Alternative method for the removal of the 180° ambiguity in the sign of the observed transverse photospheric magnetic field

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Abstract. A relatively simple method for the removal of the 180° ambiguity in the azimuth of the observed transverse photospheric magnetic field is proposed; it applies to both center of disk and off-disk center observations.

The method consists in selecting that sign which corresponds to a decrease with height of the heliographic magnetic field \( B = (B_x^2 + B_y^2 + B_z^2)^{1/2} \). For this, the observed field components at a point \( P \) have to be first transformed into heliographic components (at the same point) and then the selection rule must be applied.

The method was tested in twenty different cases of force-free field and potential magnetic configurations for which analytical solutions are available. From these models, by appropriate transformations, “observed” field components – with undetermined sign of the transverse component – were first calculated. After application of the method to these simulated observations, the heliographic analytical solutions were used as a bench mark test.

Both center of disk and off-disk center cases were considered; in the last case, all latitude angles between 0° and 90° were treated. The results were expressed as percentage of success in determining the correct sign of the observed transverse component as a function of the complexity of the heliographic magnetic field configuration as well as of the value of the latitude angle, \( \theta \).

In the center of disk case, the percentage of success varies between 100% and a minimum of about 90%, as depending on the complexity of the magnetic configuration; the performance of the method can be further improved by increasing the number of grid points. In the off disk-center case, the method is limited to relatively low latitude angles.

Finally, a comparison of the performances of this method with the magnetic shear-based method in removing the 180° ambiguity in sign, for all the cases mentioned above, is also presented.

Key words: Sun: magnetic fields – Sun: photosphere

1. Introduction

Modern vector magnetographs allow the determination of the three photospheric components, say \( B_x, B_y \) and \( B_z \), up to an intrinsic 180° ambiguity in the azimuth of the transverse component, \( B_\perp \) \((B_\perp = B_x^2 + B_y^2)^{1/2}\); this ambiguity in sign is due to the fact that \( +B_\perp \) and \( -B_\perp \) are indistinguishable in polarization measurements (see e.g. Haggard 1985).

An approximate but useful description of the coronal magnetic configurations is provided by the force-free field model, which strictly holds when the electrical currents are parallel to the magnetic fields: \( j(r) = \alpha(r) \cdot B(r) \), \( \alpha(r) \) being the force-free field function and \( r \) the position vector (see e.g. Levine 1975; Low 1985; Gary 1988).

Within the framework of force-free field (FFF) models, several methods for the removal of the 180° ambiguity in the azimuth of \( B_\perp \) have been proposed (see e.g. Haggard et al. 1984; Sakurai et al. 1985, 1987; Gary et al. 1987; Aly 1989; Cupe*man et al. 1989; Cupe*man et al. 1992). For example, the magnetic shear-based method consists of the evaluation of the azimuth angle between the observed transverse field component, \( \varepsilon B_\perp \) \((\varepsilon = \pm 1)\) and that of a potential field, \( B_{\perp,\text{p}} \), calculated by using the line-of-sight component as the boundary condition for the field normal to the image plane, \( B_{\perp,\text{p}} \) (Haggard et al. 1984). The true direction of \( B_{\perp,\text{p}} \) \((\varepsilon = 1 \text{ or } \varepsilon = -1)\) is chosen such that \( B_\perp \) and \( B_{\perp,\text{p}} \) make an acute angle: \( B_\perp \cdot B_{\perp,\text{p}} > 0 \) or \(-90° - \eta^0 \leq \Delta \Omega \leq 90° - \eta^0 \), where \( \Delta \Omega \) is the relative azimuth angle (also called magnetic shear) and \( \eta^0 \neq 1 \).

In this work we present an alternative method for the removal of the 180° ambiguity in sign applying to both center of disk and off-disk center observations. The method consists in selecting for \( B_\perp \) \((x, y, z)\), the sign which corresponds to a decrease with height of the heliographic magnetic field \( B(x, y, z) \), \( B = (B_x^2 + B_y^2 + B_z^2)^{1/2} \).

For this, the observed field components at a point \( P \) have to be first transformed into heliographic components (at the same point) and then the selection rule must be applied.

This paper is organized as follows: In Sect. 2 we (1) describe in detail the method for the removal of the 180° ambiguity in the azimuth of \( B_\perp \); (2) define the geometry and the systems of coordinates involved; and (3) describe the analytical FFF-models used to simulate observed magnetic field components as well as bench mark tests. In Sect. 3 we present the results obtained for (1) center

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of disk observations and (2) off-disk center observations, for
latitude angle \( \theta \) ranging between 0° and 90°. Also, we compare
the performance of the present method with those of the mag-
netic shear-based method, for the same models and latitude
angles. In Sect. 4 a summary of results and conclusions are
presented.

2. Method and models

2.1. Method

Let \((x, y, z)\) and \((x', y', z')\) be, respectively, heliographic and
measuring (i.e. the terrestrial viewer's) coordinate systems.

Photospheric vector magnetograph measurements provide
the line-of-sight field component \( B_x \) to and the transverse com-
ponent in the image (i.e. sky) plane, \( \varepsilon B_x, \varepsilon = \pm 1 \). This is equivalent to
providing \( B_x', (B_x', B_y', B_z') \), \( |B_x'| \) and \( |B_y'| \).

Interpreting the measurements, the following possibilities exist:

If \((B_x', B_y') > 0\):

\[ B_x > 0, \quad B_y > 0 \]

or

\[ B_x < 0, \quad B_y < 0 \]

If \((B_x', B_y') < 0\):

\[ B_x > 0, \quad B_y < 0 \]

or

\[ B_x < 0, \quad B_y > 0 \]

In this work, within the framework of the force-free field
model, we remove the ambiguity in the sign of \( B_z \) by selecting
from Eqs. (1a) and (1b) [or, from Eqs. (2a) and (2b)] that possibility
which corresponds to a decrease with height, \( z \), of the true,

\[ \frac{\partial}{\partial z} B^2 < 0, \]

where \( B^2 = B_x^2 + B_y^2 + B_z^2 \). The implementation of the method
requires the use of the steps to be described henceforth.

2.2. FFT equations and consequences

The steady state equations describing force-free magnetic field
configurations are

\[ \nabla \times \mathbf{B} = 2 \mathbf{B} \]

and

\[ \nabla \cdot \mathbf{B} = 0. \]

Equation (4) merely states that the electric current density
\( J = (4\pi)^{-1} \mathbf{V} \times \mathbf{B} \) is proportional to the magnetic field \( \mathbf{B} \).

Upon cross multiplying Eq. (4) by \( \mathbf{B} \) one finds

\[ \nabla \times (\nabla \times \mathbf{B}) = 0. \]

Utilizing the identity

\[ \mathbf{B} \times (\nabla \times \mathbf{B}) = \frac{1}{2} \nabla B^2 - (\mathbf{B} \cdot \nabla) \mathbf{B}, \]

Eq. (6) becomes

\[ \frac{1}{2} \nabla B^2 = (\mathbf{B} \cdot \nabla) \mathbf{B}. \]

In Cartesian coordinates, the \( z \)-component of Eq. (5) becomes

\[ \frac{1}{2} \frac{\partial}{\partial z} B^2 = \left( B_x \frac{\partial}{\partial x} + B_y \frac{\partial}{\partial y} + B_z \frac{\partial}{\partial z} \right) B_z. \]

Finally, inserting Eq. (5) into Eq. (9) one obtains

\[ \frac{1}{2} \frac{\partial}{\partial z} B^2 = B_x \frac{\partial B_x}{\partial x} + B_y \frac{\partial B_y}{\partial y} - B_z \left( \frac{\partial B_x}{\partial x} + \frac{\partial B_y}{\partial y} \right). \]

Equation (10) expresses the change of the magnetic field
\( \mathbf{B} = (B_x^2 + B_y^2 + B_z^2)^{1/2} \) with the height, \( z \), in the local (heliographic)

system of coordinates in which the \( z \)-axis points in the outwards
radial direction (see Fig. 1).

2.3. Transformation from heliographic
to measuring coordinates

We now consider the case of off-disk center observations allow-
ing for arbitrary latitude deviations.

2.3.1. Heliographic coordinates, \((x, y, z)\)

Let \( P, C \) and \( O \) represent, respectively, a point of observation, the
center of the disk and the center of the Sun. A local (heliographic)

system of cartesian coordinates with the origin at \( P \) can be
defined by taking the \( z \)-axis along the outwards radial direction
(continuation of the line \( OP \)) and \( x, y \) along the two directions
tangent to the surface at \( P \), as shown in Fig. 1.
2.3.2. Observation or image plane coordinates, \((x', y', z')\)

Let \(e_{x', y'}\) and \(e_{z'}\) be, respectively, the unit vectors indicating the center-of-disk–center-of-earth and \(P–\)center-of-earth directions. To a good approximation, \(e_{x', y'} \parallel e_{x'}\); then, the angle between \(e_{x', y'}\) and OP, \(\theta\), is the same as that between \(e_{x'}\) and OP. The observation system of coordinates is now defined by the unit vectors \(e_{x', y'}\), \(e_{x'}\), and \(e_{y'}\), where \(e_{x'} \perp e_{y'}\) and \(e_{y'}\), is transverse to the plane \((e_{x'}, e_{y'})\) (see Fig. 1).

Now, measuring the field components \(B_x', B_y', B_z'\), \(B_x\), \(B_y\), and \(B_z\) at a point \(P\) and knowing the latitude angle \(\theta\), the heliographic (true) field components \(B_x, B_y, B_z\) may be evaluated by using the following transformations:

\[
\begin{align*}
B_x &= B_x' \cos \theta - B_y' \sin \theta, \\
B_y &= B_y', \\
B_z &= B_z' \sin \theta + B_x' \cos \theta.
\end{align*}
\]

(11)

The inverse transformations are

\[
\begin{align*}
B_x' &= B_x \cos \theta + B_y \sin \theta, \\
B_y' &= B_y, \\
B_z' &= -B_x \sin \theta + B_z \cos \theta.
\end{align*}
\]

(12)

Upon substituting Eq. (11) into Eq. (10), after some rearrangements, one obtains the local (heliographic) change with height \((z)\) of the true magnetic field, \(B^2 = B_z^2 + B_x^2 + B_y^2\), in terms of the measured field components \(B_x', B_y', B_z'\), \(B_x, B_y, B_z\), i.e.

\[
\frac{1}{2} \frac{\partial}{\partial z} B^2 = \left( B_y \frac{\partial B_x'}{\partial y} - B_x' \frac{\partial B_y'}{\partial y} \right) \sin \theta + \left( B_y' \frac{\partial B_z'}{\partial y} - B_z' \frac{\partial B_y'}{\partial y} \right)
\]

\[
\times \cos \theta + \left( B_z' \frac{\partial B_z'}{\partial x} - B_x' \frac{\partial B_z'}{\partial x} \right).
\]

(13)

Thus, by using Eqs. (3) and (13), the ambiguity in sign of the observed transverse field component may be removed.

Obviously, the method applies for both center-of-disk and of-disk-center observations. In the center of disk case, \(\theta = 0\), the first term in the r.h.s. of Eq. (13) vanishes; the second and the third terms change sign under the transformation \(B_x' \rightarrow -B_x\) and \(B_y' \rightarrow B_y\), thus, enabling the selection of the proper sign for which the inequality (13) is satisfied. In the off-disk center case, however, the first term in the r.h.s. of Eq. (13) is finite and invariant under the transformation \(B_x' \rightarrow B_x\); Thus, for observations at \(\theta \neq 0\), one expects the method to apply when the absolute value of the sum of the second and third term in the r.h.s. of Eq. (13) is larger than that of the first term.

### 2.4. Models

As a convenient way to generate various types of photospheric magnetic configurations we use the analytical force-free field model developed by Low (1982). In this model, the magnetic configuration is produced by electric currents satisfying the FFF conditions \(\nabla \times \mathbf{B} = \alpha \mathbf{B}\) everywhere, except along the line \(y = 0, z = -a\) (below the photosphere) where an infinite straight line current is flowing. At the photosphere \((z = 0)\), the field components are

\[
\begin{align*}
B_x &= -\frac{aB_\alpha}{r} \cos \phi(r), \\
B_y &= \frac{aB_\alpha y}{r(y^2 + a^2)} \cos \phi(r) - \frac{a^2 B_\alpha}{y^2 + a^2} \sin \phi(r), \\
B_z &= \frac{a^2 B_\alpha r}{y^2 + a^2} \sin \phi(r) + \frac{aB_\alpha y}{r(y^2 + a^2)} \sin \phi(r),
\end{align*}
\]

(14)

and

\[
\begin{align*}
B_x &= \frac{a^2 B_\alpha r}{y^2 + a^2} \sin \phi(r) + \frac{aB_\alpha y}{r(y^2 + a^2)} \sin \phi(r), \\
B_y &= \frac{a^2 B_\alpha r}{y^2 + a^2} \sin \phi(r) - \frac{aB_\alpha y}{r(y^2 + a^2)} \sin \phi(r),
\end{align*}
\]

(16)

where \(B_\alpha\) is the magnitude of the field at the origin, and

\[
r^2 = x^2 + y^2 + a^2.
\]

(17)

\(\phi(r)\) represents a free generating function related to the FFF function \(x(r)\) by

\[
x(r) = -\frac{\partial \phi(r)}{\partial r}.
\]

(18)

Thus, from the heliographic field components \(B_x, B_y, B_z\) represented by Eqs. (14)–(16), and applying the transformation equations (12), one may obtain the transformed components \(B_x', B_y', B_z'\), and subsequently use \(B_x', B_y', B_z'\) and \(B_{x1}, B_{y1}, B_{z1}\) to simulate the actual observed set of data. Here, we test the method for the removal of the 180° ambiguity in the sign of the transverse field component for a variety of FFF magnetic configurations chosen to simulate various possible physical situations, namely (see Table 1 and Figs. 2–4):

- Model 1: relatively weak spatial dependence
- Model 2: relatively strong spatial dependence
- Model 3: mixed FFF-potential configurations
- Model 4: sign-changing \(\phi\) (and \(x\))
- Model 5: analytical potential case

For each of these models, four maximal values of \(\phi, |\phi|_\text{max}\), are considered, namely \(|\phi|_\text{max}/\phi_0 = 0.5, 1, 2, 4\), with \(\phi_0 = \pi/2\); the corresponding maximal \(x\)-values, \(|x|_\text{max}/(\pi/2)\), are the same as those for \(|\phi|_\text{max}\), except Model 4 where \(|x|_\text{max}/(\pi/2) = 1, 2, 4, 8\). Thus, the notations Model 1-1, 1-2, 1-3 and 1-4, for example, refer to the four constant \(|\phi|_\text{max}/\phi_0\) values chosen for the model 1, etc. We notice the consideration also of the potential configurations, Model 5: although \(x = 0\) in all 1-1…4 cases, because of the different values of the constant \(C\), the phases and therefore the field values will be also different. Thus, Fig. 2 illustrates the dependence of the magnetic configuration (Model 1) on \(|\phi|_\text{max}/\phi_0\), the strength parameter. Figs. 3 and 4 show the structures of the magnetic configurations represented by models 1–4 for \(|\phi|_\text{max}/\phi_0 = 0.5\) and 4, respectively.

### 3. Results

#### 3.1. The case of center of disk photospheric observations

The procedure followed in the implementation of the method used in this work as well as the results obtained are illustrated

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1 The derivation of these model equations is carried out in a spherical system of coordinates and assumes azimuthal symmetry as well as a radial dependence leading, to \(\phi = \phi(r)\) and \(x = x(r)\). A transformation to cartesian, heliographic coordinates then provides the results [Eqs. (14)–(18)].
Table 1. Generating functions, φ(r) and corresponding α(r) functions for the force-free and potential magnetic fields considered in this work (see Sect. 2)

| Model {1} | [1-1] φ = 0.5*(π/2) ln r | α = −0.5*(π/2)/r |
|------------------------|----------------.|------------------|
|                       | [1-2] φ = (π/2) ln r | α = −(π/2)/r |
|                       | [1-3] φ = π ln r | α = −π/r |
|                       | [1-4] φ = 2π ln r | α = −(2π)/r |
| Model {2} | [2-1] φ = 0.5*(π/2) tanh r | α = −0.5*(π/2)/(cosh^2 r) |
|                       | [2-2] φ = (π/2) tanh r | α = −(π/2)/(cosh^2 r) |
|                       | [2-3] φ = π tanh r | α = −π/(cosh^2 r) |
|                       | [2-4] φ = 2π tanh r | α = −2π/(cosh^2 r) |
| Model {3} | [3-1] φ = (π/2) (cos 2r + sin 2r) | α = 0 |
|                       | [3-2] φ = (π/2) (cos 2r + sin 2r) | α = 0 |
|                       | [3-3] φ = π (cos 2r + sin 2r) | α = 0 |
|                       | [3-4] φ = 2π (cos 2r + sin 2r) | α = 0 |
| Model {4} | [4-1] φ = (π/4) (cos 2r + sin 2r) | α = 0 |
|                       | [4-2] φ = (π/2) (cos 2r + sin 2r) | α = 0 |
|                       | [4-3] φ = π (cos 2r + sin 2r) | α = 0 |
|                       | [4-4] φ = 2π (cos 2r + sin 2r) | α = 0 |
| Model {5} | [5-1] φ = π/4 | α = 0 |
|                       | [5-2] φ = π/2 | α = 0 |
|                       | [5-3] φ = π | α = 0 |
|                       | [5-4] φ = 2π | α = 0 |

Graphically for Model 1-4 in Fig. 5. Thus, Fig. 5a shows the “true” magnetic configuration: the solid (dashed) curves give the contours of the Bz component corresponding to north (south) polarity; the heavy solid contour represents the neutral line and the arrows correspond to the transverse magnetic field components, Bz. Figure 5b shows the “data” used in the calculations – notice the replacement of the arrows by headless-sticks to indicate that only the absolute values, |Bz|, are considered to be known. Figure 5c shows the result of the application of the method for the removal of the 180° ambiguity in Bz, upon using 128 × 128 grid points. Finally, in Fig. 5d, the computed vector field components, Bz, are compared with the true ones and the disagreement is indicated by “×” (the empty, unmarked regions correspond to a successful determination of the sign).

The effect of the grid points density on the results presented in Fig. 5 is illustrated in Fig. 6. Thus, increasing (decreasing) the number of grid points used in the calculations improves (worsens) the performances of the method. This indicates that the disagreement between the calculated fields and the true fields is due to computational errors. The same conclusion is valid for the other models and cases considered here. The overall results of the calculations carried out for the 20 cases indicated in Table 1 are shown in Fig. 7. Thus, Fig. 7a presents the percentage of success in removing the 180° ambiguity in the sign of the “observed” transverse magnetic field component, Bz, for models 1–4, as a function of the maximal value of the normalized FFF generating function, |φ|/max/|φ|0; these results were obtained with 128 × 128 grid points. Figure 7b shows the corresponding results obtained upon using an increased number of grid points, namely 256 × 256. As can be seen, a general improvement of the performances of the method over the 128 × 128 case (Fig. 7a) is achieved; this is consistent with the findings illustrated in Fig. 6. In the potential case, model 5, the success is always maximal.

From these results the following conclusions emerge: within the framework of the FFF-model and the types of configurations considered in this work, the present method is able to determine satisfactorily the missing sign in the observed transverse field component. The percentage of success varies between a maximum of 100% (achieved in the potential cases, α=0; in all cases of model 2; and in the moderately nonlinear FFF cases, of models 1 and 3, namely 1.1 and 3.1) and a minimum of 91% (occurring in the most complex, sign-changing and nonlinear FFF case, model 4-4).

Finally, a comparison of the above results with those achieved upon using the magnetic shear-based method for the removal of the 180° ambiguity, indicates that the present ones are more satisfactory. This is illustrated in Fig. 8 showing the percentage of success in removing the 180° ambiguity in the sign of Bz, achieved by the two methods, upon using 128 × 128 pixels. It is worth mentioning that unlike the case of the present method, increasing the number of pixels does not improve the performances of the magnetic shear-based method.2

3.2. Off disk-center observation case

The observed off disk-center magnetic configurations can be very different from the true ones; moreover, they may be also more complex, and therefore, require more refined or special computational techniques. These features are illustrated in Figs. 9–11 showing, respectively, the structure of the configurations represented in Figs. 2–4, when viewed at a latitude angle of 45°.

2 The results in Figs. 7 and 8 pertain to the entire “observation domain” −L/2 ≤ x, y ≤ +L/2 shown in Figs 2, 3 etc. On the other hand, in Cuperman et al. 1992, in the study of the magnetic-shear based method, the corresponding results pertain to the smaller central region −L/4 ≤ x, y ≤ +L/4.
Fig. 2a–d. The FFF magnetic configuration described by Model 1 (see Table 1). The solid (dashed) curves give the contours of the $B_z$ components corresponding to north (south) polarity; the arrows represent the transverse magnetic field component, $B_y$. The heavy solid contours indicate the neutral lines. a, b, c and d correspond, respectively to cases 1.1, 1.2, 1.3, and 1.4.

Prior to summarizing the off disk-center-observation studies, we illustrate in Fig. 12 the results for the case considered in Fig. 5 (model 1-4) for $\theta = 30^\circ$. Here, the percentage of success is only 76%.

Finally, we used the present method to determine the actual sign of $B_z$ for “simulated” observed magnetic configurations characterized by all possible latitude angle, $0(0 \leq \theta \leq \pi/2)$, for all the cases listed in Table 1. The results, based on $256 \times 256$ grid points, are summarized in Fig. 14, giving the percentage of success as a function of $\theta$. Thus, when $\theta > 0$, the following results are found to hold:

(i) The success of the method depends on the complexity of the true magnetic configuration – the same success-ordering as in the $\theta = 0$ case is found, namely, models 2, 1, 3 and 4.
Fig. 3a–d. Same as in Fig. 2 for cases 1.1, 2.1, 3.1 and 4.1

(ii) The percentage of success decreases with increasing latitude angle, $\theta$ as well as the degree of FFF-linearity as expressed by the parameter $|\phi_{\text{max}}/\phi_0|$. This result, rather than being a consequence of the accuracy of computational method used, illustrates the intrinsic limitation of the method to relatively moderate latitude angles $\theta$ [see discussion following Eq. (13)].

(iii) In the potential case, the percentage of success is maximal for all latitude angles.

4. Summary
The implementation of the method proposed in this work for the removal of the $180^\circ$ ambiguity in the sign of the observed photospheric transverse magnetic field, $B_z$, reveals the following:
1. Within the framework of FFF and potential models and types of magnetic configurations considered, the method is able to remove satisfactorily the ambiguity in sign, in the case of center of disk observations.
2. The percentage of success varies between a maximum of 100% to a minimum of 91%. The maximum is achieved in the potential case ($z = 0$), in all cases of model 2 and in the moderately nonlinear other FFF cases (1.1 and 3.1); the minimum occurs in the complex, sign changing and strongly nonlinear FFF case, 4.4.

3. The percentage of success increases with increasing number of grid points (pixels) thus indicating that the disagreement between the calculated and true fields is due to computational errors. (The computation of the derivatives in the r.h.s. of Eq. (13) becomes less accurate when the computational mesh is too coarse).

4. A comparison of these results with those achieved upon using the magnetic shear-based method for the removal of the 180° ambiguity indicates that the present scheme is more satisfactory.

5. The percentage of success decreases with increasing latitude angle, $\theta$ as well as the degree of FFF nonlinearity, as expressed by the parameter $|\phi_{max}/\phi_0$ (see Eqs. (14)–(18) and

Fig. 4. Same as in Fig. 2 for cases 1.4, 2.4, 3.4 and 4.4
Fig. 5.  a Same as in Fig. 1.4; b The corresponding data used as "observations" for model 1.4 (notice the replacement of the arrows by headless-sticks, to indicate that only the absolute values of $B_z$ are considered to be known; c The results of application of the method – the computed vector field component $B_z$; d The failure of the method to determine the correct sign of $B_z$, indicated by "x". (Here, 256 x 256 grid points were used.)
Fig. 6a–d. Effect of the grid point density on the results obtained by using the present method, for the case 1.4. a–d correspond, respectively, to $32 \times 32$, $64 \times 64$, $128 \times 128$ and $256 \times 256$ grid points.
Fig. 7a and b. Summary of the results for the center of disk observation case: percentage of success in removing the 180° ambiguity in the sign of the "observed" transverse magnetic field component $B_z$ for models 1–4, as a function of the maximal value of the normalized FFF generating function, $|\phi_{\text{max}}/\phi_0|$ ($\phi_0 = \pi/2$). a 128 x 128 grid points; b 256 x 256 grid points. In the model-5 case, the success is 100%

points : 128*128

Fig. 8. Comparison of the performances of the present method (dashed curves) with those obtained by using the magnetic shear-based method (solid curves) for models 1–4. The ordinate and the abscissa are the same as in Fig. 7
Fig. 9a–d. Same as Fig. 2, for $\theta = 45^\circ$. 

points: $128 \times 128$

$\theta = 45$
Fig. 10a–d. Same as Fig. 3, for $\theta = 45^\circ$
Fig. 11a–d. Same as Fig. 4, for $\theta = 45^\circ$
Model {1_4}

points : 256x256

Fig. 12a–d. Same as Fig. 5, for $\theta = 30^\circ$
Model \{1_4\}

$\theta = 30^\circ$

Fig. 13a–d. Same as Fig. 6, for $\theta = 30^\circ$
Fig. 14a-d. Same as Fig. 7b, for latitude angles θ between 0° and 90°. a-d correspond, respectively, to models 1–4. For each of the models {1}–{4}, four cases were considered, namely |φ|/φ₀ = 0.5(--), 1.0(----), 2.0(-----) and 4.0(-----).

Table 1). This result, rather than being a consequence of the accuracy of computational method used, illustrates the intrinsic limitation of the method to relatively moderate latitude angle θ [see discussion following Eq. (13)].

6. In the potential case, the percentage of success is maximal for all latitude angles.

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