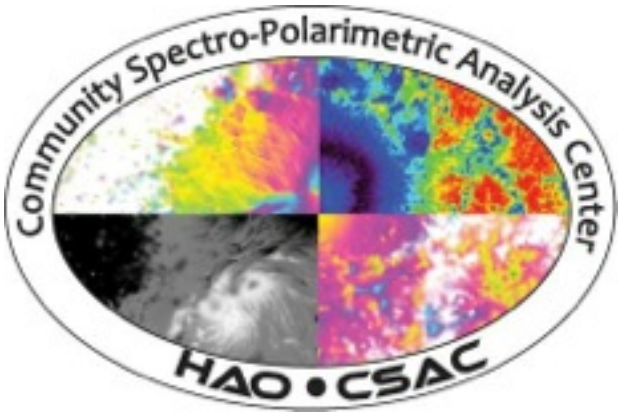

HEXIC

HAO's EXtended Inversion Code

User Manual

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1. Introduction

HEXIC is a general purpose Milne-Eddington spectral line inversion code based on the VFISV (Very Fast Inversion of the Stokes Vector, Borrero et al 2011, Centeno et al 2014) code that runs in the SDO/HMI vector magnetic field pipeline (see http://jsoc.stanford.edu/ for more information).

VFISV was developed specifically to invert full disk HMI spectropolarimetric data of the Fe I 617.3 nm line. Many aspects of this code were tailored to the HMI instrument and finely optimized to keep up with high data rate in near real time. HEXIC, albeit slower, is more versatile than its HMI counterpart. It allows, for instance, to invert spectral lines with any magnetic configuration (rather than just pure triplets) and doesn't use lookup tables for the calculation of the Voigt function. This version of HEXIC inverts data from filtergraph instruments, so it takes the instrument's transmission filter profiles as user input.

HEXIC is written in FORTRAN and has only been tested with the gfortran compiler so far. It makes use of the open source LAPACK, BLAS and DFFTPACK libraries, which are not included in this distribution and have to be downloaded and compiled separately. It currently uses one NUMERICAL RECIPES routine. To compile and create the executable first make sure that the right compiler (FC) and the paths to the Lapack, Blas and Dfftpack libraries (LIBS) are set in the Makefile. Typing "make main" will result in the compilation of all of the fortran routines and the linking to the external libraries. This will create an executable called main.x

In the forward problem, HEXIC solves the radiative transfer equation (RTE) for polarized light using the Milne-Eddington (ME) approximation to generate a set of Stokes profiles from a given model atmosphere \citep[][]{unno, rachkovsky}. The ME approximation assumes that all the parameters describing the atmosphere are constant along the line of sight (LOS) except for the source function, which varies linearly with optical depth. In addition, the generation of polarized radiation is formulated in the classical Zeeman effect regime. Traditionally, ME models applied to polarized RTE problems use up to eleven free parameters to describe the atmosphere in which the Stokes profiles are generated. There are five thermodynamical parameters: the line-to-continuum absorption ratio, η_0, the

Doppler width, $\Delta\lambda_D$, the damping parameter of the Voigt function, a, and the components of the linearized source function, B_0 and B_1, respectively. The magnetic field vector is described by three variables, i.e. the magnetic field strength, B, its inclination with respect to the LOS, θ, and its azimuth in the plane perpendicular to the line of sight, ϕ. There is also a kinematic parameter, namely the Doppler velocity, v, which characterizes the macroscopic speed of the plasma. A standard additional geometrical parameter known as the filling factor, α, quantifies the fraction of light within any given pixel that originates from a magnetized atmosphere.

The optimization scheme of HEXIC, based on a Levenberg-Marquardt minimization algorithm (see Press et al., *"Numerical Recipes in Fortran"*), takes a set of observed Stokes profiles and finds the model parameters that best describe the atmosphere in which they were generated. It achieves this by performing a non-linear minimization of a merit function, χ^2, that measures the similarity between the observed and synthetic Stokes profiles in a least squares sense.

2. User configuration files

All of the user configuration files are usually found in the USER_FILES directory (this is customizable, though). The main file is INPUT.txt, where the paths to all the other input/output files are set. This is the only file whose name and path are expected 'as is' by the code (USER_FILES/INPUT.txt). The names and the paths to the rest of the user input files can be customized inside this one.
The formats of this and the rest of the configuration, input and output files are described below.

2.1. Main input file

The main configuration file is INPUT.txt. The paths to all of the input and output files are set inside this configuration file. The mode in which the code will be run (synthesis or inversion) and all of the paths to other relevant files are specified in here.

The INPUT.txt file looks like this (empty lines or lines that start with an exclamation mark "!" or a "#" symbol are bypassed by the program that reads the file):

```
! Synthesis (s) or inversion (i) mode:
i
! Path to OBSERVATIONS:
/Users/rce/work/HEXIC/OBS/obs.txt
!Path to ATOMIC PARAMETERS:
/Users/rce/work/HEXIC/USER_FILES/LINE.txt
! Path to SYNTHETIC PROFILES:
/Users/rce/work/HEXIC/SYNTHETIC_DATA/syn.txt
! Path to results file or OUTPUT ATMOSPHERE:
/Users/rce/work/HEXIC/INVERSION_RESULTS/atmos_out.txt
!Path to GUESS model or INPUT ATMOSPHERE
/Users/rce/work/hmi/HEXIC/USER_FILES/atmos_in.txt
! Path to WEIGHTS file:
/Users/rce/work/HEXIC/USER_FILES/weights.txt
! Path to NOISE file:
/Users/rce/work/HEXIC/USER_FILES/noise.txt
! Path to SCATTERED LIGHT file:
/Users/rce/work/HEXIC/USER_FILES/scat.txt
! Path to FREE PARAMETERS file:
/Users/rce/work/HEXIC/USER_FILES/free.txt
! Path to instrument's FILTER PROFILES file:
/Users/rce/work/HEXIC/USER_FILES/filters_hmi.txt
```

2.2. Atomic parameters

This is the configuration file contains the spectral line parameters (atomic parameters and wavelength grids for the synthesis and the inversion). It is written in plain text. Everything followed by an exclamation mark '!' will be interpreted as a comment. Its name and path are set inside INPUT.txt.

```
! Spectral line parameters
!————————————————
! Number of wavelength points:
101
! Delta Lambda (in mA)
 10.5D0
! Beginning of wavelength vector with respect to Lambda0 (in mA)
```

```
 -499.0
! Number of filter positions in case of filtergtaph instrument:
8
! Filter sampling in case of filtergtaph instrument (in mA):
 65.0
! Core of line (in Angstroms):
 5250.20D0
! Values of g1, g2, j1, j2 (1=lower level, 2 = upper level)
1
3
0
1
```

The first three parameters in this file determine the wavelength vector on which the spectral line is synthesized inside the code. The first one is the number of wavelength points, the second is the wavelength sampling in mA and the third one is the origin of the wavelength vector (with respect to the central wavelength of the spectral line) in mA. With these three parameters, the wavelength grid on which the calculation of the spectral line is made, is constructed. The instrument transmission profiles provided by the user should be given on this same wavelength grid.
The following two parameters are the number of filter tuning positions and a rough value for the separation between them. The next parameter is the laboratory wavelength of the spectral line in A, followed by the quantum numbers g (Lande factor) and j (total angular momentum) for the lower and the upper levels of the transition, respectively.

2.3 Input atmosphere or guess model

This is where the input atmospheric model parameters are given to the code. It is a plain text file with 10 numbers arranged in one column. The name and path to this file are specified in INPUT.txt. In the case of 'synthesis' mode, the code will use these values to generate the output Stokes profiles. In the case of the 'inversion' mode, the code will take them as a guess atmosphere to initialize the inversion. However, most of the parameters will be overridden by an automatic initialization routine (wfa_guess.f90).
The order of the parameters in the input (and also in the output) atmospheric file is:

- Line core-to-continuum opacity ratio (non-dimensional)
- Magnetic field inclination (degrees)
- Magnetic field azimuth (degrees)
- Damping parameter (non-dimensional)
- Doppler broadening (mA)
- Magnetic field strength (gauss)
- Line-of-sight velocity (cm/s)
- Source function offset
- Source function gradient
- Stray light fraction (between 0 and 1)

2.4 Output atmosphere

This is an output file generated by the inversion. It stores the results for the atmospheric parameters that best reproduce the observations. The format is the same as for the atmos_in.txt file.

2.5 Observations file

This file should contain 4 columns (plain text) with the observed Stokes parameters (from left to right: I, Q, U, V). There should be as many rows as the number of wavelength points, and rows should go in increasing wavelength order.

```
21218.000    -15.000000    -71.000000    313.00000
20834.000    -104.00000    -141.00000    365.00000
20780.000    -78.000000    -149.00000    388.00000
20246.000    -147.00000    -195.00000    639.00000
19218.000    -216.00000    -359.00000    1082.0000
…
```

2.6 Synthetic profiles

It uses the same format as the observations file. This file will store the spectral profiles obtained from the ‘synthesis’ mode or the best fit profiles obtained by the code when run in ‘inversion’ mode.

2.7 Scattered light profiles

A scattered light profile is a fixed spectral profile of scattered light. It has the same format as the Observations and the Synthetic profiles files. Traditionally, only a non-polarized component is used for scattered light. In this case, the columns for Q, U and V should be set to zeroes.

2.8 Free parameters

This file is only relevant in the case of 'inversion' mode. Written in the same order as the model atmosphere files, it contains a column with '1' and '0'. The label '1' indicates that a model parameter should be inverted (free parameter), whilst the label '0' indicates that the model parameter will remain constant throughout the inversion (fixed parameter).

2.8 Weights

Relative weights for the four Stokes profiles, in the order: I, Q, U, V. This is also a plain text file. It is only relevant in 'inversion' mode.

```
! Weights for the 4 Stokes parameters (I, Q, U, V)
1D0    10.0D0          10.0D0          3D0
```

Bear in mind that the weights, W_S, enter the expression of the merit function, χ^2, in a quadratic form:

$$\chi^2 = N_F^{-1}\ W_S^2/\sigma_S^2\ \sum_{\lambda,S} (O_S(\lambda) - S_S(\lambda))^2)$$

where O_S represents the observed Stokes profiles, S_S the synthetic ones and σ_S is the noise associated to the former. The subscript "$_S$" represents the 4 Stokes parameters, λ is the wavelength and N_F is the number of degrees of freedom.

2.9 Noise

This file is only relevant in 'inversion' mode. It expects four values for the noise in the observations, one value for each of the four Stokes parameters (I, Q, U, V). These values are absolute, rather than relative to the continuum intensity. The format is identical as that of the weights file.

2.10. Other inversion parameters

Other parameters relevant to the inner workings of the inversion code are hard-coded inside the FORTRAN routines. These are not usually modified by the user, so that's why they are "hidden" inside the code. Most of the parameters relevant for fine-tuning of the inversion are set in inv_init.f90. Do not change them unless you know what you're doing!

3. Synthesis mode

HEXIC can be run in "synthesis" mode to generate the spectral line intensity and polarization for a given model atmosphere.

In this case, the user should specify that the mode is **s** in the first entry line of INPUT.txt. The path to the files with the input atmospheric parameters, the input atomic model and the output synthetic Stokes profiles should also be specified in this file.
The input atmospheric file should exist and contain values for the 10 parameters of a Milne-Eddington atmosphere (see section 2.3 for the correct order of the parameters).
The atomic parameters for the spectral line that the user wants to synthesize have to be formatted according to the description in 2.2.
When running the executable, the synthetic Stokes profiles will be saved in a file according to the format described in 2.5 and 2.6.

The executable file is main.x. After editing the input files to the user's satisfaction, one can call "./main.x" to execute the code. If everything goes well, the execution will have generated a file with the synthetic Stokes profiles obtained from solving the radiative transfer equation for the given model atmosphere.