Polarization calibration using pulsar

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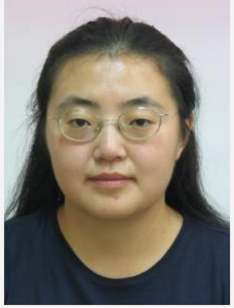

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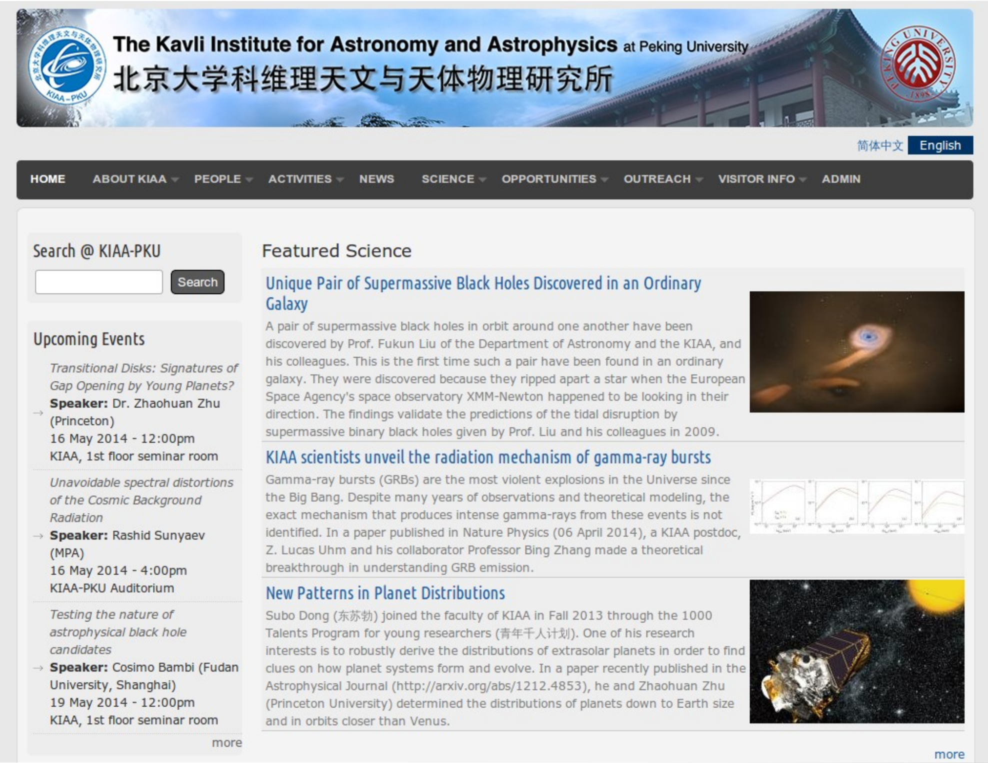
KIAA in PKU

- 44 graduate students, may increase to 75
- 120 top undergraduate students in China
- Collaborating or seeking collaboration with other astronomical research facilities in China, which are leading radio and long-wavelength projects in China.
- Seek for a broader international collaboration
- Provide research and educational opportunities

http://KIAA.pku.edu.cn



The Kavli Institute for Astronomy and Astrophysics at Peking University
北京大学科维理天文与天体物理研究所

Upcoming Events

Transitional Disks: Signatures of Gap Opening by Young Planets?
Speaker: Dr. Zhaohuan Zhu (Princeton)
16 May 2014 - 12:00pm
KIAA, 1st floor seminar room

Unavoidable spectral distortions of the Cosmic Background Radiation
Speaker: Rashid Sunyaev (MPA)
16 May 2014 - 4:00pm
KIAA-PKU Auditorium

Testing the nature of astrophysical black hole candidates
Speaker: Cosimo Bambi (Fudan University, Shanghai)
19 May 2014 - 12:00pm
KIAA, 1st floor seminar room

more

Featured Science

Unique Pair of Supermassive Black Holes Discovered in an Ordinary Galaxy

A pair of supermassive black holes in orbit around one another have been discovered by Prof. Fukun Liu of the Department of Astronomy and the KIAA, and his colleagues. This is the first time such a pair have been found in an ordinary galaxy. They were discovered because they ripped apart a star when the European Space Agency's space observatory XMM-Newton happened to be looking in their direction. The findings validate the predictions of the tidal disruption by supermassive binary black holes given by Prof. Liu and his colleagues in 2009.

KIAA scientists unveil the radiation mechanism of gamma-ray bursts

Gamma-ray bursts (GRBs) are the most violent explosions in the Universe since the Big Bang. Despite many years of observations and theoretical modeling, the exact mechanism that produces intense gamma-rays from these events is not identified. In a paper published in Nature Physics (06 April 2014), a KIAA postdoc, Z. Lucas Uhm and his collaborator Professor Bing Zhang made a theoretical breakthrough in understanding GRB emission.

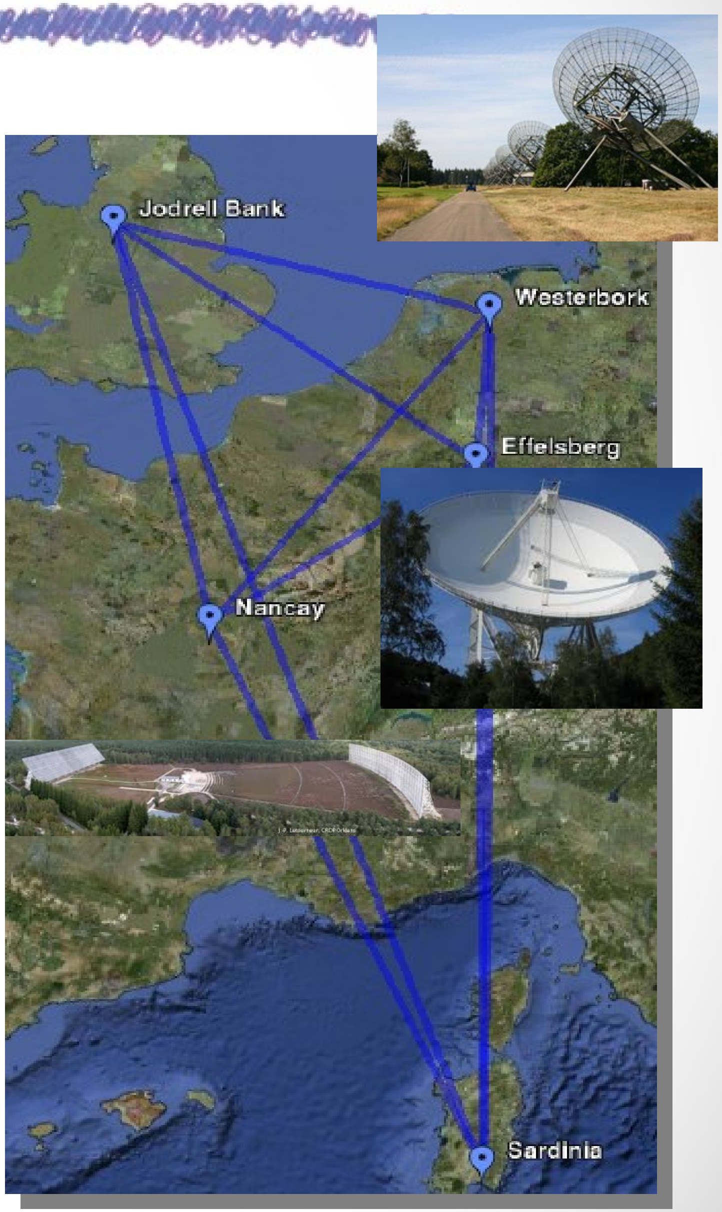
New Patterns in Planet Distributions

Subo Dong (东苏勃) joined the faculty of KIAA in Fall 2013 through the 1000 Talents Program for young researchers (青年千人计划). One of his research interests is to robustly derive the distributions of extrasolar planets in order to find clues on how planet systems form and evolve. In a paper recently published in the Astrophysical Journal (http://arxiv.org/abs/1212.4853), he and Zhaohuan Zhu (Princeton University) determined the distributions of planets down to Earth size and in orbits closer than Venus.

more

Polarization calibration

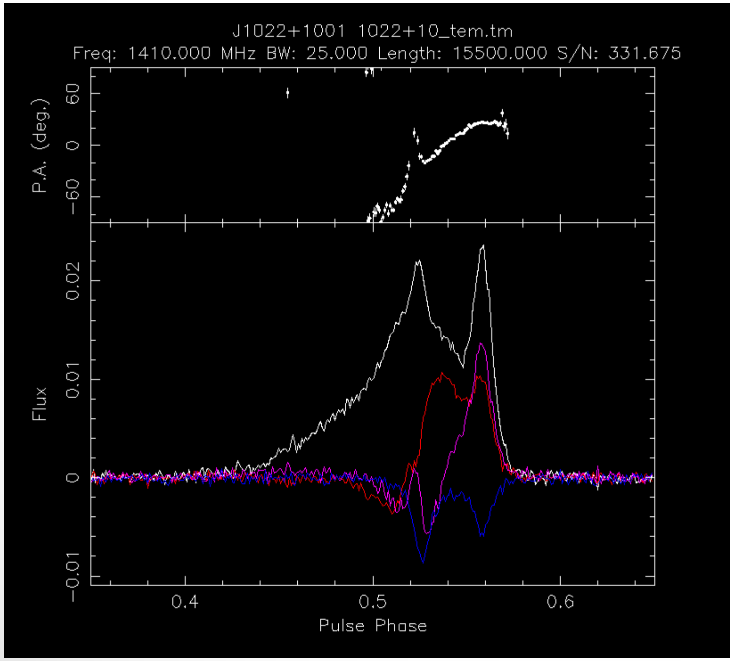
- Well known problem for radio astronomers, especially for pulsar researches
- How to calibrate efficiently without interrupting observation?
- Can we calibrate historical data without cal signal?
- Driven by Large European array of pulsars (LEAP), which is a phased array aiming at provide high quality pulsar timing data. BW 128MHz, baseband data, usually use 1MHz channelization
  - Telescope mounting are very different.
  - Polarization calibration helps to improve the SNR of fringe solutions
  - Aiming at GW detection, the high precision PSR timing need polarization calibration

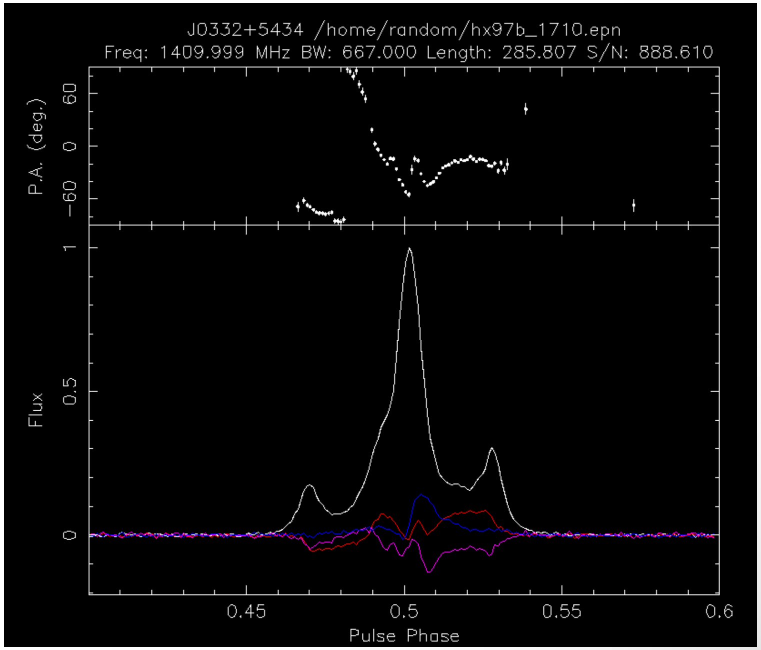


1.http://www.epta.eu.org
2. http://www.leap.eu.org

Pulsar as calibrator

- Certain millisecond pulsars have stable polarization properties.
- The polarization properties is already known.
- We can match the observed Stokes parameters to the known template to get the instrumental parameters.





Basics notations

The most general linear transformation for the electric field is by Jones matrix J

$$\boldsymbol{E}' = \boldsymbol{J}\boldsymbol{E}, \qquad \boldsymbol{E} = \begin{pmatrix} E_1 \\ E_2 \end{pmatrix} \qquad \boldsymbol{J} = \begin{pmatrix} J_{11} & J_{12} \\ J_{21} & J_{22} \end{pmatrix}$$

There are totally 2x2 complex elements in J. Thus 8 parameters are enough to describe all possible linear transformation.

Polarization is encoded in the coherency matrix (Stokes parameters):

$$C_{c,ij} = \left\langle \begin{pmatrix} E_l E_l^* & E_l E_r^* \\ E_l^* E_r & E_r E_r^* \end{pmatrix} \right\rangle \qquad \begin{pmatrix} I+V & Q-\jmath U \\ Q+\jmath U & I-V \end{pmatrix} = \begin{pmatrix} E_l E_l^* & E_l E_r^* \\ E_r^* E_l & E_r E_r^* \end{pmatrix}$$

The transformation by Jones matrix applied to Stokes parameters are described by Muller matrix. It is different presentation for the same transformation group.

$$\boldsymbol{C}' = \boldsymbol{E}'\boldsymbol{E}'^{T} = \boldsymbol{J}\boldsymbol{E}\boldsymbol{E}^{H}\boldsymbol{J}^{H} = \boldsymbol{J}\boldsymbol{C}\boldsymbol{J}^{H}.$$

$$\boldsymbol{S}' = \begin{pmatrix} I' \\ Q' \\ U' \\ V' \end{pmatrix} = \boldsymbol{M}\boldsymbol{S} = \boldsymbol{M}\cdot\begin{pmatrix} I \\ Q \\ U \\ V \end{pmatrix} \qquad \boldsymbol{M} = \begin{pmatrix} \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_0\boldsymbol{J}^T\boldsymbol{\sigma}_0] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_1\boldsymbol{J}^T\boldsymbol{\sigma}_0] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_2\boldsymbol{J}^T\boldsymbol{\sigma}_0] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_3\boldsymbol{J}^T\boldsymbol{\sigma}_0] \\ \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_0\boldsymbol{J}^T\boldsymbol{\sigma}_1] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_1\boldsymbol{J}^T\boldsymbol{\sigma}_1] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_2\boldsymbol{J}^T\boldsymbol{\sigma}_1] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_3\boldsymbol{J}^T\boldsymbol{\sigma}_1] \\ \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_0\boldsymbol{J}^T\boldsymbol{\sigma}_2] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_1\boldsymbol{J}^T\boldsymbol{\sigma}_2] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_2\boldsymbol{J}^T\boldsymbol{\sigma}_2] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_3\boldsymbol{J}^T\boldsymbol{\sigma}_2] \\ \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_0\boldsymbol{J}^T\boldsymbol{\sigma}_3] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_1\boldsymbol{J}^T\boldsymbol{\sigma}_3] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_2\boldsymbol{J}^T\boldsymbol{\sigma}_3] & \frac{1}{2}\mathrm{Tr}[\boldsymbol{J}\boldsymbol{\sigma}_3\boldsymbol{J}^T\boldsymbol{\sigma}_3] \end{pmatrix}.$$

However, the number of free parameters for M is 7, although the number of matrix elements becomes 16.

A few example

$$\begin{pmatrix} e^{-\jmath\psi} & 0 \\ 0 & e^{\jmath\psi} \end{pmatrix}$$

Rotation

$$\boldsymbol{M}_{o,r} = \begin{pmatrix} 1 & 0 & 0 & 0 \\ 0 & \cos(2\psi) & -\sin(2\psi) & 0 \\ 0 & \sin(2\psi) & \cos(2\psi) & 0 \\ 0 & 0 & 0 & 1 \end{pmatrix}$$

$$\boldsymbol{J}_{o,\,g} = \begin{pmatrix} 1 & 0 \\ 0 & \Delta e^{\jmath\phi} \end{pmatrix},$$

Gain and phase

$$\boldsymbol{M}_g = \begin{pmatrix} \frac{1}{2}(1+\Delta^2) & 0 & 0 & \frac{1}{2}(1-\Delta^2) \\ 0 & \Delta\cos\phi & -\Delta\sin\phi & 0 \\ 0 & \Delta\sin\phi & \Delta\cos\phi & 0 \\ \frac{1}{2}(1-\Delta^2) & 0 & 0 & \frac{1}{2}(1+\Delta^2) \end{pmatrix}.$$

$$\boldsymbol{J}_{c,l} = \begin{pmatrix} 1 & D\cos\theta\, e^{\jmath\phi_{\mathrm{dr}}} \\ D\sin\theta\, e^{\jmath\phi_{\mathrm{dl}}} & 1 \end{pmatrix},$$

Leakage

$$\boldsymbol{M}_l$$
$$\begin{pmatrix} \frac{1}{2}(2+D^2) & D(\sin\theta\cos\phi_{\mathrm{dr}}+\cos\theta\cos\phi_{\mathrm{dl}}) & D(\cos\theta\sin\phi_{\mathrm{dl}}-\sin\theta\sin\phi_{\mathrm{dr}}) & \frac{1}{2}D^2\cos(2\theta) \\ D(\cos\theta\cos\phi_{\mathrm{dl}}+\sin\theta\cos\phi_{\mathrm{dr}}) & 1+\frac{1}{2}D^2\cos(\phi_{\mathrm{dl}}-\phi_{\mathrm{dr}})\sin2\theta & \frac{1}{2}D^2\sin(\phi_{\mathrm{dl}}-\phi_{\mathrm{dr}})\sin2\theta & D(-\sin\theta\cos\phi_{\mathrm{dr}}+\cos\theta\cos\phi_{\mathrm{dl}}) \\ D(\cos\theta\sin\phi_{\mathrm{dl}}-\sin\theta\sin\phi_{\mathrm{dr}}) & \frac{1}{2}D^2\sin(\phi_{\mathrm{dl}}-\phi_{\mathrm{dr}})\sin2\theta & 1-\frac{1}{2}D^2\cos(\phi_{\mathrm{dl}}-\phi_{\mathrm{dr}})\sin2\theta & D(\cos\theta\sin\phi_{\mathrm{dl}}+\sin\theta\sin\phi_{\mathrm{dr}}) \\ -\frac{1}{2}D^2\cos(2\theta) & D(\sin\theta\cos\phi_{\mathrm{dr}}-\cos\theta\cos\phi_{\mathrm{dl}}) & -D(\cos\theta\sin\phi_{\mathrm{dl}}+\sin\theta\sin\phi_{\mathrm{dr}}) & \frac{1}{2}(2-D^2) \end{pmatrix}$$

Decomposition

Jones matrix can be factorized as

$$\begin{pmatrix} A & B \\ C & D \end{pmatrix} = \|A\| e^{j\phi_A} \begin{pmatrix} 1 & 0 \\ 0 & \boxed{A^{-1}D} \end{pmatrix} \begin{pmatrix} 1 & \boxed{A^{-1}B} \\ \boxed{CD^{-1}} & I \end{pmatrix}.$$

Leakage

Absolute gain

Differential gain and delay

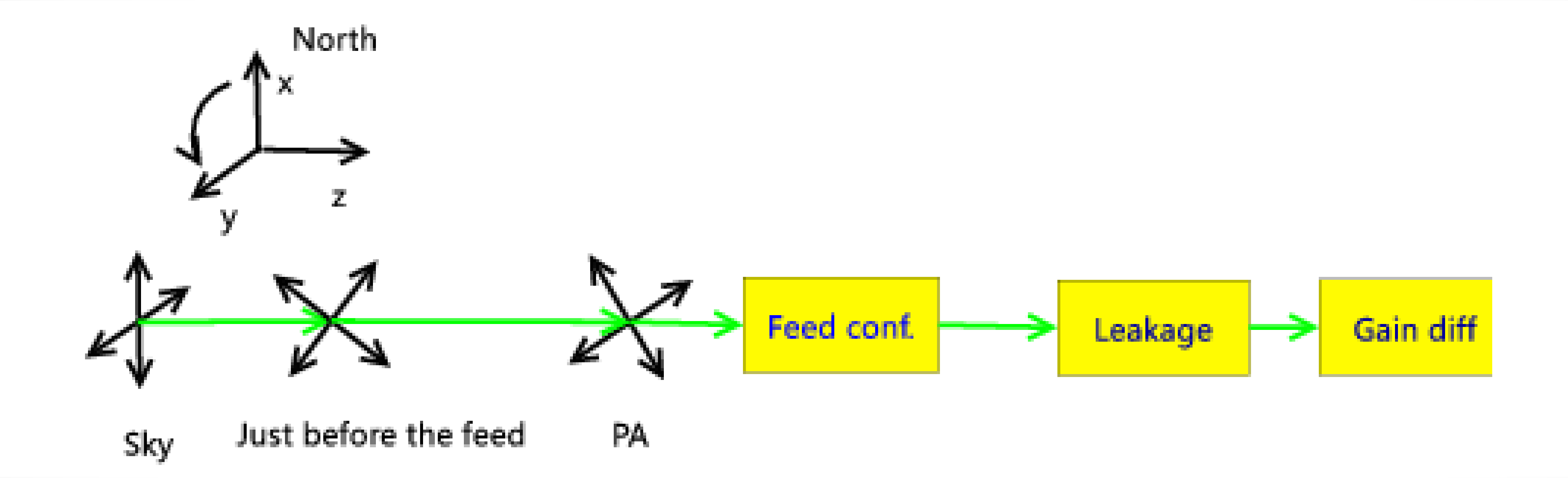
System phase

The A,B,C,D are all complex so we have 8 variable, but the system phase |A| is not measurable, so we have 7 free parameters. We use the following form for the differential gain and leakage:

$$\boxed{J_{o,g} = \begin{pmatrix} 1 & 0 \\ 0 & \Delta e^{j\phi} \end{pmatrix},} \quad \boxed{J_{c,l} = \begin{pmatrix} 1 & D\cos\theta e^{j\phi_{dr}} \\ D\sin\theta e^{j\phi_{dl}} & 1 \end{pmatrix},}$$

This is similar to the Hamaker decomposition.

Signal modeling



For each channel, we need 7 parameters.

$$S_{caled} = M_{pa}^{-1} M_{calib} M_{sys} M_{PA} S_{src}$$

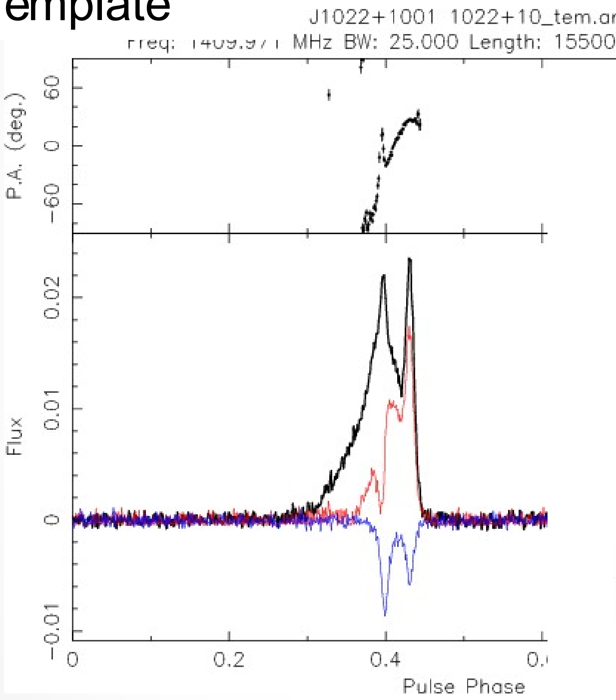
Iterative techniques

- Step0: From a uncalibrated polarization profile
- Step1: Align profile with template
- Step2: Fit for the system parameters
  --non-linear least square
- Step3: Calibrate the polarization and get a new profile
- Step4: repeat 1-3, until converge
- Step5: calculate the Jones/Muller matrix
- Jones/Muller matrices are applied to the raw baseband data (video data) or integrated data (audio data) respectively.

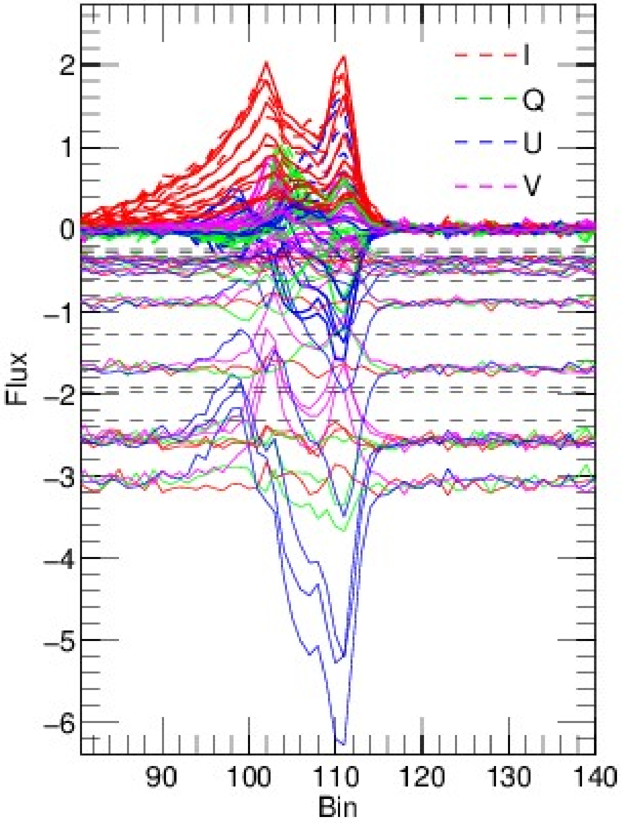
Results

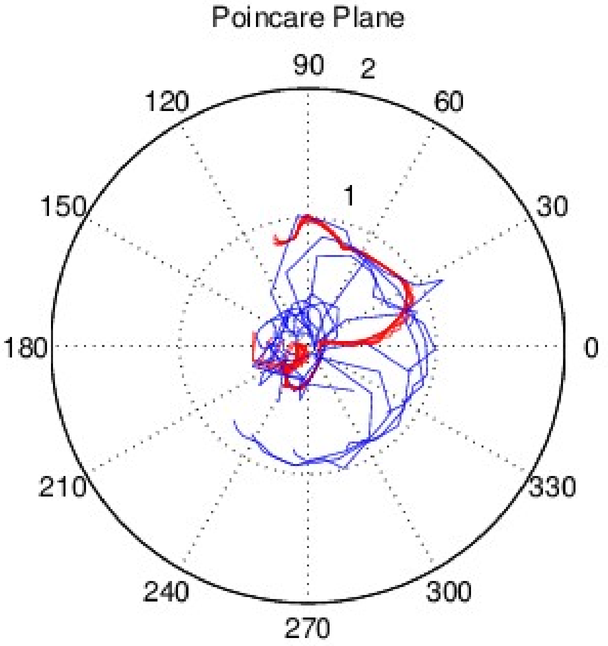
Uncalibrated 1022+12 data, for 8 one hour integration, the polarization is not stable

Template

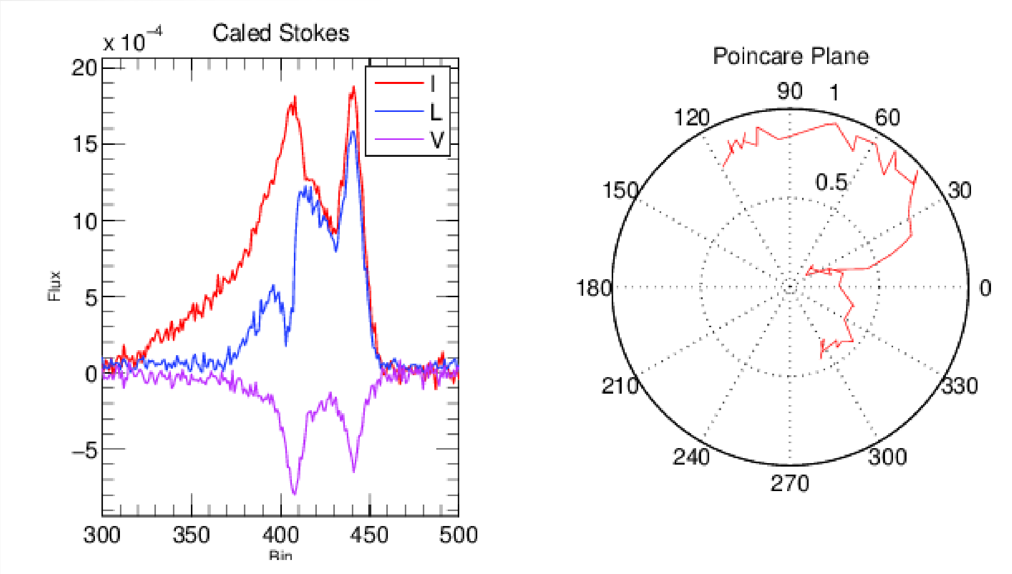


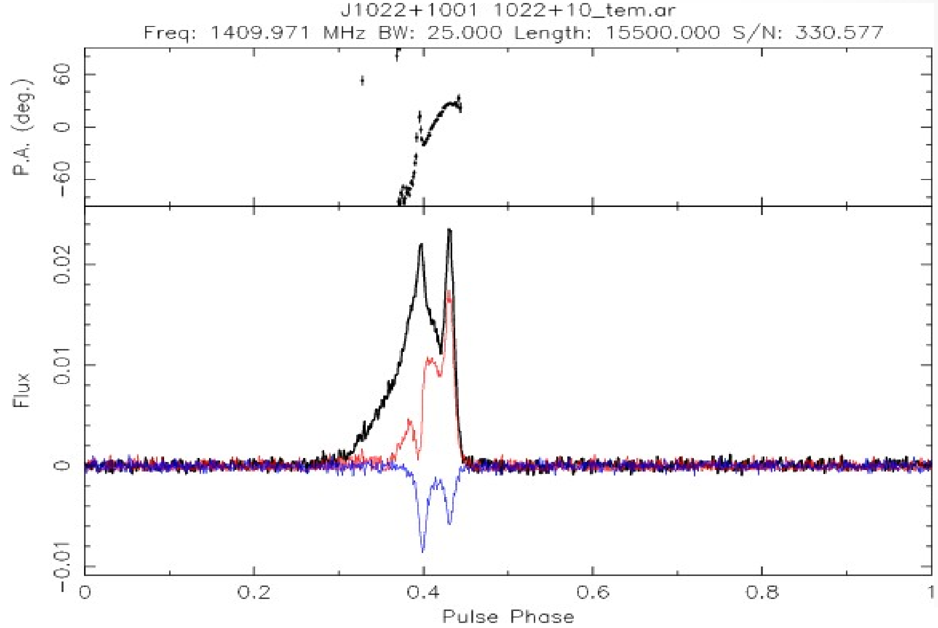
Un caled

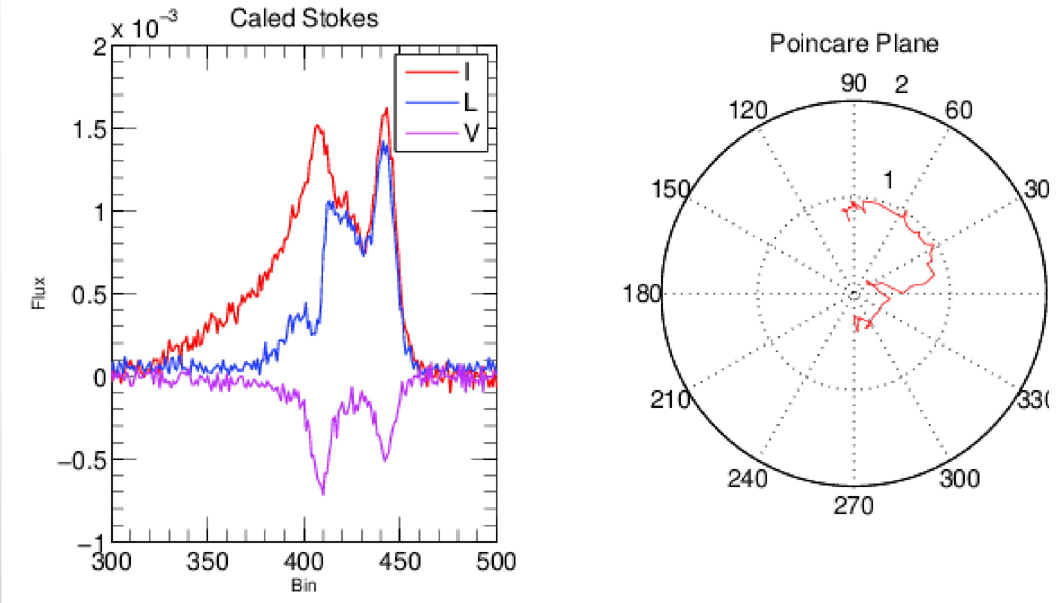


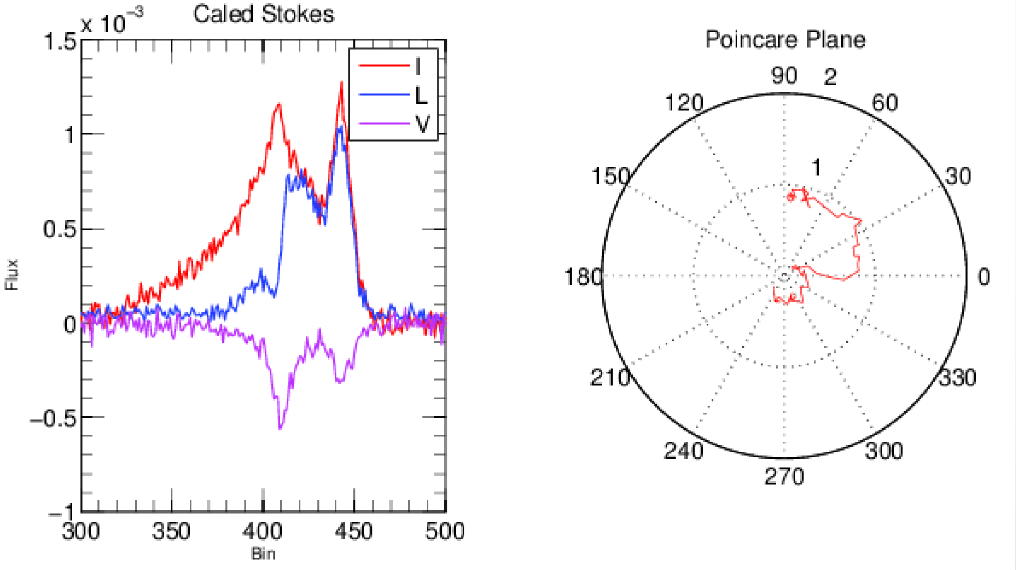


After calibration

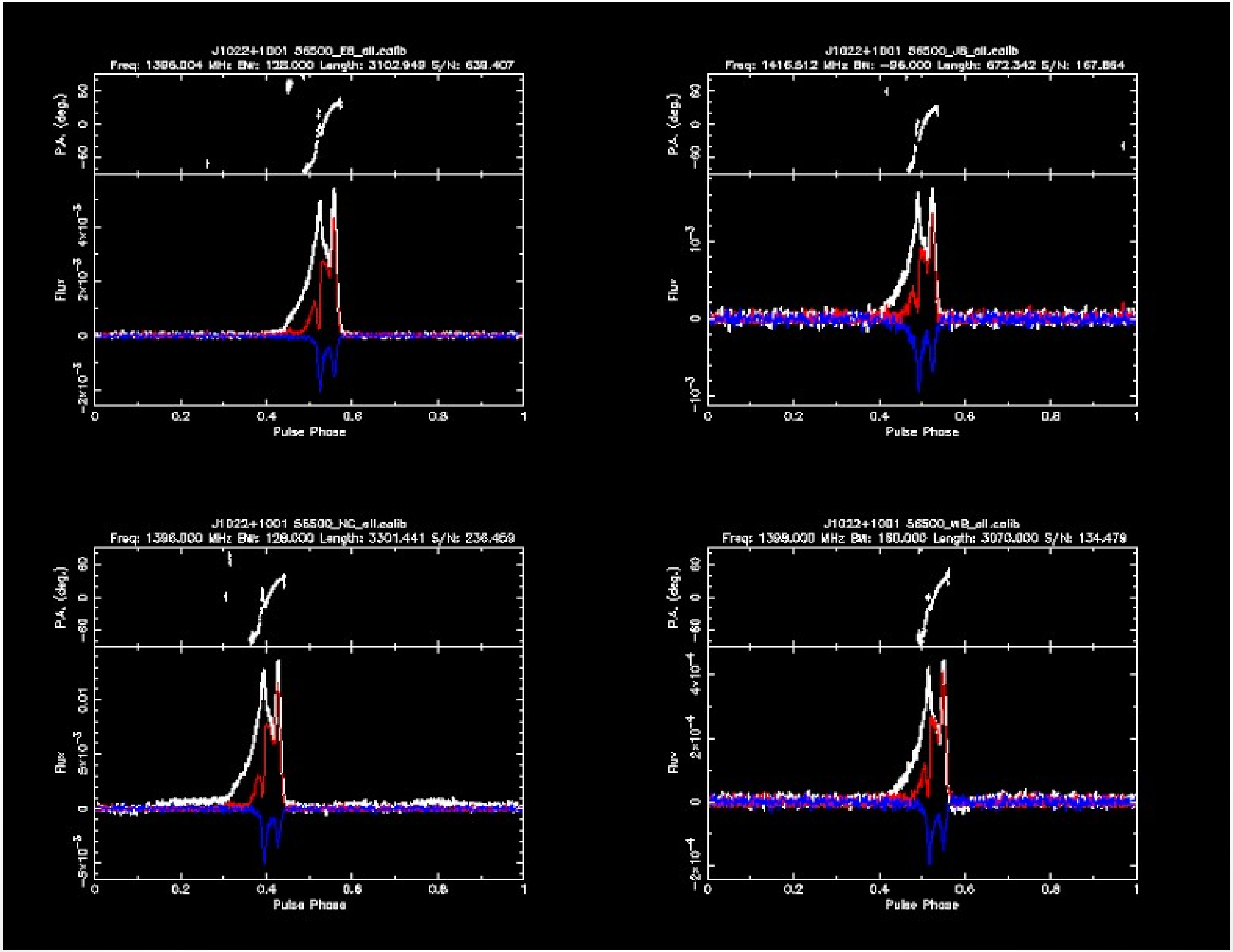








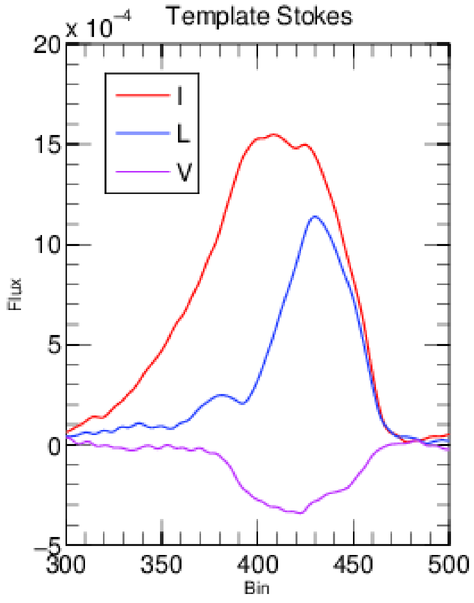
Calibrate several telescopes

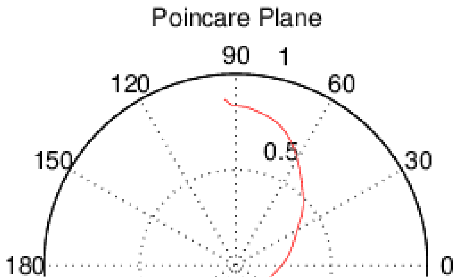


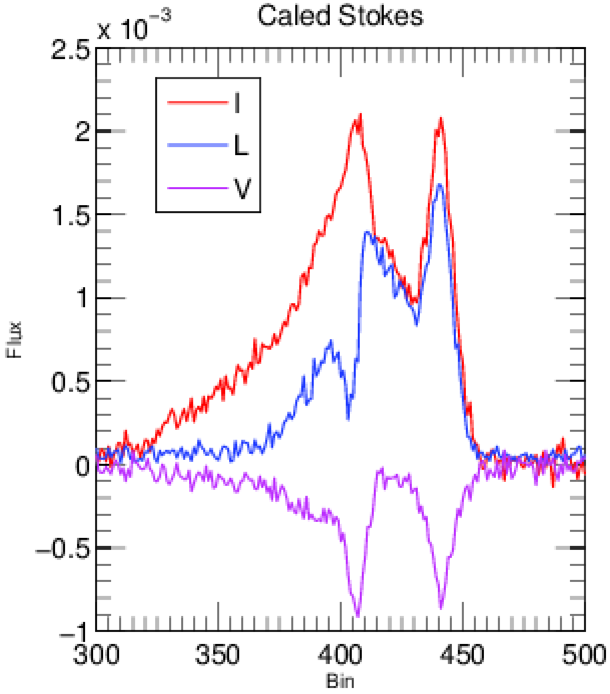
How sensitive the calibration depending on the template?

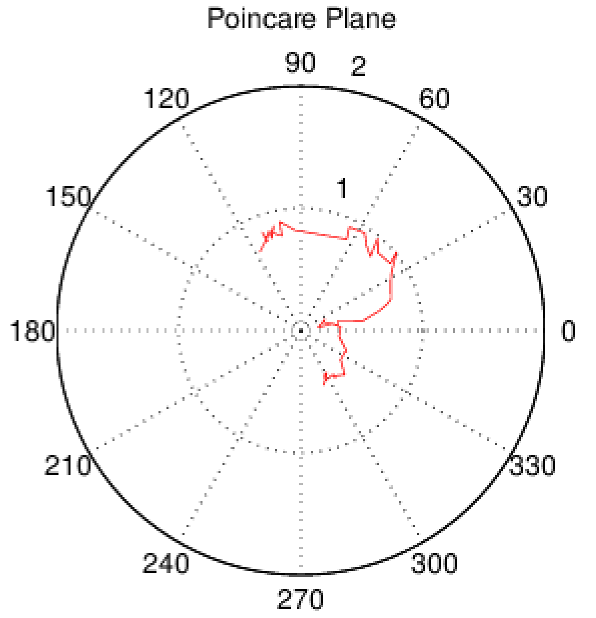
What happens, if we use a very wrong template?

---Still get correct answers!









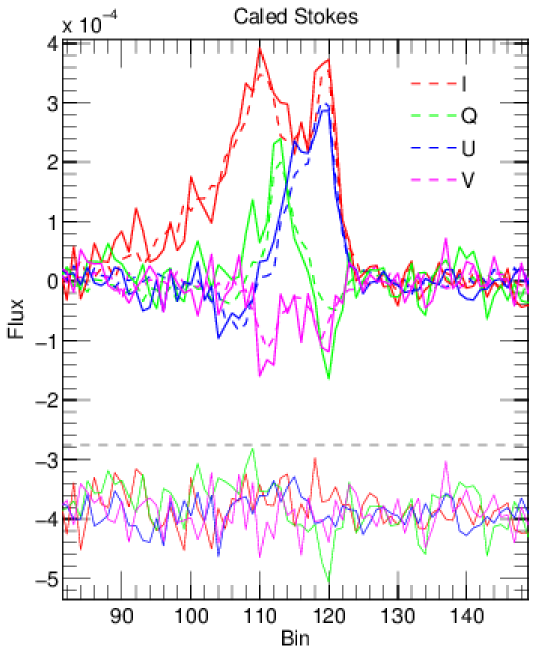
How is this possible?

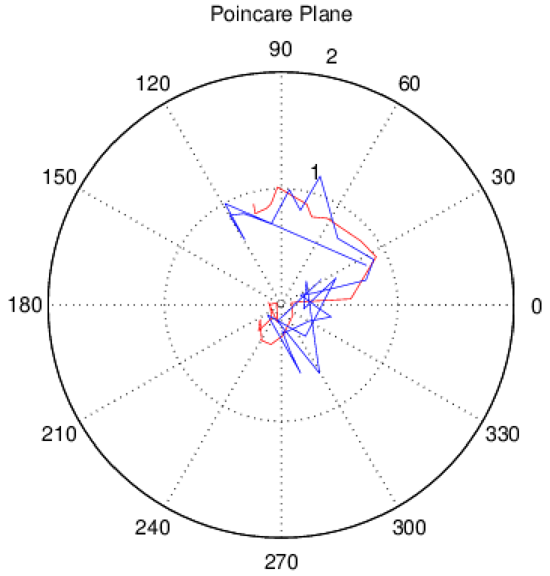
$$S_{caled} = M_{pa}^{-1} M_{calib} M_{sys} M_{PA} S_{src}$$

- As far as the calibration residual matrix (M_{calib} M_{sys}) is not commutated with M_{PA}, the information that polarization is time-invariant helped to solve both the S_{src} and M_{calib}. The intrinsic S can then be regard as a prior in the fitting.
- However, there are degeneracies, certain type of matrices commutate with $M_{PA.}$ One can show that an extra auxiliary observation of a unpolarized source or source with known V/I will be enough to break such degeneracy.

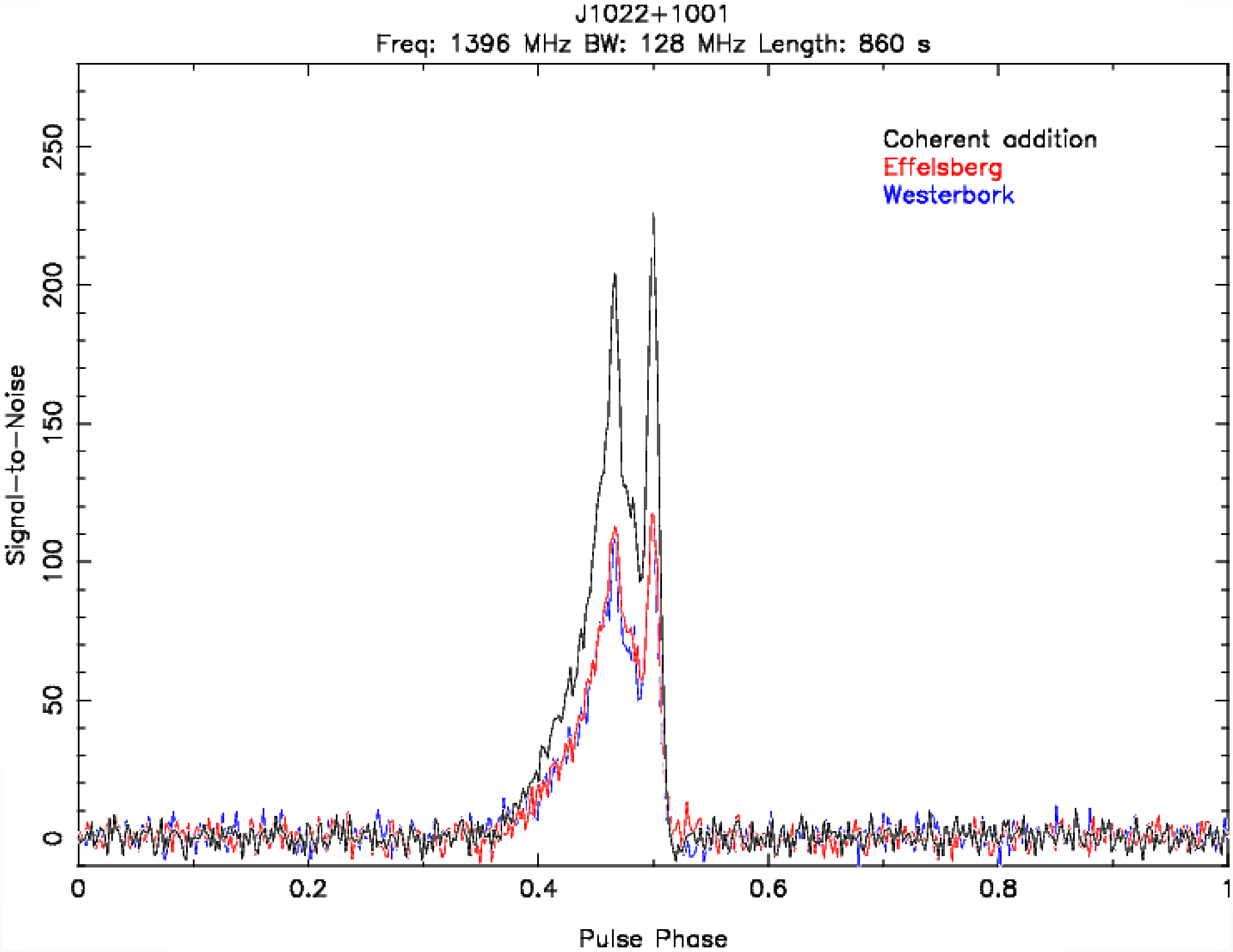
Apply the solution to data at different epoch

- Apply the solution found in August data to July data.





High coherency can be achieved for LEAP



Coherency > 95%

Recap and remarks

- We can use pulsar as cal to do polarization calibration. This could be valuable for new constructed telescopes to measure the system response. (TianMa, Yunnan 40-m, QTT, FAST, etc.)
- This can be insensitive to the template one uses.
- The results is stable, and the solution can be generalized to nearby epochs.
- It could be applied to the historical archive data, if you have a bright pulsar along with.
- Benefit future SKA calibration scheme

Thanks!