

This file is AbePSF22.txt. It contains five sections that describe version 2.0 of the Abe\_PSF2 code for IBM PC computers and compatibles running 32-bit Windows operating systems:

Section 1: A brief description of the Abe\_PSF2 computer program, in the format typically used for upload announcements.

Section 2: A more detailed description of the computer program.

Section 3: A "walk through" to make your first use of this computer program a success, and maybe even fun.

Section 4: A history of the Abe\_PSF code.

Section 5: Brief remarks on the branch of physics called optics.

## \_\_\_\_\_ Section 1: Brief description \_\_\_\_\_

Abe\_PSF2 replaces all versions of its predecessor, Abe\_PSF.

Abe\_PSF2 is a 32-bit Windows PC program that shows how the wavefront shape and the transmission function of an optical system will affect its image blur, formally called the point spread function (PSF). The image degradation from wavefront effects such as third order aberrations (coma, spherical, astigmatism) and defocus, Zernike polynomial coefficients, discontinuous phase errors (waffle, checkerboard, or random), and/or a subaperture phase plate are simulated. The blur growth from the transmission losses due to obscurations from secondary mirror struts or a central obscuration are modeled, as well as apodization effects or speckle. The pupil can be round, hexagonal, or rectangular, and the system wavelength and f/number are user selectable. All effects may be simulated independently or in combination.

Screen output is in tabular or graphical form; 2-D or 3-D plots of PSF or logarithm PSF (to show low intensity detail) are possible. An ASCII file containing pupil transmission, pupil phase, or PSF modulus values can be saved and imported into other programs. The graphical user interface is intuitive and straightforward. This program should be of interest to high school or college teachers or students who are interested in science, optics or astronomy, as well as optics professionals.

Download the compressed binary file, called abepsf22.zip, which contains the executable code, a utility, and a text file with brief and detailed descriptions and a "walkthrough" for those unfamiliar with pupil functions and diffraction point spread functions.

Special requirements: 32-bit Windows (Windows 95, Windows NT, or Win 3.11 w/ Win32s)

Abepsf22.zip corrects a bug that caused program aborts under Win95; Abe\_PSF2 replaces all versions of Abe\_PSF, which have date stamps earlier than August, 1997.

ShareWare.           \$10.           Uploaded by the author  
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## \_\_\_\_\_ Section 2: More Detailed Description \_\_\_\_\_

The point spread function (PSF) is the diffraction based image of a point object as formed in the focal plane of an optic. This image will be affected by how the optic changes the wavefront phase and transmission. Abe\_PSF2 models those effects in a 128 by 128 array of complex numbers and performs a two-dimensional fast fourier transform (FFT) to compute the PSF from the pupil function.

Abe\_PSF2 is an optics computer program for the IBM PC and compatible computers running under 32 bit Windows (Win32s or Win95 or NT). The program calculates the diffraction PSF of either a perfect wavefront or of a wavefront containing a combination of small amounts of pupil phase error, including third order aberration, defocus, Zernike phase aberrations, and discontinuous phase errors such as waffle, random, or checkerboard phase errors. A subaperture phase plate can be used to give a step phase change over a fraction of the pupil. The pupil may be round, hexagonal, or rectangular, and also may be modeled with a circular central obscuration or not, as well as an apodized or unapodized transmission. The pupil transmission apodization function can be triangular, gaussian, or supergaussian. The pupil can also exhibit the shadows associated with secondary mirror struts, and can have the varying irradiance across it caused by speckle. The wavelength and pupil diameter can be varied.

In Abe\_PSF2, the aberrations and pupil transmissions can be modeled individually or in combination. Optics textbooks often show the geometrical spots for aberrations, but not usually the diffraction PSFs, and certainly not the situation where several aberrations are together in combination, which is the usual case in practice; Abe\_PSF2 can model a wide range of combined effects. The Windows graphical user interface (GUI) makes the selection of optical system and wavefront parameters easy.

The third order aberrations that are modeled include spherical, coma, and astigmatism. Defocus is also modeled; defocus can occur both from field curvature, which is a third order aberration, or from a focal plane shift. The aberration

called distortion will cause point images to appear in the wrong place on the focal plane, but will not increase the blur; for this reason, distortion effects are not modeled in this code. The magnitude of each aberration is specified in terms of wavelengths of optical path difference (OPD) at the edge of the pupil. The field of view for asymmetric aberrations (coma and astigmatism) can be oriented either horizontally (x) or vertically (y). Complex wavefronts represented by the thirty seven "Fringe" Zernike polynomial coefficients can also be modeled.

The transmission of an unapodized pupil is 100%. If something obscures a portion of the pupil (i.e., blocks the light in a portion of it), the transmission of the obscured area is zero. The program allows for either an unobscured or a centrally obscured pupil. The obscuration is specified in terms of the linear obscuration ratio, which is the ratio of the diameter of the obscuration to the diameter of the pupil. A value of one for the obscuration ratio would correspond to a completely obscured aperture for which no light would get to the image. Typical linear obscuration ratios range from 0.1 to 0.3.

Abe\_PSF2 can also model pupils whose transmission is apodized. The usual case is without apodization, where the transmission in the pupil region is 100% on the open (unobscured) area, and 0 % outside the pupil. An apodized pupil has regions in the clear area where the transmission is less than 100% but more than zero. Abe\_PSF2 models either a triangular (cone shaped) or a supergaussian transmission apodization function. A supergaussian function "cuts off" more quickly as the supergaussian coefficient increases; a supergaussian coefficient of around 4 or 5 gives a nearly "flat top" or "pillbox" transmission function. Later, in the "walkthrough" section that follows, you'll see how to do a 3-D plot of pupil transmission to see what the apodization looks like.

Checkboxes and radio buttons in the setup dialog boxes determine whether the aberrations, obscurations, Zernike coefficients, apodizations, supergaussians, discontinuous phase functions and phase plates will be applied to the wavefront or not. When a setup dialog box is closed by the "Okay" button, a new pupil function is generated and the old PSF is discarded. However, a new PSF is not automatically generated, since several other pupil changes might be specified for the new system. It will be necessary to click on the "Create PSF" menu item in order to generate the point spread function after all of the new pupil information has been input. If you request PSF information when you have forgotten to generate the new PSF, the code will present a message box that tells you how to do the PSF.

Abe\_PSF2 has both graphical and tabular displays of the input wavefront transmission, the input wavefront phase, and the output PSF. On-screen graphics show 2-D plots (also called "slices"), or 3 dimensional isometric plots or contour plots for each of these three data sets. An ASCII file can be written with the pupil phase, pupil transmission, or the PSF array values; these can then be imported into another program (MS Excel, for example) for further manipulation and graphics hardcopy.

Abe\_PSF2 is a 32 bit program. It runs under Windows 3.1X with the help of Win32s, and it also runs under Windows 95 or NT. Be sure that the file CW3215.DLL is either in the same directory as the code, or is on a path. The file AbePSF22.ZIP contains several files: Version 1 of Abe\_PSF2.EXE, AbePSF22.TXT (this file), and CW3220.DLL.

Abe\_PSF2 is copyright Nelson Wallace, 1995-7. It is a ShareWare program and may be found at:

<ftp://lorien.creol.ucf.edu/pub/optics>

<ftp://ftp.osa.org/OptSoft/freeSoft>

Check the CREOL site for the latest upgrades.

### Section 3: Walkthrough

(You may want to print this part of the file and keep it handy as you run the program for the first time).

This walkthrough will show you how to review the default pupil function that is always created upon the start-up of the computer program. It will also tell you how to create and review the PSF that results from the pupil function. It ends with suggestions of other things to try.

Unzip the Abe\_PSF22.ZIP file. Make a directory on your hard drive called "Abe\_PSF2" and copy all of the files (.exe, .dll, .txt, etc.) into it. Then make sure you can see the .exe extension on your files. To do this, open Windows Explorer, click on the View menu item, then click on the Options submenu. When the Options dialog box opens, click on the View tab. Make sure the checkbox for the "Hide MS-DOS file extensions for file types that are registered" is not checked. Close the options dialog box. Now you can see the full filename. You could create a shortcut of Abe\_PSF2.exe and drag it onto your desktop. Or, In Windows Explorer, find the Abe\_PSF2 subdirectory, and double click on the Abe\_PSF2.exe file.

This begins the program. The program uses the full screen, displaying a menu at the top. Let's take a tour of the general optics setup first. Click on the "Setup" toplevel menu item. You'll see four submenu items. Click on "System Specifications", and then on the "Optics Specifications" menu item. An optics specifications dialog box opens, showing that the analysis wavelength is 500.000 nanometers, and that the

optics f/number is f/5.600. It also shows that the field of view for the third order aberrations is in the horizontal, or x direction. You can click on "Cancel" or "OK" to close this box. Clicking on "OK" will cause the program to accept the values shown as input, and to recalculate the pupil function (and this could take some time on slower machines); if you click on "Cancel", the program will keep the values it already had, and not recompute the pupil function; this choice is faster when reviewing data that does not need to be changed.

Click on the "Setup", "System Specifications" and "Pupil Specifications" menu items. The pupil specifications dialog box opens, showing that the pupil shape can either be round, hexagonal, or rectangular; in the current setup, the exit pupil is seen to be round, with a diameter of 10.00 millimeters. Click on "Cancel" to close this box.

The program is designed to combine different pupil phase effects and transmission effects. Let's look at how the pupil phase is specified as the sum of four effects: third order aberrations, Zernike terms, a discontinuous phase pattern, and/or a subaperture phase plate.

Click on the "Setup", "Pupil Phase", and the "Third Order Aberrations" menu items. A third order aberrations dialog box opens. Notice that this dialog box has a check in the checkbox for coma, showing that the coma aberration is enabled. Note that none of the other checkboxes are checked; none of these other aberrations will be added in to the pupil phase, even if there were numerical values in the boxes next to the checkboxes. The number "-0.400" appears in the number field next to the coma checkbox; this means the coma will be 0.4 waves at the edge of the pupil. Because coma is an asymmetric aberration, the aberration at one edge on the pupil will be 0.4 waves forward, and 0.4 waves backward at the other edge of the pupil. The minus sign in the -0.4 value shown determines whether the forward phase error occurs on the left or the right of the pupil. Click on the "Cancel" button to close the third order aberrations dialog box.

Click on the toplevel menu item "Setup", and "Pupil Phase" again, then "Zernike Coefficients". A Zernike coefficients dialog box opens. In the upper right-hand corner of this dialog box, there is a check in the checkbox that controls the 26th Zernike coefficient, showing that this phase aberration is enabled. All the other terms are turned off because their checkboxes are not checked. Click on the "Cancel" button to close the Zernike coefficients dialog box.

Click on the toplevel menu item "Setup", "Pupil Phase", then "Discontinuous Phase Pattern". The discontinuous phase

pattern dialog box opens, giving choices for the type of pattern, which are either none, a checker board, a waffle, or a random pattern. For the default condition, there is no contribution to the pupil phase from a discontinuous phase pattern. In this dialog box, it is also possible to define the amplitude of the phase pattern, in waves, and to specify the pattern's period. Click on the "Cancel" button to close the discontinuous phase pattern dialog box.

Click on the toplevel menu item "Setup", "Pupil Phase" again, then "Subaperture Phase Plate". Until now, all of the phase functions that were specified pertained to the entire pupil; the subaperture phase plate allows the user to apply a step in phase over a fraction of the aperture. The default condition is to have the "enabled" checkbox unchecked, thus disabling this feature; if it were enabled, the default numerical values would give a half-wave phase step would be applied over half of the aperture. As the dialog box shows, the size of the step (in waves) and the edge location (in pixels) are user selectable. Click on the "Cancel" button to close the subaperture phase plate dialog box.

You've now seen all of the pupil phase effects. Next let's look at tailoring the pupil transmission by apodizing the transmission and/or adding obscurations.

Click on the toplevel menu item "Setup", "Pupil Transmission", then on "Apodization of Pupil Transmission". An apodization of pupil transmission dialog box opens. This dialog box has the radio button down for "No Apodization", so the pupil transmission will be a simple top-hat function, i.e., 100% everywhere in the pupil opening that is unobscured. Triangular and circular or rectangular supergaussian apodization functions are possible, as the dialog box shows. Click on the "Cancel" button to close the apodization dialog box.

Click on the toplevel menu item "Setup", "Pupil Transmission", then on "Obscuration of Pupil Transmission". An obscuration of pupil transmission dialog box opens. For the default setup, the pupil is unobscured (the 0.1 obscuration ratio value is not used unless the "Central Obscuration" box is checked). Similarly, the checkbox by "Struts" is unchecked, so there are no shadows from struts. Click on the "Cancel" button to close the obscuration dialog box.

Click on the toplevel menu item "Setup", "Pupil Transmission", then on "Speckle". A speckle dialog box opens. For the default setup, the pupil is unspckled. Note that there are radio buttons to select small, medium, or large speckles. Click on the "Cancel" button to close the obscuration dialog box.

You've finished checking the input, i.e., specifying everything about the exit pupil. Now let's look at how the output will be shown and saved.

Click on the toplevel menu item "Setup", "Options", then on "Analysis Options". An analysis options dialog box opens. It has the checkbox marked for zooming-in on plots, and linear plots of the PSF are selected (instead of logarithmic plots). If the logarithmic plots feature were enabled, the program would plot four decades of data; the number of decades is user selectable. The program assumes that the object is infinitely distant. As a result, the PSF can be output either in linear units on the focal surface, or in terms of angles in object space. The pupil radius is 20 "steps" or array elements, sometimes loosely called "pixels". Click on the "Cancel" button to close the analysis options dialog box.

Click on the toplevel menu item "Setup", "Options", then on "Data Saving Options". A data saving options dialog box opens. This dialog box has radio buttons to select whether the save-file function will write out the pupil transmission, the pupil phase, or the PSF modulus; the start-up configuration is to save the PSF. Saving data to a file should occur quickly. Click on the "Cancel" button to close the data saving options dialog box.

Click on the "View Plots" menu item. You'll see that there are menu choices for the pupil transmission, the pupil phase (wavefront), and the PSF. Click on the "Pupil Phase, 3-D" submenu item. The wavefront phase that you see plotted on the vertical axis is the combination (i.e., sum) of the familiar comatic phase wavefront shape and the six lobed phase from the Zern 26 term that you saw turned on previously. The values for the extent of x and y axes are labeled, and the units used are millimeters. The RMS value of the wavefront OPD, in waves, is shown above the plot. Click on "View Plots" and "Pupil Phase, Contour" to see the contours of this wavefront. (You could click on one of the PSF plots, but you would only get a message saying that there is no PSF yet.) Click on "View Plots" and "Pupil Transmission, 3-D" to see the transmission of this wavefront; it is a flat-top with no central obscuration, nor strut shadows.

(Whenever you run Abe\_PSF2, it is probably a good idea to look at the 3-D plots of pupil transmission and phase, as you've just done, to be sure that your input is as you planned it to be.)

Now for the fun; let's compute the point spread function that results from this wavefront and look at it. Click on the "Create PSF" menu item. A "doing FFT" cursor will appear while the two dimensional fast Fourier transform (FFT) is performed to

compute the PSF. When the FFT processing is finished, a ding sounds and a message box titled "FFT Statistics" opens. On a 486/66, the FFT takes about 0.8 seconds; on a 120 Mhz Pentium, it's about 0.2 seconds. Click on "Okay" to close this timer box (it only appears once per session). The "Create PSF" menu item has been replaced with a grayed menu item that says "FFT Done". Click on the menu item "View Plots", and click on "PSF, 3-D". A 3-D plot of the PSF appears. The vertical (z) axis of this plot is the normalized irradiance (power per unit area) of the PSF corresponding to the wavefront with coma and the phase from Zernike coefficient number 26; the x and y axes are labeled in units of microns. The information above the plot shows that the coma has caused the centroid of the spot to be shifted 2.16 microns to the right of center. Click on the menu items "View Plots" and "PSF, Contour" to see the contours of the 3-D PSF plot.

Congratulations! You've generated your first PSF, for an unobscured pupil with coma and Zern 26 in it. There's plenty more to play with.

Next, let's set up to look at the PSF of a perfect wavefront. Click on the menu items "Setup", "Pupil Phase", and "Third Order Aberrations", then click on the "Coma" checkbox and the "X" that was there will disappear. You can leave the -0.4 number in the coma number field; when the checkbox is cleared, no coma will be added to the wavefront because the number will be ignored. Click on "Okay" (not "Cancel") to close the dialog box. You'll see a cursor saying "MAKE WAVEFRONT" appear while the new pupil function is generated, then disappear. Any open windows are now outdated, so they are automatically closed; the plots disappear. The grayed-out menu item that used to say "FFT done" has changed; it now reads "Create PSF". Similarly, use the "Setup", "Pupil Phase", and "Zernike Coefficients" menu items to open the Zernike coefficients dialog box, and to disable coefficient number 26. Close the Zernike dialog box using the "OK" button. Click on "View Plots" and then on the "Pupil Phase, 3-D" submenu item to see a flat plot that signifies a perfect wavefront, and notice that the RMS wavefront error is now essentially zero. Now it's time to generate the point spread function for this perfect wavefront. In the top level menu, click on "Create PSF" to do the FFT that will generate the new PSF. Click on "View Plots" and then on the "PSF 3-D" submenu item to see the perfect PSF's 3-D plot, and notice that the centroid is also now essentially zero. Notice how symmetrical the PSF is. Next, click on the "View Plots" and "PSF Contour" submenu item, to see the perfect PSF's contour plots. Click on the "View Plots" and "PSF,



Y-Slice" submenu item, to see the "rings" of the perfect PSF, i.e., the places near the peak where the irradiance goes to zero.

There are still other features to play with. Go back to the "Setup" menu item, and try other aberrations in different amounts. Turn on the Zern 26 coefficient alone and do a 3-D pupil phase plot to see what the Zern 26 aberration looks like. Turn on the coma alone, and do another 3-D phase plot to see what coma alone looks like. To change a value, double click on the number (the data field changes color), then type in your number and close the box. Remember that the checkbox next to the number must be checked for the program to accept the number. Redo the coma example with +0.4 waves instead of -0.4 and look at the 3-D plot of the wavefront. Try 1 wave of coma, and be sure to look at the PSF contour plot; looks familiar, right? Or try 0.166 wave (peak, not RMS) of astigmatism aberration combined with -1.0 waves of defocus; this will show the PSF near the circle of least confusion; other amounts of defocus will show either a vertical or horizontal line in the contour plot. Try adding an obscuration, then use the "View Plots" and "Pupil Transmission, 3-D" menu items to see the obscuration in the middle of the pupil. Or model a system with pupil gaussian apodization, and see that it gives a PSF without diffraction rings. Try an 85% central obscuration on a perfect (no aberrations or Zerns) wavefront and see how the diffraction rings increase; try the strut obscuration option and see the "tails" that show up in the PSF. Try a supergaussian coefficient of 6 or 8 and see a pupil transmission function that looks like a flat-top with shoulders. Make the f/number smaller (make the optics "faster") and you'll see the spot get smaller; notice the x and y plot labels. Or try turning on the Zernike coefficients one at a time, and look at the 3-D plot of the pupil wavefront phase. Make the wavelength longer and watch the PSF size increase. Look at the PSF plots in logarithmic units to see fine structure in the outer diffraction rings. Or analyze 4 waves of spherical (the Hubble problem). Or, for a perfect system, enable the subaperture phase plate, with a half-wave of phase and with its edge across the center of the aperture (the default) and see a zero develop in the middle of the PSF. Try the larger 256 by 256 array size, or the 512 by 512 size; (this latter size may cause the program to end on machines with insufficient memory).

If at any time you are unsure about what your wavefront input is, look at the plots or the tables of the pupil transmission and phase. If something looks funny, it may be because you've forgotten to turn an aberration or transmission effect off.

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#### Section 4: History

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Development of the Abe\_PSF code began in mid-1995. The first public release was version 3.6, in July of 1996. These first versions were tested on a 66 Mhz '486 running Windows for Workgroups 3.11, under Win32s for 32-bit operation, created under Borland C++ version 4.52. When, in July 1997, the code development computer was converted to Windows 95 and Borland C++ ver 5.01, a number of bugs appeared. A character array was dimensioned too small, and would cause aborts when the centroid value on plots switched from fixed to exponential format. The bugs have been fixed, and that was called Abe\_PSF is now called Abe\_PSF2. The latest version of Abe\_PSF is version 2.0. It has been thoroughly tested on Windows 95, but there may still be problems. If so, please contact me at the address below.

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#### Section 5: Optics

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If you're interested in optics, you're in good company, from Newton to Einstein. If you want to learn more about optics, I'd suggest a book called Fundamental of Optics by Jenkins and White, for starters.

When you know enough about light to ask questions and understand the answers, there's the sci.optics newsgroup on the Internet. But like anything on the Internet, you would do well, in my opinion, to look for backup on anything people tell you about there.

There's a nice collection of optics software on <ftp://lorien.creol.ucf.edu>.

For those considering a serious optics education, there's the Institute of Optics at the University of Rochester, NY; Georgia Tech, in Atlanta, GA; University of Arizona, in Tucson; CREOL, UCF, in Orlando, FL, and Oregon Institute of Technology in Klamath Falls.

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I hope you have fun, and if you get something good out of Abe\_PSF2, please send in the \$10 check; Baby needs new chips.

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