ABSTRACT

This document explains how to use DiskFit, a code that implements procedures for fitting non-axisymmetries in either kinematic or photometric data, as first described in Spekkens & Sellwood (2007, ApJ, 664, 204; hereafter SS07) for velocity fields and Reese et al. (2007, AJ, 133, 2846; hereafter R07) for images. DiskFit supercedes velfit 2.0 in that it implements a refined version of that code to fit kinematics, and corresponds to the first public release of the image fitting code described in R07. DiskFit improves upon the functionality of velfit described in SS07 and Sellwood & Zánmar Sánchez (2010, MN, 404, 1733; hereafter SZS10) as well as that for image fitting described in R07, by carrying out an optional seeing correction for both kinematic and photometric fits. The application of DiskFit to the photometry and kinematics of a nearby galaxy is illustrated in Kuzio de Naray et al. (2012, MN, 427, 2523), and the most recent version of the code is described in Sellwood & Spekkens (2015, arXiv:1509.07120).

1. Introduction

The purpose of DiskFit is to fit non-axisymmetric models either to images or to velocity fields of disk galaxies, as originally described by R07 for images and by SS07 for kinematics. DiskFit is an extension of the publicly-available velfit 2.0. It represents the first public release of the image decomposition technique described in R07. If the fit is successful, DiskFit provides a quantitative estimate of the fraction of the galaxy light in a bar when run on images, and a method for quantifying the importance of bar-like flows and a better estimate of the circular speed curve in their presence when run on velocity fields (R07; SS07; SZS10). Both the photometric and kinematic branches of DiskFit employ the same basic minimization technique, originally described by Barnes & Sellwood (2003, AJ, 125, 1164). Note that DiskFit does not simultaneously fit photometry and kinematics; the same code simply fits either type of data depending on the user’s choice of inputs.

The kinematic branch of the code, velfit, differs fundamentally from the frequently-used rotcur algorithm (Begeman 1987, PhD thesis, Kapteyn) since it fits a specific model
rather than parametrizing concentric rings of the velocity field. By the same token, the photometric branch of the code differs fundamentally from popular algorithms such as *galfit* (Peng et al. 2010, AJ, 139, 209) in that it fits non-parametric disk and bar light profiles rather than specified functional forms. It is also superior to both these algorithms in that it is capable of providing statistically valid, but realistic, estimates of the uncertainties in the fit. K12 illustrate the functionality of *DiskFit* on high-quality kinematic and photometric data for the nearby galaxy NGC 6503.

Much of the notation and parameters in these notes is defined in R07 and SS07. For concreteness, we use the notation of SS07 when there is a conflict. Users are strongly encouraged to read the appropriate article carefully before attempting to use the code on their data; this document assumes that this is the case.

It is important to understand the assumptions inherent to the image or velocity field models applied by *DiskFit*. In particular, *DiskFit* assumes that the inner disk is flat (a warp is allowed in the outer regions for kinematic fits), and that either the photometric bar or the perturbation that drives non-circular motions has a fixed principal axis (*i.e.* the non-axisymmetric kinematic model is bar-like, and *DiskFit* cannot fit for spiral arms in photometric images). It is up to users to decide whether the assumptions of a flat inner disk and a straight bar-like feature are valid for their data.

*DiskFit* therefore fits for \((x_c, y_c, \epsilon_d, \phi'_d, \phi_b)\) that best describe the photometric or kinematic disk geometry\(^1\) as a whole, where \((x_c, y_c)\) is the disk center, \(\epsilon_d\) is the disk ellipticity, \(\phi'_d\) is the disk position angle, and \(\phi_b\) is the bar or bar-like flow position angle. For kinematic data, the disk systemic velocity \(V_{\text{sys}}\) is estimated. For photometric data, the ellipticity of the bar \(\epsilon_b\) is estimated, and the user can also fit a Sérsic bulge.

Users are required to supply *DiskFit* with the 2D data to be modelled (a velocity field for kinematic fits, or an image for photometric fits). An input text file is also required, which supplies the code with various parameter values (such as a list of radii at which to tabulate the fitted model) and initial guesses for the disk parameters. The input formats are described in §2.

The code writes some messages to the screen as it runs, and both the input parameters and best fitting values are output to a text file. The code also outputs files containing the best fit model and residuals in the same format as the input data. The run-time messages

\(^1\)Note that our notation does not differentiate between *kinematic* disk geometry and *photometric* disk geometry, because they are measured in exactly the same way by *DiskFit*. Of course, if the user makes separate fits to both types of data, the fitted values will likely differ.
and output files are discussed in §3.

Finally, §5 illustrates how to apply DiskFit to sample velocity fields and images provided with the code, and §6 explains how to use the source code provided with DiskFit. The modification history of the code is given in §7.

While the majority of the code inputs and outputs pertain to both the photometric and kinematic branches of the code, there are some exceptions. Henceforth, text in this document that is colored black applies to both photometric and kinematic fits, text in green applies only to photometric fits and text in blue applies only to kinematic fits. Text in red highlights known bugs or idiosyncrasies in the current DiskFit release.

1.1. Photometric Models (R07)

The photometric models applied by DiskFit are identical to those described by R07. DiskFit fits photometric images with up to 3 components: a disk, bar and bulge. DiskFit assumes a flat, intrinsically round disk with an ellipticity $\epsilon_d$ and position angle $\phi'_d$ and a linear bar with a different apparent (projected) ellipticity $\epsilon_b$ and position angle $\phi'_b$ in the sky plane. Neither the light profiles of the disk or the bar are assumed to have a specific functional form.

Unlike the disk and bar, the bulge is parametrized by the Sérsic function

$$I(r) = I_0 \exp \left\{ -B_n \left[ \left( \frac{r}{r_e} \right)^{1/n} - 1 \right] \right\},$$

where $r_e$ is an effective radius, $n$ in the Sérsic index, and $I_0$ is the intensity scale. The constant $B_n$ is a function of the Sérsic index, and is defined by the implicit relation $\Gamma(2n) = 2\gamma(2n, B_n)$, with the $\Gamma$ function and the incomplete gamma functions having their usual definitions. This is all summarized by Graham (2001, AJ, 121, 820). We allow bulge to be spheroidal with apparent ellipticity $\epsilon_s$, with the disk plane being the plane of symmetry.

DiskFit finds the best fitting parameters for these models using the fitting technique introduced by Barnes & Sellwood (2003) (see their Appendix) and used by R07 (see their §3.1) and SS07 (see their §3.4), and can correct for minor (Gaussian) distortions due to seeing. It can estimate uncertainties on the best-fitting parameters using either of the bootstrap techniques described in §4.1 of SS07 or in Appendix B of SZS10. For photometric images, the latter technique is likely preferable, as it preserves the coherence of large-scale residuals.
**DiskFit** will also return the fraction of the light in each model component, as well as uncertainties on those values.

### 1.2. Kinematic Models (velfit)

The kinematic models implemented in **DiskFit** are the same as in velfit 2.0, described by SS07 and SZS10. **DiskFit** supersedes velfit, and should be used instead of the latter. **DiskFit** applies the models to an input velocity field, and produces output files with the best fitting model parameters. In addition to a rotation-only model, ** DiskFit** can apply the following models including non-circular flows:

- A bisymmetric model with $m = 2$ perturbations to the potential, given by eq. 5 in SS07:

  $$V_{\text{model}} = V_{\text{sys}} + \sin i \left[ \bar{V}_t \cos \theta ight. \\
  - V_{2, t} \cos(2\theta_b) \cos \theta - V_{2, r} \sin(2\theta_b) \sin \theta \left] . \right. \quad \text{(2)}$$

- A lopsided model with $m = 1$ perturbations to the potential:

  $$V_{\text{model}} = V_{\text{sys}} + \sin i \left[ \bar{V}_t \cos \theta ight. \\
  - V_{1, t} \cos(\theta_b) \cos \theta - V_{1, r} \sin(\theta_b) \sin \theta \left] . \right. \quad \text{(3)}$$

- For consistency with other work, the code can also fit radial flows, although such flows are physically poorly motivated. This model assumes $m = 0$ distortions to the flow, given by eq. 7 in SS07:

  $$V_{\text{model}} = V_{\text{sys}} + \sin i \left[ \bar{V}_t \cos \theta + \bar{V}_r \sin \theta \right] . \quad \text{(4)}$$

Superpositions of the $m = 0$ and $m = 2$ models or the $m = 0$ and $m = 1$ models are allowed by the code (though they are unlikely to produce meaningful results). **DiskFit** finds the best fitting parameters for these models using the fitting technique introduced by Barnes & Sellwood (2003) (see their Appendix) and used by R07 (see their §3.1) and SS07 (see their §3.4). For FITS input or if the text input can be regularized (see §2.1.2), **DiskFit** can estimate uncertainties on those parameters using either of the bootstrap techniques described in §4.1 of SS07 or in Appendix B of SZS10. Finally, it can correct for mild (Gaussian) distortions due to seeing or beam smearing. Note that because **DiskFit** assumes that a 2-D velocity field
represents the disk kinematics, it cannot fit either highly-inclined or nearly face-on galaxies.

**DiskFit** requires a flat inner disk, but allows for a warp in the outer disk. The disk is assumed flat to radius $r_w$, beyond which both the ellipticity and the position angle of the line of nodes varies in proportion to $(r - r_w)^2$, *i.e.* a quadratic increase with radius. The fitting procedure varies the inner warp radius $r_w$, and the peak values of the change in ellipticity, $w_{elm}$, and the change in position angle, $w_{phim}$ at the outermost radius relative to the inner flat disk in order to improve the fit to the data. The user has the option to hold any of these three warp parameters fixed at an input value as desired.

Since there are strong degeneracies between the velocity patterns of a bisymmetric density perturbation and of a normal warp, **DiskFit** will not allow the user to select both options in a single fit to the data.
2. Code Inputs

The user must supply DiskFit with: 1) input data: either a velocity field for kinematic fits (and optionally uncertainties in each velocity value), or an image for photometric fits (and optionally a mask file and uncertainty image), and 2) a text file containing initial values and other parameters. These are described in §2.1 and §2.2 below.

2.1. Input data

DiskFit allows FITS file inputs for both photometric and kinematic data. For kinematic data, the user also has the option of inputting data in text format.

Note that depending on the initial guesses for the disk geometry, DiskFit may not use all remaining pixels in the minimization. Specifically, only $D_n$ within 1.2 times the outermost ring radius relative to the input $(x_c, y_c)$ when deprojected at the input $\phi'_d$ and 0.9 times the input ellipticity are included in the fit; this is why the number of $D_n$ included in the minimization may differ from the number of $D_n$ in the input velocity field (see §3.1).

2.1.1. FITS Format

For photometric fits, the user must supply images (and optionally mask files and uncertainty files) in FITS format. For kinematic fits, the user has the option of supplying velocity fields and their uncertainties in FITS format as well. The user may specify a rectangular sub-region of the image to fit. This sub-region should be the smallest rectangular region that encompasses all of the data to be included in the fit, in order to maximize the fit speed. Note that the sub-region must contain the galaxy centre.

Since FITS files are frequently oversampled and may have an unwieldy number of pixels, DiskFit allows the user to sample the pixels more sparsely, with a stride set by the input parameter istepout. A suitable value for istepout might be the beam width in pixels. However, skipping pixels near the center of the image can cause problems with too few contributing to the innermost rings. Therefore DiskFit allows the user to include all pixels inside an ellipse of semi-major axis regrad, with the ellipse inclined and oriented at values that are typically the same as the initial estimates of $\epsilon_d$ and $\phi'_d$, but which are set independently in case the user wishes to adopt different values. The user may desire to set regrad to a larger value, e.g. one that encloses the entire bar. Note, however, that DiskFit computes $\chi^2$ assuming that all input pixels are independent, and will therefore over-estimate
the fit quality if large numbers of correlated pixels are included in the fit. The user should also supply a pixel scale for the FITS image; although this parameter is not used by DiskFit, it is usefully copied to the output file.

For photometric data, DiskFit requires that the image has been sky-subtracted. The stars must either be masked in the image, or a mask file must be supplied. DiskFit assumes that the brightest pixel in the map corresponds to the galaxy centre, and will check that this pixel falls close to the centre of the selected sub-region. DiskFit is therefore likely to crash if any bright foreground stars are not masked (even if they do not overlap the disk). If the user inputs an uncertainty image to be used in the fit, then DiskFit assigns the pixel values in this image to \( \sigma_n \) and uses them in the fit.

If the user does not input an uncertainty image for photometric data, DiskFit assumes that the photon counting statistics dominate and that the image units are in ADU. If an uncertainty image is not used, the user is required to input the constant sky level sky that was subtracted from the image (ADU), the sky sigma value \( \text{skysig} \) (ADU), and the CCD gain \( \text{gain} \) (see §2.2): these values are only used to estimate uncertainties on each pixel in the fit, and should not affect the fit itself. The net uncertainty on each pixel is then computed as:

\[
\sigma_n = \sqrt{\frac{(D_n + \text{sky})}{\text{gain}}}.
\]  

(5)

Pixels with large negative values \( D_n < -4 \text{skysig} \) are ignored by DiskFit (skysig is not used elsewhere). A sample FITS image is supplied with the code, and photometric fits to that data are carried out in §5.1.

For kinematic data, the goodness of fit function in eq. (8) of SS07 uses the net uncertainty:

\[
\sigma_n = \sqrt{\Delta_D^2 + \Delta_{\text{ISM}}^2}
\]  

(6)

for each pixel, where \( \Delta_D \) are uncertainties on each velocity value (supplied by a FITS file) and the parameter \( \Delta_{\text{ISM}} \) is a constant uncertainty that allows for ISM turbulence. For datasets where \( \Delta_D \) are not available or are under-estimated, \( \Delta_{\text{ISM}} \) encapsulates both the uncertainties on the velocity field points and ISM turbulence. In practice, the value of \( \Delta_{\text{ISM}} \) is chosen by the user to produce reasonable \( \chi^2 \) statistics: see K12 for details. The code requires \( \sigma_n \neq 0 \) (see eq. 8 of SS07). If \( \Delta_D \) are not available, \( \sigma_n = \Delta_{\text{ISM}} \). \( \Delta_{\text{ISM}} \) is passed to DiskFit in the input file (see §2.2), and defaults to 10 km s\(^{-1}\) if the input value is zero. If \( \Delta_D \) are supplied to DiskFit, the user may specify a maximum uncertainty \( \Delta_D^{\text{max}} \) above which the corresponding velocity value is ignored in the fit. Note that \( D_n \) that differ from \( V_{\text{sys}} \) by more than 500 km s\(^{-1}\) are also ignored in the fit.
For kinematic data, DiskFit has a flag to indicate whether the velocity units are in m s\(^{-1}\) or km s\(^{-1}\), but must be the same for \(D_n\) and \(\Delta_D\) (i.e. in both input FITS files). Note that since the FITS standard stipulates units of m s\(^{-1}\), this should almost always be the case for input files. Regardless of the input velocity field and uncertainty units, \(\Delta_{\text{ISM}}, V_{\text{sys}}\) and \(\Delta_{\text{max}}\) are assumed to be in km s\(^{-1}\) (see §2.2). A sample FITS velocity field is supplied with the code, and kinematic fits to that data are carried out in §5.2.

2.1.2. Text Format

The user has the option of supplying kinematic data in text format rather than in FITS format as described above. When supplied with a list of velocities, DiskFit will attempt to define a 2D array over which the data values can be sparsely and irregularly sampled. If it can regularize the data, the following message is output to the screen:

Your input data points are spaced regularly enough that they could be inserted into a 2D raster of pixels. This has both advantages and disadvantages - see section 2.1.2 of the documentation. Would you like DiskFit to rasterize your data (y/n)?

If it is not convenient to regularize the input data (too large a 2D array would be required), DiskFit outputs this message:

Input velocity list not convenient for 2D representation: pixel list used

The user interface and output formats are the same for either of the above cases. However, if a 2D array cannot be defined, DiskFit cannot correct for seeing/beam smearing, and it cannot use the radial/rescaling bootstrap method of SZS10 to estimate uncertainties. The code will crash and the user will get an error message if these functionalities are requested and a 2D array cannot be defined from the input text file. On the other hand, the code runs much faster if DiskFit does not rasterize the data. If you prefer fast execution, aren’t concerned about beam smearing and are happy to estimate uncertainties using the method of SS07, enter n. See §5.3 for an example.

The required format of the text file is as follows: the first 4 lines of the file are assumed to be header information and are ignored. Each line of data, starting at line 5, must have four values, with no predefined format. The data are read until the end of the file is encountered,
or until the number of lines exceeds the maximum allowed (default 10 000) when an error
message is printed. Accordingly, there should be no additional lines at the end of the file.
To ensure proper input to DiskFit, the input velocity field must conform to this format; the
code makes only minimal checks that this is the case.

There should be one line of data for each velocity measurement, and only one measure-
ment for each \((x_n, y_n)\) pair. The first two columns of each line are the cartesian coordinates
\((x_n, y_n)\) of the velocity measurement relative to some reference frame. The units of \((x_n, y_n)\)
are arbitrary, but must be the same for both coordinates. For the standard N-E definition of \(\phi_d\)
to apply, the \(x-\) and \(y-\)axes are assumed to be oriented E-W and N-S, respectively, with \(x\)
increasing towards the W and \(y\) increasing towards the N. The third column contains the
measured recessional velocity \(D_n\) at \((x_n, y_n)\), and the fourth column contains the estimated
uncertainty \(\Delta D\) on this velocity. The units on \(D_n\) and \(\Delta D\) must be \(\text{km s}^{-1}\).

A sample velocity field is in Fig. 27 (the adopted \((x_n, y_n)\) units here are arcsec, though
this needn’t be the case). It corresponds to the first few lines of the example field examp.vels
in §5.3.

2.2. Input Text File

The input text file passes control parameters to DiskFit as well as initial guesses for the
disk geometry. Sample input files are shown in Fig. 2, Fig. 12, and Fig. 29 for photometric
fits, kinematic fits with FITS input and kinematic fits with text input, respectively; those
examples include comments to remind the user of the content of each line. The formatting of
the input parameters is flexible for both photometric and kinematic fits, but the number per
line and their order must be as shown in these examples; only minimal checks that this is the
case are made in DiskFit. File names need not be bracketed by quotation marks unless they
include subdirectory names, but quotation marks are allowed for consistency with velfit.

The contents of the input text file are:

**Line 1:** Header. Ignored by DiskFit.

**Line 2:** Switch that specifies whether DiskFit will fit photometric or kinematic data. If
phot appears, a photometric fit is carried out, and if vels appears, a kinematic fit is carried
out. No default.

**Line 3:** If Line 2 = vels, Boolean toggles for FITS input and file units for kinematic
fits. From left to right, the toggles are:
- **FITS toggle**: If ‘T’, the input data are in FITS format. If ‘F’, the data are in a text file.
- **Velocity scale toggle**: ‘T’ means the velocity data are in m s\(^{-1}\), ‘F’ means they are in km s\(^{-1}\).

Note that since velocities are in m s\(^{-1}\) in the FITS standard, this toggle should almost always be ‘T’.

If Line 2 = phot, name (and relative path) of the mask file. Image pixels to be retained in the fit must have pixel values of 0 in the mask file, whereas non-zero mask file pixels are masked in the image. Cannot exceed 100 characters. If there is no such file, then this line should be blank or contain the word ‘None’ or ‘none’.

**Line 4**: Name (and relative path) of the file containing data to be fitted (see §2.1). Cannot exceed 100 characters. No default.

**Line 5**: For FITS input, name (and relative path) of the file containing the uncertainties on the data to be fitted (see §2.1). Cannot exceed 100 characters. If there is no such file, then this line should be blank or contain the word ‘None’ or ‘none’.

**Line 6**: For FITS input, region of the image to fit. No defaults. The first two values are the pixel coordinates of the bottom-left corner of the region, and the second two values are the number of pixels to read in in the x-direction and the y-direction. The region needs to encompass the galaxy centre. This line is ignored if the first toggle in Line 3 = ‘F’. From left to right, the parameters are:
- **x-low**: x-value of the bottom-left corner of the region to fit.
- **y-low**: y-value of the bottom-left corner of the region to fit.
- **x-range**: number of pixels, starting from x-low, to fit in the x-direction.
- **y-range**: number of pixels, starting from y-low, to fit in the y-direction.

**Line 7**: For FITS input, FITS sampling parameters. No defaults. This line is ignored if the first toggle in Line 3 = ‘F’. From left to right, the parameters are:
- **regrad**: the semi-major axis in pixels of the ellipse that bounds the region inside of which DiskFit uses all the pixels in the FITS image.
- **regpa**: the position angle in degrees of the regrad ellipse. The user will most probably wish to set this to the same value as the initial guess for \(\phi_d\) in Line 11, but a different value is allowed.
- **regeps**: the ellipticity \((1 - b/a)\) of the regrad ellipse. The user will most probably wish to set this to the same value as the initial guess for \(\epsilon_d\) in Line 11, but a different value is allowed.
- **istepout**: the stride in pixels to be used in sampling pixels outside regrad. A suitable value could be the beam width, rounded to an integer number of pixels, to avoid oversam-
- **pixscale**: the pixels scale of the FITS image, e.g. the number of arc seconds per pixel. This parameter is not used by *DiskFit*, but is copied to the output file.

**Line 8**: Name (and relative path) of the output parameter file that *DiskFit* will write. Cannot exceed 100 characters, and may only contain one period (\(\cdot\)). No default. *DiskFit* will use the root of this name and path (i.e. everything before the period) to assign output file names (see §3).

**Line 9**: Three boolean toggles that indicate which disk parameters *DiskFit* will optimize. From left to right, the toggles are:
- **Disk position angle toggle**: ‘T’ means *DiskFit* will fit for \(\phi_d\) using the value in Line 12 as the initial guess. ‘F’ means that \(\phi_d\) is held fixed the value in Line 12 during the minimization.
- **Disk ellipticity toggle**: ‘T’ means *DiskFit* will fit for \(\epsilon_d\) using the value in Line 12 as the initial guess. ‘F’ means that \(\epsilon_d\) is held fixed to the value in line 12 during the minimization.
- **Disk center toggle**: ‘T’ means *DiskFit* will fit for \((x_c, y_c)\) using the values input in Line 13 as initial guesses. ‘F’ means that \((x_c, y_c)\) are held fixed to the values in Line 13 during the minimization.

**Line 10**: Initial values of the disk position angle, \(\phi_d\), and the disk ellipticity, \(\epsilon_d\). From left to right:
- **Initial guess for \(\phi_d\)**: Position angle of the disk major axis, in the standard N-E definition. For velocity fields, this angle corresponds to the receding side of the disk: *DiskFit* will produce a good fit if the angle to the approaching side is found, but the rotation velocities \(\bar{V}_r\) will be negative. For velocity fields input in text format (Line 2 = `vels`), the \(x\)- and \(y\)-axes that define \((x_n, y_n)\) are assumed to be oriented E-W and N-S, respectively, with \(x_n\) increasing towards the W and \(y_n\) increasing towards the N.
- **Initial guess for \(\epsilon_d\)**: Defined as \(\epsilon_d = 1 - b/a\).

**Line 11**: Initial values of the disk center \(x_c\) & \(y_c\). Units must be in pixels for FITS input (first toggle of Line 3 = ‘T’), or the same as those of \(x_n\), \(y_n\) for velocity fields input in text format.

**Line 12**: Parameters that indicate whether *DiskFit* will fit for non-axisymmetric features, and related initial guesses. If first toggle is ‘F’, the remainder of this line is not read, and therefore could be blank, and *DiskFit* adopts default values. From left to right, the parameters are:
- **Non-axisymmetric Boolean toggle**: Line 2 = `phot`: ‘T’ means *DiskFit* will fit for a bar, and ‘F’ means that no bar component is included in the fit. Note that the disk light profile
is always estimated. Line 2 = \texttt{vels}: ‘T’ means that \texttt{DiskFit} will fit for non-axisymmetric flow, ‘F’ forces \((V_{2,t}, V_{2,r}) = 0\) and \((V_{1,t}, V_{1,r}) = 0\) in the model. Note that \texttt{DiskFit} always estimates the rotation velocity \(\bar{V}_t\). Note also that it is possible to model radial and non-axisymmetric flows simultaneously (2nd toggle in Line 15), but this tends to give the code too many degrees of freedom and produces non-sensical fits.

- \(\phi_b\) toggle: ‘T’ means the angle \(\phi_b\) is adjusted to improve the fit, ‘F’ means it is held fixed at the value input in the next entry. Default is ‘F’.

- \(\epsilon_b\) toggle: Line 2 = \texttt{phot}: ‘T’ means the bar ellipticity \(\epsilon_b\) is adjusted to improve the fit, ‘F’ means it is held fixed at the value input in the next entry. Default is ‘F’. If Line 2 = \texttt{vels}, no toggle should be present.

- Initial guess for \(\phi_b\) or \(\phi'_b\): If Line 2 = \texttt{phot}, the angle to the major axis in the sky plane of the non-axisymmetric distortion, \(\phi'_b\). It will be adjusted or held at this value as requested by the second toggle. If there are no prior constraints on \(\phi'_b\), we recommend an initial value \(\phi'_b = 45\) deg. Default is 0. If Line 2 = \texttt{vels}, the angle to the major axis in the disk plane of the non-axisymmetric distortion, \(\phi_b\). It will be adjusted or held at this value as requested by the second toggle. If there are no prior constraints on \(\phi_b\), we recommend an initial value \(\phi_b = 45\) deg. Default is 0. Note the different conventions in this parameter input between the photometric and kinematic branches of the code!

- Initial guess for \(\epsilon_b\): Line 2 = \texttt{phot}: the ellipticity of the bar. It will be adjusted or held at this value as requested by the third toggle. If there are no prior constraints on \(\epsilon_b\), we recommend an initial value 0.5. Default is 0.5.

- Harmonic order \(m\): Line 2 = \texttt{vels}: harmonic order of the non-circular flow. Must be 1 or 2. If \(m = 2\), \texttt{DiskFit} will fit for \((V_{2,t}, V_{2,r})\) in eq. 2, and if \(m = 1\) \texttt{DiskFit} it will fit for \((V_{1,t}, V_{1,r})\) in eq. 3. Default is 2.

**Line 13:** For Line 2 = \texttt{vels}, this line contains toggles to interpolate inner velocities and fit for radial flows. The parameters are, from left to right:

- inner interpolation Boolean toggle: ‘T’ means that the mean velocity is assumed to rise linearly from 0 at the estimated position of the center \((x_c, y_c)\), ‘F’ implies that the velocity change from the first to the second ring is extrapolated linearly inwards for pixels interior to the first ring. We recommend ‘T’ if the inner ring is close to the center and ‘F’ if the velocity map to be fitted has a region with no values near the center.

- radial flows Boolean toggle: ‘T’ means \texttt{DiskFit} will fit for radial flows, i.e. it will estimate \(\bar{V}_r(R)\) in eq. 4. ‘F’ means that \(\bar{V}_r = 0\) at all radii in the model. Note that \texttt{DiskFit} always estimates the rotation velocity \(\bar{V}_t\). Note also that it is possible to model radial and non-axisymmetric flows simultaneously, but this tends to give the code too many degrees of freedom and produces non-sensical fits.

If Line 2 = \texttt{phot} and no uncertainty image is provided on Line 5, this line contains the basic
image properties from which DiskFit computes uncertainties and rejects outliers. DiskFit assumes that these parameters are constant across the image. From left to right:
- **sky**: mean sky level that was subtracted from the input image, in ADU. No default.
- **skysig**: uncertainty on sky, in ADU. No default.
- **gain**: CCD gain. No default.
This line is only read if no uncertainty image is provided on Line 5.

**Line 14:** More parameters specific to either photometric fits or kinematic fits.
For Line 2 = **phot**, this line contains bulge model parameters. The parameters are, from left to right:
- **Bulge Boolean toggle**: ‘T’ means that DiskFit will include a bulge in the photometric model, ‘F’ means that a bulge is not included. If the toggle is ‘F’, the rest of the line is not read.
- **Bulge intensity and effective radius Boolean toggle**: 'T' means that DiskFit will fit for the intensity scale $I_0$ and effective radius $r_e$ of a Sérsic bulge, using the value input for $r_e$ that follows as a first guess. 'F' means that $r_e$ is held fixed to the input value or its default during the minimization. Note that DiskFit always fits for $I_0$, and generates an initial guess for this parameter itself. This toggle is only read if the bulge toggle is ‘T’.
- **Initial guess for $r_e$**: must be in pixels. If set to 0, the default is 1. This parameter is read only if the bulge toggle is ‘T’.

For Line 2 = **vels**, this line contains systemic velocity fitting information as well as a turbulent velocity estimate $\Delta_{\text{ISM}}$. The parameters are, from left to right:
- **$V_{\text{sys}}$ Boolean toggle**: ‘T’ means DiskFit will fit for $V_{\text{sys}}$ using eq. 10 of SS07, using the value input as the next parameter as the first guess. ‘F’ means that $V_{\text{sys}}$ is held fixed to the input value during the minimization.
- **Initial guess for $V_{\text{sys}}$**: units must be in km s$^{-1}$, regardless of the value of the velocity scale toggle in Line 3. $D_n$ that differ by more than 500 km s$^{-1}$ from $V_{\text{sys}}$ are discarded. No default.
- **$\Delta_{\text{ISM}}$**: The goodness of fit function in eq. 8 of SS07 uses $\sigma_n = \sqrt{\Delta_D^2 + \Delta_{\text{ISM}}^2}$, where $\Delta_D$ is the measurement uncertainty of the data value $D_n$. The unit of $\Delta_{\text{ISM}}$ must be km s$^{-1}$, regardless of the value of the velocity scale toggle in Line 3. A value less than or equal to 0 will default to $\Delta_{\text{ISM}} = 10$ km s$^{-1}$.
- **$\Delta_D^\text{max}$**: Pixels with $\Delta_D > \Delta_D^\text{max}$ are discarded in the fit. The unit of $\Delta_D^\text{max}$ must be km s$^{-1}$, regardless of the value of the velocity scale toggle in Line 3. No default.

**Line 15:** More parameters specific to either photometric fits or kinematic fits.
For Line 2 = **phot**, this line contains bulge model parameters. The parameters are, from left to right:
- **Sérsic index Boolean toggle**: ‘T’ means that DiskFit will fit for the Sérsic index $n$ of the
bulge, using the value input for the next parameter as a first guess. 'F' means that \( n \) is held fixed to the input value or its default during the minimization. This parameter is only read if the bulge toggle is 'T'.

- **Bulge apparent ellipticity toggle**: 'T' means that \( \text{DiskFit} \) will fit for the apparent ellipticity \( \varepsilon_s = (1 - b/a) \) of the bulge, using the value input for the next parameter as a first guess. 'F' means that \( \varepsilon_s \) is held fixed to the input value during the minimization. This parameter is only read if the bulge toggle is 'T'.

- **Initial guess for \( n \)**: If set to 0, the default is 1. This parameter is read only if the bulge toggle is 'T'.

- **Initial guess for \( \varepsilon_s \)**: No default. This parameter is read only if the bulge toggle is 'T'.

For Line 2 = \texttt{vels}, this line contains the warp toggle and parameters.

- **Warp toggle**: 'T' means that \( \text{DiskFit} \) will fit for a simple warp of the disk. 'F' means that the disk is assumed flat and the remainder of the line is not read. The ellipticity and PA of the warp are assumed to vary quadratically from the values of the inner disk plane to the outer radius. The code will not allow simultaneous fits for both a warp and bar.

- **Inner warp radius toggle**: 'T' means that \( \text{DiskFit} \) will adjust the inner radius at which the warp begins to improve the fit. 'F' means the inner radius of the warp is held at its input value.

- **Outer ellipticity toggle**: 'T' means that \( \text{DiskFit} \) will adjust the ellipticity (inclination) of the outer ring to improve the fit. 'F' means the ellipticity of the outer ring is held at its input value.

- **Outer PA toggle**: 'T' means that \( \text{DiskFit} \) will adjust the PA of the outer ring to improve the fit. 'F' means the PA of the outer ring is held at its input value.

- \( r_w \): The semi-major axis at which the warp will begin, in pixels.

- \( \text{welm} \): The value of the change in projected ellipticity of the outermost ring in the fit: in other words, the difference between the ellipticity of the inner disk and that of the outermost ring in the fit. This entry is either an initial guess, or the value to be held fixed.

- \( \text{wphim} \): The value of the PA of the outermost ring in the fit: in other words, the difference between the PA of the inner disk and that of the outermost ring in the fit. This entry is either an initial guess in degrees, or the value to be held fixed.

**Line 16**: Seeing/beam smearing correction: if this value is 0, no seeing/beam smearing is performed on the model before comparison to the data. If this value is non-zero, it corresponds to the full width half-maximum of the Gaussian resolution element of the input data. For Line 2 = \texttt{phot}, this is equal to the size of the seeing disk. For Line 2 = \texttt{vels}, this is equal to the angular resolution of the velocity field. For FITS data, the units should be pixels; for velocity fields input in text format, the units should be the same as \((x_n, y_n)\). A seeing/beam smearing correction can only be applied to velocity fields input in text for-
mat if DiskFit can find a suitable 2D array for the datapoints. As a rule of thumb, the seeing/beam smearing correction will only work if the correction is less than or equal to half the ring spacing. Obviously, this correction cannot account for non-linear beam smearing effects resulting from taking the moment of a datacube: in general, it therefore cannot fully account for beam smearing in HI or CO velocity fields.

**Line 17:** Model component smoothing parameters, as introduced in Appendix A of SZS10. We recommend using these parameters only if the best-fitting profile points oscillate undesirably about a mean trend, and then using the smallest values (say $\lambda_1 \sim \lambda_2 \sim 1 \times 10^{-4}$) that mitigate the oscillations. **These parameters should only be positive if the ring radii in Lines $\geq 21$ are evenly spaced.** From left to right, the parameters are:

- **Smoothing parameters:** $\lambda_1$ and $\lambda_2$ are defined in Appendix A of SZS10 for axisymmetric and non-axisymmetric components, respectively. If both $\lambda_1$ and $\lambda_2$ are zero or negative the fitted components will not be smoothed.

**Line 18:** Bootstrap parameters. If first toggle is ‘F’, the remainder of this line is not read, and therefore could be blank, and DiskFit adopts default values. From left to right, the parameters are:

- **Uncertainties Boolean toggle:** ‘T/F’ means DiskFit will/will not estimate uncertainties on the best fitting parameters using a bootstrap technique. The user may select either the technique described in SS07 or that described in SZS10 using the parameters that follow.
- **Random number seed:** Must be a negative integer. Different seeds produce different sequences of random numbers.
- **nunc:** Number of bootstrap realizations used to estimate uncertainties; maximum number allowed is $nunc = 1000$. As bootstrap iterations can be time consuming, DiskFit creates a flag file with a name that begins “erase” before beginning the bootstrap iterations in the same directory as the output files are written. Deleting this file at any time causes DiskFit to complete the current realization and then end gracefully.
- **junc:** The sign of this parameter determines the method used to create the pseudo-velocity maps for the bootstrap. If positive, DiskFit uses the technique in SS07, with the value of $J = junc$ being the characteristic number of adjacent points over which $\Delta V_n$ are assumed to be correlated when bootstrap samples are generated. Note that if $\Delta V_n$ are correlated and $junc = 1$, DiskFit may under-estimate the uncertainties. If $junc < 0$, DiskFit generates realizations of the image or velocity field using the rotation plus radial rescaling method described in SZS10. We recommend trying different values of $junc$ to evaluate the impact of different bootstrap methods on the estimated uncertainties. In general, if there are large-scale features in $\Delta V_n$, the user should set $junc = -1$; otherwise, the user can use either this setting or should choose the value of $junc > 0$ that best represents the size of the
“blobs” in the residual map in pixels.

**Line 19:** verbose Boolean toggle. ‘T/F’ means that DiskFit will/will not produce a line of output every time a model is generated during the minimization (ie. every call to the function func; see §6). Verbose output allows the user to monitor in more detail how the fit is progressing, but is generally undesirable as the number of lines output to the screen can be very large.

**Line 20:** Two values specifying the region over which the bar (Line 2 = phot) or non-circular flows (Line 2 = vels) are fitted. The two values must be supplied in this line only if the 2nd toggle in Line 13 (radial \(m = 0\) flow toggle; Line 2 = vels only) or the first toggle in Line 12 (non-axisymmetric toggle) is ‘T’. If both these toggles are ‘F’, then the values in this line are not read, but a line should be present, which could be blank.

- *Inner radius at which non-axisymmetries are fitted:* The input value is rounded to the radius of the nearest ring. A zero value is appropriate if non-axisymmetries are to be fitted from the center. Default is zero.
- *Outer radius at which non-axisymmetries are fitted:* The input value is rounded to the radius of the nearest ring. A large value is appropriate if non-axisymmetries are to be fitted to the last ring. Default is 10 000.

**Lines \(\geq 21\):** List of \(K'\) ring radii at which the luminosity (\(\{I_k\}\) if Line 2 = phot; see section 3.1 of R07) or velocity field (\(\{V_k\}\) if Line 2 = vels; see section 3.4 of SS07) components will be extracted. All component profiles are evaluated at these radii. If ring radii fall outside the range specified in Line 20, \(\{V_k\}\) or \(\{I_k\}\) corresponding to non-axisymmetries will be fixed to 0. Units must be the same as those of \((x_c, y_c)\), or in pixels for FITS input. Ring radii must be in increasing order, one entry per line, and no duplicates are allowed. Up to \(K' = 100\) rings may be specified. The rings need not be evenly spaced, except when the data are smoothed as set by a positive value for either \(\lambda_1\) or \(\lambda_2\) in Line 17. There must not be any extra lines after the last ring entry.

### 3. Code Outputs

During execution, DiskFit writes a series of output messages to the terminal that enable the user to check that the inputs are as expected and that the minimization is progressing. See §5 for examples of terminal output.
DiskFit writes an output parameter file in text format containing the results of the minimization. The contents of that parameter file are described in §3.1.

When the input data are in FITS format, DiskFit creates two FITS output files containing the best fitting model and the (data - model) residuals of the model, respectively. For photometric fits, a FITS file containing each separate model component is also output. The output file names are assigned automatically by DiskFit to the root of the output parameter file name specified by the user on Line 8 of the input text file (ie. everything before the period) to:

- *root*.mod.fits for the best fitting model;
- *root*.res.fits for the data-model residuals;
- *root*.dsk.fits for the disk component of the best-fitting model;
- *root*.blg.fits for the bulge component of the best-fitting model, if one exists;
- *root*.bar.fits for the bar component of the best-fitting model, if one exists.

The FITS headers are copied from the input data file. Even if the FITS image is oversampled and DiskFit uses sparsely sampled data for the fit, the output FITS files have the same size as the input data and a best fitting model value is assigned to every pixel. Note that a model value is returned at each point inside the mask region determined by DiskFit using the input guesses (see §2.1); by definition, the ellipticity of that region is lower than input by the user, and it is not necessarily equal to the ellipticity of the final model. Pixels outside the mask region are assigned a value NaN. For kinematic fits where input velocities are provided as a text file, a model text file is output rather than a FITS file even if DiskFit can find a suitable 2D array with which to represent the data (see §2.1.2). The contents of this file are described in §3.2.

When uncertainties are estimated, three additional text files are output: *root*.erase, *root*.bstrpXX where XX is the absolute value of the random number seed on line 18 of the input text file, and and *root*.csv. The first of these files contains no data, but erasing it will cause DiskFit to exit gracefully after the best-fitting model parameters of the current bootstrap realization of the data has completed. The file *root*.bstrp contains a list of the best-fitting model parameters determined at each bootstrap realization: the best-fitting parameters are listed first (in the order that they appear on-screen during the minimization, followed by the best-fitting model intensities (in the order that they are listed in the output parameter file). This file may prove useful if DiskFit crashes before exiting when a large number of bootstraps are requested, for troubleshooting unexpected results, or for
generating uncertainties from bootstrap iterations using different random number seeds using \texttt{Bootlace}. \texttt{root.csv} is a comma-separated table of all the best fitting values returned during the bootstraps; this allows for the construction of covariance plots and other useful diagnostics.

### 3.1. Output Parameter File

All input, minimization and output parameters are listed in the output parameter file, the name and path of which are specified by the user on Line 8 of the input text file. Sample output files for photometric fits and kinematic fits are given in Figs. 10 and 19, respectively. To facilitate electronic reading of the output parameter file, line numbers and formats are independent of input parameter choice. This is illustrated in §5. An explanation of each line in the output parameter file follows, with the fortran-style format in parentheses where applicable. Information in the output file is given in roughly the same order as it was provided in the input text file, and the reader is referred to §2.2 for more detailed explanations.

**Line 1:** Minimization branch used (\texttt{vels} or \texttt{phot}).

**Line 4:** Input text file used.

**Line 5:** Input data file used, and pixel scale.

**Line 6:** $(a4, f8.2, 2(a9, f8.2))$ sky, skysig and gain value for the input image if Line 2 = \texttt{phot} in the input text file. Velocity uncertainties file used, if Line 2 = \texttt{vels} in the input text file and a velocity uncertainties file was input on Line 5.

**Line 8:** $(4(a9,i7))$ For FITS input, region of the image to fit: x-low, y-low, x-range, y-range.

**Line 9:** $(3(a9,f7.2),a9,i7)$ For FITS input, FITS sampling parameters: regrad, regpa, regeps, istepout, pixscale.

**Line 12:** Output model file written.

**Line 13:** Output residuals file written for FITS input.

**Line 15:** $(5(a9,l2))$ Boolean disk fit toggles and non-axisymmetric component, in same
order as in Lines 9 – 12 of input text file.

**Line 16:** \((5(a9,l2)) \ (7(a9,l2))\) Toggles specific to either kinematic or photometric fits, in same order as in Lines 13 – 15 of input text file.

**Lines 20 – 30:** Initial values. Should be the same as those given in input text file (see §2.2).

**Line 20:** \((a35, f8.2)\) Initial value of \(\phi_d\).

**Line 21:** \((a35, f8.2)\) Initial value of \(\epsilon_d\).

**Line 22:** \((a35, 2f8.2)\) Initial values of \(x_c\) and \(y_c\).

**Line 23:** \((a35, f8.2)\) Initial value of \(\phi_b\). This line is blank if model is axisymmetric (first toggle on Line 12 = 'F' in the input text file).

**Line 24:**
**Line 2 = phot in input text file (a35, f8.2)** Initial value of \(\epsilon_b\). This line is blank if model is axisymmetric (first toggle on Line 12 = 'F' in the input text file).

**Line 2 = vels in input text file (a35, i7)** Harmonic order m. This line is blank if model is axisymmetric (first toggle on Line 12 = 'F' in the input text file).

**Line 25:**
**Line 2 = phot in input text file (a35, f8.2)** Initial value of the bulge effective radius \(r_e\). This line is blank if no bulge component is included in the model (first toggle on Line 14 = 'F' in the input text file).

**Line 2 = vels in input text file (a35, f8.2)** Initial value of \(V_{sys}\).

**Line 26:**
**Line 2 = phot in input text file (a35, f8.2)** Initial value of the bulge Sérsic index \(n\). This line is blank if no bulge component is included in the model (first toggle on Line 14 = 'F' in the input text file).

**Line 2 = vels in input text file (a35, f8.2)** Value of ISM turbulence parameter \(\Delta_{ISM}\).

**Line 27:**
**Line 2 = phot in input text file (a35, f8.2)** Initial value of the bulge apparent ellipticity \(\epsilon_s\). This line is blank if no bulge component is included in the model (first toggle on Line 14
= ‘F’ in the input text file).

**Line 2 = vels in input text file (a35, f8.2)** Error tolerance $\Delta_{D}^\text{max}$. If first toggle on Line 3 of input text file is ‘F’ (no FITS input) or if file with velocity uncertainties is not input in Line 4 of input file, this line is blank.

**Line 28:**

**Line 2 = phot in input text file:** This line is blank.

**Line 2 = vels in input text file (a35, f8.2)** Initial value of $r_w$. If model does not include a warp (first toggle is ‘F’ on Line 15 of input text file), this line is blank.

**Line 29:**

**Line 2 = phot in input text file:** This line is blank.

**Line 2 = vels in input text file (a35, f8.2)** Initial value of $welm$. If model does not include a warp (first toggle is ‘F’ on Line 15 of input text file), this line is blank.

**Line 30:**

**Line 2 = phot in input text file:** This line is blank.

**Line 2 = vels in input text file (a35, f8.2)** Initial value of $wphim$. If model does not include a warp (first toggle is ‘F’ on Line 15 of input text file), this line is blank.

**Line 32:** (a35, f8.2) Seeing/beam smearing correction parameter. If no correction is applied, line contains the string “No seeing correction applied”.

**Line 33:** (a35, 2f8.2) Model component smoothing parameters $\lambda_1$ and $\lambda_2$. If both of these values are zero or negative, line contains the string “No model component smoothing applied”.

**Line 34:** (a38,2(a7,i7),a7,f8.2) Input random number seed, number of bootstrap realizations and value of junc used to estimate uncertainties on best fitting parameters. If no uncertainties are estimated, line contains the string “No uncertainties estimated”.

**Line 35:** (a35, 2f8.2) Radial range over which the bar (Line 2 = phot in the input text file) or non-circular flows (Line 2 = vels in the input text file) are fitted. Line is blank if no bar (first toggle on Line 12 = ‘F’ in the input text file) or radial flows (vels only; 2nd toggle on Line 13 = ‘F’ in input text file) is fit, or if input radial range brackets all ring radii.

**Lines 40 – 53:** Best fitting values. If a parameter was not varied/included in the minimization, the corresponding line is blank. If DiskFit does not estimate
uncertainties on fitted values (see Line 34), uncertainties are set to 0.0.

Line 40: (a35,f8.2,a5,f5.2) Best fitting value of $\phi'_d$, in degrees.

Line 41: (a35,f8.2,a5,f5.2) Best fitting value of $\epsilon_d = (1 - b/a)$.

Line 42: (a35,f8.2,a5,f5.2) Thin disk inclination that corresponds to the best fitting value of $\epsilon_d$, in degrees.

Line 43: (a35,f8.2,a5,f5.2,a1,f8.2,a5,f5.2) Best fitting values of $(x_c, y_c)$. Units are the same as those of Line 22.

Line 44:
Line 2 = phot in input text file (a35, f8.2,a5,f5.2) Best fitting value of $\phi'_b$, the bar PA in the sky plane, in degrees. The next value is the best fitting value of $\phi_b$, the bar PA in the disk plane (see eq. 6 in SS07).

Line 2 = vels in input text file (a35,f8.2,a5,f5.2,2(a1,f8.2)) Best fitting value of $\phi_b$, the bar PA in the disk plane, in degrees. The next two values on this line are those of $\phi'_b$, the bar PA in the sky plane (see eq. 6 in SS07). Note that DiskFit can return a value for $\phi_b$ that is the direction of the minor axis of the streamlines, in which case the signs of the velocity perturbations will be opposite of their definitions in SS07 (ie., they're negative). The two values of $\phi'_b$ are computed separately with the assumptions that $\phi_b$ is the angle of either the major or minor axis. Note that the order in which $\phi_b$ and $\phi'_b$ are output depends on whether Line 2 = phot or Line 2 = vels!

Line 45:
Line 2 = phot in input text file (a35, f8.2,a5,f5.2) Best-fitting value of $\epsilon_b$.
Line 2 = vels in input text file (a35, f8.2) Best fitting value of $V_{sys}$, in km s$^{-1}$.

Line 46:
Line 2 = phot in input text file (a35, f8.2,a5,f5.2) Best-fitting value of $r_e$, in pixels.
Line 2 = vels in input text file (a35, f8.2,a5,f5.2) Best fitting value of $r_w$, in data units.

Line 47:
Line 2 = phot in input text file (a35, f8.2,a5,f5.2) Best fitting value of $I_0$, in ADU.
Line 2 = vels in input text file (a35, f8.2,a5,f5.2) Best fitting value of $\text{welm}$, in degrees.
Line 48:
Line 2 = \texttt{phot in input text file (a35, f8.2,a5,f5.2)} Best-fitting value of $n$.
Line 2 = \texttt{vels in input text file (a35, f8.2,a5,f5.2)} Best fitting value of $w_{phim}$.

Line 49:
Line 2 = \texttt{phot in input text file (a35, f8.2,a5,f5.2)} Best-fitting value of $\epsilon_s$.
Line 2 = \texttt{vels in input text file:} This line is blank.

Line 51:
Line 2 = \texttt{phot in input text file (a35, f8.2,a5,f5.2)} The fraction of the total model light in the disk, if either a bar or bulge is included in the model. Otherwise, this line is blank.
Line 2 = \texttt{vels in input text file:} This line is blank.

Line 52:
Line 2 = \texttt{phot in input text file (a35, f8.2,a5,f5.2)} The fraction of total model light in the bar, if a bar is included in the model. Otherwise, this line is blank.
Line 2 = \texttt{vels in input text file:} This line is blank.

Line 53:
Line 2 = \texttt{phot in input text file (a35, f8.2,a5,f5.2)} The fraction of total model light in the bulge, if a bulge is included in the model. Otherwise, this line is blank.
Line 2 = \texttt{vels in input text file:} This line is blank.

Line 57: (a35, i7) Number $N$ of $D_n$ included in the minimization. This may differ from the number of the input $D_n$ if the $K'$ input ring radii do not extend to the edge of the data.

Line 58: (a35, i7) Number of iterations of Powell’s direction set method used to find the best fit (see §3.4 of SS07).

Line 59: (a31, f12.6) The minimum $\chi^2_r$, $\chi^2_{r,\text{min}}$, found in the minimization. Computed as in eq. 8 of SS07.

Line 60: (a35, i7) Number of degrees of freedom $\nu$ in the fit. Used in computation of $\chi^2_r$ (see eq. 8 of SS07).

Lines $\geq 65$: $K'$ output model components at ring radii.
For photometric models (Line 2 = \texttt{phot in the input text file}), the columns are (2f10.2, 6f12.2):
Column 1: Ring radii, as in input file.
Column 2: The effective number of $D_n$ values contributing to parameters extracted at each ring. They are not integers because fractional contributions arise from the interpolation.
Column 3: Best fitting disk intensities in ADU.
Column 4: Estimated uncertainties on best fitting disk intensities. If DiskFit does not estimate uncertainties, all entries in this column are 0.0.
Column 5: Best fitting bar intensities in ADU. If a bar is not included in the model, all entries in this column are 0.0.
Column 6: Estimated uncertainties on best fitting bar intensities. If DiskFit does not estimate uncertainties, all entries in this column are 0.0.
Column 7: Parametric bulge intensities in ADU, computed using eq. 1 and input and/or best fitting bulge parameters. If a bulge is not included in the model, all entries in this column are 0.0.
Column 8: Uncertainties on parametric bulge intensities, derived by propagating the estimated uncertainties on the best fitting bulge parameters. If DiskFit does not estimate uncertainties, all entries in this column are 0.0.

For kinematic models (Line 2 = veils in the input text file), the columns are (2f10.2, 8f12.2):
Column 1: Ring radii, as in input file.
Column 2: The effective number of $D_n$ values contributing to parameters extracted at each ring. They are not integers because fractional contributions arise from the interpolation.
Column 3: Best fitting $\bar{V}_t$ (see eq. 5 of SS07), in km s$^{-1}$.
Column 4: Estimated uncertainties on best fitting $\bar{V}_t$. If DiskFit does not estimate uncertainties, all entries in this column are 0.0.
Column 5: Best fitting $\bar{V}_r$ (see eq. 7 of SS07), in km s$^{-1}$. If radial flows are not fitted in the minimization, all entries in this column are 0.0.
Column 6: Estimated uncertainties on best fitting $\bar{V}_r$. If DiskFit does not estimate uncertainties, all entries in this column are 0.0.
Column 7: Best fitting $V_{m,t}$, where $m$ is the harmonic order, in km s$^{-1}$. If $m = 1$ or $m = 2$ flows are not fitted in the minimization, all entries in this column are 0.0.
Column 8: Estimated uncertainties on best fitting $V_{m,t}$. If DiskFit does not estimate uncertainties, all entries in this column are 0.0.
Column 9: Best fitting $V_{m,r}$, where $m$ is the harmonic order, in km s$^{-1}$. If $m = 1$ or $m = 2$ flows are not fitted in the minimization, all entries in this column are 0.0.
Column 10: Estimated uncertainties on best fitting $V_{m,r}$. If velfit does not estimate uncertainties, all entries in this column are 0.0.
3.2. Output Model File

For kinematic fits where input velocities are provided as a text file (see §2.1.2), DiskFit outputs a model text file rather than a FITS file. The name of this output model file is automatically assigned by DiskFit to be the root of the output parameter file name on Line 8 of the input text file (ie. everything before the period), with '.mod' appended. The fortran-style format for the output model is (3f12.2, 2f11.2, 7f13.2). A sample output model file is given in Fig. 31. The columns of the output model file are:

Columns 1-4: \(x_n, y_n, D_n\) and \(\Delta_D\) from the input velocity field that are used in the minimization.

Column 5: \(\sigma_n\) used in the minimization. Computed from \(\sigma_n = \sqrt{\Delta_D^2 + \Delta_{\text{ISM}}^2}\), where \(\Delta_D\) is in column 4 and \(\Delta_{\text{ISM}}\) is from line 10 of the input text file (see §2.2). Units are the same as those of \(D_n\).

Column 6: Best fitting model velocity \(V_{\text{model}}\) at \(x_n, y_n\). Units are the same as those of \(D_n\).

Column 7: Difference between \(D_n\) in column 3 and \(V_{\text{model}}\) in column 6. Units are the same as those of \(D_n\).

Column 8: Difference between \(D_n\) in column 3 and \(V_{\text{model}}\) in column 6, normalized by \(\sigma_n\). Unitless.

Column 9: Sky-plane projection of \(\bar{V}_t\) at \(x_n, y_n\) (ie. \(\bar{V}_t \cos \theta \sin i\); see eq. 5 of SS07). Units are the same as those of \(D_n\). The sum of the entries in columns 9, 10, 11, 12 and \(V_{\text{sys}}\) in the output parameter file (see §3.1) equals \(V_{\text{model}}\) in column 5.

Column 10: Sky-plane projection of \(\bar{V}_r\) at \(x_n, y_n\) (ie. \(\bar{V}_r \sin \theta \sin i\); see eq. 7 of SS07). Units are the same as those of \(D_n\). If no fit for radial flows was performed (the 5th toggle in line 12 of the input text file is ‘F’; see §2.2), entries in this column are set to 0. The sum of the entries in columns 9, 10, 11, 12 and \(V_{\text{sys}}\) in the output parameter file (see §3.1) equals \(V_{\text{model}}\) in column 5.

Column 11: Sky-plane projection of \(V_{m,t}\) at \(x_n, y_n\) (ie. \(V_{m,t} \cos(m\theta_b) \cos \theta \sin i\), where \(m\) is the harmonic order in line 13 of the input text file; see §2.2 and eqs. 4, 5 of SS07). Units are the same as those of \(D_n\). If no fit for \(m = 1\) or \(m = 2\) flows was performed (the first toggle in line 13 of the input text file is ‘F’; see §2.2), entries in this column are set to 0. The sum of the entries in columns 9, 10, 11, 12 and \(V_{\text{sys}}\) in the output parameter file (see §3.1) equals \(V_{\text{model}}\) in column 5.

Column 12: Sky-plane projection of \(V_{m,r}\) at \(x_n, y_n\) (ie. \(-V_{m,r} \sin(m\theta_b) \sin \theta \sin i\), where \(m\) is the harmonic order in line 13 of the input text file; see §2.2 and eqs. 4, 5 of SS07). Units are the same as those of \(D_n\). If no fit for \(m = 1\) or \(m = 2\) flows was performed (the first toggle in line 13 of the input text file is ‘F’; see §2.2), entries in this column are set to 0. The sum of the entries in columns 9, 10, 11, 12 and \(V_{\text{sys}}\) in the output parameter file (see §3.1) equals \(V_{\text{model}}\) in column 5.
4. Bootlace

As bootstrap iterations can be time-consuming (see §5), it can be helpful to get these done in multiple DiskFit runs with different random seeds. The results from each bootstrap run are output to a file with a unique name root.bstrpXX, where XX is the absolute value of the random number seed used. These output files should be concatenated by the user in some way, into a file of the same rootname root but extension .bstrp. Then the stand alone program Bootlace reads the concatenated file, computes the means and standard deviations of all the fitted quantities, and writes these values into an output file with extension .new, combining them with the best fit values.

A Bootlace executable can be downloaded from the DiskFit website, or compiled by the user from the source code provided on that site.

5. Examples

This section describes the application of DiskFit to the sample data included with the code. In the first example (§5.1), photometric components are extracted from a calibrated image. The next two examples (§5.2, §5.3) illustrate how to extract kinematic components from velocity fields supplied in FITS and text format, respectively. Below, typewriter font denotes terminal output and italics denote user input.

5.1. Example 1: Extracting Photometric Components

In this example, photometric models are fit to the simulated image EXAMPLE/PHOT/phot.fits provided with the code and shown in Fig. 1.

The input image is shown in Fig. 1. This artificial galaxy is centered on the point \((x_c, y_c) = (130, 130)\). The exponential disk has an ellipticity of 0.3, and a position angle of 40°, while the flat bar extends to 17.5′′, has an ellipticity of 0.6 and a position angle of 10°. The Sérsic bulge has an effective radius of 5′′, an ellipticity of 0.1 and a Sérsic index of 2. The seeing is assumed to be 1′′, the sky background is 800 ADU, the sky sigma is 14.14 ADU and the gain is 4. The FITS file contains brightnesses in ADU in a map of \(256^2\) pixels that are spaced 0.5′′ apart. The lower panel of Fig. 1 shows the intensity profiles of this model. The goal of this exercise is to recover the intensity profile components and disk geometry of the model using reasonable guesses based on the appearance of the image.

Fig. 2 shows the input file for our first attempt at fitting the image in Fig. 1; the input
The first 7 lines of the input file in Fig. 2 are obtained from the characteristics of the FITS file: we will use these same parameters for all of our fits to the data. These simulated data contain no foreground stars and have Poisson uncertainties, and we therefore do not supply either a mask file (Line 3 = None) or an uncertainties file (Line 5 = None). The image fills essentially the FITS array (1 1 256 256 on Line 6). The FITS file is oversampled (the resolution is 1”, but pixscale = 0.5”). We decide to use all the pixels within an ellipse of semi-major axis of regrad = 10 pixels, that has the same orientation as the disk: we guess from the image that the disk has a PA regepa = 35°, and an ellipticity regeps = 0.4. We’ll read only every second pixel beyond regrad (istepout = 2). Line 7 of the input file is therefore ‘10.0 35.00 0.4 2 0.5’.

Lines 9–15 and Line 22 of the input file in Fig. 2 describe the model that we will fit to the image. There is clearly a bar in the inner region of the galaxy, but for simplicity we begin with a disk-only model. We wish to fit for the disk φ′d, εd, and (xc, yc), and so the toggles on Line 9 are set to ‘T T T’. Our initial guesses for φ′d and εd are on Line 10 (35 0.4; these numbers need not be the same as regepa and regeps on Line 7, but it makes sense to set them this way). We use the cursor in our favourite FITS viewer to guess (xc, yc) (130 130 on Line 13). We do not fit for a bar or a bulge, so the first toggles on Lines 12, 14 and 15 are ‘F’: the rest of those lines are not read. We supply sky, skysig and gain on Line 13; because Line 5 = None, DiskFit will use these values to compute uncertainties on the pixel values that will be used in the fit.

Lines 16–19 of the input file in Fig. 2 describe the way in which the model is fit to the data. For now, we will not use any of the related functionalities: we will not account for seeing (0 on Line 16), we will not smooth any model components (-0.01 -0.01 on Line 17), we will not estimate uncertainties on the best fitting parameters (first toggle ‘F’ on Line 18; rest of line is not read), and we will not run in verbose mode (‘F’ on Line 19). Lines ≥ 21 of the input file in Fig. 2 list the radii at which the intensity profiles will be evaluated, in pixels. We choose to derive the profiles every 5 pixels, or 2.5”, out to 80 pixels, and every 10 pixels beyond this.

To run the model, we call DiskFit from the command line. The session looks like:

```
$ ./DiskFit
```

DiskFit (v1.2.2) Copyright (C) 2017, Jerry Sellwood and Kristine Spekkens

This program comes with ABSOLUTELY NO WARRANTY. It is free software and you are welcome to redistribute it under certain conditions.
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Enter input parameter file name:
'EXAMPLE/PHOT/phot_disk.inp'

Read in input parameters from: EXAMPLE/PHOT/phot_disk.inp

Input disk eps: (deg) 0.40
Input disk PA (N->E; deg) = 35.00
Input x-center (data units) = 130.00
Input y-center (data units) = 130.00
Sky, sky sig, gain (ADU) = 800.00 14.14 4.00

Fitting for:
disk PA
disk ellipticity
disk x-center, y-center
--> Other attributes fixed to input values

Surface brightnesses extracted at radii:
   5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
   55.0 60.0 65.0 70.0 75.0 80.0 90.0 100.0 110.0

Read in photometric image from:
EXAMPLE/PHOT/phot.fits

Number of pixels in selected part of the image: 65536
Number of pixels used in fit: 7495
   diskpa:  diskel:  xcen:  ycen:
   35.0000 0.400000 130.0000 130.0000
starting iteration 1 best reduced chisq so far: 5.223E+00
   diskpa:  diskel:  xcen:  ycen:
   35.0000 0.400000 130.0000 130.0000
starting iteration 2 best reduced chisq so far: 4.195E+00
   diskpa:  diskel:  xcen:  ycen:
   30.3458 0.299131 130.0000 130.0000
starting iteration 3 best reduced chisq so far: 4.195E+00
   diskpa:  diskel:  xcen:  ycen:
Done minimization
Total number of iterations: 3
Minimum chi^2 found: 4.19463110

Wrote: EXAMPLE/PHOT/OUT/disk.mod.fits
Wrote: EXAMPLE/PHOT/OUT/disk.res.fits
Wrote out: EXAMPLE/PHOT/OUT/disk.out

Note that DiskFit writes the input parameters to the screen before starting the minimization, and then outputs one line for each iteration during the minimization. After 3 iterations, this model has converged on a solution.

The output parameter file produced by DiskFit from this session is shown in Fig. 3 and given in the file EXAMPLE/PHOT/OUT/disk.out: inspecting its contents we see that DiskFit has converged on values that seem reasonable given the characteristics of the image in Fig. 1. Fig. 4 shows the best-fitting model from the session (top, from EXAMPLE/PHOT/OUT/disk.mod.fits), and the data-model residuals from the fit (bottom, from EXAMPLE/PHOT/OUT/disk.res.fits). Note that the elliptical region denotes the part of the image that was included in the fit, which corresponds to all pixels within an ellipse with 0.9 times the input ellipticity and a semi-major axis of 1.2 times the last ring radius. The model is clearly a reasonable representation of the disk, but there are large residuals in the center corresponding to the bulge and bar. Note also the lower position angle of the best-fitting model compared to the input value: this effect arises because the bar component is “pulling” the fit towards lower PA. Note that the (very faint) residual feature at the edge of the disk stems from the abrupt cutoff in the intensity distribution at the disk edge in this artificial system.

Given the large residuals near the galaxy center, we proceed to fit a model that includes a bulge and a bar. The resulting input file is in Fig. 5 (and in EXAMPLE/PHOT/phot_full.inp): relative to the input file in Fig. 2, we have changed the first toggles on Lines 12, 14 and 15 to ‘T’. The rest of Line 12 implies that DiskFit will fit for the position angle \( \phi_b' \) of the bar, as well as the ellipticity, and that our initial guesses are \( \phi_b' = 5^\circ \) and \( \epsilon_b = 0.5 \). The rest of Lines 14 and 15 imply that we will fit for \( r_e \), \( n \) and \( \epsilon_s \) of the bulge, and that our initial guesses for these parameters are \( r_e = 10 \) pixels, \( n = 2 \) and \( \epsilon_s = 0.2 \). Line 20 of the input file constrains the bar region to lie within 40 pixels. Finally, we correct for seeing (which slows the minimization considerably), recalling that the pixel scale is 0.5′′/pix and the seeing is
1", so we set the value in Line 16 to 2.

The output from the resulting DiskFit session is:

$ ./DiskFit

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Enter input parameter file name:
'EXAMPLE/PHOT/phot_full.inp'

Read in input parameters from: EXAMPLE/PHOT/phot_full.inp

Input disk eps: (deg) 0.40
Input disk PA (N->E; deg) = 35.00
Input x-center (data units) = 130.00
Input y-center (data units) = 130.00
Sky, sky sig, gain (ADU) = 800.00 14.14 4.00

Fitting for:
disk PA
disk ellipticity
disk x-center, y-center
Bar profile
Bar PA
Bar ellipticity
Sersic bulge profile
bulge effective radius
bulge ellipticity
bulge Sersic index
--> Other attributes fixed to input values

Surface brightnesses extracted at radii:
  5.0 10.0 15.0 20.0 25.0 30.0 35.0 40.0 45.0 50.0
  55.0 60.0 65.0 70.0 75.0 80.0 90.0 100.0 110.0

Fitting for a bar component
Axisymmetric model outside 40.0000000
Read in photometric image from:
EXAMPLE/PHOT/phot.fits

Number of pixels in selected part of the image: 65536
Number of pixels used in fit: 7495

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
35.0000 0.400000 130.0000 130.0000 5.0000 0.5000 2.0000 10.0000
starting iteration 1 best reduced chisq so far: 1.838E+00

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
35.0000 0.400000 130.0000 130.0000 5.0000 0.5000 2.0000 10.0000
starting iteration 2 best reduced chisq so far: 9.880E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
39.7292 0.306540 129.9456 129.9945 11.2600 0.5840 0.1452 1.9261 10.2458
starting iteration 3 best reduced chisq so far: 9.661E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
39.7868 0.296544 129.9724 130.0020 10.1976 0.5922 0.1642 1.8599 9.8996
starting iteration 4 best reduced chisq so far: 9.644E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
40.1117 0.295312 129.9752 130.0020 9.9729 0.5915 0.1767 1.7654 9.3224
starting iteration 5 best reduced chisq so far: 9.640E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
40.0680 0.294546 129.9824 130.0015 10.0080 0.5911 0.1782 1.7407 9.2075
starting iteration 6 best reduced chisq so far: 9.637E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
39.9375 0.293748 129.9915 130.0015 10.0621 0.5910 0.1793 1.6921 8.8601
starting iteration 7 best reduced chisq so far: 9.636E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blg-el: blg-n: r-blг:
39.9686 0.293608 129.9917 130.0011 10.0666 0.5910 0.1781 1.6867 8.7471
starting iteration 8 best reduced chisq so far: 9.636E-01

diskpa: diskel: xcen: ycen: bar-pa: bar-el: blг-el: blг-n: r-blг:
39.9960 0.292754 129.9911 130.0007 10.0630 0.5908 0.1741 1.6716 8.3626

Done minimization
Total number of iterations: 8
Minimum chi^2 found: 0.963589013

Wrote: EXAMPLE/PHOT/OUT/full.mod.fits
Wrote: EXAMPLE/PHOT/OUT/full.res.fits
Wrote: EXAMPLE/PHOT/OUT/full.dsk.fits
The output file is shown in Fig. 6, and the best-fitting model and data – model residuals are shown in Fig. 7. The individual model components are shown in Fig. 8. We find a much better fit to the data: the value of $\chi^2_r$ is now about unity, and there are no large features in the residual image (the residuals at the edge of the bar and disk reflect the abrupt edge to these components in this artificial dataset).

With a satisfactory model in-hand, we estimate uncertainties on the model parameters. We therefore re-run DiskFit with the input file in Fig. 9. The only difference between the files in Fig. 9 and the previous run in Fig. 5 is on Line 18, where the first toggle is set to ‘T’; the remainder of that line indicates that we will use a random number seed of -50, estimate uncertainties using 5 bootstrap realizations. In practice, one would want to use many more realizations: a good approach is to run DiskFit several times (perhaps on different cores) with a small number of realizations and different random number seeds, and then to concatenate the results using the routing Bootlace (see §3). Because of the presence of coherent features in the residual image, we’ll adopt the radial + rescaling method of SZS10 which preserves them, so $\text{junc} = -1.0$.

The run through DiskFit produces (after some time) the output file in Fig. 10. Note that the best-fitting model values are identical to those in Fig. 6, and the output FITS files are identical to those in Fig. 7: the only difference is that DiskFit has now estimated uncertainties on the best-fitting parameters and intensity profiles. Note that DiskFit has also written the output files EXAMPLE/PHOT/OUT/err.erase, which contains no data but will cause the code to exit gracefully if erased (in case the user decides to halt the execution before the number of bootstraps initially specified is completed), and EXAMPLE/PHOT/OUT/err.bstrp50, which contains the best-fitting parameters of each bootstrap realization of the data (useful for troubleshooting, and for running Bootlace). Note the ‘50’ appended to err.bstrp50 is the absolute value of the random number seed used to generate the file: this is useful if many DiskFit runs are used to build up the required number of bootstraps and stitched together using Bootlace (see §3). DiskFit has also output EXAMPLE/PHOT/OUT/err.csv, which contains the final minimization results for all parameters so that covariance plots can be constructed.

Comparing the best-fitting values to those of the artificial dataset, we find that DiskFit recovers the disk and bar parameters. However, the best fitting bulge $r_e$ is over-estimated by $\sim 3\sigma$, the Sérsic $n$ is under-estimated by $\sim 6\sigma$, and the bulge ellipticity over-estimated by $\approx 3\sigma$. 

Wrote: EXAMPLE/PHOT/OUT/full.bar.fits
Wrote: EXAMPLE/PHOT/OUT/full.blg.fits
Wrote out: EXAMPLE/PHOT/OUT/full.out
several $\sigma$. The culprit is lack of resolution: the seeing correction improves the estimates of the bulge properties, but it is not accurate when the profile shape changes significantly within a seeing disk. Caution should therefore be exercised when interpreting bulge parameter values in DiskFit.

### 5.2. Example 2: Extracting Kinematic Components, FITS File Input

In this example, kinematic models are fit to the simulated velocity field EXAMPLE/VELS/FITS/vels.fits, provided with the code and shown in Fig. 11.

This artificial model is centered on the point $(x_c, y_c) = (128.5, 128.5)$ and has a systemic velocity of $V_{sys} = 100 \text{ km s}^{-1}$. The disk is inclined at $60^\circ$, the position angle of the major axis is $40^\circ$, and it contains a weak bar at the angle $\phi_b = 20^\circ$ to the major axis. The FITS file contains the velocities in m s$^{-1}$ in a map of $256^2$ pixels that are spaced $1''$ apart, and the non-axisymmetric velocities associated with the bar drop below 1 km s$^{-1}$ at $R \simeq 100''$. Gaussian random deviates have been added to the velocity field points to mimick a mean measurement error $\{\Delta_D\} = 2 \text{ km s}^{-1}$ and ISM turbulence $\Delta_{\text{ISM}} = 2 \text{ km s}^{-1}$. The lower panel of Fig. 11 shows the radial variation of the velocity field components of this model. The goal of this exercise is to recover the velocity field components and disk geometry of the model using reasonable guesses based on the appearance of the velocity field.

Fig. 12 shows the input file for our first attempt at fitting the velocity field in Fig. 11; the input file is also located in EXAMPLE/VELS/FITS/vels_disk.inp.

The first 7 lines of the input file in Fig. 12 are obtained from the characteristics of the FITS file: we will use these same parameters for all of our fits to the data. The velocity field is in m s$^{-1}$ (T T on Line 3), there are no uncertainties (no data on Line 5), and the data fills essentially the whole image (1 1 255 255 on Line 6). The FITS file is oversampled. We decide to use all the pixels within an ellipse of semi-major axis of $\text{regrad} = 12$ pixels, that has the same orientation as the disk: we guess from the velocity field that the disk has a PA $\text{regpa} = 45^\circ$, and an ellipticity $\text{regeps} = 0.45$. We’ll read only every sixth pixel beyond $\text{regrad}$ (istepout = 6; the resolution is 6", but pixscale = 1"). Line 7 of the input file is therefore ’12.0 45.00 0.45 6 1.0’.

Lines 9–15 and Line 20 of the input file in Fig. 12 describe the model that we will fit to the velocity field. The “kinks” in the isovels near the velocity field center in Fig. 11 suggest that there are non-circular flows, but for simplicity we begin with a rotation-only model. We wish to fit for the disk $\phi'_d$, $\epsilon_d$, and $(x_c, y_c)$, and so the toggles on Line 9 are set to ‘T T T’. Our initial guesses for $\phi'_d$ and $\epsilon_d$ are on line Line 10 (45.00 0.45; these numbers need not be
the same as \texttt{regpa} and \texttt{regeps} on Line 7, but it makes sense to set them this way). We use the cursor in our favourite FITS viewer to guess \((x_c, y_c)\) (130.50 126.50 on Line 11). We do not fit for non-circular flows, so the first toggle on Line 12 is ‘F’: the rest of that line is not read. We will allow the code to interpolate to 0, but not to fit radial flows (‘T F’ on Line 13). We wish to fit for \(V_{\text{sys}}\); looking at the values near the velocity field centre, we will guess that \(V_{\text{sys}} \sim 110 \text{ km s}^{-1}\). For now, we’ll assume a turbulence value of \(\Delta_{\text{ISM}} = 1.0 \text{ km s}^{-1}\). We’ll set \(\Delta_{B}^{\text{max}} = 25 \text{ km s}^{-1}\), although this value is not applied to our data because no uncertainty file was provided to \texttt{DiskFit} on Line 5. Thus, Line 14 of the input file is ‘T 110.00 1.0 25.0’. We will not fit a warp model, so the first toggle on Line 15 is ‘F’: the rest of that line is not read. Finally, Line 20 is not read because we do not fit for non-circular flows.

Lines 16–19 of the input file in Fig. 12 describe the way in which the model is fit to the data. For now, we will not use any of the related functionalities: we will not account for seeing (0 on Line 16), we will not smooth any model components (-0.01 -0.01 on Line 17), we will not estimate uncertainties on the best fitting parameters (first toggle ‘F’ on Line 18; rest of line is not read), and we will not run in verbose mode (‘F’ on Line 19). Lines \(\geq 21\) of the input file in Fig. 12 list the radii at which the model velocity components will be evaluated, in pixels.

To run the model, we call \texttt{DiskFit} from the command line (below and throughout, italics denote terminal input, while fixed width text denotes terminal output). The session looks like:

```
$ ./DiskFit
```

\texttt{DiskFit (v1.2.2) Copyright (C) 2017, Jerry Sellwood and Kristine Spekkens}

\texttt{This program comes with ABSOLUTELY NO WARRANTY. It is free software and you are welcome to redistribute it under certain conditions. See <http://www.gnu.org/licenses/> for details.}

\texttt{Enter input parameter file name:}
\texttt{’EXAMPLE/VELS/FITS/velsf_disk.inp’}

\texttt{Enter input parameter file name}
\texttt{’EXAMPLE/VELS/FITS/velsf_disk.inp’}

\texttt{Read in input parameters from: EXAMPLE/VELS/FITS/velsf_disk.inp}
Input disk eps: (deg) 0.45
Input disk PA (N->E; deg) = 45.00
Input x-center (data units) = 130.50
Input y-center (data units) = 126.50
Input disk systemic velocity (km/s) = 110.00

Fitting for:
disk PA
disk ellipticity
disk x-center, y-center
disk systemic velocity
--> Other attributes fixed to input values

Velocity field components extracted at radii:

<table>
<thead>
<tr>
<th>Radius (km)</th>
<th>3.0</th>
<th>9.0</th>
<th>15.0</th>
<th>21.0</th>
<th>27.0</th>
<th>33.0</th>
<th>39.0</th>
<th>45.0</th>
<th>51.0</th>
<th>57.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.0</td>
<td>69.0</td>
<td>75.0</td>
<td>81.0</td>
<td>87.0</td>
<td>93.0</td>
<td>99.0</td>
<td>105.0</td>
<td>111.0</td>
<td>117.0</td>
<td></td>
</tr>
<tr>
<td>123.0</td>
<td>129.0</td>
<td>135.0</td>
<td>141.0</td>
<td>147.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Read in measured velocities and uncertainties from:
EXAMPLE/VELS/FITS/vels.fits

Number of datapoints read in: 1224
Number of datapoints to be used in fit: 1224

diskpa: diskel: xcen: ycen:
45.0000 0.450000 130.5000 126.5000

starting iteration 1 best reduced chisq so far: 2.630E+02

diskpa: diskel: xcen: ycen:
45.0000 0.450000 130.5000 126.5000

starting iteration 2 best reduced chisq so far: 5.658E+01

diskpa: diskel: xcen: ycen:
37.9961 0.502716 126.7732 127.7305

starting iteration 3 best reduced chisq so far: 4.650E+01

diskpa: diskel: xcen: ycen:
38.3531 0.491903 128.1498 128.3482

starting iteration 4 best reduced chisq so far: 4.616E+01

diskpa: diskel: xcen: ycen:
38.1431 0.500719 128.2253 128.3680
starting iteration  5 best reduced chisq so far: 4.615E+01
  diskpa:  diskel:  xcen:  ycen:
  38.1281  0.501726  128.2325  128.3615

Done minimization
Total number of iterations:  5
Minimum chi^2 found:  46.1519241

Wrote: EXAMPLE/VELS/FITS/OUT/disk.mod.fits
Wrote: EXAMPLE/VELS/FITS/OUT/disk.res.fits
Wrote out: EXAMPLE/VELS/FITS/OUT/disk.out

Note that DiskFit writes the input parameters to the screen before starting the minimization, and then outputs one line for each iteration during the minimization. After 5 iterations, this model has converged on a solution.

The output parameter file produced by DiskFit from this session is shown in Fig. 13 and given in the file EXAMPLE/VELS/FITS/OUT/disk.out: inspecting its contents we see that DiskFit has converged on values that seem reasonable given the characteristics of the velocity field in Fig. 11. Fig. 14 shows the best-fitting model from the session (top, from EXAMPLE/VELS/FITS/OUT/disk.mod.fits), and the data-model residuals from the fit (bottom, from EXAMPLE/VELS/FITS/OUT/disk.res.fits). The model is clearly a reasonable representation of the data, but there are coherent features in the residuals that indicate the presence of non-circular flows.

We therefore proceed to fit a model that includes bar-like non-circular flows. The resulting input file is in Fig. 15 (and in EXAMPLE/VELS/FITS/velsf_bli.inp): relative to the input file in Fig. 12, we have changed the first toggle on Line 12 to ‘T’: the rest of that line implies that DiskFit will fit for the position angle $\phi_b$ of the non-circular flow of order $m = 2$ (thus a bar-like flow). We have no prior constraint on this value, so we set $\phi_b = 45^\circ$. Line 20 of the input file constrains the non-circular flow region to lie between 3–110 pixels.

The output from the resulting DiskFit session is:
$ ./DiskFit

DiskFit (v1.2.2) Copyright (C) 2017, Jerry Sellwood and Kristine Spekkens

This program comes with ABSOLUTELY NO WARRANTY. It is free software and you are welcome to redistribute it under certain conditions.
Enter input parameter file name:
'EXAMPLE/VELS/FITS/vels_bi.inp'

Enter input parameter file name
'EXAMPLE/VELS/FITS/velsf_bi.inp'

Read in input parameters from: EXAMPLE/VELS/FITS/velsf_bi.inp

Input disk eps: (deg) 0.45
Input disk PA (N->E; deg) = 45.00
Input x-center (data units) = 130.50
Input y-center (data units) = 126.50
Input disk systemic velocity (km/s) = 110.00

Fitting for:
disk PA
disk ellipticity
disk x-center, y-center
non-axisymmetric disk components
PA of non-axisymmetric component
disk systemic velocity
--> Other attributes fixed to input values

Velocity field components extracted at radii:

<table>
<thead>
<tr>
<th>3.0</th>
<th>9.0</th>
<th>15.0</th>
<th>21.0</th>
<th>27.0</th>
<th>33.0</th>
<th>39.0</th>
<th>45.0</th>
<th>51.0</th>
<th>57.0</th>
</tr>
</thead>
<tbody>
<tr>
<td>63.0</td>
<td>69.0</td>
<td>75.0</td>
<td>81.0</td>
<td>87.0</td>
<td>93.0</td>
<td>99.0</td>
<td>105.0</td>
<td>111.0</td>
<td>117.0</td>
</tr>
<tr>
<td>123.0</td>
<td>129.0</td>
<td>135.0</td>
<td>141.0</td>
<td>147.0</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Fitting for m = 2 bisymmetric flow (radial and tangential components)
in addition to rotation velocities
Non-axisymmetric flows set to 0 in rings beyond 111.000000000

Read in measured velocities and uncertainties from:
EXAMPLE/VELS/FITS/vels.fits
Number of datapoints read in: 1224
Number of datapoints to be used in fit: 1224

\begin{verbatim}
   diskpa: diskel: xcen: ycen: phi_b:
   \hspace{1.5cm} 45.0000 0.450000 130.5000 126.5000 45.0000
starting iteration 1 best reduced chisq so far: 1.308E+02
   diskpa: diskel: xcen: ycen: phi_b:
   \hspace{1.5cm} 45.0000 0.450000 130.5000 126.5000 45.0000
s starting iteration 2 best reduced chisq so far: 1.993E+01
   diskpa: diskel: xcen: ycen: phi_b:
   \hspace{1.5cm} 40.2138 0.504280 126.6734 127.9762 76.7601
starting iteration 3 best reduced chisq so far: 8.249E+00
   diskpa: diskel: xcen: ycen: phi_b:
   \hspace{1.5cm} 40.0038 0.507144 128.5576 128.5575 110.1908
starting iteration 4 best reduced chisq so far: 8.198E+00
   diskpa: diskel: xcen: ycen: phi_b:
   \hspace{1.5cm} 40.0893 0.502564 128.5681 128.5756 108.4951
starting iteration 5 best reduced chisq so far: 8.197E+00
   diskpa: diskel: xcen: ycen: phi_b:
   \hspace{1.5cm} 40.0579 0.502611 128.5681 128.5774 108.4545
\end{verbatim}

Done minimization
Total number of iterations: 5
Minimum \(\chi^2\) found: 8.19682789

Wrote: EXAMPLE/VELS/FITS/OUT/bi.mod.fits
Wrote: EXAMPLE/VELS/FITS/OUT/bi.res.fits
Wrote out: EXAMPLE/VELS/FITS/OUT/bi.out

The output file is shown in Fig. 16, and the best-fitting model and data – model residuals are shown in Fig. 7. We find a much better fit to the data: the value of \(\chi^2\) is much lower than before (recall that we have arbitrarily set \(\Delta_{\text{ISM}} = 1 \text{ km s}^{-1}\); we’ll tweak this below), and there are no visible features in the residual velocity field. Note that the fitted disk-plane bar angle of 108.46° is \(\simeq 90°\) away from the true angle, \textit{i.e.} the code has found the bar minor axis (see §3.1). This is a perfectly acceptable fit, because the values of \(V_{2,t}\) \& \(V_{2,r}\) are all negative. The next two values on this output line give the corresponding bar angle in the sky plane, assuming that DiskFit has found the bar major axis and minor axis respectively. Note that
this model fit is very similar to that in Example 2 of the velfit2.0 documentation, which is expected since DiskFit invokes the same code as its predecessor.

With a satisfactory model in-hand, we refine the model fit. We experiment with $\Delta_{\text{ISM}}$, and find that $\Delta_{\text{ISM}} = 2.8 \, \text{km s}^{-1}$ produces $\chi^2 \sim 1$; Line 14 of the input file therefore becomes ‘T 110.00 2.8 25.0’. We elect not to correct for beam smearing (line 16 is ‘0’): this slows the code considerably, is not accurate for velocity fields derived by taking the moment of a datacube, and generally requires that the rings be spaced wider than a beam width apart, which is not the case here. Finally, we estimate uncertainties on the model parameters, and set the first toggle on Line 20 to ‘T’. The remainder of that line indicates that we will use a random number seed of -50, estimate uncertainties using 5 bootstrap realizations, and we’ll adopt the radial + rescaling method of SZS10: Line 20 therefore reads ‘T -50 5 -1.0’. In practice, one would want to use many more realizations: a good approach is to run DiskFit several times (perhaps on different cores) with a small number of realizations and different random number seeds, and then to concatenate the results using the routing Bootlace (see §3).

We therefore re-run DiskFit with the input file in Fig. 18, also in the file EXAMPLE/VELS/FITS/velsf_err.inp. The run through DiskFit produces the output file in Fig. 19, and the corresponding model and residuals are in Fig. 20. Note that DiskFit has also written the output files EXAMPLE/VELS/FITS/OUT/err.erase, which contains no data but will cause the code to exit gracefully if erased (in case the user decides to halt the execution before the number of bootstraps initially specified is completed), and EXAMPLE/VELS/FITS/OUT/err.bstrp50, which contains the best-fitting parameters of each bootstrap realization of the data (useful if the code crashes before the bootstraps are complete). Note that the ‘50’ appended to this file is the absolute value of the random number seed used in the run, which is handy if you are running the code many times to build up a large number of bootstrap realizations to estimate uncertainties (see §3). DiskFit has also output EXAMPLE/VELS/FITS/OUT/err.csv, which contains the final minimization results for all parameters so that covariance plots can be constructed.

Comparing the input velocity field properties to those of the best fitting model, it is clear that DiskFit has recovered the kinematic structure of this simulated data.

For illustrative purposes we fit a radial flow model to the simulated data. We change the first toggle on Line 12 of the input file to ‘F’ (and thus this line is no longer read), and the second toggle on Line 13 to ‘T’. To speed up the code, we do not estimate uncertainties (first toggle on Line 18 is ’F’). For direct comparison with the bar-like flow model, we reset $\Delta_{\text{ISM}} = 1 \, \text{km s}^{-1}$ on Line 14. DiskFit will now search for radial flows in the radial range of 3 – 110 pixels. We leave all other input parameters fixed, to produce the input file in Fig. 21.
and given in EXAMPLE/VELS/FITS/velsf_rad.inp. The best fitting model parameters are in Fig. 22, with the model and residuals in Fig. 23. We find that a radial flow model also provides a good fit to the data; however, radial flows are not physically well-motivated, and, at least in this example, simply parametrize the underlying bar-like flow.

Finally, we search for a symmetric warp in the simulated data. These data do not contain a warp, which should be borne out by the fit. We do not fit for either radial or bar-like flows (DiskFit will not simultaneously fit for bar-like flows and a warp, since the two produce degenerate signatures in the velocity field), and we therefore set the first toggle on Line 12 and the second toggle on Line 13 to 'F'. To fit for a warp, we set all of the toggles on Line 15 to 'T'. To get a sense of the uncertainties on the best fitting parameters, Line 20 remains 'T -50 5 -1.0'. We have no constraint on $r_w$, $w_{phim}$ and $w_{elm}$: we guess $r_w = 90$ pixels, $w_{phim} = 0$, and $w_{elm} = 0$, such that Line 15 becomes 'T T T T 90 0 0'. The resulting input file is in Fig. 24 and given in EXAMPLE/VELS/FITS/velsf_warp.inp. The best fitting model parameters are in Fig. 25, with the model and residuals in Fig. 7. It is clear that this model does not describe the data well, and the warp parameters are poorly constrained and consistent with 0 to within a few $\sigma$.

5.3. Example 3: Extracting Kinematic Components, Text File Input

In this final example, we fit a kinematic model to a velocity field input in text format, contained in EXAMPLE/VELS/TEXT/vels.txt. The format of the text file is illustrated in Fig. 27: the velocity field is given in units of arcsec and km s$^{-1}$; as expected by DiskFit, the coordinate system is such that $x_n$ increases to the W and $y_n$ increases to the N.

The model velocity components and velocity field themselves are plotted in Fig. 28. In Fig. 28, $\bar{V}_t$ is given by the black line, and corresponds to a power-law $\bar{V}_t = 80[r/27.8]^{0.35}$ km s$^{-1}$. $V_{2,t}$ and $V_{2,r}$ are given by the red and blue lines, respectively, and are described by $V_{2,t} = 25 \sin(r/10)$ km s$^{-1}$ for $r/10 \leq \pi$, and $V_{2,r} = 0.85V_{2,t}$. The bar axis is $\phi_b = 40^\circ$. The velocity field is obtained by projecting the disk at $\phi'_b = 85^\circ$ with an inclination of $55^\circ$ about $(x_c, y_c) = (2.0, 0.0)$ and $V_{sys} = 490$ km s$^{-1}$. Gaussian random deviates have been added to the velocity field points to mimick a mean measurement error $\{\Delta_D\} = 2$ km s$^{-1}$ and ISM turbulence $\Delta_{ISM} = 2$ km s$^{-1}$. Note that the velocity field points are regularly spaced in this example, but they need not be.

We refer the reader to §5.2 for a step-by-step guide on how to “build” a bar-like flow model by inspecting the data, and here provide the input file to fit the model velocity field with little comment. We will fit a bar-like flow model, with reasonable initial guesses for
the disk geometry. The resulting input file is given in Fig. 29, and in the file EXAMPLE/VELS/TEXT/velst_err.inp.

From the velocity field in Figs. 28 we construct the input text file that is required by velfit. We guess that \((x_c, y_c) \approx (0, 0)\), \(V_{\text{sys}} \approx 500 \text{ km s}^{-1}\), inclination \(\approx 60^\circ\), \(\phi_d' \approx 80^\circ\). The velocity field has \(\sim 1000\) independent points and extends about 50\arcsec along the major axis, so we choose to extract velocity field components at radii separated by 2.5\arcsec out to \(r = 50\arcsec\). We set \(\Delta_{\text{ISM}} = 2.0 \text{ km s}^{-1}\).

The corresponding input file is shown in Fig. 29: the inputs are very similar to those in Fig. 18, but with the FITS toggle on Line 3 = ‘F’ and the input filename altered. The DiskFit output is:

```
$ ./DiskFit

DiskFit (v1.2.2) Copyright (C) 2017, Jerry Sellwood and Kristine Spekkens

This program comes with ABSOLUTELY NO WARRANTY. It is free software
and you are welcome to redistribute it under certain conditions.
See <http://www.gnu.org/licenses/> for details.

Enter input parameter file name:
'EXAMPLE/VELS/TEXT/velst_err.inp'

1127 velocity points read from file EXAMPLE/VELS/TEXT/vels.txt
Your input data points are spaced regularly enough that they
could be inserted into a 2D raster of pixels.
This has both advantages and disadvantages -
see section 2.1.2 of the documentation
Would you like DiskFit to rasterize your data (y/n)?
(Enter n if you are inexperienced or do not understand)

At this step in the execution, DiskFit has paused because the code is able to rasterize
the input text data (see §2.1.2). The user is required either to allow DiskFit to carry out
the fit on the rasterized data (in this case type y), or to fit the input text data as a pixel
list (in this case type n). See §2.1.2 for a discussion of the advantages and disadvantages
of each option, but unless you require a seeing correction or the radial-rescaling method of
estimating uncertainties, type n. Note that if your data are sampled irregularly enough that
DiskFit cannot find a reasonably-sized (1024 \(\times\) 1024) raster to represent them, you will not
be given the above choice. In this case, we therefore proceed:

Read in input parameters from: EXAMPLE/VELS/TEXT/velst_err.inp

Input disk eps: (deg) 0.50
Input disk PA (N->E; deg) = 80.00
Input x-center (data units) = 0.00
Input y-center (data units) = 0.00
Input disk systemic velocity (km/s) = 500.00

Fitting for:
disk PA
disk ellipticity
disk x-center, y-center
non-axisymmetric disk components
PA of non-axisymmetric component
disk systemic velocity
--> Other attributes fixed to input values

Velocity field components extracted at radii:
  2.5  5.0  7.5  10.0  12.5  15.0  17.5  20.0  22.5  25.0
  27.5  30.0  32.5  35.0  37.5  40.0  42.5  45.0  47.5  50.0

Fitting for $m = 2$ bisymmetric flow (radial and tangential components) in addition to rotation velocities

Read in measured velocities and uncertainties from:
EXAMPLE/VELS/TEXT/vels.txt

Input velocity list not convenient for
2D representation: pixel list used

Number of datapoints read in: 1127
Number of datapoints to be used in fit: 1124
  diskpa: diskel: xcen: ycen: phi_b:
  80.0000  0.500000  0.0000  0.0000  45.0000
starting iteration 1 best reduced chisq so far: 1.890E+00
The output parameter file for this run is given in Fig. 30 and the output model file is in Fig. 31. Comparing the output parameters and uncertainties with the input values, we see that DiskFit has recovered the example field properties nicely. Note this model fit is very similar to that in Example 1 of the velfit2.0 documentation, which is expected since DiskFit invokes the same code as its predecessor.

6. Source Code

This section describes the source code for DiskFit found in CODE/, and provides some instructions for compiling it. Note that you will need to procure and modify some Numerical Recipes procedures in order to compile DiskFit: in accordance with their licensing
regulations, we have not redistributed them. Even if the reader does not intend to compile it, it is our hope that access to the source code will give them a better sense of how the code works, troubleshooting tools should problems arise, and a starting point for incorporating DiskFit into your favourite galactic dynamics package.

The CODE/ directory contains source code for DiskFit (*.f), a module file (alldata.f), a definitions file (commons.h) and a directory called LINPACK/ that contains the requisite LINPACK\(^2\) routines. The code is written in (fixed-form) Fortran 90. The main program in DiskFit.f drives the routine: look in this file to decipher the inner workings of the code.

The following steps need to be carried out in order to compile the source code. Because the details of this process are highly platform-dependent, we provide only a general outline here:

- Acquire a Fortran 90 compiler.
- Acquire the Numerical Recipes routines\(^3\) BRENTE, F1DIM, HPSORT, LINMIN, MNBRAK, MOMENT, POWELL, RAN1 and SELECT. HPSORT and SELECT are used as-is by DiskFit. However, you will need to modify BRENTE, F1DIM, LINMIN, MNBRAK, MOMENT, POWELL and RAN1 to read in double precision (\texttt{real*8}) variables rather than single-precision (\texttt{real}) ones: see §6.1 below. Rename these files brentdbl.f, f1dimdbl.f, linmindbl.f, mnbrakdbl.f, momentdbl.f, powelldbl.f, and ran1dbl.f.
- You may wish to compile the routines in CODE/LINPACK/ and the newly-modified Numerical Recipes routines into libraries that your compiler can find.
- Download and install the CFITSIO package\(^4\) for reading and writing FITS files. You will need to link this library even if you do not plan to read FITS files with DiskFit. The executables included in DiskFit version 1.2 are compiled with CFITSIO version 3.34.
- Compile DiskFit.f, linking the other programs in CODE/, the LINPACK routines, the Numerical Recipes routines and the CFITSIO libraries.

The stand-alone code Bootlace can also be compiled from the source (driven by the main program bootlace.f) in the same way.

\(^2\)http://www.netlib.org/linpack/

\(^3\)Fortran 77 or Fortran 90 version; see http://www.nr.com/

\(^4\)http://heasarc.nasa.gov/fitsio/fitsio.html
If you have specific questions about how to compile the code, please send an email to Kristine.Spekkens@rmc.ca; we’d be happy to help.

6.1. Numerical Recipes Modifications

We cannot redistribute the Numerical Recipes routines that DiskFit requires, but we have obtained permission to distribute the differences between the original (f77) recipes and the modified versions required to compile the code (W. T. Vetterling, priv. comm.). Here they are:

```
bash-3.2$ diff orig/brent.for dble/brent_dbl.for
1c1
< FUNCTION brent(ax,bx,cx,f,tol,xmin)
---
> FUNCTION brent_dbl(ax,bx,cx,f,tol,xmin)
3c3
< REAL brent,ax,bx,cx,tol,xmin,f,CGOLD,ZEPS
---
> REAL*8 brent_dbl,ax,bx,cx,tol,xmin,f,CGOLD,ZEPS
7c7
< REAL a,b,d,e,etemp,fu,fv,fw,fx,p,q,r,tol1,tol2,u,v,w,x,xm
---
> REAL*8 a,b,d,e,etemp,fu,fv,fw,fx,p,q,r,tol1,tol2,u,v,w,x,xm
81c81
< brent=fx
---
> brent_dbl=fx
```

```
bash-3.2$ diff orig/f1dim.for dble/f1dim_dbl.for
1c1,2
< FUNCTION f1dim(x)
---
> FUNCTION f1dim_dbl(x)
> implicit none
3c4
< REAL f1dim,func,x
```
bash-3.2$ diff orig/linmin.for dble/linmin_dbl.for
1c1
< SUBROUTINE linmin(p,xi,n,fret)
---
> SUBROUTINE linmin_dbl(p,xi,n,fret)
3c3
< REAL fret,p(n),xi(n),TOL
---
> REAL*8 fret,p(n),xi(n),TOL
7c7
< REAL ax,bx,fa,fb,fx,xmin,xx,pcom(NMAX),xicom(NMAX),brent
---
> REAL*8 ax,bx,fa,fb,fx,xmin,xx,pcom(NMAX),xicom(NMAX),brent_dbl
9c9
< EXTERNAL f1dim
---
> EXTERNAL f1dim_dbl
17,18c17,18
< call mnbrak(ax,xx,bx,fa,fx,fb,f1dim)
< fret=brent(ax,xx,bx,f1dim,TOL,xmin)
---
> call mnbrak_dbl(ax,xx,bx,fa,fx,fb,f1dim_dbl)
> fret=brent_dbl(ax,xx,bx,f1dim_dbl,TOL,xmin)
bash-3.2$ diff orig/mnbrak.for dble/mnbrak_dbl.for
1,2c1,2
<    SUBROUTINE mnbrak(ax,bx,cx,fa,fb,fc,func)
<    REAL ax,bx,cx,fa,fb,fc,func,GOLD,GLIMIT,TINY
---
>    SUBROUTINE mnbrak_dbl(ax,bx,cx,fa,fb,fc,func)
>    REAL*8 ax,bx,cx,fa,fb,fc,func,GOLD,GLIMIT,TINY
5c5
<    REAL dum,fu,q,r,u,ulim
---
>    REAL*8 dum,fu,q,r,u,ulim

bash-3.2$ diff orig/moment.for dble/moment_dbl.for
1c1
<    SUBROUTINE moment(data,n,ave,adev,sdev,var,skew,curt)
---
>    SUBROUTINE moment_dbl(data,n,ave,adev,sdev,var,skew,curt)
3c3
<    REAL adev,ave,curt,sdev,skew,var,data(n)
---
>    REAL*8 adev,ave,curt,sdev,skew,var,data(n)
5c5
<    REAL p,s,ep
---
>    REAL*8 p,s,ep

bash-3.2$ diff orig/powell.for dble/powell_dbl.for
1c1
<    SUBROUTINE powell(p,xi,n,np,ftol,iter,fret)
---
>    SUBROUTINE powell_dbl(p,xi,n,np,ftol,iter,fret)
3c3
<    REAL fret,ftol,p(np),xi(np,np),func,TINY
---
>    REAL*8 fret,ftol,p(np),xi(np,np),func,TINY
8c8
\begin{verbatim}
< REAL del,fp,fptt,t,pt(NMAX),ptt(NMAX),xit(NMAX)
---
> REAL*8 del,fp,fptt,t,pt(NMAX),ptt(NMAX),xit(NMAX)
23c23
< call linmin(p,xit,n,fret)
---
> call linmin_dbl(p,xit,n,fret)
40c40
< call linmin(p,xit,n,fret)
---
> call linmin_dbl(p,xit,n,fret)

bash-3.2$ diff orig/ran1.for dble/ran1_dbl.for
1c1
< FUNCTION ran1(idum)
---
> FUNCTION ran1_dbl(idum)
3c3
< REAL ran1,AM,EPS,RNMX
---
> REAL*8 ran1_dbl,AM,EPS,RNMX
25c25
< ran1=min(AM*iy,RNMX)
---
> ran1_dbl=min(AM*iy,RNMX)
\end{verbatim}
7. Modification History

- **Version 1.2.2:** Minor bug fixes and feature additions, almost all on the photometric side of the code. Changes from last version:
  
  - Angles and uncertainties for components with position angles of 90 deg are now reported correctly.
  - Change to minimization code to prevent DiskFit from returning unphysical large bulges.
  - Added `root.csv` file to outputs when uncertainties are estimated in order to allow for the construction of covariance plots.
  - Bi-weight estimator (robust against large outliers) now used to compute uncertainties from bootstrap-resampled minimizations.

- **Version 1.2.1:** Bug fix for 64-bit FITS file output.

- **Version 1.2:** Upgrade to Fortran 90 from Fortran 77. The major difference is therefore that there are no code restrictions on the sizes of the FITS or text files that can be input. Other changes from last version:
  
  - A mask file and uncertainty file can now be input on the photometric side.
  - The bootlace routine can now be used to concatenate output files from the kinematic branch or from the photometric branch of the code.
  - A bug in the seeing/beam smearing correction algorithm has been corrected.
  - A bug in the rasterization algorithm used for text file input in the kinematic branch of the code has been corrected.
  - A minor bug that caused the variables `npts` (effective number of $D_n$ per ring) and `wphim` (warp position angle) in the kinematic branch of the code to be mis-reported in some model fits has been fixed.
  - Some run-time screen outputs have been re-formatted.

- **Version 1.1:** Minor bug fixes and modifications to improve code stability. Changes from last version:
  
  - FITS files containing 64-bit reals can now be read, in addition to files containing 32-bit reals or 16-bit integers.
  - A minor bug that changed the line numbers in the output text file for some minimizations has been fixed.
– minimizations using text file inputs with velocities in m/s are now allowed.
– Some run-time screen outputs have been re-formatted.

• **Version 1.0**: First release.
Fig. 1.— Top panel: artificial sky-subtracted image of a nearby galaxy to be modelled by \DiskFit in Example 1 (see §5.1). The colorscale is logarithmic, and shown at the bottom of the image in ADU. The exponential disk has an ellipticity of 0.3, and a position angle of $40^\circ$, while the flat bar extends to 17.5$''$ (35 pixels), and has an ellipticity of 0.6 and a position angle of $10^\circ$. The Sérsic bulge has an effective radius of 5$''$, an ellipticity of 0.1 and a Sérsic index of 2. The seeing is assumed to be 1$''$, the sky background is 800 ADU, the sky sigma is 14.14 ADU and the gain is 4. The \textsc{fits} file contains brightnesses in ADU in a map of 256$^2$ pixels that are spaced 0.5$''$ apart. Bottom panel: intensity profiles of the disk (black line), bar (blue line) and bulge (green line), on a logarithmic scale.
#PHOTOMETRY EXAMPLE, DISKFIT

phot
None
'EXAMPLE/PHOT/phot.fits'
None
1 1 256 256
10.0 35.00 0.4 2 0.5
'EXAMPLE/PHOT/OUT/disk.out'
T T T
35 0.4
130 130
F T T 5.00 0.5
800.0 14.14 4.0
F T 10
F T 2 0.2
F -50 50 -1.0
0.
-0.01 -0.01
F -50 50 -1.0
0. 40.
5.0
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
50.0
55.0
60.0
65.0
70.0
75.0
80.0
90.0
100.0
110.0

Fig. 2.— Input file for disk-only fit to the image in Fig. 7: EXAMPLE/PHOT/phot_disk.inp.
Minimization output, phot
-------------------------
Input files:
EXAMPLE/PHOT/phot_disk.inp
EXAMPLE/PHOT/phot.fits

sky: 800.00 skysig: 14.14 gain: 4.00

FITS region: x-low: 1 y-low: 1 x-range: 256 y-range: 256
FITS sampling: regred: 10.00 regpa: 35.00 regeps: 0.40 istpout: 2

Output model and (data-model) residuals files:
EXAMPLE/PHOT/OUT/disk.mod.fits
EXAMPLE/PHOT/OUT/disk.res.fits

Disk toggles: PA: T eps: T center: T non-axi: F phib: F

Input values
-------------
disk PA, phi_d'prime (deg): 35.00
disk eps: 0.40
x,y center (data units): 130.00 130.00

No seeing correction applied
No model component smoothing applied
No uncertainties estimated

Best fitting values
-------------------
disk PA, phi_d'prime (deg): 30.72 +/- 0.00
disk eps: 0.30 +/- 0.00
disk incl (deg): 45.52 +/- 0.00
x,y center (data units): 130.00 +/- 0.00, 130.00 +/- 0.00
Minimization Details

# points Dn used in fit: 7495
# iterations in minimization: 3
Minimum chi**2 found: 4.194631
Degrees of freedom in fit: 7472

Fitted intensities (radii in pixels, intensities in ADU):

<table>
<thead>
<tr>
<th>r</th>
<th>npts</th>
<th>Idisk</th>
<th>eIdisk</th>
<th>Ibar</th>
<th>eIbar</th>
<th>Ibulge</th>
<th>ebulge</th>
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<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
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<tr>
<td>15.00</td>
<td>82.23</td>
<td>894.20</td>
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<td>0.00</td>
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<tr>
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<td>650.75</td>
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<td>372.60</td>
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<td>0.00</td>
</tr>
<tr>
<td>35.00</td>
<td>192.24</td>
<td>280.61</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
<td>0.00</td>
</tr>
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Fig. 3.— Output file containing best-fitting parameters produced by DiskFit using the disk-only model input file in Fig. 2: EXAMPLE/PHOT/OUT/disk.out.
Fig. 4.— Best fitting disk-only model (top) and data–model residuals (bottom) found by DiskFit using the input file in Fig. 2. The model colorscale is logarithmic, while that of the residuals is linear; both are shown at the bottom of the image in ADU. The corresponding FITS files are EXAMPLE/PHOT/OUT/disk.mod.fits (top) and EXAMPLE/PHOT/OUT/disk.res.fits (bottom).
#PHOTOMETRY EXAMPLE, DISKFIT

phot # 2 vels/phot switch
None # 3 PHOT: file name with mask file
'EXAMPLE/PHOT/phot.fits' # 4 file name with input data
None # 5 file name for image uncerts
1 1 256 256 # 6 FITS region to fit: (xlow,ylow) & (xrange,yrange)
10.0 35.00 0.4 6 0.5 # 7 FITS sampling: regrad, regpa, regeps, istepout, pixscale
'EXAMPLE/PHOT/OUT/full.out' # 8 file name for output parameters
T T T #9 Disk toggles: fit for PA, fit for eps, fit for cen
35 0.4 #10 initial guess for disk PA and eps=(1-b/a)
130 130 #11 initial guess for disk center
T T T 5.00 0.5 #12 PHOT: bar, bar PA & bar eps fit toggles, initial bar PA & eps
800.0 14.14 4.0 #13 PHOT: image params: sky, sky sig, gain
T T 10 #14 PHOT: bulge, r_e fit toggle, initial r_e
T T 2 0.2 #15 PHOT: fit for Sersic n & bulge eps, initial n & eps
2. #16 Seeing/beam smearing FWHM for correction - 0 to skip
-0.01 -0.01 #17 Model component smoothing lambda_1 + lambda_2
F -50 5 -1.0 #18 Uncertainties: toggle, seed, nunc, junc
F #19 Verbose toggle
0. 40. #20 Min, max radii for bar/noncirc flow fit
5.0 #21 ring radii
10.0
15.0
20.0
25.0
30.0
35.0
40.0
45.0
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75.0
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90.0
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Fig. 5.— Input file for disk, bar and bulge model fit to the image in Fig. 7: EXAMPLE/PHOT/phot_full.inp.
Minimization output, phot
-------------------------
Input files:
EXAMPLE/PHOT/phot_full.inp
EXAMPLE/PHOT/phot.fits pixscale 0.50 arcsec/pix
sky: 800.00 skysig: 14.14 gain: 4.00

FITS region:  x-low: 1  y-low: 1  x-range: 256  y-range: 256
FITS sampling: regrad: 10.00  regpa: 35.00  regeps: 0.40  istpout: 2

Output model and (data-model) residuals files:
EXAMPLE/PHOT/OUT/full.mod
EXAMPLE/PHOT/OUT/full.res

Disk toggles: PA: T  eps: T  center: T  non-axi: T  phib: T
phot toggles: bbulge: T  lr_e: T  lsersn: T  blg eps: T  bar eps: T

Input values
------------
disk PA, phi_d'prime (deg): 35.00
disk eps: 0.40
x,y center (data units): 130.00 130.00
Bar PA (deg): 5.00
Bar eps: 0.50
Bulge r_e (pixels): 10.00
Sersic n: 2.00
Bulge eps: 0.20

Seeing correction applied. FWHM (data units): 2.00
No model component smoothing applied
No uncertainties estimated
Non-axisymmetries fixed to 0 outside range: 5.00 40.00

Best fitting values
------------------
disk PA, phi_d'prime (deg): 39.98 +/- 0.00
disk eps: 0.29 +/- 0.00
disk incl (deg): 44.99 +/- 0.00
x,y center (data units): 129.99 +/- 0.00, 130.00 +/- 0.00
Non-axisymmm phib (sky plane, deg): 10.05 +/- 0.00, -129.15
Bar eps: 0.59 +/- 0.00
Bulge r_e (pixels): 8.36 +/- 0.00
Bulge I_0 (ADU): 364.62 +/- 0.00
Sersic n: 1.67 +/- 0.00
Bulge eps: 0.17 +/- 0.00

Disk light fraction (%): 79.92 +/- 0.00
Bar light fraction (%): 9.85 +/- 0.00
Bulge light fraction (%): 10.23 +/- 0.00
Minimization Details

# points Dn used in fit: 7495
# iterations in minimization: 8
Minimum chi^2 found: 0.963589
Degrees of freedom in fit: 7458

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Fig. 6.— Output file containing best-fitting parameters produced by DiskFit using the disk, bulge and bar model input file in Fig. 5: EXAMPLE/PHOT/OUT/full.out.
Fig. 7.— Best fitting disk, bulge and bar model (top) and data – model residuals (bottom) found by DiskFit using the input file in Fig. 5. The model colorscale is logarithmic, while that of the residuals is linear; both are shown at the bottom of the image in ADU, and are identical to the scales in Fig. 4. The corresponding FITS files are EXAMPLE/PHOT/OUT/full.mod.fits (top) and EXAMPLE/PHOT/OUT/full.res.fits (bottom).
Fig. 8.— Disk (top), bar (middle) and bulge (bottom) components of the best fitting model in Fig. 7. The colorscale in all panels is identical to that of the model in Fig. 7. The corresponding FITS files are EXAMPLE/PHOT/OUT/full.dsk.fits (top), EXAMPLE/PHOT/OUT/full.bar.fits (middle) and EXAMPLE/PHOT/OUT/full.blg.fits (bottom).
#PHOTOMETRY EXAMPLE, DISKFIT

```
phot # 2 vels/phot switch
None # 3 PHOT: file name with mask file
'EXAMPLE/PHOT/phot.fits' # 4 file name with input data
None # 5 file name for image uncerts
1 1 256 256 # 6 FITS region to fit: (xlow,ylow) & (xrange,yrange)
10.0 35.00 0.4 2 0.5 # 7 FITS sampling: regrad, regpa, regeps, istepout, pixscale
'EXAMPLE/PHOT/OUT/err.out' # 8 file name for output parameters
T T T # 9 Disk toggles: fit for PA, fit for eps, fit for cen
35 0.4 #10 initial guess for disk PA and eps=(1-b/a)
130 130 #11 initial guess for disk center
T T T 5.00 0.5 #12 PHOT: bar, bar PA & bar eps fit toggles, initial bar PA & eps
800.0 14.14 4.0 #13 PHOT: image params: sky, sky sig, gain
T T 10 #14 PHOT: bulge, r_e fit toggle, initial r_e
T T 2.0 #15 PHOT: fit for Sersic n & bulge eps, initial n & eps
2. #16 Seeing/beam smearing FWHM for correction - 0 to skip
-0.01 -0.01 #17 Model component smoothing lambda_1 + lambda_2
T -50 5 -1.0 #18 Uncertainties: toggle, seed, nunc, junc
F #19 Verbose toggle
0. 40. #20 Min, max radii for bar/noncirc flow fit
5.0 #21 ring radii
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80.0
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100.0
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Fig. 9.— Input file for disk, bar and bulge fit to the image in Fig. 7, and allowing DiskFit to estimate uncertainties on the best-fitting parameters.
Minimization output, phot
---------------------------------
Input files:
EXAMPLE/PHOT/phot_err.inp
EXAMPLE/PHOT/phot.fits pixscale 0.50 arcsec/pix
sky: 800.00 skysig: 14.14 gain: 4.00
FITS region: x-low: 1 y-low: 1 x-range: 256 y-range: 256
FITS sampling: regrad: 10.00 regpa: 35.00 regeps: 0.40 istpout: 2
Output model and (data-model) residuals files:
EXAMPLE/PHOT/OUT/full.mod.fits
EXAMPLE/PHOT/OUT/full.res.fits
Disk toggles: PA: T eps: T center: T non-axi: T phib: T
phot toggles: 1bulge: T 1r_e: T 1sersn: T blg eps: T bar eps: T
Input values
-------------
disk PA, phi_d'prime (deg): 35.00
disk eps: 0.40
x,y center (data units): 130.00 130.00
Bar PA (deg): 5.00
Bar eps: 0.50
Bulge r_e (pixels): 10.00
Sersic n: 2.00
Bulge eps: 0.20

Seeing correction applied. FWHM (data units): 2.00
No model component smoothing applied
Uncertainties estimated via bootstrap: seed: -50 nunc: 5 junc: -1.00
Non-axisymmetries fixed to 0 outside range: 5.00 40.00

Best fitting values
-------------------
disk PA, phi_d'prime (deg): 39.98 +/- 0.56
disk eps: 0.29 +/- 0.00
disk incl (deg): 44.99 +/- 0.39
x,y center (data units): 129.99 +/- 0.00, 130.00 +/- 0.01
Non-axisym phib (sky plane, deg): 10.05 +/- 0.28, -129.15
Bar eps: 0.59 +/- 0.00
Bulge r_e (pixels): 8.36 +/- 1.42
Bulge l_0 (ADU): 364.62 +/- 25.61
Sersic n: 1.67 +/- 0.05
Bulge eps: 0.17 +/- 0.02
Disk light fraction (%): 79.92 +/- 2.81
Bar light fraction (%): 9.85 +/- 0.40
Bulge light fraction (%): 10.23 +/- 2.74
Minimization Details

# points Dm used in fit: 7495
# iterations in minimization: 8
Minimum chi^2 found: 0.963589
Degrees of freedom in fit: 7458

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Fig. 10.— Output file containing best-fitting parameters produced by DiskFit using the input file in Fig. 9. Note that the best-fitting values are the same as in Fig. 6.
Fig. 11.— Velocity field, in FITS format, to be modelled by DiskFit in Example 2 (see §5.2). The colorscale at the bottom of the image is in m s$^{-1}$. This artificial model is centered on the point $(x_c, y_c) = (128.5, 128.5)$ and has a systemic velocity of $V_{\text{sys}} = 100$ km s$^{-1}$. The disk is inclined at $60^\circ$, the position angle of the major axis is $40^\circ$, and it contains a weak bar at the angle $\phi_b = 20^\circ$ to the major axis. The FITS file contains the velocities in m s$^{-1}$ in a map of $256^2$ pixels that are spaced $1''$ apart, and the non-axisymmetric velocities associated with the bar drop below 1 km s$^{-1}$ at $R \simeq 100''$. Gaussian random deviates have been added to the velocity field points to mimick a mean measurement error $\{\Delta_D\} = 2$ km s$^{-1}$ and ISM turbulence $\Delta_{\text{ISM}} = 2$ km s$^{-1}$.
KINEMATICS EXAMPLE, DISKFIT
# beamsize = 6.00'' # pixscale-> 1.00''/pix # ringstep = 3.0pix
vels # 2 vels/phot switch
T T # 3 VELS: I/O toggles: FITS I/O, vels in m/s
'EXAMPLE/VELS/FITS/vels.fits' # 4 file name with input data
None # 5 VELS + FITS: file name for velocity uncerts
1 1 255 255 # 6 FITS region to fit: (xlow,ylow) & (xrange,yrange)
12.0 45.00 0.45 6 1.0 # 7 FITS sampling: regrad, regpa, regeps, istepout, pixscale
'EXAMPLE/VELS/FITS/OUT/disk.out' # 8 file name for output parameters
T T T # 9 Disk toggles: fit for PA, eps & cen
45.00 0.45 #10 initial guess for disk PA and eps=(1-b/a)
130.50 126.50 #11 initial guess for disk center
F T 45.00 2 #12 VELS: non-circ. flow + flow PA fit toggle, initial flow PA, order m
T F #13 VELS: inner interpolation + radial flows fit toggles
T T T 90 0 0 #14 VELS: toggle to fit Vsys, initial guess Vsys, delta_ISM, & vely errtol
0. #15 VELS: warp toggles - warp, fit radius, ellip & pa, initial rw, welm & wphim
-0.01 -0.01 #16 Seeing/beam smearing: If non-zero, seeing/beam FWHM for correction.
F -50 5 -1.0 #17 Model component smoothing lambda_1 & lambda_2
F #18 Uncertainties: toggle, seed, nunc, junc
3.0 110.00 #19 Verbese toggle
3.0 #20 Min, max radii for bar/noncirc flow fit
9.0
15.0
21.0
27.0
33.0
39.0
45.0
51.0
57.0
63.0
69.0
75.0
81.0
87.0
93.0
99.0
105.0
111.0
117.0
123.0
129.0
135.0
141.0
147.0

Fig. 12.— Input file for disk-only fit to the velocity field in Fig. 11: EXAMPLE/VELS/FITS/velsf_disk.inp.
Minimization output, vels

Input files:
EXAMPLE/VELS/FITS/velsf_disk.inp
EXAMPLE/VELS/FITS/vels.fits

FITS region: x-low: 1 y-low: 1 x-range: 255 y-range: 255
FITS sampling: regrad: 12.00 regpa: 45.00 regeps: 0.45 istpout: 6

Output model and (data-model) residuals files:
EXAMPLE/VELS/FITS/OUT/disk.mod.fits
EXAMPLE/VELS/FITS/OUT/disk.res.fits

Disk toggles: PA: T eps: T center: T non-axi: F phib: F

Input values

---
disk PA, phi_d^prime (deg): 45.00
disk eps: 0.45
x,y center (data units): 130.50 126.50
Vsys (km/s): 110.00
Delta_ISM (km/s): 1.00

---
No seeing correction applied
No model component smoothing applied
No uncertainties estimated

Best fitting values

---
disk PA, phi_d^prime (deg): 38.13 +/- 0.00
disk eps: 0.50 +/- 0.00
disk incl (deg): 60.11 +/- 0.00
x,y center (data units): 128.23 +/- 0.00, 128.36 +/- 0.00
Vsys (km/s): 100.07 +/- 0.00
Minimization Details

# points Dm used in fit: 1224
# iterations in minimization: 5
Minimum chi^2 found: 46.151924
Degrees of freedom in fit: 1194

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Fig. 13.— Output file containing best-fitting rotation-only model parameters produced by DiskFit using the input file in Fig. 12: EXAMPLE/VELS/FITS/OUT/disk.out.
Fig. 14.— Best fitting rotation-only model (top) and data–model residuals (bottom) found by DiskFit using the input file in Fig. 12. The colorscale at the bottom of each panel is in m s$^{-1}$. The corresponding FITS files are EXAMPLE/VELS/FITS/OUT/disk.mod.fits (top) and EXAMPLE/VELS/FITS/OUT/disk.res.fits (bottom).
Fig. 15.— Input file for bar-like flow fit to the velocity field in Fig. 11: EXAMPLE/VELS/FITS/velsf_bi.inp.
Minimization output, vels

Input files:
EXAMPLE/VELS/FITS/velsf_bi.inp
EXAMPLE/VELS/FITS/vels.fits

FITS region: x-low: 1 y-low: 1 x-range: 255 y-range: 255
FITS sampling: regrad: 12.00 regps: 45.00 regeps: 0.45 istpout: 6

Output model and (data-model) residuals files:
EXAMPLE/VELS/FITS/OUT/bi.mod.fits
EXAMPLE/VELS/FITS/OUT/bi.res.fits

Disk toggles: PA: T eps: T center: T non-axi: T phib: T

Input values

disk PA, phi_d'prime (deg): 45.00
disk eps: 0.45
x,y center (data units): 130.50 126.50
Non-axisymm phib (deg): 45.00
Harmonic order m: 2
Vsys (km/s): 110.00
Delta_ISM (km/s): 1.00

No seeing correction applied
No model component smoothing applied
No uncertainties estimated
Non-axisymmetries fixed to 0 outside range: 3.00 111.00

Best fitting values

disk PA, phi_d'prime (deg): 40.06 +/- 0.00
disk eps: 0.50 +/- 0.00
disk incl (deg): 60.17 +/- 0.00
x,y center (data units): 128.57 +/- 0.00, 128.58 +/- 0.00
Non-axisymm phib (disk plane, deg): 108.45 +/- 0.00, -16.09, 49.48
Vsys (km/s): 100.01 +/- 0.00
Minimization Details

# points Dn used in fit: 1224
# iterations in minimization: 5
Minimum chi^2 found: 8.196828
Degrees of freedom in fit: 1155

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Fig. 16.— Output file containing best-fitting parameters of the bar-like flow model produced by DiskFit using the input file in Fig. 15: EXAMPLE/VELS/FITS/OUT/bi.out.
Fig. 17.— Best fitting bar-like flow model (top) and data–model residuals (bottom) found by DiskFit using the input file in Fig. 15. The colorscale at the bottom of each panel is in m s$^{-1}$, and matches that in Fig. 14. The corresponding FITS files are EXAMPLE/VELS/FITS/OUT/bi.mod.fits (top) and EXAMPLE/VELS/FITS/OUT/bi.res.fits (bottom).
Fig. 18.— Input file for bar-like flow model fit to the image in Fig. 11, and allowing DiskFit to estimate uncertainties on the best-fitting parameters: EXAMPLE/VELS/FITS/vels_err.inp.
Minimization output, vels
------------------------

Input files:
EXAMPLE/VELS/FITS/velsf_err.inp
EXAMPLE/VELS/FITS/vels.fits pixscale 1.00 arcsec/pix

FITS region: x-low: 1 y-low: 1 x-range: 255 y-range: 255
FITS sampling: regrad: 12.00 regpa: 45.00 regeps: 0.45 istpout: 6

Output model and (data-model) residuals files:
EXAMPLE/VELS/FITS/OUT/bi.mod.fits
EXAMPLE/VELS/FITS/OUT/bi.res.fits

Disk toggles: PA: T eps: T center: T non-axi: T phib: T

Input values
-------------
disk PA, phi_d'prime (deg): 45.00
disk eps: 0.45
x,y center (data units): 130.50 126.50
Non-axisymm phib (deg): 45.00
Harmonic order m: 2
Vsys (km/s): 110.00
Delta_ISM (km/s): 2.80

No seeing correction applied
No model component smoothing applied
Uncertainties estimated via bootstrap: seed: -50 nunc: 5 junk: -1.00
Non-axisymmetries fixed to 0 outside range: 3.00 111.00

Best fitting values
-------------------
disk PA, phi_d'prime (deg): 40.06 +/- 0.05
disk eps: 0.50 +/- 0.00
disk incl (deg): 60.18 +/- 0.03
x,y center (data units): 128.57 +/- 0.05, 128.58 +/- 0.01
Non-axisymm phib (disk plane, deg): 108.42 +/- 3.02, -16.14, 49.46
Vsys (km/s): 100.01 +/- 0.00
Minimization Details

---------------------

# points Dn used in fit: 1224
# iterations in minimization: 5
Minimum chi^2 found: 1.045514
Degrees of freedom in fit: 1155

Fitted velocity components (radii in data units, velocities in km/s):

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Fig. 19.— Output file containing best-fitting parameters produced by DiskFit using the input file in Fig. 18: EXAMPLE/VELS/FITS/OUT/err.out.
Fig. 20.— Best fitting bar-like flow model (top) and data–model residuals (bottom) found by DiskFit using the input file in Fig. 18. The colorscale at the bottom of each panel is in m s$^{-1}$, and matches that in Fig. 14. The corresponding FITS files are EXAMPLE/VELS/FITS/OUT/err.mod.fits (top) and EXAMPLE/VELS/FITS/OUT/err.res.fits (bottom).
KINEMATICS EXAMPLE, DISKFIT

# beamsize = 6.00'' # pixscale-> 1.00''/pix # ringstep = 3.0pix
vels

T T

EXEMPLE/VELS/FITS/vels.fits'

None

I I 255 255

12.0 45.00 0.45 6 1.0

EXEMPLE/VELS/FITS/OUT/rad.out'

T T

45.00 0.45

130.50 126.50

F T 45.00 2

T T 110.0 1.0 25.0

F T T T 90 0 0

0.

-0.01 -0.01

F -50 5 -1.0

F 3.00 110.00

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15.0

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111.0

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129.0

135.0

141.0

147.0

Fig. 21.— Input file for radial flow model fit to the image in Fig. 11: EXAM-
PLE/VELS/FITS/velsf_rad.inp.
Minimization output, vels
-------------------------
Input files:
EXAMPLE/VELS/FITS/velsf_rad.inp
EXAMPLE/VELS/FITS/vels.fits pixscale 1.00 arcsec/pix

FITS region: x-low: 1 y-low: 1 x-range: 255 y-range: 255
FITS sampling: regrad: 12.00 regpa: 45.00 regeps: 0.45 istpout: 6

Output model and (data-model) residuals files:
EXAMPLE/VELS/FITS/OUT/rad.mod.fits
EXAMPLE/VELS/FITS/OUT/rad.res.fits

Disk toggles: PA: T eps: T center: T non-axi: F phib: F

Input values
-------------
disk PA, phi_d prime (deg): 45.00
disk eps: 0.45
x,y center (data units): 130.50 126.50

Vsys (km/s): 110.00
Delta_ISM (km/s): 1.00

No seeing correction applied
No model component smoothing applied
No uncertainties estimated
Non-axisymmetries fixed to 0 outside range: 3.00 111.00

Best fitting values
---------------------
disk PA, phi_d prime (deg): 40.00 +/- 0.00
disk eps: 0.50 +/- 0.00
disk incl (deg): 60.03 +/- 0.00
x,y center (data units): 128.50 +/- 0.00, 128.55 +/- 0.00
Vsys (km/s): 100.04 +/- 0.00
Minimization Details

# points Dn used in fit: 1224
# iterations in minimization: 5
Minimum chi^2 found: 8.851554
Degrees of freedom in fit: 1175

Fitted velocity components

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Fig. 22.— Output file containing best-fitting parameters of a radial flow model produced by DiskFit using the input file in Fig. 21: EXAMPLE/VELS/FITS/OUT/rad.out.
Fig. 23.— Best fitting radial flow model (top) and data–model residuals (bottom) found by DiskFit using the input file in Fig. 21. The colorscale at the bottom of each panel is in m s\(^{-1}\), and matches that in Fig. 14. The corresponding FITS files are EXAMPLE/VELS/FITS/OUT/rad.mod.fits (top) and EXAMPLE/VELS/FITS/OUT/rad.res.fits (bottom).
Fig. 24.— Input file for warp model fit to the image in Fig. 11: EXAMPLE/VELS/FITS/vels_warp.inp.
Minimization output, vels

Input files:
EXAMPLE/VELS/FITS/velsf_warp.inp
EXAMPLE/VELS/FITS/vels.fits   pixscale 1.00 arcsec/pix

FITS region:   x-low:  1   y-low:  1   x-range:  255   y-range:  255
FITS sampling:   regrad:  12.00   regpa:  45.00   regeps:  0.45   istpout:  6

Output model and (data-model) residuals files:
EXAMPLE/VELS/FITS/OUT/warp.mod.fits
EXAMPLE/VELS/FITS/OUT/warp.res.fits

vels toggles:   interp0:  T   radial:  F   Vsys:  T   warp:  T   r_w:  T   welm:  T   wphim:  T

Input values

---
disk PA, phi_d'prime (deg):  45.00
disk eps:  0.45
x,y center (data units):  130.50 126.50

Vsys (km/s):  110.00
Delta_ISM (km/s):  1.00

r_w (data units):  90.00
Warp eps welm:  0.00
Warp PA wphim:  0.00

No seeing correction applied
No model component smoothing applied
Uncertainties estimated via bootstrap:   seed:  -50   nunc:  10   junc:  -1.00

Best fitting values

---
disk PA, phi_d'prime (deg):  32.93 +/- 2.21
disk eps:  0.52 +/- 0.02
disk incl (deg):  61.37 +/- 1.52
x,y center (data units):  128.50 +/- 0.06, 128.54 +/- 0.16

Vsys (km/s):  100.01 +/- 0.23
r_w (data units):  9.00 +/- 26.42
Warp eps welm:  -2.37 +/- 1.48
Warp PA wphim:  10.28 +/- 4.07
Minimization Details

# points Dn used in fit: 1224
# iterations in minimization: 11
Minimum chi^2 found: 25.192924
Degrees of freedom in fit: 1191

Fitted velocity components (radii in data units, velocities in km/s):

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Fig. 25.— Output file containing best-fitting parameters for the warp model produced by DiskFit using the input file in Fig. 24: EXAMPLE/VELS/FITS/OUT/warp.out.
Fig. 26.— Best fitting warp model (top) and data – model residuals (bottom) found by DiskFit using the input file in Fig. 21. The colorscale at the bottom of each panel is in m s$^{-1}$, and matches that in Fig. 14. The corresponding FITS files are EXAMPLE/VELS/FITS/OUT/warp.mod.fits (top) and EXAMPLE/VELS/FITS/OUT/warp.res.fits (bottom).
SAMPLE VELOCITY FIELD, TEXT FORMAT

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<th>EVEL</th>
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<td>km/s</td>
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Fig. 27.— Sample velocity field in text format: EXAMPLE/VELS/TEXT/vels.txt.
Fig. 28.— The sample velocity field in EXAMPLE/VELS/TEXT/vels.txt. The top panel shows the velocity components used to generate the velocity field. $\bar{V}_t$ is given by the black line, and corresponds to a power-law $\bar{V}_t = 80[r/27.8]^{0.35}$ km s$^{-1}$. $V_{2,t}$ and $V_{2,r}$ are given by the red and blue lines, respectively, and are described by $V_{2,t} = 25 \sin(r/10)$ km s$^{-1}$ for $r/10 \leq \pi$, and $V_{2,r} = 0.85V_{2,t}$. The bar axis is $\phi_b = 40$ deg. The bottom panel shows the velocity field obtained by projecting the disk at $\phi_b' = 85$ deg with an inclination of 55 deg about $(x_c, y_c) = (2.0, 0.0)$ and $V_{sys} = 490$ km s$^{-1}$. Gaussian random deviates have been added to the velocity field points to mimick a mean measurement error $\{\Delta_D\} = 2$ km s$^{-1}$ and ISM turbulence $\Delta_{ISM} = 2$ km s$^{-1}$. 
KINEMATICS EXAMPLE, TEXT FILE

vels # 2 vels/phot switch
F F # 3 VELS: I/O toggles: FITS I/O, vels in m/s
'EXAMPLE/VELS/TEXT/vels.txt' # 4 file name with input data
None # 5 VELS + FITS: file name for velocity uncerts
None # 6 FITS region to fit: (xlow,ylow) & (xrange,yrange)
None # 7 FITS sampling: regrad, regpa, regeps, istepout, pixscale
'EXAMPLE/VELS/TEXT/OUT/err.out' # 8 file name for output parameters
T T T # 9 Disk toggles: fit for PA, eps & cen
80.00 0.5 #10 initial guess for disk PA and eps=(1-b/a)
0.0 0.0 #11 initial guess for disk center
T T 45.00 2 #12 VELS: non-circ. flow + flow PA fit toggle, initial flow PA, order m
T F #13 VELS: inner interpolation + radial flows fit toggles
T 500.00 2.0 25.0 #14 VELS: toggle to fit Vsys, initial guess Vsys, delta_ISM, & vely errtol
F T T 90 0 0 #15 VELS: warp toggles - warp, fit radius, ellip & pa, initial rw, welm & wphim
0 #16 Seeing/beam smearing: If non-zero, seeing/beam FWHM for correction.
-0.01 -0.01 #17 Model component smoothing lambda_1 & lambda_2
T -50 5 1.0 #18 Uncertainties: toggle, seed, nunc, junc
F #19 Verbose toggle
0.0 50.00 #20 Min, max radii for bar/noncirc flow fit
2.5 #21 Ring radii
5.0
7.5
10.0
12.5
15.0
17.5
20.0
22.5
25.0
27.5
30.0
32.5
35.0
37.5
40.0
42.5
45.0
47.5
50.0

Fig. 29.— Input file for bar-like flow fit to the velocity field in Fig. 27: EXAMPLE/VELS/TEXT/velst_err.inp.
Minimization output, vels

Input files:
EXAMPLE/VELS/TEXT/velst_err.inp
EXAMPLE/VELS/TEXT/vels.txt

Output model and (data-model) residuals files:
EXAMPLE/VELS/TEXT/OUT/err.mod

Disk toggles: PA: T eps: T center: T non-axi: T phib: T

Input values

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<th>Parameter</th>
<th>Value</th>
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<tr>
<td>disk eps</td>
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<tr>
<td>x,y center (data units)</td>
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<tr>
<td>Non-axisymm phib (deg)</td>
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<td>Delta_ISM (km/s)</td>
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No seeing correction applied
No model component smoothing applied
Uncertainties estimated via bootstrap: seed: -50 nunc: 5 junc: 1.00

Best fitting values

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<td>disk eps</td>
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<td>disk incl (deg)</td>
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<td>x,y center (data units)</td>
<td>2.16 +/- 0.03, 0.02 +/- 0.04</td>
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<td>Non-axisymm phib (disk plane, deg)</td>
<td>31.24 +/- 6.22, 104.15, 41.73</td>
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<td>Vsys (km/s)</td>
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Minimization Details

# points Dm used in fit: 1124
# iterations in minimization: 5
Minimum chi^2 found: 1.001667
Degrees of freedom in fit: 1058

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Fig. 30. — Output file containing best-fitting parameters produced by DiskFit using the input file in Fig. 29: EXAMPLE/VELS/TEXT/OUT/err.out.
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Fig. 31.— Output model file from the DiskFit run produced by the input file in Fig. 29.