Depth-dependent Inversion of a Sunspot: 
I. Inversion Strategy

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Outline

1 Introduction

2 Data

3 Inversion Strategy

4 Comparison of 1D & 2D inversion results

5 Conclusions and Future Plans
Introduction

- Understanding 3D structure of sunspot has been one of the major motivations in Solar Physics.

- Considerable advances have been achieved theoretically (Rempel et al. 2009a,b; Rempel & Schlichenmaier 2011) and observationally (Solanki et al. 1993; Westendorp Plaza et al. 1998, 2001b,a; Solanki 2003; Mathew et al. 2003; Borrero & Ichimoto 2011) for last two decades.

- Many of the issues are yet to be resolved: to count a few magnetic canopy structure; thermal-magnetic relationships on fine scale structure; the closest sunspot model, chiefly out of flux tube model (Solanki & Montavon 1993) and gappy penumbra model (Scharmer & Spruit 2006), is yet to be identified; equilibrium of sunspots; etc.

- Instructive recent reviews: Borrero & Ichimoto, lrsp, 2011
  : Rempel & Schlichenmaier, lrsp, 2011
Inversion: a process that returns most probable atmosphere that gave rise to the observed spectra.

ME inversions, simpler atmosphere, analytically solution possible, fast (Harvey et al., 1972; Landi Degl’Innocenti & Landolfi 2004):
- HeLIx (Lagg et al., 2004)
- MERLIN (Lites et al., 2007)

Depth-dependent inversions (use response functions) (Landi Degl’Innocenti & Landi Degl’Innocenti, 1977):
- SIR (Ruiz Cobo & del Toro Iniesta 1992)
- SPINOR (Frutiger et al., 2000)

Line forming region (log $\tau_{\text{min-max}}$)

RTEs for polarized light in LTE are solved numerically

$\chi^2$ minimization
Data

- NOAA AR 10933, observed from SOT/SP onboard Hinode

- The sunspot was observed very close to disk center ($\mu=0.99$) on 05 Jan 2007 at 1213 UT.

- The spectral lines used for polarimetric measurements are FeI 6301.5 and 6302.5 Å.

- 0.16 arcsec/pixel
Inversion Strategy

- SPINOR (Stokes-Profiles-INversion-O-Routines) used for inversion of the observed Stokes profiles (*Frutiger et al.*, 2000)
- Solves Unno-Rachkowsky RTEs under LTE
- Employs response functions
- HSRA atmosphere is used as continuum level
- Levenberg-Marquardt algorithm is used to minimize merit function

\[
\chi^2_0 = \sum_{k=1}^{N} \frac{(I_{k,\text{syn}} - I_{k,\text{obs}})^2}{\sigma_k^2}
\]

- Physical parameters are interpolated at finer grids
After repeating inversion with different degrees of freedom to field stratification, we find that the inversion with three node positions gives the best results.

The free parameters in the inversion are temperature, magnetic field strength, inclination, azimuth, line-of-sight velocity, micro and macro turbulent velocities. The macro turbulent velocity is supposed to be constant with depth.

The inversion is optimized to obtain the best solutions for the umbra (including umbral dots, light bridges and dark background), the penumbra (including dark and bright fibrils) and quiet Sun.
Initialisation of parameters

- may find a local minimum

- we provide closest values of each parameters to each pixel

- how do we do it?

- re-iterate/re-invert full sunspot unless the lowest chi-square is achieved

- it really helps!!
Early Inversions

- Good/smooth outputs for other parameters except temperature
- Problem: Intensity was normalized to continuum
- Solution: I normalize to a standard/known quiet Sun atmosphere
I normalised to Harvard-Smithsonian Reference Atmosphere (HSRA)

- fixes the Intensity problem

- problem: ring like structures in middle penumbra appears: fits became poorer

- overall: solutions over full sunspot seems unrealistic
There are three possibilities for problem:

1. our atmospheric model is too simple
   (unlikely, as we have tried many)

2. limited resolution (multiple components)

   profiles depicting 2\textsuperscript{nd} component->

3. some instrumental effect in the data
Telescope diffraction:

because of telescope diffraction, the observed data is degraded and much of the signal directed to a pixel go to neighbouring pixels and vice-versa: local stray light!

- blurred polarization signals
- loss of contrast

Orozco Suarez et al., 2007 first tried to correct this for a quiet Sun region observed by Hinode (SOT/SP) using unpolarized straylight
Local stray light correction: I. Unpolarized straylight

- We use instrumental psf: ~76% of light from neighbouring pixels
- stray light fraction $\alpha$ fitted

- problem: $I_c$ unrealistic
- $\alpha$ maps/values inconsistent with instrumental psf
Local stray light correction: II. Polarized stray light

- psf convolved with all Stokes profiles I, Q, U and V
- $\alpha$ fixed at 76%

- all parameters: smooth
- fits: good! contrast: gained
- overall: code seems to find realistic solutions: 1D best inversion results
- BUT stray light computed from solution not consistent with stray light used in inversion
2D inversions (Michiel’s SGS next Tuesday: 10th July)

- Spatial coupling of profiles to adjacent pixels
- NO stray light
- increases contrast drastically & resolution can go up to diffraction limit
- profile fits: excellent!
- all parameters: smooth
- overall: code seems to find most consistent solutions (self-consistent)
- no signal is lost due to subtraction
- stable to spatial oversampling of the solution

: 2D best inversion results
: 2D doubled resolution inversions
Comparison of results obtained from 1D and 2D inversions

- ~ 1/4\textsuperscript{th} of sunspot; 12 contours
- comparing output maps
- comparing profile fits
- comparing 3D structures of local pixels
- scatter plots
- comparing azimuthal averages: global properties
Scatter plots
Field gradients in umbra; 2D more realistic?

Inner-middle penumbra: similar except at log\(\tau\)~0

Middle-outer penumbra: ~similar
Field inclination in umbra; 2D better?

inner-middle penumbra: similar except at logτ~0

middle-outer penumbra: similar
Temperature: seems good match everywhere!
velocity in umbra 2D more correct?
inner-middle penumbra: matches
outer penumbra: 1D steeper; 2D more realistic?
Conclusions

USE 2D inversions

or

if using 1D inversions

must include polarized local stray light corrections

Future Plans

Sunspot

Global Properties (Magnetic, Thermal and Velocity)
Fine Scale Structures
Equilibrium Forces
Thanks!