SimpliFIDO

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1 Introduction

FIDO, the ForeCAT In situ Data Observer, is a tool that allows for comparison of a simple flux rope model with in situ observations. While the model was designed to work with the coronal CME deflection model ForeCAT, the inputs can be taken from anywhere, but it does use the same torus shape as ForeCAT. SimpliFIDO has some of the functionality of the full FIDO model removed, it only includes a single flux rope model and CME shape and has been made more user-friendly.

2 Method

FIDO determines when a synthetic spacecraft is within the CME, uses this information to determine it's position in a simple flux rope model, and converts the magnetic field to spacecraft coordinates. FIDO assumes that a CME propagates in a radial direction and there are two options for the expansion. The CME can either maintain a constant angular with, known as self-similar expansion, or undergo no expansion. In the case of no expansion, the angular width corresponds to the value at the time the impact begins. The radial speed and angular width are input parameters. The synthetic satellite is assumed to be at 1 AU near Earth and it propagates in an orbit as simulation time progresses. This currently cannot be changed without modifying the actual code.

The CME is represented with a torus. This shape is only meant to represent the flux rope portion of a CME, not any sheath or shock structure so caution should be used to compare with the right portion of the in situ observations. Figure 1 shows this torus. The torus has a circular cross section but the toriodal axis (dashed line in Figure 1) can have an elliptical shape. The shape of the CME can be specified by four lengths, a, b, c, and d, as shown in Figure 1, which all evolve as the CME propagates and expands. A more intuitive description is to use the angular width and radial distance, combined with two "shape parameters" A and B. A is the ratio of the height to the width, a/c, and B is the ratio of the cross-sectional width to the full width, b/c. If A is one then the toroidal axis is circular.

FIDO determines the distance between the synthetic spacecraft and the CME's toroidal axis as a function of time. Once the spacecraft enters the CME it also determines the orientation of the poloidal and toroidal directions at that location within the CME. This information is then combined with the Lundquist force-free flux rope model.

In this model, the toroidal and polodial magnetic field strength is determined simply by the distance from the toroidal axis. Note that this model is meant for a two-dimensional cross section, it is not necessarily self-consistent to apply it to the full three-dimensional structure. The effects should be minimal except for particularly oblique encounters. The toroidal and poloidal magnetic field, B_t and B_p, are given by

$$B_t = B_0 J_0 \left(\frac{2.4 d_t}{b} \right) \tag{1}$$

$$B_p = B_0 H J_1 \left(\frac{2.4 d_t}{b} \right) \tag{2}$$

where B_0 is the total magnetic field strength, d_t is the distance from the toroidal axis, b is the cross-sectional width (same as Figure 1), H is the handedness of the flux rope, and J is a Bessel function. B_0 can be signed, indicating the direction of the toroidal field relative to the axis defined by the tilt. For example, a northward pointing torus with positive B_0 and H has positive B_z and poloidal field that rotates from east to west. A northward torus with

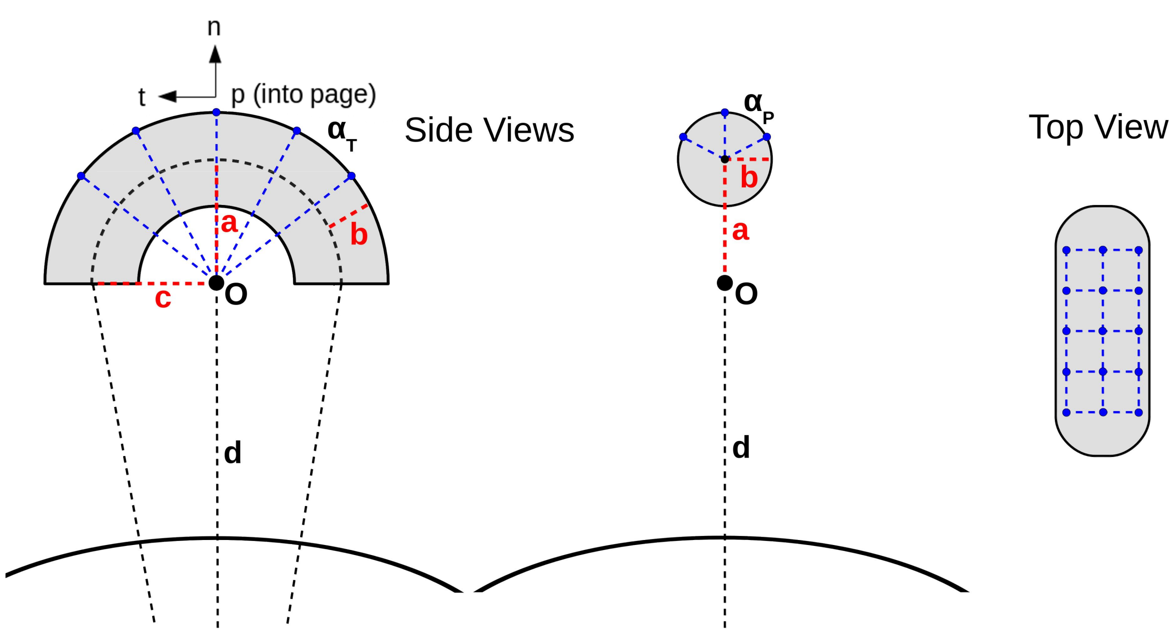

Figure 1: Diagram of the torus shape.

negative B_0 and positive H has southward B_z and poloidal field that rotates from west to east. There is a degeneracy in FIDO parameters as the orientation is allowed to vary the full 360° so orientations differing by 180 with opposite B_0 will match.

The magnitude of the toroidal and poloidal components are combined with the orientation of the CMEs toroidal and poloidal components. The magnetic field vector is then converted into GSE coordinates.

3 The SimpliFIDO GUI

Figure 2 shows the FIDO GUI. It is composed of 12 text boxes for inputing the model parameters, one check box for the "Autonormalize" feature, three buttons for saving, updating the plot, and quitting, a toggle for the expansion, and a panel that shows the comparison of the model results and observations. The text boxes are divided so that the left hand side corresponds to typically free parameters (which are often constrained by observations or other simulations) that can be adjusted (within reason) to change the model. The right hand side includes the location of the Earth (or satellite), which is a function of time and not a free parameter, and the CME boundary, which are also fixed values, though their determination can be difficult, particularly for the stop time. It is best to use boundaries determined elsewhere where plasma signatures are considered in addition to the magnetic field, rather than trying to keep this as an additional free parameter within FIDO.

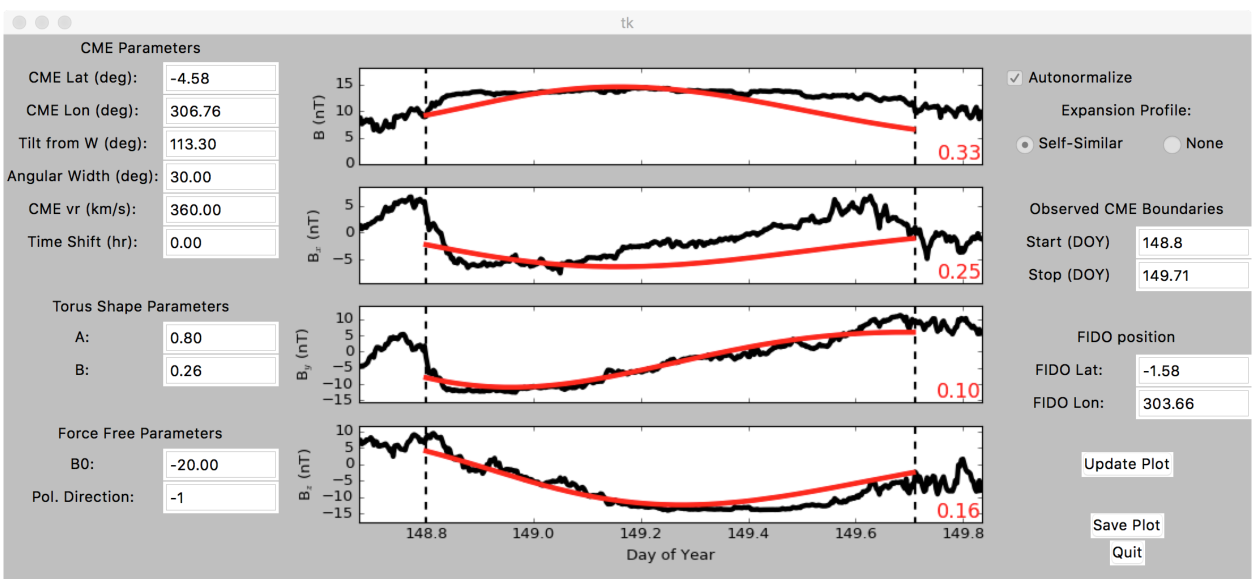

Figure 2: The FIDO GUI.

3.1 Input

FIDO needs each input box filled to perform a simulation. The model is designed to take an text file at start up and will automatically fill the text boxes for convenience. FIDO is run by typing `python FIDO.py sampleinput.txt` into the command line.

The text file contains a list of keywords and the values of their input parameters. FIDO is set up so that the keywords can be in any order within the text file, but the keywords must be formatted exactly as shown in the sample file, including the colon. Note that not every parameter is required to be in the input file, but FIDO cannot run until all values are filled in. The only required parameter is `insitufile`, which points to the file containing the in situ data. The format of the in situ data is discussed in Section 5 and the remaining parameters are listed below.

- `CME_lat:` The latitude of the nose of the CME, which is the center grid point and farthest point radially, given in degrees in Heliocentric coordinates
- `CME_lon:` The longitude of the nose of the CME, given in degrees. Any Heliocentric longitude system can be use (Carrington or Stonyhurst) but it should be the same as used for the Earth's longitude.
- `CME_tilt:` The orientation (in degrees) of the CME torus ranging between ±180°. This is measured by the angle between the toroidal axis and the solar equator, with positive values measured counterclockwise from the west direction (i.e. pointing north is 90°). This direction corresponds to the direction typically used in the literature, but different authors may have different conventions.
- `CME_AW:` The angular width of the CME in degrees, measured from nose to flank. Technically this is half of the full angular width (i.e. from flank to flank), but is what is typically reported and matches the GCS reconstructions. FIDO cannot use angular widths greater than 90°.
- `CME_Ashape:` The ratio of the CME height to the CME width (a/c in Figure 1). Reasonable values would be between about 0.5 and 1.5, but there is no strict limit.
- `CME_Bshape:` The ratio of the CME cross-sectional width to the CME width (b/c in Figure 1). This must be lower than 1.
- `CME_vr:` The radial speed of the CME in km/s. This is equivalent to the speed of the CME nose, not the average speed over the full CME, which would vary depending on the trajectory through the CME. Caution should be applied when pulling values from observations to make sure that the appropriate value is used.
- `CME_B0:` The magnitude used in the Lundquist flux rope model, in nT. The sign indicates the toroidal magnetic field direction, either parallel or antiparallel to the toroidal direction. If `Autonormalize` is selected then the magnitude is ignored but the direction still affects the results.
- `CME_pol:` The handedness of the flux rope with 1 indicating right-handed and -1 indicating left-handed.
- `tshift:` An offset used to adjust the start time of the modeled CME. FIDO is set to automatically align the front of the modeled results with the value given in `CME_start`. This parameter shifts the modeled CME by the given number of hours. This parameter is typically not needed or used, but is still included.

- `Earth_lat:` The latitude of the Earth in Heliocentric coordinates. If considering a target other than a near-Earth satellite then the latitude of that satellite.

- `Earth_lon:` The longitude of the Earth (or other target) in Heliocentric coordinates. As with the CME longitude, any reference point can be used for zero longitude, the important factor is the relative difference between the two longitudes.

- `CME_start:` Day of year corresponding to the start of the in situ CME. This can be updated from the initial value, the range of the plot window will not change but the vertical line will move and the calculations will reflect the change. FIDO will not run if it is set outside the plot range. FIDO automatically sets the plot range as three hours on either side of the initial start/stop times so if these values need to change more than this the initial text file should be updated.

- `CME_stop:` Day of year corresponding to the end of the in situ CME. Same behavior as `CME_start:`

- `Autonormalize:` Option to scale the total magnetic field strength to automatically match the observed magnetic field strength. The autonormalize value is chosen to match the average of the observed and simulated total magnetic field strength during the four hours in the center of the CME. This can be set to True or False and will default to True if unspecified.

- `Launch_GUI:` An option not to launch the GUI and simply save the results automatically instead. This can be useful for running multiple simulations from a bash script. The default is True if unspecified.

- `Save_Profile:` Only a text file option, there is no corresponding button in the GUI. When set to True it will output a simple text file with FIDO results. The default is False.

- `Expansion_Model:` The mode of expansion, this can be set only to "Self-Similar" or "None". FIDO defaults to self-similar if nothing is specified.

These parameters can be updated within the GUI after it is initialized. The plot does not update automatically, the "Update Plot" buttom must be used to apply the new parameters.

3.2 Output

The result of the simulation is the total magnetic field strength, B, and the magnetic field components, B_x, B_y, and B_z, as a function of time. These are displayed from top to bottom in the figure within the GUI. The red lines show the FIDO simulation results and the black line shows the in situ observations. The dashed vertical lines correspond to the start and stop times of the CME.

The button "Save Plot" will create a png file with the current version of the figure, and output the input parameters into a text file, which can then be used to reinitialize FIDO to the same state. The name of the saved figure and text files are determined by the name of the file used to initialize FIDO and it will print to the terminal the name used.

If `Save_Profile:` is set then the simulation results will be output to a text file to be read in by other programs. The calculated magnetic field is stored as global variables `obsBx`, `obsBy`, and `obsBz`, and the time as `tARR`. The default is to print columns of the time, B_x, B_y and B_z for every index in the array. This can be modified to output in any desired format by altering the code within `save_plot`.

3.3 Scores

As a metric of the quality of fit, we include a score value for the fit as a whole, and the individual vector components. These are shown in red in the bottom right of each panel. Note that the top score is a measure for the whole CME, not specifically for the fit of the total magnitude.

For the fit as a whole FIDO uses the vector magnitude of the average absolute error in each of the hourly-averaged individual components, weighted by the average total observed magnetic field strength. A perfect fit corresponds to a score of zero and the worst fit possible, assuming autonormalization or at least comparable total magnitudes, is two, which occurs when each vector component has the correct magnitude but opposite sign for the CME duration. A score one is a somewhat arbitrary but reasonable cutoff for a "good" fit. This corresponds to the error in each of the components being roughly less than or equal to the magnitude of that component, which can only occur if the model has the correct sign of the component for the majority of the CME.

For each of the vector components FIDO uses the average absolute error of the hourly-averaged values weighted by the average total observed magnetic field strength. The root mean square of the scores for the three components is the total score. FIDO does not normalize by the individual observed magnitudes as the scores can become misleading and overemphasize the significance of a component with a small magnitude.

4 Improving Fits

After using FIDO for some time one begins to develop intuition for how the relative geometry of flux rope and observer influences the in situ profiles, but it can be difficult to make these connections initially. One struggle can be determining why a CME does not impact when it was expected to. First, one should double check the input parameters for typos. Next, the angular width and/or cross-sectional width B can be increased to slightly increase the size of the CME see if it is just barely missing. If this fails, it is often useful to move the CME latitude and longitude close to the observer position, then slowly increment the values towards the original input and see where failure occurs. Often the position may seem "close" relative to the angular width, but the tilt may be such that it falls near the thinner dimension of the CME where the relavant size is the cross-sectional width. In such cases, it may be appropriate to increase B as it is often poorly constrained from observations.

With a simple flux rope model the magnetic field transitions from poloidal field near the front to toroidal in the center then back to poloidal near the rear (with the rear poloidal direction being opposite of that at the front in Cartesian space). For impacts near the CME nose, the toroidal axis will fall within the yz-plane (i.e. perpendicular to the radial direction). For a vertical CME the toroidal direction will align with z, for a horizontal CME it will align with x. By changing the orientation of the CME one can move the magnetic field between these two directions. As the impact moves away from the nose the toroidal axis gains an x-component due to the curvature of the CME torus, making the simple picture less straightforward.

The poloidal magnetic field falls within the plane perpendicular to the toroidal axis, meaning the x-direction and some combination of the y- and/or z-direction. Near the CME nose, if the spacecraft trajectory cuts perfectly through the center of the cross-section of the CME then B_x goes to zero as the poloidal field there has no radial component. Observations with little to no B_x are highly likely to be impacts very near the center of the CME in the cross-sectional direction, and adjusting the parameters to reflect such can be an easy way to improve the quality of the fit. Again, for flank hits the picture is not quite as simple.

5 In Situ Data

FIDO was designed to read in ACE data. The expected input format is columns of fractional day of year, B_x, B_y, and B_z. The data can be accessed through a web interface at the ACE website `http://www.srl.caltech.edu/ACE/ASC/level2/lvl2DATA_MAG.html`. The four minute-averages are recommended as they show the small scale features within the observations (which FIDO cannot reproduce, but are worth visualizing). The appropriate date range must be chosen then one can pick the parameters to export. Occasionly CMEs extend over multiple time intervals if the split date falls in the middle. In this case multiple files must be downloaded and stitched together.

Alternatively ACE provides a direct link to downloads (information at `http://www.srl.caltech.edu/ACE/ASC/level2/new/hint.html`). The following example has been modified to produce the desired output for FIDO, only the start date and time (sd and st) and end date and end time (ed and et) need to be modified. The data is likely output as `mag_level2_dat_4min.txt` in the Downloads folder, but this may vary from computer to computer.

```
http://www.srl.caltech.edu/ACE/ASC/level2/new/ACEL2Server.cgi?datasetID=mag_
level2_data_4min&TPARAM=fp_doy&PARAM=Bgse_x&PARAM=Bgse_y&PARAM=Bgse_z&sd=2010-05-27&
st=00:00:00&ed=2010-05-30&et=23:59:59&dataformat=TEXT&nonint=1
```

Clicking on the link should download a file. If you try to copy and paste from the pdf you may have issues, which could also occur when you copy it to a text file to edit the start and stop times. When the link is copied it often adds in either spaces or return symbols at the line breaks in the pdf (between "mag_" and "level" and between "&" and "st"). Delete these so that the link is one continuous line otherwise the website gives an error file.

Any other data source can be used instead of ACE data with minor changes. If the data is formatted in DOY, B_x, B_y, B_z then the only change should be the number of lines in the header, currently `skip_header` is set to 44 for the ACE output.

6 Python Packages

Most of the packages used by FIDO are common packages that are likely included in any distribution (math, matplotlib, pylab, numpy, random, scipy, sys) but if any are missing then FIDO will not run. The only somewhat uncommon package is Tkinter, which is used to build the GUI. Unfortunately, getting Tkinter running can sometimes be a bit of a challenge. There are often issues with "backends" but some of the initial lines of FIDO try to account for this and solve some common issues. The current version of FIDO runs without issue on a Mac Laptop running High Sierra and a Linux machine running CentOS 7.4 but has yet to be tested on Windows.