# Modeling geometrical and intensity distortions for WALOP


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**Abstract**

Cold dust grains align such that the shorter axis is along the direction of galactic magnetic field. This causes polarized(along longer axis) emission(black body) also in the range of cosmic microwave background(CMB), eventually contaminating primordial CMB B-mode polarization data. We need to know the galactic magnetic field for modeling decorrelations of dust emission for different frequency.

Star lights are intrinsically unpolarized but when transmitted through dust clouds, gets selectively polarized along shorter axis of grains(directly leading us to direction of magnetic field). We plan to measure star light polarization in optical region. Every optical instruments are anisotropic to some extent that introduces further polarization. Measurement of polarization has evolved into a separate challenge, as we are dealing with very low degree of polarization($\leq 2\%$). Here I present methods for accounting the instrumental polarization and correcting starlight polarization.


## Science Goals

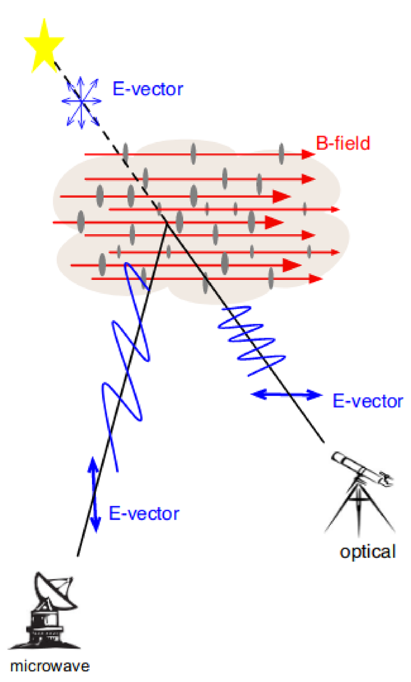


**Figure 1:** The same dust grain that radiates polarized emission in CMB region induces starlight polarization in optical region. Dust grains align their short axis with the direction of the magnetic field.

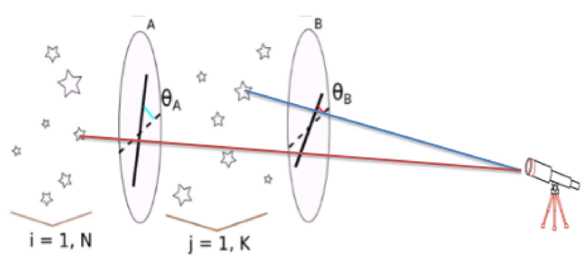


**Figure 2:** With distance information we can deduce direction of ISM magnetic field in sky plane in presence of dust clouds.

## Stokes Parameters

The Stokes parameters are a set of values that describe all polarization states of electromagnetic radiations.

**Why use Stokes parameters instead of polarization ellipse?**

- Relates polarization states by observable quantities that is intensities.
- Can demonstrate partially polarized light unlike the usual polarization ellipse conventions.
- Equally efficient for incoherent lights.
- Can also deal with quantum nature of light.

Stokes Parameters$(I, Q, U, V)$ are measured as following.

$$I = I_{0^\circ} + I_{90^\circ}$$

$$Q = I_{0^\circ} - I_{90^\circ} = Ip\cos(2\psi)\cos(2\chi)$$
$$U = I_{45^\circ} - I_{135^\circ} = Ip\sin(2\psi)\cos(2\chi)$$
$$V = I_{RCP} - I_{LCP} = Ip\sin(2\chi)$$

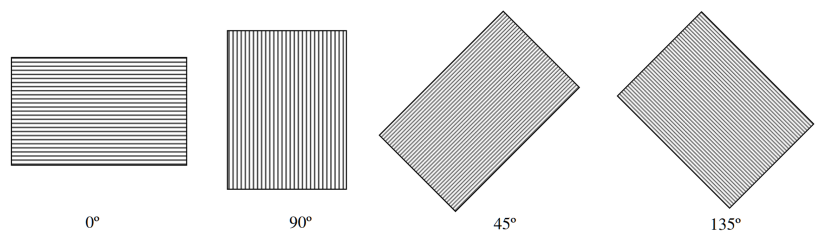


**Figure 3:** Measuring Stokes parameters using simple polarizer.

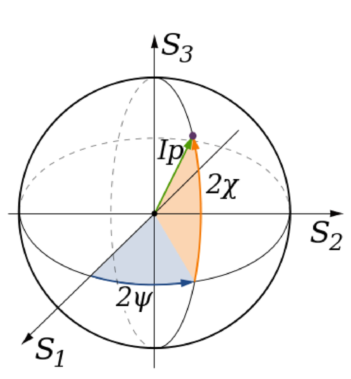


**Figure 4:** Stokes vector in Poincare sphere $(S_0, S_1, S_2, S_3) = (I, Q, U, V)$.

Here $I_{angle}$ are intensity measures for the corresponding (angle with positive x axis) plane of polarization. $I_{RCP}$ and $I_{LCP}$ are intensity measured for right circular and left circular polarization respectively. $p$ is degree of polarization and $\psi$ is angle of polarization. We rarely confront circular polarization for star lights.

$$p = \frac{\sqrt{Q^2 + U^2}}{I} = \sqrt{q^2 + u^2}$$

$$\psi = \frac{1}{2}\tan^{-1}\frac{u}{q}$$

## Polarimeters

Measuring starlight polarization($\leq 2\%$) in a very challenging task. We use four channel polarimeters that give $q$ and $u$ in one shot. Wollaston prisms are generally used to separate E-rays and O-rays(fig 5). Here I brief nature of polarimeters.

## Four Channel Polarimeters

- Uses two Wollaston prism with axis perpendicular to each other.
- Uses two half wave plates already rotated by $22.5^\circ$ to rotate light wave by $45^\circ$ .
- Gives $u$ and $v$ in one shot.
- None of the components are moving, reduces errors in measurement.

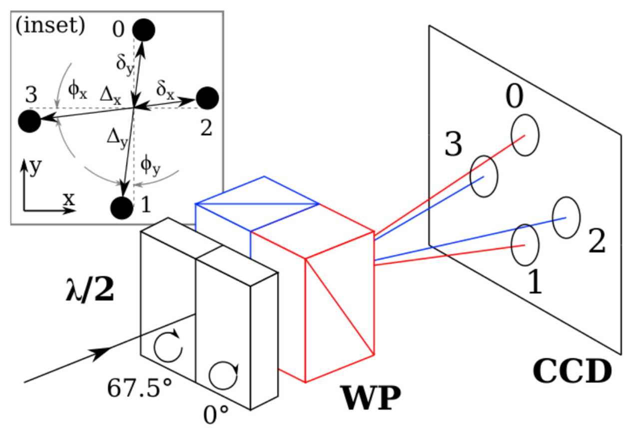


**Figure 5:** RoboPol: A four channel polarimeter.

## Pasiphae WALOP

PASIPHAE (Polar-Areas Stellar-Imaging in Polarization High-Accuracy Experiment) aims to map, with unprecedented accuracy, the polarization of millions of stars at areas of the sky away from the Galactic plane, in both the Northern and the Southern hemispheres.

- Upgraded version of RoboPol, designed to make a survey of whole sky.
- Will be mounted on the 1.3 m telescope of the Skinakas observatory in Crete, Greece.
- Polarimeter split angle is about $15^\circ$. So we need four CCDs to image.
- **High sensitivity:** The 4-CCD design splits the sky background to four (as is done for the light from point sources), increasing the photometric signal-to-noise ratio over the single-CCD design.
- **Large field of view:** $30' \times 30'$ (0.25 square degrees per exposure), enabling a wide-field survey.
- One will be installed at the Skinakas 1.3 m telescope and the other at South African Astronomical Observatory(SAAO)'s 1m telescope.

$$q = \frac{N_0 - N_1}{N_0 + N_1}, u = \frac{N_2 - N_3}{N_2 + N_3}$$

$$\sigma_q = \sqrt{\frac{4(N_1^2\sigma_0^2 + N_0^2\sigma_1^2)}{(N_0 + N_1)^4}}, \sigma_u = \sqrt{\frac{4(N_3^2\sigma_2^2 + N_2^2\sigma_3^2)}{(N_2 + N_3)^4}}$$

where $N_0, N_1, N_2, N_3$ are the intensities of the upper, lower, right and left spots and $\sigma_0, \sigma_1, \sigma_2, \sigma_3$ are their uncertainties.

## WALOP: Spatial Model

The spatial model predicts the actual location of the four spots on the CCD, given their location on CCD$(x', y')$. This model tries to model geometrical distortions introduces by instrument.

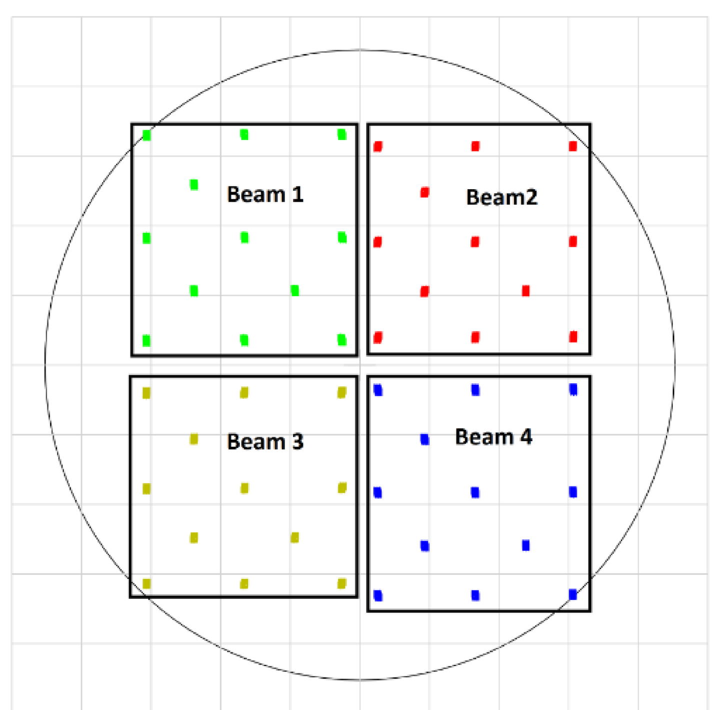


**Figure 6:** WALOP: 4-beams on 4-CCDs

- Modeled with 4-D general polynomials.
- $x = f_x(x', y')$
- $y = f_y(x', y')$
- $error = |\vec{r}_{\text{data}} - \vec{r}_{\text{model}}|$
- Used ensemble and cross matching techniques to create 4000 data points.
- Used Stochastic Gradient Descent Method(SGDM) to minimize the cost function.

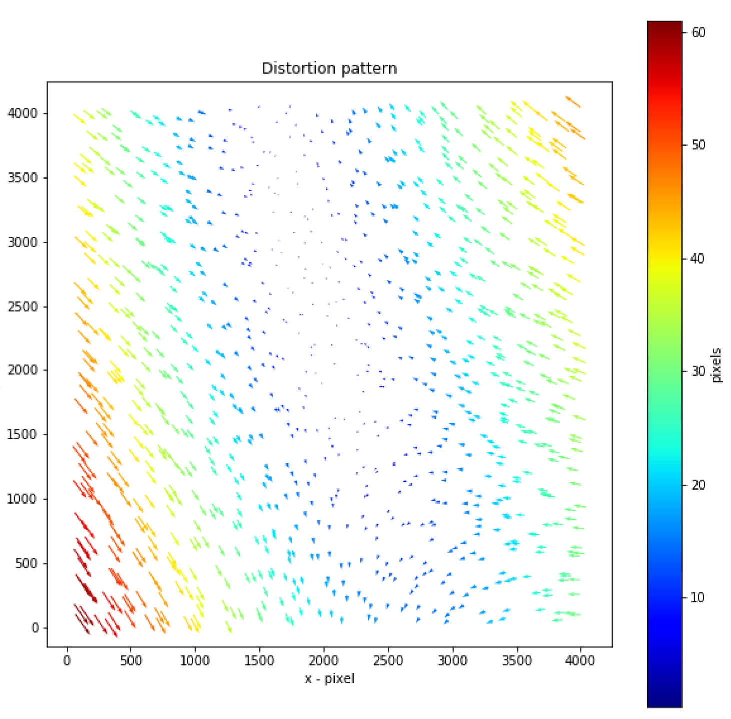


**Figure 7:** Spatial distortion map for WALOP output(beam-1).

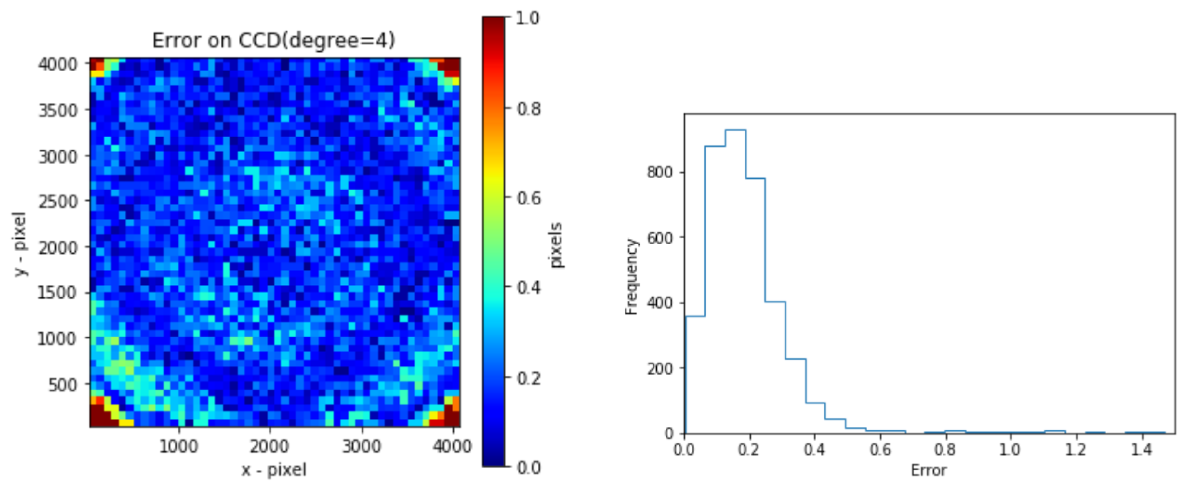


**Figure 8:** Left: Errors in predicting real coordinates. Right: Histogram of errors. Errors are less then 0.5 pixel except for corners.

## WALOP: PSF Modeling

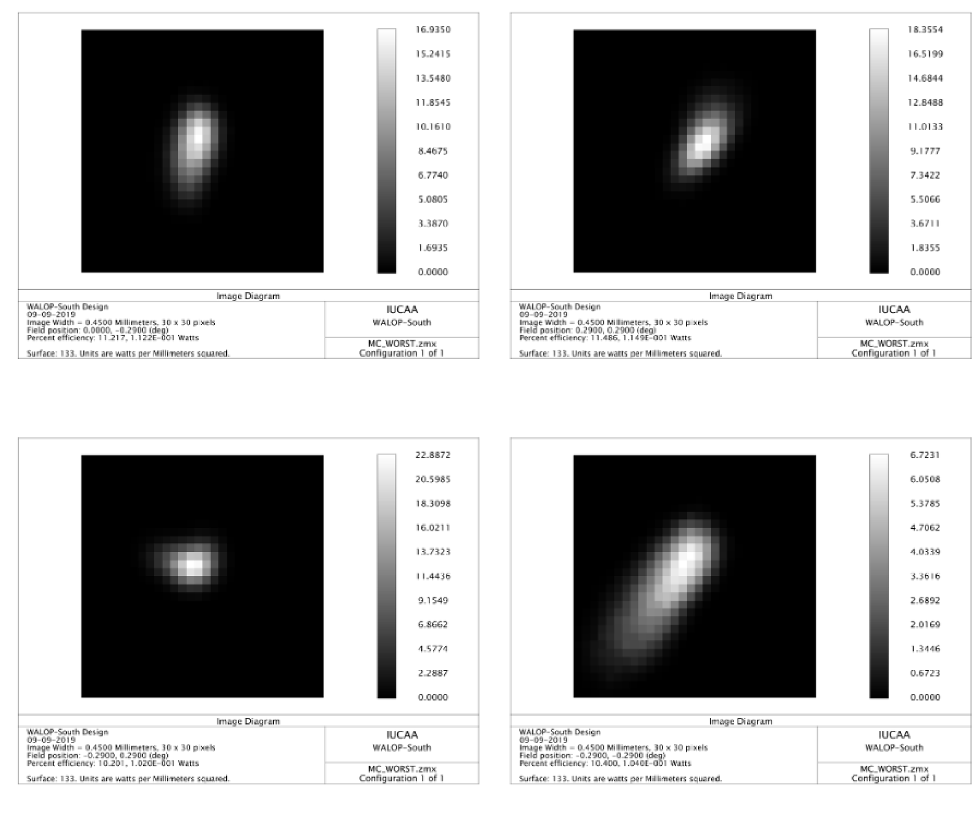

**Figure 9:** Some PSF from WALOP Zemax simulation for various field of view.

## Polar Shapelets

- $PSF(r, \varphi) = \sum_{n=0}^{n=\infty}\sum_{m=-n}^{m=n} b_{n,m}\chi_{n,m}(r, \varphi; \beta)$
- $b_{n,m} = \iint_R PSF(r, \varphi)\chi_{n,m}(r, \varphi; \beta)drd\varphi$
- $\chi_{n,m}(r, \varphi; \beta) = \frac{(-1)^{\frac{n-|m|}{2}}}{\beta^{|m|+1}}\left[\frac{\left(\frac{n-|m|}{2}\right)!}{\pi\left(\frac{n+|m|}{2}\right)!}\right]^{\frac{1}{2}} \times r^{|m|}L_{\frac{n-|m|}{2}}^{|m|}\left(\frac{r^2}{\beta^2}\right)\exp\left(\frac{-r^2}{2\beta^2}\right)\exp(im\varphi)$
- $L_x^k(x) = \frac{1}{x!}\sum_{i=0}^{i=x}\frac{x!}{i!}\left({}^{k+x}C_{n-i}\right)(-x)^i$
- Overlap integral can be solved simply by matrix multiplication.
- This formalism does not involves any kind of fitting so it can also run in parallel.

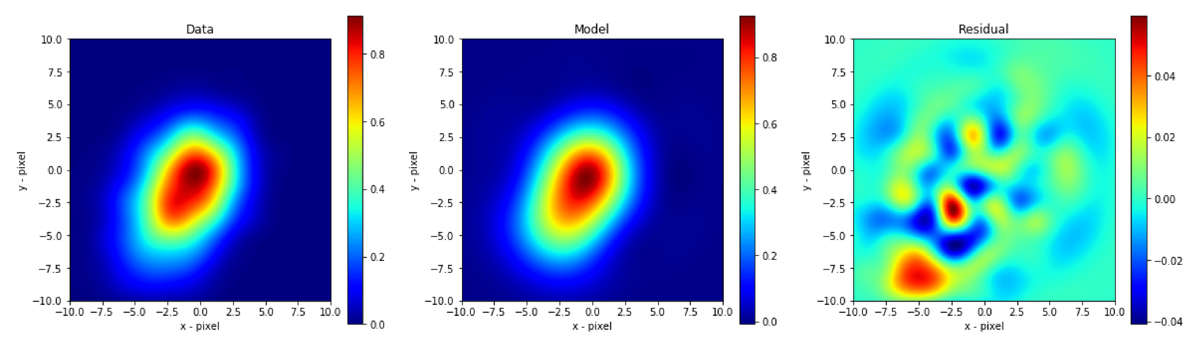


**Figure 10:** Modeling one of the field of view PSF with polar shapelets

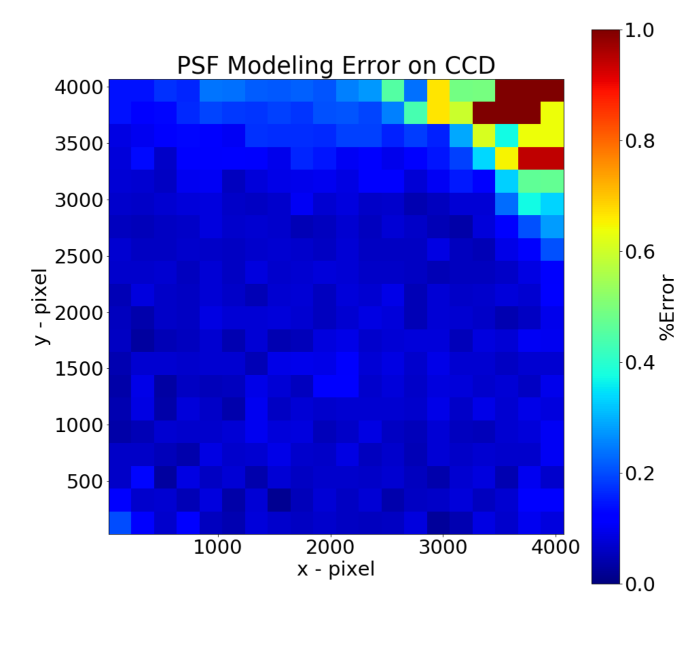


**Figure 11:** Volume error in PSF modeling on CCD.

## Forthcoming Research

My future plan is to contribute pipeline code for WALOP polarimeters,

What pipeline can do?

- Perform a high accuracy photometry.
- Account for geometrical and intensity distortions and correct them.
- Operate the instrument independently.
- Take CCD image as the raw data and gives Stokes parameters after correcting all distortions.

## References


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[2] "Wollaston prism". AMS Glossary. Retrieved 2013-04-29.

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[4] PASIPHAE: A high-Galactic-latitude, high-accuracy optopolarimetric survey https://arxiv.org/pdf/1810.05652.pdf