可視赤外・サブミリ偏光観測と較正法に関する考察

A Discussion on the Calibration of Polarimetric Observations in the regime of Optical/IR and Submillimeter wavelengths

～可視近赤外偏光観測チュートリアル～

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Polarization of light in mathematics

- Amplitude of electrical field in x− and y−coordinate: E_x, E_y
  - $E_x = A_x \exp\{i(\varepsilon_x + \omega t - 2\pi z/\lambda)\} = A_x e^{i\Phi x}$
  - $E_y = A_y \exp\{i(\varepsilon_y + \omega t - 2\pi z/\lambda)\} = A_y e^{i\Phi y}$
  - Φ_x, Φ_y are the phase at time t and position z
  - Light amplitude is $\sqrt{A_x{}^2 + A_y{}^2}$
  - Phase difference $\gamma \equiv \Phi_y - \Phi_x$
    - $A_x = A_y$ and γ = +90° : right−handed circ.
    - $A_x = A_y$ で γ = −90° : left−handed circ.
    - γ = 0° : lineary pol.
    - Generally, elliptical pol. (180° > γ >0° : right−haned, −180° < γ <0° left−handed)

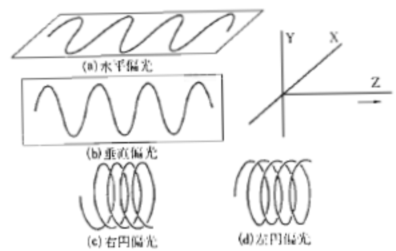


図 1·1 水平に進行する単色光線の瞬間写真

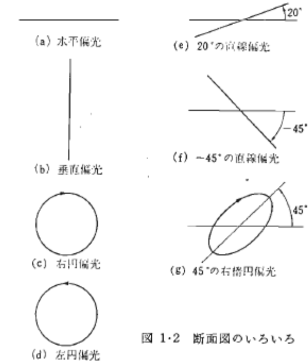


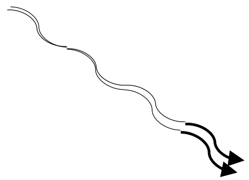
図 1·2 断面図のいろいろ

- Combination of two monochromatic polarization is calculated by simple sum of two monochromatic polarization vectors.
- However, the combination of actual lights (rays) is too complicated to produce meaningful result.

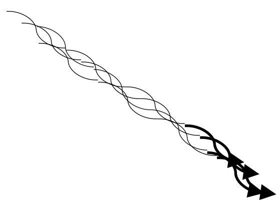
Coherence of light（可干渉性）

Coherent light: A group of rays of which the phases are (nearly) identical

- They can be interfered when they join with a small angle



- When they are not coherent totally, the combination is simple: The sum of intensity.



Combination of rays: More actual ways

- For coherent rays: Stokes vector; Mueller matrix
- For incoherent rays: Jones vector; Jones matrix

Jones vector（1941−）

- Applicable for fully polarized light
- Applicable for coherent lights of which the phases work predominantly

- Two parameters： Orthogonal components of electric field
  - $\begin{pmatrix} E_x \\ E_y \end{pmatrix}$ or $\begin{pmatrix} A_x e^{i(\varepsilon_x + \omega t)} \\ A_y e^{i(\varepsilon_y + \omega t)} \end{pmatrix}$ or $e^{i\omega t}\begin{pmatrix} A_x e^{i\varepsilon_x} \\ A_y e^{i\varepsilon_y} \end{pmatrix}$ or $\begin{pmatrix} A_x e^{i\varepsilon_x} \\ A_y e^{i\varepsilon_y} \end{pmatrix}$

- Intensity is root of sum of squares of E_x and E_y

- Combination of rays is calculated by sum of each parameters as

$$\begin{pmatrix} E_{3x} \\ E_{3y} \end{pmatrix} = \begin{pmatrix} E_{1x} + E_{2x} \\ E_{1y} + E_{2y} \end{pmatrix}$$

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Stokes vector (1852–)

- Applicable for any polarized light; fully/partly polarized, unpolarized
- Applicable for both monochromatic and colored light ⇒ widely usable

- Four Stokes parameters: Each parameter has dimension of intensity (or flux)
  - I : 強度 $= \langle A_x^2 + A_y^2 \rangle$
  - Q : 水平直線優越分($0° - 90°$ 成分) $= \langle A_x^2 - A_y^2 \rangle$
  - U : 45° 直線優越分(直線$45° - 135°$ 成分) $= \langle 2A_xA_y \cos\gamma \rangle$
  - V : 右向き円優越分(右円ー左円成分) $= \langle 2A_xA_y \sin\gamma \rangle$

  $\langle\rangle$ denotes time average

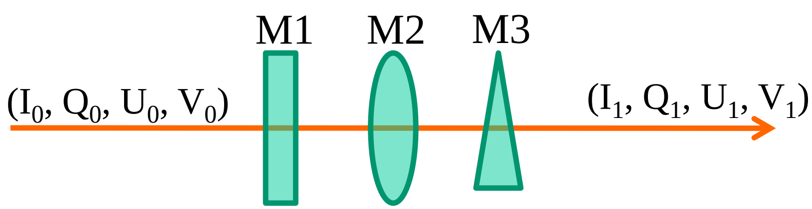
- Stokes parameters are additive
  - Sum of incoherent rays 1 and 2 follows as

$$I_3 = I_1 + I_2,\ \ Q_3 = Q_1 + Q_2,\ \ U_3 = U_1 + U_2,\ \ V_3 = V_1 + V_2,$$

- Usable with Mueller matrices

Mueller matrix (1940’s–)

- 4×4 square matrix： **M**
- Usable with Stokes vector
- Each optical component can be represented by a Mueller matrix



$$\begin{pmatrix} I_1 \\ Q_1 \\ U_1 \\ V_1 \end{pmatrix} = \mathbf{M3}\,\mathbf{M2}\,\mathbf{M1} \begin{pmatrix} I_0 \\ Q_0 \\ U_0 \\ V_0 \end{pmatrix}$$

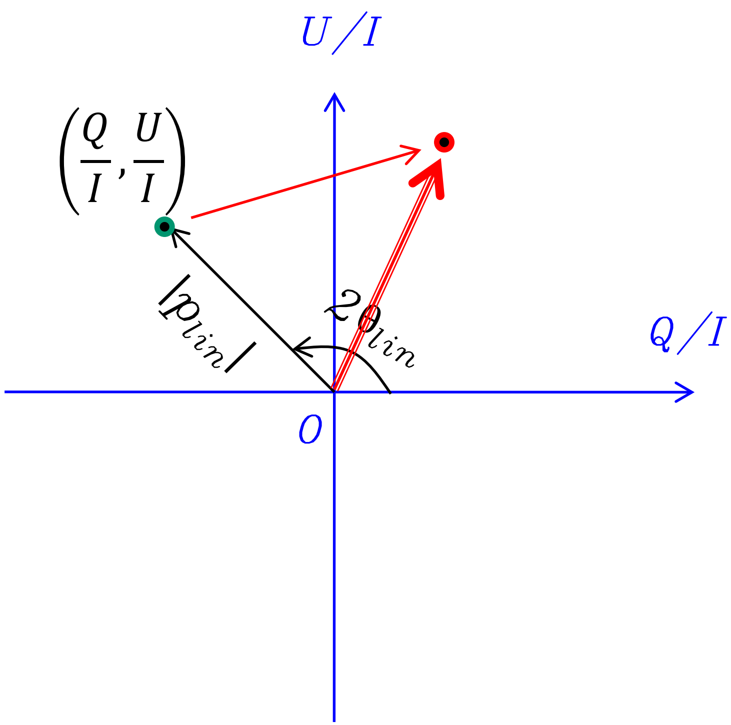
Outgoing ray　　Incident ray

Description of astronomical polarization

- Generally, incoherent, and partly-polarized
- Stokes vectors are useful in many cases

  (Especially, observational astronomy, because it is represented only by intensity/flux dimensions)
- Intensity of unpolarized component I_0、intensity of linearly polarized one I_{lin}、intensity of circularly polarized one I_{circ}
  - $I = I_0 + \sqrt{I_{lin}{}^2 + Icirc^2}$
  - $I_{lin} = \sqrt{Q^2 + U^2}$、$I_{circ} = V$
- Degree of linear polarization p_{lin}、circular p_{circ}
  - $p_{lin} = \frac{I_{lin}}{I}$、$p_{circ} = \frac{I_{circ}}{I}$
- Position angle of linear polarization (polarization angle) θ_{lin}
  - $\theta_{lin} = \frac{1}{2} \arctan\frac{U}{Q}$
- Relational expression
  - $Q = I_{lin} \cos 2\theta$、$U = I_{lin} \cos 2\theta$、$\frac{Q}{I} = p_{lin} \cos 2\theta$、、$\frac{U}{I} = p_{lin} \sin 2\theta$

QU plane (QU diagram)



(Q/I, U/I) plane is also similar to (Q, U) plane for small Q/I, U/I (<0.1).

- Distance from the origin denotes (linear) polarization degree p_{lin}
- Half position angle denotes polarization angle θ_{lin}

$$Q/I = p_{lin}\cos(2\theta_{lin})$$

$$U/I = p_{lin}\sin(2\theta_{lin})$$

- Vectorial summation is visually (easily) recognizable

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Principle polarimetry in Opt/NIR regime

Principal mechanism of polarization 1

双極子散乱

入射光により電気振動子が励起されて放射

- 電子散乱
- レイリー散乱
- ミー散乱
- 反射・屈折

（入射光との合成・干渉； マクスウェル方程式と界面での接続条件でも解ける）

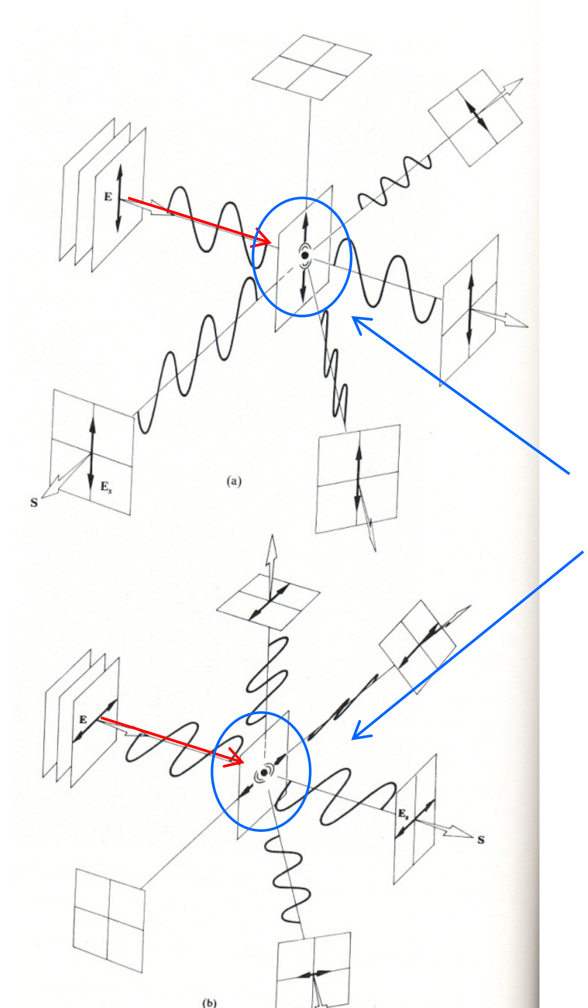
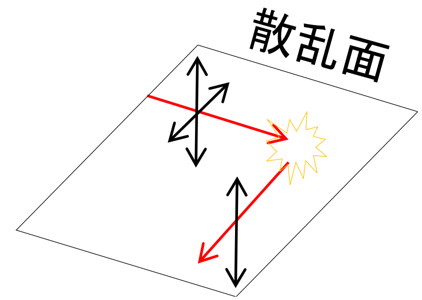


Fig. 8.36 Scattering of polarized light by a molecule.

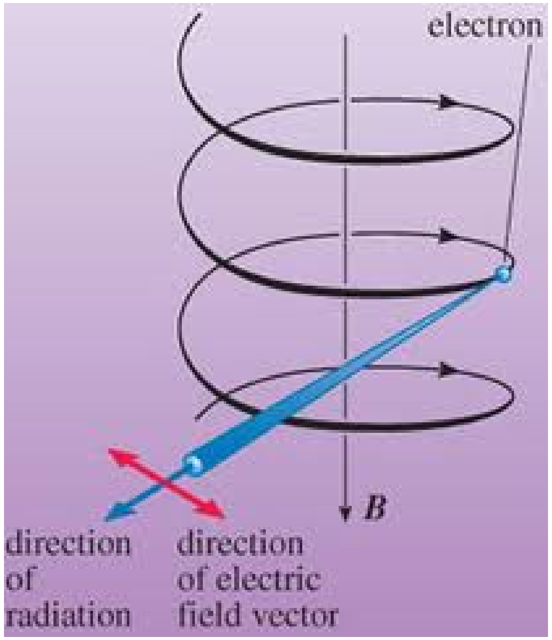


散乱面に垂直な方向に偏光

Principal mechanism of polarization 2

シンクロトロン放射

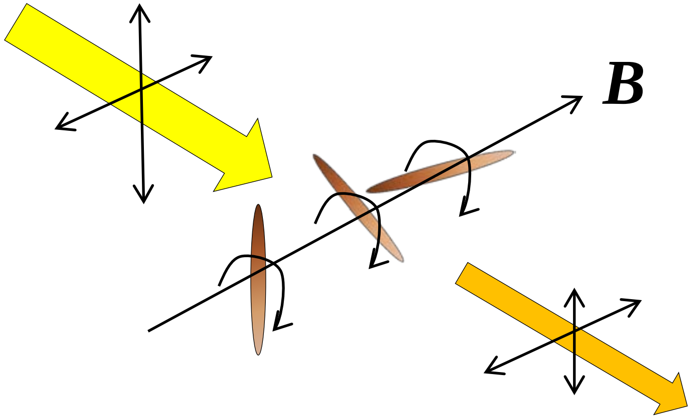
磁場中をらせん状に動く電子により放射（サイクロトロン放射の相対論的電子版; 高周波による連続光）



磁場に垂直な方向に偏光

星間偏光（ミー散乱）

（銀河磁場等により）整列した非球状粒子による選択吸収（dichroism）



透過光は磁場に平行な方向に偏光

Optical component for polarimetry

- Polarizer (polarizing filter)
  - Only a linearly polarization component transmits (polyvinyl, wiregrid, liquid crystal, etc)
  - Another (orthogonally polarized) component is absorbed or reflected.
- Polarizing beam splitter
  - Two orthogonally polarized lights are transmitted (or reflected) to different direction.
- Wave plate (retarder, modulator)
  - Producing a difference of the phases (= retardance) for two orthogonally polarized lights after transmission of birefringent material(複屈折製結晶)

Example of beam splitter

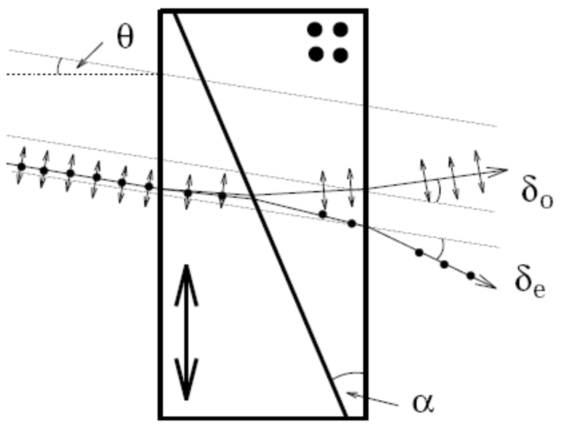


Fig. 1. Schematic representation of a Wollaston prism and ray–tracing (adapted from Fig. 11 of Bennet 1995)

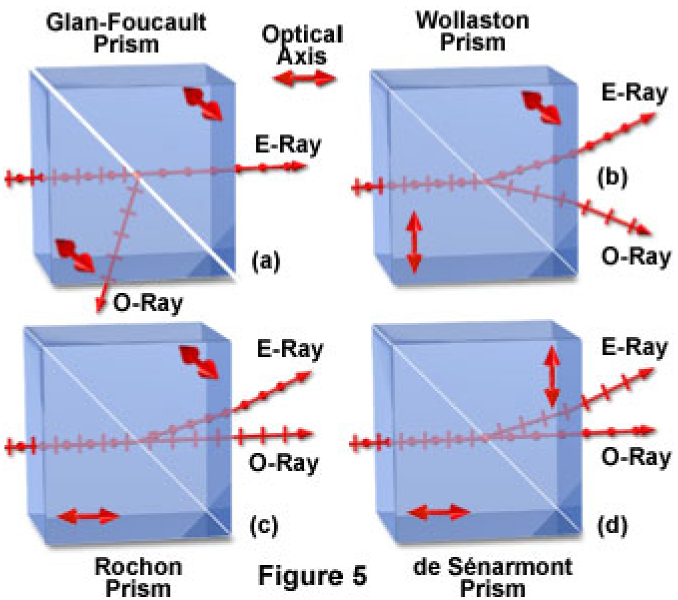


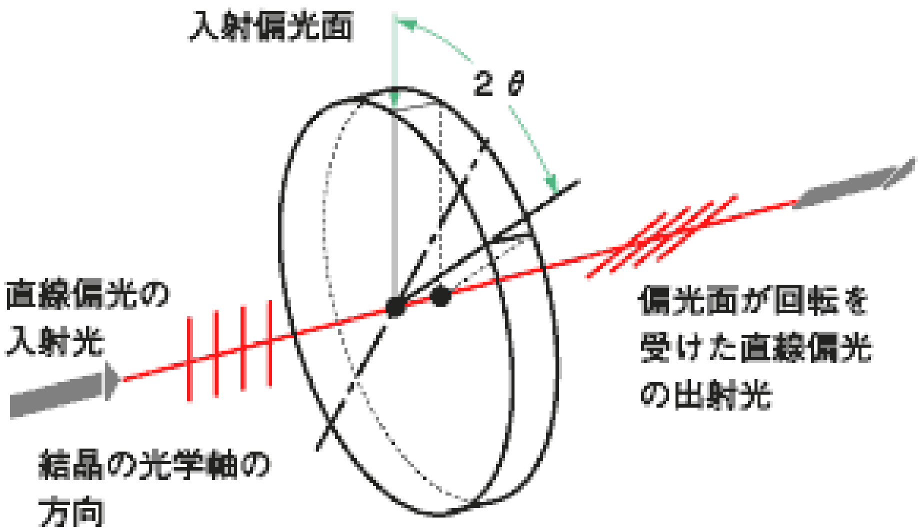
Figure 5

- Wollaston/Rochon prism: Separation angle of o- and e-rays are small
- Glan prism: Separation angle is nearly ~90 degs (completely separated)

Half-wave plate（λ/2 波長板）

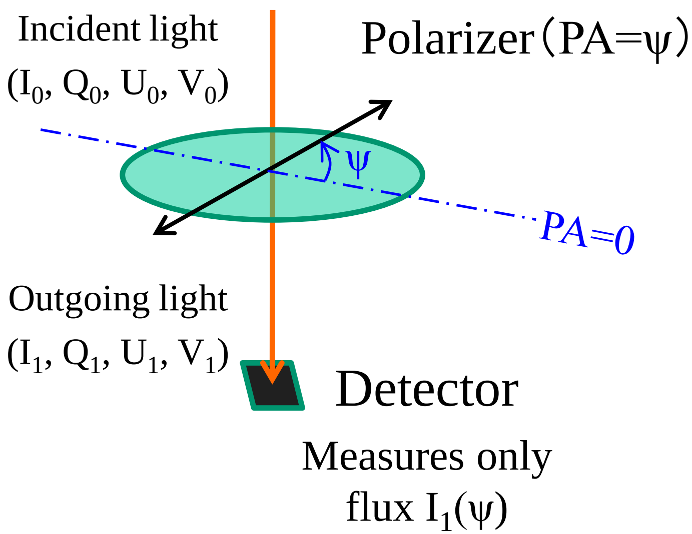
A half-wave plate at position angle θ makes rotation of position angle by 2θ without any change of degree of polarization.

Rotation of a half-wave plate at the entrance of and astronomical instrument corresponds to the rotation of the instrument.



A most simple (linearly) polarimetry

From telescope

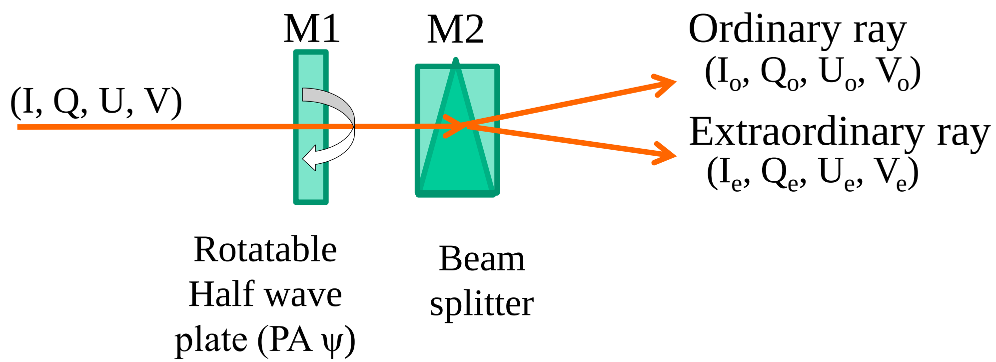


$$\frac{Q_0}{I_0} = \frac{I_1(0°) - I_1(90°)}{I_1(0°) + I_1(90°)}$$

$$\frac{U_0}{I_0} = \frac{I_1(45°) - I_1(135°)}{I_1(45°) + I_1(135°)}$$

- Since it measures flux ratio, some incompleteness of the system (cross-talk of polarizer, etc.) are canceled
- But, since it requires a few different exposures, the result is subject to the time variation of atmospheric condition and error of telescope guiding.

A better method for linear polarimetry



Different efficiency for o- and e-rays within instrument

Variability due to atmospheric condition

$$I_o(\psi) = I/2 \cdot \{1 + Q/I \cos(4\psi) + U/I \sin(4\psi)\} \cdot k_o \cdot \kappa(t)$$
$$I_e(\psi) = I/2 \cdot \{1 - Q/I \cos(4\psi) - U/I \sin(4\psi)\} \cdot k_e \cdot \kappa(t)$$

$$a_1 = \sqrt{\frac{I_e(0°)}{I_o(0°)} \Big/ \frac{I_e(45°)}{I_o(45°)}}, \quad a_2 = \sqrt{\frac{I_e(22.5°)}{I_o(22.5°)} \Big/ \frac{I_e(67.5°)}{I_o(67.5°)}}$$

k_o and k_e are canceled
$\kappa(t)$ is also canceled

$$\frac{Q}{I} = \frac{1 - a_1}{1 + a_1} \qquad \frac{U}{I} = \frac{1 - a_2}{1 + a_2}$$

•偏光に依存する透過効率ko, keや大気透過率κ(t)が打ち消せるため、高精度が得やすい

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Calibration for Opt/NIR Polarimetry

- Instrumental polarization(軸対象な望遠鏡焦点では0.01–1%)
  - 望遠鏡や観測装置内部の軸対称性のずれなどで生じる偏光
  - 無偏光標準星(ゼロ偏光)の観測で器械偏光のストークスベクトルを求め、差し引く
- Instrumental depolarization (~polarization efficiency factor)
  - 光学系の不完全性(位相のずれ、直線ー円偏光変換、散乱光等)による「消」偏光
  - 偏光板、偏光プリズムを用いて(ノミナル)100%偏光を入射し、測定、および補正
- Origin and direction of PA of polarization
  - 強偏光標準星(星間偏光)を観測し、方位角原点を補正
  - 波長板を回す観測の場合、天球面に対する回転方向の自由度が出るので、(少なくとも最初は)2つの異なる標準星の観測をするのが良い
- Calibrator
  - Polarizer (producing nominal 100% polarization)
  - Standard stars (interstellar, highly-polarized; nearby normal star, unpolarized)

Typically $p/\Delta p > \sim 10$

Subaru/FOCAS Polarimetric performance 1/2

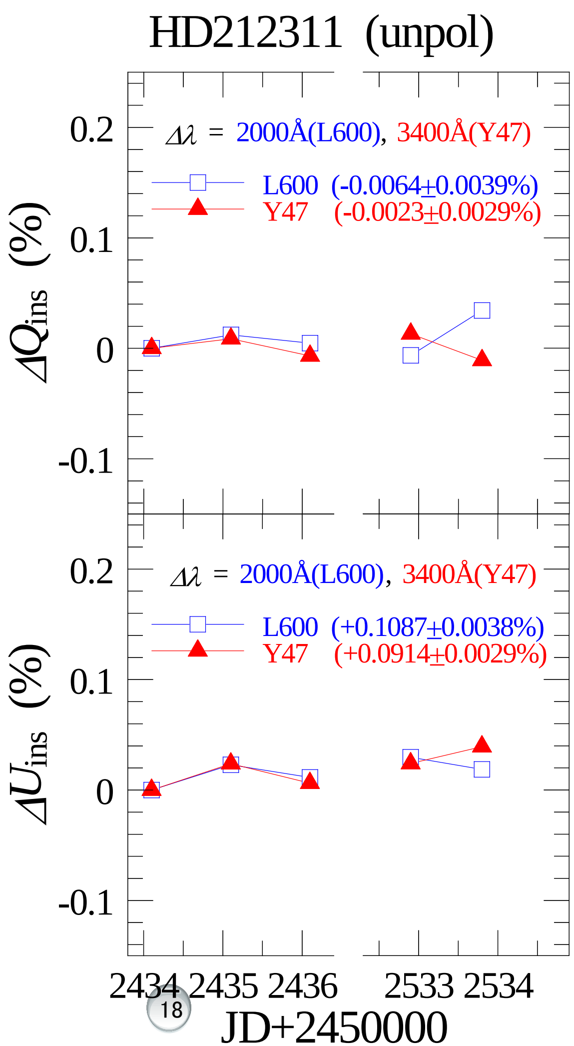
器械偏光の安定性

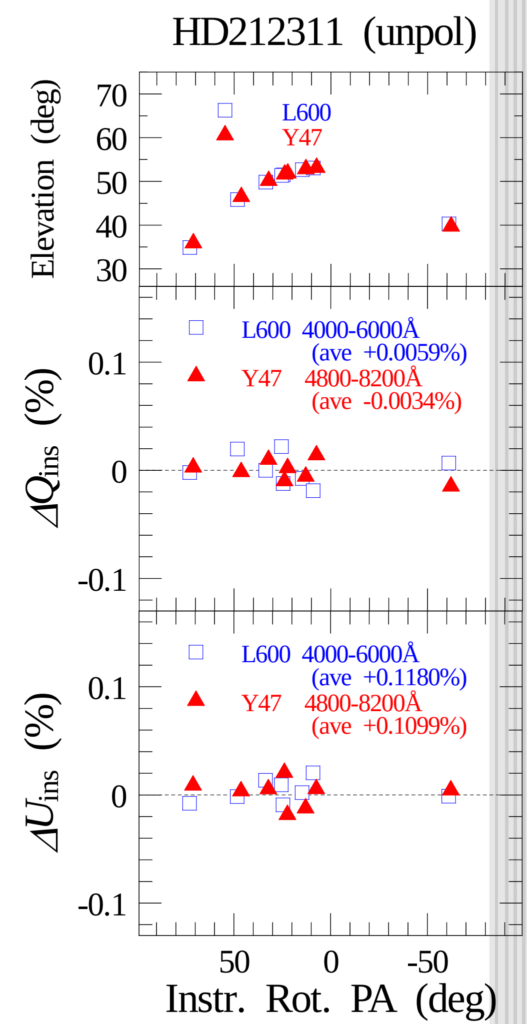
Dp_{instr} < 0.05 % at any position within FOV independently of

- telescope position,
- PA of image rotator,
- with or w/o ADC,

etc.

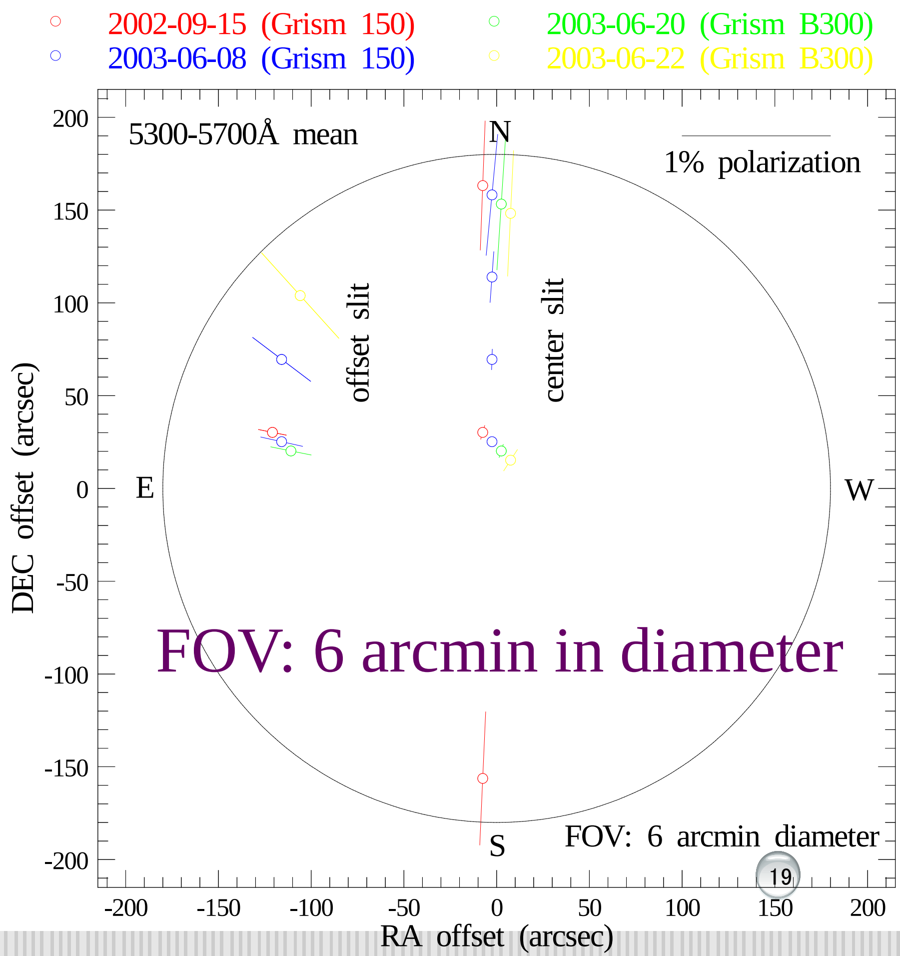
ADC = Atmospheric Dispersion Corrector





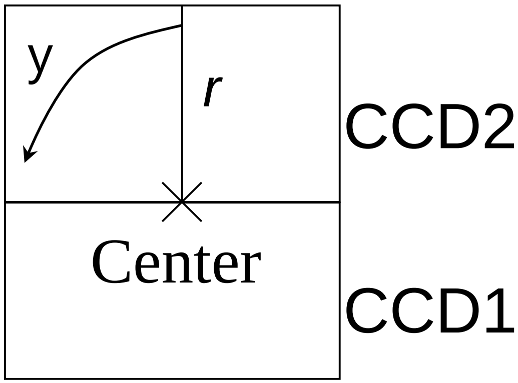
Subaru/FOCAS Polarimetric performance 2/3

◆ 視野内の器械偏光のラジアル・パターン



p_{instr} prop.to r^{-b}, b~4

PA_{instr} ~ y



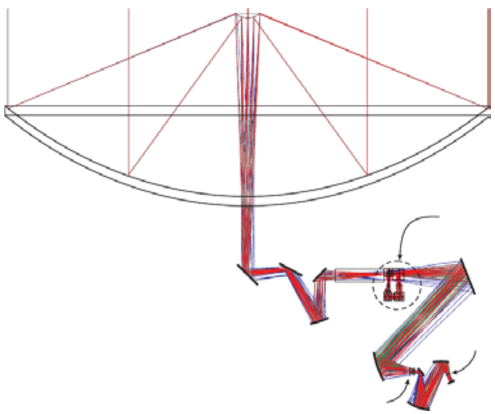
p_{instr} ~ 0.05 % at center of FOV

p_{instr} ~ 0.9 % at r = 2.5 arcmin

Any position, Dp_{instr} < 0.05 %

Application for JCMT/SCUBA2-Pol

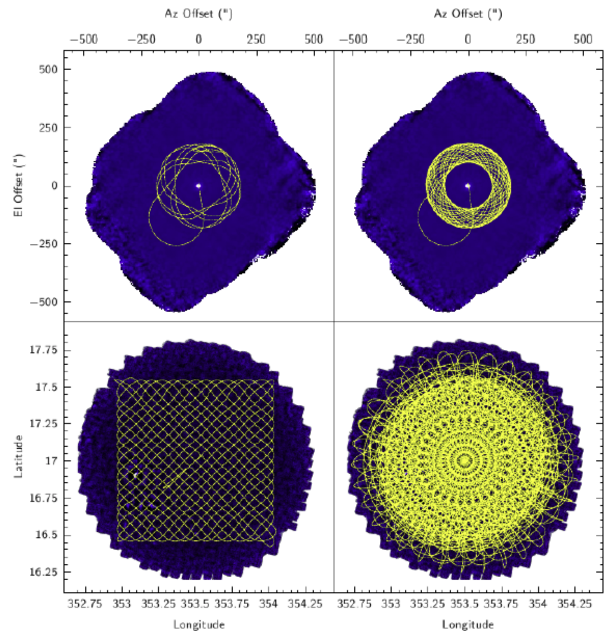
Holland+ 2013
Leclerc+ 2015



非軸対象の反射系

→望遠鏡の向きに応じた器械偏光

Scan pattern of sky



半波長板を回転させながら望遠鏡を動かし続けて一定領域をスキャン

$$I_o(\psi) = I/2 \cdot \{1 + Q/I\ \cos(4\psi) + U/I\ \sin(4\psi)\} \cdot k_o \cdot \kappa(t)$$

$\psi \rightarrow \psi, t$　器械偏光（＋ほかの偏光）の依存性が複雑に

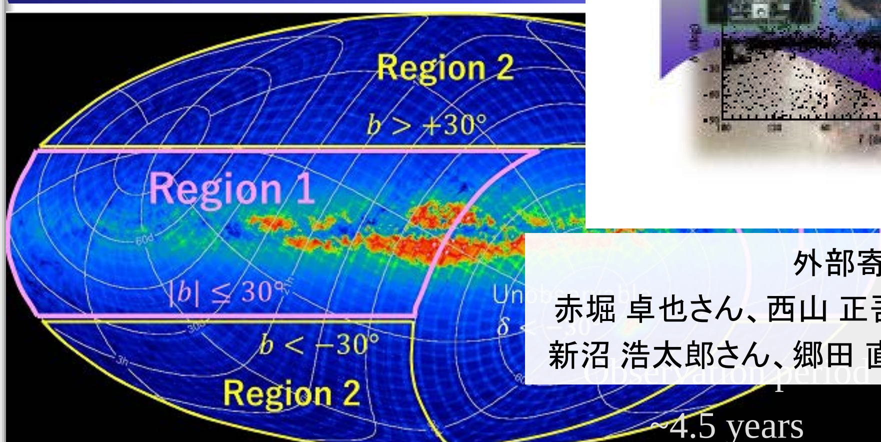
SGMAP: Optical Polarimetry Survey Project

Search for Galactic Magnetic-field by All-sky Polarimetry Survey

Using a dedicated 1m … ed telescope and an optical 2-band (g' … imeter

Several million stars … 0°) will be surveyed in optical 2 bands simul…

First homogeneous p… (in northern hemisphere)



…e optical polarimetric data may …e to estimation/masking of fore- …terstellar polarization in CMB B-mode study. And also other fruitful collaborative studies (interstellar matter, etc.) are expected.

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Summary

- Stokes vectors can treat incoherent light.
- Each Stokes parameter is additive.
- Most Opt/NIR polarimetry is performed for \`relative photometry' for artificially polarization-modulated light.
- Typical accuracy of Opt/NIR polarimetry is <~0.1% in case of using beam-splitter and axi-symmetric optics