CASA VLBI

WORKSHOP 2020

2-6 NOVEMBER 2020

LECTURE 11: POLARIZATION CALIBRATION

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CASA Common Astronomy Software Applications

JIVE Joint Institute for VLBI ERIC

RadioNet

JUMPING JIVE Joint Institute for VLBI ERIC

Polarization Calibration in VLBI

AIPS tools and status of CASA tools

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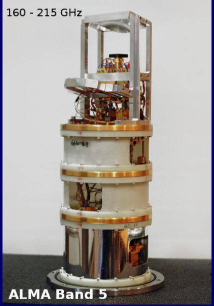
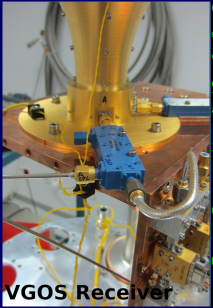
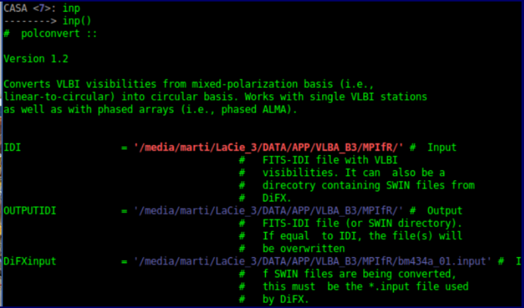
Basic Concepts

Dterms: The Root of All Evil







- The signal is split into orthogonal polarizations (e.g., OMTs, reflection gratings, T-septums, ...)
- Polarizations can also be converted in different ways (e.g., quarter waveplates, software).
- None of these devices is perfect. Signals from one polarization are leaked into the other.
- Such a leakage (with a given amplitude and delay/phase) is modelled with the Dterms.

The MEq: A Full-Stokes Interferometry Formalism

For a source with a generic (polarized) brightness distribution, the visibility matrix between two antennas a and b (with no DDEs) is

$$\mathcal{V}_{ab}^{obs} = J_a \left[\int_{\alpha,\delta} \mathcal{S}\, e^{-\frac{2\pi j}{\lambda}(u\,\alpha + v\,\delta)} \frac{d\alpha\, d\delta}{z} \right] (J_b)^H ,$$

where J are the calibration Jones matrices (e.g., Smirnov 2011).

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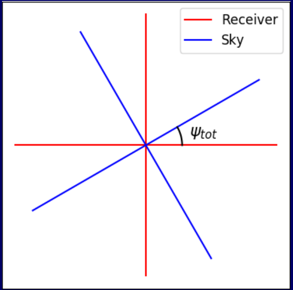
Let us remember the classical interferometer equation:

$$V_{ab}^{obs} = G_a\, G_b^* \int_{\alpha,\delta} I(\alpha,\delta)\, e^{-\frac{2\pi j}{\lambda}(u\,\alpha + v\,\delta)} \frac{d\alpha\, d\delta}{z}$$

Receiver Frame vs. Sky Frame

$$P_{xy} = \begin{pmatrix} \cos\psi & -\sin\psi \\ \sin\psi & \cos\psi \end{pmatrix} \qquad P_{rl} = \begin{pmatrix} e^{j\psi} & 0 \\ 0 & e^{-j\psi} \end{pmatrix}$$

- The parallactic angle, ψ, is the (time-dependent) rotation of the antenna-mount axis w.r.t. the sky.
- It is deterministic. In VLBI, it's good to apply it before the phase (and delay/rate) calibration.
- The Receiver and Sky frames are related by a rotation $\psi_{tot} = \psi + \psi_0$ (where ψ_0 is the antenna feed angle).



Antenna Feeds with Circular Polarizers

The visibility matrix (Rec. Frame) is

$$\mathcal{V}_{ab} = \begin{pmatrix} R_a R_b^* & R_a L_b^* \\ L_a R_b^* & L_a L_b^* \end{pmatrix}$$

The brightness matrix (Sky Frame) is

$$\mathcal{S} = \begin{pmatrix} I+V & Q+jU \\ Q-jU & I-V \end{pmatrix}$$

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Rotation matrix: $P(\psi_{tot}) = \begin{pmatrix} e^{j\psi_{tot}} & 0 \\ 0 & e^{-j\psi_{tot}} \end{pmatrix}$

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$$\mathcal{V}_{ab}^{Sky} = P(-\psi_{tot}^a)\mathcal{V}_{ab}^{Rec} P(\psi_{tot}^b)$$

$$\mathcal{S}_{ab}^{Rec} = P(\psi_{tot}^a)\mathcal{S}_{ab}^{Sky} P(-\psi_{tot}^b) = \begin{pmatrix} (I+V)\,e^{j\delta} & (Q+jU)\,e^{j\Delta} \\ (Q-jU)\,e^{-j\Delta} & (I-V)\,e^{-j\delta} \end{pmatrix}$$

where $\Delta = \psi_{tot}^a + \psi_{tot}^b$ and $\delta = \psi_{tot}^a - \psi_{tot}^b$

Jones Calibration Matrices. Examples

- Gain, $G^{Rec} = \begin{pmatrix} A_R(t)\, e^{j\phi_x(t)} & 0 \\ 0 & A_L(t)\, e^{j\phi_y(t)} \end{pmatrix}$

- Bandpass, $B^{Rec} = \begin{pmatrix} A_R(\nu)\, e^{j\phi_x(\nu)} & 0 \\ 0 & A_L(\nu)\, e^{j\phi_y(\nu)} \end{pmatrix}$

- Pol. leakage $D^{Rec} = \begin{pmatrix} 1 & D_R(\nu) \\ D_L(\nu) & 1 \end{pmatrix}$

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- NOTE 1: The Jones matrices are defined in (and should be applied on) the **Receiver Frame**.
- NOTE 2: For circular feeds, the parallactic-angle correction is a diagonal matrix, which conmutes with G^{Rec} and B^{Rec}. Hence, we do not care much about the difference between receiver and sky frames.

Changing Frame on Jones Matrices

$$\mathcal{V}_{cal}^{Sky} = J^{Sky}\,\mathcal{V}_{uncal}^{Sky}$$

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- Gain, $G^{Sky} = \begin{pmatrix} A_R(t)\,e^{j\phi_x(t)} & 0 \\ 0 & A_L(t)\,e^{j\phi_y(t)} \end{pmatrix}$ $\rightarrow$ Is independent of ψ_{tot}
- Pol. leakage $D^{Sky} = \begin{pmatrix} 1 & D_R(\nu)e^{j2\psi_{tot}} \\ D_L(\nu)e^{-j2\psi_{tot}} & 1 \end{pmatrix}$ $\rightarrow$ Depends on ψ_{tot}!

Changing Frame on Jones Matrices

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We can use the time dependence of ψ_{tot} to decouple the effects of source polarization (which are constant on the sky frame) from the instrumental polarization (which is constant on the receiver frame).

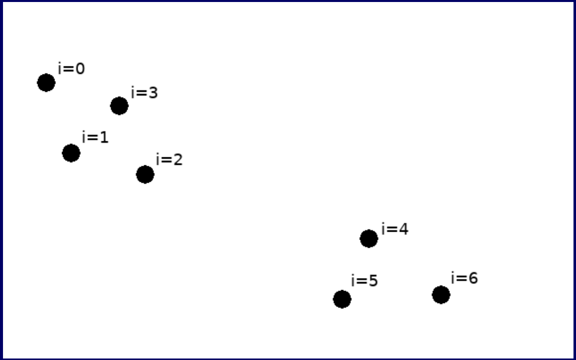
LPCAL and PolSolve: Algorithms and Conventions

VLBI Polarimetry Software

The problem of using spatially-resolved polarization calibrators

- **Inverse Modelling**.
  - **LPCAL**: Based on AIPS (Leppänen et al. 1995). Pretty old, but well established and tested.
  - **GPCAL**: Based on AIPS/ParselTongue (Park et al. 2020). Overcomes some LPCAL limitations.
  - **PolSolve**: Based on CASA (I. Marti-Vidal et al. 2020). Overcomes some LPCAL limitations.
- **Forward Modelling**.
  - **EHTim** (A. Chael et al. 2018, 2020)
- **MCMC**.
  - **DMC** (D. Pesce 2020) and **THEMIS** (Broderick et al. 2020)

Modelling Polarization Structures I: Slicing



$$\mathcal{V}_I(u,v) = \sum_i^N I_i e^{\frac{2\pi}{\lambda} j(u\alpha_i + v\delta_i)}$$

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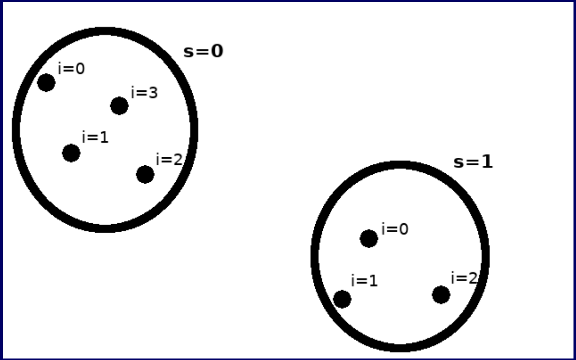

$$\mathcal{V}_I(u,v) = \sum_s \sum_i^{N_s} I_i^s \, e^{\frac{2\pi}{\lambda} j (u\alpha_i^s + v\delta_i^s)}$$

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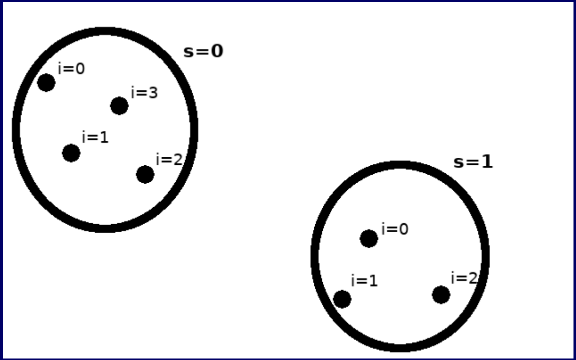

$$\mathcal{V}_I(u,v) = \sum_s \sum_i^{N_s} I_i^s e^{\frac{2\pi}{\lambda} j (u\alpha_i^s + v\delta_i^s)}$$

$$\mathcal{V}_Q(u,v) = \sum_s q_s \left[\sum_i I_i^s e^{\frac{2\pi}{\lambda} j (u\alpha_i^s + v\delta_i^s)} \right]$$

$$\mathcal{V}_U(u,v) = \sum_s u_s \left[\sum_i I_i^s e^{\frac{2\pi}{\lambda} j (u\alpha_i^s + v\delta_i^s)} \right]$$

- We split the set of CLEAN components into disjoint pieces (a.k.a. *subcomponents*) of assumed constant fractional polarization.

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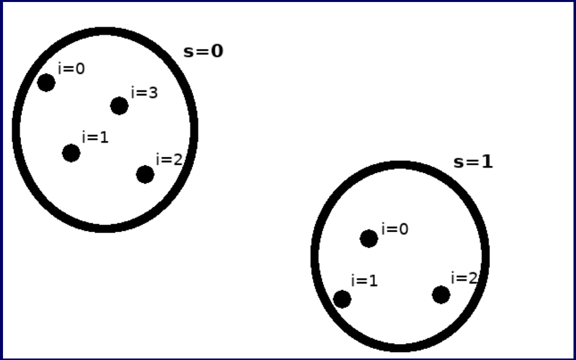

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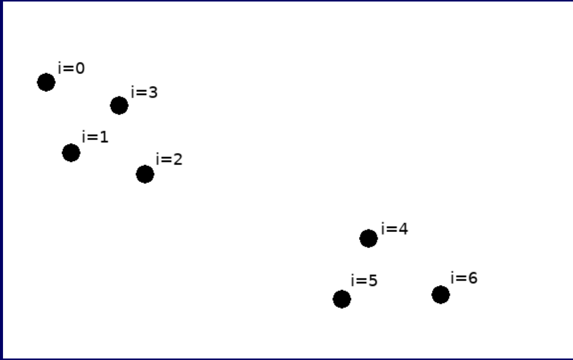
- We split the set of CLEAN components into disjoint pieces (a.k.a. *subcomponents*) of assumed constant fractional polarization.
- We fit the antenna Dterms **and** the subcomponent polarization (q_s and u_s) **together**.

Modelling Polarization Structures I: PolSelfCal



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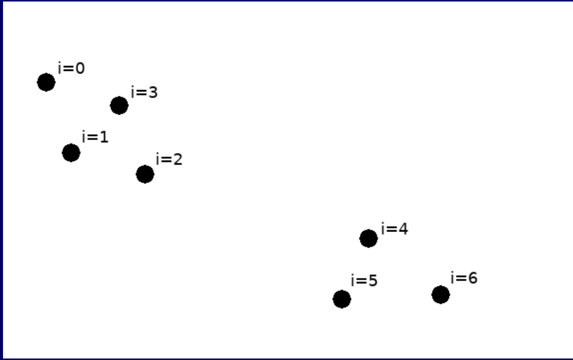

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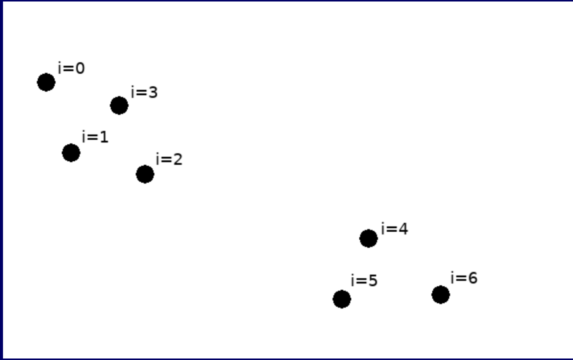

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- We only fit the antenna Dterms, keeping the full-polarization image model fixed. We iterate the procedure (similar to hybrid imaging of Stokes I).

The LPCAL Algorithm

- Fits the Dterms (and source polarization) using a linear approximation (i.e., it does *not* apply the full Meq) and the slicing approach.
- Computes the error function *in the Sky frame*.

$$\chi^2 = \sum_{i,pol} W_i \left(\mathcal{V}^{Sky}_{mod,pol} - \mathcal{V}^{Sky}_{obs,pol} \right)^2_i$$

where *pol* can be *RL* and *LR*, and (for visibilities with baseline *a*-*b*):

$$\mathcal{V}^{Sky}_{mod,RL}(u,v) = \sum_s (q_s + j u_s) \left[\sum_k I^s_k e^{2\pi j (u\alpha^s_k + v\delta^s_k)} \right] + \left((D^{Sky}_R)_a + (D^{Sky}_L)^*_b \right) \mathcal{V}^{Sky}_{obs,I}$$

and similarly for LR. The fitting parameters are q_s, u_s, and the Dterms (D_R and D_L for antennas a and b). All these parameters *are linear with* $\mathcal{V}^{Sky}_{mod,RL}$.

- Reduces the polarization calibration to a mere *linear least-squares* problem (i.e., just a matrix inversion, and that's it!).

The PolSolve Algorithm

- Fits the Dterms (and source polarization) using the full Meq (i.e., second-order approximation; good for very high fractional polarizations and/or Dterms). Uses either the slicing or the polarization selfcal approach.
- Computes the error function *in the Receiver Frame*.

$$\chi^2 = \sum_{i,pol} W_i \left(\mathcal{V}^{Rec}_{mod,pol} - \mathcal{V}^{Rec}_{obs,pol} \right)^2_i$$

where *pol* can be *RL* and *LR*, and (for visibilities with baseline *a*-*b*):

$$\mathcal{V}^{Rec}_{mod,RL}(u,v) = \left(\sum_s (q_s + j u_s) I^s_{mod} \right) (e^{-j\Delta}) + ((D_R)_a + (D_L)^*_b)\, \mathcal{V}^{Rec}_{obs,I} + (D_L)_a\, (D_R)^*_b\, \mathcal{V}^{Rec}_{obs,LR}$$

and similarly for LR. The fitting parameters are the same as with PolSolve.

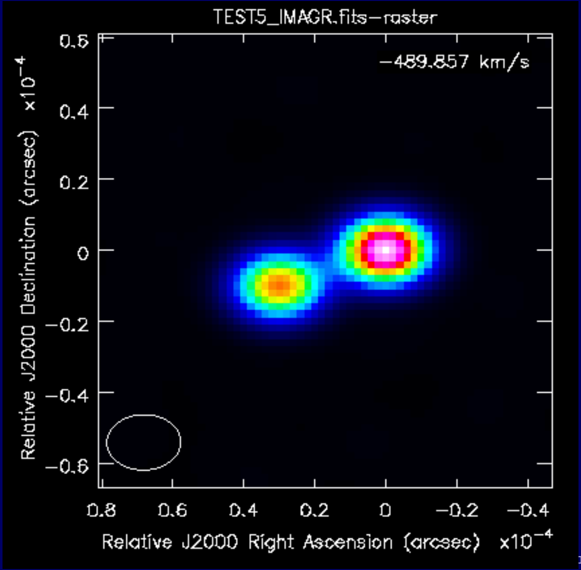
- Current developments: multi-source calibration, wide-band fitting, graphical interface (for sub-component editing), dealing with Stokes V, linear polarizers, etc.

PolSolve vs. LPCAL

LPCAL vs. PolSolve (synthetic data)

- **Source** (double source):
  - **Comp #1:** 1.4 Jy with $m = 25.00\%$, EVPA $= 26.57^\circ$.
  - **Comp #2:** 1.0 Jy with $m = 28.43\%$, EVPA $= 70.36^\circ$.
  - **Coordinates**: J2000 12h30m49.4234 -12d23m28.0439
- **Observing frequency**: 230 GHz
- **Bandwidth**: 1 GHz (4 spectral channels).
- **On-source time**: 3 hr (10 scans of 0.3 h each); **Total time**: 12 h.
- **Stations** (eight EHT telescopes):
  - ALMA, APEX, Arizona, JCMT, LMT, SMA, SPT, PV.
- **Noise**: $\tau = 0.01$; $T_{sky} = 250\,\mathrm{K}$; $T_{ground} = 270\,\mathrm{K}$; $T_{rec} = 50\,\mathrm{K}$.
- **Dterms**: Random Gaussian amplitude distribution (centered on 7% with $\sigma = 2\%$) and random Uniform phase distribution.

LPCAL vs. PolSolve (synthetic data)



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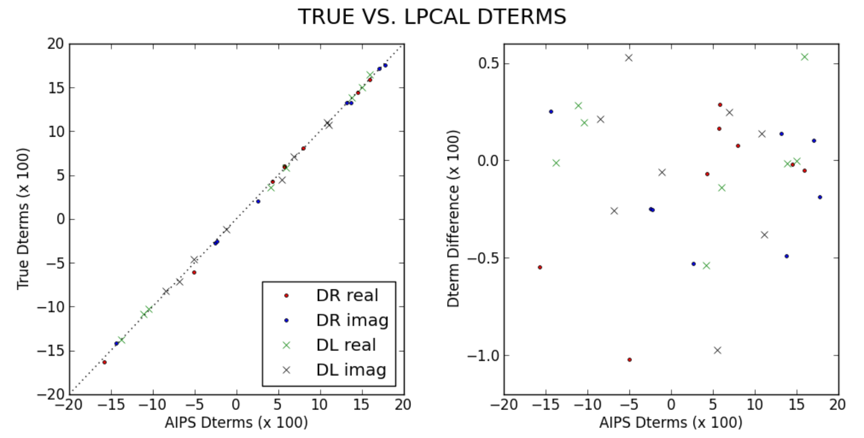

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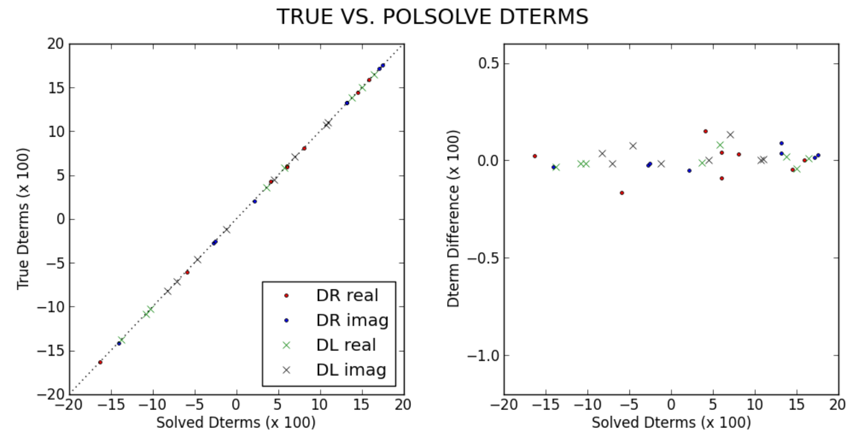
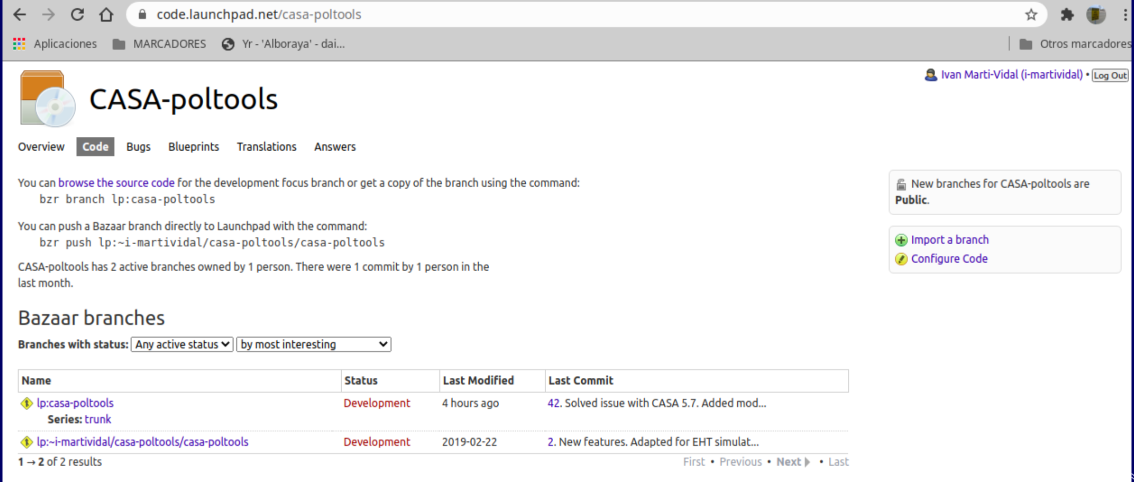


Using PolSolve

PolSolve Installation

Download it:



code.launchpad.net/casa-poltools

Aplicaciones MARCADORES Yr - 'Alboraya' - dai... Otros marcadores

Ivan Marti-Vidal (i-martividal) • Log Out

CASA-poltools

Overview Code Bugs Blueprints Translations Answers

You can browse the source code for the development focus branch or get a copy of the branch using the command:

```
bzr branch lp:casa-poltools
```

You can push a Bazaar branch directly to Launchpad with the command:

```
bzr push lp:~i-martividal/casa-poltools/casa-poltools
```

CASA-poltools has 2 active branches owned by 1 person. There were 1 commit by 1 person in the last month.

New branches for CASA-poltools are **Public**.

Import a branch
Configure Code

Bazaar branches

Branches with status: Any active status | by most interesting

Name	Status	Last Modified	Last Commit
lp:casa-poltools **Series:** trunk	Development	4 hours ago	42. Solved issue with CASA 5.7. Added mod...
lp:~i-martividal/casa-poltools/casa-poltools	Development	2019-02-22	2. New features. Adapted for EHT simulat...

1 → 2 of 2 results First • Previous • **Next** • Last

PolSolve Installation

Compile and install:

```
####################################
### OPTION 1:

   3.2.- Just run in a terminal (from the PolSolve directory):

      rm -f *.so
      $CASABASE/bin/python setup.py build_ext --inplace

   (where $CASABASE is the path to your CASA installation).
```

```
#######################################

Now, it's time to load the task into CASA:

4.- Run "buildmytasks" in that directory:

    $CASAPATH/bin/buildmytasks


5.- Edit the file /home/you/.casa/init.py
    You may need to execute CASA at least once,
    to have that ".casa" directory with the proper content.
    In that "init.py", add the lines:

       import sys
       sys.path.append('/home/you/.casa/PolTools')
       execfile('/home/you/.casa/PolTools/mytasks.py')


6.- That's it! You should be able to run the new tasks in CASA!
    Just doing:

         task polsolve    or   tget polsolve
         task polsimulate    or   tget polsimulate


    should load the tasks.
```

PolSolve Interface: Keywords

```
---------> inp()
#  polsolve :: Version 1.0.1b - Leakage solver for circular polarizers and extended polarization calibrators.

vis                 =  'AUX2.ms'        #  Name of input measurement set. The
                                        #   data should already be calibrated
                                        #   (in bandpass and gains).
spw                 =        '0'        #  Spectral window(s) to be fitted. Can
                                        #   be an integer, a list of integers,
                                        #   or a CASA-like selection string.
                                        #   Default = all spws are used.
field               =      'M87'        #  Field name (or id) to use as
                                        #   calibrator. Follows CASA syntax for
                                        #   several fields.
mounts              = ['AZ', 'NR', 'NR', 'NL', 'AZ', 'NL', 'NL', 'NL', 'AZ'] #  L
                                        #   ist of the antenna mounts (must be
                                        #   given  in the same order as the
                                        #   ANTENNA table  of the ms). Use this
                                        #   in case the mounts  were not
                                        #   properly imported into the ms. A
                                        #   mount type is specified with two
                                        #   characters. Supported mounts:  alt-
                                        #   az ('AZ'),  equatorial ('EQ'),  X-Y
                                        #   ('XY'),  Nasmyth Right ('NR') and
                                        #   Nasmyth Left ('NL').  Default means
                                        #   all antennas are alt-az.
feed_rotation       =         []        #  Rotation of the feed of each antenna
                                        #   with respect to the local
                                        #   horizontal-vertical frame. One value
                                        #   per antenna. Empty list assumes a
                                        #   null feed angle for all antennas.
```

PolSolve Interface: Keywords

```
DR          =         []        #  List of complex numbers (length equal
                                #   to the number of antennas). If not
                                #   empty,   these are the a-priori
                                #   values of   the DR leakage terms to
                                #   use   in the fit. The name of a
                                #   file, with the list pickled, can
                                #   also be given.
DL          =         []        #  List of complex numbers (length equal
                                #   to the number of antennas). If not
                                #   empty,   these are the a-priori
                                #   values of   the DL leakage terms to
                                #   use   in the fit. The name of a
                                #   file, with the list pickled, can
                                #   also be given.
DRSolve     = [True, True, False, False, True, False, True, False, False] #  L
                                #   ist of booleans (length equal to the
                                #   number of antennas). If not empty,
                                #   it will tell which DR terms are
                                #   fitted.   The DR[i] term will be
                                #   fitted if   DRSolve[i] is True.
                                #   Otherwise, DR[i]   will be fixed to
                                #   its a-priori value.   Default (i.e.,
                                #   empty list) means   to fit all DRs.
DLSolve     = [True, True, False, False, True, False, True, False, False] #  J
                                #   ust as DRSolve, but for the DL
                                #   terms
```

PolSolve Interface: Keywords

```
CLEAN_models      =     [[1.0]]          #  List of CLEAN model files (CCs given
                                         #   in PRTAB format). Each file will
                                         #   correspond to a source component
                                         #   with   the same polarization state.
                                         #   If one number   is given (instead of
                                         #   a list of filenames),  a centered
                                         #   point source (with that   flux
                                         #   density) will be used.  If more than
                                         #   one field is fitted, CLEAN_models
                                         #   will  be a List of Lists (with one
                                         #   list per field).   If names of CASA
                                         #   IQU[V] model image(s) are   given
                                         #   (i.e., filenames ended   with
                                         #   ".model"), these   models will be
                                         #   used and FIXED (i.e.,   Pfrac, EVPA
                                         #   and PolSolve will NOT be used).   If
                                         #   equal to "model_column", the model
                                         #   column   (for all correlation
                                         #   products) will be used.
```

PolSolve Interface: Keywords

```
Pfrac          =     [[0.0]]        # List of fractional polarizations (one
                                    #  number   per source component).
                                    #  Pfrac    values must fall between 0
                                    #  and 1.  If more than one field is
                                    #  fitted,   this will be a List of
                                    #  Lists (one list per field).
EVPA           =     [[0.0]]        # List of EVPAs in degrees (one number
                                    #  per source component). Angles   are
                                    #  measured from North to East.  If
                                    #  more than one field is fitted,
                                    #  this will be a List of Lists (one
                                    #  list per field).
PolSolve       =    [[True]]        # List of booleans (one per source
                                    #  component)   that tell which source
                                    #  components   are to be fitted in
                                    #  polarization.   If PolSolve[i] is
                                    #  True, the fractional   polarization
                                    #  and EVPA of the ith source
                                    #  component will be fitted, together
                                    #  with   the antenna Dterms. If False,
                                    #  all   Stokes parameters of the ith
                                    #  component will   be fixed in the
                                    #  fit.   Empty list means to fit the
                                    #  polarization   of all the source
                                    #  components.  If more than one field
                                    #  is fitted,   this will be a List of
```

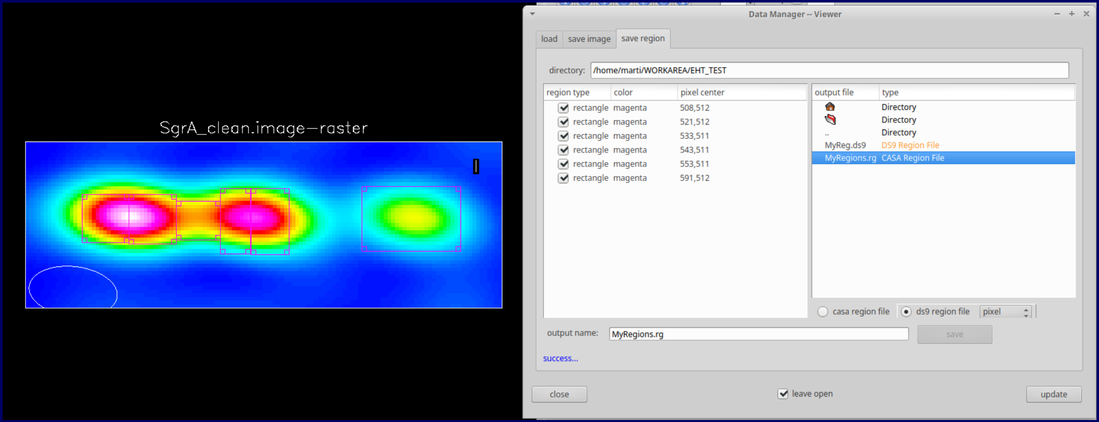
PolSolve Interface: Keywords


```
parang_corrected    =     True        #  If True, the data are assumed to be
                                      #   already corrected for parallactic
                                      #   angle.   This is usually the case,
                                      #   unless   you are working with data
                                      #   generated with   polsimulate with no
                                      #   parang correction.
target_field        =      ''         #  List of sources to which apply the
                                      #   Dterm (and parangle) correction. It
                                      #   must follow the CASA syntax if a
                                      #   range of field ids is given. Empy
                                      #   list means NOT to apply the Dterms
                                      #   (i.e., just save them in a
                                      #   calibration table). If you want to
                                      #   apply the calibration, DO NOT FORGET
                                      #   TO *ALWAYS* RUN CLEARCAL BEFORE
                                      #   POLSOLVE!!
```

PolSolve Interface: Keywords

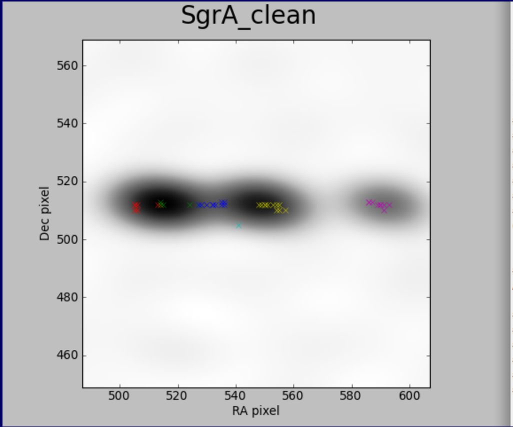
```
plot_parang         =    True      # If True, plot the time evolution of
                                   #  the antenna feed angles (i.e.,
                                   #  parallactic angle plus correction
                                   #  from the antenna mounts).
min_elev_plot       =    10.0      #  In degrees. If plot_parang is True,
                                   #  points with elevations lower than
                                   #  this limit will be plotted in red.
                                   #  THIS DOES NOT FLAG THE DATA. If you
                                   #  want to flag them, run the flagdata
                                   #  task.
wgt_power           =     1.0      #  Power for the visibility weights.
                                   #  Unity means to leave the weights
                                   #  untouched (i.e., equivalent to
                                   #  natural weighting, but for the fit).
                                   #  Zero means equal weights for all
                                   #  visibilities (i.e., equivalent to
                                   #  uniform weighting for the fit).
rewgt_pfrac         =     0.0      # Modify the weights by
                                   #  1/(1+rewgt_pfrac*p), where p is the
                                   #  source contribution to the
                                   #  visibility fractional polarization
                                   #  (estimated from the best-fit model
                                   #  with the original weights).
linear_approx       =   False      # If True, solve the polarimetry by
                                   #  assuming linear dependence of
                                   #  visibilities with Dterms (i.e., a la
                                   #  LPCAL; faster).
plot_residuals      =    True      # If True, plot the residual cross-hand
                                   #  visibilities vs. difference of
                                   #  parallactic angle.
```

PolSolve Interface: Slicing approach



First, run (t)`CLEAN`, set the regions (e.g., with `imview`) and save them into a file. and estimate de Dterms

PolSolve Interface: Slicing approach




```python
import numpy as np
import pylab as pl
import os, sys
import glob

# The user should use the task "imview" to get the pixel coordinates of the
# BLC and TRC of the boxes that will define the polarization sub-components.
# In this case, we are using several sub-components, stored in the "MyRegions.rg"
# file. The helper task called "CCextract" takes all the CASA (or DS9) regions
# defined there (you can use  boxes, circles, ellipses, etc.), extracts the
# CC components of each region and saves them in ascii format, to be read by
# PolSolve:
CCextract(model_image='SgrA_clean.model',
          regions='MyRegions.rg',make_plot=True)

## Get all the subcomponent files:
ALLCCs = glob.glob('SgrA_clean.model.CC??')

# NOTE: CCextract has an option to make a plot of the CLEAN deltas in each
# sub-component (using different colors). In addition, you should pay attention
# to the warnings regarding CLEAN components appearing in more than one region.
# If this happens, the CLEAN component is only added to the region first
# appearing in the list. This behaviour can indeed be used to make fancy
# boolean region conditions!
```

Second, execute `CCextract` (generate CC files from the regions). and estimate de Dterms

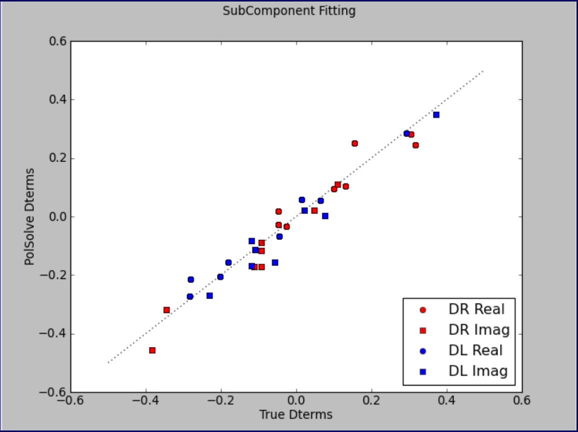
PolSolve Interface: Slicing approach

```
Undoing parang correction
 ITER 7. ChiSq 7.084e-04 ; Model Factors:  0 -> 1.000e+00
Fitting results:
FIELD ID 0:

Source id 0 (POLSIM), Component #0: Pfrac =  1.1783 +/- 0.006 ; EVPA =  -3.28 +/- 0.15 deg. (Q/I = 1.170e+00 +/- 6.33
Source id 0 (POLSIM), Component #1: Pfrac =  0.0607 +/- 0.001 ; EVPA =  34.84 +/- 0.41 deg. (Q/I = 2.107e-02 +/- 8.82
Source id 0 (POLSIM), Component #2: Pfrac =  0.5079 +/- 0.004 ; EVPA = -66.59 +/- 0.23 deg. (Q/I = -3.473e-01 +/- 3.9
Source id 0 (POLSIM), Component #3: Pfrac =  0.5037 +/- 0.002 ; EVPA =  22.29 +/- 0.09 deg. (Q/I = 3.588e-01 +/- 1.52
Source id 0 (POLSIM), Component #4: Pfrac =  28.9944 +/- 0.206 ; EVPA =  30.28 +/- 0.22 deg. (Q/I = 1.425e+01 +/- 2.1
Source id 0 (POLSIM), Component #5: Pfrac =  0.2301 +/- 0.001 ; EVPA = -48.12 +/- 0.10 deg. (Q/I = -2.498e-02 +/- 7.9

 Dterms (Right):
Antenna #0 (AA):  Real =  9.58e-02 +/- 5.7e-04; Imag = -8.85e-02 +/- 5.7e-04 | Amp = 0.1304 | Phase: -42.71 deg.
Antenna #1 (AP):  Real = -3.49e-02 +/- 6.2e-04; Imag =  1.10e-01 +/- 6.2e-04 | Amp = 0.1151 | Phase: 107.67 deg.
Antenna #2 (AZ):  Real =  1.05e-01 +/- 1.6e-03; Imag = -1.15e-01 +/- 1.6e-03 | Amp = 0.1560 | Phase: -47.58 deg.
Antenna #3 (JC):  Real =  2.81e-01 +/- 1.2e-03; Imag = -1.71e-01 +/- 1.2e-03 | Amp = 0.3287 | Phase: -31.40 deg.
Antenna #4 (LM):  Real = -2.62e-02 +/- 5.8e-04; Imag =  2.06e-02 +/- 5.8e-04 | Amp = 0.0333 | Phase: 141.93 deg.
Antenna #5 (SM):  Real =  1.89e-02 +/- 2.6e-03; Imag = -4.55e-01 +/- 2.5e-03 | Amp = 0.4550 | Phase: -87.62 deg.
Antenna #6 (SP):  Real =  2.46e-01 +/- 1.3e-03; Imag = -3.17e-01 +/- 1.3e-03 | Amp = 0.4015 | Phase: -52.21 deg.
Antenna #7 (PV):  Real =  2.51e-01 +/- 1.5e-03; Imag = -1.73e-01 +/- 1.5e-03 | Amp = 0.3049 | Phase: -34.55 deg.

 Dterms (Left):
Antenna #0 (AA):  Real = -2.06e-01 +/- 5.7e-04; Imag = -1.12e-01 +/- 5.7e-04 | Amp = 0.2346 | Phase: -151.46 deg.
Antenna #1 (AP):  Real =  5.65e-02 +/- 6.5e-04; Imag =  2.01e-02 +/- 6.5e-04 | Amp = 0.0600 | Phase: 19.62 deg.
Antenna #2 (AZ):  Real = -1.57e-01 +/- 1.6e-03; Imag = -2.70e-01 +/- 1.6e-03 | Amp = 0.3125 | Phase: -120.07 deg.
Antenna #3 (JC):  Real = -2.13e-01 +/- 1.2e-03; Imag =  4.01e-03 +/- 1.2e-03 | Amp = 0.2133 | Phase: 178.92 deg.
Antenna #4 (LM):  Real =  2.86e-01 +/- 6.3e-04; Imag = -1.68e-01 +/- 6.4e-04 | Amp = 0.3314 | Phase: -30.41 deg.
Antenna #5 (SM):  Real = -6.82e-02 +/- 2.6e-03; Imag = -1.55e-01 +/- 2.6e-03 | Amp = 0.1694 | Phase: -113.74 deg.
Antenna #6 (SP):  Real =  5.94e-02 +/- 1.2e-03; Imag = -8.12e-02 +/- 1.2e-03 | Amp = 0.1006 | Phase: -53.80 deg.
Antenna #7 (PV):  Real = -2.71e-01 +/- 1.2e-03; Imag =  3.50e-01 +/- 1.2e-03 | Amp = 0.4432 | Phase: 127.74 deg.

CASA <7>:
```

```
# Solve for Dterms and source polarization:
polsolve(vis='SgrA_polsimulate.ms',
## The mounts should be given following the order of the ANTENNA table:
         mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## This is the list of ascii files created by "CCextract":
         CLEAN_models=ALLCCs,
## Initial guesses of the polarization state of each sub-component:
         Pfrac=[0. for pi in ALLCCs], EVPA=[0. for pi in ALLCCs],
## Solve for the polarization of all three sub-components:
PolSolve=[True for pi in ALLCCs],
## Apply the full non-linear Dterm model:
linear_approx=False)

## Change the name of the Dterm CASA table, to keep it:
os.system('rm -rf LPCAL.Dterms')
os.system('cp -r SgrA_polsimulate.ms.spw_0.Dterms LPCAL.Dterms')

## READ FITTED DTERMS:
tb.open('SgrA_polsimulate.ms.spw_0.Dterms')
DTS = tb.getcol('CPARAM')
tb.close()



## RECOVER SIMULATED DTERMS:
```

Finally, use the CC files with `polsolve` and estimate de Dterms

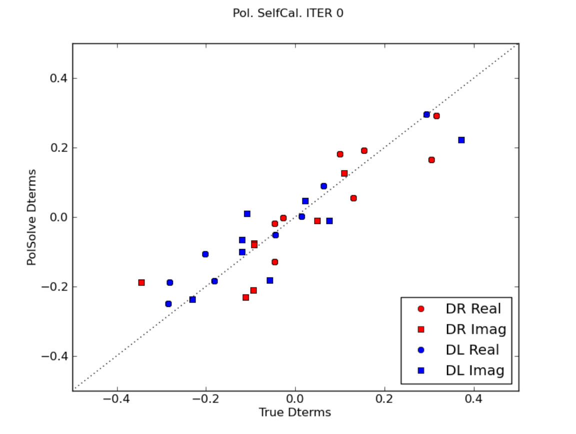
PolSolve Interface: Slicing approach



Finally, use the CC files with `polsolve` and estimate de Dterms

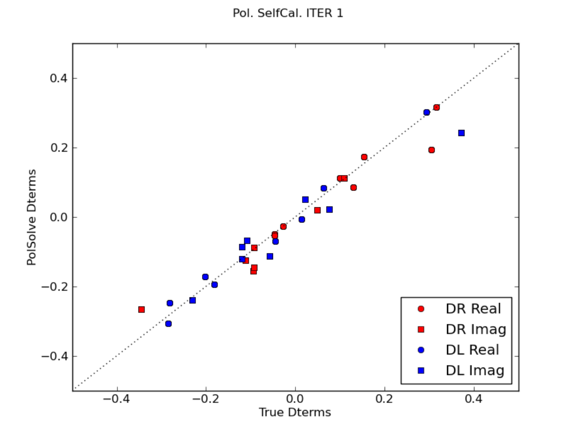
PolSolve Interface: Pol. SelfCal

```
# ITERATE!!
for i in range(NITER):

  print '\n\n ITERATION %i\n\n'%i

## We CLEAN the image, using the visibilities stored in
# the "corrected" column of the measurement set:
  os.system('rm -rf SgrA_SC_clean*')
  tclean(vis='SgrA_polsimulate.ms',
    imagename='SgrA_SC_clean',
    specmode = 'mfs',
    niter = 200,
    interactive=False,
    imsize=1024,
    cell = '0.000001arcsec',
    stokes = 'IQUV',
    mask = 'TCLEAN.mask', ## We use the mask that we created manually.
    weighting = 'uniform',
    deconvolver='hogbom',
    gain=0.1,
    restart=False)

# We remove the previous Dterm table:
  os.system('rm -rf SgrA_polsimulate.ms.spw_0.Dterms')

# Solve for the Dterms:
  polsolve(vis='SgrA_polsimulate.ms',
## If we set "target_field", the Dterms will not only be
# estimated, but also APPLIED to the "corrected" column.
# This is ESSENTIAL for the self-cal approach to work:
        target_field='POLSIM', # Source name
## Antenna mounts (the ordering should be that of the ANTENNA table):
        mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## If "CLEAN_models" is the path to a (full-polarization) CASA image,
## the self-calibration approach is activated:
        CLEAN_models='SgrA_SC_clean.model',
# These values are not really used:
        Pfrac=[0.], EVPA=[0.], PolSolve=[False],
## Set this to True, if you want to test the linear Dterm model:
        linear_approx=False)
```



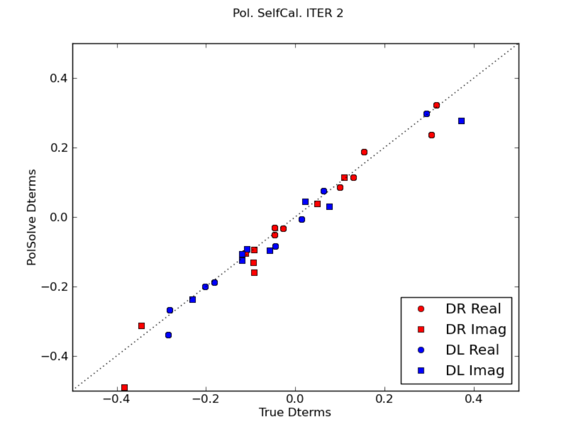
PolSolve Interface: Pol. SelfCal

```
# ITERATE!!
for i in range(NITER):

  print '\n\n ITERATION %i\n\n'%i

## We CLEAN the image, using the visibilities stored in
# the "corrected" column of the measurement set:
  os.system('rm -rf SgrA_SC_clean*')
  tclean(vis='SgrA_polsimulate.ms',
    imagename='SgrA_SC_clean',
    specmode = 'mfs',
    niter = 200,
    interactive=False,
    imsize=1024,
    cell = '0.000001arcsec',
    stokes = 'IQUV',
    mask = 'TCLEAN.mask', ## We use the mask that we created manually.
    weighting = 'uniform',
    deconvolver='hogbom',
    gain=0.1,
    restart=False)

# We remove the previous Dterm table:
  os.system('rm -rf SgrA_polsimulate.ms.spw_0.Dterms')

# Solve for the Dterms:
  polsolve(vis='SgrA_polsimulate.ms',
## If we set "target_field", the Dterms will not only be
# estimated, but also APPLIED to the "corrected" column.
# This is ESSENTIAL for the self-cal approach to work:
        target_field='POLSIM', # Source name
## Antenna mounts (the ordering should be that of the ANTENNA table):
        mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## If "CLEAN_models" is the path to a (full-polarization) CASA image,
## the self-calibration approach is activated:
        CLEAN_models='SgrA_SC_clean.model',
# These values are not really used:
        Pfrac=[0.], EVPA=[0.], PolSolve=[False],
## Set this to True, if you want to test the linear Dterm model:
        linear_approx=False)
```



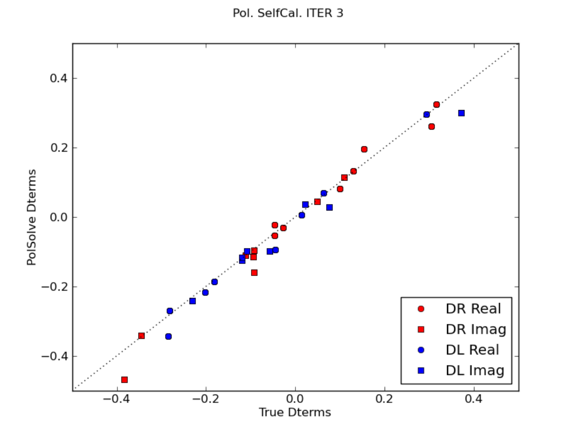
PolSolve Interface: Pol. SelfCal

```
# ITERATE!!
for i in range(NITER):

  print '\n\n ITERATION %i\n\n'%i

## We CLEAN the image, using the visibilities stored in
# the "corrected" column of the measurement set:
  os.system('rm -rf SgrA_SC_clean*')
  tclean(vis='SgrA_polsimulate.ms',
    imagename='SgrA_SC_clean',
    specmode = 'mfs',
    niter = 200,
    interactive=False,
    imsize=1024,
    cell = '0.000001arcsec',
    stokes = 'IQUV',
    mask = 'TCLEAN.mask', ## We use the mask that we created manually.
    weighting = 'uniform',
    deconvolver='hogbom',
    gain=0.1,
    restart=False)

# We remove the previous Dterm table:
  os.system('rm -rf SgrA_polsimulate.ms.spw_0.Dterms')

# Solve for the Dterms:
  polsolve(vis='SgrA_polsimulate.ms',
## If we set "target_field", the Dterms will not only be
# estimated, but also APPLIED to the "corrected" column.
# This is ESSENTIAL for the self-cal approach to work:
        target_field='POLSIM', # Source name
## Antenna mounts (the ordering should be that of the ANTENNA table):
        mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## If "CLEAN_models" is the path to a (full-polarization) CASA image,
## the self-calibration approach is activated:
        CLEAN_models='SgrA_SC_clean.model',
# These values are not really used:
        Pfrac=[0.], EVPA=[0.], PolSolve=[False],
## Set this to True, if you want to test the linear Dterm model:
        linear_approx=False)
```



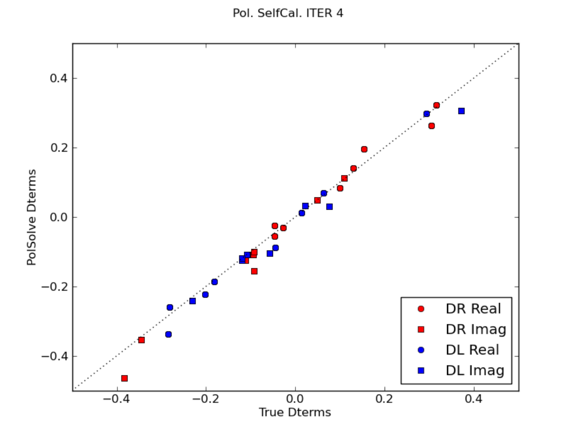
PolSolve Interface: Pol. SelfCal

```
# ITERATE!!
for i in range(NITER):

  print '\n\n ITERATION %i\n\n'%i

## We CLEAN the image, using the visibilities stored in
# the "corrected" column of the measurement set:
  os.system('rm -rf SgrA_SC_clean*')
  tclean(vis='SgrA_polsimulate.ms',
    imagename='SgrA_SC_clean',
    specmode = 'mfs',
    niter = 200,
    interactive=False,
    imsize=1024,
    cell = '0.000001arcsec',
    stokes = 'IQUV',
    mask = 'TCLEAN.mask', ## We use the mask that we created manually.
    weighting = 'uniform',
    deconvolver='hogbom',
    gain=0.1,
    restart=False)

# We remove the previous Dterm table:
  os.system('rm -rf SgrA_polsimulate.ms.spw_0.Dterms')

# Solve for the Dterms:
  polsolve(vis='SgrA_polsimulate.ms',
## If we set "target_field", the Dterms will not only be
# estimated, but also APPLIED to the "corrected" column.
# This is ESSENTIAL for the self-cal approach to work:
        target_field='POLSIM', # Source name
## Antenna mounts (the ordering should be that of the ANTENNA table):
        mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## If "CLEAN_models" is the path to a (full-polarization) CASA image,
## the self-calibration approach is activated:
        CLEAN_models='SgrA_SC_clean.model',
# These values are not really used:
        Pfrac=[0.], EVPA=[0.], PolSolve=[False],
## Set this to True, if you want to test the linear Dterm model:
        linear_approx=False)
```



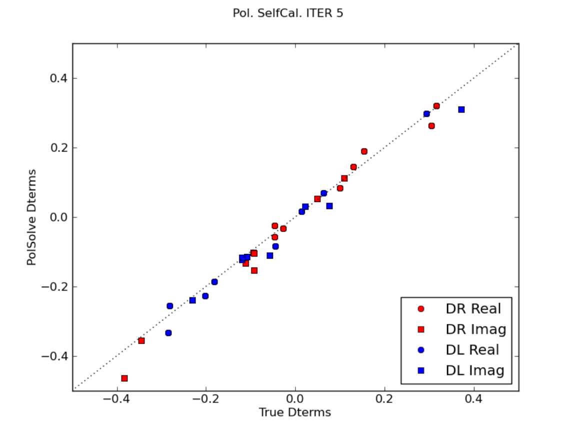
PolSolve Interface: Pol. SelfCal

```
# ITERATE!!
for i in range(NITER):

  print '\n\n ITERATION %i\n\n'%i

## We CLEAN the image, using the visibilities stored in
# the "corrected" column of the measurement set:
  os.system('rm -rf SgrA_SC_clean*')
  tclean(vis='SgrA_polsimulate.ms',
    imagename='SgrA_SC_clean',
    specmode = 'mfs',
    niter = 200,
    interactive=False,
    imsize=1024,
    cell = '0.000001arcsec',
    stokes = 'IQUV',
    mask = 'TCLEAN.mask', ## We use the mask that we created manually.
    weighting = 'uniform',
    deconvolver='hogbom',
    gain=0.1,
    restart=False)

# We remove the previous Dterm table:
  os.system('rm -rf SgrA_polsimulate.ms.spw_0.Dterms')

# Solve for the Dterms:
  polsolve(vis='SgrA_polsimulate.ms',
## If we set "target_field", the Dterms will not only be
# estimated, but also APPLIED to the "corrected" column.
# This is ESSENTIAL for the self-cal approach to work:
        target_field='POLSIM', # Source name
## Antenna mounts (the ordering should be that of the ANTENNA table):
        mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## If "CLEAN_models" is the path to a (full-polarization) CASA image,
## the self-calibration approach is activated:
        CLEAN_models='SgrA_SC_clean.model',
# These values are not really used:
        Pfrac=[0.], EVPA=[0.], PolSolve=[False],
## Set this to True, if you want to test the linear Dterm model:
        linear_approx=False)
```

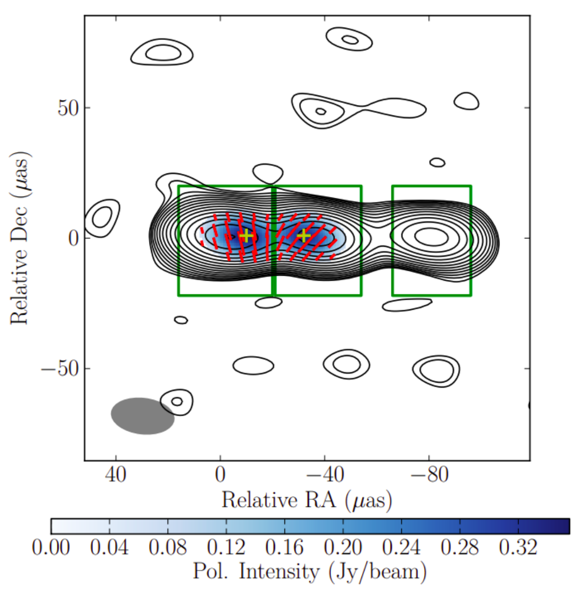


PolSolve Interface: Pol. SelfCal

```
# ITERATE!!
for i in range(NITER):

  print '\n\n ITERATION %i\n\n'%i

## We CLEAN the image, using the visibilities stored in
# the "corrected" column of the measurement set:
  os.system('rm -rf SgrA_SC_clean*')
  tclean(vis='SgrA_polsimulate.ms',
    imagename='SgrA_SC_clean',
    specmode = 'mfs',
    niter = 200,
    interactive=False,
    imsize=1024,
    cell = '0.000001arcsec',
    stokes = 'IQUV',
    mask = 'TCLEAN.mask', ## We use the mask that we created manually.
    weighting = 'uniform',
    deconvolver='hogbom',
    gain=0.1,
    restart=False)

# We remove the previous Dterm table:
  os.system('rm -rf SgrA_polsimulate.ms.spw_0.Dterms')

# Solve for the Dterms:
  polsolve(vis='SgrA_polsimulate.ms',
## If we set "target_field", the Dterms will not only be
# estimated, but also APPLIED to the "corrected" column.
# This is ESSENTIAL for the self-cal approach to work:
        target_field='POLSIM', # Source name
## Antenna mounts (the ordering should be that of the ANTENNA table):
        mounts=['AZ', 'NR', 'NR', 'AZ', 'NL', 'NL', 'AZ', 'NL'],
## If "CLEAN_models" is the path to a (full-polarization) CASA image,
## the self-calibration approach is activated:
        CLEAN_models='SgrA_SC_clean.model',
# These values are not really used:
        Pfrac=[0.], EVPA=[0.], PolSolve=[False],
## Set this to True, if you want to test the linear Dterm model:
        linear_approx=False)
```



And finally...



50
0
−50
Relative Dec (μas)
40
0
−40
−80
Relative RA (μas)
0.00 0.04 0.08 0.12 0.16 0.20 0.24 0.28 0.32
Pol. Intensity (Jy/beam)

SUMMARY

- Instrumental polarization can be decoupled from source polarization thanks to the Earh rotation. We *need* it to calibrate our data.

- Polarization calibration in VLBI is tricky (structure effects from the calibrators). Several approaches to account for it:
  - Inverse modelling (i.e., " à la CLEAN "). The only (known) option for CASA is `polsolve`. Other options (for AIPS/Difmap) are `LPCAL` and `GPCAL`.
  - Forward modelling (i.e., " à la MEM "). E.g., `EHTim`.
  - MCMC methods (i.e., " à la brute-force "). E.g., `THEMIS` and `DMC`.

- `polsolve` is an unofficial CASA task, which applies the calibration directly into the CORRECTED data column (due to CASA limitations in the handling of antenna mounts).
  This is a highly non-standard procedure.

- Several options available: subcomponent fitting (e.g., LPCAL approach) or polarization self-calibration (see, e.g., Cotton 1993).

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CASA VLBI

JUMPING JIVE
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