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Stokes inversion techniques: recent advances and new challenges

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Abstract. Inversion techniques (ITs) allow us to infer the magnetic, dynamic, and thermal properties of the solar plasma from polarization line profiles. These methods have improved our understanding of the solar atmosphere for over two decades. In the last years, major progress has resulted from the application of ITs to state-of-the-art observations. In this review I summarize the main results achieved both in the photosphere and in the chromosphere. I also discuss the challenges facing ITs in the near future. Understanding the limitations of spectral lines, implementing more complex atmospheric models in current ITs, and devising efficient strategies for the analysis of the data delivered by upcoming ground-based and space-borne instruments are among the most important issues that need to be addressed. It is argued that proper interpretations of diffraction-limited Stokes profiles will not be possible without accounting for gradients of the atmospheric parameters. The feasibility of determining gradients in real time from the observations provided by space-borne instruments is examined.

1. Introduction

We derive information on the physical properties of the solar atmosphere by interpreting the polarization profiles of spectral lines. Extracting this information is not easy, because the observed profiles depend on the atmospheric parameters in a highly non-linear manner through the absorption matrix and the source function vector. To disentangle these effects, least-squares inversion techniques (ITs) based on analytical or numerical solutions of the radiative transfer equation were developed in the past. These methods compare the observed Stokes profiles with synthetic profiles emerging from an initial guess model atmosphere. The misfit is used to modify the atmospheric parameters until the synthetic profiles match the observed ones. This yields a model atmosphere capable of explaining the observed profiles, within the assumptions and limitations of the model.

The first least-squares IT was proposed by Auer et al. (1977). Many other codes have been developed since then (cf. Table 1 in del Toro Iniesta 2003). Today we have an IT for almost any application we may be interested in (LTE or non-LTE line formation; one-component or multi-component model atmospheres; photospheric or chromospheric lines; etc). These codes have been used intensively to study the magnetism of the solar atmosphere, and now they are essential tools for the analysis of spectropolarimetric measurements.

Despite the achievements of least-squares ITs, there are still concerns among the community about the uniqueness of inversion results. In general, these concerns are not well founded. Most ITs have been shown to yield unique results independently of the initial guess, provided the model atmosphere is not changed (e.g., Ruiz Cobo & del Toro Iniesta 1992; Bellot Rubio et al. 2000; Socas-Navarro et al. 2000). Of course, the same observations analyzed in terms of more complex (and hopefully more realistic) atmospheres will produce different results. This, however, is a problem shared by all inference techniques. ITs make the problem explicit because it is easy to repeat the inversions adopting different physical scenarios, whereas other methods do not allow for that possibility. The main advantage of ITs over classical methods is that the assumptions may be varied to see the differences in the resulting model atmospheres. In any case, major efforts are being made to implement even more realistic models in current ITs, for a better interpretation of the observations.

This paper concentrates on recent achievements and future challenges of ITs. Additional information on ITs can be found in the reviews by del Toro Iniesta & Ruiz Cobo (1996), Socas-Navarro (2001) and del Toro Iniesta (2003).

2. Recent advances

During the last years there have been no significant improvements in classical least-squares ITs. In particular, no new algorithms have appeared and existing codes have not been optimized for speed. However, the experience accumulated has been used to develop new codes for specific purposes. The complexity of both atmospheric and line-formation models has also been increased. For example, a few years ago the most sophisticated inversions of Stokes profiles from sunspots were based on one-component models with gradients of the physical parameters (Westendorp Plaza et al. 2001), while two-component inversions are now performed on a routine basis (Bellot Rubio et al. 2004; Borrero et al. 2004). Recently, Sánchez Almeida (2005) has inverted a full spot in terms of micro-structured magnetic atmospheres. This model easily creates asymmetries in the profiles, reproducing the net circular polarization (NCP) of the Fe I 630 nm lines observed in the penumbra. Finally, Borrero et al. (2005) have gone one step further by inverting penumbral profiles in terms of an uncombed model. They use two different components which represent inclined penumbral flux tubes embedded in a more vertical magnetic field. The model is successful in reproducing the shapes of abnormal Stokes V profiles near the neutral line, for visible and infrared lines considered separately. The synthetic NCPs, however, are a bit smaller than the observed ones, implying that there is still some room for improvement.

An important advance in the field of Stokes inversions has been the development of fast inversion codes for real-time analysis of the huge volume of data expected from space-borne instruments. Other significant achievements have come from the application of classical ITs to state-of-the-art observations. These issues are examined in more detail in the next subsections.

2.1. Fast inversion codes

Conceptually, the simplest inversion is one that uses a look-up table. The idea is to create a database of synthetic Stokes profiles from a large number of known model atmospheres, and look for the profile in the database which is closest to the observed profile. The corresponding model is adopted as representative of the physical conditions of the atmosphere from which the profile emerged. Despite its simplicity, this method had seldom been put into practice until Rees et al. (2000) drew attention to Principal Component Analysis (PCA) as a means to accelerate the search in the look-up table. By virtue of PCA, the Stokes profiles can be expressed in terms of a few coefficients only. Using these coefficients, the comparison between observed profiles and those in the database is performed very quickly, because the calculation does not involve the many wavelength points describing the full line profiles. PCA forms the basis of a number of inversion codes developed in the last years.

The construction of the database is the most critical part of any IT based on look-up tables. Its size increases dramatically with the number of free model parameters and, as a consequence, the search becomes slower and slower. To keep the problem tractable, only Milne-Eddington (ME) atmospheres have been used to build databases for the inversion of photospheric lines. Even with this simplifying assumption, the space of model parameters is sampled coarsely. The discrete nature of the database introduces numerical errors, and so PCA-based inversions are less accurate than full ME inversions (e.g., Skumanich & Lites 1987). However, the method gives an idea of the quality of the fit in terms of the so-called PCA distance. When this distance is large, the observed profile cannot be associated with any profile in the database, making it possible to identify pixels that deserve closer attention.

A nice feature of PCA inversions is that the search algorithm is independent of the database. The synthesis of Stokes profiles may be very time-consuming, but the inversion will always be fast. This opens the door to the analysis of lines for which atomic polarization effects are important. López Ariste & Casini (2002) have developed a PCA inversion code to exploit the diagnostic potential of the Hanle effect in the He I D_3 line at 587.6 nm. The database is created using a line formation code which solves the statistical equilibrium of a quantum He atom with 5 terms, in the presence of magnetic fields. Coherences between fine-structure levels within each atomic term are accounted for to treat the Zeeman and Hanle regimes, including level crossing (incomplete Paschen-Back effect). This code has been applied to prominences (López Ariste & Casini 2003; Casini et al. 2003) and spicules (López Ariste & Casini 2005).

The speed of PCA inversions makes it possible to handle large amounts of data in real time. Since 2004, PCA is used at THEMIS to analyze MTR measurements of the Fe I 630 nm lines. Full maps are inverted in about 10 minutes, which is approximately the time needed to take the observations. At the telescope, PCA is very useful for quick-look analyses, allowing one to select interesting targets or to continue the observation of interesting regions. Of course, real-time analyses are appealing, but it is important to keep in mind the limitations of PCA inversions. In most cases, a proper analysis of the observations will require more sophisticated ITs which however can use the results of the PCA inversion as initial guesses.

Another promising technique explored in the last years is Stokes inversion based on artificial neural networks (ANNs). The idea was introduced by Carroll & Staude (2001) and developed by Socas-Navarro (2003, 2005a). Essentially, an ANN is an interpolation algorithm. One starts by setting up the structure of the network, that is, the number of layers and the number of neurons in each layer. The input layer receives the observations (the Stokes profiles or a suitable combination thereof) and the last layer outputs the atmospheric parameters we are looking for. Before applying the ANN to real data, it has to be trained. To this end, Stokes profiles synthesized using different ME atmospheres are presented to the ANN in order to find the synaptic weights and biases of the neurons that return the correct model parameters used to synthesize the profiles. The training process is very time-consuming but, once accomplished, the ANN will invert a full map in a matter of seconds. Indeed, ANNs are the fastest ITs available nowadays. For the moment, however, they have not been used in any scientific application.

Several strategies have been explored to optimize the performance of ANNs. It seems that the best choice is to invert one parameter at a time with a dedicated ANN. Finding all atmospheric parameters with a single ANN is possible, but requires a larger number of neurons and the training process becomes very complicated.

As shown by Socas-Navarro (2005a), the mean field strengths inferred with the help of ANNs are reasonably accurate from a statistical point of view. They resemble those provided by full ME inversions on average. However, the errors can be very large for individual pixels, as indicated by the large rms uncertainties (Fig. 8 in the above mentioned paper shows that the rms uncertainty for fields of 1.2 kG is 0.3 kG, i.e., 25%; the relative uncertainty is larger for weaker fields). This means that ANNs may be appropriate for quick-look analyses and other applications where high precision is not required. For detailed studies of physical processes, however, current ANNs seem not to be accurate enough.

A limitation of both PCA-based inversions and ANNs is the use of ME atmospheres, which precludes the determination of gradients of physical parameters from the observed profiles. It remains to be seen whether these methods can be modified to recover gradients along the line of sight in a reliable way. As discussed in Sect. 3.3, gradients appear to be essential for the analysis of very high angular resolution observations.

2.2. Application of ITs to state-of-the-art observations

Major breakthroughs have come from the application of ITs to state-of-the-art observations, particularly spectropolarimetric measurements in the near-infrared (IR), simultaneous observations of visible and IR lines, spectropolarimetry of molecular lines, and very high spatial resolution observations.

The development of polarimeters for the IR, most notably the Tenerife Infrared Polarimeter (TIP; Martínez Pillet et al. 1999), has opened a new window with lines that offer excellent magnetic sensitivity and chromospheric coverage. One example is the He I triplet at 1080.3 nm, which has become an essential tool to investigate the upper chromosphere. The formation of the triplet is complex and not really well understood. However, since the triplet lines are nearly optically thin, ME atmospheres provide a good description of their shapes. The first inversion code specifically designed for He I 1080.3 nm, HELIX, was presented by Lagg et al. (2004). It is based on the Unno-Rachkovsky solution of the radiative transfer equation and includes an empirical treatment of the Hanle effect. Outside active active regions, the linear polarization profiles of He I 1080.3 nm show the signatures of the Hanle effect, which needs to be taken into account for correct retrievals of vector magnetic fields. HELIX uses the genetic algorithm PIKAIA, rather than the more common Marquardt algorithm employed by other least-squares ITs. Using the magnetic field information obtained with HELIX, Solanki et al. (2003) were able to trace individual coronal loops in an emerging flux region. They found upflows at the apex of the loops and downdrafts in the footpoints, which is what one expects for magnetic loops rising from deeper layers. Other applications of the code have been presented by Orozco et al. (2005), Lagg (2005), and Solanki et al. (2006).

Routine observations of the infrared triplet of Ca II at 850 nm are now possible with THEMIS and the Spectro-Polarimeter for INfrared and Optical Regions (SPINOR; Socas-Navarro et al. 2006a) at the Dunn Solar Telescope on Sacramento Peak. The Ca II triplet lines are excellent diagnostics of the chromosphere, with the advantage that their interpretation is much simpler than that of other chromospheric lines such as Ca II H and K, and Hα. However, they still require non-LTE computations. First non-LTE inversions of the Ca II triplet lines observed with SPINOR have been presented by Socas-Navarro (2005b) and Socas-Navarro et al. (2006b). Although these analyses are very demanding in terms of computational resources, they hold great promise for quantitative diagnostics of the thermal and magnetic structure of the solar chromosphere.

Simultaneous observations of visible and infrared lines improve the accuracy of inversion results due to their different sensitivities to the various atmospheric parameters (Cabrera Solana et al. 2005). Several instruments provide such observations, including TIP and POLIS (POlarimetric Littrow Spectrograph; Beck et al. 2005) at the German VTT in Tenerife, and SPINOR. Figure 1 shows examples of Stokes V profiles of Fe I 630.15 nm, Fe I 630.25 nm, Fe I 1564.8 nm and Fe I 1565.2 nm observed in the penumbra of AR 10425 near the neutral line. These profiles were taken strictly simultaneously with TIP and POLIS on August 9, 2003. Both the visible and infrared lines exhibit large asymmetries and even pathological shapes indicating the presence of two magnetic components in the resolution element. We have carried out an inversion of these profiles in terms of an uncombed penumbral model using the code described by Bellot Rubio (2003). The best-fit profiles from the simultaneous inversion are represented by the solid lines. The quality of the fits is certainly remarkable, but it should be stressed that even better fits are achieved from the inversion of only the visible or the infrared lines. Indeed, fitting both sets of lines simultaneously is much more difficult, because a model atmosphere appropriate for the visible lines may not be appropriate for the infrared lines, and vice versa. Inverting the two sets of lines simultaneously thus constrains the range of acceptable solutions. The lower panels of Fig. 1 show the uncombed model resulting from the inversion (Beck et al., in preparation). The dashed lines represent a penumbral flux tube with larger line-of-sight (LOS) velocities than the background atmosphere, indicated by the solid lines. In the flux tube, the magnetic field is weaker and more horizontal than in the background. These inversions confirm that the uncombed model is able to explain the observed shapes of both visible and infrared lines. At the same time, they allow us to determine the position and width of the penumbral tubes, which is not easy from visible or infrared lines alone.

The new polarimeters have also made it possible to observe molecular lines, providing increased thermal sensitivity. Molecular lines are mostly seen in

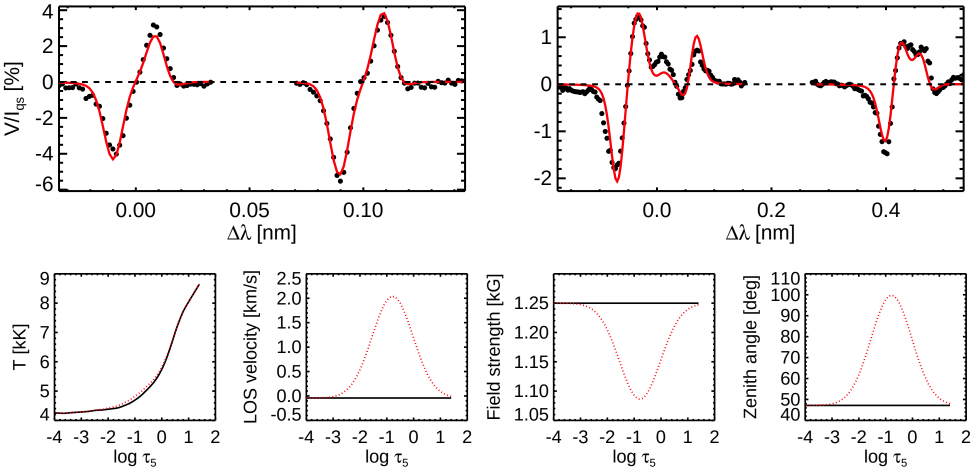

Figure 1. *Top:* Stokes V profiles of the pair of Fe I lines at 630 nm *(left)* and the Fe I lines at 1565 nm *(right)* observed simultaneously with POLIS and TIP in the limb-side penumbra of AR 10425, near the neutral line. Dots indicate the observations, solid the best-fit profiles resulting from a simultaneous uncombed inversion of the data. *Bottom:* Uncombed model inferred from the inversion. From left to right: temperature, LOS velocity, field strength and field inclination in the background (solid) and the flux-tube (dashed) components. From Beck et al. (in preparation).

sunspot umbrae, because higher temperatures dissociate the parent molecules. Usually, they show smaller polarization signals than atomic lines. There are two codes capable of inverting molecular lines: SPINOR (Frutiger & Solanki 1998) and the one developed by Asensio Ramos (2004). SPINOR has been used to invert the two OH lines at 1565.2 nm and 1565.3 nm, improving the determination of umbral temperatures (Mathew et al. 2003). The second code has been used to invert the CN lines at 1542 nm (Asensio Ramos et al. 2005). These lines are very interesting because in the umbra they show large linear polarization signals but very small Stokes V signals, just the opposite behavior of atomic lines.

Finally, major progress has come from the application of ITs to high spatial resolution spectroscopic and spectropolarimetric measurements. The main advantage of high angular resolution is that the results are less dependent on filling factor issues. An example of the inversion of high spatial resolution Stokes profiles is the work of Socas-Navarro et al. (2004), who derived the magnetic and thermal properties of umbral dots from observations taken with the La Palma Stokes Polarimeter (Martínez Pillet et al. 1999). These observations achieve an angular resolution of about $0\overset{\prime\prime}{.}7$. Another very promising type of measurements are those provided by Fabry-Pérot interferometers such as the Interferometric Bidimensional Spectrometer (IBIS; Cavallini et al. 2000) and the TElecentric SOlar Spectrometer (TESOS; Kentischer et al. 1998), which has recently been equipped with the KIS/IAA Visible Imaging Polarimeter (VIP; Bellot Rubio et al., in preparation). Combined with adaptive optics systems, these instruments are able to perform 2D vector spectropolarimetry at high spatial, spectral and temporal resolution, which is necessary for investigating large fields of view and fast processes. An example of the inversion of 2D spectroscopic measurements with TESOS is the derivation of the thermal and kinematic properties of a sunspot penumbra at different heights in the atmosphere (Bellot Rubio et al. 2006; see also Bellot Rubio 2004). The angular resolution of these observations is $0''.5$.

In the future, significant progress may come from the routine inversion of lines showing hyperfine structure, such as Mn I 553.77 nm and Mn I 874.09 nm (López Ariste et al. 2002). These lines exhibit sign reversals in the core of Stokes V and multiple peaks in Stokes Q and U for weak fields. Interestingly enough, the shape of the anomalies depends only on the field strength, not on the magnetic flux. Such an unusual behavior can be used to investigate the magnetism of the quiet Sun. In fact, from the shape of the observed profiles it would be possible to determine directly the strength of the magnetic field, even in the weak field regime. To exploit the diagnostic potential of these lines, however, it is necessary to implement the appropriate Zeeman patterns in existing ITs and to lower the noise level of current observations, which is barely enough to detect the subtle signatures induced by hyperfine structure.

3. Challenges

ITs have proven to be powerful tools to investigate the properties of the solar atmosphere. Their application to high precision spectropolarimetric measurements, however, has started to raise concerns on the limitations of some spectral lines. This is an important problem that deserves further investigation. Other challenges facing ITs in the near future include the implementation of more realistic model atmospheres and the development of strategies for the analysis of the large amounts of data to be delivered by upcoming instruments.

3.1. Limitations of spectral lines

Collados (2006) and Martínez González et al. (2006) have shown that it is possible to fit a given set of Stokes profiles of the pair of Fe I lines at 630 nm with very different field strengths by simply changing the temperature stratification. This quite unexpected result suggests that, in order to determine realistic field strengths in the quiet Sun from visible lines, it is necessary to fix somehow the temperature stratification. Apparently, this does not seem to be possible by using visible lines alone.

We have found a similar problem with the Fe I 630 nm lines even in the umbra, where the strong field regime applies. More specifically, we have detected a crosstalk problem between the stray light coefficient, the temperature, the macroturbulence, and the magnetic field strength and inclination (see Cabrera Solana et al. 2006). The results of a one-component inversion of umbral profiles with the stray light contamination as a free parameter do differ from those in which the stray light factor is fixed to the value inferred from a simultaneous inversion of visible and IR lines. With a mere difference of 7% in the stray light factor, the temperatures at $\tau_5 = 1$ from the two inversions differ by about 150 K, and the field strength by some 200 G. The fits in both cases are equally good, so it is not possible to decide which inversion is better. It appears that the relatively small Zeeman splitting of visible lines does not allow to clearly distinguish between enhancements of temperature and larger stray light factors, which produces crosstalk among the various atmospheric parameters.

Given these concerns, it seems necessary to perform more detailed analyses of the limitations of visible and infrared lines, for a better understanding of the results obtained from them. To minimize the risk of crosstalk problems in the inversion, it is desirable to use simultaneous observations in different spectral ranges. This will require modifications of current inversion codes to account for different scattered light levels and different instrumental profiles in the different spectral ranges.

3.2. Implementation of more realistic atmospheric models

The new observational capabilities, in particular the availability of simultaneous observations of visible and infrared lines, offer us a unique opportunity to increase the realism of the atmospheric models implemented in existing ITs. The need for better models is indicated by the small (sometimes systematic) residuals observed in inversions of profiles emerging from complex magnetic structures.

As an example, consider the uncombed penumbral model. Right now we use two different lines of sight to represent the background and flux tube atmospheres (cf. Bellot Rubio 2003 and Borrero et al. 2005), but this is a very simplistic treatment. The background field lines have to wrap around the flux tube, and so the properties of the background cannot be the same far from the tube and close to it. This may have important consequences for the generation of asymmetrical Stokes profiles. In much the same way, the flux tube is not always at the same height within the resolution element, because the magnetic field is not exactly horizontal. Therefore, different rays will find the tube at different heights. Finally, lines of sight crossing the center of the tube sense the properties of the tube over a larger optical depth range than lines of sight crossing the tube at a distance from its axis. Neither of these effects are modeled by current inversion codes. Probably, the subtle differences between observed and best-fit profiles (cf. Fig. 1) would disappear with a more complex treatment of the geometry of penumbral flux tubes.

3.3. Analysis of data from next-generation instruments

Stokes polarimetry at the diffraction limit is needed to study the physical processes occurring in the solar atmosphere at their intrinsic spatial scales. We are pushing our technological capabilities to a limit by building grating spectropolarimeters and filter magnetographs for diffraction-limited observations. On the ground, examples of already operational or upcoming state-of-the-art instruments include TIP, POLIS, DLSP, SPINOR, IBIS and TESOS+VIP. Among space-borne instruments we have the spectropolarimeter and filter polarimeter onboard Solar-B, SUPOS and IMaX onboard SUNRISE, HMI onboard SDO, and VIM onboard Solar Orbiter.

These instruments will deliver data of unprecedented quality in terms of spatial and spectral resolution. We hope to further our understanding of the solar magnetism with them. However, the success of this endeavor will critically depend on our ability to extract in an appropriate way the information contained in the observations. We do not only want to investigate the morphology and temporal evolution of the various solar structures from diffraction-limited

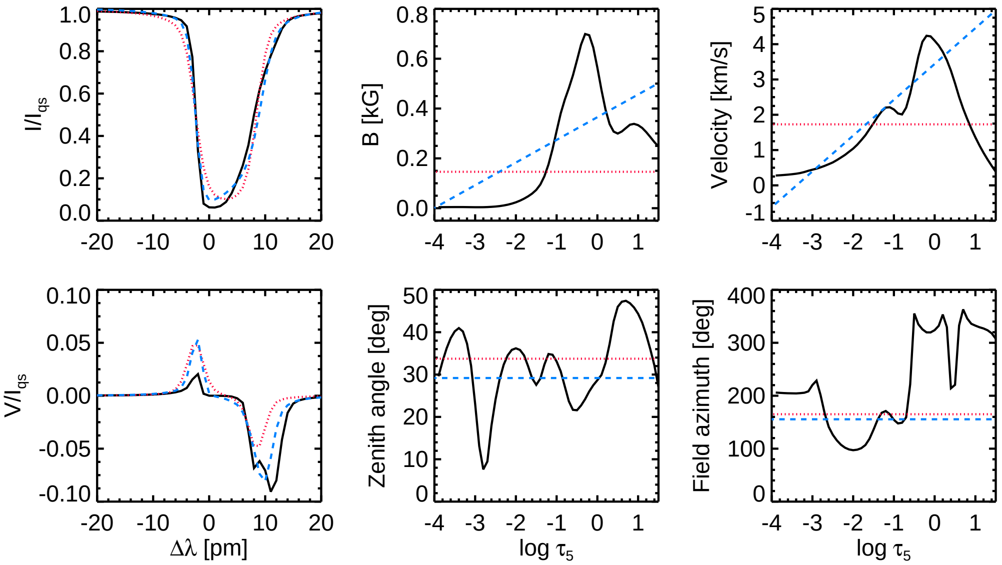

Figure 2. *Left:* High spatial resolution Stokes I and V profiles of Fe I 525.0 nm emerging from an intergranular lane as computed from MHD simulations (solid). Dotted and dashed lines represent the best-fit profiles from a ME inversion and a SIR inversion with gradients, respectively. *Middle and right:* Stratifications of atmospheric parameters used to compute the simulated profiles. The results of the ME inversion and the SIR inversion are given by the dotted and dashed lines, respectively.

images, but also to derive their magnetic and kinematic properties accurately using polarization measurements. Reliable determinations of vector magnetic fields call for least-squares inversions. The problem is the enormous data flows expected: classical least-squares ITs are considered to be too slow for real-time analyses of the observations. This is the reason why it is taken for granted that the most sophisticated analyses of the data will be based on ME inversions. The question naturally arises as to whether or not ME atmospheres are appropriate for the interpretation of Stokes measurements at the diffraction limit.

To shed some light on this issue, I have used the MHD simulations of Vögler et al. (2005) to synthesize the Stokes profiles of the IMaX line (Fe I 525.06 nm) emerging from a typical magnetic concentration in an intergranular lane. The atmospheric parameters needed for the calculation have been taken from a simulation run with average magnetic flux density of 140 G. Figure 2 displays the atmospheric stratifications and the corresponding Stokes profiles at $0\farcs1$ resolution (solid lines). The dotted lines show the results of a ME inversion of the synthetic profiles. As can be seen, the fits to Stokes I and V are not very successful, due to the extreme asymmetries of the profiles. The atmospheric parameters inferred from the ME inversion are some kind of average of the real stratifications, but the significance and usefulness of these average values are questionable when the parameters feature such strong variations along the LOS. An inversion of the same profiles with SIR (Ruiz Cobo & del Toro Iniesta 1992) allowing for gradients of field strength and velocity with height (dashed lines) yields much better fits to Stokes I and V. Although there is still room for improvement, the important point is that this simple inversion is able to recover the vertical gradients of field strength and velocity with less free parameters than a ME inversion (8 as opposed to 9). This additional information could be essential to understand many physical processes, so it is important to have it.

Present-day computing resources are sufficient to determine gradients from the high spatial resolution observations delivered by *grating instruments* such as POLIS and the Solar-B spectropolarimeter (Solar-B/SP; Lites et al. 2001). A SIR inversion of the four Stokes parameters of 2 spectral lines (10 free parameters, 135 wavelength points, model atmosphere discretized in 41 grid points) takes 0.7 s on a dual Xeon workstation running at 2.8 GHz. Optimizing the code, a cadence of 0.5 s would easily be reached. The real-time analysis of a full POLIS slit (450 pixels in 10 s) would then require 20 such workstations. The analysis of Solar-B/SP data (1000 pixels every 10 s) would require 50 workstations. The total cost in the latter case would be $125 000, which is only a minor fraction of the cost of the instrument itself.

The situation is rather different for vector magnetographs. These instruments measure only a few wavelength points, i.e., line profiles are not available. Probably, the most we can do with this kind of data is a full ME inversion[1]. An additional complication is that the data rates will be huge, much larger than those expected from grating instruments. For example, HMI will observe about 10^6 pixels every 80-120 s. To cope with such data flows, PCA methods and ANNs are being proposed as the only option to invert the observations in real time. We have already mentioned that on average the results of these methods coincide with those from ME inversions. However, since large errors occur for many individual pixels, it is clear that ME inversions would be preferable over PCA or ANN inversions.

But, how to perform ME inversions of vector magnetograph data at the required speed? The solution could be hardware inversion on Field Programmable Gate Arrays (FPGAs), which is about 10^3 times faster than software inversion depending on the frequency of the processor and the implementation of the algorithm. At the IAA, we are studying the feasibility of such an electronic inversion for the analysis of VIM data (Castillo Lorenzo et al. 2006). The first working prototype is expected to be ready by the end of 2007.

4. Summary

Inversion techniques have become essential tools to investigate the magnetism of the solar atmosphere. Nowadays, they represent the best option to extract the information contained in high precision polarimetric measurements. The reliability and robustness of Stokes inversions have been confirmed many times with the help of numerical tests. Part of the community, however, is still concerned with uniqueness issues. These concerns will hopefully disappear with the implementation of more realistic model atmospheres.

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[1] However, it remains to be seen whether vertical gradients can also be recovered from observations with limited wavelength sampling. Work in this direction is being done at the IAA in preparation for the analysis of data from IMaX and VIM (Orozco Suárez et al. 2006).

During the last years, major progress in the field has resulted from the application of ITs to state-of-the-art observations. The advent of spectropolarimeters for the near infrared has represented a breakthrough, allowing the observation of atomic and molecular lines that provide increased magnetic and thermal sensitivity, and extended chromospheric coverage. The potential of simultaneous observations of visible and infrared lines for precise diagnostics of solar magnetic fields has just started to be exploited. Visible and infrared lines constrain the range of acceptable solutions, which is especially useful for the investigation of complex structures with different magnetic components and/or discontinuities along the line of sight. Finally, we have began to invert spectropolarimetric observations at very high spatial resolution, with the aim of reaching the diffraction limit of current solar telescopes ($0\farcs1$–$0\farcs2$). High spatial resolution allows to separate different magnetic components that might coexist side by side, thus facilitating the determination of their properties.

The application of ITs to these observations is casting doubts on the capabilities of certain lines for investigating particular aspects of solar magnetism. A detailed study of the limitations of spectral lines, in particular the often used pair at 630 nm, seems necessary to clarify their range of usability. An obvious cure for any problem that might affect the observables is to invert visible and infrared lines simultaneously. This will require modifications of current ITs to account for different instrumental effects in the different spectral ranges.

Perhaps the most important challenge facing ITs in the next years is the analysis of the enormous amounts of data expected from upcoming space-borne solar polarimeters. So far, the efforts have concentrated on the development of fast PCA-methods and ANNs for real-time inversions of the data. However, the unprecedented quality of these observations in terms of spectral and spatial resolution makes it necessary to explore the feasibility of more complex inversions capable of, e.g., determining gradients of field strength and velocity along the line of sight. Tests with numerical simulations demonstrate the importance of gradients to reproduce the very large asymmetries of the Stokes profiles expected at a resolution of $0\farcs1$–$0\farcs2$. Current computing resources allow us to determine gradients from full line profiles observed with grating spectropolarimeters such as the one onboard Solar-B, at a very reasonable cost. Gradients may also be recovered from high-resolution filtergraph observations. In any case, real-time ME inversions of data with limited wavelength sampling seem possible using Field Programmable Gate Arrays. The feasibility of these electronic ME inversions needs to be assessed. At the same time, it is important to continue the development of PCA and ANN methods to provide the more complex ME inversions with good initial guesses.

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References

Asensio Ramos, A. 2004, Ph.D. Thesis, Universidad de La Laguna
Asensio Ramos, A., Trujillo Bueno, J., & Collados, M. 2005, ApJ, 623, L57
Auer, L.H., House, L.L., & Heasley, J.N. 1977, Solar Phys., 55, 47
Beck, C., Schmidt, W., Kentischer, T., & Elmore, D. 2005, A&A, 437, 1159
Bellot Rubio, L.R. 2003, ASP Conf. Series, 307, 301

Bellot Rubio, L.R. 2004, Reviews in Modern Astronomy, 17, 21

Bellot Rubio, L.R., Ruiz Cobo, B., & Collados, M. 2000, ApJ, 535, 475

Bellot Rubio, L.R., Balthasar, H., & Collados, M. 2004, A&A, 427, 319

Bellot Rubio, L.R., Schlichenmaier, R., & Tritschler, A. 2006, A&A, submitted (astro-ph/0601423)

Borrero, J.M., Solanki, S.K., Bellot Rubio, L.R., Lagg, A., & Mathew, S.K. 2004, A&A, 422, 1093

Borrero, J.M., Lagg, A., Solanki, S.K., & Collados, M. 2005, A&A, 436, 333

Cabrera Solana, D., Bellot Rubio, L.R., & del Toro Iniesta, J.C. 2005, A&A, 439, 687

Cabrera Solana, D., Bellot Rubio, L.R., & del Toro Iniesta, J.C. 2006, these proceedings

Carroll, T. A., & Staude, J. 2001, A&A, 378, 316

Casini, R., López Ariste, A., Tomczyk, S., & Lites, B. W. 2003, ApJ, 598, L67

Castillo Lorenzo, J.L., Orozco Suárez, D., Bellot Rubio, L.R., López Jiménez, A.C., & del Toro Iniesta, J.C. 2006, these proceedings

Cavallini, F., Berrilli, F., Cantarano, S., & Egidi, A. 2000, ESA SP-463, 607

Collados, M. 2006, these proceedings

Frutiger, C., & Solanki, S.K. 1998, A&A, 336, L65

Kentischer, T.J., Schmidt, W., Sigwarth, M., & Uexküll, M.V. 1998, A&A, 340, 569

Lagg, A. 2005, ESA SP-596

Lagg, A., Woch, J., Krupp, N., & Solanki, S.K. 2004, A&A, 414, 1109

Lites, B.W., Elmore, D.F., & Streander, K.V. 2001, ASP Conf. Series, 236, 33

López Ariste, A., & Casini, R. 2002, ApJ, 575, 529

López Ariste, A., & Casini, R. 2003, ApJ, 582, L51

López Ariste, A., & Casini, R. 2005, A&A, 436, 325

López Ariste, A., Tomczyk, S., & Casini, R. 2002, ApJ, 580, 519

Martínez González, M.J., Collados, M., & Ruiz Cobo, B. 2006, A&A, submitted

Martínez Pillet, V., et al. 1999, ASP Conf. Series, 183, 264

Mathew, S.K., et al. 2003, A&A, 410, 695

Orozco Suárez, D., Lagg, A., & Solanki, S.K., 2005, ESA SP-596

Orozco Suárez, D., Bellot Rubio, L.R., & del Toro Iniesta, J.C. 2006, these proceedings

Rees, D.E., López Ariste, A., Thatcher, J., & Semel, M. 2000, A&A, 355, 759

Ruiz Cobo, B., & del Toro Iniesta, J.C. 1992, ApJ, 398, 375

Sánchez Almeida, J. 2005, ApJ, 622, 1292

Skumanich, A., & Lites, B.W. 1987, ApJ, 322, 473

Socas-Navarro, H. 2001, ASP Conf. Series, 236, 487

Socas-Navarro, H. 2003, Neural Networks, 16, 355

Socas-Navarro, H. 2005a, ApJ, 621, 545

Socas-Navarro, H. 2005b, ApJ, 631, L167

Socas-Navarro, H., Trujillo Bueno, J., & Ruiz Cobo, B. 2000, ApJ, 530, 977

Socas-Navarro, H., Martínez Pillet, V., Sobotka, M., & Vázquez, M. 2004, ApJ, 614, 448

Socas-Navarro, H., Elmore, D., Pietarila, A., Darnell, A., Lites, B.W., & Tomczyk, S. 2006a, Solar Phys., in press (astro-ph/0508685)

Socas-Navarro, H., Martínez Pillet, V., Elmore, D., Pietarila, A., Lites, B.W., & Manso Sainz, R. 2006b, Solar Phys., in press (astro-ph/0508667)

Solanki, S.K., Lagg, A., Woch, J., Krupp, N., & Collados, M. 2003, Nature, 425, 692

Solanki, S.K., et al. 2006, these proceedings

del Toro Iniesta, J.C. 2003, Astronomische Nachrichten, 324, 383

del Toro Iniesta, J.C., & Ruiz Cobo, B. 1996, Solar Phys., 164, 169

Vögler, A., Shelyag, S., Schüssler, M., Cattaneo, F., Emonet, T., & Linde, T. 2005, A&A, 429, 335

Westendorp Plaza, C., del Toro Iniesta, J.C., Ruiz Cobo, B., Pillet, V.M., Lites, B.W., & Skumanich, A. 2001, ApJ, 547, 1130