High-Fidelity Wideband VLBI Polarimetry

VLBI with Linear-Polarization Feeds

Ivan Martí-Vidal

Dpt. Astronomia i Astrofísica
Universitat de València (Spain)

with V. Pérez, E. Albentosa, J. González, F. Jaron, et al.

Life begins at 40 (Bologna, 22–26 May 2023)

Vniversitat de València

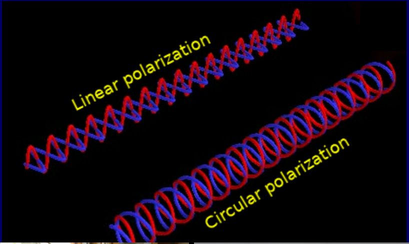
Linear vs. Circular Polarization Feeds.

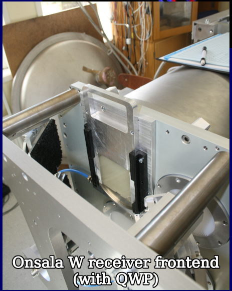
- Advantages of circular (RL) feeds:
  - Parallactic angle is just a phase correction.
  - Parallactic angle commutes with antenna gains.
  - Single-pol. observations can still be calibrated.

  Perfect for VLBI!

- Advantages of linear (XY) feeds:
  - Allow for high polarization “purity” across wider bandwidths.
  - Abolute EVPA calibration.
  - Simpler frontends.

  Good for ultra-wideband reveivers!





Linear vs. Circular Polarization Feeds

What do you prefer for your calibration/imaging analysis?

Linear vs. Circular Polarization Feeds

What do you prefer for your calibration/imaging analysis?

THIS?

$$\frac{V_{RR} + V_{LL}}{2} = FT\,(I)\,.$$

Linear vs. Circular Polarization Feeds

What do you prefer for your calibration/imaging analysis?

THIS?

$$\frac{V_{RR} + V_{LL}}{2} = FT\,(I)\,.$$

OR THIS?

$$V_{+} = FT\left(\begin{bmatrix} I\cos\psi^{-} + Q\cos\psi^{+} + U\sin\psi^{+} + jV\sin\psi^{-} & I\sin\psi^{-} - Q\sin\psi^{+} + U\cos\psi^{+} + jV\cos\psi^{-} \\ I\sin\psi^{-} - Q\sin\psi^{+} + U\cos\psi^{+} - jV\cos\psi^{-} & I\cos\psi^{-} - Q\cos\psi^{+} - U\sin\psi^{+} - jV\sin\psi^{-} \end{bmatrix}\right)$$

(where $\psi^{+} = \psi_a + \psi_b$ and $\psi^{-} = \psi_a - \psi_b$, being ψ_a and ψ_b the *parallactic angles* of the antennas).

PolConvert (Martí-Vidal et al. 2016))

- It takes VLBI products (correlated in either a linear and/or mixed polarization basis) and generates new versions of the products, written in a circular polarization basis.
- How? It "just" estimates the cross-polarization (a.k.a. "X-Y") bandpass of each antenna (phase & amplitude) and uses this information to transform:

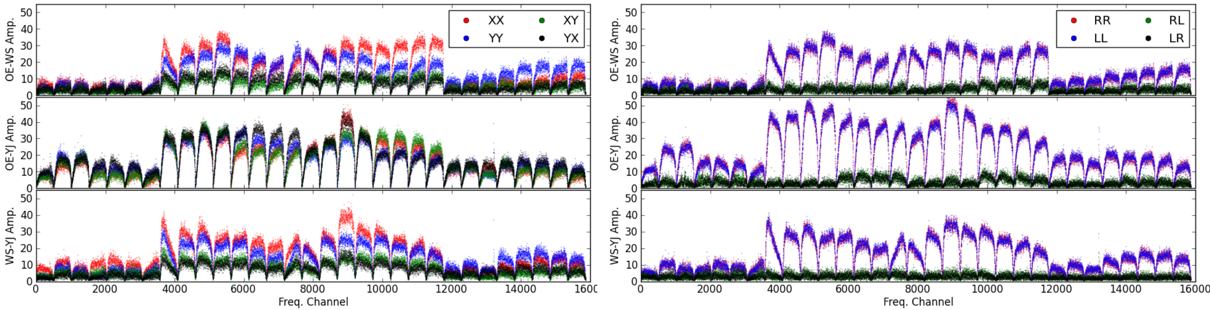
$$(\mathbf{XX}, \mathbf{XY}, \mathbf{YX}, \mathbf{YY}) \text{ or } (\mathbf{XR}, \mathbf{XL}, \mathbf{YR}, \mathbf{YL}) \rightarrow (\mathbf{RR}, \mathbf{RL}, \mathbf{LR}, \mathbf{LL})$$

PolConvert (Martí-Vidal et al. 2016))

Vniversitat de València

- It takes VLBI products (correlated in either a linear and/or mixed polarization basis) and generates new versions of the products, written in a circular polarization basis.
- How? It "just" estimates the cross-polarization (a.k.a. "X-Y") bandpass of each antenna (phase & amplitude) and uses this information to transform:

$$(XX, XY, YX, YY) \text{ or } (XR, XL, YR, YL) \rightarrow (RR, RL, LR, LL)$$

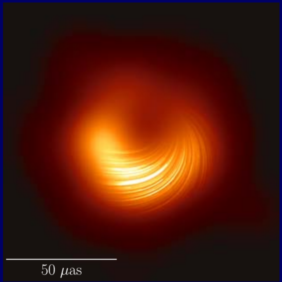


VLBI with Linear Polarizers

- PolConvert (Martí-Vidal et al. 2016), based on the RIME (Hamaker et al. 1996):

$$\begin{bmatrix} I+V & Q+jU \\ Q-jU & I-V \end{bmatrix}_{ab} = C_{\odot +} \begin{bmatrix} 1 & 0 \\ 0 & \rho_a \end{bmatrix} \begin{bmatrix} XX & XY \\ YX & YY \end{bmatrix} \begin{bmatrix} 1 & 0 \\ 0 & \rho_b^* \end{bmatrix} C_{+\odot}$$

where ρ_a is the cross-polarization gain (amplitude+phase) between X and Y at antenna a. It is derived by least-squares fitting (GCPFF, Martí-Vidal et al. 2016).



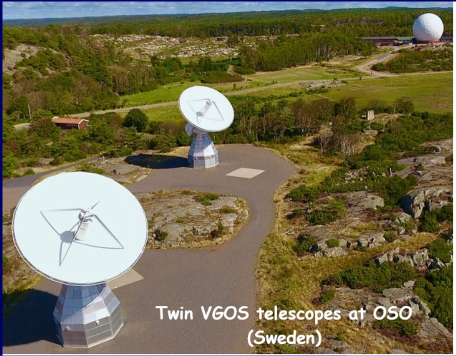
EHT Collaboration (2021)

PolConvert has been successfully used in:

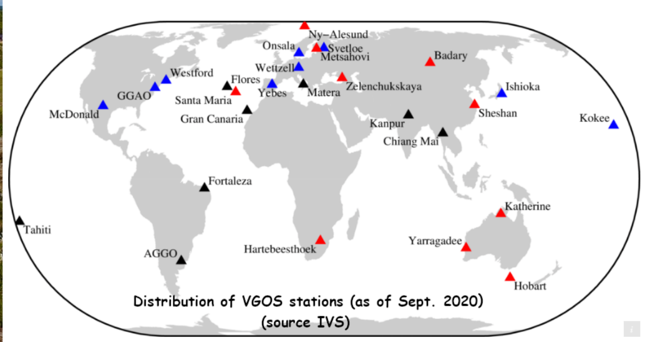
- ALMA-VLBI (GMVA and EHT).
- EVN (e.g., Effelsberg at C-band).
- ATCA and KVN (Q/W bands).
- VGOS (all stations linear).

VLBI Global Observing System (VGOS)

- International VLBI Service (IVS).
- Geodesy with a 1 mm precision (in 24 h experiments).
- Earth Orientation Parameters continuously monitored (i.e., 24/7!!).
- Frequency coverage spaced between 2–14 GHz (recording rate up to 16 Gbps).
- Currently, one full session every 2 weeks (correlated at MIT/Haystack).



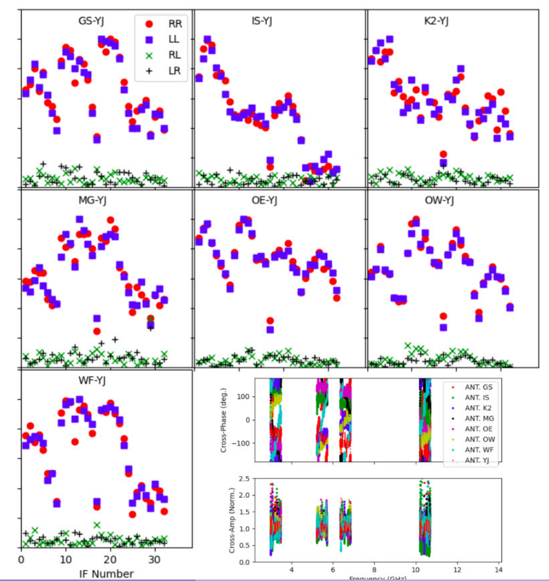
Twin VGOS telescopes at OSO (Sweden)



Distribution of VGOS stations (as of Sept. 2020)
(source IVS)

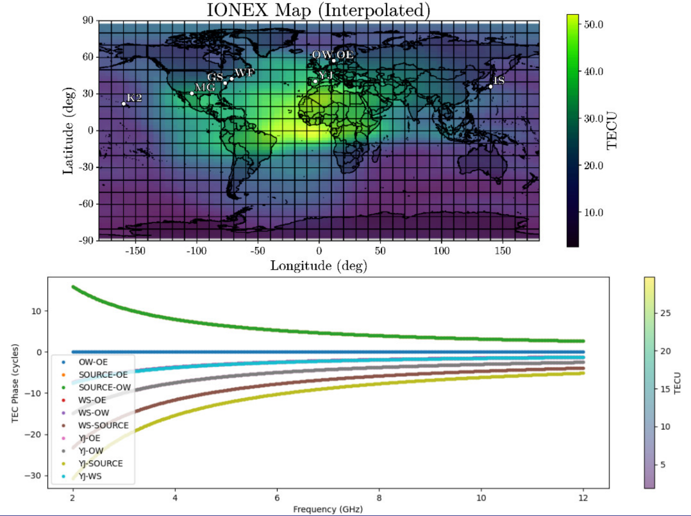
PolConvert on VGOS. Epoch VO2187

- 6–7 July 2022 (24h observing time).
- 8 antennas (7 locations).
- 1024 total bandwidth (8×32 MHz)
- Freq. from ∼3 to ∼11 GHz.
- 74 sources and 1 950 scans (30 s).
  - 1803+784, OJ287, 3C418, 1849+670, ...



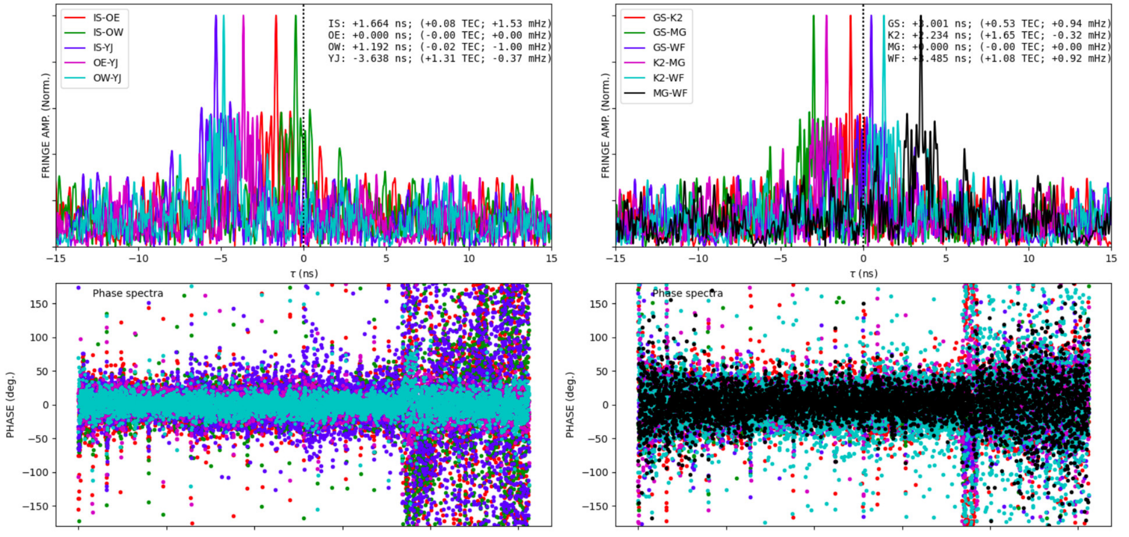
V. Pérez, I. Martí-Vidal et al. (in prep.)

VO2187. Wideband Global Fringe Fitting

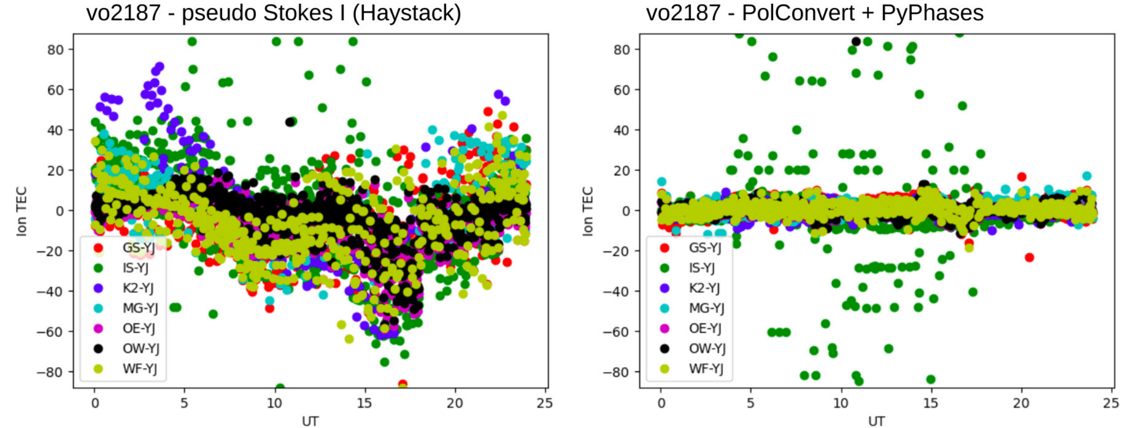


PolConvert now includes a global wideband fringe fitter (with IONEX priors).

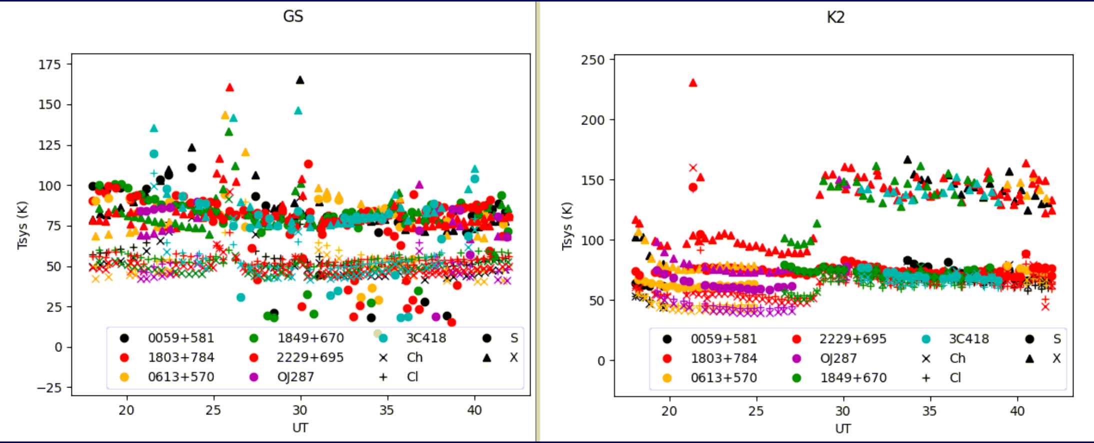
VO2187. Wideband Global Fringe Fitting



VO2187. Wideband Global Fringe Fitting



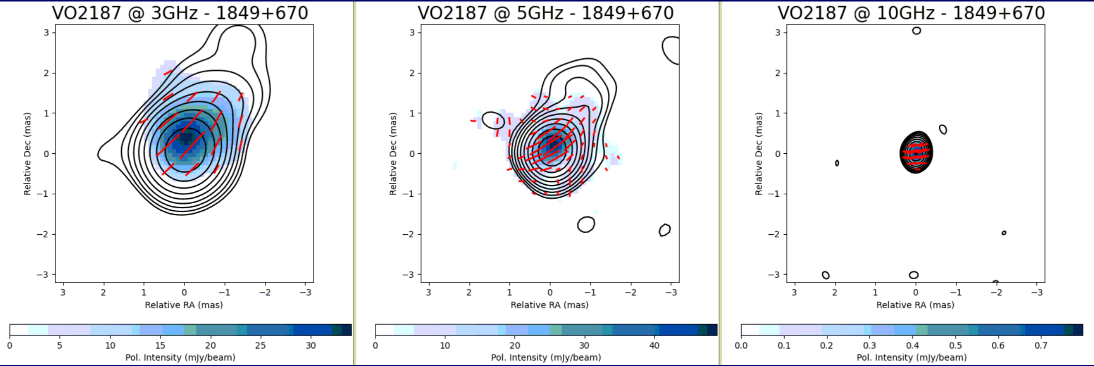
VO2187. Amplitude Calibration



Thanks to C. Garc ía-Miró and F. Paredes (Yebes/IGN)

… and Full Polarization Images!

VNIVERSITAT D VALÈNCIA



Morphological and polarization analysis on-going (V. Pérez et al., in preparation)

Summary

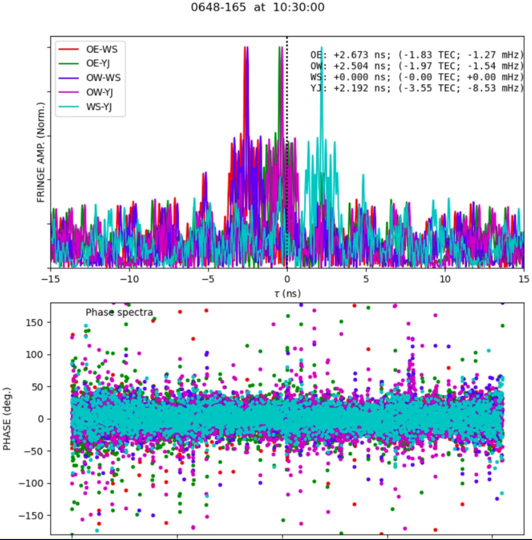
VNIVERSITAT DE VALÈNCIA

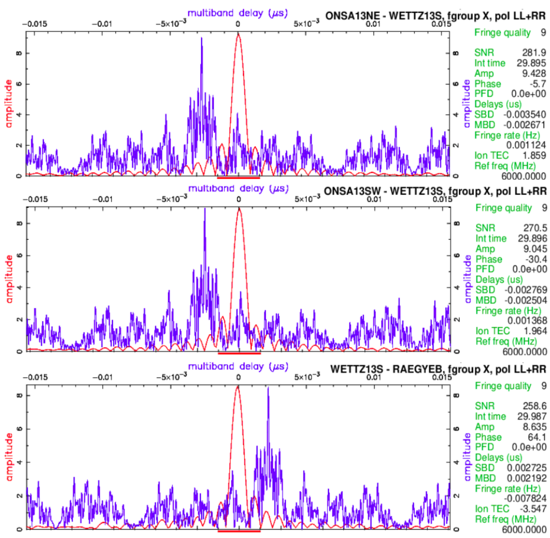
- PolConvert allows to perform full-polarization VLBI from observations using linear feeds.
- Transforms linear-linear and linear-circular into circular-circular, by fitting the instrumental polarization.
- We have developed a Wideband Global Fringe Fitting, which fits dispersive and non-dispersive terms (subtracting IONEX priors).
- We are able to fully calibrate (in polarization!) a VGOS epoch and make images!
- Analysis of results will be published soon!

Thanks!

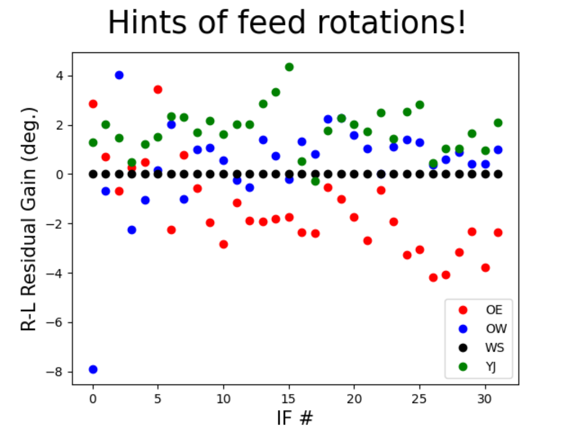
Backup Slides

Polconverted VGOS Fringes



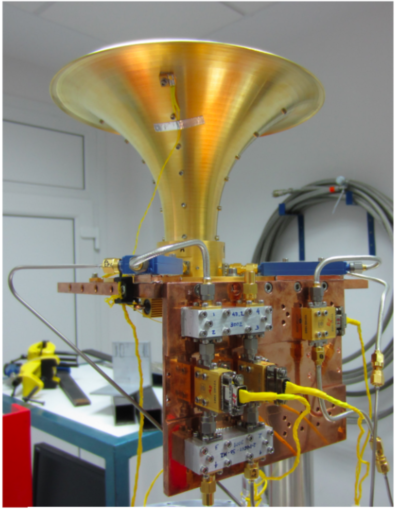


The precision of PolConvert



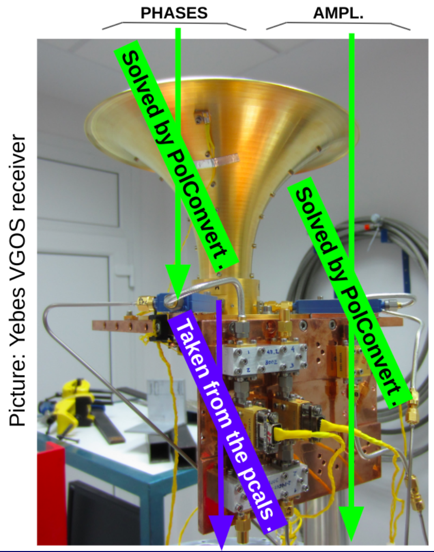
From GFF on several scans (EV0287) of different sources (NRAO150 and 0552+398).
These quantities are *consistent* among epochs and calibrators!

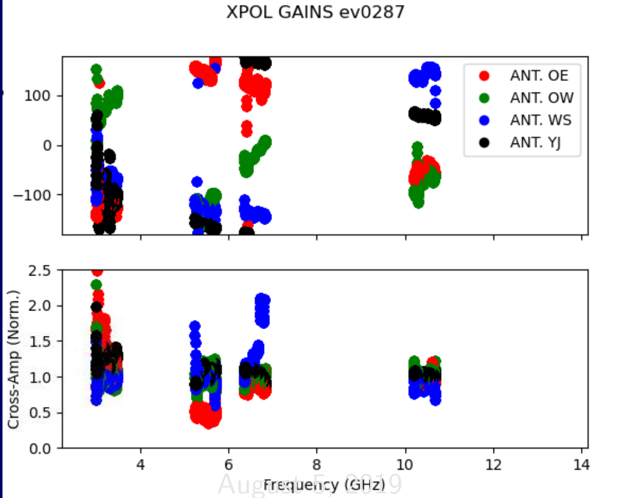
VGOS Calibration with PolConvert



Picture: Yebes VGOS receiver

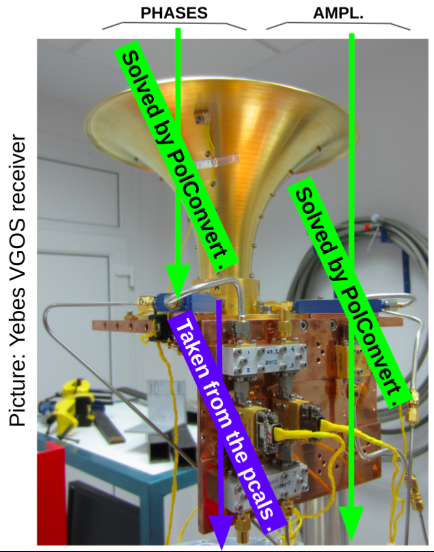
VGOS Calibration with PolConvert

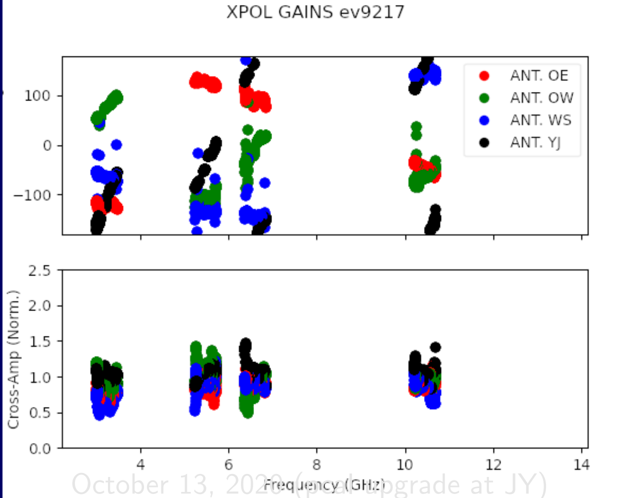




VGOS Calibration with PolConvert

VNIVERSITAT DE VALÈNCIA





VLBI with linear polarizers

Vniversitat de València

Main features/issues:

- Pseudo-I only accounts for phase (delay) differences among polarizers. Amplitude effects are not taken into account.
- Pseudo-I only handles total intensity. Source polarization cannot be retrieved.
- PolConvert generates data "as if" they had been observed with circular polarizers. Old (standard) analysis routines can still be used:

$$(XX,\ XY,\ YX,\ YY) \rightarrow (RR,\ RL,\ LR,\ LL)$$

- PolConvert accounts for amp & phase gain effects, which (if not corrected) can lead to high instrumental polarization.

Building Stokes I for VGOS

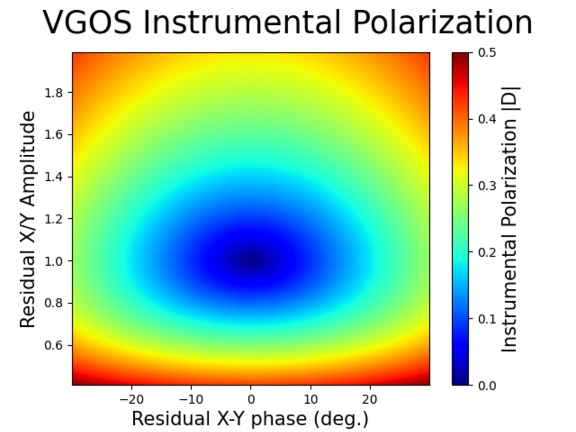
Universitat de València

Main features/issues:

- Pseudo-I only accounts for phase (delay) differences among polarizers. Amplitude effects are not taken into account.
- Pseudo-I only handles total intensity. Source polarization cannot be retrieved.
- PolConvert generates data "as if" they had been observed with circular polarizers. Old (standard) analysis routines can still be used.
- PolConvert accounts for amplitude gain effects, which (if not corrected) can lead to high instrumental polarization. PolConvert minimizes these effects.

Post-conversion Instrumental Polarization

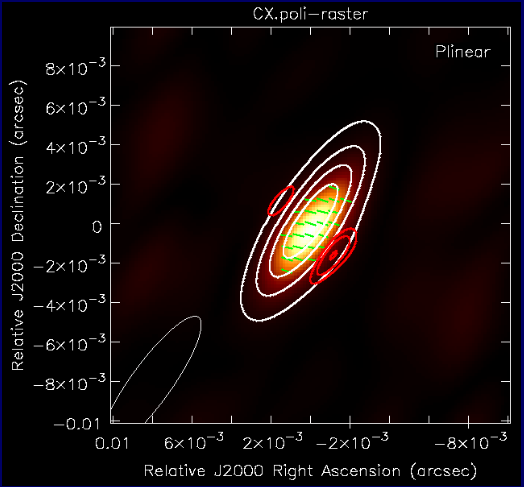
Vniversitat de València



$$I_{cal} \rightarrow I_{pseudo} \times (1 + D_a D_b^* + D_a^* D_b) + p\,(D_a + D_b^*) + p^*(D_a^* + D_b)$$

High D implies undesired effects from the source polarization, p.

VGT 260: Full-pol. structure of 3C 279!



Full-polarization MFS (Ch-X) VGOS image.

How does PolConvert Work?

VNIVERSITAT DE VALÈNCIA

Martí-Vidal et al. (2016)

Calibrates the X-Y cross-pol complex gains and converts to circular basis after correlation.

- $V_{\odot\odot} = C_{\odot +} \times G \times V_{+\odot}$ with $V_{+\odot} = \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix}$

How does PolConvert Work?

Martí-Vidal et al. (2016)

Calibrates the X-Y cross-pol complex gains and converts to circular basis after correlation.

- $V_{\odot\odot} = C_{\odot +} \times G \times V_{+\odot}$ with $V_{+\odot} = \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix}$
- The algorithm hast to find G to calibrate $V_{+\odot}$ *before* conversion.
  The effect of G is that of a *polarization leakage*:

How does PolConvert Work?

Martí-Vidal et al. (2016)

Calibrates the X-Y cross-pol complex gains and converts to circular basis after correlation.

- $V_{\odot\odot} = C_{\odot +} \times G \times V_{+\odot}$ with $V_{+\odot} = \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix}$
- The algorithm hast to find G to calibrate $V_{+\odot}$ *before* conversion. The effect of G is that of a *polarization leakage*:
- We are converting:

$$V'_{\odot\odot} \propto \begin{pmatrix} 1 & -j \\ 1 & j \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} \times \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix}$$

  where ρ is the Y/X gain ratio.
- We can re-write: $V'_{\odot\odot} \propto \begin{pmatrix} 1 & D \\ D & 1 \end{pmatrix} \times V_{\odot\odot}$, where $D = \dfrac{1-\rho}{1+\rho}$

How does PolConvert Work?

Martí-Vidal et al. (2016)

Calibrates the X-Y cross-pol complex gains and converts to circular basis after correlation.

- $V_{\odot\odot} = C_{\odot+} \times G \times V_{+\odot}$ with $V_{+\odot} = \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix}$
- The algorithm hast to find G to calibrate $V_{+\odot}$ *before* conversion.
  The effect of G is that of a *polarization leakage*:
- We are converting:

  $$V'_{\odot\odot} \propto \begin{pmatrix} 1 & -j \\ 1 & j \end{pmatrix} \times \begin{pmatrix} 1 & 0 \\ 0 & \rho \end{pmatrix} \times \begin{pmatrix} V_{xr} & V_{xl} \\ V_{yr} & V_{yl} \end{pmatrix}$$

  where ρ is the Y/X gain ratio.
- We can re-write: $V'_{\odot\odot} \propto \begin{pmatrix} 1 & D \\ D & 1 \end{pmatrix} \times V_{\odot\odot}$, where $D = \frac{1-\rho}{1+\rho}$
- If $\rho \sim 1$, we can use ordinary pol. calibration to correct for this effect

Calibration Approach (non-ALMA)

Martí-Vidal et al. (2016)

Global *Cross-Polarization* Fringe Fitting: $\min\left[\chi^2(\vec{\rho})\right]$ with

$$\chi^2(\vec{\rho}) = \sum_k (RR_k/LL_k - 1)^2 + \lambda \left[\sum_k (RL_k^2 + LR_k^2)\right]$$

$$\chi^2 = \chi^2_{+\odot} + \chi^2_{\odot\odot} \text{ with } \chi^2_{+\odot} = \sum_k \omega_k \left[\frac{V^k_{xr}\rho_+^{-1} - jV^k_{yr}}{V^k_{xl}\rho_+^{-1} + jV^k_{yl}}(e^{\psi_+})(e^{\psi^*_\odot})(\rho_\odot^{-1})^* - 1\right]^2$$

Calibration Approach (non-ALMA)

Martí-Vidal et al. (2016)

Global *Cross-Polarization* Fringe Fitting: $\min\left[\chi^2(\vec{\rho})\right]$ with

$$\chi^2(\vec{\rho}) = \sum_k (RR_k/LL_k - 1)^2 + \lambda\left[\sum_k (RL_k^2 + LR_k^2)\right]$$

$$\chi^2 = \chi^2_{+\odot} + \chi^2_{\odot\odot} \text{ with } \chi^2_{+\odot} = \sum_k \omega_k \left[\frac{V^k_{xr}\rho_+^{-1} - jV^k_{yr}}{V^k_{xl}\rho_+^{-1} + jV^k_{yl}}(e^{\psi_+})(e^{\psi^*_\odot})(\rho_\odot^{-1})^* - 1\right]^2$$

- The idea is to derive all the cross-polarization gains in one shot (for both linear and circular polarizers).
- This approach is independent of the source structure! (and you don't even need to fringe-fit nor amplitude-correct first!)

Calibration Approach (non-ALMA)

Vniversitat de València

Martí-Vidal et al. (2016)

Global *Cross-Polarization* Fringe Fitting: $\min\left[\chi^2(\vec{\rho})\right]$ with

$$\chi^2(\vec{\rho}) = \sum_k (RR_k/LL_k - 1)^2 + \lambda\left[\sum_k \left(RL_k^2 + LR_k^2\right)\right]$$

$$\chi^2 = \chi^2_{+\odot} + \chi^2_{\odot\odot} \text{ with } \chi^2_{+\odot} = \sum_k \omega_k \left[\frac{V^k_{xr}\rho_+^{-1} - jV^k_{yr}}{V^k_{xl}\rho_+^{-1} + jV^k_{yl}}(e^{\psi_+})(e^{\psi^*_\odot})(\rho_\odot^{-1})^* - 1\right]^2$$

- The idea is to derive all the cross-polarization gains in one shot (for both linear and circular polarizers).
- This approach is independent of the source structure! (and you don't even need to fringe-fit nor amplitude-correct first!)
- And you can get the absolute EVPA calibration for free!!!