Handbook for Grad-Shafranov reconstruction of magnetic flux ropes

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based on the code by Qiang Hu, now at University of Alabama at Huntsville

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The MATLAB GS program package can be downloaded as a zip file

at this DOI: 10.6084/m9.figshare.5840913

For a Quickstart to MATLAB, take a look at the tutorials in the program help or online at

http://www.mathworks.com/help/techdoc/index.html

https://de.wikipedia.org/wiki/Matlab

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If this code is to be used as part of a scientific publication, please include us as co-authors.

Introduction

The **Grad-Shafranov (GS) reconstruction method** has recently become widely used in the space physics community in different contexts. It has been invented about 10 years ago by a group around Prof. Sonnerup at Dartmouth University. It has been often used on structures in space plasmas which can be described in the approximation of magnetohydrostatics such as the magnetopause, flux transfer events, flux ropes in the Earth's magnetotail, as well as magnetic flux ropes and magnetic clouds in the solar wind. Its main point is to assume **invariance and time-independency** so the MHD equations in equilibrium, including plasma pressure, can simply be numerically integrated as an initial value problem. There exist some variations of the basic method (see Sonnerup, 2006, JGR, and recent papers by e.g. Teh et al.), however, this document is restricted to its use on magnetic flux ropes in the solar wind in the version of Hu and Sonnerup (2002).

Where the programs come from

In this document a program package in MATLAB is described as a basis for learning the method and for future reference and deals with the use of the method on in situ data of any kind of magnetic flux ropes. These programs are based on those used by Qiang Hu for his 2002 JGR paper (for references see below) which were part of his PhD thesis at Dartmouth university. They were extended by Christian Möstl (Space Research Institute, Graz, Austria) during his PhD thesis (finished in 2009) to include a graphical user interface (GUI), which makes it easy to apply the reconstruction method for a single event after the satellite data have been put into a proper format. For a quick start, there are some events included in this package to play around with, so you can omit the next step if you want.

If you want to use your own events:
A program to read merged plasma and magnetic field data from the ACE satellite is provided: "getace.m".
This program converts the ACE data files obtained from

ftp://spdf.gsfc.nasa.gov/pub/data/ace/merged/4_min_merged_mag_plasma

(on Mac, use e.g. FileZilla to download data from this source)

to a proper format which can be read by the reconstruction programs. If you are interested to use the complete ACE data, please download the ACE data yourself from the source above into the directory "ACEDATA\4_min_merged_mag_plasma" (Windows) "ACEDATA/4_min_merged_mag_plasma" (MAC) relative to the "root" path. I have included in this package the merged ACE Data for the **years 2003 and 2004 only**. The files produced by "getace.m" are saved as MATLAB internal data files ".mat" in the subdirectory "ACEDATA" relative to the root.

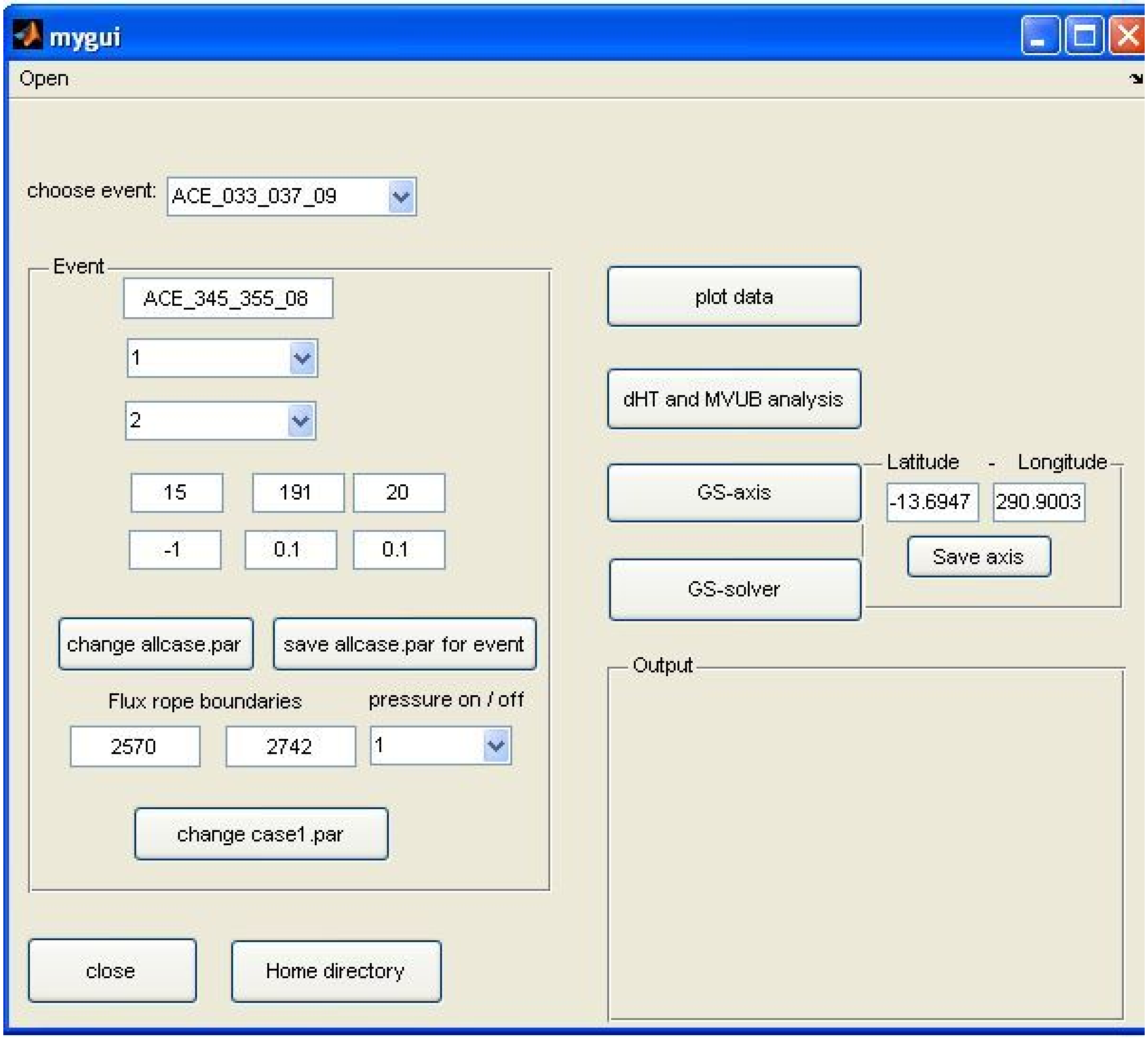
Current state of research
The technique has been introduced for MCs/MFRs (magnetic clouds and magnetic flux ropes) in the solar wind, applied to many MC/MFR events (including multiple ropes) and extended to multi-spacecraft observations. Recent research has focused on extension to 3D and time dependent structures (search ADS for papers by Sonnerup and W.-L. Teh), bent flux ropes (unpublished by Qiang Hu), and improvements on the numerical

solver (Isavnin et al. 2011). The code was also tested using numerical simulations of CMEs, where it was shown that the reconstructed field topology is wrong if the real field is essentially 3D and not 2.5 D (Al-Haddad et al., 2011).

Quick start

The programs can be unzipped to any desired folder. **The path to this folder, lets call it the "root", should then be added to the MATLAB paths under "File"-> "Set Path" without subfolders.** Be sure to change directory inside MATLAB to the "root" folder before running the gui. A graphical user interface can now be started by **typing "mygui" in the MATLAB command line**.

A window pops up which looks like this:



Under the menu point "open" another gui (acegui) can be opened to plot data from ACE and create new events (see below how to use getace.m)

Choose Event: This scroll down menu shows a list of all the folders which have the correct name format in the present directory. Select the event which you would like to analyse further - switching between different events is thus very easy. The format is always "spacecraft name_day of year begin (three digits)_day of year end (three digits)_ year (two digits)."

If a new event directory has been generated by using "the getace.m program", the GUI has to be started again (click the close button and restart). This is because the GUI searches for filenames with the correct length for the scroll down menu only at startup.

Try to choose the event ACE_323_325_03 for a start. Then run all the programs beginning from "plot data" downwards with the pre-installed parameters so you see how a good reconstruction looks like.

Event: This box shows all information necessary for controlling the programs to the right. The parameters in the upper part, i.e.

1

2

15 191 20

-1 0.1 0.1

control the GS-solver program (see below).

The flux rope boundaries (in data points units, so trial and error is necessary) can be adjusted in the bottom part. Also the plasma pressure can be set to on/off by setting the pulldown menu to 1 or 0.

You need to press "change case1.par" to make the changes effective

Example: press "plot data"; try changing the boundaries; press "change case1.par" ; press "plot data" again. Now the boundaries are different.

The boundaries can also be selected by clicking twice while using the “getace” program (in write mode, see below).

Plot data: plots a data figure onscreen as well as a an eps output of this figure in the event directory.

dhT and MVUB analysis: carries out the deHoffmann Teller and Minimum Variance Analysis. The minimum variance direction is the first approximation to search for the GS axis.

GS axis This is basically the core of the method and the most complex part. The Pt(A) function is searched to be single-valued. This orientation is then the subsequent flux rope axis. Wait until a residue map is generated. (see Hu and Sonnerup, 2002). Click left on the plot to check a given direction. Click right anywhere and the direction with the black dot is used.
Note: if you want any other direction than the "black dot" click left, note the orientation (command window) and click right; you can then "force" the GS solver to use your own axis by typing it into "Latitude" and "Longitude" on the right in mygui. You can actually use any latitude / longitude angle you want. These angles are defined as: longitude going from GSE +X (0°) to GSE +Y (90°) and latitude going from GSE -Z (-90°) to ecliptic (0°) to GSE +Z (90°)

GS-Solver: Creates a magnetic field map perpendicular to the invariant axis and a nice version of the Pt(A) plot, both as .eps files (map.... .eps and pta.... eps). To control this program some parameters in the Event box can be set manually, from top to bottom as in the GUI window above:
1 % this is currenlty a redundant parameter and is not used
2 % the order of the fitting polynomial for Pt(A) - usually 2.
15 191 20 %15 is the grid size in the x direction; 191 in the y direction

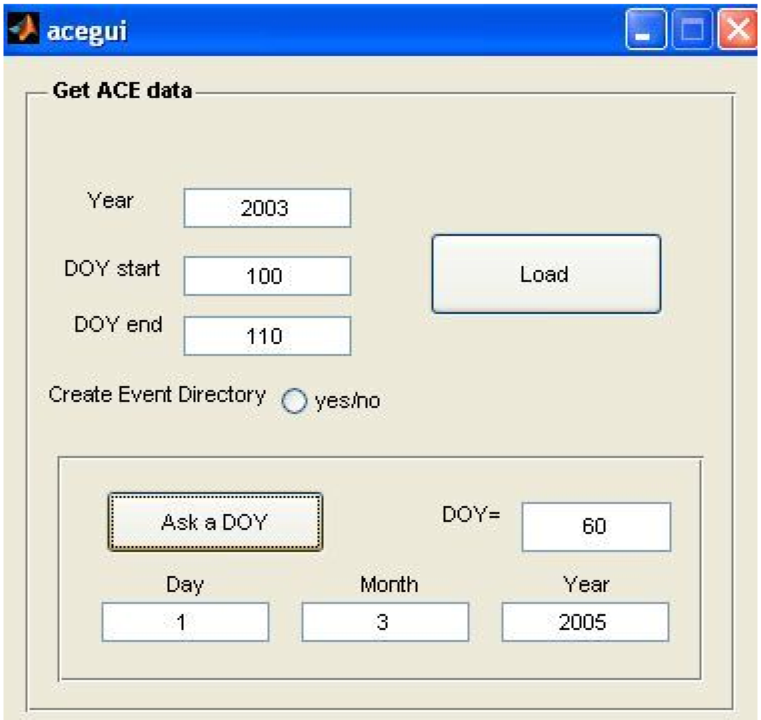
(can be varied); 20 is an offset of the spacecraft trajectory in the y direction
-1 0.1 0.1   % -1/0/1 controls the boundary Ab (see below); 0.1 and 0.1 control how much the polynomial overlaps with the   exponential functions, i.e. higher values result in suppressing the polynomial more and more (play with it).
See also Möstl et al. 2009 (Solar Physics) for more info on these parameters.

The boundary *Ab* is the white contour in the magnetic field map and indicates where the single-valuedness of *Pt(A)* breaks down.

0: lets you set the boundary with a left-click of the mouse
1: indicates that for calculating the axial flux and the axial current everything to the right of Ab is counted.
-1: flux and current calculated but everything left of Ab (in Pt(A)) is counted
(This just says that if the maximum of Pt is positive/negative in A, Ab has to be set to +1/-1, respectively, to get the correct flux and current)

How to use getace.m:

you can either use this GUI by using Ctrl+A or the "open" menu in mygui:



at the bottom here you can ask for a DOY if you know the date.

OR: directly in the command line, type for example

>> getace(2004,312,316,0)

to see an in situ plot from the year 2004 from days of year 312-316 of 2 magnetic clouds unleashed by the same active region on the Sun in November 2004 (if you want to know what was going on there, check out the paper Harra et al. 2007, Solar Physics, DOI:10.1007/s11207-007-9002-x). If you want to check your reconstruction results for one of these magnetic clouds, take a look at Qiu et al. (2007, ApJ, see below).

Setting the last variable **to "0" means that only the figure is created and nothing is saved.** Setting **"1" indicates that an event directory (in**

this "ACE_312_316_04") created for further reconstruction using the GUI and that the converted data is saved in the "DATA" directory. Then you must also set boundaries of the magnetic flux rope interval by clicking with the left mouse button, first to the left, then to the right. This can be changed later again by using the same command with which you called "getace.m". If you now start the GUI, you should be able to see the event in the "choose event" scroll down menu.

try

```
>> help getace
```

to see a summary.

Typical error handling:

- If the gui does not start, check if you are in the "root" directory. It might be necessary to type

```
>> cd ..
```

to change the directory back to the root for the next try.

- if something doesn't work after clicking a button, try clicking "Home directory" at the bottom.

- If you kill a figure manually while a program runs, it crashes and maybe you are left in the wrong directory.
 Then the next program will crash if it looks for a file which isn't there.
In any other case, kill the gui and restart. Restart MATLAB in tough cases ;-).

- if there are too many open windows, type

>> close all

Typing
>> help mygui
results in a quick start help.

Literature

The central paper which describes in detail everything thats necessary to know about GS reconstruction on flux ropes is

Q. Hu and B. U. Ö. Sonnerup. “Reconstruction of magnetic clouds in the solar wind: Orientations and configurations”. Journal of Geophysical Research (Space Physics) 107 (2002) 10–1.

A selected list of refereed papers in major journals where the technique has been introduced for MCs/MFRs in the solar wind, applied to many MC/MFR events (including multiple ropes) and extended to multi-spacecraft observations:

Q. Hu and B. U. Ö. Sonnerup. “Reconstruction of magnetic flux ropes in the solar wind”. Geophys. Res. Lett. 28 (2001) 467–470.

Q. Hu, C. W. Smith, N. F. Ness, and R. M. Skoug. “Multiple flux rope magnetic ejecta in the solar wind”. Journal of Geophysical Research (Space Physics) 109 (2004) 3102.

Q. Hu, C. W. Smith, N. F. Ness, and R. M. Skoug. “On the magnetic topology of October/November 2003 events”. Journal of Geophysical Research (Space Physics) 110 (2005).

J. Qiu, Q. Hu, T. A. Howard, and V. B. Yurchyshyn. “On the Magnetic Flux Budget in Low-Corona Magnetic Reconnection and Interplanetary Coronal Mass Ejections”. ApJ 659 (2007) 758–772.

Y. Liu, J. G. Luhmann, K. E. J. Huttunen, R. P. Lin, S. D. Bale, C. T. Russell, and A. B. Galvin. “Reconstruction of the 2007 May 22 Magnetic Cloud: How Much Can We Trust the Flux-Rope Geometry of CMEs?” ApJL 677 (2008) L133–L136.

C. Möstl, C. Miklenic, C. J. Farrugia, M. Temmer, A. Veronig, A. B. Galvin, B. Vrsnak, and H. K. Biernat. “Two-spacecraft reconstruction of a magnetic cloud and comparison to its solar source”. Annales Geophysicae, 26 (2008) 3139–3152.

C. Möstl, C. J. Farrugia, H. K. Biernat, M. Leitner, E. K. J. Kilpua, A. B. Galvin, and J. G. Luhmann. “Optimized Grad-Shafranov Reconstruction of a Magnetic Cloud Using STEREO- Wind Observations”. Sol. Phys. 256 (2009) 427–441.

C. Möstl, C. J. Farrugia, M. Temmer, C. Miklenic, A. M. Veronig, A. B. Galvin, M. Leitner, and H. K. Biernat. "Linking Remote Imagery of a Coronal Mass Ejection to Its In Situ Signatures at 1 AU". ApJL 705 (2009) L180–L185.

Möstl, C., C. J. Farrugia, C. Miklenic, M. Temmer, A. B. Galvin, J.G. Luhmann, K.E.J. Huttunen, M. Leitner, T. Nieves-Chinchilla, A. Veronig and H.K. Biernat, Multi-spacecraft recovery of a magnetic cloud and its origin from magnetic reconnection on the Sun, *Journal of Geophysical Research (Space Physics)*, 114, A04102, doi:10.1029/2008JA013657, 2009.

E. K. J. Kilpua, P. C. Liewer, C. Farrugia, J. G. Luhmann, C. Möstl, Y. Li, Y. Liu, B. J. Lynch, et al. "Multispacecraft Observations of Magnetic Clouds and Their Solar Origins between 19 and 23 May 2007". Sol. Phys. 254 (2009) 325–344.

Al-Haddad et al. 2011, ApJL,
http://adsabs.harvard.edu/abs/2011ApJ...738L..18A

Isavnin et al., 2011, Solar Physics
http://adsabs.harvard.edu/abs/2011SoPh..273..205I