Mem. S.A.It. Vol. 78, 148

Memorie della

A suite of community tools for spectro-polarimetric analysis

B. Lites, R. Casini, J. Garcia, and H. Socas-Navarro[1]

High Altitude Observatory – National Center for Atmospheric Research, P.O. Box 3000, Boulder, CO 80307, USA
e-mail: lites@ucar.edu

Abstract. The National Center for Atmospheric Research (NCAR) has undertaken a 3-year initiative to develop the Community Spectro-polarimetric Analysis Center (CSAC). The goal of this effort is to provide the community with standardized tools for extracting the solar magnetic field vector and related atmospheric parameters from spectro-polarimetric observations. The emphasis will be to develop portable, efficient, and well-documented procedures for analysis of data from the many new and upcoming observational facilities, both ground- and space-based. The initial focus of CSAC will be the development of robust methods for inversion of Stokes spectral data, starting with a standard Milne-Eddington inversion that has been the workhorse for analysis of data from e.g. the Advanced Stokes Polarimeter. Upon completion of that code, the program will move to more sophisticated methods that embrace more realistic and detailed models of the solar atmosphere. Very fast methods for inversion (neural networks or pattern recognition techniques, for example) are also candidates. Finally, the CSAC is intended to eventually provide standardized methods for resolution of the 180-degree field azimuth ambiguity, and for visualization of the resulting magnetic field vector maps. CSAC is formulated as a community effort, and as such will receive guidance and input from the community.

Key words. Sun: magnetic fields – Sun: data analysis – Sun: polarimetry – Sun: spectroscopy

1. Identifying A Need For Community Access to Analysis Tools

Solar magnetic fields are responsible for most of the variability of the Sun and for most solar phenomena and structures. High precision spectro-polarimetric observations form the basis for comprehensive and quantitative inference of the magnetic field vector and related thermodynamic properties of the solar atmosphere. Many new spectro-polarimeters for solar observations now exist, or are coming online within the next few years (see Table 1), and they will demand stable, efficient, and well-understood analysis procedures. Techniques for extraction of the magnetic field vector to high quantitative accuracy are complex, and existing codes are not user-friendly. They often are computationally sluggish. New techniques now under development for fast inversion of polarimetry of photospheric lines (e.g. Principal Components Analysis, Artificial Neural Networks) should become available to

Send offprint requests to: B. Lites

Table 1. Modern full Stokes polarimeters for solar observation.

Ground-Based Full Stokes Polarimeters	Type	Developers	Year
Advanced Stokes Polarimeter (ASP)	Spectrograph	HAO,NSO (USA)	1992
Imaging Vector Magnetograph (IVM)	F-P Filtergraph	U. Hawaii (USA)	1992
ZIMPOL II	Flexible	ETH Zürich (CH)	1996
THEMIS	Spectrograph	(F, I)	1997
La Palma Stokes Polarimeter (LPSP)	Spectrograph	IAC (E)	1998
Tenerife Infrared Polarimeter (TIP)	Spectrograph	IAC (E)	1998
Polarimetric Littrow Spectrograph (POLIS)	Spectrograph	KIS (D), HAO (USA)	2002
Diffraction-Limited Spectro-Polarimeter (DLSP)	Spectrograph	HAO,NSO (USA)	2003
SOLIS-VSM	Spectrograph	NSO (USA)	2003
Swedish Solar Telescope	Spectrograph	ROYAC (S)	2005
ATST Visible/Near IR Polarimeter	Spectrograph	HAO,NSO (USA)	2012
Space-Based Full Stokes Polarimeters	Type	Developers	Year
HINODE	Spectrograph	J,USA	2006
HMI, Solar Dynamics Observatory	Michelson Filter	USA	2008
Sunrise (Balloon)	Spectrograph, FP Filter	D/USA/E	2009
Solar Orbiter	FP Filter	EU	2012

the community for rapid access to vector magnetic field maps.

Inversion techniques are under development in a number of new areas. More sophisticated analyses, including gradients of fields and atmospheric parameters along the line-of-sight (LOS) provide a more detailed picture of the atmosphere. These techniques are becoming more commonplace in recent analyses. Measurements of lines forming above the photosphere, including the chromosphere, corona, and prominences/filaments, and embracing at once the Hanle, Zeeman, and Paschen-Back field regimes, promise to provide more reliable measurements of the field vector above the photosphere. CSAC will serve as a community clearinghouse for such routines.

In addition to standardized inversion codes, the community is also in need of codes for post-inversion processing of vector magnetic field data. In particular, community input is sought for resolution of the 180å ambiguity of the field azimuth in the observers frame and display and visualization of vector field structure.

2. Standards for the CSAC Library of Analysis Tools

Analysis codes to be made available to the community will conform to modern software standards. The objectives of the software development are summarized as follows:

- Codes are highly transportable (written in C, C++), callable from IDL
- Supported under Unix, Linux, Solaris
- Efficient coding, appropriate for parallel architecture
- Well documented, commented, and tested
- Flexibility to accommodate data from a wide variety of instruments
- Standardized input/output
- Standards for presentation in solar coordinates
- Filters provided to convert input data from major instruments (HINODE, DLSP, SOLIS, etc.)
- Codes maintained at a HAO/NCAR
- Examples of input/output data provided
- Open source for user modification, experimentation, and community input
- Online access to all analysis tools
- User forum for suggested modifications, additions

3. MERLIN: Towards Efficient Tools For Photospheric Vector Fields

The most accurate and reliable measures of the magnetic field vector in the solar atmosphere derive from detailed spectral profiles of full Stokes polarimetric observations, especially when profiles of more than one spectral line are available. Traditionally, this extraction has been carried out by inversion, in this case meaning the process of least-squares fitting of the observed profiles using a model for the solar atmosphere. Analytic solutions for the transfer of polarized radiation, as influenced by the Zeeman effect, exist for the case of the simple Milne-Eddington (M-E) model of a stellar atmosphere. Much experience with this technique demonstrates that it yields an excellent representation of the average field vector in the LOS formation region of photospheric lines.

Although M-E inversions suffer some limitations in a few circumstances (i.e., magnetic canopies outside of sunspot penumbrae) they nonetheless provide the most reliable and accurate means to infer the vector field for maps of e.g. entire active regions. In this sense, they are the modern workhorse analysis technique for photospheric vector field measurement. The first priority for CSAC is to implement a robust, transportable, transparent, fast, and reliable M-E inversion code. The HAO inversion code accompanying Advanced Stokes Polarimeter (ASP) data is quite robust and reliable. However, it is not easily transportable, it has an excellent but very slow initialization procedure, the coding is not transparent, and it is specialized for the (soon to be) obsolete ASP instrument. The new version of this code is intended to correct all of these deficiencies. Some features of the new code, MERLIN (Milne-Eddington gRid Linear Inversion Network), are as follows:

- Written in C; data management functions written in C++
- Initialization by ASP genetic algorithm (slow) or artificial neural network (fast)
- Constructed for GRID architecture for parallel computing
- Client and server machines will communicate over TCP/IP, so data may be either local or remote
- MERLIN will serve as a model for subsequent implementation of more sophisticated inversion techniques

Fig. 1 compares the results of the MERLIN inversion on high-resolution sunspot data from the Diffraction-Limited Spectro-Polarimeter (DLSP) to that of the ASP inversion code operating on the same data. In general, MERLIN and ASP results are very close, but in fact the MERLIN results are better *at every pixel* than the ASP code results, in the sense that the χ^2 of the solution is lower. Thus, the MERLIN results represent a further convergence of the iterative fit. Both MERLIN and ASP solutions were initialized with the same estimates provided by a genetic algorithm. Note in Fig. 1 that there are regions of the penumbra in which there is a systematic difference in the fit from the two codes indicating improvements of the fit that could make some difference in physical interpretation of the results.

Fig. 2 illustrates the data processing concept, not only for MERLIN, but for the other inversion methods that will eventually be included in CSAC. In general, spectropolarimetric data are voluminous, and will be maintained by database management systems at central data sites. An OPeNDAP server running at the data site will generate data in the format expected by MERLIN, and assign it a URL. The Inversion Engine running locally communicates with the OPeNDAP server to acquire the data for processing. Locally, the Inversion Engine (Fig. 3) consists of a Client server that controls the processing of data by the GRID servers, and interfaces with the user. Since this software system is web-based, it is quite flexible. It may run on a single machine, or any collection of machines that make up the GRID. The data may be served either locally or remotely by an OPeNDAP server. The final system will include a graphical user interface for specification of parameters that define the particular inversion (e.g. indices specifying subsets of a map, lower limit of net polarization for which inversion is to be attempted, etc.)

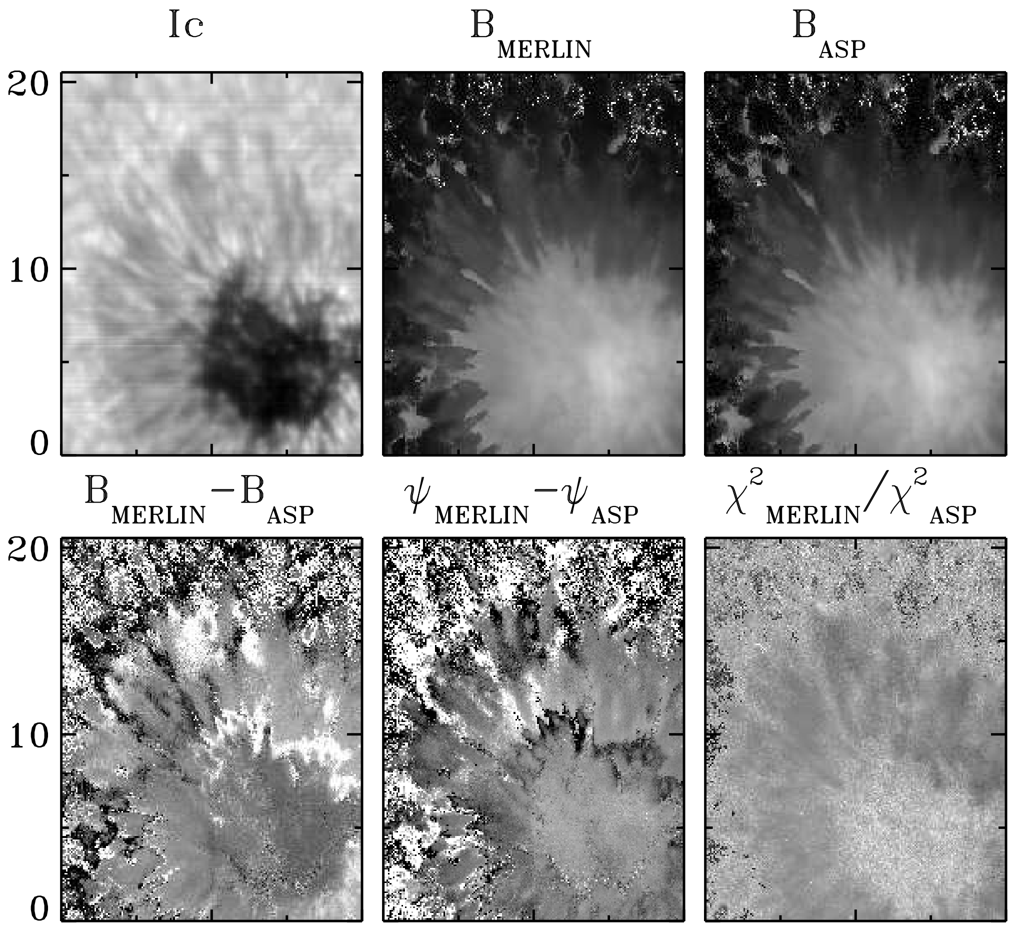

Fig. 1. Comparisons are made between inversions based on the M-E model atmosphere carried out with the new CSAC code MERLIN and the ASP inversion code. From left to right, top to bottom: continuum intensity Ic; strength of the magnetic field from the MERLIN inversion code (B_{MERLIN}), scaled 0-3000 Gauss; similarly scaled field strength from the ASP code (B_{ASP}); difference in field strengths inferred by the two codes, gray-scale is ±100 Gauss; difference in field inclinations to the LOS, scaled ±2°; ratio of the chi-squares of the fit to the data in the two codes, scaled 0 to 1 (dark to white).

4. Advanced Inversion Codes

Table 2 summarizes codes that are presently envisioned as part of CSAC. With increasing spatial resolution one encounters increasingly asymmetric profiles indicative of varying atmospheric conditions along the LOS. This appears to be the case especially in the quiet Sun. Inversion codes are now in widespread use that go beyond the M-E formulation by allowing for gradients in the magnetic field, Doppler velocity, and thermal properties of the atmosphere along the LOS. The SIR code (Ruiz Cobo & del Toro Iniesta 1992) is an inversion program widely used to extract more detailed information about atmospheric structure than is allowed by the M-E approach. A similar code, LILIA, has been developed at HAO to address more complex model atmospheres. Not only does it allow for gradients along the

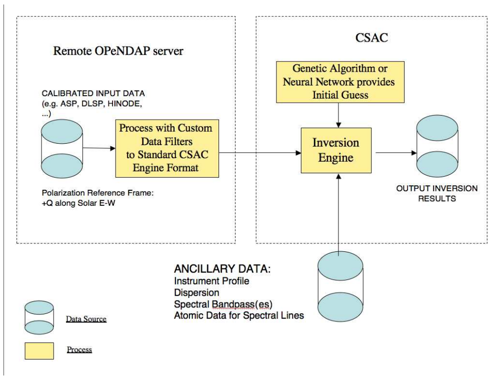

Fig. 2. Architecture of the generalized data processing system showing the processes running at the data site on the left, and the processes running at the site of the inversion on the right.

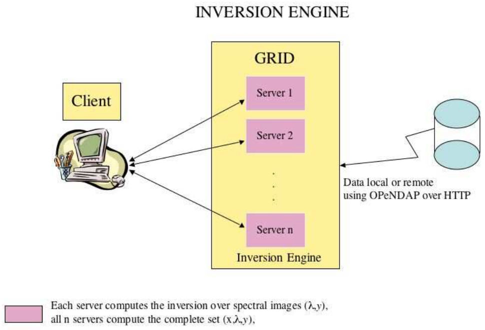

Fig. 3. Client and server interaction within the inversion engine. The client process organizes the processing by sending a URL to each machine indicating the location of the next data set to be processed on the OPeNDAP remote data server.

LOS, it may also fit two magnetic components plus one non-magnetized component in the observing pixel. For implementation in CSAC, LILIA will be coded following the same standards as the MERLIN code.

The past few years have seen the application of new techniques for data fitting to the problem of extraction of magnetic fields from solar polarimetric data. Among these techniques are pattern recognition (Principal Components Analysis: PCA), Artificial Neural Networks (ANN), and a generalization of the ANN approach: Support Vector Machines (SVMs). At present, we are placing emphasis on the ANN routine DIANNE summarized in Table 2, as it will be implemented as an initial guess for the MERLIN routine, and ultimately also for LILIA. The Neural Network approach shows considerable promise as a very fast method to arrive at reasonably accurate guesses for the magnetic field vector, the filling factor, and the Doppler shift of the line (Socas-Navarro 2005c).

The MISMA approach (Sanchez Almeida 1997, 2000, 2005) allows one to characterize the polarization arising from structures on a micro-scale (comparable to or less than a photon mean-free-path in the lines in question). Such structures easily produce the commonly observed large asymmetries of the Stokes profiles. For this reason, we plan to make this inversion technique available to the community. 2 Looking into the future, more emphasis will be given to measurement of magnetic fields above the photosphere. At present, there are two candidate codes that address chromospheric structures. First is a non-LTE code, NICOLE, for extracting fields from spectropolarimetric observations of chromospheric lines. This technique (Socas-Navarro et al. 2001) has been applied successfully for extraction of the variations of physical parameters from the photosphere into the chromosphere (Socas-Navarro 2005a,b). The second is PROZHAIC, which is aimed at the very important problem of extracting measures of the vector field from observations of solar prominences and filaments. In these structures, polarization in spectral lines such as the He I lines may be dominated by either scattering polarization or the Zeeman effect, or it may result from a mixture of both. PROZHAIC is able to treat all three regimes in a self-consistent way. This code is based on the PCA technique. Some early results of application of this technique to solar observations may be found in López Ariste & Casini (2005); Casini et al. (2005).

Acknowledgements. We are grateful to M. Haganaar and A. Tritschler for providing us with polarimetric data from the Diffraction Limited Spectro-Polarimeter with which to carry out tests of the MERLIN inversion code. The authors gratefully

Table 2. Candidate Inversion Codes for CSAC

INVERSION CODE	TECHNIQUE	APPLICABILITY	ATTRIBUTES	REFERENCE
MERLIN (Milne-Eddington gRid Linear Inversion Network)	Standard Milne-Eddington model, least-squares fit by Marquardt algorithm	Single or multi-line Stokes profile observations of photospheric lines, blends	Robust, slow, limited to M-E model assumptions	Skumanich & Lites 1987; widespread use
LILIA (LTE based on the Lorien Inversion Algorithm)	Least-squares fitting, LTE 1-D atmosphere in HSE (comparable to IAC SIR)	Retrieves detailed depth variation of magnetic field and model atmosphere	Slow, robustness decreases with model complexity	Socas-Navarro 2001; Operational, being improved
DIANNE (Direct Inversion using Artificial Neural Networks)	Neural network technique for direct inversion of observed profiles	Must train network with observed or theoretical profiles	Extraordinarily fast, quantitative accuracy being evaluated	Socas-Navarro 2003; refinement underway
MISMA (Micro-Structured Magnetic Atmospheres)	Least-squares, HSE thin flux tube approximation	Optically thin structures, reproduces asymmetries	One physical model may not apply in some situations	Sánchez Almeida 1997; working inversion code
NICOLE (Non-LTE Inversion Code based on Lorien Engine)	Least Squares, 1-D atmosphere, chromos-pheric non-LTE line formation	Structure along LOS, chromosphere. Zeeman effect only	Computationally intensive; issues with robustness	Under development
PROZHAIC (PROminence Zeeman HAnle effect Inversion Code	PCA, database of theoretically generated profiles	Encompasses Hanle and Zeeman effects in optically thin case	Applied to He I D_3, 10830 prominence/ filamaent observations	López Ariste & Casini et al. 2005; development continues

acknowledge the National Center for Atmospheric Research for providing funding for this research through the CSAC Strategic Initiative. The National Center for Atmospheric Research is sponsored by the National Science Foundation.

References

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

Casini, R., Bevilacqua, R., & López Ariste, A. 2005, ApJ, 622, L1265

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

Sanchez Almeida, J., 1997, ApJ, 491, 993

Socas-Navarro, H. 2001, *Stokes Inversion Techniques: Recent Achievements and Future Horizons*, in ASP Conf. Ser 236: Advanced Solar Polarimetry – Theory, Observation, and Instrumentation, ed. M Sigwarth, 487

Sanchez Almeida, J., 1997, ApJ, 532, 1215

Sanchez Almeida, J., 1997, ApJ, 622, 1292

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

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

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

Socas-Navarro, H., 2005, ApJ, 633, L57

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

Socas-Navarro, H.,Trujillo Bueno, J., Ruiz Cobo, B. 2001, ApJ, 550, 1102