A new strategy for polarization calibration of VLBI data

Magenta: D-term model

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Polarimetry with VLBI

Jet Launching Mechanism

Narayan & Quataert (2005)

Black Hole Accretion

Moscibrodzka (2017)

Magnetic Field + High Resolution

VLBI Polarimetry
Polarimetry with VLBI

Jet Launching Mechanism

Theory & Simulation

Observations

Black Hole Accretion

B field geometry

Accretion Dynamics & rate

Narayan & Quataert (2005)

Moscibrodzka+ (2017)

Asada+ (2002)

Park+ (2019)
Observed Voltages

\[
V_L = G_L (E_L + D_L E_R e^{-2i\phi}) \\
V_R = G_R (E_R + D_R E_L e^{2i\phi})
\]
Polarimetry with VLBI: (known to be) not easy

Observed Voltages

\[ V_L = G_L(E_L + D_L E_R e^{-2i\phi}) \]
\[ V_R = G_R(E_R + D_R E_L e^{2i\phi}) \]

‘Correct’ source signal
Polarimetry with VLBI: (known to be) not easy

Observed Voltages

\[ V_L = G_L (E_L + D_L E_R e^{-2i\phi}) \]
\[ V_R = G_R (E_R + D_R E_L e^{2i\phi}) \]

‘Correct’ source signal

‘Instrumental’ polarization (often called “D-Terms”): a fraction of the signal from the opposite polarization is ‘leaked’ → needs to be properly calibrated.
Polarimetry with VLBI: not easy

\[ V_L = G_L(E_L + D_L E_R e^{-2i\phi}) \]
\[ V_R = G_R(E_R + D_R E_L e^{2i\phi}) \]

\[ R_i L_j = G_{iR} G_{jL}^* \left( P_{ij} + D_{iR} I e^{2i\phi_i} + D_{jL}^* I e^{2i\phi_j} + D_{iR} D_{jL}^* P_{ij} e^{2i(\phi_i + \phi_j)} \right) \]

\[ L_i R_j = G_{iL} G_{jR}^* \left( P_{ij}^* + D_{iL} I e^{-2i\phi_i} + D_{jR}^* I e^{-2i\phi_j} + D_{iL} D_{jR}^* P_{ij} e^{-2i(\phi_i + \phi_j)} \right) \]
Polarimetry with VLBI: not easy

Cross-hand visibilities

\[ V_L = G_L(E_L + D_L E_R e^{-2i\phi}) \]
\[ V_R = G_R(E_R + D_R E_L e^{2i\phi}) \]

\[ R_{iLj} = G_{iR} G_{jL}^* \left( P_{ij} + D_{iR} I e^{2i\phi_i} + D_{jL}^* I e^{2i\phi_j} + D_{iR} D_{jL}^* P_{ij} e^{2i(\phi_i + \phi_j)} \right) \]

\[ L_{iRj} = G_{iL} G_{jR}^* \left( P_{ij}^* + D_{iL} I e^{-2i\phi_i} + D_{jR}^* I e^{-2i\phi_j} + D_{iL} D_{jR}^* P_{ij} e^{-2i(\phi_i + \phi_j)} \right) \]
Polarimetry with VLBI: not easy

Cross-hand visibilities

\[ V_L = G_L(E_L + D_L E_R e^{-2i\phi}) \]
\[ V_R = G_R(E_R + D_R E_L e^{2i\phi}) \]

Source-intrinsic signal

\[ R_{iL} = G_{iR} G_{jL}^* \left( P_{ij} + D_{iR} I e^{2i\phi_i} + D_{jL}^* I e^{2i\phi_j} + D_{iR} D_{jL}^* P_{ij} e^{2i(\phi_i+\phi_j)} \right) \]

\[ L_{iR} = G_{iL} G_{jR}^* \left( P_{ij}^* + D_{iL} I e^{-2i\phi_i} + D_{jR}^* I e^{-2i\phi_j} + D_{iL} D_{jR}^* P_{ij} e^{-2i(\phi_i+\phi_j)} \right) \]
Polarimetry with VLBI: not easy

Cross-hand visibilities

\[
R_{iL} = G_{iR} G_{jL}^* \left( P_{ij} + D_{iR} e^{2i\phi_i} + D_{jL}^* e^{2i\phi_j} + D_{iR} D_{jL}^* P_{ij} e^{2i(\phi_i + \phi_j)} \right)
\]

\[
L_{iR} = G_{iL} G_{jR}^* \left( P_{ij}^* + D_{iL} e^{-2i\phi_i} + D_{jR}^* e^{-2i\phi_j} + D_{iL} D_{jR}^* P_{ij} e^{-2i(\phi_i + \phi_j)} \right)
\]

Source-intrinsic signal

D-Terms

(that we want to calibrate!)
Polarimetry with VLBI: not easy

\[ R_{iL} = G_{iR} G_{jL}^* \left( P_{ij} + D_{iR} I e^{2i\phi_i} + D_{jL}^* I e^{2i\phi_j} + D_{iR} D_{jL}^* P_{ij} e^{2i(\phi_i + \phi_j)} \right) \]

\[ L_i R_j = G_{iL} G_{jR}^* \left( P_{ij}^* + D_{iL} I e^{-2i\phi_i} + D_{jR}^* I e^{-2i\phi_j} + D_{iL} D_{jR}^* P_{ij} e^{-2i(\phi_i + \phi_j)} \right) \]

\( \varphi \) : Parallactic angles

Sinusoidal variation over parallactic angles
(Or “circular rotation” on the complex plane)
AIPS task **LPCAL**: a conventional calibration tool

Source Polarization

D-Terms

2nd order terms

\[ \tilde{\tau}_{i,j}^{RL}(u,v) = P(u,v) + D_{iR} \tilde{r}_{i,j}^{LL}(u,v)e^{2i\phi_i} + D_{jL}^* \tilde{r}_{i,j}^{RR}(u,v)e^{2i\phi_j} + P^*(u,v)D_{iR}D_{jL}^*e^{2i(\phi_i+\phi_j)} \]

\[ \tilde{\tau}_{i,j}^{LR}(u,v) = P^*(u,v) + D_{iL} \tilde{r}_{i,j}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^* \tilde{r}_{i,j}^{LL}(u,v)e^{-2i\phi_j} + P(u,v)D_{iL}D_{jR}^*e^{-2i(\phi_i+\phi_j)} \]

‘Model’ visibility for total intensity

What AIPS LPCAL does is...

\[ \tilde{\tau}_{i,j}^{RL}(u,v) = pF(u,v) + D_{iR} \tilde{r}_{i,j}^{LL}(u,v)e^{2i\phi_i} + D_{jL}^* \tilde{r}_{i,j}^{RR}(u,v)e^{2i\phi_j} + pF^*(u,v)D_{iR}D_{jL}^*e^{2i(\phi_i+\phi_j)} \]

\[ \tilde{\tau}_{i,j}^{LR}(u,v) = pF^*(u,v) + D_{iL} \tilde{r}_{i,j}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^* \tilde{r}_{i,j}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^*e^{-2i(\phi_i+\phi_j)} \]

Assume a ‘constant fractional polarization’ for a source

Ignore
Some situations where LPCAL does not show a good performance...

LPCAL can fit the model to ‘a single source’ visibility data

1. There are often not many scans for ‘long baseline antennas’. → D-term estimation accuracy is limited for those antennas.
Some situations where LPCAL does not show a good performance...

LPCAL can fit the model to ‘a single source’ visibility data

2. When we have a small number of antennas (such as the KVN).
→ difficult to determine which source is ‘the best calibrator’?
Some situations where LPCAL does not show a good performance...

LPCAL ignores the 2\textsuperscript{nd} order terms.

\[
\tilde{r}_{ij}^{RL}(u, v) = \sum_s p_s F_s(u, v) + D_{iR}r_{ij}^{RR}(u, v)e^{2i\phi_i} + D_{jL}^*r_{ij}^{RR}(u, v)e^{2i\phi_j} + \sum_s p_s^* F_s(u, v)D_{iR}D_{jL}^*e^{2i(\phi_i + \phi_j)}
\]

\[
\tilde{r}_{ij}^{LR}(u, v) = \sum_s p_s^* F_s(u, v) + D_{iL}r_{ij}^{RR}(u, v)e^{-2i\phi_i} + D_{jR}^*r_{ij}^{RR}(u, v)e^{-2i\phi_j} + \sum_s p_s F_s(u, v)D_{iL}D_{jR}^*e^{-2i(\phi_i + \phi_j)}
\]

Ignore

3. When the D-terms are large and source polarization is large → cannot ignore the 2\textsuperscript{nd} order terms.
Some situations where LPCAL does not show a good performance...

4. When antennas have quite different sensitivities (e.g., ALMA + EHT, GBT + VLBA) → We must properly take antenna weights into account (not possible for LPCAL).
How to improve?

Let’s develop a new algorithm which fits the model to ‘multiple sources’ visibilities simultaneously.

Possible advantages are

(i) increase in ‘effective’ signal-to-noise ratio (we have more data points).
(ii) improvement of the D-term accuracy thanks to the 2\textsuperscript{nd} order terms included.
(iii) less efforts and time required (no need to figure out which calibrator is the best)
(iv) controlling weights for different antennas and sources are flexible (which might be important for the EHT).
How does it work?

1. Extract the visibilities and weights into ascii files
2. Obtain the best-fit D-Term model
3. Obtain the D-Term calibrated UVfits file

All these processes can be done by running a single script. It takes a few minutes to less than 15 minutes depending on the data size.
Does it work well?

VLBA

Brewster – Fort Davis

Circles : LHS (data)
Magenta : RHS (model)

\(i_{ij}^{RL}(u,v) = p F(u,v) + D_{iR}r_{ij}^{LL}(u,v)e^{2i\phi_i} + D_{jL}^{*}r_{ij}^{RR}(u,v)e^{2i\phi_j} + p^{*}F(u,v)D_{iR}D_{jL}^{*}e^{2i(\phi_i+\phi_j)}\)

\(i_{ij}^{LR}(u,v) = p^{*}F(u,v) + D_{iL}r_{ij}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^{*}r_{ij}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^{*}e^{-2i(\phi_i+\phi_j)}\)
Does it work well?

VLBA

Los Alamos – Pie Town

Circles : LHS (data)  \( \tilde{r}_{ij}^{RL}(u,v) = pF(u,v) + D_{iR}r_{ij}^{LL}(u,v)e^{2i\phi_i} + D_{jR}^*r_{ij}^{RR}(u,v)e^{2i\phi_j} + p^*F(u,v)D_{iR}D_{jR}^*e^{-2i(\phi_i+\phi_j)} \)

Magenta : RHS (model)  \( \tilde{r}_{ij}^{LR}(u,v) = p^*F(u,v) + D_{iL}r_{ij}^{RR}(u,v)e^{-2i\phi_i} + D_{jL}^*r_{ij}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jL}e^{-2i(\phi_i+\phi_j)} \)
Does it work well?

**VLBA**

Mauna Kea – Saint Croix

Circles : LHS (data)
Magenta : RHS (model)

\[
\begin{align*}
\tilde{r}_{ij}^{RL}(u,v) &= pF(u,v) + D_{iR}r_{ij}^{LL}(u,v)e^{2i\phi_i} + D_{jL}^{*}r_{ij}^{RR}(u,v)e^{2i\phi_j} + p^{*}F(u,v)D_{iR}D_{jL}^{*}e^{2i(\phi_i+\phi_j)} \\
\tilde{r}_{ij}^{LR}(u,v) &= p^{*}F(u,v) + D_{iL}r_{ij}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^{*}r_{ij}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^{*}e^{-2i(\phi_i+\phi_j)}
\end{align*}
\]
Does it work well?

HSA

Effelsberg – Los Alamos

Circles: LHS (data)
Magenta: RHS (model)

\[
\begin{align*}
\tilde{r}_{ij}^{RL}(u,v) &= pF(u,v) + D_{iR}r_{ij}^{LL}(u,v)e^{2i\phi_i} + D_{jL}^*r_{ij}^{RR}(u,v)e^{2i\phi_j} + p^*F(u,v)D_{iR}D_{jL}^*e^{2i(\phi_i+\phi_j)} \\
\tilde{r}_{ij}^{LR}(u,v) &= p^*F(u,v) + D_{iL}r_{ij}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^*r_{ij}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^*e^{-2i(\phi_i+\phi_j)}
\end{align*}
\]
Does it work well?

KaVA (5 Stations)

Mizusawa - Iriki

Circles : LHS (data)  \[
\tilde{r}_{ij}^{RL}(u,v) = pF(u,v) + D_{ii}r_{i,j}^{LL}(u,v)e^{2i\phi_i} + D_{jj}^{*}r_{i,j}^{RR}(u,v)e^{2i\phi_j} + p^{*}F(u,v)D_{iR}D_{jL}^{*}e^{2i(\phi_i+\phi_j)}
\]

Magenta : RHS (model)  \[
\tilde{r}_{ij}^{LR}(u,v) = p^{*}F(u,v) + D_{iL}r_{i,j}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^{*}r_{i,j}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^{*}e^{-2i(\phi_i+\phi_j)}
\]
Does it work well?

KaVA (5 Stations)

Iriki - Ulsan

Circles : LHS (data)
Magenta : RHS (model)

\[
\begin{align*}
\hat{r}_{ij}^{RL}(u, v) &= p F(u, v) + D_{iR} r_{ij}^{LL}(u, v) e^{2i\phi_i} + D_{jR} r_{ij}^{RR}(u, v) e^{2i\phi_j} + p^* F(u, v) D_{iR} D_{jR} e^{2i(\phi_i+\phi_j)} \\
\hat{r}_{ij}^{LR}(u, v) &= p^* F(u, v) + D_{iL} r_{ij}^{RR}(u, v) e^{-2i\phi_i} + D_{jR} r_{ij}^{LL}(u, v) e^{-2i\phi_j} + p F(u, v) D_{iL} D_{jR} e^{-2i(\phi_i+\phi_j)}
\end{align*}
\]
Does it work well?

**KVN**

**Tamna – Yonsei**

Circles : LHS (data)

Magenta : RHS (model)

\[
\hat{r}_{ij}^{RL}(u,v) = pF(u,v) + D_{iR}r_{ij}^{RL}(u,v)e^{2i\phi_i} + D_{jL}^*r_{ij}^{RR}(u,v)e^{2i\phi_j} + p^*F(u,v)D_{iR}D_{jL}^*e^{2i(\phi_i+\phi_j)}
\]

\[
\hat{r}_{ij}^{LR}(u,v) = p^*F(u,v) + D_{iL}r_{ij}^{RR}(u,v)e^{-2i\phi_i} + D_{jR}^*r_{ij}^{LL}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D_{jR}^*e^{-2i(\phi_i+\phi_j)}
\]
Probing the linear polarization of AGN jets at mm wavelengths with the KVN VLBA (BU) 43 GHz

KVN 86 – 142 GHz

VLBA (BU) 43 GHz

2018 Feb 20

3C279

43.1 GHz

86.3 GHz

94.7 GHz

129.8 GHz

141.7 GHz

KVN 86 – 142 GHz

3C279

VLBA 43 GHz

\(\chi\) [deg]

\(\lambda^2\) [cm^2]

\(\square\ A, \, RM = -11535 \pm 1977 \, \text{rad/m}^2\)
Probing the linear polarization of AGN jets at mm wavelengths with the KVN

VLBA (BU) 43 GHz

3C273

VLBA 43 GHz

KVN 86 – 142 GHz

A, RM = 5540 ± 2140 rad/m²

χ² [cm²]

χ [deg]
Probing the linear polarization of AGN jets at mm wavelengths with the KVN
Probing the linear polarization of AGN jets at mm wavelengths with the KVN

VLBA (BU) 43 GHz

KVN 86 – 142 GHz

Dec (mas)

RA (mas)

KVN 86 – 142 GHz

A, RM = 380118 ± 9000 rad/m²

λ² [cm²]
Summary

— A new algorithm for polarization calibration of VLBI data has been developed. Which advantages does it have?

(i) It increases effective signal to noise ratio and improves the calibration accuracy. → powerful for studying low-polarization sources (such as M87!).

(ii) It will solve the problem of global VLBI arrays that there is not much common sky for a single source. → will be important for on-going and future global VLBI studies by using GMVA + ALMA, EHT + ALMA, and satellite missions.

(iii) It is easy to use (you can just run a single script). → Don’t spend much time to figure out which calibrator is the best. You can use all!

(iv) It will be very effective for future KVN polarization observations where we have a small number of baselines but usually have many different sources observed. → You can do a unique science with the KVN (linear polarization and Rotation Measure analysis at 2 ~ 3 mm).
Please use my code for your studies!
AIPS task **LPCAL**: a conventional calibration tool

Source Polarization

\[
\tilde{r}^{RL}_{ij}(u,v) = P(u,v) + D_{iR}r^{LL}_{ij}(u,v)e^{2i\phi_i} + D^*_{jL}r^{RR}_{ij}(u,v)e^{2i\phi_j} + P^*(u,v)D_{iR}D^*_{jL}e^{2i(\phi_i+\phi_j)}
\]

\[
\tilde{r}^{LR}_{ij}(u,v) = P^*(u,v) + D_{iL}r^{RR}_{ij}(u,v)e^{-2i\phi_i} + D^*_{jR}r^{LL}_{ij}(u,v)e^{-2i\phi_j} + P(u,v)D_{iL}D^*_{jR}e^{-2i(\phi_i+\phi_j)}
\]

D-Terms

2nd order terms

‘Model’ visibility for total intensity

\[
\tilde{r}^{RL}_{ij}(u,v) = pF(u,v) + D_{iR}r^{LL}_{ij}(u,v)e^{2i\phi_i} + D^*_{jL}r^{RR}_{ij}(u,v)e^{2i\phi_j} + p^*F(u,v)D_{iR}D^*_{jL}e^{2i(\phi_i+\phi_j)}
\]

\[
\tilde{r}^{LR}_{ij}(u,v) = p^*F(u,v) + D_{iL}r^{RR}_{ij}(u,v)e^{-2i\phi_i} + D^*_{jR}r^{LL}_{ij}(u,v)e^{-2i\phi_j} + pF(u,v)D_{iL}D^*_{jR}e^{-2i(\phi_i+\phi_j)}
\]

What AIPS LPCAL does is...

Assume a ‘constant fractional polarization’ for a source

There is almost no astronomical object having a constant polarization across its structure.
Clean I map. Array: BFHKLMNOPS
OJ287 at 8.332 GHz 1995 Nov 22

Map center: RA: 08 54 48.875, Dec: +20 05 30.542 (2000.0)
Map peak: 2.02 Jy/beam
Contours: 0.00188 Jy/beam x (1 2 4 8 16 32 64)
Beam FWHM: 2.07 x 1.03 (mas) at -1.77°
Assume a constant fractional polarization for the CLEAN components in each ‘box’
AIPS task **LPCAL**: a conventional calibration tool

\[
\tilde{r}^{RL}_{ij}(u, v) = P(u, v) + D_{iR}r^{LL}_{ij}(u, v)e^{2i\phi_i} + D_{jL}^*r^{RR}_{ij}(u, v)e^{2i\phi_j} + P^*(u, v)D_{iR}D_{jL}^*e^{2i(\phi_i + \phi_j)} \\
\tilde{r}^{LR}_{ij}(u, v) = P^*(u, v) + D_{iL}r^{RR}_{ij}(u, v)e^{-2i\phi_i} + D_{jR}^*r^{LL}_{ij}(u, v)e^{-2i\phi_j} + P(u, v)D_{iL}D_{jR}^*e^{-2i(\phi_i + \phi_j)}
\]

Source Polarization

\[\text{What AIPS LPCAL does is...}\]

\[
\tilde{r}^{RL}_{ij}(u, v) = \sum_s p_s F_s(u, v) + D_{iR}r^{LL}_{ij}(u, v)e^{2i\phi_i} + D_{jL}^*r^{RR}_{ij}(u, v)e^{2i\phi_j} + \sum_s p_s^* F_s(u, v)D_{iR}D_{jL}^*e^{2i(\phi_i + \phi_j)} \\
\tilde{r}^{LR}_{ij}(u, v) = \sum_s p_s^* F_s(u, v) + D_{iL}r^{RR}_{ij}(u, v)e^{-2i\phi_i} + D_{jR}^*r^{LL}_{ij}(u, v)e^{-2i\phi_j} + \sum_s p_s F_s(u, v)D_{iL}D_{jR}^*e^{-2i(\phi_i + \phi_j)}
\]

‘Model’ visibility for each source sub-components

\[\text{Ignore}\]

Assume a ‘constant fractional polarization’ for each source sub-components

2\textsuperscript{nd} order terms
Does it work well?

When ignoring the 2\textsuperscript{nd} order terms and comparing with the LPCAL result, they are consistent within $\sim 10^{-4}$ levels.
Does it work well?

When ignoring the 2nd order terms and comparing with the LPCAL result, they are consistent within $\sim 10^{-4}$ levels.
Does it work well?

BJ020A

OJ 287 + OQ 208

OJ 287
Does it work well?

OJ 287 + OQ 208

OQ 208
Does it work well?

If the multi-source fitting code works well, then the results must be consistent with the single-source fitting results (because OJ 287 and OQ 208 are good calibrators). → This is the case!