Asteroseismic Stellar Modelling with AIMS

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Abstract The goal of AIMS (Asteroseismic Inference on a Massive Scale) is to estimate stellar parameters and credible intervals/error bars in a Bayesian manner from a set of asteroseismic frequency data and so-called classical constraints. To achieve reliable parameter estimates and computational efficiency, it searches through a grid of pre-computed models using an MCMC algorithm — interpolation within the grid of models is performed by first tessellating the grid using a Delaunay triangulation and then doing a linear barycentric interpolation on matching simplexes. Inputs for the modelling consist of individual frequencies from peak-bagging, which can be complemented with classical spectroscopic constraints. AIMS is mostly written in Python with a modular structure to facilitate contributions from the community. Only a few computationally intensive parts have been rewritten in Fortran in order to speed up calculations.

1 Introduction

The AIMS (Asteroseismic Inference on a Massive Scale) software was developed by D. R. Reese as one of the deliverables for the SPACEINN network, a European project specialised in helio- and asteroseismology. The goal of this software is to estimate stellar parameters and reliable error bars for a given set of asteroseismic and classical constraints. The present tutorial explains how to use this software through various simple examples. Specifically, it explains how to find stellar parameters and error bars for a given set of constraints, generate a binary grid file usable by AIMS, and test the accuracy of the interpolation for a given grid. The necessary files and data to run the examples in this tutorial are available at the following website: http://bison.ph.bham.ac.uk/spaceinn/aims/tutorial/.
2 Getting started

2.1 Prerequisites and downloads for the tutorial

The following will be needed to run the examples in this tutorial:

- **Python modules.** The following Python modules and utilities are needed by AIMS: emcee, corner, dill, Scipy, Numpy, f2py, Matplotlib. The last four are included in most distributions.

- **A grid of models.** AIMS works by comparing observational data to a grid of pre-computed models. The tutorial website provides two binary grids (data_mesa and data_cestam), which will be used for finding model fits to a set of observed stars, as well as a folder containing a non-binary subset of one of the grids, which we shall use when trying to generate a binary grid. When “unpacked” by AIMS, some of the grids take up a lot of live memory. Accordingly, a “light” version of the CESTAM grid, data_cestam_reduced, has been provided.

- **File(s) with observational data.** The tutorial website provides files with observational data for three stars (Stars 1–3). The mode frequencies were obtained from peak-bagging of Kepler data for the so-called LEGACY project (Lund et al. 2017). Spectroscopic data were obtained from the Stellar Parameters Classification tool (SPC; Buchhave et al. 2012).

2.2 Downloading and installing AIMS

The latest version of the AIMS package, currently version 1.2, can be downloaded from the following site: http://bison.ph.bham.ac.uk/spaceinn/aims/version1.2/index.html. This file is unpacked as follows:

```
tar -zxvf AIMS.tgz
```

The AIMS program itself is contained within the AIMS folder.

As mentioned earlier, the latest version of AIMS contains some Fortran subroutines which need to be compiled before running AIMS. This is done via the f2py program. A Makefile has been provided for convenience. Please edit the Makefile by inserting the appropriate Fortran compiler and compilation options. Then run the following command:

```
maint
```

This will produce a file called aims.fortran.so which can be used by AIMS.

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1 In some cases, this problem can further be compounded by the use of parallelisation, which is activated by setting parallel=True in AIMS_configure.py.
3 Running AIMS: model fit

We shall first consider running AIMS with the goal of optimising the fit to a given set of observational constraints, such as mode frequencies, ratios, and spectroscopic parameters. In Sect. 5 we will look into testing the interpolation scheme in AIMS. Figure 1.1 of the overview document\(^2\) provides a simple schematic flowchart with the basic working components of AIMS.

3.1 Setting up the configuration file

Before running the AIMS program, a binary file with the grid must first be created — we will come to this in Sect. 4. Assuming in the mean time that has been done, the most important concern is to set up the configuration file: AIMS\_configure.py.

Most parameters in the configuration file are well documented and should be self-explanatory — for instance, you can choose which asteroseismic parameters to fit\(^3\) (individual frequencies, ratios, or average asteroseismic parameters), the name of the binary grid to use, which parameters should be output from the optimisation, control parameters for the MCMC, which grid parameters to use in the optimisation and which priors to set on these etc.

Two parameters are of special relevance:

- **write\_data** should be set to False (see Sect. 4 for when this should be True).
- **test\_interpolation** should be set to False (see Sect. 5 for when this should be True).

It is also very important to put the correct values for the grid\_params and user\_params parameters. These values will depend on the binary grid being used. They are provided on the tutorial website and can also be obtained with the analyse\_grid.py utility\(^4\), which should be run in the AIMS folder.

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\(^2\) [http://bison.ph.bham.ac.uk/spaceinn/aims/version1.2/_downloads/Overview.pdf](http://bison.ph.bham.ac.uk/spaceinn/aims/version1.2/_downloads/Overview.pdf)

\(^3\) The user should be careful not to choose a set of asteroseismic parameters which are redundant, as this would lead to a singular covariance matrix and poor numerical results.

\(^4\) [http://bison.ph.bham.ac.uk/spaceinn/aims/tutorial/download/analyse_grid.py](http://bison.ph.bham.ac.uk/spaceinn/aims/tutorial/download/analyse_grid.py)
3.2 Observational constraints

The file with observational constraints follows a very similar format to the one used with the Asteroseismic Modeling Portal\(^5\) (AMP), apart from a few minor differences\(^6\). This format is described as follows:

- Characters following a “#” are ignored, and the ordering of the lines is unimportant.
- A set of lines, one per individual mode, describe the asteroseismic observables. If the keyword \texttt{read\_n} is set to \texttt{True}, then four columns should be given, namely, the degree of the mode \((l)\), the radial order \((n)\), the frequency in cyclic \(\mu\)Hz \((f)\), and its associated error bar \((\delta f)\). If \texttt{read\_n} is \texttt{False}, then only \(l\), \(f\), and \(\delta f\) should be given. Note that in AIMS, even if you choose to work with frequency combinations such as ratios, the asteroseismic inputs are still individual frequencies — AIMS will use these to calculate the frequency combinations, associated error bars, and correlations.
- Optionally, non-asteroseismic constraints may be included in addition to the asteroseismic observables. The first column must consist of a character or a keyword, e.g., “T or Teff” \((T_{\text{eff}})\), “L or Luminosity” \((L/L_\odot)\), “R or Radius” \((R/R_\odot)\), “M, Fe\_H or M\_H” \([M/H]\), “g or \log g” \((\log g)\), or “Rho” \((\rho)\). This is followed by a central value and an error.
- If a non-asteroseismic constraint is included, e.g., “Teff 5777 50”, then it is assumed that this parameter follows a Gaussian distribution. Alternatively, you may explicitly define the distribution to be used, e.g., “Teff Uniform 5727 5837” meaning a uniform distribution from 5727 to 5837 K. You can adopt either a “Uniform”, “Gaussian” (the default), or “Truncated\_gaussian” probability distribution.
- The average asteroseismic parameters \(\nu_{\text{max}}\) (“numax”) and \(\Delta \nu\) (“Dnu”) can also be supplied here as a constraint\(^7\).

The following gives an example of how the constraints file may look like:

```
0 1847.63576435 0.76075810437
1 1904.67149676 0.827874359443
2 1954.85689326 0.751669075869
3 1968.18957034 0.212209047899
...  
T 6120 80
Fe\_H -0.06 0.12
numax 2763 100
```

\(^5\) See https://amp.phys.au.dk/guide/fileformat.
\(^6\) See http://bison.ph.bham.ac.uk/spaceinn/aims/version1.2/formats.html#format-of-a-file-with-observational-constraints.
\(^7\) We note that this is not the preferred way of supplying \(\Delta \nu\), as it does not correctly take into account correlations with other asteroseismic constraints. A better approach is to introduce the large separation via the \texttt{seismic\_constraints} variable in \texttt{AIMS\_configure.py}. 
3.3 Running AIMS

Once the grid and configuration file are set up, one simply runs the program as follows:

```
./AIMS.py observational_constraints_file
```

AIMS will then import the Python configuration file, AIMS_configure.py, so make sure you do not modify the name of this file. Output generated from AIMS will then be saved to a run folder with the same name as your constraints file, so give your constraints file a sensible name so that you can distinguish the results from several runs for the same star. The variable output_dir in AIMS_configure.py specifies the path to the root folder which contains all of the run folders.

3.4 Understanding the results

The results from AIMS are obtained from the posterior distributions of the MCMC run on the model grid, as illustrated in the right panel of Fig. 1. In AIMS_configure.py, you can define the set of stellar parameters for which you want an output, as well as which plots to create. For computational reasons, such parameters are only calculated for a subset of the MCMC samples, except for those parameters actively used in the MCMC optimisation. Accordingly, AIMS produces two files with the samples: `samples.txt` with all of the MCMC samples but only the parameters involved in the optimisation, and `samples_big.txt` with a subset of the samples but all of the stellar parameters. The corresponding files `results.txt` and `results_big.txt` provide summary statistics for the above samples, namely, the distribution averages and standard deviations, along with correlations between different model parameters. The samples files may, of course, be used to extract different summary statistics (e.g., median or mode) for the parameters. The file `best_MCMC_model.txt` gives the stellar parameters and computed mode frequencies for the best model from the MCMC, whereas `best_grid_model.txt` gives the best model from the initial grid search used to initialise the MCMC (i.e., prior to interpolation within the grid). The left panel of Fig. 1 shows the échelle diagram produced from the observations and from the best MCMC model.

4 Creating your own binary grid files with AIMS

To compute a binary grid file, you first need to calculate a grid of models with your favourite stellar evolution code, as well as oscillation modes for each model. Information for each model should then be entered into a “model list” file. The first line of this file should contain a prefix which is typically the root folder of the grid of models and, optionally, a postfix giving the end part of the filenames with
Fig. 1 Example of output plots from an AIMS run. Left: Échelle diagram for the best MCMC model showing the observed frequencies, theoretical frequencies, and surface-corrected theoretical frequencies. Right: Triangle plot with correlation maps between different stellar parameters for the MCMC samples. The blue lines indicate the results obtained from the initial full-grid search.

Table 1 Columns in “model list” file

| Column # | 1 | 2 | 3 | 4 | 5 | 6 | 7 | 8 | 9, 10… |
|----------|---|---|---|---|---|---|---|---|--------|
| Parameter| Model name | Mass | Rad. | Lum. | Z₀ | X₀ | Age | Tₑff | user_params |
| Unit     | … | g | cm | g cm⁻² | … | … | … | Myr | K | … |

The mode frequencies, the default value being “.freq”. The following lines then contain multiple columns with the information for each model in the grid. Below we show an example of a model list file (see column description in Table 1):

/home/dreese/models_inversions/Grid_6819/ml1.6.ovh0.0.ovhe0.00.z0.01756.y0.26/
ml1.6.z0.01756.y0.26_n2026.FGONG 3.18272E+33 9.411631E+11
  2.689504E+35 0.01756 0.72244 2.402848E+03 4543.38696
ml1.6.z0.01756.y0.26_n2093.FGONG 3.18272E+33 9.645173E+11
  2.811105E+35 0.01756 0.72244 2.402920E+03 4537.93601
ml1.6.z0.01756.y0.26_n1986.FGONG 3.18272E+33 9.010663E+11
  3.745062E+35 0.01756 0.72244 2.402825E+03 4565.49605
ml1.6.z0.01756.y0.26_n1575.FGONG 3.18272E+33 1.166064E+12

The prefix plus each model name in the first column, plus the postfix gives the name of a file that contains the oscillation parameters of the model. These files can come in one of two formats, as specified by the mode_format variable in AIMS_configure.py. One of the formats is a Fortran binary format known
as the “grand summary” file from the ADIPLS code (Christensen-Dalsgaard 2008) and is described on pages 32–33 of the ADIPLS documentation. The other format is a text format (described below) and which is what is used in this tutorial.

The text version of the oscillation parameter files begins with a one-line header followed by five columns which correspond to \( l \), \( n \), frequency, \( \text{dfreq\_var} \), and mode inertia. Note that the \( \text{dfreq\_var} \) column is currently discarded, as are frequencies above the estimated cut-off frequency times the value of the \( \text{cutoff} \) variable in AIMS\_configure.py.

To generate a binary grid you should specify to following relevant parameters in AIMS\_configure.py:

- `write\_data` should be set to `True`.
- `list\_grid` gives the filename of the model list file (see above).
- `binary\_grid` gives the filename of the binary file that will be generated. If `write\_data` is set to `False`, this is the binary grid that will be loaded.
- `grid\_params` specifies the parameters relevant to the grid you want to generate (excluding age, which will be dealt with separately). It is extremely important that each set of values for these parameters corresponds to a unique evolutionary track, since AIMS reconstructs these tracks based on these values. For instance, if mass and \( Z \) are the parameters which describe your grid, then pairs of values such as \((\text{mass} = 1 \, \text{M}_\odot, \, Z = 0.02)\) should correspond to a unique track.
- `user\_params` specifies supplementary parameters which describe your grid. This variable should contain a pair of strings for each supplementary parameter. The first string should give the parameter’s name. The second string should be a nice \LaTeX\ version of the name to be used in plot titles.
- `npositive` should be set to `True` if you only want to save \( n \geq 0 \) modes (i.e., acoustic modes) in the binary file.
- `cutoff`: frequencies above this value times the estimated cut-off frequency (as based on a scaling law) will be discarded. For example, if `cutoff=1.1` then only frequencies below \( 1.1 \nu_c \) are kept.
- `agsm\_cutoff`: this only applies to binary “grand summary” files from ADIPLS. If set to `True`, then only frequencies for which \( i\text{case}=10010 \) (i.e., which are below the cut-off frequency when using an isothermal boundary condition) are kept.

The binary file is then simply generated by running:

```
./AIMS\_py
```

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8 http://astro.phys.au.dk/~jcd/adipack.n/
9 http://astro.phys.au.dk/~jcd/adipack.n/notes/adiab\_prog.ps.gz
10 The names “\( X_s \)” and “\( Z_s \)” should be used for the surface hydrogen and metallicity content, as some of the functions in AIMS specifically look for these variables.
5 Testing interpolation accuracy

5.1 Calculating interpolation errors

Since AIMS works by interpolating in a pre-computed grid of stellar models, it also includes a way of testing the accuracy of the interpolation. To test the interpolation you should specify to following options in AIMS_config.py:

- `write_data` should be set to `False`.
- `test_interpolation` should be set to `True`.
- `interpolation_file` gives the name of the binary file that will contain the output of the test. The results saved in this file can then be plotted using `plot_interpolation_test.py`.

The interpolation test is then simply run as:

```
./AIMS.py
```

5.2 Various interpolation errors

There are two basic components to model interpolation in AIMS, each of which contributes to interpolation error:

- **Age interpolation**: this is interpolation along a given evolutionary track.
- **Track interpolation**: this is interpolation as a function of the other model parameters, such as mass, metallicity, mixing length parameter, or whatever parameters are relevant to your grid.

The first type of interpolation is dealt with through a simple linear interpolation between two adjacent models on the evolutionary track. The second uses Delaunay...
tessellation before calculating linear barycentric weights. For a more detailed description of interpolation in AIMS, we refer the reader to chapter 4 of the overview document.

The interpolation tests carried out in AIMS allow the user to estimate the error from both types of interpolation. For the age interpolation, we number the models on a given evolutionary track, starting at \( n = 0 \). As schematically illustrated in Fig. 2, the age interpolation tests involve combining models \( n - n_{\text{incr}} \) and \( n + n_{\text{incr}} \), and seeing how well the interpolated frequencies reproduce the frequencies of model \( n \). This test is carried out throughout the entire track except for the \( n_{\text{incr}} \) models at either end. Figure 2 schematically illustrates these interpolation tests for \( n_{\text{incr}} = 2 \). AIMS carries out tests for \( n_{\text{incr}} = 1 \) and 2 in order to assess the impact of the time step on the age interpolation.

Testing track interpolation (see Figs. 3 and 4) is more complicated because it is based on a Delaunay tessellation. The approach used in AIMS involves randomly selecting half of the evolutionary tracks, creating a new tessellation from these, and using this to interpolate to the remaining tracks. Figure 4 illustrates such a partitioning of the evolutionary tracks.

When comparing frequencies from an interpolated model with those from the original model, AIMS calculates different types of error bars. First of all, separate error bars are obtained for radial (\( l = 0 \)) and for non-radial modes. These are further subdivided into the following categories:

- the maximum error;
- a root-mean square (RMS) error;
- an RMS error only based on the modes between \( 0.8 \nu_{\text{max}} \) and \( 1.2 \nu_{\text{max}} \), where \( \nu_{\text{max}} \) is the frequency at maximum power (this is obtained from the models via a scaling relation).

### 5.3 Analysing the results

The results in the generated interpolation file can be visualised with plot_interpolation_test.py by running:

```
plot_interpolation_test.py interpolation_file
```

Currently, this program only works for 3D model grids (including the age dimension).

Running this program will generate a series of plots that can be used to assess the errors introduced by the interpolation. The first 9 plots are 3D plots which show various errors as a function of the grid parameters, excluding age. These plots come in groups of three: the first two plots in a group show age interpolation errors for \( n_{\text{incr}} = 1 \) and 2, and the third shows track interpolation errors. The groups of plots correspond to the following:
Fig. 3 Average track interpolation errors for radial modes as a function of stellar parameters.

- **Plots 1–3:** Maximum interpolation errors for radial modes as a function of stellar parameters. For each model along a track, the maximum error is obtained. Then the maximum along the entire track is calculated.
- **Plots 4–6:** Average interpolation errors for radial modes as a function of stellar parameters. The RMS average is calculated along the entire track. Figure 3 shows such a plot for track interpolation errors.
- **Plots 7–9:** Average interpolation errors for radial modes restricted to the interval $0.8v_{\text{max}}$ to $1.2v_{\text{max}}$ as a function of stellar parameters. The RMS average is calculated along the entire track.

These plots are displayed in individual windows. Thanks to Python’s interactive capabilities, it is possible to rotate the plots and to zoom in or out.

Two additional 2D interactive plots display the positions of the evolutionary tracks in the stellar parameter space. The first of these shows all of the evolutionary tracks as blue dots. Clicking on a blue dot opens up a new window with two new plots which show how the age interpolation errors, for both radial and non-radial modes, vary as a function of stellar age. The second plot shows a partitioning of the evolutionary tracks used in the track interpolation tests as described above. An example of such a plot is shown in the left panel of Fig. 4. Clicking on a blue dot on this plot opens up a new window with two new plots with track interpolation errors as a function of age, like the ones shown in the right panel of Fig. 4.

More information on the individual plotting functions can be found in the comments within the plot_interpolation_test.py file as well as at the following website: http://bison.ph.bham.ac.uk/spaceinn/aims/version1.2/plot_interpolation_test.html.
Fig. 4 Testing interpolation accuracy. **Left:** Interactive plot with the positions of the evolutionary tracks in parameter space. The yellow dots correspond to the tracks with which a new tessellation is created, as represented by the connecting lines. The blue dots represent tracks where the interpolation is tested. **Right:** Clicking on a blue dot produces plots with the track interpolation errors as a function of stellar age.

6 Recommended reading

For more information on the use of Bayesian inference in model optimisation, we recommend Bazot et al. (2012) and Gruberbauer et al. (2013). For details on the affine-invariant MCMC optimisation scheme used (emcee), we refer the reader to Goodman & Weare (2010) and Foreman-Mackey et al. (2013). For details on asteroseismic grid-based analysis in general, we refer to Gai et al. (e.g., 2011).

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