Handling NIRIS Data: Calibration, Processing, and Inversion

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BBSO Summer School 2024
Big Bear Solar Observatory, NJIT/CSTR
2024 August 1

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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

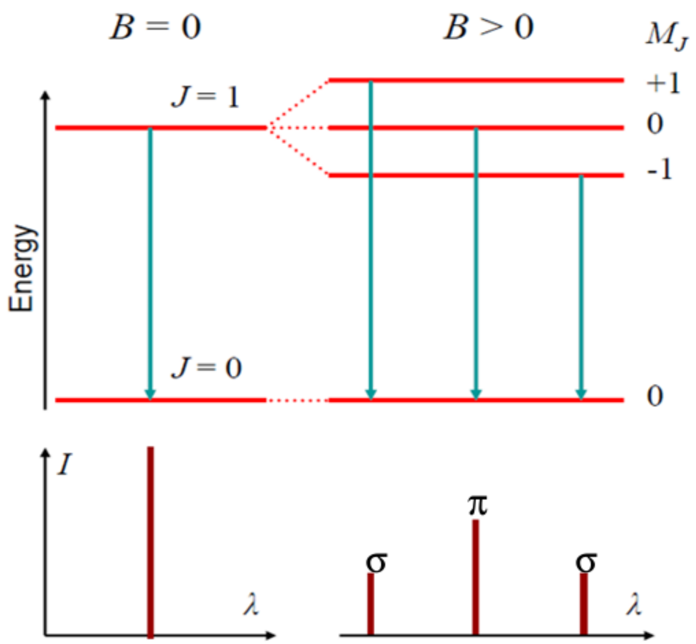
- High-resolution spectroscopy and polarimetry using Zeeman-sensitive spectral lines in the NIR
  - Zeeman splitting is a function of $g\lambda^2 B$

Line	Wavelength	Lande factor g_{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 μm

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_ℓ) 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
π (non-shifted)	+ linear polarization	none
σ (shifted)	− linear polarization	circular polarization

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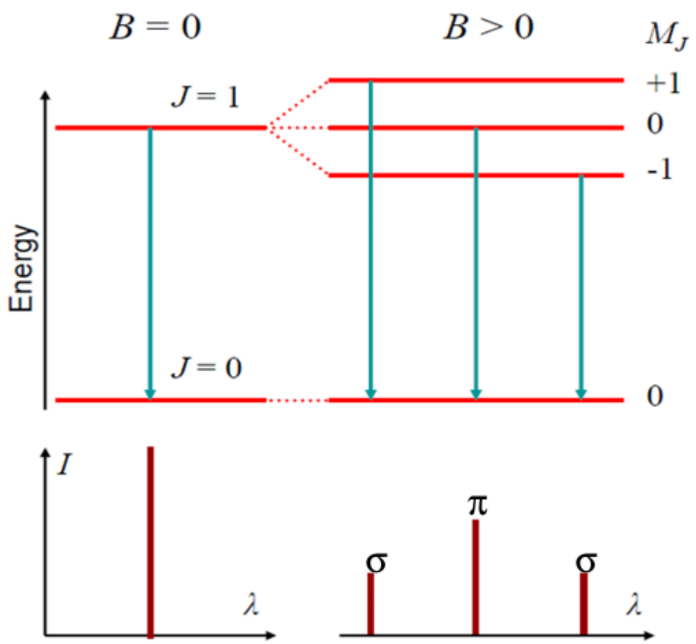
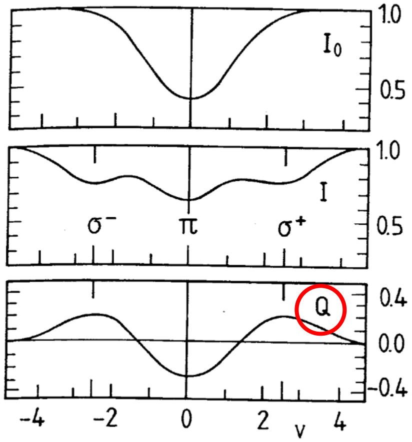


- Resulting Zeeman triplet:

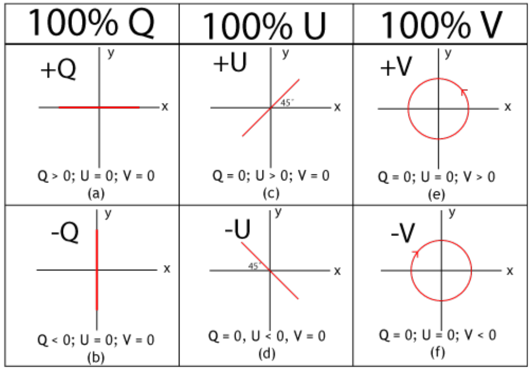
Component	$\vec{B} \perp$ to LOS	$\vec{B} \parallel$ to LOS
π (non-shifted)	+ linear polarization	none
σ (shifted)	− linear polarization	circular polarization

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

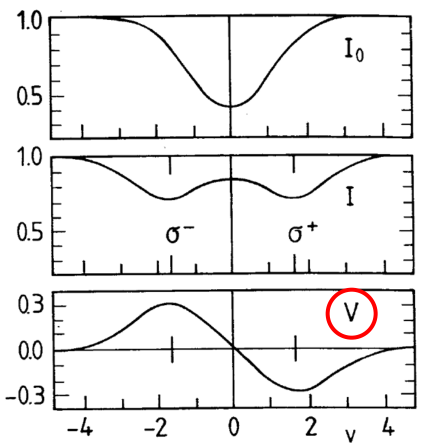
Exploiting the Zeeman effect



- 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



Component	$\vec{B}$ **⊥ to LOS**	$\vec{B}$ **∥ to LOS**
π (non-shifted)	+ linear polarization	none
σ (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")

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  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

NIRIS optical design

- Passband depends on FPI effective FWHM and max angle of incident beam
- FPIs in telecentric configuration – placed near a focus of solar image
  - Every image point has the same incident angle entering the FPIs
    - Enables passband invariance across FOV (for an ideal FPI)
- Mechanically rotating birefringent modulator
  - Zero-order waveplate with retardation $\delta = 0.3525\lambda \pm \lambda/350$
  - "Matches" frame rate of camera – 16 frames acquired in one rotation of the modulator
    - (Reality: not perfectly matched → need to correct for this mismatch)

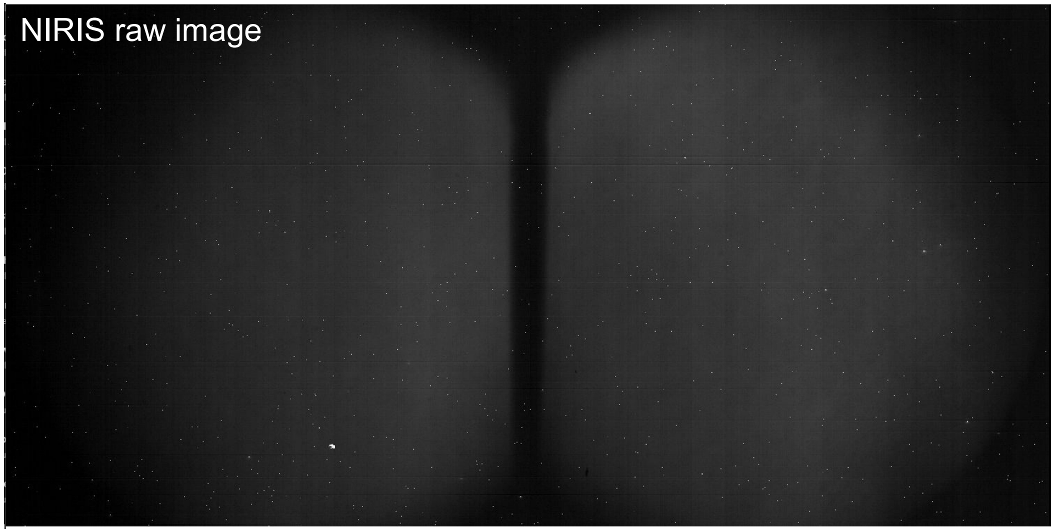
Part II: NIRIS data processing

NIRIS raw data

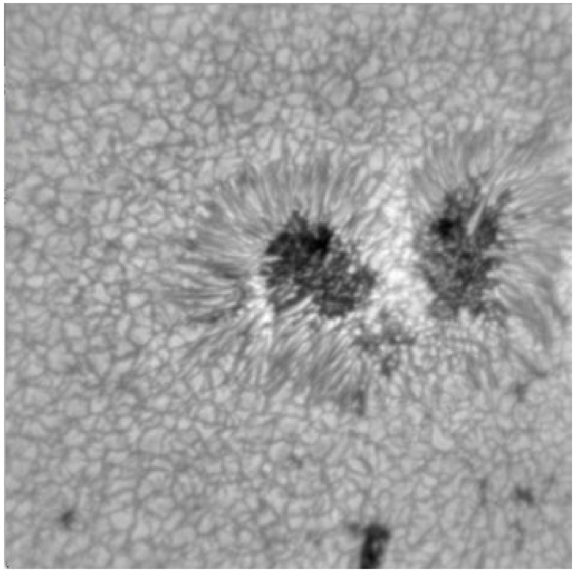
- Correct each image of the scan with darks and flats:

$$\frac{\text{images}-\text{dark}}{\text{flats}-\text{dark}} * (\text{spectral profile of flats})$$

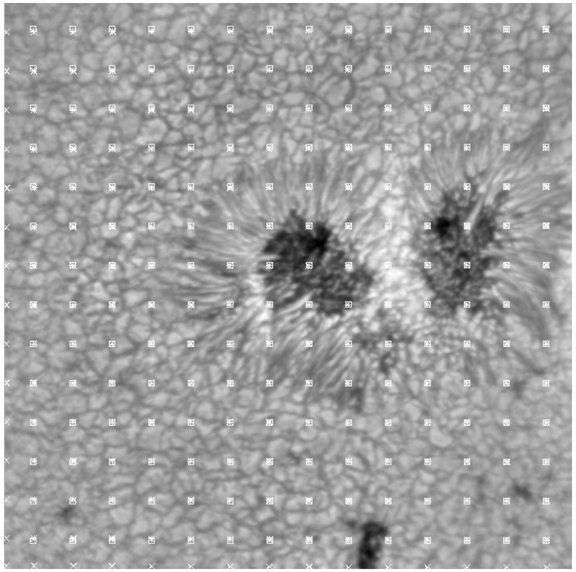
- Mask hot pixels/extreme values with median of surrounding pixels



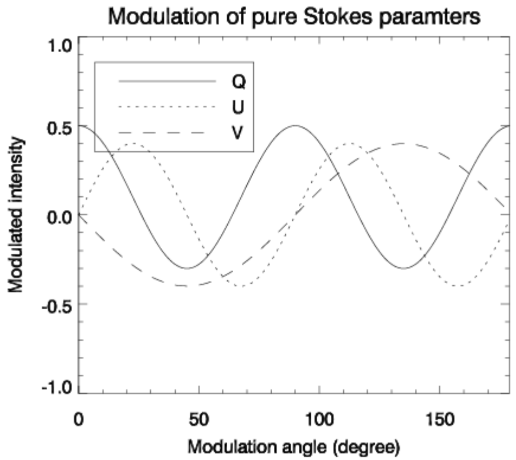
NIRIS raw data

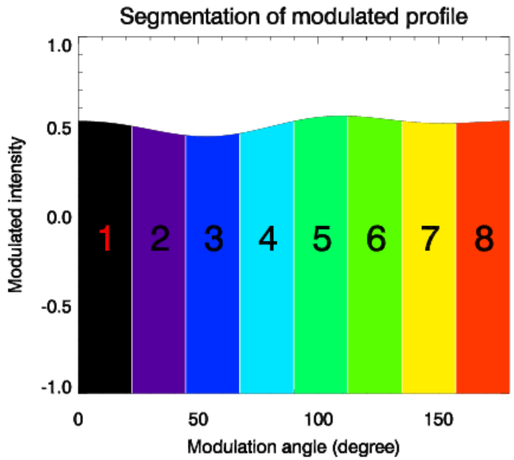


- Split the mirror images and perform rough co-alignment
  - Translational shifts of images only
  - Maximize cross-correlation between images
- Rotational alignment of mirror images
- Another translational alignment (sub-pixel accuracy)
- Register and de-stretch mirror images
- Add the images for total signal, take the difference of the images to find Q, U, V



Separating I, Q, U, V images





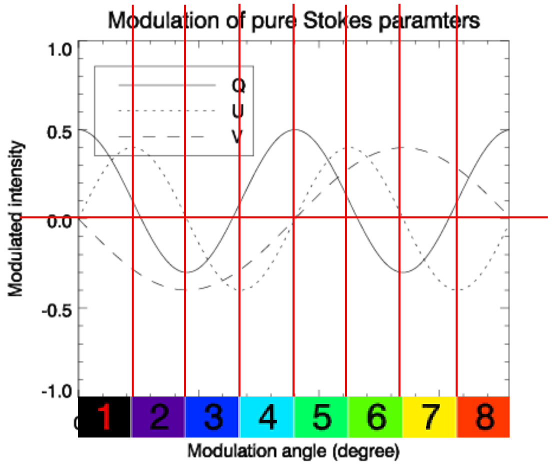
- Modulator waveplate (frequency ω) modulates polarization states differently
  - Q and U (linear polarization) modulated at 4ω
  - V (circular polarization) modulated at 2ω
- Observed modulated profile is a combination of I, Q, U, V:

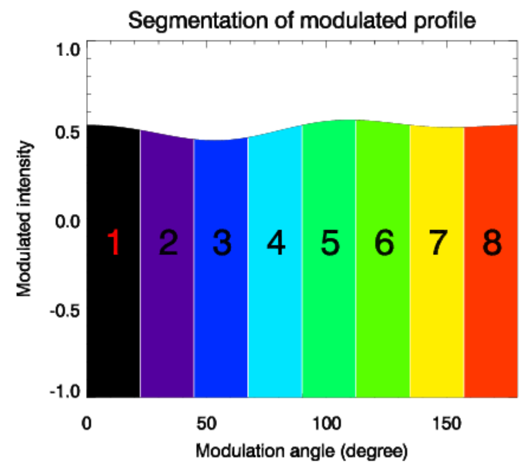
modulation angle

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

waveplate retardation

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 ϕ when integrating over the frames
  - For a perfectly matched camera frame rate:

$$Q' = \int_{0}^{\pi/8} I'' d\theta - \int_{\pi/8}^{\pi/4} I'' d\theta - \int_{\pi/4}^{3\pi/8} I'' d\theta + \int_{3\pi/8}^{\pi/2} I'' d\theta + \int_{\pi/2}^{5\pi/8} I'' d\theta - \int_{5\pi/8}^{3\pi/4} I'' d\theta - \int_{3\pi/4}^{7\pi/8} I'' d\theta + \int_{7\pi/8}^{\pi} I'' d\theta$$

$$U' = \int_{0}^{\pi/8} I'' d\theta + \int_{\pi/8}^{\pi/4} I'' d\theta - \int_{\pi/4}^{3\pi/8} I'' d\theta - \int_{3\pi/8}^{\pi/2} I'' d\theta + \int_{\pi/2}^{5\pi/8} I'' d\theta + \int_{5\pi/8}^{3\pi/4} I'' d\theta - \int_{3\pi/4}^{7\pi/8} I'' d\theta - \int_{7\pi/8}^{\pi} I'' d\theta$$

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$$U' = \int_{0}^{\pi/8} I'' d\theta + \int_{\pi/8}^{\pi/4} I'' d\theta - \int_{\pi/4}^{3\pi/8} I'' d\theta - \int_{3\pi/8}^{\pi/2} I'' d\theta + \int_{\pi/2}^{5\pi/8} I'' d\theta + \int_{5\pi/8}^{3\pi/4} I'' d\theta - \int_{3\pi/4}^{7\pi/8} I'' d\theta - \int_{7\pi/8}^{\pi} I'' d\theta$$

  - Our case:

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

Separating I, Q, U, V images

- Remember: our camera frame rate isn't exactly matched with the modulator frequency – there will be some offset ϕ when integrating over the frames
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$$U' = \int_0^{\pi/8} I'' d\theta + \int_{\pi/8}^{\pi/4} I'' d\theta - \int_{\pi/4}^{3\pi/8} I'' d\theta - \int_{3\pi/8}^{\pi/2} I'' d\theta + \int_{\pi/2}^{5\pi/8} I'' d\theta + \int_{5\pi/8}^{3\pi/4} I'' d\theta - \int_{3\pi/4}^{7\pi/8} I'' d\theta - \int_{7\pi/8}^{\pi} I'' d\theta$$

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

Leakage between Q and U

Calibrating I, Q, U, V images

- Our case:

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

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

  - Similar effect for U and V

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

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\phi & \sin 4\phi & 0 \\ 0 & -\sin 4\phi & \cos 4\phi & 0 \\ 0 & 0 & 0 & \sec 2\phi \end{bmatrix} \begin{bmatrix} I'' \\ Q'' \\ U'' \\ V'' \end{bmatrix}$$

Calibrating I, Q, U, V images

- Our case:

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

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

  - Similar effect for U and V

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

Demodulated signal that has passed through optical chain

$$\begin{bmatrix} I' \\ Q' \\ U' \\ V' \end{bmatrix} = \overbrace{\begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 4\phi & \sin 4\phi & 0 \\ 0 & -\sin 4\phi & \cos 4\phi & 0 \\ 0 & 0 & 0 & \sec 2\phi \end{bmatrix}}^{\mathbf{M}_{\phi}} \begin{bmatrix} I'' \\ Q'' \\ U'' \\ V'' \end{bmatrix}$$

Measured at detector

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 4×4 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 $\mathbf{M}$:

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

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

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- Trace the path of the light:
  1. $\vec{S}$ 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:
  1. $\vec{S}$ is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by $\mathbf{T}$
  2. 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:

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- Trace the path of the light:
    1. $\vec{S}$ is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by $\mathbf{T}$
    2. 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, $\mathbf{R}(\text{dec})$
    3. 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:

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  1. $\vec{S}$ is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by $\mathbf{T}$
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  3. 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, $\mathbf{R}(\mathrm{HA})$
  4. The light passes through all stationary optical elements past M4, whose effects are quantified by $\mathbf{M}_{\mathrm{rest}}$

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:

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- Trace the path of the light:
  1. $\vec{S}$ is altered as the beam passes through the primary and secondary mirrors, whose effects are quantified by $\mathbf{T}$
  2. 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, $\mathbf{R}(\mathrm{dec})$
  3. 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, $\mathbf{R}(\mathrm{HA})$
  4. The light passes through all stationary optical elements past M4, whose effects are quantified by $\mathbf{M}_{\mathrm{rest}}$
  5. The light reaches the camera

Calibrating I, Q, U, V images

- Signal after phase correction:

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

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

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

Calibrating I, Q, U, V images

- Signal after phase correction:

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

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

$$\vec{S} = \mathbf{M}^{-1}(\mathrm{HA}, \mathrm{dec})\mathbf{M}_\phi\vec{S}''$$

$$= [\mathbf{M}_{\mathrm{rest}}\mathbf{R}(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec})\mathbf{M}_3]^{-1}\mathbf{M}_\phi\vec{S}''$$

Calibrating I, Q, U, V images

- The problem is now reduced to finding $\mathbf{M}(\mathrm{HA}, \mathrm{dec})$ for any HA and dec

$$\vec{S} = \mathbf{M}^{-1}(\mathrm{HA}, \mathrm{dec})\mathbf{M}_{\phi}\vec{S}''$$

$$\mathbf{M}(\mathrm{HA}, \mathrm{dec}) = \mathbf{M}_{\mathrm{rest}}\mathbf{R}(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec})\mathbf{M}_3$$

Calibrating I, Q, U, V images

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$$\mathbf{M}(\mathrm{HA}, \mathrm{dec}) = \mathbf{M}_{\mathrm{rest}}\mathbf{R}(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec})\mathbf{M}_3$$

These are simple 4×4 rotation matrices:

$$\mathbf{R}(\theta) = \begin{bmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos 2\theta & -\sin 2\theta & 0 \\ 0 & \sin 2\theta & \cos 2\theta & 0 \\ 0 & 0 & 0 & 1 \end{bmatrix}$$

Calibrating I, Q, U, V images

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These are Mueller matrices for M3 and M4, which we can model:

$$M_{\mathrm{mirror}} = \begin{bmatrix} 1 & \frac{1-r_s/r_p}{1+r_s/r_p} & 0 & 0 \\ \frac{1-r_s/r_p}{1+r_s/r_p} & 1 & 0 & 0 \\ 0 & 0 & \frac{2\sqrt{r_s/r_p}\cos\delta}{1+r_s/r_p} & \frac{2\sqrt{r_s/r_p}\sin\delta}{1+r_s/r_p} \\ 0 & 0 & \frac{-2\sqrt{r_s/r_p}\sin\delta}{1+r_s/r_p} & \frac{2\sqrt{r_s/r_p}\cos\delta}{1+r_s/r_p} \end{bmatrix}$$

Calibrating I, Q, U, V images

- The problem is now reduced to finding $\mathbf{M}(\mathrm{HA}, \mathrm{dec})$ for any HA and dec

$$\vec{S} = \mathbf{M}^{-1}(\mathrm{HA}, \mathrm{dec})\mathbf{M}_{\phi}\vec{S}''$$

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These are Mueller matrices for M3 and M4, which we can model:

r_s/r_p ratio of reflectivity of s and p polarizations

δ surface retardation of mirror

$$M_{\mathrm{mirror}} = \begin{bmatrix} 1 & \frac{1-r_s/r_p}{1+r_s/r_p} & 0 & 0 \\ \frac{1-r_s/r_p}{1+r_s/r_p} & 1 & 0 & 0 \\ 0 & 0 & \frac{2\sqrt{r_s/r_p}\cos\delta}{1+r_s/r_p} & \frac{2\sqrt{r_s/r_p}\sin\delta}{1+r_s/r_p} \\ 0 & 0 & \frac{-2\sqrt{r_s/r_p}\sin\delta}{1+r_s/r_p} & \frac{2\sqrt{r_s/r_p}\cos\delta}{1+r_s/r_p} \end{bmatrix}$$

Calibrating I, Q, U, V images

- The problem is now reduced to finding $\mathbf{M}(\mathrm{HA}, \mathrm{dec})$ for any HA and dec

$$\vec{S} = \mathbf{M}^{-1}(\mathrm{HA}, \mathrm{dec})\mathbf{M}_{\phi}\vec{S}''$$

$$\mathbf{M}(\mathrm{HA}, \mathrm{dec}) = \mathbf{M}_{\mathrm{rest}}\underbrace{\mathbf{R}(\mathrm{HA})\mathbf{M}_{4}\mathbf{R}(\mathrm{dec})\mathbf{M}_{3}}$$

We can compute the Mueller matrix for the moving parts of the telescope

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We can compute the Mueller matrix for the moving parts of the telescope

Now we just need to measure the Mueller matrix of all the (stationary) optics between M4 and the camera

This should be constant over time

Finding calibration matrix $\mathbf{M}_{\mathrm{rest}}$

- We can measure $\mathbf{M}(\mathrm{HA}, \mathrm{dec}_0)$ (details to come) over one day, and use this to find $\mathbf{M}_{\mathrm{rest}}$:

$$\mathbf{M}(\mathrm{HA}, \mathrm{dec}_0) = \mathbf{M}_{\mathrm{rest}}\mathbf{R}(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec}_0)\mathbf{M}_3$$

$$\mathbf{M}_{\mathrm{rest}} = \mathbf{M}\underbrace{(\mathrm{HA}, \mathrm{dec}_0)}_{\text{Measured (or simulated from measurements)}}[\mathbf{R}\underbrace{(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec}_0)}_{\text{Modeled}}\mathbf{M}_3]^{-1}$$

Measuring $\mathbf{M}(\mathrm{HA}_i, \mathrm{dec}_0)$

- Calibration optics:
  - Linear polarizer (LP)
  - Quarter wave plate (QWP)
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  - Keep both optical elements in the beam for duration of measurements
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  - At every LP position, rotate the QWP a full $360°$, in $10°$ increments
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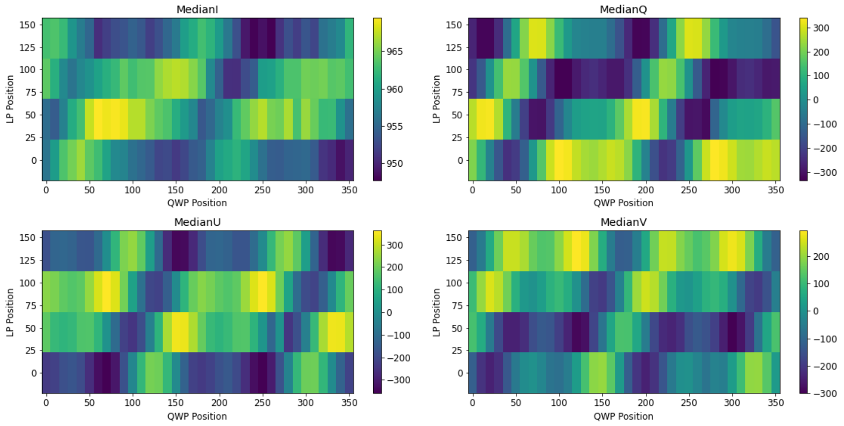
- 10 minutes to complete a full sequence (i)
  - Run every $30 - 60$ minutes
    - $\sim$1,872 data cubes, size $(2048 \times 1024 \times 32)$

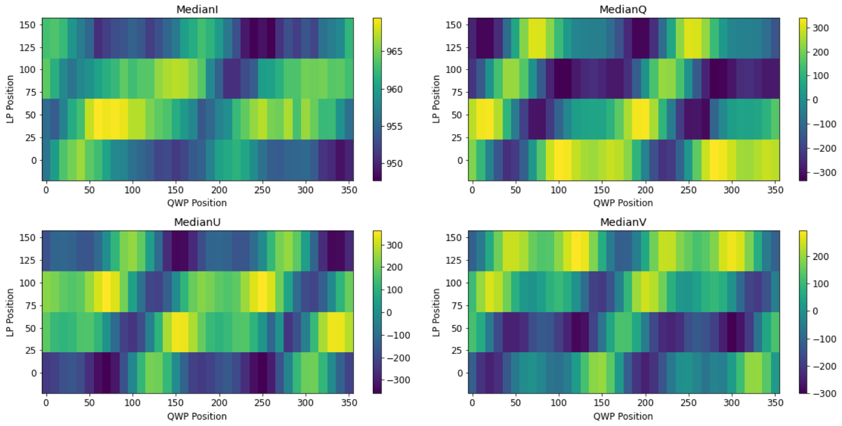
Measuring $\mathbf{M}(\mathrm{HA}_i, \mathrm{dec}_0)$



- Theoretical I, Q, U, V signals:

$$\vec{S}_i' = \mathbf{M}(\mathrm{HA}_i, \mathrm{dec}_0)\mathbf{M}_{QWP}\mathbf{M}_{LP}\vec{S}_i$$

Measuring $\mathbf{M}(\mathrm{HA}_i, \mathrm{dec}_0)$



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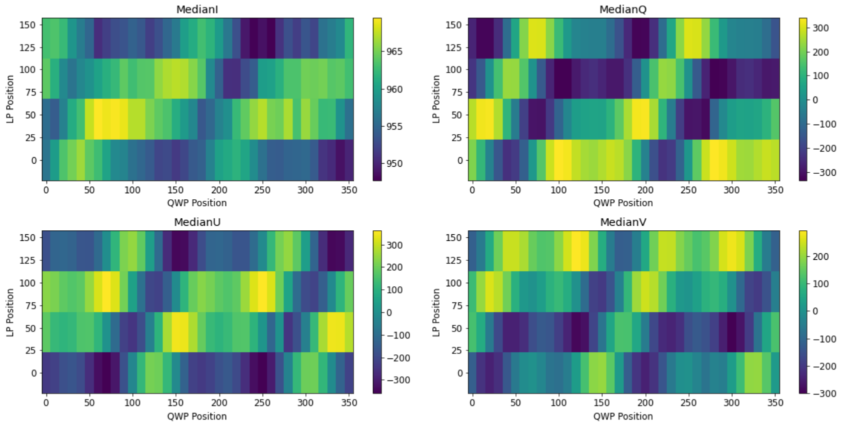
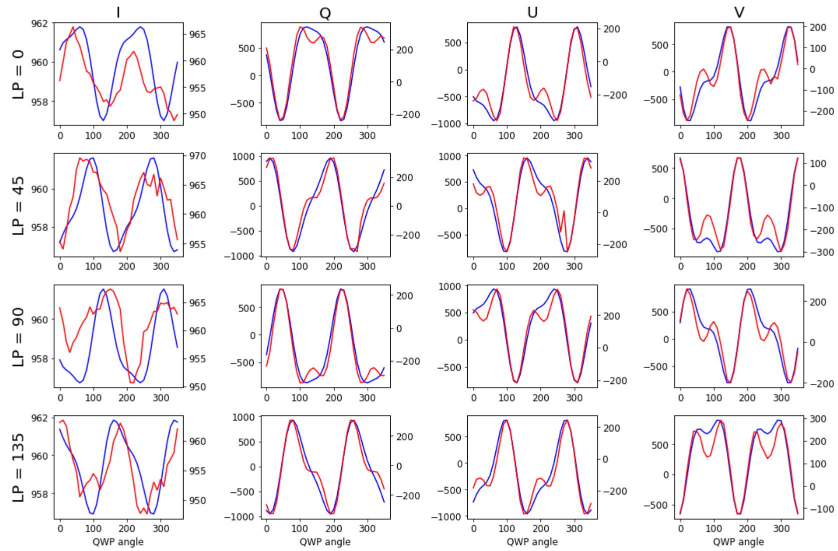
Unknowns:
All 16 elements of $\mathbf{M}(\mathrm{HA}_i, \mathrm{dec}_0)$

Unknowns:
θ_{LP} orientation of LP transmission axis
θ_{QWP} orientation of QWP fast axis
δ_{QWP} QWP surface retardation

Measuring $\mathbf{M}(\mathrm{HA}_i, \mathrm{dec}_0)$





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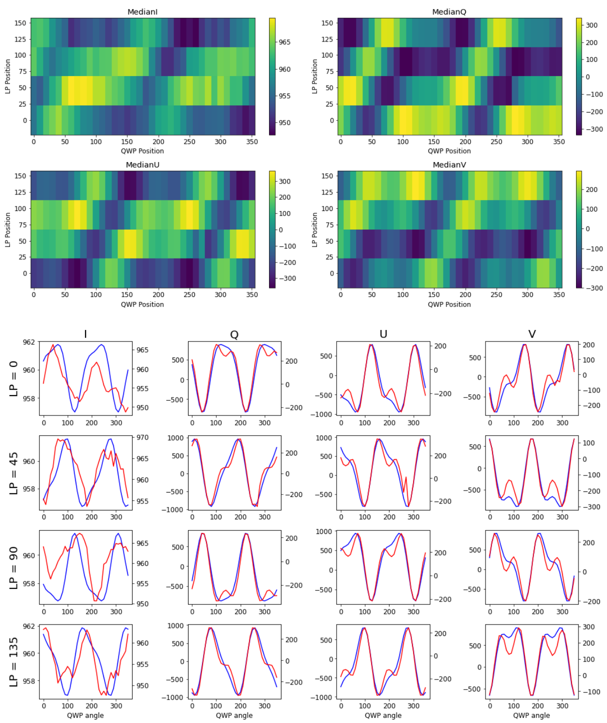
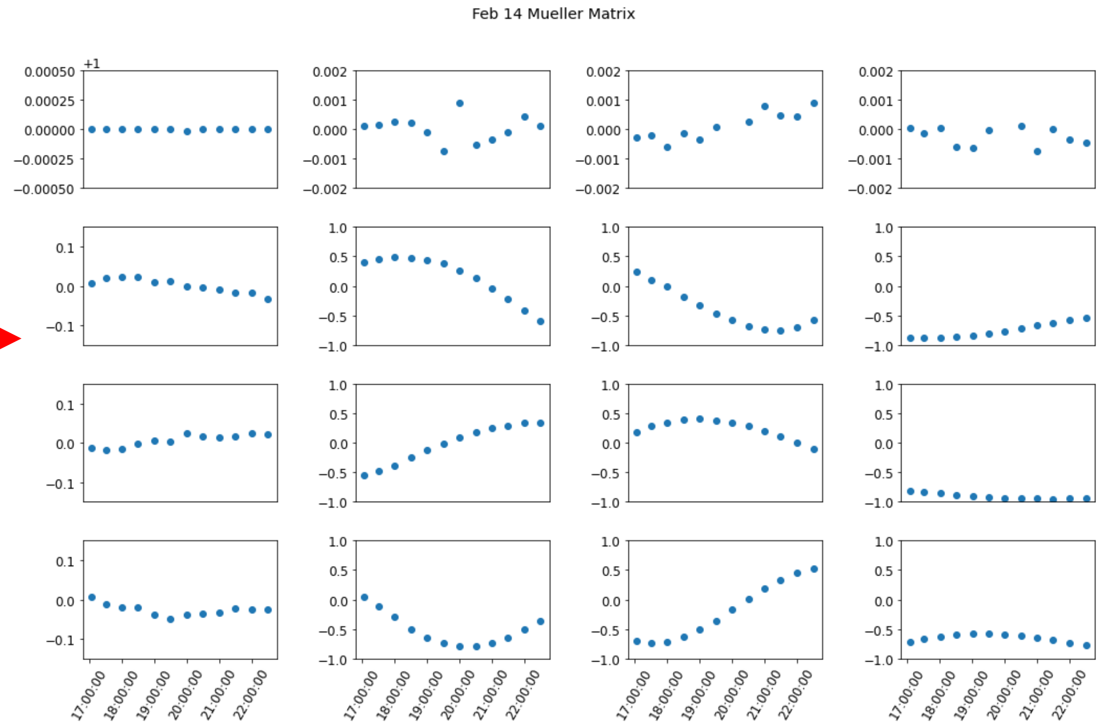
- Fit all these parameters to the measured I, Q, U, V signals (red)

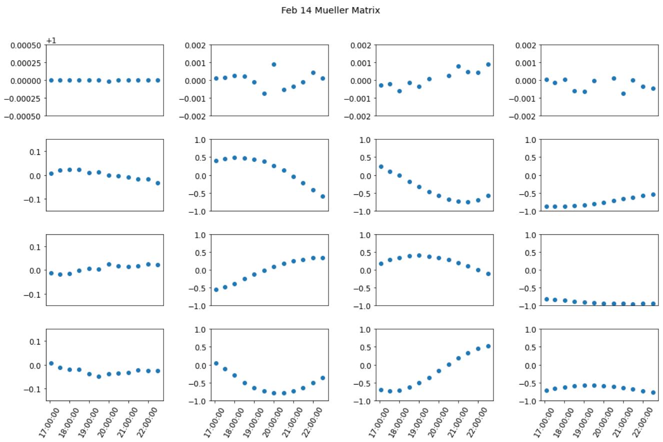
Measuring $\mathbf{M}(\mathrm{HA}, \mathrm{dec}_0)$

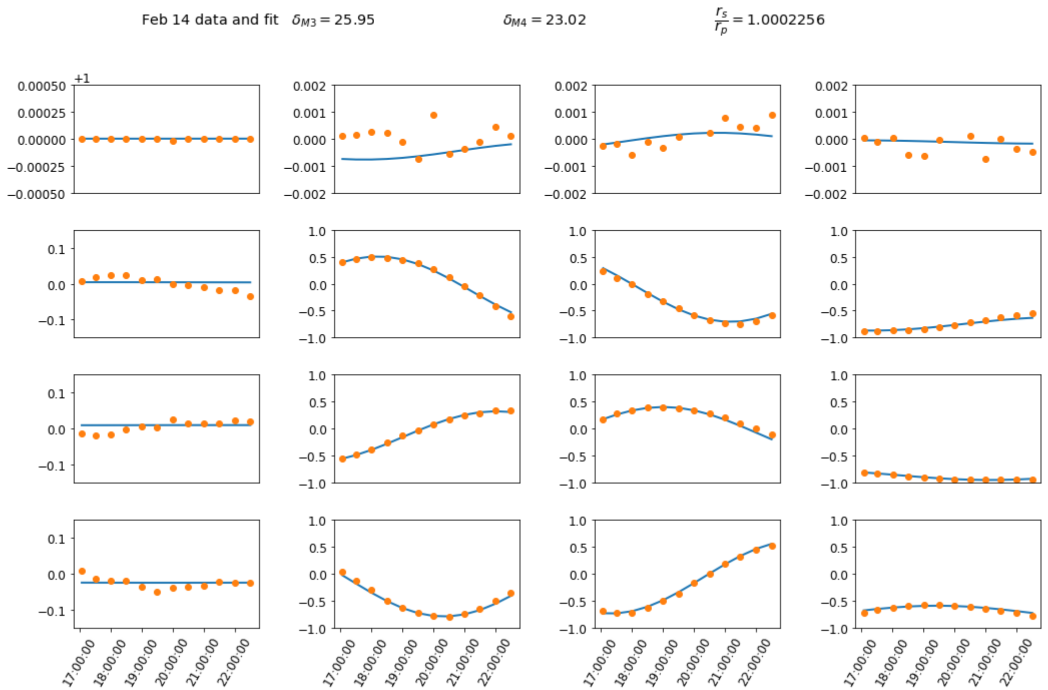




$$\mathbf{M}(\mathrm{HA}, \mathrm{dec}_0) = \mathbf{M}_{\mathrm{rest}}\mathbf{R}(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec}_0)\mathbf{M}_3$$

Measuring $\mathbf{M}(\mathrm{HA}, \mathrm{dec}_0)$

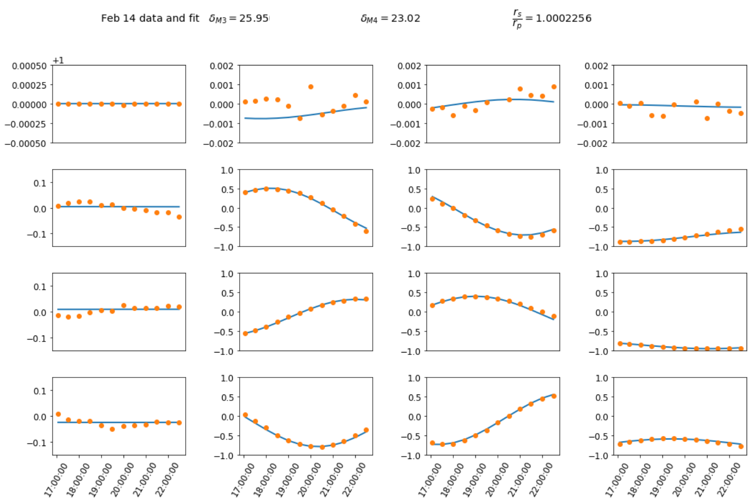


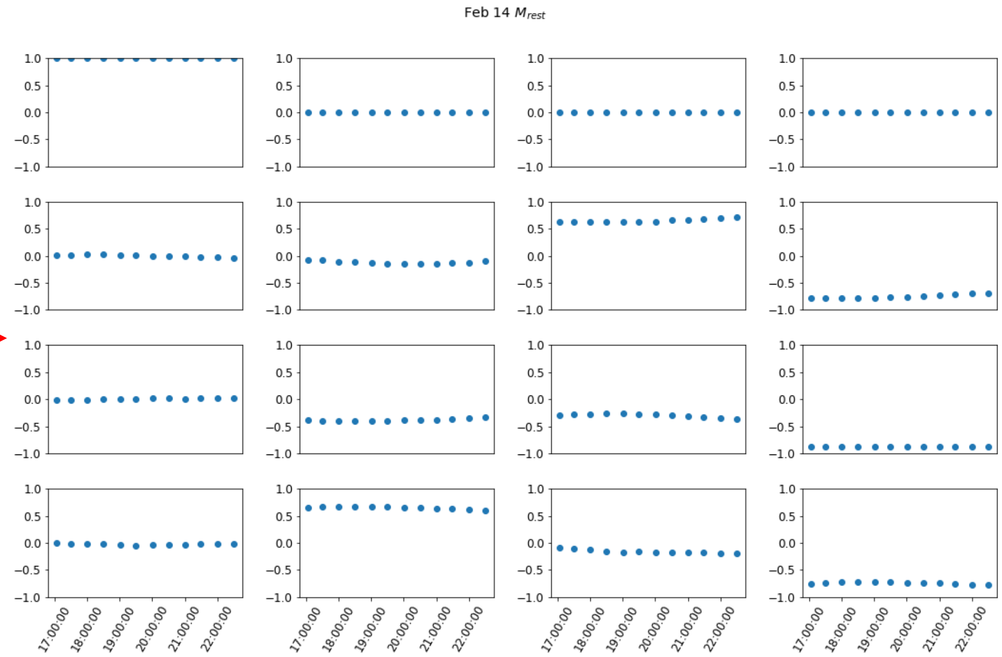


Unknowns:
δ_{M3} surface retardation of M3
δ_{M4} surface retardation of M4
r_s/r_p reflectivity ratio

Fit: minimize variation in $\mathbf{M}_{\mathrm{rest}}$

Finding $\mathbf{M}_{\mathrm{rest}}$





$$\mathbf{M}_{\mathrm{rest}} = \mathbf{M}(\mathrm{HA}, \mathrm{dec}_0)[\mathbf{R}(\mathrm{HA})\mathbf{M}_4\mathbf{R}(\mathrm{dec}_0)\mathbf{M}_3]^{-1}$$

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

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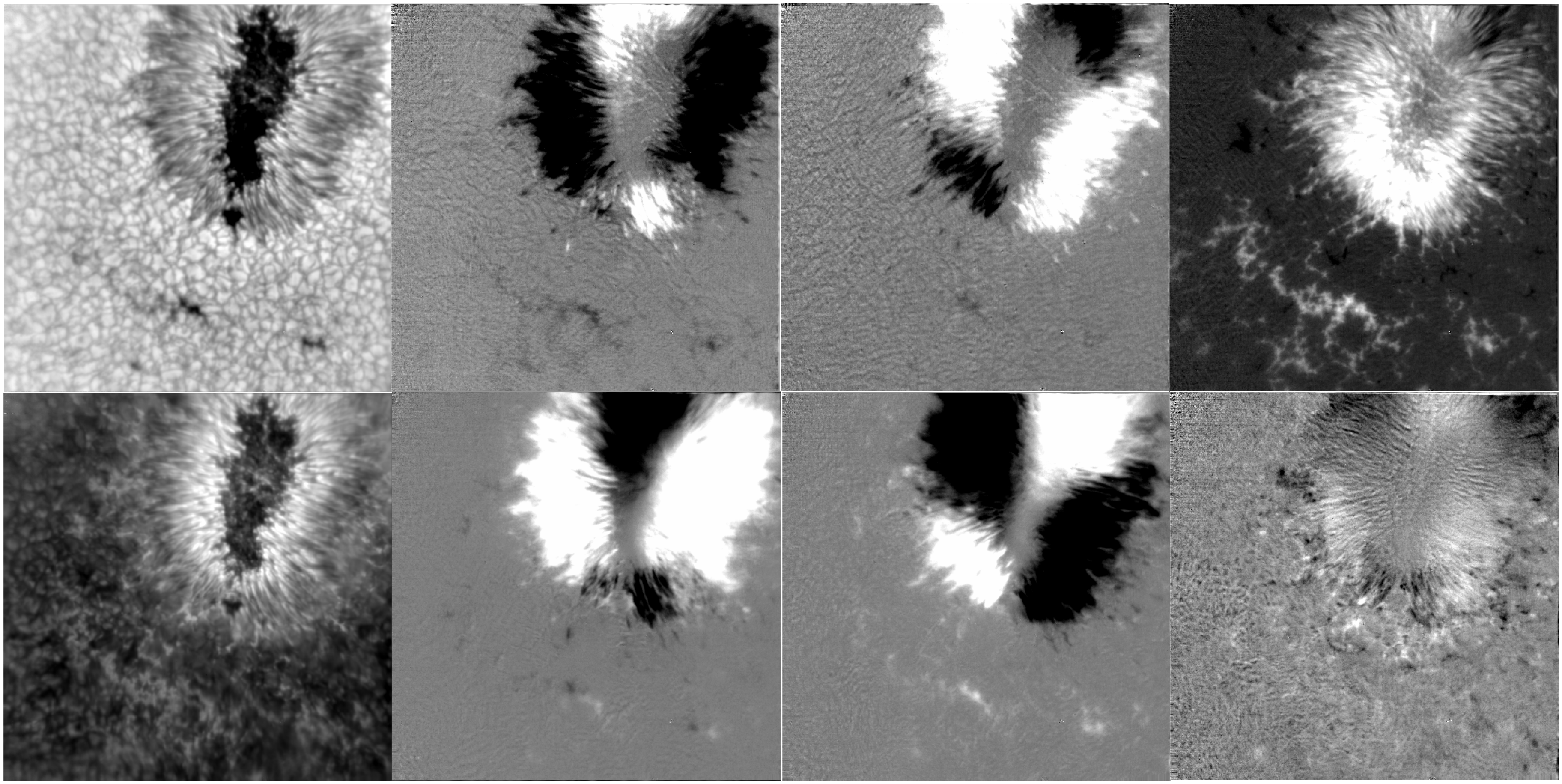
- Apply a different calibration matrix for each observation date/time

2024/05/19 calibrated data

Nearing line center (step 18)

Line center (step 21)



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- 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

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- 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: $\vec{I} \equiv [I, Q, U, V]^T$
  - τ_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:

$$\text{measurements} + \text{instrumental error} \rightarrow \text{physical quantities} + \text{uncertainties}$$

- 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
    - γ Inclination with respect to LOS
    - φ Azimuth
  - Ad hoc variables
    - ξ_{mic} Micro-turbulence velocity
    - ξ_{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!

Afternoon tutorial: applying Mueller calculus

- github.com/taylorbaildon/NIRIS-tutorial
- Jupyter notebook will step you through different Stokes vector transformations
- Brief, self-explanatory – let me know if you need help