

# Handling NIRIS Data: Calibration, Processing, and Inversion

Taylor Baildon

BBSO Summer School 2024

Big Bear Solar Observatory, NJIT/CSTR

2024 August 1

**NJIT**

New Jersey Institute of Technology

# Outline

- PART I: NIRIS Instrument
  - Brief review of scientific principles and goals
  - Instrumental design
- PART II: NIRIS Data Processing
  - Steps in the NIRIS pipeline
  - Calibration of instrumental crosstalk
- PART III: Inverting NIRIS Data
  - Brief review of Stokes inversions

# Part I: NIRIS instrument

# Science enabled by NIRIS

- High-resolution spectroscopy and polarimetry using Zeeman-sensitive spectral lines in the NIR
  - Zeeman splitting is a function of  $g\lambda^2B$

Line	Wavelength	Lande factor $g_{\text{eff}}$	Target
Fe I doublet	1564.85 nm	3	Deep photosphere
	1565.29 nm	1.53	
He I multiplet	10829.08 Å	2.0	Upper chromosphere, base of corona
	10830.25 Å	1.75	
	10830.34 Å	0.875	

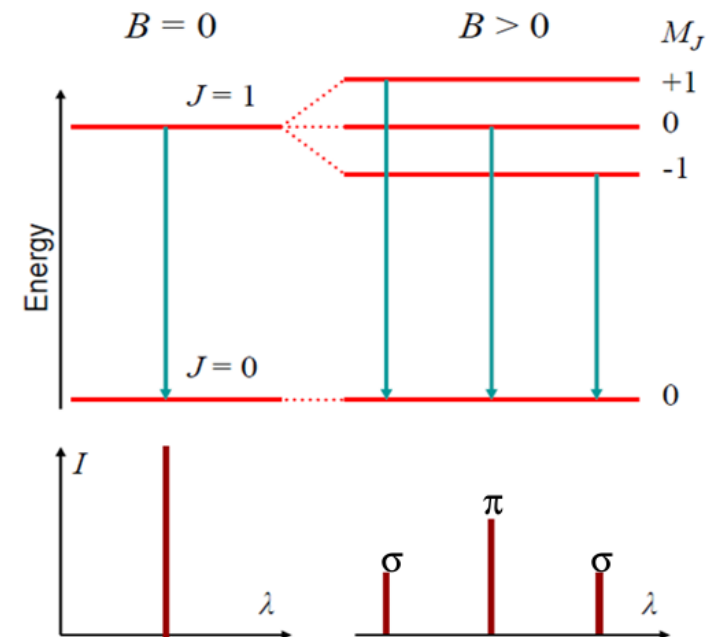
- Imaging deepest photosphere through base of corona
  - Photosphere opacity minimum at  $1.6 \mu\text{m}$

# Exploiting the Zeeman effect

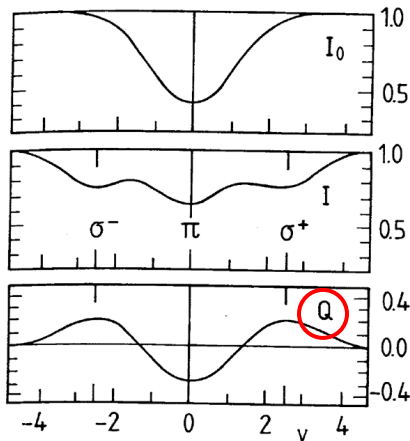
- The (orbital) magnetic moments of an atom's electrons interact with an external magnetic field
  - States having different magnetic quantum numbers ( $m_\ell$ ) shift in energy in the presence of a magnetic field:  $V = -\vec{\mu} \cdot \vec{B}$
- Resulting Zeeman triplet:

Component	$\vec{B} \perp$ to LOS	$\vec{B} \parallel$ to LOS
$\pi$ (non-shifted)	+ linear polarization	none
$\sigma$ (shifted)	- linear polarization	circular polarization

- No information about direction of  $\vec{B}$  from the intensity spectrum alone**



# Exploiting the Zeeman effect

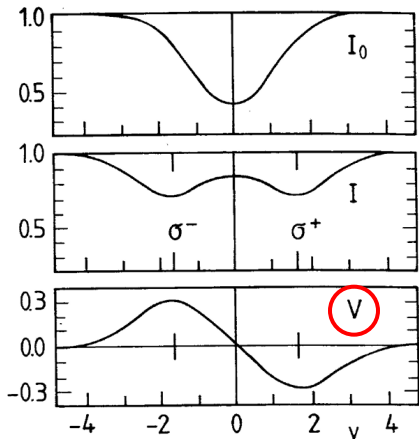


- We can get information about the direction of  $\vec{B}$  by looking at the polarization of the observed spectrum
  - Stokes parameters:  $I, Q, U, V$

- Transverse Zeeman effect
  - $\vec{B}$  perpendicular to LOS

- Longitudinal Zeeman effect
  - $\vec{B}$  along LOS

100% Q	100% U	100% V
<p>+Q</p> <p><math>Q &gt; 0; U = 0; V = 0</math> (a)</p>	<p>+U</p> <p><math>Q = 0; U &gt; 0; V = 0</math> (c)</p>	<p>+V</p> <p><math>Q = 0; U = 0; V &gt; 0</math> (e)</p>
<p>-Q</p> <p><math>Q &lt; 0; U = 0; V = 0</math> (b)</p>	<p>-U</p> <p><math>Q = 0; U &lt; 0; V = 0</math> (d)</p>	<p>-V</p> <p><math>Q = 0; U = 0; V &lt; 0</math> (f)</p>



Component	$\vec{B} \perp$ to LOS	$\vec{B} \parallel$ to LOS
$\pi$ (non-shifted)	+ linear polarization	none
$\sigma$ (shifted)	- linear polarization	circular polarization

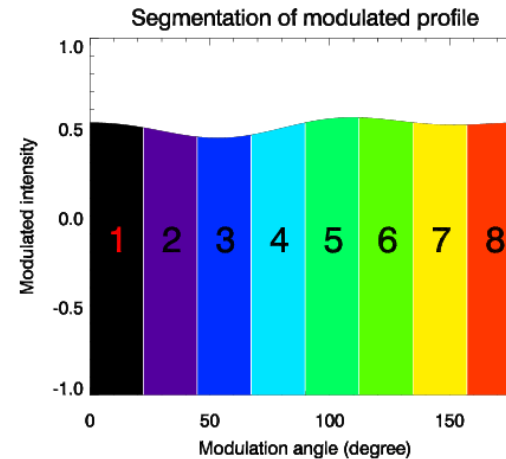
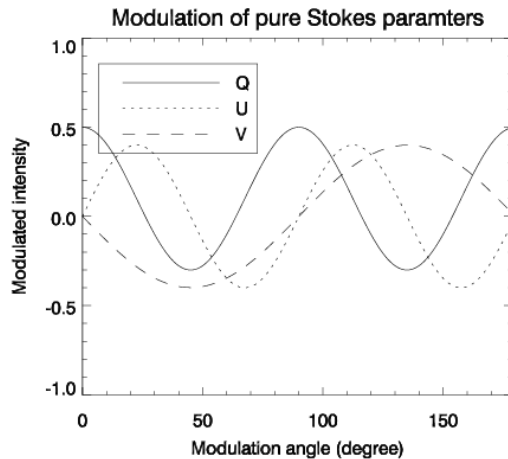
# Measuring magnetic fields with NIRIS

- Method for inferring  $\vec{B}$  using polarization measurements:
  1. Measure  $I(\lambda), Q(\lambda), U(\lambda), V(\lambda)$
  2. Relate  $I(\lambda), Q(\lambda), U(\lambda), V(\lambda)$  to  $\vec{B}$  using a radiative transfer theory
    - This will include Zeeman effect, Hanle effect (depolarization through scattering), assumptions about solar atmosphere, etc.
  3. Find  $\vec{B}$  by solving the inverse problem (“Stokes inversion”)
- NIRIS: dual Fabry-Perot system that performs dual-beam polarimetry
  - 2 FPIs are used as a tunable narrow-band filter, scans over spectral line
  - Dual-beam design reduces seeing-induced polarization crosstalk
    - Beam splitter separates orthogonal linear polarizations
    - Combinations of the two resulting images produce  $I, Q, U, V$  images

# Part II: NIRIS data processing



# Separating $I, Q, U, V$ images

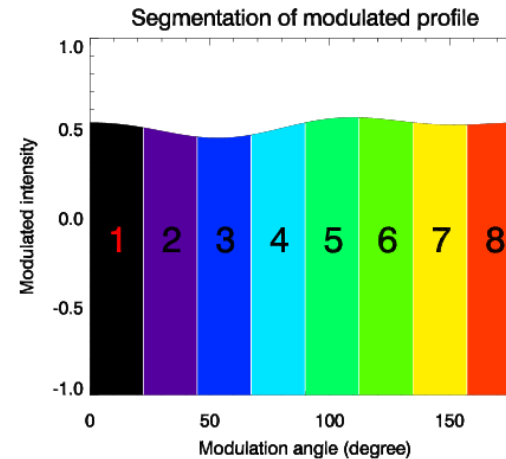
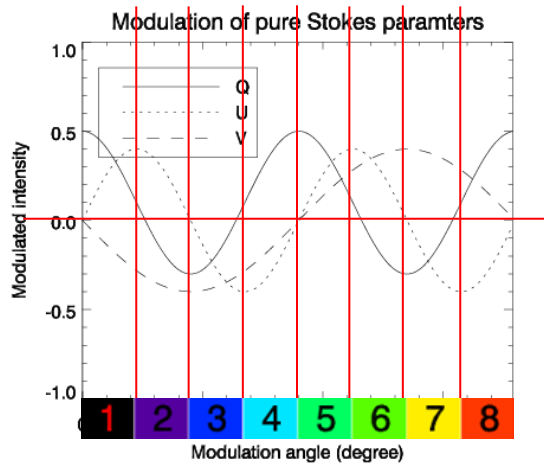


- Modulator waveplate (frequency  $\omega$ ) modulates polarization states differently
  - $Q$  and  $U$  (linear polarization) modulated at  $4\omega$
  - $V$  (circular polarization) modulated at  $2\omega$
- Observed modulated profile is a combination of  $I, Q, U, V$ :

$$I'' = \frac{1}{2} \left[ I' + \frac{Q'}{2} \left( (1 + \cos \delta) + (1 - \cos \delta) \cos 4\theta \right) + \frac{U'}{2} (1 - \cos \delta) \sin 4\theta - V' \sin \delta \sin 2\theta \right]$$

waveplate retardation
modulation angle

# Separating $I, Q, U, V$ images



$$I = +1 + 2 + 3 + 4 + 5 + 6 + 7 + 8$$

$$Q = +1 - 2 - 3 + 4 + 5 - 6 - 7 + 8$$

$$U = +1 + 2 - 3 - 4 + 5 + 6 - 7 - 8$$

$$V = -1 - 2 - 3 - 4 + 5 + 6 + 7 + 8$$

- $I, Q, U, V$  signals can be recovered via different linear combinations of integrations 1 – 8

# Separating $I, Q, U, V$ images

- Remember: our camera frame rate isn't exactly matched with the modulator frequency – there will be some offset  $\phi$  when integrating over the frames
  - For a perfectly matched camera frame rate:

$$Q' = \int_0^{\pi/8} I'' d\theta - \int_{\pi/8}^{\pi/4} I'' d\theta - \int_{\pi/4}^{3\pi/8} I'' d\theta + \int_{3\pi/8}^{\pi/2} I'' d\theta + \int_{\pi/2}^{5\pi/8} I'' d\theta - \int_{5\pi/8}^{3\pi/4} I'' d\theta - \int_{3\pi/4}^{7\pi/8} I'' d\theta + \int_{7\pi/8}^{\pi} I'' d\theta$$

$$U' = \int_0^{\pi/8} I'' d\theta + \int_{\pi/8}^{\pi/4} I'' d\theta - \int_{\pi/4}^{3\pi/8} I'' d\theta - \int_{3\pi/8}^{\pi/2} I'' d\theta + \int_{\pi/2}^{5\pi/8} I'' d\theta + \int_{5\pi/8}^{3\pi/4} I'' d\theta - \int_{3\pi/4}^{7\pi/8} I'' d\theta - \int_{7\pi/8}^{\pi} I'' d\theta$$

- Our case:

$$Q'' = \int_{\phi}^{\pi/8+\phi} I'' d\theta - \int_{\pi/8+\phi}^{\pi/4+\phi} I'' d\theta - \int_{\pi/4+\phi}^{3\pi/8+\phi} I'' d\theta + \int_{3\pi/8+\phi}^{\pi/2+\phi} I'' d\theta + \int_{\pi/2+\phi}^{5\pi/8+\phi} I'' d\theta - \int_{5\pi/8+\phi}^{3\pi/4+\phi} I'' d\theta - \int_{3\pi/4+\phi}^{7\pi/8+\phi} I'' d\theta + \int_{7\pi/8+\phi}^{\pi+\phi} I'' d\theta$$

$$= Q' \cos 4\phi - U' \sin 4\phi$$

Leakage between  $Q$  and  $U$

# Calibrating $I, Q, U, V$ images

- Our case:

$$\begin{aligned}
 Q'' &= \int_{\phi}^{\pi/8+\phi} I'' d\theta - \int_{\pi/8+\phi}^{\pi/4+\phi} I'' d\theta - \int_{\pi/4+\phi}^{\frac{3\pi}{8}+\phi} I'' d\theta + \int_{\frac{3\pi}{8}+\phi}^{\pi/2+\phi} I'' d\theta + \int_{\pi/2+\phi}^{\frac{5\pi}{8}+\phi} I'' d\theta - \int_{\frac{5\pi}{8}+\phi}^{\frac{3\pi}{4}+\phi} I'' d\theta - \int_{\frac{3\pi}{4}+\phi}^{\frac{7\pi}{8}+\phi} I'' d\theta + \int_{\frac{7\pi}{8}+\phi}^{\pi+\phi} I'' d\theta \\
 &= Q' \cos 4\phi - U' \sin 4\phi
 \end{aligned}$$

– Similar effect for  $U$  and  $V$

- Correct for leakage caused by phase offset by multiplying the Stokes vector by a restoration matrix:

$$\begin{array}{c} \text{Demodulated} \\ \text{signal that has} \\ \text{passed through} \\ \text{optical chain} \end{array} \rightarrow \begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \overbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\phi & \sin 4\phi & 0 \\ 0 & -\sin 4\phi & \cos 4\phi & 0 \\ 0 & 0 & 0 & \sec 2\phi \end{bmatrix}}^{M_\phi} \begin{bmatrix} I'' \\ Q'' \\ U'' \\ V'' \end{bmatrix} \leftarrow \begin{array}{c} \text{Measured at detector} \end{array}$$

# Calibrating $I, Q, U, V$ images

- NIRIS uses many different optical elements that are difficult to model
- We are trying to recover the “true” Stokes vector  $\vec{S}$ , but the polarization of the light entering the telescope is altered as it passes through the telescope and relay optics
- The way an optical element alters polarization of light is described by a  $4 \times 4$  Mueller matrix  $\mathbf{M}$ :

$$\vec{S}' = \mathbf{M}\vec{S}$$

- Every element of the NIRIS relay optics alters the polarization of the incident beam
  - We can quantify the total effect of an optical chain using one Mueller matrix  $\mathbf{M}$ :

$$\mathbf{M} = \mathbf{M}_1 \mathbf{M}_2 \mathbf{M}_3 \dots \mathbf{M}_n$$

# Calibrating $I, Q, U, V$ images

- Starting with the telescope Mueller matrix  $\mathbf{T}$  (combined effects of primary and secondary mirrors), the signal after phase correction is:

$$\vec{S}' = \mathbf{MS} = [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3\mathbf{T}] \vec{S}$$

- Trace the path of the light:

# Calibrating $I, Q, U, V$ images

- Starting with the telescope Mueller matrix  $\mathbf{T}$  (combined effects of primary and secondary mirrors), the signal after phase correction is:

$$\vec{S}' = \mathbf{MS} = [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3\mathbf{T}] \vec{S}$$

- Trace the path of the light:
  - $\vec{S}$  is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by  $\mathbf{T}$

# Calibrating $I, Q, U, V$ images

- Starting with the telescope Mueller matrix  $\mathbf{T}$  (combined effects of primary and secondary mirrors), the signal after phase correction is:

$$\vec{S}' = \mathbf{MS} = [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3\mathbf{T}] \vec{S}$$

- Trace the path of the light:
  - $\vec{S}$  is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by  $\mathbf{T}$
  - The beam reflects off mirror 3 ( $\mathbf{M}_3$ ) and is sent down the declination axis of the telescope, resulting in a rotation in dec,  $\mathbf{R}(\text{dec})$



# Calibrating $I, Q, U, V$ images

- Starting with the telescope Mueller matrix  $\mathbf{T}$  (combined effects of primary and secondary mirrors), the signal after phase correction is:

$$\vec{S}' = \mathbf{MS} = [\mathbf{M}_{\text{rest}} \mathbf{R}(\text{HA}) \mathbf{M}_4 \mathbf{R}(\text{dec}) \mathbf{M}_3 \mathbf{T}] \vec{S}$$

- Trace the path of the light:
  - $\vec{S}$  is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by  $\mathbf{T}$
  - The beam reflects off mirror 3 ( $\mathbf{M}_3$ ) and is sent down the declination axis of the telescope, resulting in a rotation in dec,  $\mathbf{R}(\text{dec})$
  - The beam reflects off mirror 4 ( $\mathbf{M}_4$ ) and is sent down the polar axis of the telescope, resulting in a rotation in hour angle,  $\mathbf{R}(\text{HA})$

# Calibrating $I, Q, U, V$ images

- Starting with the telescope Mueller matrix  $\mathbf{T}$  (combined effects of primary and secondary mirrors), the signal after phase correction is:

$$\vec{S}' = \mathbf{MS} = [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3\mathbf{T}] \vec{S}$$

- Trace the path of the light:
  - $\vec{S}$  is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by  $\mathbf{T}$
  - The beam reflects off mirror 3 ( $\mathbf{M}_3$ ) and is sent down the declination axis of the telescope, resulting in a rotation in dec,  $\mathbf{R}(\text{dec})$
  - The beam reflects off mirror 4 ( $\mathbf{M}_4$ ) and is sent down the polar axis of the telescope, resulting in a rotation in hour angle,  $\mathbf{R}(\text{HA})$
  - The light passes through **all stationary optical elements past M4**, whose effects are quantified by  $\mathbf{M}_{\text{rest}}$

# Calibrating $I, Q, U, V$ images

- Starting with the telescope Mueller matrix  $\mathbf{T}$  (combined effects of primary and secondary mirrors), the signal after phase correction is:

$$\vec{S}' = \mathbf{MS} = [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3\mathbf{T}] \vec{S}$$

- Trace the path of the light:
  - $\vec{S}$  is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by  $\mathbf{T}$
  - The beam reflects off mirror 3 ( $\mathbf{M}_3$ ) and is sent down the declination axis of the telescope, resulting in a rotation in dec,  $\mathbf{R}(\text{dec})$
  - The beam reflects off mirror 4 ( $\mathbf{M}_4$ ) and is sent down the polar axis of the telescope, resulting in a rotation in hour angle,  $\mathbf{R}(\text{HA})$
  - The light passes through all stationary optical elements past M4, whose effects are quantified by  $\mathbf{M}_{\text{rest}}$
  - The light reaches the camera

# Calibrating $I, Q, U, V$ images

- Signal after phase correction:

Phase correction applied to measured signal  $\vec{S}''$

$$\vec{S}' = \mathbf{M}(\text{HA, dec})\vec{S} = [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3\cancel{\mathbf{T}}]\vec{S}$$

$$\mathbf{M}_\phi\vec{S}'' = \underbrace{[\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3]}_{\mathbf{M}(\text{HA, dec})}\vec{S}$$

- Now we can (theoretically) find the “true” Stokes vector  $\vec{S}$  from the measured signal  $\vec{S}''$ :

$$\begin{aligned}\vec{S} &= \mathbf{M}^{-1}(\text{HA, dec})\mathbf{M}_\phi\vec{S}'' \\ &= [\mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3]^{-1}\mathbf{M}_\phi\vec{S}''\end{aligned}$$

# Finding calibration matrix $M_{rest}$

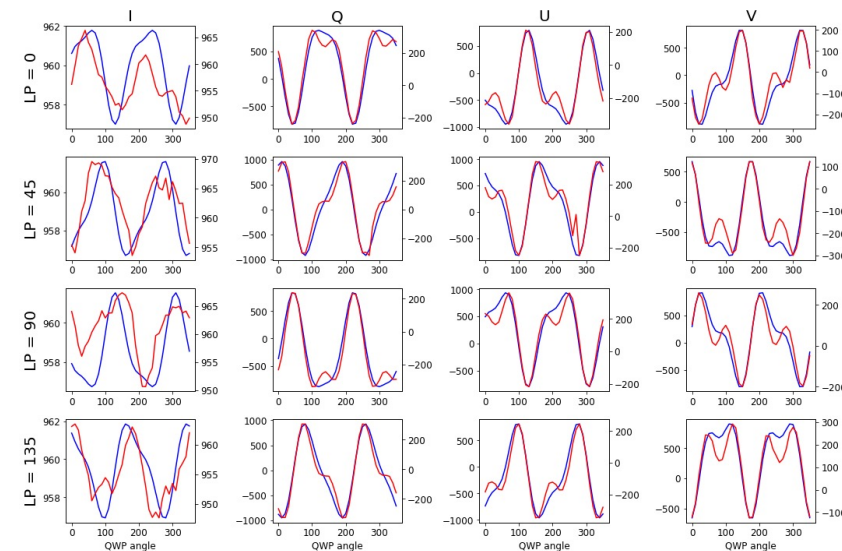
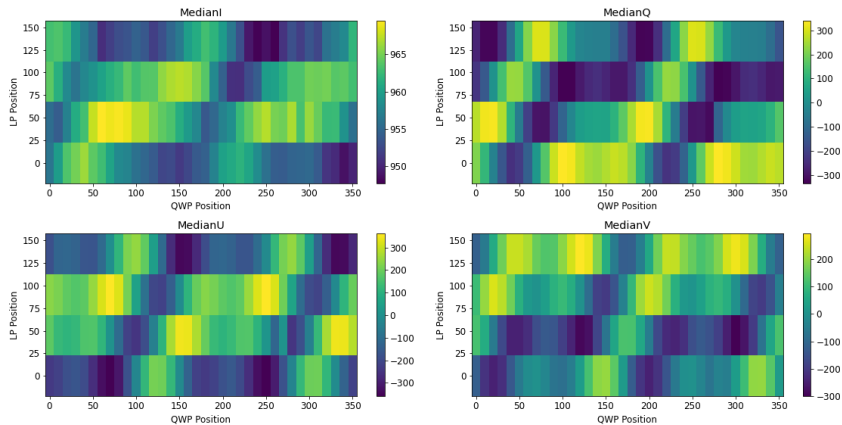
- We can measure  $M(HA, dec_0)$  (details to come) over one day, and use this to find  $M_{rest}$ :

$$M(HA, dec_0) = M_{rest}R(HA)M_4R(dec_0)M_3$$



$$M_{rest} = \underbrace{M(HA, dec_0)}_{\substack{\text{Measured} \\ \text{(or simulated from} \\ \text{measurements)}}} \underbrace{[R(HA)M_4R(dec_0)M_3]^{-1}}_{\text{Modeled}}$$

# Measuring $M(HA_i, dec_0)$



- Theoretical  $I, Q, U, V$  signals:

$$\vec{S}'_i = M(HA_i, dec_0) M_{QWP} M_{LP} \vec{S}_i$$

Unknowns:

All 16 elements of  $M(HA_i, dec_0)$

Unknowns:

$\theta_{LP}$  orientation of LP transmission axis

$\theta_{QWP}$  orientation of QWP fast axis

$\delta_{QWP}$  QWP surface retardation

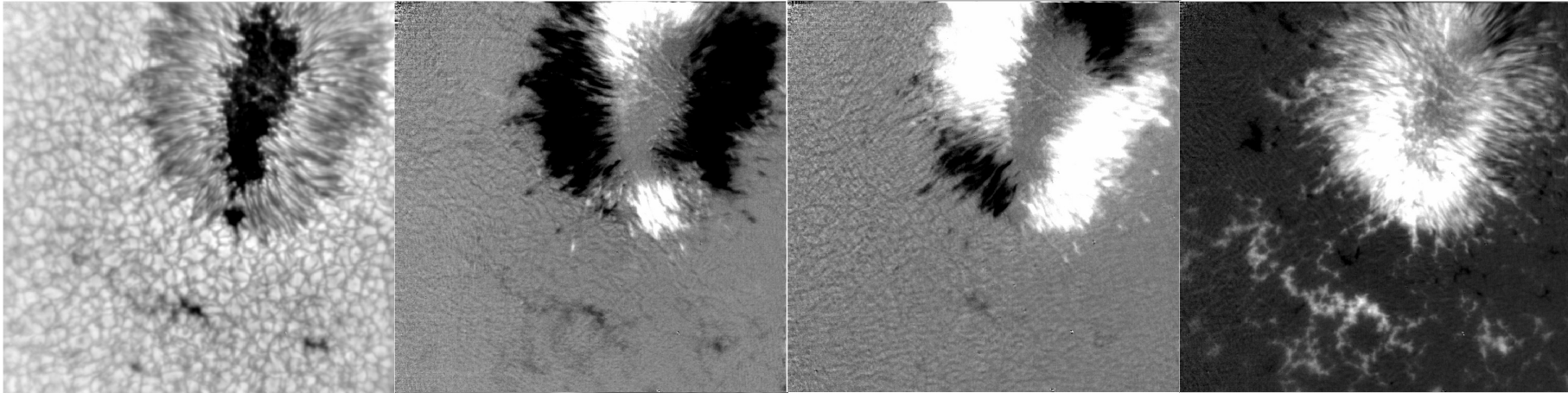
- Fit all these parameters to the measured  $I, Q, U, V$  signals (red)

# Simulating $\mathbf{M}(\text{HA}, \text{dec})$ from $\mathbf{M}_{\text{rest}}$

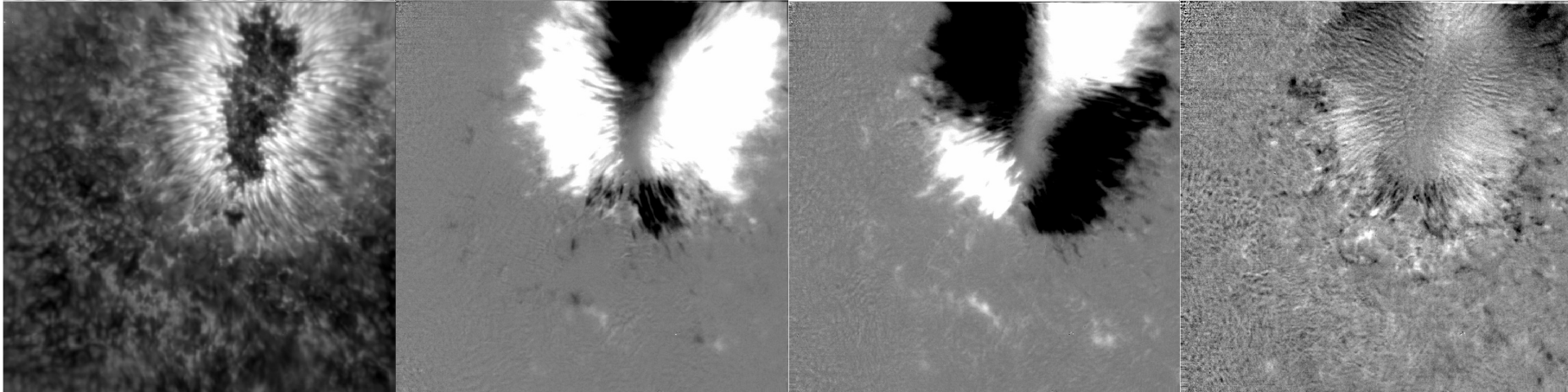
- Take calibration measurements throughout the day, once per year, to find  $\mathbf{M}(\text{HA}, \text{dec}_0)$
- Find  $\mathbf{M}_{\text{rest}}$  from  $\mathbf{M}(\text{HA}, \text{dec}_0)$
- Use  $\mathbf{M}_{\text{rest}}$  to calculate  $\mathbf{M}(\text{HA}, \text{dec})$  – for any combination of HA and dec (i.e. any day of the year)
  - $\mathbf{M}(\text{HA}, \text{dec}) = \mathbf{M}_{\text{rest}}\mathbf{R}(\text{HA})\mathbf{M}_4\mathbf{R}(\text{dec})\mathbf{M}_3$
- Apply a different calibration matrix for each observation date/time

# 2024/05/19 calibrated data

Nearing line center (step 18)



Line center (step 21)





# Back to the NIRIS pipeline...

- Surprise! Another crosstalk correction
  - A finer correction for  $Q \leftrightarrow V$  and  $U \leftrightarrow V$  crosstalk
    - Notable residual crosstalk in images with strong magnetic fields (ARs)
  - Choose crosstalk weights that optimize the symmetry (antisymmetry) of the  $Q, U (V)$  Stokes profiles
    - Deviations from symmetric (antisymmetric)  $Q, U (V)$  profiles are indicative of additional crosstalk
    - Iterative process
- Image processing finished! Results:
  - cal processed images after Mueller matrix crosstalk calibration (QS)
  - cals processed images after iterative crosstalk correction (AR)

# Part III: Inverting NIRIS Data

# Stokes inversions using NIRIS data

- Straight forward problem:
  - Assumptions:
    - Properties of the solar atmosphere are known
    - Four Stokes profiles are unknown
  - Solve the radiative transfer equation (RTE) directly to find Stokes profiles
- Inverse problem:
  - For our Solar observations:
    - Four Stokes profiles are known (measured)
    - Properties of the solar atmosphere are unknown
  - Requires inversion of the RTE

# Stokes inversions using NIRIS data

- Radiative transfer equation:  $\frac{d\vec{I}}{d\tau_c} = \tilde{K}(\vec{I} - \vec{S})$ 
  - $\vec{I}$  Stokes pseudo-vector:  $\vec{I} \equiv [I, Q, U, V]^T$
  - $\tau_c$  optical depth at continuum wavelength
  - $\vec{S}$  source function vector
  - $\tilde{K}$  propagation matrix; accounts for:
    - Absorption – withdrawal of same amount of energy from all polarization states
    - Pleochromism – differential absorption for the polarization states
    - Dispersion – transfer among polarization states
- Mapping between two spaces:
  - measurements + instrumental error  $\rightarrow$  physical quantities + uncertainties
- Mapping represents the physics that generates observables from given physical conditions in the object
  - Same observable can yield different results in inversion, depending on assumed underlying physics

# Stokes inversions using NIRIS data

- Model atmosphere parameters:
  - $T$  Temperature
  - $p$  Pressure
  - $v_{LOS}$  Bulk line-of-sight velocity field
  - $\vec{B}$  Magnetic vector field
    - $B$  Strength
    - $\gamma$  Inclination with respect to LOS
    - $\varphi$  Azimuth
  - Ad hoc variables
    - $\xi_{mic}$  Micro-turbulence velocity
    - $\xi_{mac}$  Macro-turbulence velocity
    - $f$  Filling factor
- Inversion methods:
  - Local thermodynamic equilibrium (LTE)
  - Weak-field
  - Micro-structured magnetic atmospheres (MISMA)
  - Milne-Eddington (ME)

# Summary

- NIRIS targets Zeeman-sensitive lines in the NIR to obtain information about Solar magnetic fields and other quantities of interest
- NIRIS uses dual-beam polarimetry to measure Stokes profiles
  - These profiles are used in Stokes inversion methods to obtain magnetic field vector maps
- Instrumental cross-talk needs to be carefully calibrated to yield accurate Stokes inversion results
  - Mueller calculus
  - Iterative fine correction
- The newly-implemented NIRIS cross-talk calibration method works!