MAX PLANCK INSTITUTE
FOR SOLAR SYSTEM RESEARCH

Disambiguation of vector magnetograms by stereoscopic observations from SDO/HMI and Solar Orbiter/PHI

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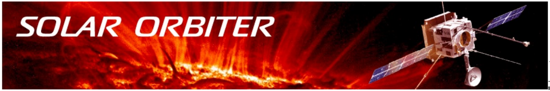
ESPM-16
6 - 10 September 2021, WWW



PHI

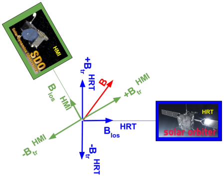
Stereoscopic opportunity

Inversion of spectropolarimetric (SP) observations provides estimations of $\vec{B}$ in

- amplitude
- inclination with respect to observer
- direction **but not orientation** of transverse component

$\Longrightarrow$ ambiguity in the orientation of the transverse component

The ambiguity is a **parity problem** (Semel *et al.*, 1998) of the transverse component $B_{tr} > 0$ in each pixel of the **detector image plane**:



$$\vec{B} = \vec{B}_{los} + \sigma B_{tr} \vec{t}, \qquad \text{with } \sigma = \pm 1$$

$\Longrightarrow$ disambiguation $\equiv$ fixing σ in each pixel

New possibility opened by SO:
Use observations from SDO to remove the B_{tr}-ambiguity on SO (and vice versa)

There are three aspects to this problem

- Geometry of the problem
- Finite (and variable) resolution of detectors
- Effect of viewing angle on spectropolarimetric observations ($\Longrightarrow$ on disambiguation)

Geometry

Find the relation between the field components on the SDO and SO image planes

Choose

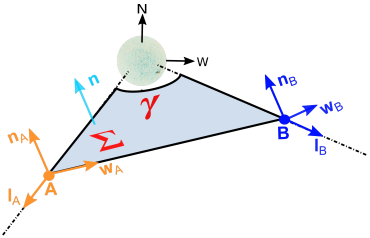
- Plane Σ through SDO (A), SO (B), and the Sun, with normal $\vec{n}$
- Telescope reference system using line-of-sight (LoS) and $\vec{n}$

One can show that the sign of the transverse component is given by

$$\sigma = \frac{B^{\mathrm{B}}_{\mathrm{los}} - B^{\mathrm{A}}_{\mathrm{los}} \cos\gamma}{B^{\mathrm{A}}_{\mathrm{w}} \sin\gamma} = \pm 1$$

where

- $\vec{B}_{\mathrm{los}}$ and B_{w} with azimuth on $[0, \pi]$
- γ is the SDO - SO separation angle



Hence the **stereoscopic disambiguation method (SDM)**

- in principle, solves the disambiguation problem exactly
- provides σ as an analytical expression at all γ (no assumptions made)
- may fail at locations where σ is undefined $\Longrightarrow$ confidence maps

Variable resolutions

SO has a highly eccentric orbit $\Longrightarrow$ How does the SDM depend on resolution?

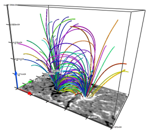
Test on synthetic magnetograms

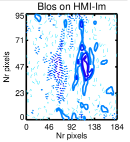
- extract a “photosphere” from different solar-relevant simulations
- reproject from different SO distances/resolutions (r_Δ) and γ
- remove parity and apply the SDM

For instance, for a Pencil simulation of an AR, the rate of success (η) is $\simeq$ 100% except for

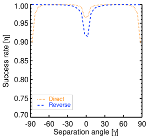
- $\gamma \simeq 0$ (no stereoscopy)
- $\gamma \simeq \pm\pi/2$ quadrature
- when HRT/FDT is used to disambiguate HMI (still above 80%)

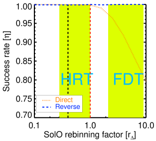
Combining different test fields and effects (errors, calibration, noise etc) we can study the dependence of the SDM method on several source of inaccuracies in different areas of relevance





3D view (left) and magnetogram (right)



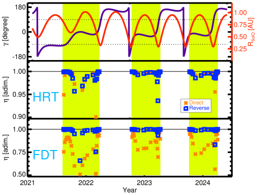


$\eta(\gamma, r_\Delta = 0.6)$; $\eta(\gamma = 40^\circ, r_\Delta)$

Application to SO orbit

- SO orbit links γ and r_Δ
- Select a test field (here Pencil-AR)
- Add estimations of error sources (here none)

$\Longrightarrow$ estimation of the SDM accuracy at each SO position



Right: Accuracy of SDM as a function of SO orbit; green areas corresponds to $\gamma \in [-\pi/2; \pi/2]$

Optical path and γ

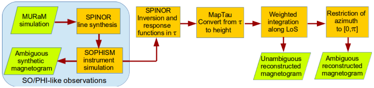
Even pointing at the same spatial location, emission may come from different plasma parcels

Different $\gamma \Longrightarrow$ different optical paths $\Longrightarrow$ different plasma conditions $\Longrightarrow$ emission from different heights

- How big is this effect?
- How is SDM affected by it?

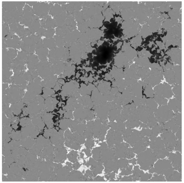
Use **reconstructed magnetograms**: PHI-like observation of simulated emission from Muram simulations of pore and quiet sun $\Longrightarrow$ observation-like magnetograms that retains parity information ($\Longrightarrow$ usable as a test)

Reconstructed magnetograms

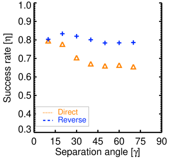


- Synthetic PHI obs. of Muram-QS (SOPHISM)
- Fitted model atmosphere (SPINOR)
- τ-dependent responce functions (SPINOR)
- γ-dependent reconstruction of contributions
- Instrumental degradation

Apply SDM to reconstructed magnetograms (with parity information removed!)



- Constraint from simulation: r_Δ=1 $\Longrightarrow$ SO/HRT at 1AU
- Not much lower η than geometrical case ($\simeq$ 80-85%)
- HRT/FDT (reverse) better than HMI (direct)
- From geometrical case: 10-15% higher η is expected at smaller r_Δ
- η grows from 80% to 95% (reverse) for field above 500 G
- $\Longrightarrow$ accuracy mostly affected in weak-field areas



Accuracy above 90% can be reached even on QS despite combined effect of SP and geometry

For more information on

- applications to active region, pore, and quiet-sun test fields
- effects of measurements errors and field strength
- preliminary study of optical path effects

see the electronic material on the conference website
Poster session 3.2

and our submitted article on Solar Physics

Disambiguation of vector magnetograms by stereoscopic observations from SDO/HMI and Solar Orbiter/PHI

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Thank you for your attention
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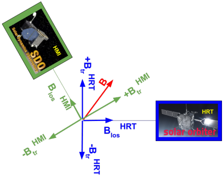
Stereoscopic view

The ambiguity is a **parity problem** (Semel *et al.*, 1998) of the transverse component $B_{tr} > 0$ in each pixel of the **detector image plane**:



$$\vec{B} = \vec{B}_{los} + \sigma B_{tr} \vec{t}, \qquad \text{with } \sigma = \pm 1$$

$\Longrightarrow$ disambiguation $\equiv$ fixing σ in each pixel

New possibility opened by SO:
Use observations from SDO to remove the B_{tr}-ambiguity on SO (and vice versa)

- At finite SDO-SO angles, the (unambiguous) HMI-LoS vector has a component along the (ambiguous) transverse HRT vector (and vice versa)
- Similarly, the orientation of the B_{tr} on the two detectors are also (less intuitively) related

There are three aspects to this problem

- Geometry of the problem
- Finite (and variable) resolution of detectors
- Effect of viewing angle on spectropolarimetric observations ($\Longrightarrow$ on disambiguation)

Geometry

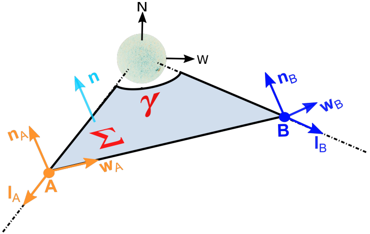
Relation between the field components on the SDO and SO detector planes

- Plane Σ through SDO, SO, and the Sun, with normal $\vec{n}$
- For each detector, define a reference system such that
  - $\vec{l}$ is along the LoS
  - $(\vec{w}, \vec{n})$ is the (rotated) image plane

  linking of the components along $\vec{n}$

  $\Longrightarrow$ 2D problem with only one σ
- Equating $\vec{B} = \vec{B}_{\rm los} + \sigma B_{tr} \vec{t}$ in the two detectors A and B

$$\sigma = \frac{B^{\rm B}_{\rm los} - B^{\rm A}_{\rm los} \cos\gamma}{B^{\rm A}_{\rm w} \sin\gamma}$$



Input:

$\vec{B}_{\rm los}$ and $B_{\rm w}$ with azimuth on $[0, \pi]$

γ detectors separation angle

Alternative expression:

$$\tilde{\sigma} = \frac{B^{\rm A}_{\rm los} \sin\gamma}{B^{\rm A}_{\rm w} \cos\gamma - B^{\rm B}_{\rm w}}$$

In principle, with two viewpoints the disambiguation problem is solved exactly

$\Longrightarrow$ σ is given by an analytical expression at all γ (no assumptions)

$\Longrightarrow$ Allows to study the effect of finite (and variable) resolution of telescopes

Geometrical tests

Tests

Construction of geometrical tests

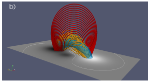
- Magnetogram: extract one layer from simulations
- Build a series of inclined views of the magnetogram
  - Detector A: SDO/HMI is the view from the top
  - Detector B: SO/HRT-FDT is the view at a finite γ (fore-shortening + rotation of $\vec{B}$)
- Remove parity information from both magnetograms (azimuth within $[0; \pi]$)

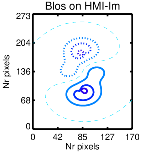
Apply the sterescopic disambiguation method (SDM)

- different γ at the same SO-distance (orbital position)
- different SO-distance for the same γ, variable resolution as $r_\Delta = \Delta_{SO}/\Delta_{HMI}$
- direct : disambiguate $\vec{B}_{tr}$ of HMI using HRT-FDT
- reverse : disambiguate $\vec{B}_{tr}$ of HRT-FDT using HMI ($A \rightarrow B$)

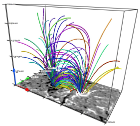
η = fraction of successfully disambiguated pixels

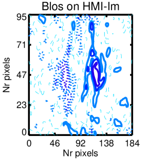
TD: Smooth and resolved



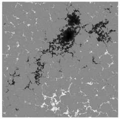


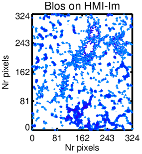
Pencil: AR-like, mix of large and small scales





Muram: Pore in quiet sun





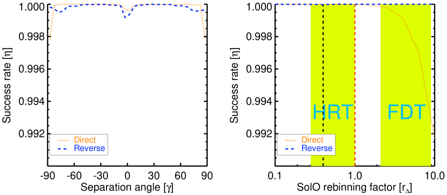
Simulations LoS magnetograms

Proof of concept : TD

Fraction of correctly disambiguated pixels [η] as a function of

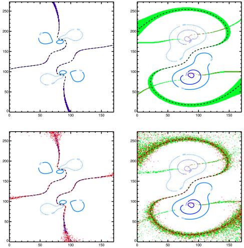
- Separation [$\gamma, r_\Delta = 0.6$] : $\simeq$100%
- Resolution [$r_\Delta, \gamma = 40^\circ$] : 100% the HRT range, 99% at end of FDT
- For both direct and reverse

$\Longrightarrow$ In ideal conditions (smooth and resolved) SDM reaches 100% accuracy



Left: $\eta(\gamma, r_\Delta = 0.6)$; Right: $\eta(r_\Delta, \gamma = 40^\circ)$

Since the SDM equations are exact, then error-prone areas are known!



Left: Maps of errors (red dots) for σ on HMI and $\tilde{\sigma}$ on HRT, without (top) and with (bottom) noise added

Errors in disambiguation may occur where

- $B_\mathrm{w} \simeq 0$ (violet, left column) for σ
- or $\vec{B}_\mathrm{los} \simeq 0$ (green, right column) for the $\tilde{\sigma}$
- This is better seen when noise is added to the test field (bottom row)

- ▶ Error prone areas can be identified before disambiguation
- ▶ Combine σ and $\tilde{\sigma}$ to maximize accuracy

$\Longrightarrow$ SDM includes confidence maps!

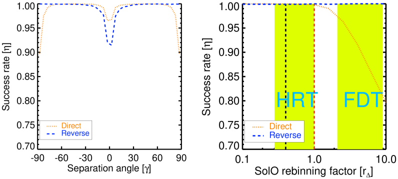
Less idealized tests

Pencil (AR-like)

Accuracy $\simeq$ 100% except for

- $\gamma \simeq 0$ (no streoscopy)
- $\gamma \simeq \pm\pi/2$ quadrature
- when HRT/FDT is used to disambiguate HMI (still above 80%)

$\Longrightarrow$ $\simeq$100% accuracy also on AR-like field, but first clear effects of resolution on η



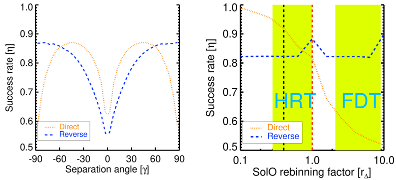
Left: $\eta(\gamma, r_\Delta = 0.6)$; Right: $\eta(\gamma = 40^\circ, r_\Delta)$

Muram (QS-like)

Accuracy is strongly varying according to

- γ, best for $\gamma \simeq 40^\circ$
- HRT range up to 95% at perihelion
- FDT below 60% (competes with the coin)

$\Longrightarrow$ Even for QS there are operability windows to apply the SDM



Left: $\eta(\gamma, r_\Delta = 0.6)$; Right: $\eta(\gamma = 40^\circ, r_\Delta)$

$\Longrightarrow$ SDM works, but what are the main source of errors?

Parametric studies

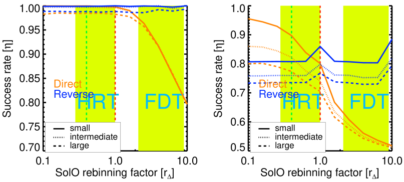
Effect of measurement errors on success rate

Adding a simple error model as = $S + \vec{E} * \vec{B}$ with absolute (S) and relative (E_x) contributions

Case	$S\,(G)$	$E_x = E_y$	E_z
small	0.01 (20)	0.05	0.01
intermediate	0.035 (70)	0.30	0.05
large	0.05 (100)	0.50	0.30

- Affects mostly higher resolution
- Hardly any effect on Pencil-AR
- Significant (6-10%) for HRT
- Small effect on FDT

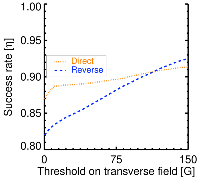
$\Longrightarrow$ Mostly QS-area from FDT, expected



$\eta(r_\Delta, \gamma = 40^\circ)$ for Pencil-AR (left) and Muram-QS (right)

Threshold on included pixels

Success rate improves if only pixels with $|B_{tr}|$ above threshold are counted (e.g. $\gamma = 40^\circ$, $r_\Delta = 0.6$)



$\Longrightarrow$ Up to 10% better for 150G Muram QS

Several other tests were performed:

- Mix of SDM formulae
- Interpolation technique (linear,cubic, spline)
- Resolution of the test field (effect of un-resolved scales)

which indicate possible improvements

- Fine-tuning using error maps
- Dedicated interpolation methods (weighted nearest-neighbour)

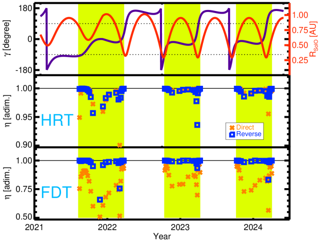
Stereoscopic disambiguation

Combining different test fields and effects we can study the dependence of the SDM method on several source of inaccuracies in different areas of relevance

- Translate SO orbit into γ, r_Δ
- Select a test field (here Pencil-AR)
- Add estimations of error sources (here none)

$\Longrightarrow$ estimation of the SDM accuracy at each SO position

Right: Accuracy of SDM as a function of SO orbit; green area corresponds to $\gamma \in [-\pi/2; \pi/2]$



But ... are we actually measuring the same field?

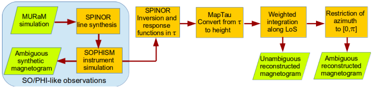
Optical path and γ

Study the effect of viewing angle γ on the $\vec{B}$ obtained from spectroplarimetric (SP) inversion

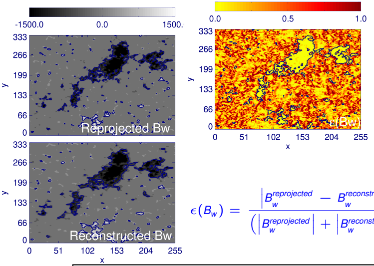
- How big is this effect?
- How is SDM affected by it?

Use **reconstructed magnetograms**: PHI-like observation of simulated emission from Muram-QS to get observed magnetograms that retains parity information ($\Longrightarrow$ usable as a test)

Reconstructed magnetograms



- Synthetic PHI obs. of Muram-QS (SOPHISM)
- Fitted model atmosphere (SPINOR)
- τ-dependent responce functions (SPINOR)
- γ-dependent reconstruction of contributions
- Instrumental degradation



$$\epsilon(B_w) = \frac{\left|B_w^{reprojected} - B_w^{reconstructed}\right|}{\left(\left|B_w^{reprojected}\right| + \left|B_w^{reconstructed}\right|\right)}$$

Optical path effect: Compare the two SP inversions

Reprojected	observed at $\gamma = 0^\circ$, reprojected at $\gamma = 40^\circ$
Reconstructed	observed at $\gamma = 40^\circ$

Differences due to SP are

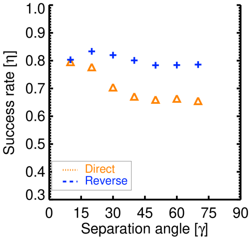
- Qualitatively small
- Quantitatively significant, especially on weak field
- No SDM, only SP effects!
- Strong field areas are unaffected

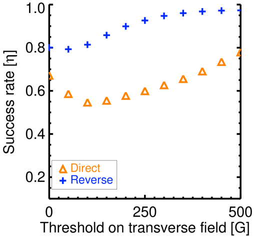
Observations from different angles differ in measured values

Effect on SDM

Apply SDM to reconstructed magnetograms (with parity information removed!)

- Constraint from simulation: r_Δ=1 $\Longrightarrow$ SO/HRT at 1AU
- Not much lower η than geometrical case ($\simeq$ 80-85%)
- HRT/FDT (reverse) better than HMI (direct)
- From geometrical case: η at smaller r_Δ is expected to be 10-15% higher





Accuracy is mostly affected in weak-field areas

- at $\gamma = 40°$ ($r_\Delta = 1$)
- Considering pixel with field above threshod
- η grows from 80% to 95% (reverse)
- To be repeated for AR / shorter distance (new simulations)

Muram-QS is a very challenging test!

Accuracy above 90% can be reached even on QS despite combined effect of SP and geometry

Conclusions

Stereoscopic disambiguation method

Geometrical tests

- 100% accuracy in idealized conditions
- For high-res (HRT), $\simeq$100% for ARs
- Full characterization of orbit, measurement errors, method parameters
- Up to 95% accuracy even in quiet sun
- Confidence maps of disambiguation

SP effects

- Viewing angle affects measured $\vec{B}$
- Weak-field areas are more prone to SP effects
- Range accuracy 80-90% in QS depending on field strength

Operability windows can be defined that maximise accuracy $\Longrightarrow$ observation planning

Outlook

- Apply to Muram simulations of sunspot (big numerical effort)
- Benchmark against traditional, single-view disambiguations methods
- Application to PHI observations soon ...