** to calculate the Strehl ratio based on the point spread performance of the OPD compared with that of the diffraction limited case.

19.2 MTF analysis

Select **Analyse / MTF** to calculate **Modulation Transfer Function**. The MTF is plotted in the top left screen, and horizontal and vertical graphs through the centre of the image are plotted beside and below as shown in Fig. 50. The horizontal scale is in terms of a normalised aperture, lines/mr or lines/mm depending on the settings in the MTF Parameters menu.

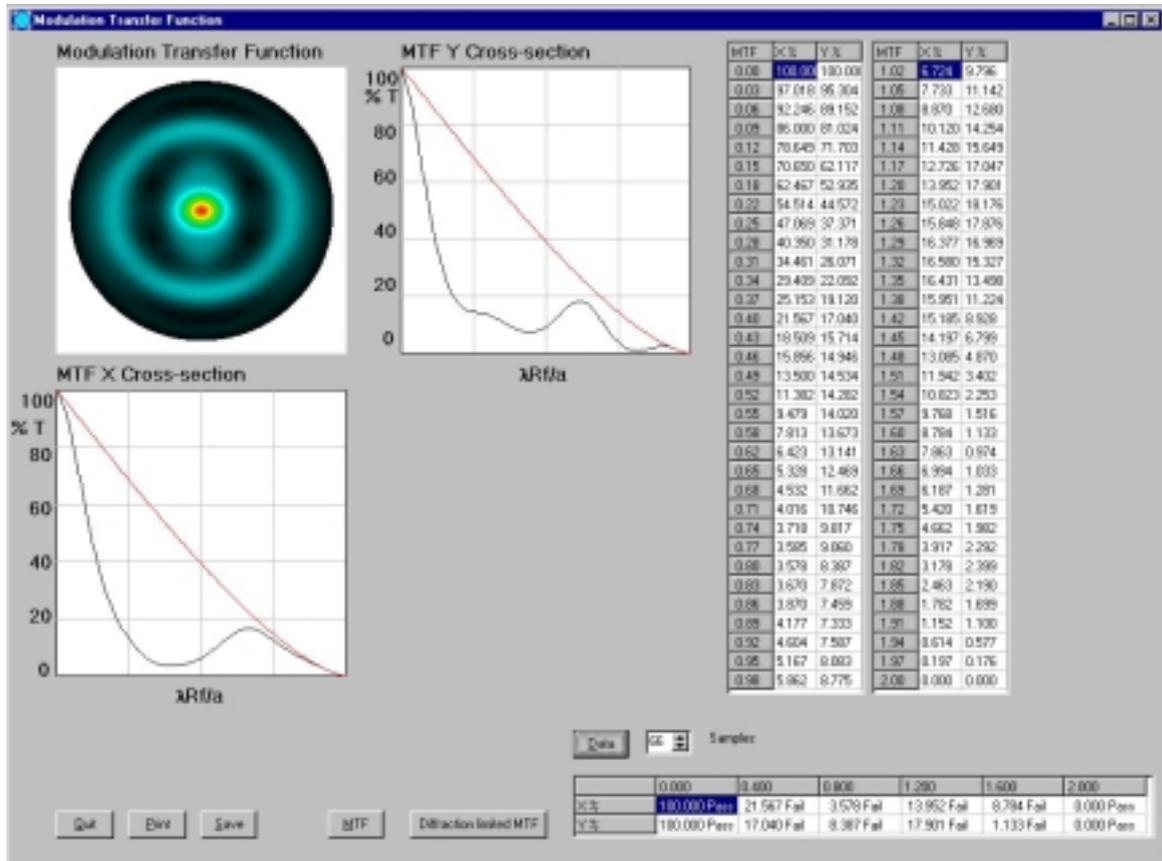


Fig. 50: MTF analysis screen

Select **Diffraction limited MTF** and the diffractio limit will be plotted in red between the 100% and 0% points as shown in Fig. 50.

Data produces an on-screen table of values of MTF, with the number of data points set by the spin wheel. **Save** prompts the user for a file name and then records the tabular data to disc in a form accessible to spreadsheet or other Windows applications.

Print outputs the PSF/MTF screen to any hard copy device supported by the Windows operating system.

19.3 MTF analysis options

Calculations performed within the MTF software are controlled by settings entered in the Parameters – MTF screen. Select Parameters from the top level screen and click on the MTF tab. The MTF Parameters panel will be displayed as shown in Fig. 51.

19.4 Coherent / Incoherent

Select the required calculation by checking the appropriate radio button. Note that although the interferometer will use coherent light to obtain the fringe pattern, it is the light source with which the optic is designed to be used that must be entered.

The change between coherent and incoherent illumination changes the result by a factor 2, with incoherent yielding the best resolution. For further information, the user is referred to the standard texts, such as Principles of Optics (Born & Wolf) published by Pergamon Press.



Fig. 51: MTF parameters screen

19.5 MTF units

Choice of the **Normalised Units** produces MTF curves plotted between zero and unity (coherent) and 2 (incoherent illumination). Selection of **Lines / mm** requires the user to enter the F-number of the optic being measured while **Cycles / mrad** requires entry of the optic aperture in mm.

19.6 MTF fixed values

Some applications require the interpolation of the MTF table to particular values as defined in a Q.A. specification, and this requirement is met by Fringe Master analysis software. The user enters the tabular values required in the 6 left hand boxes as shown in Fig. 50. The units must be appropriate for the MTF units chosen. The user then enters the “Pass values” for the transmission at the corresponding spatial frequencies.

For example, the “Pass value” at 400 lines / mm has been set to 60% in Fig. 50. Referring to back Fig. 50, it will be seen that the result of that particular measurement was $T = 56.4\%$ in the X orientation (shown as a “fail”) and $T = 61.4\%$ in Y (shown as a “pass”).

MTF analysis can be performed as an “auto-run” element as described in Section 22 below on page 44.

20. Zernike analysis

This section contains information on how to access the Zernike analysis software. More information on the use and implementation of Zernike analysis within Fringe Master is given in Section 21 on page 41.

Zernike analysis can be used in two ways in Fringe Master. Firstly, an OPD surface calculated from analysis of a fringe pattern can be used as input and the Zernike coefficients calculated up to 45th order. Secondly, coefficients can be entered directly, and the associated OPD can be calculated, plotted and analysed. This leads to great versatility in the way the system can be used.

For example, an OPD could be obtained from a fringe pattern, and Zernike analysis performed. One or more of the resulting Zernike coefficients can be adjusted and the OPD re-evaluated. Thus the contribution to overall performance of particular features can be determined.

Alternatively, a completely artificial OPD could be constructed from Zernike coefficients for input to a propagation or ray trace code.

Select Analyse and then Zernike from the Fringe Master toolbar. The Zernike analysis panel will be presented as shown in Fig. 52

20.1 Zernike Order

The number of Zernike coefficients to be calculated is adjusted by typing a number up to 45 in the **Zernike Order** panel, followed by **<return>**. Alternatively, the number can be adjusted using the up/down arrows beside the panel.

To reduce the calculation time required, the number of coefficients should not be set to a value higher than is required as calculation takes approximately one second per coefficient.

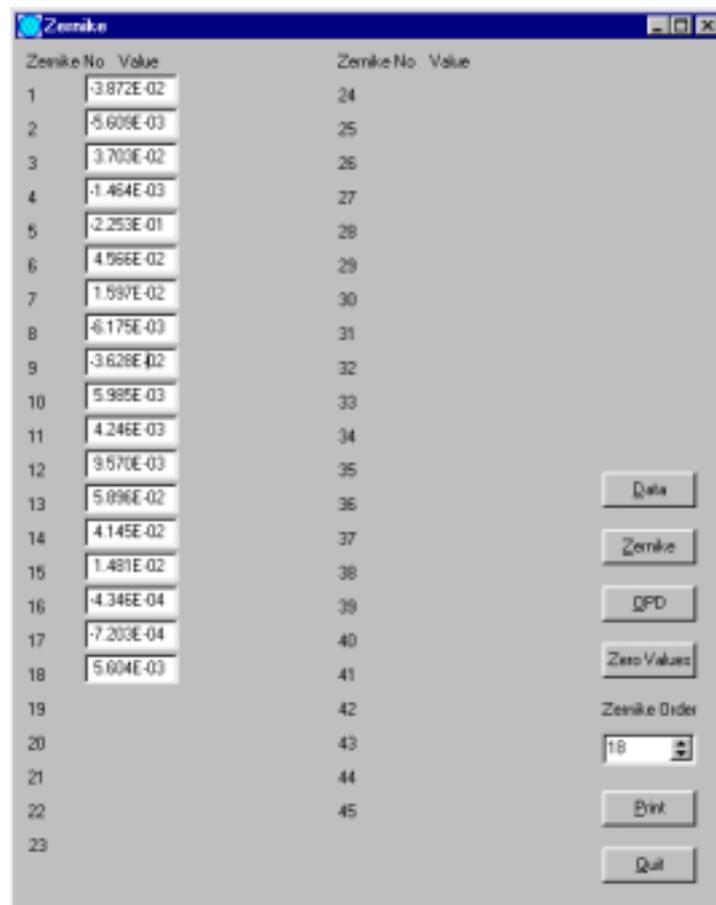


Fig. 52: The Zernike analysis screen

20.2 Zernike calculation

Selecting the **Zernike** button starts the calculation of Zernike coefficients. If a calculation has been performed previously, the previous values will be displayed when the screen is loaded.

20.3 Zero Values

This sets all coefficients to zero.

20.4 Data

This option writes the values of the coefficients to a disc file in a format compatible with loading into a spreadsheet, optical analysis software or other Windows application.

20.5 OPD

This option generates an OPD distribution from the coefficients displayed in the Zernike analysis panel and plots it in the Fringe Master OPD plot area on the top level screen. The fringe pattern which would have produced such an OPD is then generated and plotted in the fringe pattern plot area on the top level screen.

The fringe pattern and OPD so produced may be analysed using Fringe Master in the usual way. For example, the OPD may be analysed in terms of Seidel coefficients (see section 18 on page 34) or OPD histogram (section 13 on page 30).

20.6 Print

The Print option sends a bitmap of the Zernike analysis results screen to the printer via the Windows printer interface screen.

NOTES

- 1 *In order to analyse the fringes generated using the static fringe version of Fringe Master,, it will be necessary to introduce horizontal tilt into the OPD by adjusting the 3rd coefficient. A value of 2 will generate 4 light and dark bands if the system is set to double pass (see section 7.1 on page 20)*
- 2 *Care must be taken when entering coefficients explicitly. The existing number, plus the exponent, should be deleted and the required number entered, followed by <return>.*
- 3 *The OPD scale must be adjusted to a suitable value in order to avoid overflowing the display. Such an overflow invalidates the subsequent calculations. The OPD scale is set as described in section 7.5 on page 20.*

21. Zernike Polynomials & their use in Fringe Master™

21.1 Introduction

The polynomials that are almost universally applied to fringe analysis are those devised by Fritz Zernike in 1934. International Standards for the measurement and interpretation of interferograms are currently being drafted (ISO 14999 and 10110). They are likely to recommend that Zernike polynomials be used for the numerical analysis of optical wavefronts.

The orthogonal nature of the polynomials means that the individual terms describing tilt, spherical power, astigmatism etc. can be identified, measured and subtracted from the numerical description of the wavefront. Any residual aberrations can be separately identified and used to quantify the quality of the laser beam.

21.2 Zernike representation

A phase surface can be described by a distribution denoting the distance W of the surface of constant phase from some reference surface (usually a sphere). If the wavefront is continuous and sufficiently smooth, it can be represented by a two-dimensional function of the radial and azimuth cylindrical co-ordinates $\mathbf{W}(\rho, \theta)$. A suitable function, when the aperture of the beam is circular and has unity radius, is a linear combination of Zernike polynomials Z_r so that:

$$\mathbf{W}(\rho, \theta) = \sum A_r \cdot Z_r$$

The first term $A_1 \cdot Z_1$ is the "piston" or constant term since $Z_1 = 1$. The terms with $r = 2$ and 3 are the required tilt terms about the x and y axes where $Z_2 = \rho \cdot \sin \theta$ and $Z_3 = \rho \cdot \cos \theta$. The coefficients A_r are the product of a normalising term and a constant representing the contribution of the r^{th} Zernike polynomial to the total wavefront aberration.

The Zernike polynomials are defined by generalised expressions. The first 45 have been implemented in the Fringe Master software and are defined in Fig. 53 on page 43 below.

NOTE: Different sources number the coefficients differently. If in doubt, refer to Fig. 53.

21.3 Wavefront Fitting

The fringe analysis software derives the values of the wavefront at a large number of discrete points in the transverse plane. To derive the Zernike polynomial description of this wavefront, the measured values must be interpolated to provide a uniform fine distribution of N measurements over a normalised circular aperture. When this is done, the values of the coefficients A_r can be calculated from:

$$A_r = \frac{\sum W_i \cdot Z_r}{\sum Z_r^2}$$

where W_i is the interpolated value of the wavefront displacement at the i th position and Z_r is the r^{th} Zernike polynomial evaluated at that position.

When interferograms are used to measure the quality of optical components, up to 36 Zernike polynomials can be used to extract the fine detail of any aberrations.

21.4 Uncertainties

The above method of calculating the values of the coefficients of the Zernike polynomials is dependent on the availability of a sufficiently large number of uniformly distributed measurements over a circular aperture. If these conditions are not satisfied, the orthogonality

of the polynomials cannot be assumed. The uncertainty in the estimation of the aberrations in a beam from this cause is to be investigated.

From Fig. 53, it will be seen that higher orders consist of a number of terms. Consider for example Z_5 . This describes the spherical power, or focal shift, of the wavefront. In the case of a zero power, flat wavefront, this term should be identically equal to zero. With a normalised radius, it follows that in order for the sum to equate to zero, the sum of positive terms must equal the sum of negative terms. The negative terms lie within a circle of radius given by $r_{\text{crit}} < 1/\sqrt{2}$, the positive terms lie outside this radius. On this radius itself, each term is zero.

The OPD is calculated within a window around the beam on a rectangular mesh of finite size and pitch. Clearly there will not be an exact balance between positive and negative terms. Firstly, even on an infinite mesh, balance can only be obtained within a circular window. Secondly the rectangular digitisation introduces a level of error which can not be overcome. This is particularly severe for small radius windows and for higher order terms that contain higher powers of the radius, ρ .

From the above it is clear that the rectangular digitisation causes errors in the calculation of the Zernike amplitudes and leads to breaking of the orthogonality. For example, the spherical term varies as the tilt is changed, e.g. the two terms are not independent, or orthogonal. This effect can be minimised by zooming the optical system of the interferometer so that the fringe pattern fills the field of view.

The level of balance was found to be of the order of 1% for circular windows covering approximately 60% of the camera field of view.

For further information on Zernike polynomials and their use, the user is referred to the standard texts, such as Principles of Optics (Born & Wolf) published by Pergamon Press.

<u>Term</u>	<u>Zernike</u>	<u>Normalⁿ</u>	<u>Interpretation</u>
1	1	1	Piston
2	$\rho \cdot \sin\theta$	2	Tilt about y-axis
3	$\rho \cdot \cos\theta$	2	Tilt about x-axis
4	$\rho^2 \cdot \sin 2\theta$	$\sqrt{6}$	Astigmatism with axis at $\pm 45^\circ$
5	$2\rho^2 - 1$	$\sqrt{3}$	Focus shift
6	$\rho^2 \cdot \cos 2\theta$	$2\sqrt{2}$	Astigmatism with axis at 0° or 90°
7	$\rho^3 \cdot \sin 3\theta$	$2\sqrt{2}$	Triangular astigmatism with base on x-axis
8	$(3\rho^3 - 2\rho) \cdot \sin\theta$	$2\sqrt{2}$	Third order coma along the x-axis
9	$(3\rho^3 - 2\rho) \cdot \cos\theta$	$2\sqrt{2}$	Third order coma along the y-axis
10	$\rho^3 \cdot \cos 3\theta$	$\sqrt{10}$	Triangular astigmatism with base on y-axis
11	$\rho^4 \cdot \sin 4\theta$	$\sqrt{10}$	
12	$(4\rho^4 - 3\rho^2) \cdot \sin 2\theta$	$\sqrt{10}$	
13	$6\rho^4 - 6\rho^2 + 1$	$\sqrt{5}$	Third order spherical aberration
14	$(4\rho^4 - 3\rho^2) \cdot \cos 2\theta$	$\sqrt{10}$	
15	$\rho^4 \cdot \cos 4\theta$	$\sqrt{10}$	
16	$\rho^5 \cdot \sin 5\theta$	$\sqrt{12}$	
17	$(5\rho^5 - 4\rho^3) \cdot \sin 3\theta$	$\sqrt{12}$	
18	$(10\rho^5 - 12\rho^3 + 3\rho) \cdot \sin\theta$	$\sqrt{12}$	
19	$(10\rho^5 - 12\rho^3 + 3\rho) \cdot \cos\theta$	$\sqrt{12}$	
20	$(5\rho^5 - 4\rho^3) \cdot \cos 3\theta$	$\sqrt{12}$	
21	$\rho^5 \cdot \cos 5\theta$	$\sqrt{12}$	
22	$\rho^6 \cdot \sin 6\theta$	$\sqrt{14}$	
23	$(6\rho^6 - 5\rho^4) \cdot \sin 4\theta$	$\sqrt{14}$	
24	$(15\rho^6 - 20\rho^4 + 6\rho^2) \cdot \sin 2\theta$	$\sqrt{14}$	
25	$(20\rho^6 - 30\rho^4 + 12\rho^2 - 1)$	$\sqrt{7}$	Fifth order spherical aberration
26	$(15\rho^6 - 20\rho^4 + 6\rho^2) \cdot \cos 2\theta$	$\sqrt{14}$	
27	$(6\rho^6 - 5\rho^4) \cdot \cos 4\theta$	$\sqrt{14}$	
28	$\rho^6 \cdot \cos 6\theta$	$\sqrt{14}$	
29	$\rho^7 \cdot \sin 7\theta$	4	
30	$(7\rho^7 - 6\rho^5) \cdot \sin 5\theta$	4	
31	$(21\rho^7 - 30\rho^5 - 10\rho^3) \cdot \sin 3\theta$	4	
32	$(35\rho^7 - 60\rho^5 + 30\rho^3 - 4\rho) \cdot \sin\theta$	4	
33	$(35\rho^7 - 60\rho^5 + 30\rho^3 - 4\rho) \cdot \cos\theta$	4	
34	$(21\rho^7 - 30\rho^5 + 10\rho^3) \cdot \cos 3\theta$	4	
35	$(7\rho^7 - 6\rho^5) \cdot \cos 5\theta$	4	
36	$\rho^7 \cdot \cos 7\theta$	4	
37	$\rho^8 \cdot \sin 8\theta$	$\sqrt{18}$	
38	$(8\rho^8 - 6\rho^6) \cdot \sin 6\theta$	$\sqrt{18}$	
39	$(28\rho^8 - 42\rho^6 + 15\rho^4) \cdot \sin 4\theta$	$\sqrt{18}$	
40	$(56\rho^8 - 105\rho^6 + 60\rho^4 - 10\rho^2) \cdot \sin 2\theta$	$\sqrt{18}$	
41	$(70\rho^8 - 140\rho^6 + 90\rho^4 - 20\rho^2 + 1)$	$\sqrt{9}$	
42	$(56\rho^8 - 105\rho^6 + 60\rho^4 - 10\rho^2) \cdot \cos 2\theta$	$\sqrt{18}$	
43	$(28\rho^8 - 42\rho^6 + 15\rho^4) \cdot \cos 4\theta$	$\sqrt{18}$	
44	$(8\rho^8 - 6\rho^6) \cdot \cos 6\theta$	$\sqrt{18}$	
45	$\rho^8 \cdot \cos 8\theta$	$\sqrt{18}$	

Fig. 53: Definition and interpretation of Zernike terms

22. Auto run facility

Fringe Master's *Auto run* facility enables a number of functions to be performed with a single key press. This is especially useful for the analysis of similar fringe patterns in a repetitive or production environment where the window position and size is kept constant. It is suggested that the successful analysis of an image is verified using individual commands before initiating an *Auto run* sequence

22.1 Starting Auto run

The Auto run function is activated by clicking the *Auto run* button which is found on the Fringe Master toolbar on the top level screen as shown in Fig. 54.

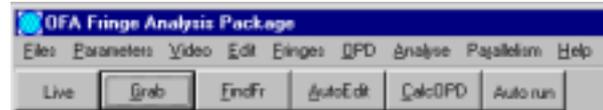


Fig. 54: *Auto run* button on the Fringe Master tool bar

22.2 Auto run options

The *Auto run* button performs a number of Fringe Master functions, selected by the user from the *Auto setup* tab in the *Parameters* menu. The selection panel is shown in Fig. 55.

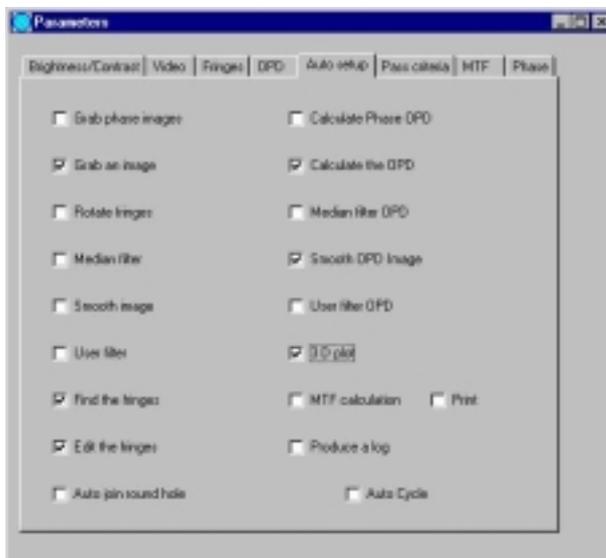


Fig. 55: *Auto run* options selected from the *Auto setup* menu

The options will be recognised as the principal functions performed by Fringe Master in the acquisition and analysis of fringe patterns.

The Auto setup enables images to be grabbed, smoothed, fringes and OPD to be found, OPD smoothing and hard copy output.

The range of the smooth and median filters and the choice of user filter are set in the **Process Image** menu (see Section 11 on page 25), and stored in the *.dat* set-up file. It is these values which will be used with *Auto run*.

The choice of options selected is stored in the *.dat* file and is loaded each time the Fringe Master software is run.

22.3 Auto Cycle

A further enhancement of the *Auto run* facility is the option to repeat the Auto run sequence automatically. This is enabled by checking the *Auto Cycle* box as shown in Fig. 55. This causes the cycle to repeat until halted by the user. This option is intended primarily for demonstration purposes, but may be useful in a production environment.

When the *Auto run* button is clicked, if *Auto Cycle* is selected, a **STOP** button is drawn to the toolbar on the top level screen as shown in Fig. 56



Fig. 56: The *Auto Cycle* STOP button

NOTE: The status of the *Auto Cycle* check box is NOT stored in the configuration file and must be re-enabled if required each time Fringe Master is loaded.

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