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Solar & Astrophysics Laboratory

Small-scale Solar Magnetic Dynamics

Current Observations and Measurement Methods

Tom Berger, Lockheed Martin Solar and Astrophysics Lab

UCSB/ITP Conference on Magnetohydrodynamics, January 16 2002

Tom Berger, ITP Conference 16-Jan-02

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Outline

- Photospheric flowfield measurements
  - Local correlation tracking
  - Object tracking
- Magnetic field measurements
  - Magnetic fields in the photosphere
  - Review of the Zeeman effect in spectral lines
  - Solar Polarimetry
  - Filter magnetogram calibration

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Photospheric flowfield

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Physical Parameters of the (non-magnetic) Photosphere

- T_{avg} = 5770 K (Blackbody peak),
  - Tmin ~4200 K at 500 km above $\tau = 1$
- log(P) = 6.15 dyn/cm^2
- log(ρ) = -6 g/cm^3
- Spectral line width diagnostics
  - $v_{thermal}$ = 1.4 km/sec
  - $v_{microturb}$ = 1.1 km/sec
  - $v_{macroturb}$ = 1.6(vert) - 2.8(horiz) km/sec
  - $v_{LW} = (v_{th}^2 + v_{mi}^2 + v_{ma}^2)^{1/2}$ = 2.4 - 3.3 km/sec
- v_{sound} = 7.4 km/sec
- Opacity dominated by H^- ion

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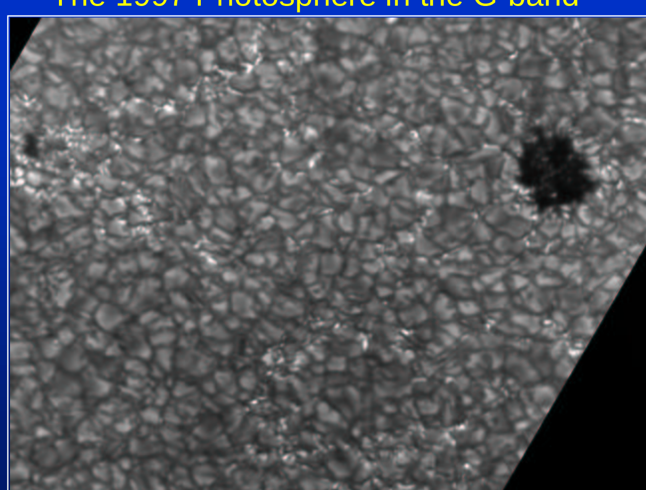
The 1997 Photosphere in the G-band



29 Mm

Swedish Vacuum Solar Telescope, La Palma, 12-June-1997
Obsever: Tom Berger, Phase diversity restoration: Mats Lofdahl

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Flowfield Measurement Techniques

- **Doppler Velocity Measurements**
  - Spectral methods
  - Weak or no Zeeman sensitivity in spectral line
  - Horizontal flows from limbward measurements
  - SOHO/MDI precision = 20 m/s (Ni I 6768Å line, ~2400 km resolution)
- **Local Correlation Tracking (LCT)**
  - Image pattern analysis method
  - Results depend on resolution of image *and* grid size
  - Precision ~ 100 m/s at 200 km resolution
- **Object Tracking**
  - image segmentation method
  - Results depend on success of object identification
  - Precision ~ 100 m/s at 200 km resolution

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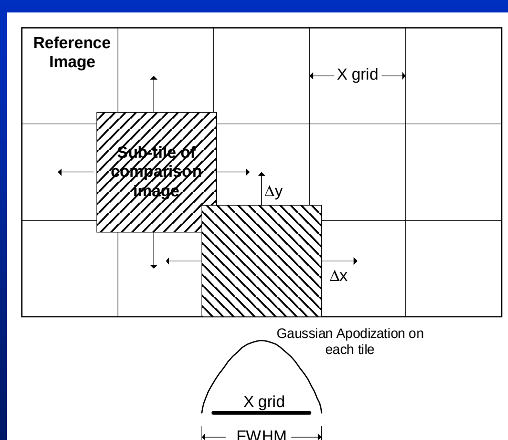
LCT Measurement Techniques

- **Minimum cross-correlation coefficient**
  November & Simon ApJ 333, 427, 1988
- **Minimum absolute (or square) difference**
  Lockheed method
- **Optical flow model**
  Hurlburt et al., Physics of Fluids, 1997
  Iterative matrix minimization



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LCT Measurements

30-May-1998 SVST G-band LCT flowfield
362 km tile width

Time span: 3 hours 10 min (7:50 – 11:00 UT)
Cadence = 23 seconds

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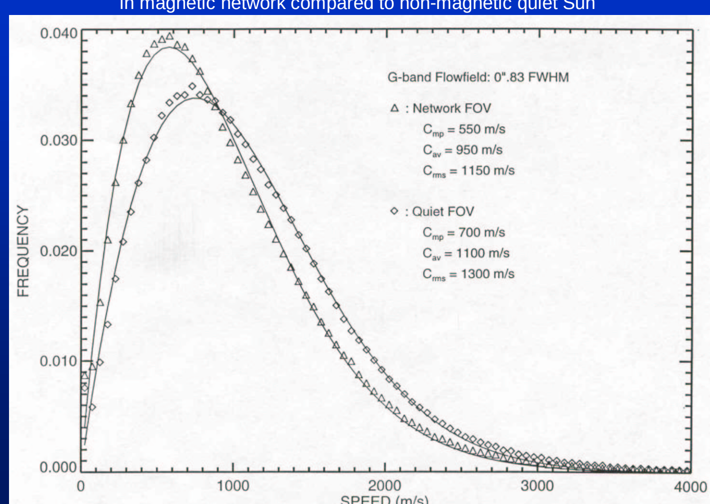
LCT Measurements

Magnetic vs. non-magnetic regions: ~30% decrease in modal speed in magnetic network compared to non-magnetic quiet Sun



From Berger et al., ApJ, **495**,973, 1998

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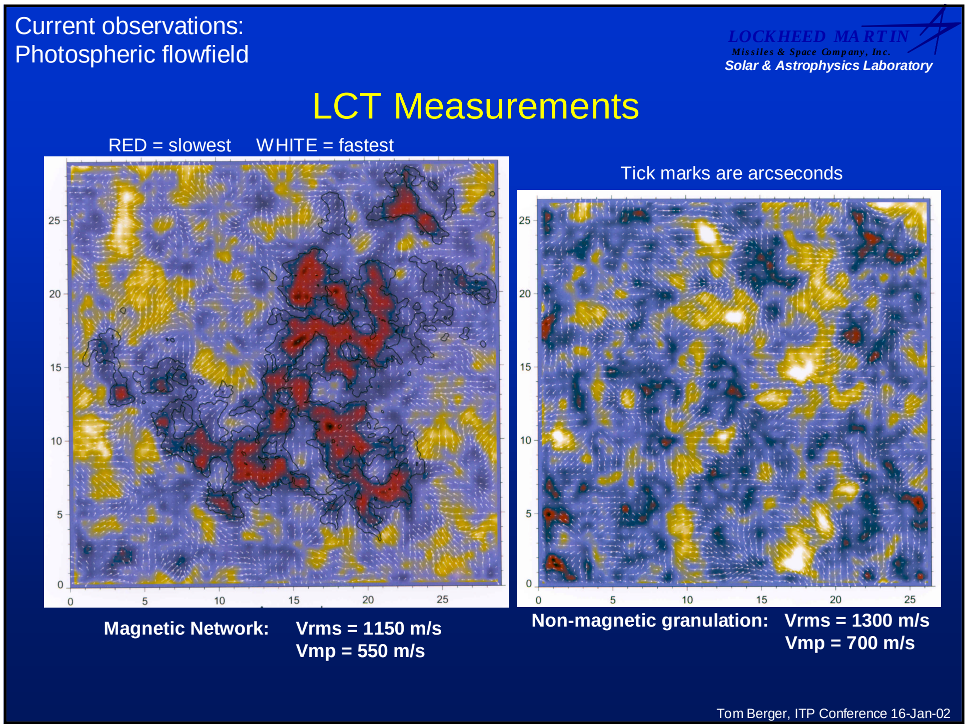
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LCT Measurements
RED = slowest WHITE = fastest
Tick marks are arcseconds
Magnetic Network: Vrms = 1150 m/s
Vmp = 550 m/s
Non-magnetic granulation: Vrms = 1300 m/s
Vmp = 700 m/s
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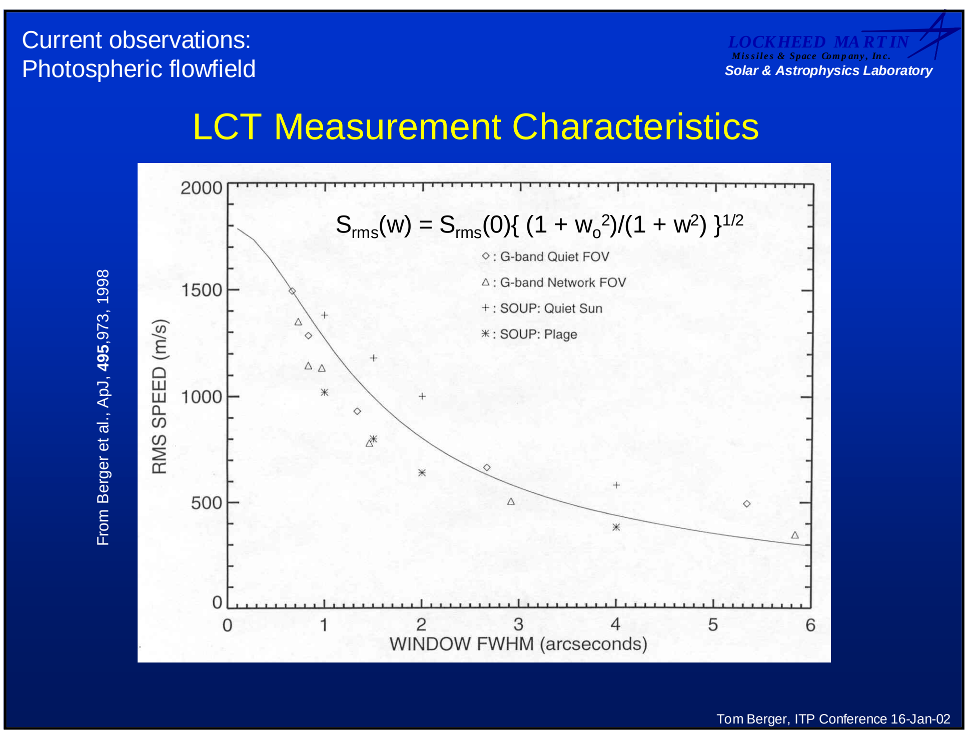
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LCT Measurement Characteristics
From Berger et al., ApJ, 495,973, 1998
$S_{rms}(w) = S_{rms}(0)\{ (1 + w_o^2)/(1 + w^2) \}^{1/2}$
◇ : G-band Quiet FOV
△ : G-band Network FOV
+ : SOUP: Quiet Sun
✳ : SOUP: Plage
RMS SPEED (m/s)
WINDOW FWHM (arcseconds)
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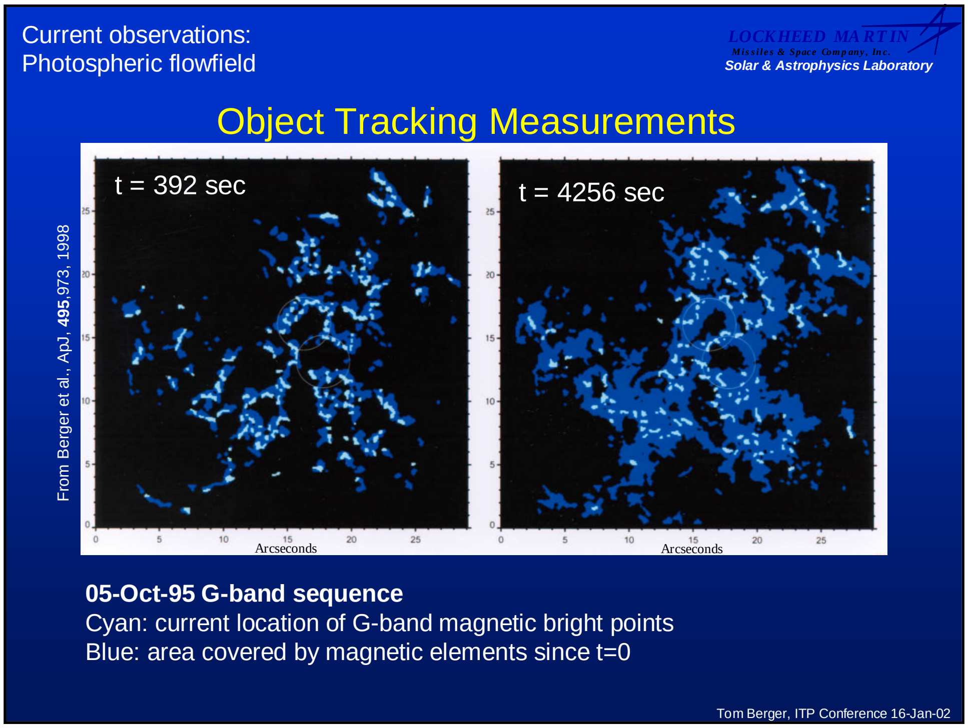
Current observations:
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Object Tracking Measurements
From Berger et al., ApJ, 495,973, 1998
t = 392 sec
t = 4256 sec
Arcseconds
Arcseconds
05-Oct-95 G-band sequence
Cyan: current location of G-band magnetic bright points
Blue: area covered by magnetic elements since t=0
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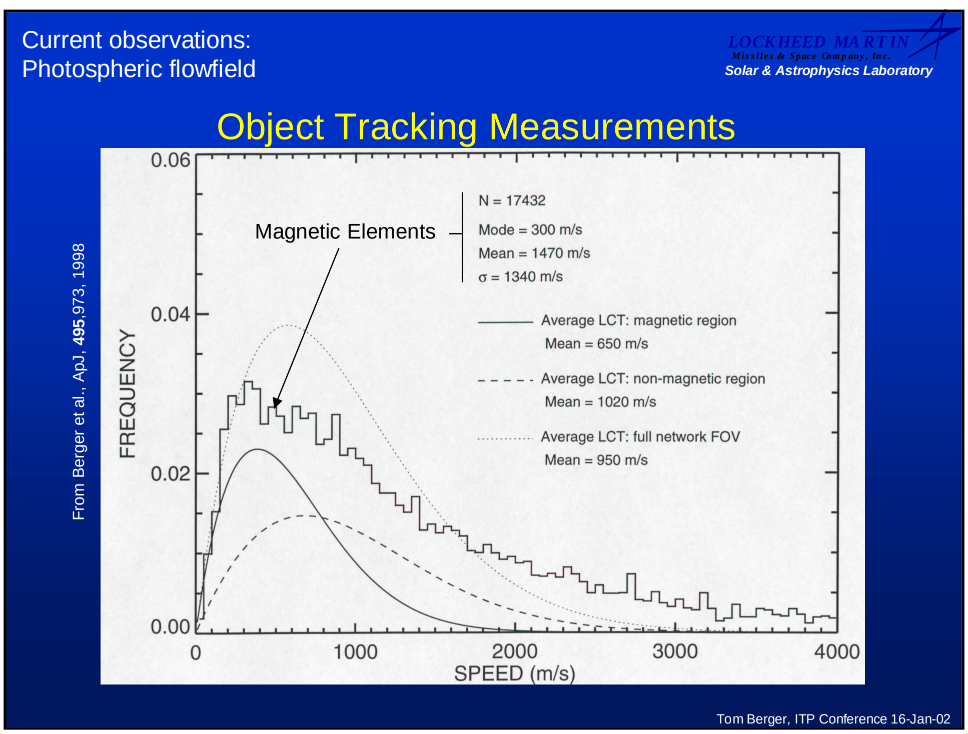
Current observations:
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Object Tracking Measurements
From Berger et al., ApJ, 495,973, 1998
FREQUENCY
0.06
0.04
0.02
0.00
Magnetic Elements
N = 17432
Mode = 300 m/s
Mean = 1470 m/s
σ = 1340 m/s
Average LCT: magnetic region
Mean = 650 m/s
Average LCT: non-magnetic region
Mean = 1020 m/s
Average LCT: full network FOV
Mean = 950 m/s
0
1000
2000
3000
4000
SPEED (m/s)
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Current observations:
Photospheric flowfield

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Summary

• Techniques for measuring horizontal and vertical flowfields in the photosphere are mature.

• Major LCT assumption: image intensity is a "passive scalar" which is advected in the flowfield; we track brightness fluctuations.

• Warning: Doppler, LCT, and Object Tracking results are all spatial/temporal resolution and algorithm dependent!

See Simon et al., 4th SOHO Workshop Proceedings, 1995, for LCT comparisons using single MDI dataset

Current observations:
Magnetic Field

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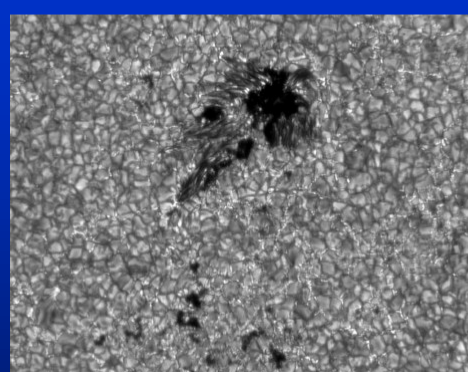
Magnetic Fields in the Photosphere

- Sunspots
  - Diameter: 30,000 km
  - Lifetime: days – weeks
  - Field strength: 2000 - 3000 Gauss
- Pores
  - Diameter: 10,000 km
  - Lifetime: hours – days
  - Field strength: 1900 - 2500 Gauss
- Magnetic network elements
  - Diameter: < 200 km
  - Lifetime: minutes
  - Field strength: 500 - 1500 Gauss
- Turbulent "granular" fields
  - Lifetime: ? Seconds?
  - Field strength: 4 – 40 Gauss?



SVST 12-May-1998 G-band 4305Å

Focus: Magnetic network elements – plage or supergranular network

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Magnetic Field Measurement Techniques

- Zeeman-effect Measurements
  - Spectrometer-based instruments
    - Advanced Stokes Polarimeter (ASP) at Sac Peak
    - Kitt Peak Magnetograph
    - MSU Near IR Magnetograph at Sac Peak (Lin&Rimele, ApJ,514,448,1997)
  - Imaging filter-based instruments
    - Michelson Doppler Imager (MDI) on SOHO
    - Solar Optical Universal Polarimeter (SOUP) at La Palma
    - Video Filter Magnetogram (VFM) at Big Bear
    - Zurich Imaging Polarimeter (ZIMPOL) at Sac Peak
- Hanle-effect Measurements
  - Depolarization due to scattering – potentially useful for measuring weak, "turbulent", fields in granulation (Stenflo, Keller, Gandorfer, A&A, 329, 319, 1998)

Focus: Zeeman-effect measurements in the visible spectrum, imaging filter-based instruments, particularly SOUP

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Magnetic Field

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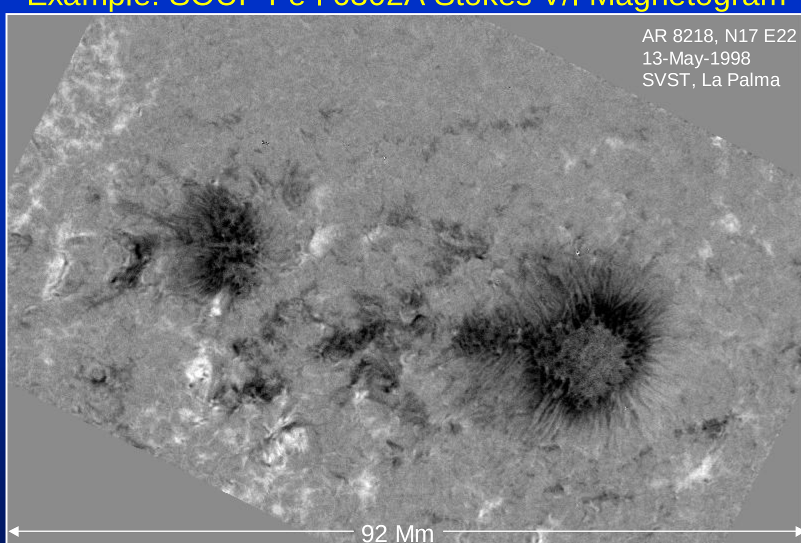
Example: SOUP Fe I 6302Å Stokes V/I Magnetogram



Maximum spatial resolution ~250 km

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The Zeeman Effect

In a magnetic field, the energy levels of a given atomic transition split into three ("normal") or more ("anomolous") components.

In the normal Zeeman effect, the three components are the σ^+, σ^-, and π components with peak wavelengths given by

$\lambda_{\sigma^-} = \lambda_0 - \Delta\lambda_B$

$\lambda_{\pi} = \lambda_0$

$\lambda_{\sigma^+} = \lambda_0 + \Delta\lambda_B$

where λ is the center wavelength of the transition and

$$\Delta\lambda_B = 4.7 \times 10^{-13} \lambda^2 g B$$

is the wavelength shift of the σ components in Å. Here g is the Landé g-factor and B is the magnetic field strength in units of Gauss.

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The Zeeman Effect (cont.)

In a sunspot with B = 3000 G, the splitting of Fe I 6302.25A = 0.15A which is much larger than the Doppler broadening $\Delta\lambda_D$ of the line. Thus direct measurement of field strength (via direct measurement of line splitting) in a sunspot is easy.

Unfortunately for small-scale magnetic elements, $\Delta\lambda_B$ δ $\Delta\lambda_D$, therefore direct measurement of magnetic splitting and hence field strength is not possible in the visible.

Good news: $\Delta\lambda_B \propto \lambda^2$. In the IR regime, magnetic fields of ~100 Gauss are directly measurable. (Lin & Rimmele, ApJ, 514, 448, 1999)

Bad news: IR detectors are still limited to relatively large pixel sizes with low formats. (e.g. 128x128 pixels in Lin & Rimmele 1999)

Solution in the visible (where detectors and optics are nice): use polarization of σ and π components to infer strength (and direction!) of field.

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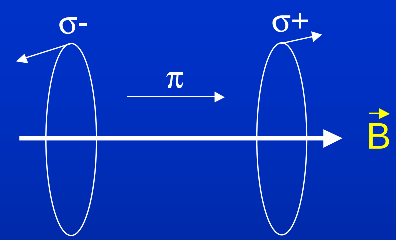
Solar Polarimetry

The σ components are circularly polarized with axis parallel to B and the π component is linearly polarized parallel to B.



The polarization state of a light beam can be completely described by the Stokes vector: (I, Q, U, V) where the components are related to the electric field components $E_x = \varepsilon_X \cos(\omega t - kz)$ and $E_y = \varepsilon_y \cos(\omega t - kz + \varepsilon)$ by

$I = \langle \varepsilon_X^2 + \varepsilon_Y^2 \rangle$ $Q = \langle \varepsilon_X^2 - \varepsilon_Y^2 \rangle$ $U = 2 \langle \varepsilon_X \varepsilon_Y \cos \varepsilon \rangle$ $V = 2 \langle \varepsilon_X \varepsilon_Y \sin \varepsilon \rangle$

$\langle \; \rangle$ = time average to account for finite spectral bandwidth of real light.

Basic principle: by measuring the Stokes vector components of a given light beam (i.e. spectral line) , can INVERT the radiative transfer to infer $\vec{B}$.

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Magnetic Field

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Solar Polarimetery (cont.)

Why uses 4D Stokes vectors instead of simpler 2D Jones vectors? Because we observe INTENSITIES not ELECTRIC FIELDS.

LTE radiative transfer equations for the Stokes vector (with no Hanle effect):

$$\cos\theta \, dI_\lambda / d\tau = (1 + \eta_\lambda)(I_\lambda - B_\lambda)$$

where I_λ is the Stokes vector at wavelength λ, B_λ is the Planck function, θ is the angle between local vertical and the light beam, and η_λ is the absorption coefficient matrix given by

$$\eta_\lambda = \begin{matrix} \eta_I & \eta_Q & \eta_U & \eta_V \\ \eta_Q & \eta_I & 0 & 0 \\ \eta_U & 0 & \eta_I & 0 \\ \eta_V & 0 & 0 & \eta_I \end{matrix}$$

Off-diagonals = 0 when no magnetooptical effects present.

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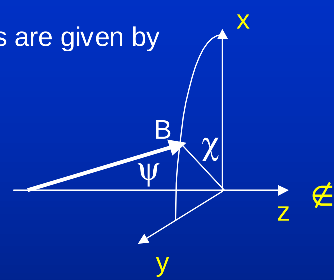
Solar Polarimetry (cont.)

The Stokes component absorption coefficients are given by



$$\eta_I = \eta_0/2 \sin^2\psi + (\eta_+ + \eta_-)(1 + \cos^2\psi)/4$$
$$\eta_Q = [\ \eta_0/2 - (\eta_+ + \eta_-)/4\ ] \sin^2\psi \cos 2\chi$$
$$\eta_U = [\ \eta_0/2 - (\eta_+ + \eta_-)/4\ ] \sin^2\psi \sin 2\chi$$
$$\eta_V = (\eta_+ - \eta_-)/2 \cos\psi$$

η_0 = central wavelength absorption coefficient (π component)
η_+ = absorption coefficient of $\sigma+$ component
η_- = absorption coefficient of $\sigma-$ component

For Zeeman triplet:

$$\eta_\pm(\lambda) = \eta_0(\lambda \pm \Delta\lambda_B)$$

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Magnetic Field

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Solar Polarimetry (cont.)

Simplest solution: longitudinal field. Set $\psi = 0$.
(see e.g. Stix, The Sun, Springer, 1991)

$$\eta_I = (\eta_+ + \eta_-)/2$$
$$\eta_V = (\eta_+ - \eta_-)/2$$

Solution for I and V is simple:

$$I = ½\ [\ I_0(\lambda + \Delta\lambda_B) + I_0(\lambda - \Delta\lambda_B)\ ]$$
$$V = ½\ [\ I_0(\lambda + \Delta\lambda_B) - I_0(\lambda - \Delta\lambda_B)\ ]$$

where $I_0(\lambda)$ is the line profile in the absence of magnetic field.
For weak fields $\Delta\lambda_B < \Delta\lambda_D$. Expand in $\Delta\lambda_B$:

$$V \sim (dI_0/d\lambda)\ \Delta\lambda_B \propto (dI_0/d\lambda)\ B_{long} = (dI_0/d\lambda)\ B \cos\psi$$

$$V \propto B \cos\psi$$

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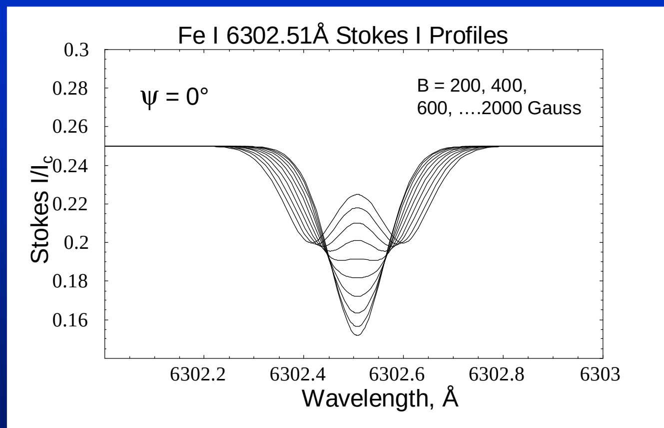
Stokes Polarimetry: Calculated Stokes Profiles



Unno solutions: Milne-Eddington atmosphere with gaussian line profiles

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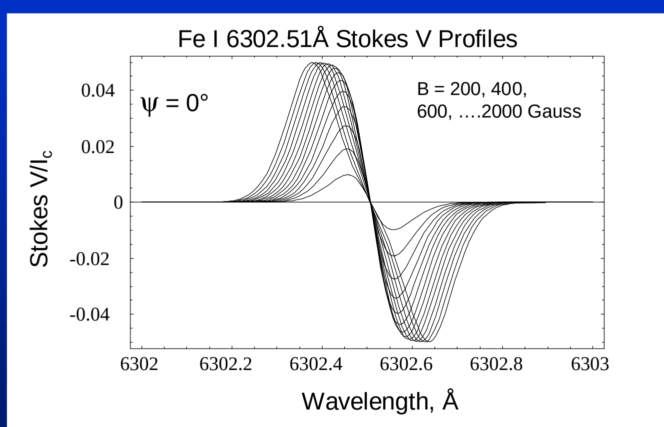
Stokes Polarimetry: Calculated Stokes Profiles



Note phenomenon of “Zeeman saturation”: above about 1800 Gauss, the peak V amplitude no longer increases.

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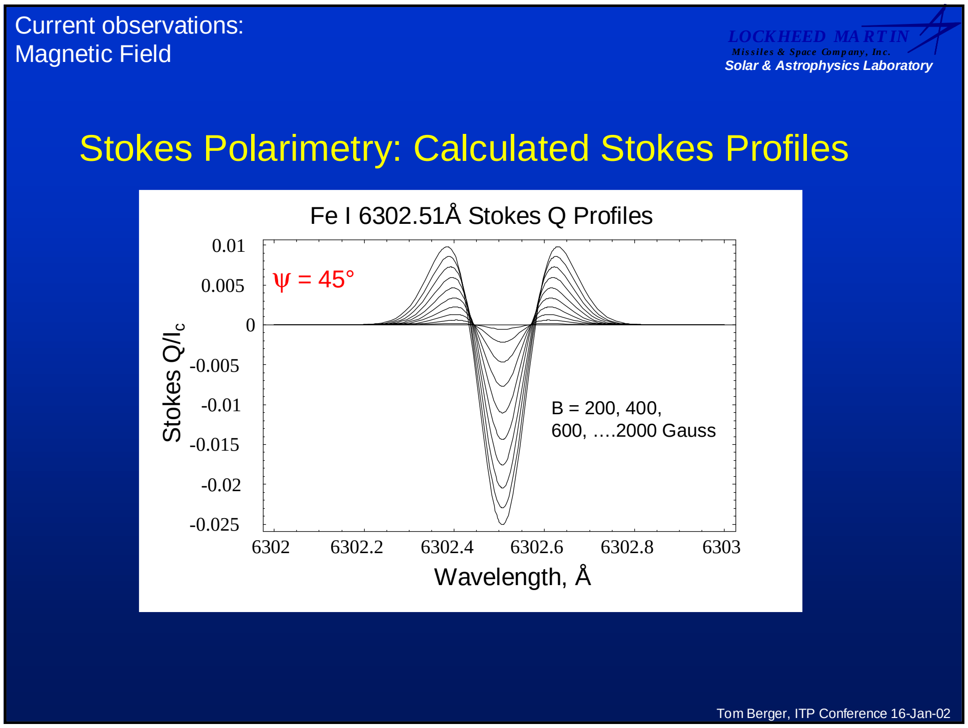
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Stokes Polarimetry: Calculated Stokes Profiles
Fe I 6302.51Å Stokes Q Profiles
ψ = 45°
Stokes Q/Ic
0.01
0.005
0
-0.005
-0.01
-0.015
-0.02
-0.025
B = 200, 400,
600, ….2000 Gauss
6302
6302.2
6302.4
6302.6
6302.8
6303
Wavelength, Å
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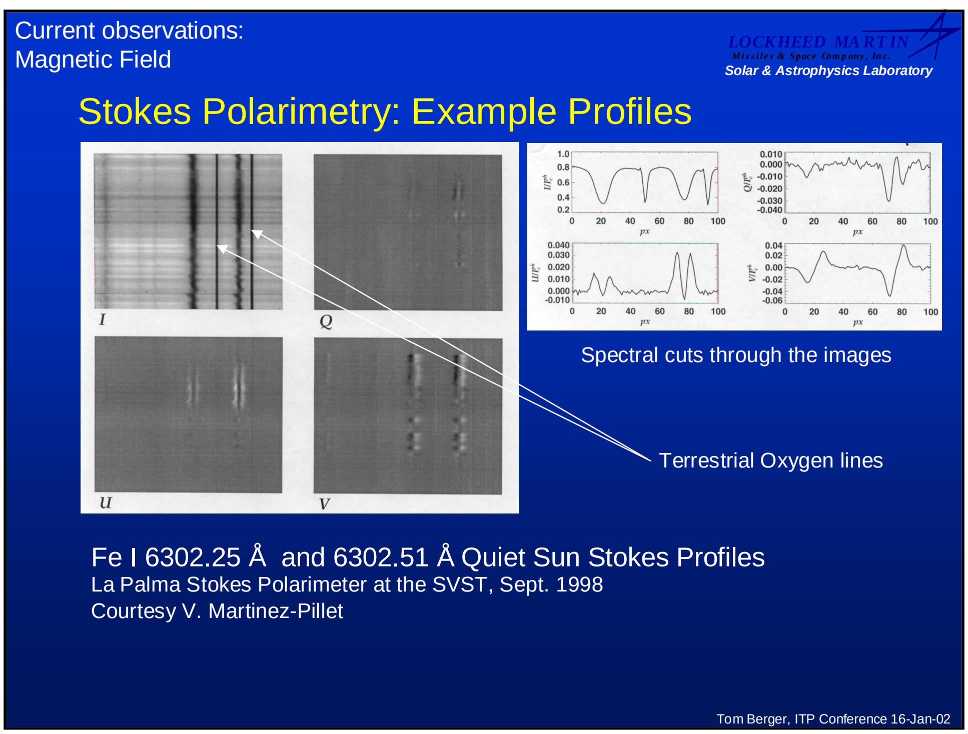
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Stokes Polarimetry: Example Profiles
I
Q
U
V
Spectral cuts through the images
Terrestrial Oxygen lines
Fe I 6302.25 Å and 6302.51 Å Quiet Sun Stokes Profiles
La Palma Stokes Polarimeter at the SVST, Sept. 1998
Courtesy V. Martinez-Pillet
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Magnetic Field

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Stokes Polarimetry: Ideal Inversion Algorithm

Ideal algorithm:

1. Measure spectral profile of I
   (no polarization)
2. Measure spectral profiles of Q and U
   (linear polarization at 0° and 45°)
3. Measure spectral profile of V
   (circular polarization difference)
4. Iterate radiative transfer solution to Eqn. 1 with B, ψ, and χ as parameters until model profiles match observed profile

Voila: you have the inferred magnetic field VECTOR.

The ASP performs essentially this algorithm using a Milne-Eddington model atmosphere for the radiative transfer solution.

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Magnetic Field

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Stokes Polarimetry: Flux, Flux Density & Filling Factor

Every real instrument INTEGRATES physical quantities over the detector elements (e.g. pixels).

We don't measure V, we measure: $\int_{pixel} V \bullet dA \propto \int_{pixel} B\cos\psi \bullet dA$

Longitudinal Magnetic Flux.
Units are Maxwell (cgs) and Weber (SI)

We report: $\int_{pixel} V \bullet dA \,/\, A_{pixel}$ A_{pixel} is the projected pixel area on the Sun.

Longitudinal Magnetic Flux Density
CGS units are Mx cm^{-2} = **Gauss**.

Define the "filling factor" f as the fraction of the pixel area occupied by magnetic field:

$$f \equiv \int_{pixel} dA(B \neq 0) \,/\, A_{pixel}$$

Then (if B is constant in magnetic region):

$$V_{meas} = \int_{pixel} V \bullet dA \propto B\, f \cos\psi$$

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Stokes Polarimetry: Vector Magnetographs

Advantages:

- Can give highly sensitive estimates of magnetic field vector.
- By measuring ALL Stokes profiles, can include the unknown filling factor as a parameter in the inversions.

ASP inversion gives B, ψ, χ, and f for every pixel.

Disadvantages:

- Accurate inversion requires high S/N which necessitates long integration times and hence reduced spatiotemporal resolution (at least for seeing-limited instruments).
- Spectral resolution necessary to accurately measure I, Q, U, and V profiles requires a spectrometer and hence slit scanning to build up "images".

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Magnetic Field

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Stokes Polarimetry: Filter Magnetographs

Sacrafice measurement of the full magnetic field vector in order to get a faster inference on the magnitude of the field. Can achieve this by using only Stokes V.

Filter magnetograph instruments typically only measure approximate Stokes V profiles and use the weak field approximation to yield

$$M(I, V) \propto B f \cos \psi$$

Where M is "magnetogram signal", i.e. not an accurate Stokes V profile.

Note that M depends on the unknown filling factor: since we don't have enough information to invert the measurements, we cannot deconvolve f from B$\cos \psi$.

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Stokes Polarimetry: Filter Magnetograph Example

SOUP magnetograms are typically "one-point" spectral sample Stokes V/I magnetograms.

Algorithm:

1. Set filter (bandpass 120 mÅ, compare ASP at 25 mÅ) to wavelength in blue wing of line, about –60mÅ from λ_0 .
2. Take image with Right Circular Polarization filter (I_{RCP})
3. Take image with Left Circular Polarization filter (I_{LCP})
4. Form

$$M = (I_{LCP} – I_{RCP}) / (I_{LCP} + I_{RCP}) \sim V / I$$

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Magnetic Field

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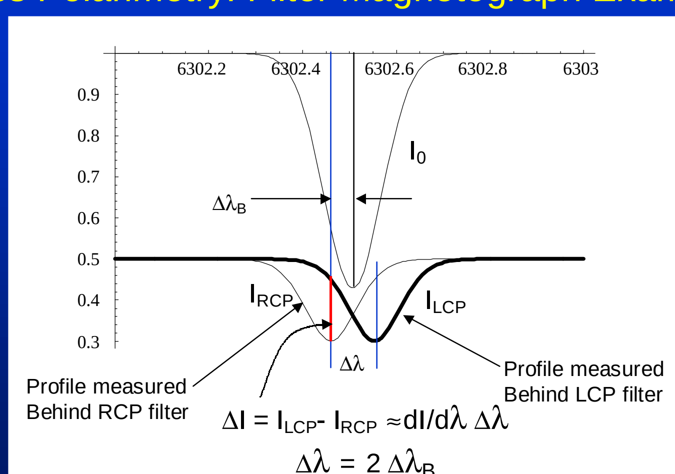
Stokes Polarimetry: Filter Magnetograph Example



SOUP 1-point spectral sample Stokes-V magnetogram algorithm

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Stokes Polarimetry: Filter Magnetographs

Advantages:

- Filters have wide bandpasses and therefore short exposures that can give high spatiotemporal resolution.
- No scanning required so get “instantaneous” wide FOV measurement.

Disadvantages:

- Spectral resolution is generally too poor to get good Stokes profiles. Thus limited to longitudinal field strength estimates.
- Fields with differing strengths, filling factor, and angle of inclination combinations can give the same M values: cannot disentangle f or ψ from B in the magnetogram signal M.
- Requires calibration of M against some standard in order to give estimates of longitudinal field strength.

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Magnetic Field

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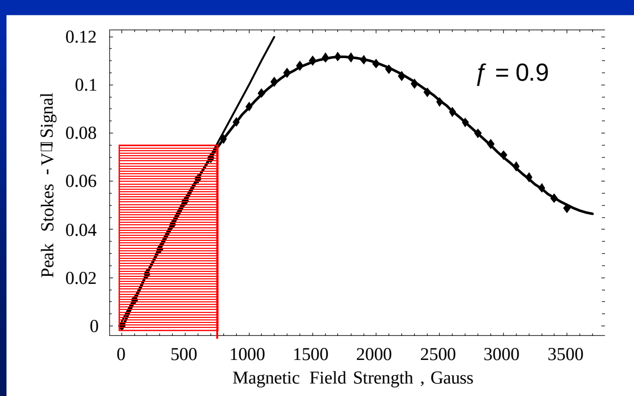
Stokes Polarimetry: SOUP Magnetogram Response

Model SOUP bandpass as a gaussian profile (FWHM 120 mÅ, T = 13%) fixed at –60mÅ in Fe I 6302.51Å line. Include filling factor in definition of M:

$$I_{RCP} = f I_{mag} + (1-f) I_{non\text{-}mag}$$



Points: Model
Peak V/I is about what we measure at SVST in good seeing

Bold curve: 4th order fit

Linear regime:
B < 800 G
Slope implies calibration of 10,180 “Gauss” / M

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SOUP Filter Magnetogram Calibration

To calibrate M_{SOUP} to Mx cm^{-2}, can compare to cotemporal ASP map of longitudinal magnetic flux density, B_{app}, where “app” stands for “apparent” to emphasize instrumental nature:

$$B_{app}(ASP) = B_{ASP}\, f_{ASP} \cos \psi_{ASP}$$

Algorithm:

1. Plot M_{SOUP} vs. $B_{app}(ASP)$ for each pixel in cotemporal images.

2. Fit linear function to average data

3. Slope of linear fit gives weak field calibration constant, α for SOUP:

$$M = \alpha\, B_{app}(ASP)$$

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Current observations:
Magnetic Field

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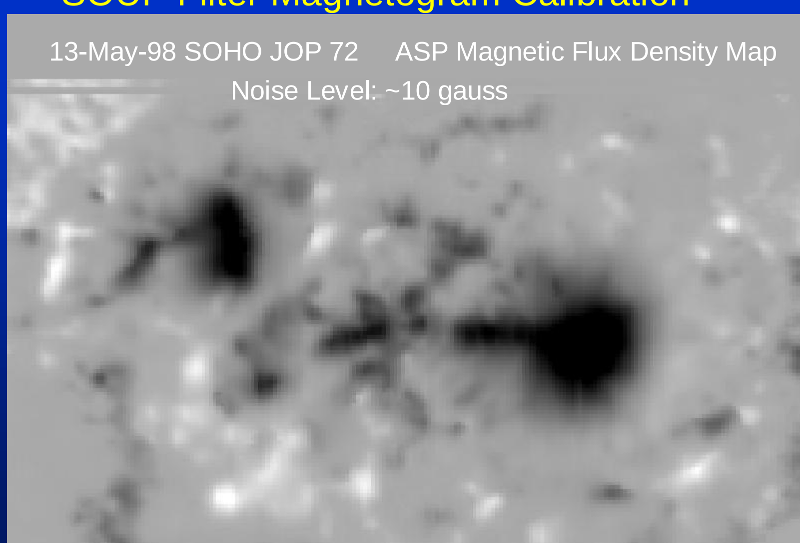
Missiles & Space Company, Inc.
Solar & Astrophysics Laboratory

SOUP Filter Magnetogram Calibration



Note: seeing was not optimal for this scan; ASP can achieve MUCH better spatial resolution under better seeing conditions.

Tom Berger, ITP Conference 16-Jan-02

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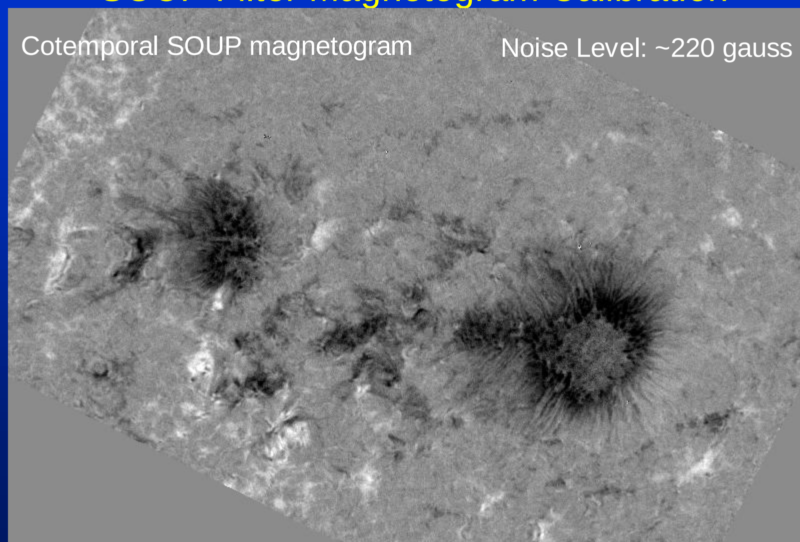

Note: seeing was outstandingly good during acquisition of the LCP and RCP images that make up this magnetogram. Max angular resolution in magnetogram ~0.3 arcseconds.

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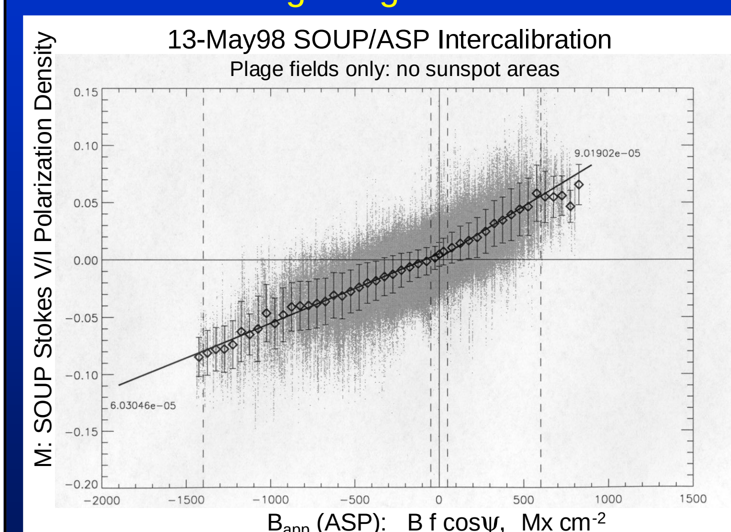

Notes:

1. SOUP is very linear out to about 800 Mx cm^{-2}
2. Slope of negative branch gives linear calibration constant of 16,600 “Gauss” / M.
3. Slope of positive polarity is significantly greater than negative branch.
4. Largest source of noise is the non-simultaneity of LCP and RCP images which have different seeing.

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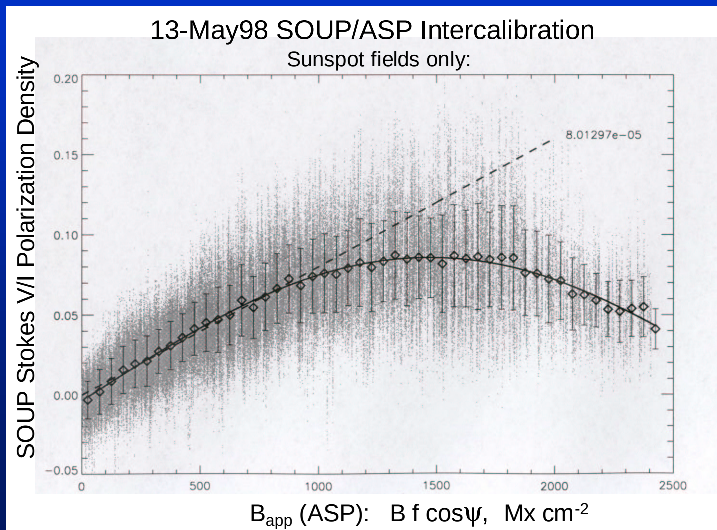

Notes:

1. In strong field regions, SOUP is linear out to about 900 Mx cm^{-2}.

2. Response shows 4th order drop off in agreement with polarimetric models.

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Filter Magnetograms: Summary

- Stokes V filter magnetograms measure “circular polarization density”. This is related to line-of-sight “magnetic flux density” which is proportional to field strength ONLY in the linear “weak field” regime.

- Calibration is non-trivial. Precision can be below 1%, but accuracy is often no better than ±50%.

- The unresolved nature of small-scale magnetic fields on the Sun means that magnetogram response is HIGHLY spatial resolution dependent via the filling factor parameter.

- There are other filter algorithms in use: MDI uses a polarimetric center-of-gravity algorithm (Rees & Semel, A&A, 74, 1979) to infer the wavelengths of σ+ and σ- components. These magnetograms exhibit linearity out to 2000 Mx cm^{-2} when compared against ASP, but not necessarily better accuracy.

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Filter Magnetograms: Summary

- Flux accounting requires caution:

  e.g. flux emergence can appear "unipolar" in Stokes V magnetograms because one component can have a significantly greater angle to the line-of-sight than the other.

  e.g. minority polarity structures can be preferentially "blended" away by spatial resolution effects leading to apparent flux imbalance. This is definitely seen in comparisons of SOUP to MDI and ASP magnetograms and possibly seen in MDI magnetograms of flare regions (e.g. Fletcher & Hudson, SolPhys,2002)

- Best use of filter magnetograms is for high spatial and temporal resolution studies of magnetic field morphology and dynamics.

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