Contents

SCIENTIFIC/TECHNICAL/MANAGEMENT SECTION

We propose here to the Cross-Discipline Infrastructure Building Programs section of the NASA/ Targeted Research and Technology program for a small series of workshops aimed at providing the Living With a Star community the most robust, well-understood Milne-Eddington Unno-Rachkovsky based inversion techniques for inferring the solar photospheric magnetic field structure. The strategy will be to employ "hare & hound" tests of the multiple inversion codes available today on synthetic data generated from analytic models and MHD simulations of the solar atmosphere. The final product will be a full understanding of how details of the implementations of inversion codes affect the resulting field maps, fully defined metrics by which to evaluate the effects, publicly-available test data for future inversion development, and a community-guided and community-supported "Standard" implementation of a Milne-Eddington based Inversion code, with modular ability to be applied to data from a wide variety of instruments.

1 OBJECTIVES AND EXPECTED SIGNIFICANCE

The magnetic field permeating the solar atmosphere governs much of the structure, morphology, irradiance and dynamics observed in the Sun. Quantities derived from the photospheric magnetic field have been used for years to characterize solar active regions and their propensity for solar activity. The magnetic flux in an active region is believed to energize the hot coronal plasma seen in EUV or X-rays. In short, the inference of the magnetic field at the lower boundary of the solar atmosphere in a manner which best characterizes the physical state of the atmosphere, is the building block for investigations of the rest of the solar atmosphere and its influence on the heliosphere.

We may say that measurements of active-region photospheric vector magnetic fields have become quite routine. Daily magnetic field maps of solar sunspot groups began production from NASA/Marshal Space Flight Center, National Astronomical Observatory Japan, Huairou Solar Observatory, the University of Hawaiʻi and other observatories easily three decades ago, partly in support for NASA-supported missions such as Skylab and *Yohkoh*. Intentionally ignoring any futile attempt at listing all observatories and instruments developed in the intervening years, the international solar physics community now supports not just a plethora of ground-based instruments but two space-based observatories tasked with measuring the photospheric vector magnetic field – albeit with distinctly different and complementary abilities and scientific focus.

However, we do *not* measure the magnetic field in the solar photosphere; we measure light. As stressed by [11], we interpret the effects of the (highly) structured magnetic field on photons as they pass outward from the $\tau = 1$ layer through a (highly) dynamic and stratified solar atmosphere. Through independent study of the thermodynamics and atomic physics involved in the path of the light, and the effects of the presence of a magnetic structure, forward models are constructed. With these it is then possible to approach the inverse problem, of inferring the presence and character of the solar magnetic field.

Of course, the effects of limited spatial, temporal, spectral resolution of instruments, and the physical limitation of spectral line formation (limiting the available resolution in optical depth), lead to averaging in all dimensions. This of course provides no end of consternation regarding disentangling the true nature of the solar magnetic structure [46, 47]. It also allows for some basic understanding since a vast majority of the emergent spectra, as analyzed in the Stokes formalism, can be described fairly well by models which employ various simplifying assumptions.

Before proceeding, we present a list of terms used herein (since producing a magnetogram is, for the majority of the community, a fairly esoteric "black box"):

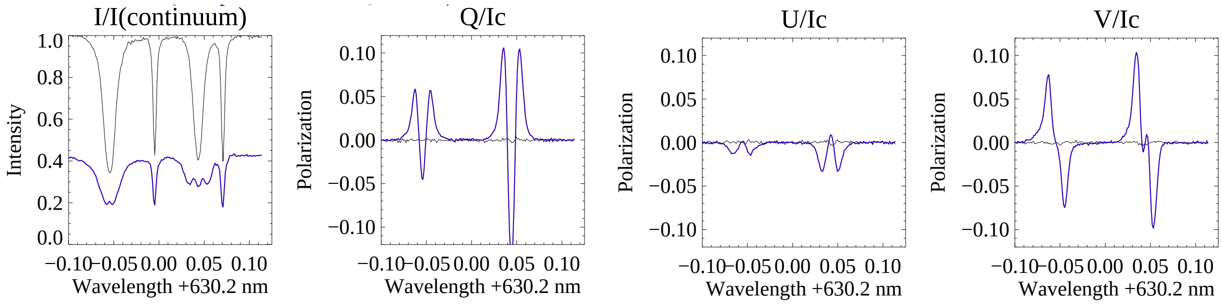

Figure 1: Examples of polarization spectra in the 630.2nm region, using the Stokes formalism of I (total intensity), Q, U linear polarization at a 45 deg angle from each other, and the circular polarization V. Spectra from both a quiet sun (low-polarization) area (black) and a pixel with signal from a sunspot penumbra (blue) are shown. Spectra such as these (or obtained with worse/better spectral/spatial/temporal resolution) comprise the input for inversion codes.

Stokes Spectra: characterize the total intensity (I), magnitude and direction of linear (Q, U) and circular (V) polarization as a function of wavelength in a particular convention whereby two measures of the (partially) polarized linear component 45° apart. See Figure 1. The behavior of the Stokes spectra as a function of wavelength is also governed by the Zeeman splitting of the particular spectral line as it reacts to the magnitude and direction of a magnetic field in the line-forming region.

Inversion: The process of inferring the magnitude and direction of a magnetic field and the (relevant) thermodynamic character of the plasma in the line-forming region from spectropolarimetric data.

Optimization/Minimization Algorithm: the process by which the "observed" Stokes spectra are matched to a "best-fit model". Comes in two *basic* flavors: **local**, which finds the best fit within the general area of parameter space that it starts in, and **global** which tries to search all of parameter space for a "best fit".

Initial Guess: the location in parameter space where one begins the (local) optimization. May be completely ad-hoc ("every pixel begins with an assumed field strength of 100 G") or a quick-look type of computation based on the Stokes spectra. May or may not be relevant to a particular code, especially if a global optimization.

Merit Function $\boldsymbol{\chi^2} = \sum_i w_i (P_i^{\rm obs} - P_i^{\rm model})^2$: a measure of the difference between the observed Stokes spectra, $P_i^{\rm obs}$, and the model spectra, $P_i^{\rm model}$, for any particular place in parameter space. May (or may not) be normalized by a weighting function, w_i; in the standard statistical definition of χ^2, the weights are determined from the random noise in the measurements by $w_i = 1/\sigma_i^2$, but other weights are frequently use in inversion codes. Used by the optimization methods (and humans) to judge how well the model is fitting the observations.

Noise: degree of scatter about the true (or average) value due to photon-statistics, instrument-induced bias, detector quantum noise, etc. May be random (e.g., photon statistics) or systematic (instrumental calibration problems).

Uncertainty: a measure of the reliability of a value for a parameter from the inversion.

Magnetic Fill Fraction: (f), the fractional area of a resolution element ("pixel") containing plasma that generates the polarization signal (and is assumed filled with magnetic field with a single strength and direction).

Field Strength: ($|\boldsymbol{B}|$) the intrinsic field strength, in units of Gauss, of magnetic field producing the polarization signal observed. The product $f \times |\boldsymbol{B}|$ is considered the area-averaged field strength, usually quoted in $\mathrm{Mx/cm^2}$.

Magnetic Vector: ($\boldsymbol{B}$) the vector description of the field occupying the inferred fill fraction, in terms of **field strength** $|\boldsymbol{B}|$, **inclination angle** relative to the plane of the sky γ, and the (180 deg ambiguous) **azimuthal angle** ϕ in the plane of the sky.
Scattered/Stray light: light entering into a pixel from outside that pixel. May (or may not) be polarized. Often included to help characterize the magnetic fill fraction.
Source Function: used in the equations of radiative transfer, this is the ratio of emission to absorption: $S_\nu = j_\nu/\kappa_\nu$. In strict local thermodynamic equilibrium ("LTE"), $S_\nu = B_\nu$, i.e. the Planck function. *"The physics of calculating S_ν can be complicated"*[17, Chapter 5]
Milne-Eddington atmosphere: assumes that the atmosphere within which the spectral line in question is formed is described with a source function that varies linearly with optical depth: $\S_n u = B_0 + B_1\tau$; there are no velocity (or magnetic field) gradients along the line of sight, and the rest of quantities affecting the atmosphere are depth-independent. Some Milne-Eddington inversions treat $B_0,\ B_1$ separately, some consider only their ratio.
Unno-Rachkovsky Equations: the first analytic derivations of the transfer equations for polarized light, including magneto-optical effects (Faraday rotation), for absorption processes in the context of Solar spectral lines [61, 40]. Later derivations by others were more rigorous with respect to underlying physics [25, 21, 59].

In the present context, we use "Milne-Eddington Unno-Rachkovsky" ("MEUR") as a shorthand for inversions based on the radiative transfer equations under the simplifying assumptions of a Milne-Eddington atmosphere. Inversion methods which use fundamentally different approximations, formalisms, or models have been and are being developed, primarily by our colleagues in Europe. Some consider atmospheric models that are explicitly in LTE ([53, 45]), or extend to Non-LTE [56]; others are based on very complex underlying magnetic models [46, 47, 5]. One may easily argue that more sophisticated approaches perform "better", in that (for example) they retrieve gradients with height of parameters assumed constant under the MEUR assumptions. Other approaches include inferring physical parameters from, e.g., Principal Component Analysis of the Stokes spectra [41, 51, 54, 1] which may (or may not) include MEUR-based synthesis for model-spectra comparisons. Nevertheless, inversions using MEUR assumptions do return reasonable height-averaged results [64, 38], and hence why this class of inversion is very suitable for a wide variety of solar physics investigations.

Indeed, inversions of Stokes polarization spectra using algorithms based on MEUR simplifications of the radiative transfer equations form the basis for the vast majority of inversion codes available today. These are the workhorses of our field, producing photospheric vector magnetograms for much of the publicly-available data. Setting aside differences in the underlying instrumentation providing the Stokes spectra in question, in principle, since the physics upon which these codes are based is the same, the answers retrieved should be the same. They are not (Figure 2).

The "devil's in the details", and "the details" in this case can be summarized by one word: *"implementation"*. The problem of inversion can be approached quite differently, often due to the fact that codes were developed to take advantage of (or handle the limitations of) certain instruments. This fact has hampered direct comparisons of the output from different sources of vector magnetic field maps[1].

The general approach of an MEUR-based inversion follows thus: for each pixel of interest, minimize the difference between the observed set of Stokes $[I,\ Q,\ U,\ V]$ and a set of synthetic spectra

[1]The, "Vector Magnetic Field Comparison Group", is an informal US-based (but not limited) community group interested in inter-comparisons between, e.g., SDO/HMI, SOLIS/VSM, Hinode/SP, THEMIS, DST/FIRS and other data sources. The PI, Co-Is, and many Collaborators listed for this proposal are involved, see for example poster presentations at the Hinode-3 (Leka et al) and Hinode-4 (Sainz Dalda et al) meetings. This proposal is a complementary, but separate, effort.

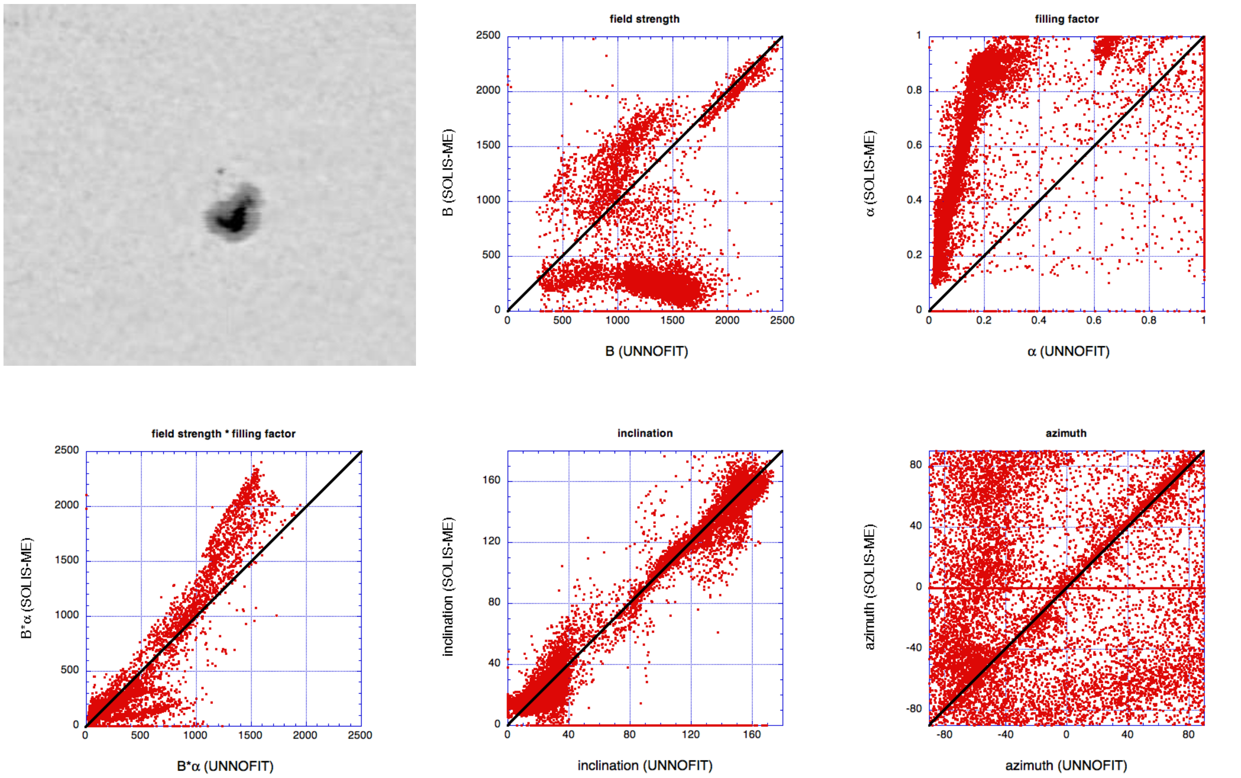

Figure 2: Comparison of two inversions on SOLIS data from 02 May 2007, NOAA AR 10953, for which a continuum intensity image is shown top-left. For all, resulting parameters from the SOLIS pipeline MEUR inversion (y-axis) are compared to the results from the MEUR-based UNNOFIT code (x-axis). (Descriptions of the codes can be found in § 2.1.) The parameters shown (clockwise from top-left) are field strength, fill fraction, azimuth angle, inclination angle, and area-averaged field ($f \times |\boldsymbol{B}|$). The existence of this scatter is the reason for this proposal.

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generated with appropriate conditions under the MEUR assumptions, and report the thermodynamic and magnetic parameters of this "best fit" model and their associated uncertainties.

Some of the common differences among codes include the optimization method use, starting condition, exactly how the merit criterion (e.g., χ^2) is computed, and the treatment of fill fraction. The latter issue is surprisingly complex. In dark areas, umbrae for example, one expects a unity fill fraction (or very close, depending on spatial resolution) and instrumental scattered light may contaminate the signal from quiet-sun or the nearby penumbra, influencing the inferred field strength [23]. In weak-signal areas, there is a degeneracy whereby the behavior of Stokes V is the same with varying $|\boldsymbol{B}|$ as with varying f, and the two cannot be distinguished independently.

Differences in implementation can lead to different answers. For example, in Figure 3 we demonstrate the results achieved by applying the HAO/ASP inversion code (see § 2.1) to the same data from the Hinode/SP, but changing *only* the treatment of the initial guess. The final results compare quite favorably, qualitatively. Still, the results do *not* agree perfectly, and the disagreement between the final χ^2 indicates that the inversion code is quite sensitive to the initial guess, sometimes ending the inversion in a very different part of parameter-space. This demonstration is *not* to say that codes are not tested thoroughly. Rather, this is an example (and not an isolated one) of a particular inversion code being very sensitive to the implementation and "user-chosen inputs" – in

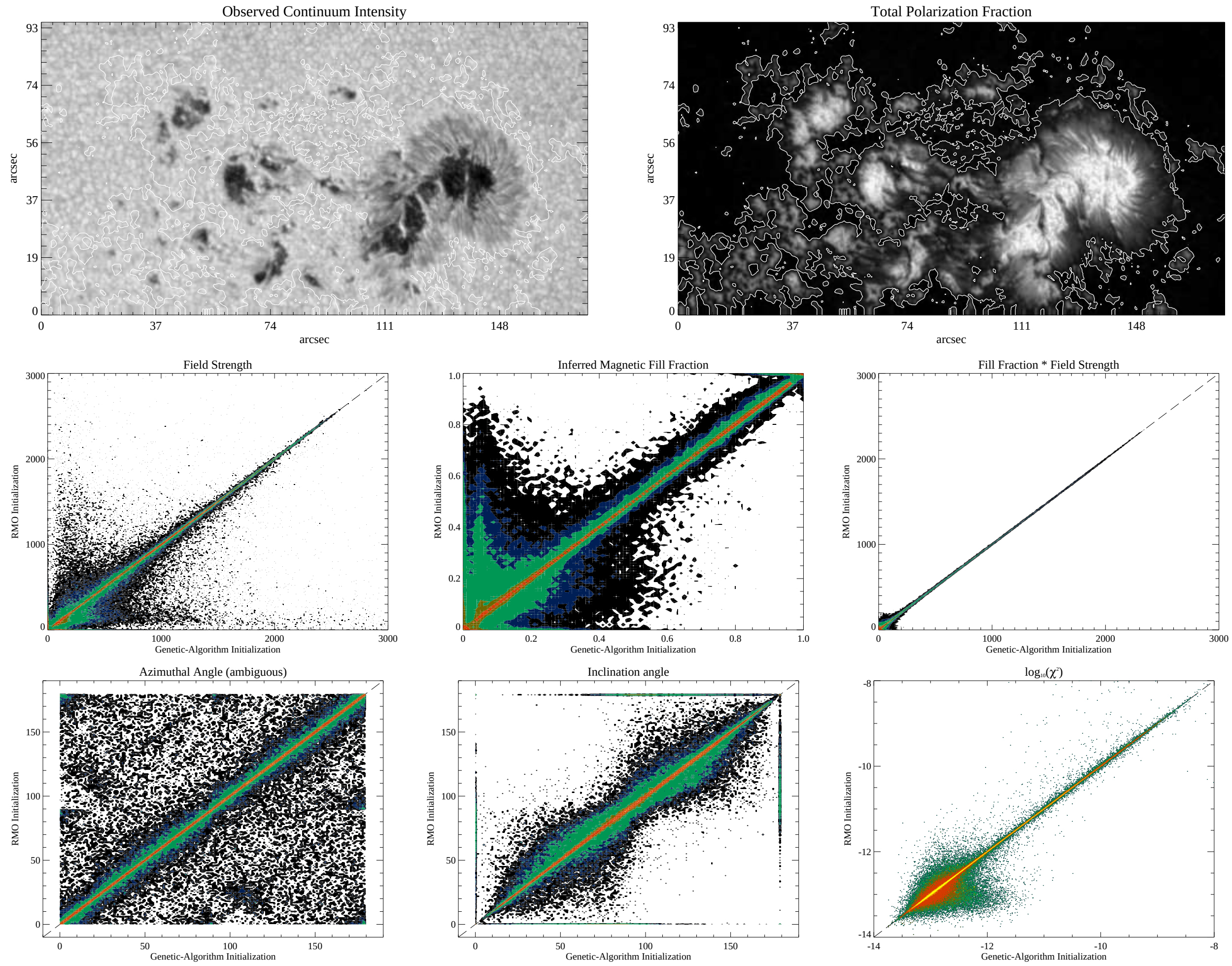

Figure 3: Top, Left: Image constructed in the continuum intensity of NOAA Active Region 11029 observed by the Hinode/SP at roughly 10:45UT on 2009 October 27. Contours indicate the 1% total polarization threshold. **Right:** Image of the total polarization, also with the 1% total polarization threshold indicated. The Stokes spectra for these data were input to the HAO/ASP inversion code (courtesy B. Lites, HAO). **Middle/Bottom:** Comparisons (through 2D density contours) of the results from the two inversions where the *sole* difference is how the initial guess is computed. For all, the levels are: $[0.1, 0.5, 1, 5, 10, 50, 90]\%$ of the number in the highest-populated bin, with the density increasing from dark blue→green→red→yellow. One inversion run used the "integral method" [44, "RMO"] to compute the initial magnetic parameters and one which used a genetic algorithm [16, 10, 9] to attempt to find the best initial part of parameter space for the final optimization. Parameters plotted are (clockwise from middle-left): field strength, fill fraction, area-averaged $f \times |\boldsymbol{B}|$, $\log_{10}(chi^2)$, inclination angle, and (ambiguous) azimuthal angle. For all, the agreement is good, but not perfect, and with significant scatter. What isn't known is the right answer.

this case, it is clear that either a more robust final optimization is needed, or a very robust way of providing an initial guess. Which approach would be best?

2 TECHNICAL APPROACH AND METHODOLOGY

We focus this investigation solely to inversion methods based on the assumptions of Milne-Eddington Unno-Rachkovsky simplifications.

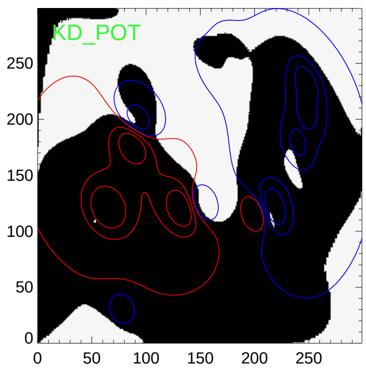

Table II. Results for Ambiguity Resolution Algorithms.

Solution	Fluxtube and arcade				Multi-pole at $\mu \neq 1.0$			
	$\mathscr{M}_{\text{area}}$	$\mathscr{M}_{\text{flux}}$	$\mathscr{M}_{B_h(s)}$	$\mathscr{M}_{J_z}$	$\mathscr{M}_{\text{area}}$	$\mathscr{M}_{\text{flux}}$	$\mathscr{M}_{B_h(s)}$	$\mathscr{M}_{J_z}$
Acute Angle (potential, FFT)								
NJP (J. Jing)	0.67	0.49	0.92	-0.07	0.76	0.85	0.87	0.10
YLP (Y. Liu)	0.64	0.54	0.90	-0.08	0.82	0.86	0.88	0.08
KLP (K.D Leka)	0.75	0.69	0.94	0.25	0.64	0.90	0.73	0.20
Acute Angle (potential, Greens Func.)								
BBP (V. Yurchyshyn)	0.72	0.65	0.92	0.04	0.78	0.88	0.90	0.25
JLP (J. Li)	0.70	0.64	0.90	-0.01	0.71	0.81	0.83	0.13
Acute Angle (LFFF)								
HSO (H.N. Wang)	0.87	0.70	0.99	0.68	0.85	0.94	0.94	0.60

Figure 4: Left: an example of a graphical "failure map" of results from an ambiguity resolution algorithm run on synthetic data (see [34] for details). Black areas are correctly solved, white areas are wrong, blue/red contours indicate areas of strong field in the underlying magnetogram. **Right:** an excerpt from the table of quantitative metrics comparisons for the same study [34].

The approach used will follow those we have used for numerous recent algorithm testing efforts (e.g., two workshops on ambiguity resolution algorithms, see [34, 29], the many workshops for comparisons of non-linear force free field extrapolations [48, 33, 12], the "All Clear Forecast Workshop" [4], and correlation-tracking comparisons [63]), that being a somewhat formal "hare & hound" structure that relies on synthetic data generated to test specific questions. The advantage to using synthetic data is that the answers the algorithms strive to recover are known, and the performance of the algorithms can be judged objectively (Figure 4).

The questions to be addressed include how to best handle magnetic fill fraction and field strength (mentioned above), what are the best weightings for $[I,\ Q,\ U,\ V]$ and related, how to incorporate noise estimations into the merit functions, which parameters can be fixed (not fit) without severe ramifications, initial starting guess sensitivity and (related) optimization algorithms and their implementations. How sensitive are the resulting fit parameters to the definition of the merit function to begin with (e.g., the definition of χ^2)? What is, in fact, needed to obtain a robust answer? Also to be considered *in depth* will be how to weight, calculate, estimate and report uncertainties.

The synthetic data will first be generated directly from MEUR-based synthesis codes using analytic magnetic models as boundary conditions. Appropriate data sets already exist from previous efforts (funded in part by NASA contracts NNH05CC75C and NNH09CE60C). Later, as the answers to some questions get answered, the synthetic data will necessarily need to be more realistic: we will rely upon MHD simulations that include a believable atmosphere and full radiative transfer treatment (see § 2.2, below). Again, the goal is to refine what effectively should be a "standard" in solar magnetic field interpretation but which is presently not available due to the impacts of different implementations.

We will address these questions through systematic application of different MEUR-based codes (see § 2.1, below) to the synthetic data, requesting that they be run in their original state, with specified parameters turned on/off, specifying (or overriding) the codes' initial guesses, specifying weighting ratios, *etc.*, as needed to test a particular topic in a controlled manner. The data will be made available at least a month prior to the workshops and the requested specifics of runs provided at that time. A repository will be made available for results, with code developed for performing real-time comparisons and metrics calculation, so that during the workshops the time is spent in productive, focused discussions and evaluations.

One topic very early in this project will be, "what makes a good evaluation metric?" A simple "fraction of pixels correct" is an easy starting point, especially when paired with a "failure map" to help understand what features of the test data cause the worst problems (Figure 4). Scatter plot comparisons can be described with regression slopes and correlation coefficients; the former measures systematic errors while the latter measures random errors. These can also be used to test whether uncertainty estimates reported by the codes are consistent. With thought, more sophisticated evaluation criteria can be devised that reflect particular kinds of success or failure [34, 29, 33].

2.1 Inversion Codes

We present here concise descriptions of MEUR-based codes which will be used in the comparisons. This is by no means an exhaustive list of MEUR-based inversion codes; if additional researchers with additional codes are identified at a later time and are interested in participating in the comparisons, we will certainly include them.

HAO/ASP Inversion Code: was developed by B. Lites, A. Skumanich, and P. Seagraves [50, 30] initially for use with the "Stokes II" spectropolarimeter[2], and was the inversion method of choice for data from the NSO/HAO Advanced Stokes Polarimeter [13]. Long considered the "industry standard", the ASP inversion uses an initial guess provided by either the "integral method" [44] which provides a fast estimate of $|\boldsymbol{B}|$, γ, ϕ – or a call to a genetic algorithm [16, 9] with nominally a few hundred individuals and generations by which to explore the magnetic and thermodynamic parameter space – prior to invoking Marquardt's algorithm for final optimization. The χ^2 measure(s) use a weighting (effectively a fixed $\frac{1}{\sigma^2}$ in the χ^2 calculation) for $[I,\ Q,\ U,\ V]$ in a [1,100,100,10] ratio. Magnetic parameters fit are field strength, inclination, azimuth angle and fill fraction; thermodynamic parameters fit are continuum source function, gradient with optical depth, damping parameter, Doppler shift, and Doppler width. The magnetic fill fraction and field strength are fit separately, using a "scattered light profile" constructed from the I profile in low-polarization pixels within the available field of view. An additional instrumental "smearing" or macroturbulent parameter can be included but is not fit. The convergence criteria is satisfied when the combined normalized (but not "reduced") fractional change in $\chi^2 < 1\%$.

MERLIN was developed by B. Lites and J. Garcia at NCAR under the framework of the Community Spectro-polarimtetric Analysis Center (CSAC; `http://www.csac.hao.ucar.edu/`). The code is based on the HAO/ASP Inversion Code [50] and is currently mainly used for inversion of Hinode SOT/SP data [22, 60]. MERLIN uses a genetic algorithm to find an initial guess [16, 10, 9], typically with a few dozen individuals and a hundred generations. A Levenberg-Marquardt algorithm is used to find the final solution. MERLIN fits the same parameters as the ASP code. Like the ASP code, MERLIN weighs the χ^2 for $[I, Q, U, V]$ in a [1,100,100,10] ratio, and also employs a "scattered light profile" derived from I profiles of neighboring pixels that display a low degree of polarization.

MILOS was developed by David Orozco Suárez. Originally, it was intended to analyze data coming from the Imaging Magnetograph Experiment (filter-based vector polarimeter) onboard the *Sunrise* mission and to perform an analysis of the sensitivity of the Stokes profiles to changes on the various MEUR model parameters through the so-called Response Functions [39]. It uses the Levenberg-Marquardt method as optimization algorithm and analytic Response Functions. The χ^2 weighting (typically [1,10,10,1]), the $\frac{1}{\sigma^2}$, and initial guess are provided by the user. It has been widely used to analyze data from Hinode/SP assuming a simple one-component model filling the resolution element with a 'stray-light' contamination factor (total of nine free parameters plus fixed instrumental smearing, if required). The 'stray-light profile' (non-magnetic component) is

[2]the Stokes II was later adopted at Mees Solar Observatory as the Haleakalā Stokes Polarimeter, [35]

calculated locally, i.e., averaging the observed intensity profiles in a box several arcsec-wide centered on the pixel, regardless of polarization signal. The aim is to model the effects of the telescope's PSF on the data although the 'stray-light profile' acts also as a magnetic fill fraction. The code is originally written in IDL to make it flexible although there exist versions in Fortran and C++. The latter is a working engineering code that is being implemented on reconfigurable electronics (FPGA) for carrying out real time inversions for the ESA Solar Orbiter mission. The synthesis and Response Functions modules undergo extensive operation tests at the present time.

The inversion code presently in use for **SOLIS/VSM** ("Synoptic Optical Long-term Investigations of the Sun" (SOLIS) "Vector SpectroMagnetograph" (VSM) at the National Solar Observatories (NSO)) pipeline data processing is based on the HAO/ASP inversion code described above. The optimization uses a Levenberg-Marguardt algorithm with a convergence criterion of the fractional change in chi^2 is < 0.01 and a calculated f-probability is > 0.1. The maximum number of iterations is set to 40 and if convergence fails, the code returns zero for all fit parameters. The fit also fails to converge if the damping factor used in the LM algorithm exceeds 100, in this case the fit parameters are also set to zero; the final result can be sensitive to the rate at which this governing factor increases or decreases with each iteration. The initial guesses for azimuth and inclination angles are the output from the SOLIS quicklook (QL) magnetograms; for field strength, the initial guess takes the greater of the QL result or a fixed value of 1KG. The SOLIS MEUR-based code fits 12 parameters: inclination, magnetic field strength, azimuth, Doppler width, line opacity, damping width, line center of 1^{st} and 2^{nd} Fe lines, slope of source function, DC offset of line intensity, line opacity (fixed), translation of scattered light profile, unpolarized light scattering fraction. A standard error of the fitted parameters is calculated, however only the error of the azimuth and Doppler width, and combined normalized χ^2 of $[I,\ Q,\ U,\ V]$ profiles are currently returned.

The **"GENESIS" (GENEtic Stokes Inversion Strategy)** inversion code [20] was developed by Dr. Brian Harker (NSO) and Kenneth Mighell (NOAO) and is under scrutiny to replace the code currently deployed within the SOLIS VSM data reduction pipeline. The code fits for the standard MEUR model parameters in a two-component model atmosphere (one magnetic, one nonmagnetic) which is mixed via a filling factor, and is implemented in C such that spectral line calculations can be performed in parallel on a graphics processing unit (GPU). GENESIS seeks to find the global minimum of the χ^2 hypersurface through an exhaustive exploration of the available parameter space by a binary genetic algorithm. Hence, the code is not plagued by sensitive dependence on an initial guess, as are codes based on (e.g.) the Levenberg-Marquardt algorithm. The initial population is generated quasi-randomly (for diverse coverage) and seeded with specific solutions that represent prior knowledge of the problem (derived from, e.g., a quick-look calculation directly from the Stokes spectra). Weighting is by an "inverse-max" technique, that equalizes the importance of deviations in all four Stokes profiles in calculating the χ^2 figure of merit. The traditionally large computation time required by genetic algorithms is mitigated here by utilizing a massively-parallel GPU for the spectral line calculations for each iteration (generation) to accelerate the processing and making it run 20-30 times faster than the serial version.

UNNOFIT is an inversion code for magnetically sensitive lines based on a 1-D Milne-Eddington model atmosphere [7]. The Stokes spectra are normalized to the continuum intensity so that a single parameter (the ratio of the source function terms) describes the atmosphere. Other parameters are returned from the inversion: the magnetic field strength and direction, the line-of-sight velocity, the Doppler width, the line strength - all assumed depth-independent. A magnetic filling factor is assumed, but due to the data noise only the product of this filling factor with the magnetic field strength, the "local average magnetic field strength", is physically meaningful, but not the field strength and filling factor individual values. The magnetic and non-magnetic atmospheres are assumed to be identical except for the presence/absence of the magnetic field, and the filling factor is determined together with the other parameters. The theoretical profile is from the Unno-Rachkovsky analytical solution (modified for a Zeeman multiplet in the UNNOFIT2 version). The Levenberg-Marquardt algorithm is used for fitting the observed four Stokes spectra with the theoretical curves, the needed partial derivatives being analytically evaluated. The initial guess consists of 20 different random initializations, the better result being retained as the final result. No micro- or macro-turbulence effect is added to the theoretical profile. Different weights may be assumed for each Stokes contribution to the χ^2 merit function, but the default is uniform weighting.

The **Two-Component Magneto-Optical ("2C MO")** inversion code is a Milne-Eddington code implemented in IDL (Jaeggli, Lin). The equations of polarized radiative transfer were taken from [26] and [21] and the complex Voigt function for each line is calculated following [32]. The four Stokes components are fit simultaneously using the IDL function "curvefit" which uses a gradient-expansion algorithm to compute the least-squares solution to non-linear functions of arbitrary parameters supplied by the user. Eleven parameters are considered: the magnetic field strength, inclination, and azimuth; the source function and gradient; the line center (velocity), doppler width, damping parameter, and ratio of the line to continuum absorption (η_0); the line center of the scattered light component and the magnetic filling fraction. The scattered light profile is produced by taking a median of selected quiet sun profiles. An initial guess to the magnetic field parameters is generated from the Stokes spectra using a quick look method, other parameters are supplied with a constant guess. The Stokes profiles are assigned relative weighting in the fit based on the amount of signal in each, the measurement errors for the profiles are not provided to the fit.

Finally, the inversion which needs a new name: **"The Very Fast Inversion of the Stokes Vector (VFISV)"** was developed by Juan Borrero and built for speed [8]. VFISV assumes a standard Milne-Eddington Atmosphere to the retrieve magnetic field vector, line-of-sight velocity, source function, Doppler broadening as well as the macroturbulence and the stray light filling factor. It works only on normal Zeeman triplets, thus is suitable for the Fe I 6302.5nm line included in the Hinode/SP spectral range, for data from the Imaging Vector Magnetograph [36, 24, 23], and for the Fe I 617.33nm line being used for SDO/HMI. The distributed version relies upon a neural net approach to provide the initial guess, which is trained using the SIR code synthesis module for the particular line and instrument (including noise levels) for which it is to be used. A Levenberg-Marquardt optimization follows. As of this writing, the version used in the SDO/HMI vector-field pipeline does not use the neural net for an initial guess, but is relying upon either an integral-method or fixed-guess approach. Included are various methods for treating the scattered light and magnetic fill fraction; for IVM data, the local scattered-light profile option is being used and the fill fraction is included in the fit. Also at this writing, for the SDO/HMI vector-field pipeline, no treatment of the scattered light is being included and the fill fraction is fixed at unity.

2.2 Realistic Synthetic Data: Stokes Spectra from MHD Simulations of the Sun

Three different cases will be modeled: quiet Sun, plage and active region. Active region and plage models already exist (Figure 5), while the quiet Sun case remains to be initiated. Here, we summarize the salient points of the MHD modeling effort, as it is important to understand the limitations of what will be used for the synthetic data against which the inversion results will be evaluated.

The code solves the equations for mass, momentum and internal energy in conservative form, plus the induction equation for the magnetic field. The flow is fully compressible, in three dimensions, and on a staggered mesh. $\boldsymbol{\nabla} \cdot \boldsymbol{B}$ is conserved, horizontal boundary conditions are periodic, while top and bottom boundary conditions are transmitting. The magnetic field is made to tend toward a potential field at the top and at the bottom is given a specified value in inflows and ex-

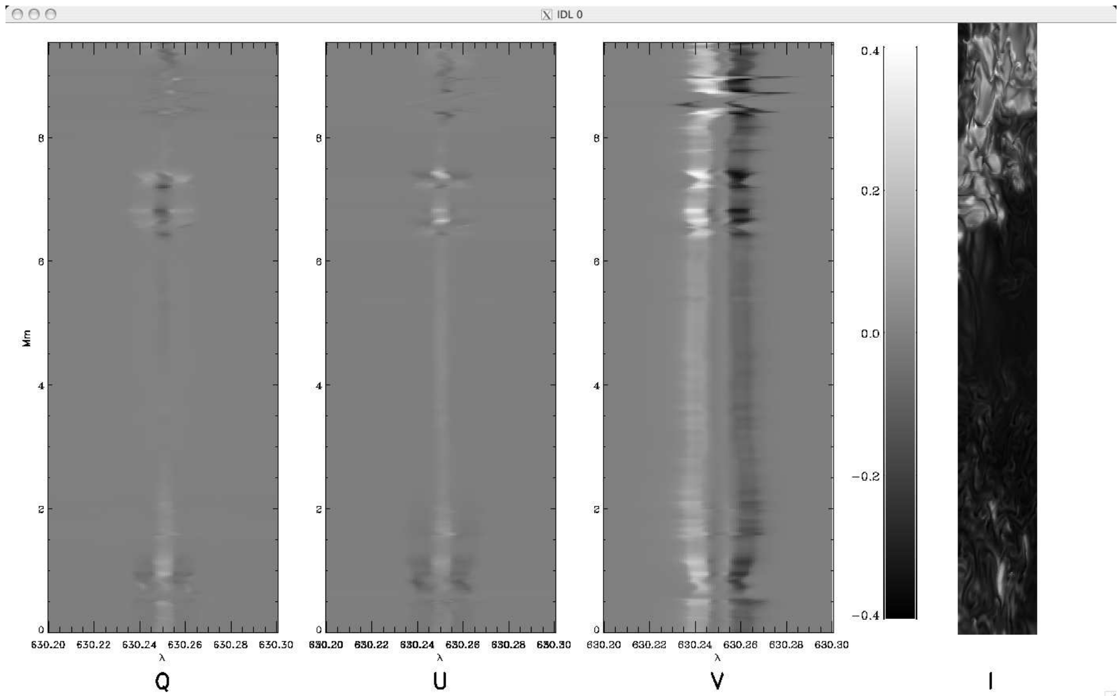

Figure 5: Emergent Stokes spectra in the 630.25nm line from a "slit" placed across the "proto sunspot" (seen in the continuum-intensity slice, right) of recent simulations by Co-I Stein and computed by forward-integration through a solar-like atmosphere with complex gradients along the line of sight in field and velocity, all of which strongly influence the emergent line shapes.

trapolated in outflows. The code is stabilized by diffusion in the momentum, energy and induction equations.

Ionization energy accounts for 2/3 of the energy transported near the solar surface and must be included to obtain the observed solar velocities and temperature fluctuations [57]. A tabular equation of state is used that includes local thermodynamic equilibrium (LTE) ionization of the abundant elements, as well as hydrogen molecule formation, to obtain the pressure and temperature as a function of log density and internal energy per unit mass.

The radiative heating/cooling is calculated by solving the radiation transfer equation in both continua and lines using the Feautrier method [15], assuming Local Thermodynamic Equilibrium (LTE). The number of wavelengths for which the transfer equation is solved is drastically reduced by using a multi-group method whereby the opacity and the source function at each wavelength is binned by magnitude [37, 58, 62]. In general, calculated emergent spectral line widths, Doppler shifts, and asymmetries from the simulations are in excellent agreement with observations [2].

The computation domain is 48×48 Mm wide by 20 Mm deep; an initial advection of weak, horizontal, uniform, untwisted magnetic flux by inflows at the bottom is gradually subjected to increasing field strength (for strong-field cases), and the simulation is run until substantial magnetic flux appears at the surface (approximately the rise time of 32 hours). Once the magnetic field collects into its unipolar areas, the field is artificially increased to make the pores expand into proto-sunspots (see Figure 5). In the active region simulation, dark pores have formed with magnetic field strengths greater than 2.5 kG and with incipient penumbras. This study is similar to that of M. Rempel [43, 42], but has a larger horizontal scale, extends deeper and will have a more complex and natural magnetic field topology. In the plage simulation, we see an increasing mean unsigned magnetic flux as the field is being swept to the granule boundaries and then to the meso-granule boundaries.

For the quiet Sun simulation, the initial 1 kG horizontal magnetic flux will not be increased, and will simply be transported by the convective motions toward the surface. Running on a grid 1008x1008x500 or larger will allow dynamo action to occur as well as magneto-convection with the imposed field. Both will contribute to the small scale, quiet-Sun-like, surface magnetic field.

Emergent Stokes $[I,\ Q,\ U,\ V]$ spectra are calculated with the Stokes spectral synthesis code from the "LTE Inversion based on the Lorien Iterative Algorithm (LILIA)"[3], [53, 55], which is based on the synthesis code from the "SIR" code that uses Response Functions for inverting [45]. Local thermodynamic equilibrium is assumed for a 1D plane-parallel atmosphere, and the depth-stratification of the temperature, density, magnetic field vector, line-of-sight velocity, as well as the macroturbulence are all effectively integrated along the line of sight for the height of formation of the line in question. Hence, the emergent Stokes spectra are no longer (anti-)symmetric as with MEUR-synthesized spectra; gradients in velocity and the magnetic field vector routinely produce multi-lobed and asymmetric spectra as are also routinely observed in data from, *e.g.,* Hinode/SP and other facilities with $< 1''$ spatial resolution.

3 RELEVANCE AND PERCEIVED IMPACT

The Heliophysics research field has matured to the point that qualitative morphological studies of the photospheric magnetic field are no longer sufficient to address NASA strategic goals and science outcomes. Indeed, in the description for TR&T Topic #1.2.3, "Science Analysis for the Solar Dynamics Observatory (SDO)", it states "This topic challenges proposers to use the data from the Solar Dynamics Observatory (SDO) to characterize the properties, evolution, and terrestrial consequences of the solar magnetic field." The photospheric vector magnetic field constitutes the boundary condition for many of the studies likely to have been submitted to this and other topics.

Characterizing the solar photospheric boundary has been (and will continue to be) one basis for developing predictive capabilities for solar flares, coronal mass ejections, and energetic particle events [19, 52, 28, 18, 3, 14]. Solar Flares impact and effect the Earth's ionosphere; the acceleration of solar energetic particles is likely tied to the heliospheric magnetic fields configuration, whose boundary is at the solar photosphere. In this sense, providing consistent and quantitative measurements of the photospheric vector magnetic fields *along with a full understanding of the limitations of the measurements being offered* is required for progress on many of this year's solicited topics.

But this is not an SDO-centered proposal. The codes we propose to test are the "standard-bearers" for producing solar photospheric vector magnetic field maps from almost every observatory that is, or has been, engaged in spectropolarimetric observations. New codes are being developed based on the same simplifying assumptions, but tailored for new instruments with new capabilities. The assumptions themselves are not in question here, although we recognize that they *are* assumptions and more sophisticated algorithms *do* exist. It is the mechanics of implementing those assumptions into inversion codes which must be clarified for the community, so that when one describes using a "Milne Eddington" based code in a manuscript, one need not cite anything beyond "as implemented following *(results from this proposal)*." The research can progress without fear that the results are subject to change depending on *which* Milne Eddington inversion was used.

Hence, the proposed workshops are critically timely and important to the goals of NASA's Living With A Star program. In addition, the proposed workshops are very narrowly focused on testing and validating already-developed tools, and even more specifically, differences in their implementation, rather than investigating completely new approaches. The workshops will be held

[3] http://www.csac.hao.ucar.edu/csac/nextGeneration.jsp#lilia

in Boulder, Colorado, which is home of the host institution, requires no travel for collaborators from NCAR/HAO, and is central for originating locations for all other collaborators and Co-Is. One graduate student is a confirmed collaborator, and funds have been requested for yet-unnamed participants and could easily be graduate students.

4 WORK PLAN

4.1 Structure and Focus of the Workshops

As mentioned above, the PI and Co-I Barnes have directed or been involved with a variety of efforts similar to this which employ "hare & hound" approaches to test the performance of existing algorithms [34, 29, 49, 33, 48, 12, 63]. One lesson learned: start simple. Very simple.

First Things First: We will begin by a systematic comparison of the different codes' synthesis modules. If differences arise between computed synthetic Stokes spectra for a given MEUR atmosphere and magnetic vector, those must be identified and mitigated before proceeding further.

Keep it Simple: Synthetic data generated using MEUR-based Stokes-spectra synthesis codes (such as were validated above) based on known boundary conditions (e.g., any of the cases used in prior comparisons, as for Figure 4, [34, 29]) will be used to investigate the basic aspects of optimization and merit functions.

As a slightly more appropriate but still very simple case, we will consider magnetostatic solutions for constructing a model boundary condition [31, 6]. In this approach, for any specified distribution of radial field on the surface, the corresponding horizontal components of the field can be calculated along with a self-consistent pressure and density (from which a temperature can be determined). Thus, these models can be used to simulate unresolved structure while also specifying the (not unreasonable) thermodynamic properties of the plasma for input into MEUR-based Stokes synthesis modules.

More Realism: Realistic Magneto-Hydrodynamic simulations of a dynamic, evolving, Solar-like plasma – coupled with an atmosphere that includes an explicit treatment of radiative transfer through 0.5Mm above the local $\tau_c = 1$ layer (where, on average $\tau_c \approx 0.01$), form the final tests of the inversion codes (§ 2.2). Data from the MHD simulations carried out by Co-I Stein form the basis for this set of tasks, for nowhere will appear the simplifying assumptions of a Milne-Eddington or Unno-Rachkovsky in generating the emergent Stokes spectra.

4.2 Key Milestones

The key milestones for this 3-year request will consist of the three workshops – preparing for them, holding them, interpreting the results from them and then writing a manuscript describing them. The subjects we propose to concentrate on for each are described below (but we must allow for flexibility as the series progresses):

First Workshop (target: February/March 2012): Topics: synthesis code comparison, metrics, and the simplest test cases. Pre-Workshop preparation will include identifying a set of test cases for the synthesis modules, constructing a simple synthetic test case, specifying data formats suitable to all participants and aiding in any wrapper/reformatter writing needed for Collaborators, and establishing repositories at NWRA for submitted results so that real-time comparisons can be made. Workshop discussions will be focused on determining metrics by which results are judged and comparison of the results on hand. A manuscript describing the results will follow.

Second Workshop (target: February/March 2013): Topics: the treatment of fill fraction and field strength, optimization methods (plus any time-critical topic identified between Workshops).

Test cases will include MEUR-generated synthetic data constructed to include areas of low magnetic fill fraction, obtained by spatially averaging the emergent Stokes spectra [29, 27], as well as synthetic data from the MHD simulations of Co-I Stein. Pre-Workshop, the test cases will be distributed and solutions collected, such that comparisons can be made prior to (or during) the workshop, additional metrics developed (if needed), and discussion can focus on learning what the results mean. A manuscript describing the results will follow.
Third Workshop (target: February/March 2014): Having adopted what was learned in the first two workshops, this will target "throwing everything into the ring". Synthetic data will be generated based on the simulations from Co-I Stein, and the resulting spectra manipulated to add photon noise, instrumental profiles, temporal, spatial, and spectral averaging. Still, the underlying answer will be essentially "known", and – if in the ensuing years codes have been updated with the findings from the first two workshops, these final tests should validate that the community has available MEUR inversion(s) whose answers will differ solely due to the different Stokes spectra input, not due to implementation differences. A manuscript describing the results will follow.

All workshops will be advertised in *SolarNews*, however a limit will be placed on the number of attendees to ensure focused discussions and productive comparison work during the face-to-face time. In addition to the Collaborators committed to participating (§ 4.4), we have requested travel funds for two additional participants, one domestic and one international, to help ensure broad community participation from groups not committed at this time.

4.3 Data Sharing Plan:

The strength of investing in systematic, detail-oriented testing of algorithms is the long-term payoff. The test cases generated for these workshops, and the standardized, quantitative, informative metrics that we will devise by which results can judged, will be made available for testing other MEUR codes in the future, most likely hosted at NWRA, with links to code/test cases from CSAC, NSO, etc. Co-I Stein has already made (and will continue to make) the results from his simulation, including emergent Stokes spectra, publicly available[4].

The availability of independent test cases and evaluation metrics is crucial for progress. The PI and Co-I Barnes have made publicly available the test cases used for the testing of azimuthal ambiguity resolution algorithms[5]; they have worked with colleagues developing new codes to test them on the published cases, returning the resulting evaluation metrics to the developer.

It is a lofty goal to have, as a final product, a new Milne-Eddington Unno-Rachkovsky based inversion code which incorporate the results of our comparisons and hence provides the community with a single "go-to" code that has all of the best elements. Ideally such a code would have its "guts" in a modular architecture so that with appropriate customized wrappers, it could be applied to data from a wide variety of instruments. If a clear picture of such a code emerges over the course of our comparisons, then the task of finding resources to produce it will be investigated at the appropriate time.

4.4 Key Personnel

Dr. K.D. Leka (NWRA) has experience running and interpreting the results from a half-dozen inversion codes, and just wants to know which one she should use to just get on with the science she wants to do. Dr. Leka has worked with spectropolarimetric data for two decades with a dozen instruments, beginning with the Haleakalā Stokes Polarimeter and then assisting Dr. Don

[4] `http://steinr.pa.msu.edu/ bob/stokes/README`
[5] `www.cora.nwra.com/AMBIGUITY_WORKSHOP`

Mickey with construction and commissioning of the Imaging Vector magnetograph. She lead the effort for systematic evaluation of ambiguity-resolution algorithms, and has been involved with choreographed comparisons of magnetographs, non-linear force-free field extrapolations and flare prediction schemes. Dr. Leka will represent "Stokesfit" (developed by Dr. T.R. Metcalf and distributed through *SolarSoft*, the "Triplet" code (developed by Dr. B.J. LaBonte as an alternative inversion for data from the IVM), the HAO/ASP inversion code (as adapted for use with Hinode/SP data), and a non-HMI implementation of VFISV targeted for the future release of archive IVM data. As Principal Investigator, Dr. Leka will be responsible for all aspects of this project.

Dr. Graham Barnes (NWRA) has broad expertise in numerical methods, statistical analysis, optimization methods and general inversion approaches. He has hosted or participated in algorithm-comparison workshops on wide-ranging subjects including ambiguity-resolution, non-linear force-free field extrapolations and flare prediction schemes, and provided model data and metrics definitions to most. Dr. Barnes will help define workshop focus and approach, provide some of the "simple" test data, and help define performance metrics for the comparisons.

Mr. Eric Wagner (NWRA) is one of NWRA's support engineers, with broad computer and programming expertise. He has been responsible for re-writing and optimizing the IVM data-reduction code package and installing numerous inversion packages at NWRA for use with a variety of data sources including the IVM, SOLIS, Hinode/SP, and SDO/HMI. Mr. Wagner will be responsible for setting up format standards and helping Collaborators write reformatters or wrappers as needed to work with the test data, and collating the results at NWRA for analysis.

Dr. Robert Stein (Michigan State University) brings a lifetime of expertise in Magneto-Hydrodynamic Simulation to the project, and a recent interest in using the results of simulation to test algorithms used for observational interpretation of solar magnetic fields and helioseismic signals and magnetic fields.

Dr. Aimee Norton (James Cook University, Australia; Adjunct Astronomer at NSO) has over ten years of experience with spectro-polarimetric instruments. She served as a Project Scientist for HMI (2003-2006), assisting in the spectral line selection and development of the vector field observing capability. She also served as Project Scientist for the Synoptic Optical Long-term Investigations of the Sun (SOLIS VSM, 2007-2009) assisting to implement the present ME inversion code. Dr. Norton will assist the PI in developing the targeted tasks with which to challenge the different inversion codes, bringing to the overall project (like the PI) a broad understanding of instruments and approaches being used presently for inversions.

Dr. Alexei Pevtsov (National Solar Observatories) is Program Scientist for the SOLIS/VSM project, which is actively pursuing the best MEUR inversion code to use for inverting data from this facility. As the NSO Institutional PI, Dr. Pevtsov will direct and coordinate efforts regarding the SOLIS MEUR code and Dr. Harker's code for this comparison effort.

The following Collaborators have committed to participating in this effort, by running code that they oversee on test data provided, submitting the results, participating in the comparison workshops and helping write relevant manuscripts:

Ms. Sarah Jaeggli (U. Hawai'i) has helped build and commission the Facility InfraRed Spectromagnetograph for the NSO/Dunn Solar Telescope as part of her graduate thesis work at U. Hawai'i. She developed the ME-based "2C MO" for the inversion of the multi-line multi-height data available from this instrument.

Dr. Rebecca Centeno Elliot (NCAR/HAO) is the Project Scientist at HAO for the HMI vector magnetic field pipeline inversion module, based on the Very Fast Inversion of Stokes Vectors [8] by Juan Manuel Borrerro.

Dr. David Orozco Suárez (NAOJ, Japan) developed the "MILOS" inversion code that performs a localized calculation of the stray-light profile for a more accurate determination of the non-magnetic component within each pixel. He is presently involved in the development of the "first electronic (FPGA-based) real-time ME inverter", initially targeted for use for the ESA *Solar Orbiter* mission.

Dr. Veronique Bommier (CNRS, France) developed "UNNOFIT" and "UNNOFIT2", the latter of which explicitly explores simultaneous treatment of magnetic field strength and fill-fraction, for use with data from the THEMIS telescope.

Dr. Alfred de Wijn (NCAR/HAO) is a member of the NCAR/HAO "Community Spectro-polarimetric Analysis Center" project, and oversees the "MERLIN" code presently being used for pipeline- and user-customized inversion of Hinode/SP data.

Dr. Brian Harker (National Solar Observatories) has developed an MEUR inversion code which incorporates a full genetic optimization and runs on a graphical processing unit. As NSO is considering transitioning to this approach for SOLIS pipeline data reduction, establishing the best approach for the inversions' implementation is key.

Dr. Roberta Toussaint (National Solar Observatories) is the software support scientist for the SOLIS program. With direction from Dr. Alexei Pevtsov, she will run the SOLIS ME-based inversion code on the test data provided and in the manner(s) needed for the workshops. She will also coordinate with Dr. Brian Harker on NSO results from the two codes there.

In addition, two NWRA staff, Ms. Janet Biggs (The NWRA/CoRA Division Operations Manager) and Mr. Andy Frahm (The NWRA/CoRA Division Administrative and IT Assistant) will be available for logistical and technical support prior to and during the workshops, supported in full by NWRA/CoRA Division overheads. Both have extensive experience organizing scientific conferences and workshops, both large and small (e.g., `http://www.cora.nwra.com/Canfield/`, `http://www.cora.nwra.com/Meteoroids2010/`).

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K.D. Leka

Professional Preparation

University of Hawai'i	Astronomy	Ph.D., 1995
University of Hawai'i	Astronomy	M.S., 1992
Yale University	Astronomy and Physics	B.S., 1989

Appointments

07/03 – present: Senior Research Scientist, NWRA/CoRA
06/98 – 06/03: Research Scientist, NWRA/CoRA
05/97 – 05/98: Research Associate, NRC, at the Space Environment Center/NOAA
12/94 – 04/97: Postdoctoral Fellow, Advanced Study Program, NCAR

Relevant Scientific, Technical and Managerial Performance

Dr. KD Leka has served as Principal Investigator for over a dozen projects funded by NASA, the NSF, and AFOSR, and has been co-investigator on many more. The topics have ranged from studying the structure and evolution of sunspot magnetic fields, instigating "hare & hound" testing of analysis algorithms, and predicting solar flares. Dr. Leka is an expert at observational solar spectropolarimetry and magnetograph instrumentation, data analysis, and interpretation. She was one of the personnel involved in building, installing, and commissioning the Imaging Vector Magnetograph at U. Hawai'i, and has worked with data from a dozen magnetograph systems both spectrograph- and imaging-based, over the last two decades. Dr. Leka also routinely instructs undergraduates, graduate students and postdocs on the analysis and interpretation of vector field data. She presently leads the effort for the HMI pipeline modules handling azimuthal ambiguity resolution and active-region characterization for space-weather related products.

Select Publications Relevant to this Proposal

Wheatland, M. S. and Leka, K. D.; 2010, "Achieving Self-Consistent Nonlinear Force-Free Modeling of Solar Active Regions", *Astrophys. J.*submitted.

Leka, K.D. 2010, "Effects of Limited Resolution on SpectroPolarimetric data, from the Subtle to the Supreme", *Proceedings of the Sixth Solar Polarization Workshop*, Kuhn, J. et al (eds), Astronomical Society of the Pacific *in press*.

Ferguson, R., Komm, R., Hill, F., Barnes, G. and Leka, K. D. 2010, "Subsurface Verticity of Flaring versus Flare-Quiet Active Regions", *Solar Phys.*, *OnlineFirst*.

Crouch, A. D.; Barnes, G.; Leka, K. D. 2009, " Resolving the Azimuthal Ambiguity in Vector Magnetogram Data with the Divergence-Free Condition: Application to Discrete Data", *Solar Phys.*, **260**, 271.

Leka, K. D., Barnes, G., Crouch, A., Metcalf, T. R., *and 3 co-authors* 2009, "Resolving the 180° Ambiguity in Solar Vector Magnetic Fields: Evaluating the Effects of Noise and Spatial Resolution", *Solar Phys.*, **260**, 83.

DeRosa, M., Schrijver, C., Barnes, G., Leka, K. D., Lites, B.W. *and 11 co-authors* 2009, "A Critical Assessment of Nonlinear Force-Free Field Modeling of the Solar Corona for Active Region 10953", *Astrophys. J*, **696**, 1780.

Barnes, G. and Leka, K. D. 2008, "Evaluating the Performance of Solar Flare Forecasting Methods", *Astrophys. J.*, **688L**, 107.

Barnes, G., K.D. Leka, E.A. Schumer, and D.J. Della-Rose: 2007, "Probabilistic Forecasting of Solar Flares from Vector Magnetogram Data", *Space Weather*, **5**, S09002.

Leka, K. D. and Barnes, G. 2007, "Photospheric Magnetic Field Properties of Flaring vs. Flare-Quiet Active Regions IV: A Statistically Significant Sample", *Astrophys. J*, **656**, 1173.

Leka, K. D., Barnes, G., Crouch, A. 2009, "An Automated Ambiguity-Resolution Code for Hinode/SP Vector Magnetic Field Data", in B. Lites (ed), "The Second Hinode Science Meeting", ASP Conference Series, *in press*.

Metcalf, T. R., Leka, K. D., Barnes, G., Lites, B.W. *and 11 co-authors*, 2006, "An Overview of Existing Algorithms for Resolving the 180° Ambiguity in Vector Magnetic Fields: Quantitative Tests with Synthetic Data",*Solar Physics*, **237**, 267.

Leka, K.D., Fan, Y. and Barnes, G. 2005, "On the Availability of Sufficient Twist to Trigger the Kink Instability", *Astrophys. J.*,**626**, 1091.

Barnes, G. and Leka, K. D. 2006, "Photospheric Magnetic Field Properties of Flaring vs. Flare-Quiet Active Regions III: Magnetic Charge Topology Models", *Astrophys. J*, **636**, 1303.

Metcalf, T. R., Leka, K.D. and Mickey, D. L. 2005, "Magnetic Free Energy in AR10486 on October 29, 2003", *Astrophys. J.*, **623**, L53.

Leka, K.D., and Barnes, G. 2003, "Photospheric Magnetic Field Properties of Flaring Versus Flare-Quiet Active Regions. II. Discriminant Analysis", *Astrophys. J.*, **595**, 1296.

Leka, K.D., and Barnes, G. 2003, "Photospheric Magnetic Field Properties of Flaring Versus Flare-Quiet Active Regions. I. Data, General Approach, and Sample Results", *Astrophys. J.*, **595**, 1277.

Leka, K.D., and Metcalf, T.R. 2003, "Active Region Magnetic Structure Observed in the Photosphere and Chromosphere", *Solar Physics*, **212**, 361.

Leka, K. D. and Steiner, O. 2001, "Understanding Small Solar Magnetic Elements: Comparing Numerical Models to Observations", *Astrophys. J.*, **552**, 354.

Leka, K. D., 1997, "The Vector Magnetic Fields and Thermodynamics of Sunspot Light Bridges: The Case for Field-Free Disruptions in Sunspots" *Astrophys. J.*, **484**, 900.

Lites, B. W., Leka, K. D., Skumanich, A., Martinez Pillet, V., and Shimizu, T., 1996, "Small-Scale Horizontal Magnetic Fields in the Solar Photosphere", *Astrophys. J.*, **460**, 1019.

Leka, K. D., Canfield, R. C., McClymont, A. N., and van Driel-Gesztelyi, L., 1996, "Evidence for Current-Carrying Emerging Flux", *Astrophys. J.*, **462**, 547.

Mickey, D. L., LaBonte, B. J., and Leka, K. D., 1999, "The Imaging Vector Magnetograph at Haleakalā II: Reconstruction of Stokes Spectra", *Solar Phys.*, **189**, 1.

Mickey, D. L., Canfield, R.C., LaBonte, B. J., Leka, K. D., Waterson, M. F., and Weber, H. M., 1996, "The Imaging Vector Magnetograph at Haleakalā", *Solar Phys.*, **168**, 229.

Eric L. Wagner

Professional Preparation

University of Colorado at Boulder   Computer Science   B.S., 1993

Appointments

2009 – present:	Support Engineer NorthWest Research Associates, Inc. CoRA Division, Boulder, Colorado
2001 – 2009:	Freelance C/UNIX/Linux Programmer, System Administrator
1999 – 2001:	Engineer/Programmer East West Communications Inc., New York City
1998 – 2002:	Consultant Engineer/Technician Posthorn Recordings Inc., New York City
1995 – 1998:	Recording Engineer/Technician Quintessential Sound Inc., New York City
1994 – 1995:	Software Engineer Geotechnical Engineering Software Activity, Boulder, Colorado
1993 – 1995:	Software Engineer and Lab Administrator Bechtel Computer Aided Design Laboratory, Dept. of Civil Engineering, University of Colorado at Boulder
1992 – 1993:	Research Assistant High Performance Scientific Computing Laboratory, Dept. of Computer Science, University of Colorado at Boulder

Relevant Technical Performance

Mr. Wagner has a strong background in scientific programming, code optimization, and software design, with experience in Linux system administration of web/data servers. He is familiar with a wide array of audio and data formats, along with related conversion and archival methods, and has worked with many types of storage media and filesystems. After his first year of college, he spent a summer working as a technician's assistant at Exabyte Inc., gaining experience with the Exabyte tape format used for early IVM archives.

Graham Barnes

Professional Preparation

Cornell University	Physics Major, Astronomy Minor	Ph.D., 1999
Cornell University	Physics Major, Astronomy Minor	M.S., 1995
Yale University	Mathematics and Physics	B.S., 1992

Appointments

01/03 – present: Research Scientist, NorthWest Research Associates, Inc., Colorado Research Associates Division

12/02 – 04/05: Visiting Scientist, High Altitude Observatory, National Center for Atmospheric Research

08/01 – 12/02: Postdoctoral Researcher, NorthWest Research Associates, Inc., Colorado Research Associates Division

12/00 – 06/01: Visiting Scientist, High Altitude Observatory, National Center for Atmospheric Research

10/98 – 10/00: Postdoctoral Research Fellow, Dept. of Mathematics, Monash University, Australia

Selected Publications

Leka, K.D., G. Barnes, A.D. Crouch, T.R. Metcalf, G.A. Gary, J. Jing, and Y. Liu: 2009 'Resolving the 180° Ambiguity in Solar Vector Magnetic Field Data: Evaluating the Effects of Noise, Spatial Resolution, and Method Assumptions'. *Solar Phys.*, **260**, 83.

DeRosa, M.L., C.J. Schrijver, G. Barnes and 16 coauthors: 2009, 'A Critical Assessment of Non-Linear Force-Free Field Modeling of the Solar Corona for a Recent Solar Active Region'. *Astrophys. J.*, **696**, 1780.

Barnes, G. and K.D. Leka: 2008, "Evaluating the Performance of Solar Flare Forecasting Methods". *Astrophys. J. Letters*, **688**, L107.

Schrijver, C.J., M.L. DeRosa, T.R. Metcalf, G. Barnes and 13 coauthors: 2008, "Non-Linear Force-Free Modeling of a Solar Active Region Around the Time of a Major Flare and Coronal Mass Ejection". *Astrophys. J.*, **675**, 1637.

Metcalf, T.R., M.L. DeRosa, C.J. Schrijver, G. Barnes, and 5 coauthors: 2007, "Non-Linear Force-Free Modeling of Coronal Magnetic Fields. II. Modeling a Filament Arcade from Simulated Chromospheric and Photospheric Vector Fields", *Solar Phys.*, **247**, 269.

Metcalf, T.R., K.D. Leka, G. Barnes, and 12 coauthors: 2006, "An Overview of Existing Algorithms for Resolving the 180° Ambiguity in Vector Magnetic Fields: Quantitative Tests with Synthetic Data", *Solar Phys.*, **237**, 267.

Scientific, Technical and Management Performance on Prior Research

Dr. Barnes has or is presently serving as P.I. on grants and contracts from the NSF, NASA and AFOSR. He has extensive experience in workshops for comparing different methods of solving the same problem, including leading a NASA TR&T project to compare the performance of existing flare forecasting methods, and participating in an ongoing series of workshops on Nonlinear Force-Free Field extrapolations, as well as several workshops comparing methods of removing the 180° ambiguity in vector magnetograms.

Vita: Robert Stein

Education:

B.S. University of Chicago, 1957 (Mathematics and Physics)
M.A. Columbia University, 1960 (Physics)
Ph.D. Columbia University, 1966 (Physics)

Employment:

Professor Emeritus, Michigan State University, 2007-
Professor of Physics and Astronomy, Michigan State University, 1981-2007
Visiting Scientist, Center for Turbulence Research, NASA Ames & Stanford Univ., 2004
Visiting Scientist, Institute of Theoretical Physics, UCSB, 1990, 2002
Visiting Scientist, High Altitude Observatory, 1972, 1990, 1992, 1998
Associate Professor of Astronomy and Astrophysics, Michigan State University, 1976-1981
Assistant Professor of Astrophysics, Brandeis University, 1969-1976
Visiting Fellow, Joint Institute for Laboratory Astrophysics, 1973-1974
Research Fellow, Harvard College Observatory, 1967-1969
Research Fellow, Mt. Wilson and Palomar Observatories, 1966-1967

National Committees:

Consultant, "Astronomy and Astrophysics in the New Millennium", National Research Council Panel on Theory, Computation and Data Exploration.
Science Working Group, Advanced Technology Solar Telescope.

Professional Affiliations:

American Astronomical Society
International Astronomical Union

Fellowships and Honors:

Visiting Fellow, Joint Institute for Laboratory Astrophysics, 1973-1974
Norwegian Academy of Science and Letters, 1994–

Recent Related Publications:

- "Solar Flux Emergence Simulations", (Stein, R. F.; Lagerfjärd, A.; Nordlund, Å.; and Georgobiani, D.), Solar Phys., Online First, 10.1007/s11207-010-9510-y, 2010.
- "Supergranulation Scale Convection Simulations", (Stein, R. F., Georgobiani, D., Schafenberger, W., Nordlund, Å. and Benson, D.), in *Proceedings 15th Cambridge Workshop on Cool Stars, Stellar Systems and the Sun*, AIP Conf. Proc., **1094**, 764-767, 2009.
- "Accurate Radiation Hydrodynamics and MHD Modeling of 3-D Stellar Atmospheres", (Nordlund, Å and Stein, R. F.) in *Recent Directions in Astrophysical Quantitative Spectroscopy and Radiation Hydrodynamics*, AIP Conf. Proc., **1171**, 242-259, 2009.
- "Solar Surface Convection", (Nordlund, Å., Stein, R. F. and Asplund, M.), Liv. Rev. Sol. Phys., **6**, 2, 2009.
- "Rapid Temporal Variability of Faculae: High-Resolution Observations and Modeling", 9 De Pontieu, B.; Carlsson, M.; Stein, R. F.; Rouppe van der Voort, L.; Löfdahl, M.; van Noort, M.; Nordlund, Å. and Scharmer, G.), Astrophys. J. **646**, 1405-1420, 2006.
- "Solar Small Scale Magneto-Convection", (Stein, R. F. & Nordlund, Å.), Astrophys. J. **642**, 1246-1255, 2006.
- "Observational manifestations of solar magneto-convection — center-to-limb variation", (Carlsson, M., Stein, R.F., Nordlund, Å., Scharmer, G.B.), ApJ, **610**, L137, 2004.

Current and Pending Support
K.D. Leka

Project/Proposal Title: Porting and Maintenance of Existing Code to the HMI Pipeline PI: (NWRA subcontract): Dr. Douglas Braun Status: Current Source of Support: Stanford University (subcontract), NASA Contact Person: Dr. Philip Scherrer (650) 723-1504 (pscherrer@solar.stanford.edu) Total Award Amount: $680,000 Total Award Period Covered: 05/01/05 – 04/30/12 Person-Months Per Year Committed to the Project: 1.5
Project/Proposal Title: A Comparison of Flare Forecasting Methods PI: Dr. Graham Barnes Status: Current Source of Support: NASA - LWS TR&T Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $276,576 Total Award Period Covered: 04/16/09 – 04/15/12 Person-Months Per Year Committed to the Project: 2.0
Project/Proposal Title: Stopping and Asking Directions: Exploiting div(B)=0 for Azimuthal Ambiguity Resolution PI: Dr. K.D. Leka Status: Current Source of Support: NASA SR&T Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $446,953 Total Award Period Covered: 03/17/09 – 03/16/12 Person-Months Per Year Committed to the Project: 2.0
Project/Proposal Title: Continuing in the Right Direction: Azimuthal Ambiguity Resolution for High-Cadence Vector Magnetic Field Maps PI: Dr. K.D. Leka Status: Current Source of Support: NASA - GI Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $400,000 Total Award Period Covered: 08/10/09 – 08/09/13 Person-Months Per Year Committed to the Project: 2.0
Project/Proposal Title: Discriminating Helioseismic Signatures of Fast- and Slow-Mode Coupling in Magnetic Regions PI: Dr. Charles Lindsey Status: Current Source of Support: NASA - GI Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $350,110 Total Award Period Covered: 05/01/10 – 04/30/13 Person-Months Per Year Committed to the Project: 0.5
Project/Proposal Title: Data Services Continuation: The Imaging Vector Magnetograph Resident Archive PI: Dr. KD Leka Status: Pending Source of Support: NASA - HDEE Contact Person: Dr. Jeffrey Hayes 202-358-0353 HQ-HDEE@mail.nasa.gov Total Award Amount: $152,889 Total Award Period Covered: 01/24/11 – 01/23/15 Person-Months Per Year Committed to the Project: 0.8
Project/Proposal Title: Polarization as a new tool to study the solar wind acceleration PI: Dr. Moncef Derouich Status: Pending Source of Support: NSF - SHINE Contact Person: Dr. Paul Bellaire 703-292-8529 pbellair@nsf.gov Total Award Amount: $328,200 Total Award Period Covered: 01/01/11 – 12/31/13 Person-Months Per Year Committed to the Project: 0.7

Project/Proposal Title: Using SDO/HMI data to investigate the energization of the coronal magnetic field PI: Dr. Graham Barnes Status: Pending Source of Support: NASA - LWS TR&T Contact Person: Dr. Madhulika Guhathakurta 202-358-1992 lws.trt@nasa.gov Total Award Amount: $546,803 Total Award Period Covered: 10/01/11 – 09/30/14 Person-Months Per Year Committed to the Project: 4.0
Project/Proposal Title: A Study of White-Light Flares Observed by the Solar Dynamics Observatory PI: Dr. Charles Lindsey Status: Pending Source of Support: NASA - LWS TR&T (subcontract through UC Berkeley) Contact Person: Dr. Hugh Hudson 510-643-0333 hhudson@ssl.berkeley.edu Total Award Amount: $89,156 Total Award Period Covered: 06/01/11 – 05/31/14 Person-Months Per Year Committed to the Project: 0.5
Project/Proposal Title: Improving HMI Magnetogram, Dopplergram and Helioseismology Analysis Procedures PI: Dr. K.D. Leka Status: Pending Source of Support: NASA - LWS TR&T (subcontract through Michigan State University) Contact Person: Dr. Robert Stein 517-432-8802 stein@pa.msu.edu Total Award Amount: $67,532 Total Award Period Covered: 07/01/11 - 06/30/14 Person-Months Per Year Committed to the Project: 1.0

Current & Pending covers the time during the period of proposed effort

Current and Pending Support
Eric Wagner

Project/Proposal Title: Porting and Maintenance of Existing Code to the HMI Pipeline PI: (NWRA subcontract): Dr. Douglas Braun Status: Current Source of Support: Stanford University (subcontract), NASA Contact Person: Dr. Philip Scherrer (650) 723-1504 (pscherrer@solar.stanford.edu) Total Award Amount: $680,000 Total Award Period Covered: 05/01/05 – 04/30/12 Person-Months Per Year Committed to the Project: 0.3
Project/Proposal Title: Stopping and Asking Directions: Exploiting div(B)=0 for Azimuthal Ambiguity Resolution PI: Dr. K.D. Leka Status: Current Source of Support: NASA SR&T Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $446,953 Total Award Period Covered: 03/17/09 – 03/16/12 Person-Months Per Year Committed to the Project: 0.5
Project/Proposal Title: Continuing in the Right Direction: Azimuthal Ambiguity Resolution for High-Cadence Vector Magnetic Field Maps PI: Dr. K.D. Leka Status: Current Source of Support: NASA - GI Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $400,000 Total Award Period Covered: 08/10/09 – 08/09/13 Person-Months Per Year Committed to the Project: 0.5
Project/Proposal Title: Data Services Continuation: The Imaging Vector Magnetograph Resident Archive PI: Dr. KD Leka Status: Pending Source of Support: NASA - HDEE Contact Person: Dr. Jeffrey Hayes 202-358-0353 HQ-HDEE@mail.nasa.gov Total Award Amount: $152,889 Total Award Period Covered: 01/24/11 – 01/23/15 Person-Months Per Year Committed to the Project: 1.73

Current & Pending covers the time during the period of proposed effort

CURRENT AND PENDING SUPPORT

Graham Barnes

Project/Proposal Title: Porting and Maintenance of Existing Code to the HMI Pipeline PI: (NWRA subcontract): Dr. Douglas Braun Status: Current Source of Support: Stanford University (subcontract), NASA Contact Person: Dr. Philip Scherrer (650) 723-1504 (pscherrer@solar.stanford.edu) Total Award Amount: $680,000 Total Award Period Covered: 05/01/05 – 04/30/12 Person-Months Per Year Committed to the Project: 1.0
Project/Proposal Title: A Comparison of Flare Forecasting Methods PI: Dr. Graham Barnes Status: Current Source of Support: NASA - LWS TR&T Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $276,576 Total Award Period Covered: 04/16/09 – 04/15/12 Person-Months Per Year Committed to the Project: 2.3
Project/Proposal Title: Stopping and Asking Directions: Exploiting div(B)=0 for Azimuthal Ambiguity Resolution PI: Dr. K.D. Leka Status: Current Source of Support: NASA SR&T Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $446,953 Total Award Period Covered: 03/17/09 – 03/16/12 Person-Months Per Year Committed to the Project: 2.0
Project/Proposal Title: Continuing in the Right Direction: Azimuthal Ambiguity Resolution for High-Cadence Vector Magnetic Field Maps PI: Dr. K.D. Leka Status: Current Source of Support: NASA - GI Contact Person: Dr. Jeffrey Newmark, 202-358-0684, jeffrey.newmark@nasa.gov Total Award Amount: $400,000 Total Award Period Covered: 08/10/09 – 08/09/13 Person-Months Per Year Committed to the Project: 2.0
Project/Proposal Title: Polarization as a new tool to study the solar wind acceleration PI: Dr. Moncef Derouich Status: Pending Source of Support: NSF - SHINE Contact Person: Dr. Paul Bellaire 703-292-8529 pbellair@nsf.gov Total Award Amount: $328,200 Total Award Period Covered: 01/01/11 – 12/31/13 Person-Months Per Year Committed to the Project: 0.7
Project/Proposal Title: Using SDO/HMI data to investigate the energization of the coronal magnetic field PI: Dr. Graham Barnes Status: Pending Source of Support: NASA - LWS TR&T Contact Person: Dr. Madhulika Guhathakurta 202-358-1992 lws.trt@nasa.gov Total Award Amount: $546,803 Total Award Period Covered: 10/01/11 – 09/30/14 Person-Months Per Year Committed to the Project: 4.0
Project/Proposal Title: A Study of White-Light Flares Observed by the Solar Dynamics Observatory PI: Dr. Charles Lindsey Status: Pending Source of Support: NASA - LWS TR&T (subcontract through UC Berkeley) Contact Person: Dr. Hugh Hudson 510-643-0333 hhudson@ssl.berkeley.edu Total Award Amount: $89,156 Total Award Period Covered: 06/01/11 – 05/31/14 Person-Months Per Year Committed to the Project: 0.5

Current & Pending covers the time during the period of proposed effort

From d.orozco@nao.ac.jp Thu Oct 28 18:28:25 2010
Date: Fri, 29 Oct 2010 09:28:22 +0900
From: David Orozco Suarez <d.orozco@nao.ac.jp>
To: K.D. Leka <leka@cora.nwra.com>
Subject: Letter of Committment

To whom it may concern;

I acknowledge that I am identified by name as Collaborator to the investigation, entitled "Community Workshops to Validate Inversions for Vector Magnetic Field Maps", that is submitted by Dr. KD Leka to the NASA Research Announcement NNH10ZDA001N-LWSTRT, and that I intend to carry out all responsibilities identified for me in this proposal. I understand that the extent and justification of my participation as stated in this proposal will be considered during peer review in determining in part the merits of this proposal. I have read the entire proposal, including the management plan and budget, and I agree that the proposal correctly describes my commitment to the proposed investigation.

For the purposes of conducting work for this investigation, my participating organization is the National Astronomical Observatory of Japan.

Sincerely,

David Orozco Suárez

BUDGET JUSTIFICATION

1 Summary of Personnel and Work Effort

Year 1:	FTE	Responsibility
Leka	0.17	Overall direction of first workshop.
		Run inversion codes.
		Interpret and supervise the publication of results from workshop.
Barnes	0.13	Construct simple test data.
		Define metrics for performance of inversion codes.
Wagner	0.17	Write reformatters or wrappers.
		Collate results at NWRA.
Stein	0.08	Advise on extant data.
Toussaint	0.06	Run SOLIS ME-based inversion code on first data set provided.
Workshop Participants	as needed	Run inversion codes on first data set provided.
Biggs/Frahm	as needed	Administrative support for first workshop.
Year 2:		
Leka	0.17	Overall direction of second workshop.
		Run inversion codes.
		Interpret and supervise the publication of results from workshop.
Barnes	0.13	Construct simple test data.
		Define metrics for performance of inversion codes.
Wagner	0.17	Write reformatters or wrappers.
		Collate results at NWRA.
Stein	0.08	Run MHD code and generate synthetic spectra.
Toussaint	0.06	Run SOLIS ME-based inversion code on second data set provided.
Workshop Participants	as needed	Run inversion codes on second data set provided.
Biggs/Frahm	as needed	Administrative support for second workshop.
Year 3:		
Leka	0.17	Overall direction of third workshop.
		Run inversion codes.
		Interpret and supervise the publication of results from workshop.
Barnes	0.13	Construct simple test data.
		Define metrics for performance of inversion codes.
Wagner	0.17	Write reformatters or wrappers.
		Collate results at NWRA.
Stein	0.08	Run MHD code and generate synthetic spectra.
Toussaint	0.06	Run SOLIS ME-based inversion code on third data set provided.
Workshop Participants	as needed	Run inversion codes on third data set provided.
Biggs/Frahm	as needed	Administrative support for third workshop.

2 Narrative

Proposed resources for each year of this three-year effort will fund PI Leka for two month, Co-I Barnes for 1.5 months, Support Engineer Wagner for two months, Co-I Stein for one month, and Toussaint for three weeks. The details of the role of each of the above are given in the Scientific/Technical/Management Section. All team members will participate in the workshops, and assist in publishing the results. Travel funds are requested for ten workshop participants for one week, including all (non-local) team members, plus two unspecified participants. Travel funds for an additional, contiguous week are requested for Co-I Stein to help with pre-workshop preparations, and for Collaborator Norton due to the length of travel required from Australia, and to help with pre-workshop preparations. Finally, funds are requested to cover publication charges for one paper for each workshop, and for logistical support for 20 participants in each workshop.

3 Facilities and Equipment

NorthWest Research Associates, Inc. (NWRA, `www.nwra.com`) is a scientific research group with a primary focus in the geophysical sciences that includes, but is not limited to: oceanography, sea-ice mechanics, and atmospheric, ionospheric, and solar physics. NWRA is owned and operated by the Principal Investigators of the company and has 83 employees and offices in three locations:

- **Seattle, WA**, home of NWRA Headquarters and the Seattle Division, with 36 employees, 11,183 square feet of office space (including a technical library and two conference rooms), and 1,553 square feet of laboratory space. The Seattle facility is approximately ten miles from the University of Washington.

- **Boulder, CO**, home of Colorado Research Associates (CoRA) Division, with 35 employees and 11,365 square feet of office space. The Boulder facility is adjacent to the NCAR Foothills Lab.

- **Monterey, CA**, location of the Monterey office of NWRA, with 5 employees and 1,156 square feet of office space. The primary focus of the Monterey office is the analysis, evaluation, and mitigation of the effects of ionospheric propagation disturbances on U.S. radar and communications systems. The Monterey facility is downtown, approximately 0.5 mile from the Naval Postgraduate School.

NWRA also employs individual researchers who work in the following areas: Columbia (MO), Corvallis (OR), Hampton (VA), and Nashua (NH).
The research described in this proposal will be performed in the CoRA Division facility located in the city of Boulder, CO. The main conference room at this location can accommodate a workshop of 20 participants, and the existence of two additional conference rooms will allow for parallel sessions, if needed. This facility provides the scientists with the latest in computing and networking technology infrastructure. Scientists define their own personal computing platform to best meet their individual needs. Many scientists have additional offsite High Performance Computing (HPC) accounts. Networking servers and data acquisition servers are housed in a protected and separately cooled server room. Daily and monthly backups, with offsite storage, and closely monitored firewalls, provide protection and security.