Measuring Solar Magnetic Fields

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We have a difficulty in measuring the magnetic field on one hand, and a difficulty in computing the magnetic field model on the other hand. The latter difficulty is close to being resolved. The former, however, still stands.

What I will focus on

- Magnetic field of active region
- Photospheric and chromospheric magnetic fields
- Cartesian coordinates
- Space observations (SOHO/MDI, Hinode/SOT)

What I will not talk about

- Quiet-Sun magnetic field observations
- Full-disc magnetic field observations
- Ground-based observatories
- Radiative transfer during flaring activity
- Helioseismology
- Susan Boyle
How to measure the magnetic field?

1. Simple Zeeman-Doppler effect
2. Polarisation and Stokes parameters
3. Inverting the magnetic field components
   3.1 Line-of-sight (LOS) magnetograms
   3.2 Vector magnetograms
4. Related issues
5. More …
1. Zeeman Effect

**Definition**

- Splitting of a spectral in the presence of an external magnetic field
- The splitting is proportional to the magnetic field strength and the Landé factor.

For an atom, the Hamiltonian of the system is

\[ H = H_0 + H_m \]

where \( H_0 \) is the unperturbed Hamiltonian and \( H_m \) is the perturbation due to the magnetic field:

\[ H_m = -\vec{\mu} \cdot \vec{B} \]

**Landé g factor:**

\[
\frac{g_L j(j + 1) + l(l + 1) - s(s + 1)}{2j(j + 1)} + g_S \frac{j(j + 1) - l(l + 1) + s(s + 1)}{2j(j + 1)}
\]
If the field is strong enough or the Landé factor large enough, then the Zeeman splitting is observable.

The distance between the different lines is proportional to the strength of the magnetic field.
2. Polarisation and Stokes parameters

Linear polarisation of a line  
Q and U give the transverse field components

Circular polarisation  
V gives the line-of-sight components
2. Polarisation and Stokes parameters

Example of the visible Fe I 6302.5Å line

Polarisation measurements are I, V/I, Q/I, U/I

Polarisation observations: I ± V, I ± Q, I ± U

To produce a vector magnetogram: about 30 images are needed (e.g. Imaging Vector Magnetograph, Mees Solar Observatory, Hawaii)
3. Inverting the magnetic field components

3.1 *Line-of-sight magnetograms*

From Zeeman splitting

From \{I, V\} Stokes profiles
3. Inverting the magnetic field components

3.2 *Vector magnetograms*

Four Stokes parameters

Radiative Transfer

*To be added:*
- straight light
- instrument setup (dark current, flatfield)
- seeing
- ...

Intensity
+ magnetic field vector
3. Inverting the magnetic field components

3.2 Vector magnetograms

Radiative Transfer Unno-Rachkovsky method based on the nonlinear least-square fitting of Stokes parameters (Skumanich & Lites 1987) allows us to determine the three components of the magnetic field along the line-of-sight and in the plane perpendicular to the line-of-sight (strength and azimuthal angle). Other methods exist as developed by the HAO group and others: PCA, …

\[ I = (I, Q, U, V) \]

Continuum intensity,
\[ B=(B_{los}, B_{trans}, B_{azim}) \]
4. Related issues

Filling factor  
we assume that the filling factor in active region is 1
not reasonable assumption for the quiet Sun  
(Hinode/SOT estimate the filling factor in quiet Sun as low as 0.2)

Seeing  
no seeing problem for space observation, important for ground-based observatories then need of adaptative optics

180 degree ambiguity  
we have derived the transverse field strength and the azimuthal angle; to convert into Cartesian coordinates, we need to solve the 180 degree ambiguity on the transverse components;
several methods: annealing, potential field, minimising div(B), …; see Metcalf et al. 2007 for a comparison of different methods

Difficulty: cannot take into account the emergence of a twisted flux tube
5. More magnetic field measurements

- **Hanle effect – QS, prominences**
  
  (see right picture)

- **Radio emission**
  
  gyrofrequency proportionnal to the magnetic field strength; measure in the low corona

- **Infrared lines**
  
  - On disk observations (e.g., Dominguez Cerdena et al. 2006)
  
  - Off limb inference of the magnetic field with near infrared lines; Solar-C (Kuhn et al. 2006)

- **Coronal seismology**
  
  Deriving magnetic field strength, density and temperature from coronal wave properties

- **Hard Xray**
  
  (Kontar et al. 2008)
Product of the magnetic observations

Line-of-sight magnetic fields

Vector magnetic fields in Cartesian coordinates
How to analyse magnetic fields?

1. Characteristic parameters
2. Advanced parameters
   2.1 PIL, Magnetic energy
   2.2 Current density, CIL
3. 3D magnetic configurations
   2.1 Magnetic Energy
   2.2 Geometry of field lines
   2.3 Magnetic Helicity
   2.4 Magnetic Topology
   2.5 Time series
1. Characteristic parameters

*Magnetic flux*

- Total unsigned magnetic flux
- Net magnetic flux

*Characteristic length*

- Distance between the centre of mass of magnetic polarities
- Radius of the circle including 90% of magnetic flux

*Characteristic magnetic field*

- Distribution of magnetic field components: Bz and Bt
- Moments of the distribution: mean value, standard deviation
2.1 PIL, magnetic energy

PIL  polarity inversion line
NOT neutral line!

Magnetic energy can be estimated from the virial theorem (Molodensky 1974, Wheatland and Metcalf 2006)

\[
\frac{1}{2 \mu_0} \int_{z>0} B^2 \, dV = \frac{1}{\mu_0} \int_{z=0} \left( B_x x + B_y y \right) B_z \, dx \, dy
\]

Problem  How to define the origin of the magnetogram?
2.2 Current density, CIL

Current density and the force-free function $\alpha$

\[ \alpha = \frac{1}{B_z} \left( \frac{\partial B_y}{\partial x} - \frac{\partial B_x}{\partial y} \right). \]

CIL  current inversion line
1. *Measuring the line-of-sight magnetic field*
2. *Accessing, analysing and visualising the data*
3. *Common effects*
   1. *Saturation*
   2. *Projection effects*
   3. *Energetic particles*
4. *Examples*
1. Measuring the line-of-sight magnetic field

The longitudinal (or line-of-sight) magnetic field is measured using the Zeeman-Doppler shift of a photospheric line.

MDI/SOHO magnetograms (NiI at 6768Å) show the photospheric motions and the complexity of active regions
2. Accessing SOHO/MDI database

MDI data request page
http://soi.stanford.edu/data/data_request.html

MDI data request page by time range
http://soi.stanford.edu/production/time_range.html

SSSC lev1.4/1.7, lev1.5/1.8 and SHT Time Range DS

All the mdi, lev1.4/1.7 or lev1.5/1.8 or sht datasets will be found for the hour(s) you select. (lev1.7/1.8 will be made from available 1.4/1.5)

Start Hour: year: 2000  month: 01  day: 01  hour: 00

☐ Only do Start Hour  ☐ Do through the Stop Hour (may be long, depending on range)

Stop Hour: year: 2000  month: 01  day: 01  hour: 00

Display by: ☐ Data Product  ☐ Time

☐ lev1.4  ☐ lev1.5  ☐ lev1.7  ☐ lev1.8  ☐ sht

Submit  Clear
# 2. Accessing SOHO/MDI database

## SOI Data Request Summary

<table>
<thead>
<tr>
<th>Select Program</th>
<th>Level</th>
<th>Series</th>
<th>SN</th>
<th>Date</th>
<th>Byte</th>
</tr>
</thead>
</table>

- Directory
- RCP to remote disk
  - Host name
  - User name
  - Directory
- FTP to requestor
  - Host name
  - User name: `anonymous`
  - Password: `daemon@tarax.stanford`
  - Remote Directory

- External Media
  - Media Type: `Exabyte (High Density)`
  - System Type (for Exabytes): `SGI Irix`
  - Your mailing address
    - 
    - 
    - 
    - 

[Continue] [Clear]
2. SOHO/MDI magnetograms

See practical on *How to read MDI fits files*

MDI fits files contain:

- Header satellite, pointing, date-time, housekeeping information
- Data

Characteristic pixel size: 1.98 arcsecond for full disc

Field-of-view: full disc or partial (white square)

Cadence: 96 minutes or 1 minute

Noise level: <10 G for 96 minutes, ~20 G for 1 minute (different exposure time)
3. Common effects

10 arcsecond annulus out of the limb
3. Common effects

Saturation in strong field region -> saturation in sunspots (low intensity regions)
3. Common effects

Change of sign of the line-of-sight magnetic field strength from the East limb to the West limb in the penumbra of the sunspot.
Change of sign of the line-of-sight magnetic field strength due to high energy particles

-> high Doppler shifts outside the wavelength range of the instrument
Watch the clock
Solar Optical Telescope, Hinode/SOT

from K. Ichimoto

Hinode workshop 2007
1. Accessing Hinode/SOT data

DARTS JAXA data archive/ search system
http://darts.isas.jaxa.jp/hinode/top.do

Quick Look movies (NAOJ)
http://solar-b.nao.ac.jp/QLmovies/index_e.shtml

Operation info. at LMSAL (timeline for pointing, target, obs. purpose etc.)
https://sot.lmsal.com/operations/timeline/
1. Accessing Hinode/SOT data

SSW IDL:

IDL> hinode_server_select, /darts ; set a remote server
IDL> time0 = '09-Dec-2006T11:30:00'
IDL> time1 = '09-Dec-2006T15:00:00'
IDL> sot_cat, time0, time1, /level0, cat, files, /URLS
IDL> help, files
FILES STRING = Array[2994]
IDL> ss = sot_umodes(cat,/int) ; interactive selection of data
IDL> sock_copy, files[ss], out_dir='./demo' ; copy to local disk
IDL> lfiles = file_list('./demo', '*.fits*')
IDL> read_sot, lfiles[0], index, dat ; read SOT fits file
IDL> help, index, dat
INDEX STRUCT = -> MS_250671422001 Array[1]
DAT INT = Array[2048, 1024]
IDL> tvscl,dat

Sample programs for tutorial are found in $SSW/hinode/sot/doc/paris/* .pro
2. Analysing SOT filtergrams

- Camera readout errors: `fg_shift_pix.pro`
  - Central 2 vertical lines of camera dropped in partial-camera readout.
  - Top line wrapped around to bottom.
  - 1x1 and 2x2 are supported. 4x4 still in development.

- Dark current and pedestal subtraction: `fg_dark_sub.pro`
  - FG camera 4096 x 2048 split-frame read-out: 2048x2048 frames. Each has different pedestal.
  - Pedestal is temperature dependent. Linear combination of camera and electronics box temperatures.
  - 1x1 and 2x2 are supported. 4x4 still in development.

- Flat field correction: `fg_flatfield.pro`
  - Flat fields are created by Kuhn-Lin algorithm.
  - Currently there are flat images only for
    - CN 388.3 (also used for Ca II H-line images)
    - G-band 430.5
    - Blue continuum 450.5
    - Green continuum 555.0
    - Red continuum 668.4
    - Fe I 630.2 (affected by a big bubble)
    - Na ID 589.6 (affected by a big bubble)
    - Mg Ib 517.3 (affected by a big bubble)
    - H-alpha 656.3 (affected by a big bubble)

- Bad camera pixel correction via map: `fg_bad_pix.pro`
- Cosmic ray removal: `sot_nospike.pro`
- Correction for BFI/NFI plate-scale difference and image shifts: `fg_reg_wave.pro`
2. Analysing SOT filtergrams

- Accomplished via fg_prep.pro
  (Tom Berger: berger@lmsal.com, Yukio Katsukawa: yukio.katsukawa@nao.ac.jp)

- BFI simple filtergrams corrected completely

- NFI data product corrected:
  - FG  (simple filtergram)
  - FGIV (shuttered IV)
  - FGIQUV (shuttered IQUV)
  - Shutterless modes still in development.

- Polarization calibration still in development

- Call formats

  IDL> fg_prep, index, data, index_out, data_out, /despike

  IDL> fg_prep, filename_list, -1, index_out, data_out, /despike

  IDL> fg_prep, index, data, index_out, data_out, /despike, $
      x0=256, y0=256, subimgx=768, submigy=512