Polarization in Interferometry

Calibration Tutorial

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Chalmers University of Technology (Sweden)

European Radio Interferometry School
Dwingeloo (October 2017)

TUTORIAL - ALMA B5

How we will proceed in this Tutorial

- There are three scripts and one measurement set provided:
  - `scriptForCalibration.py` → Standard calibration.
  - `scriptForPolCalibration.py` → Polarization calibration.
  - `ERIS2017_helper.py` → Some helper functions for plotting, hacking tables, etc.
  - `ERIS_2017.Polarization_Tutorial.DATA.ms` → ALMA Band 5 (commissioning full-pol) observations of VY CMa.
- The script is almost ready to go. Just a few lines have to be uncommented (after discussion).
- The steps will be performed one by one. Results after each step will be discussed.
- Freedom to choose among different options (e.g., bandpass, reference antenna, etc.) and to "play" with (i.e., *hack*) the calibration tables.
- The script to obtain the final image of the target will be fully written by you!

Polarization Calibration Tutorial
ALMA Band 5

PART I: Standard Calibration

- Look at the schedule. Understand the observations.
- Putting a model to the primary flux calibrator. Check "model column".
- Bandpass calibration
  - Fast phase calibration (i.e., optimize coherence).
  - Bandpass calibration. Does it vary with time?
- Gain calibration
  - Fast phase & slow amplitude
  - Absolute flux-density scaling
  - Slow phase (for phase referencing)
  - Check X/Y cross-phases. What happens to the ref. antenna?

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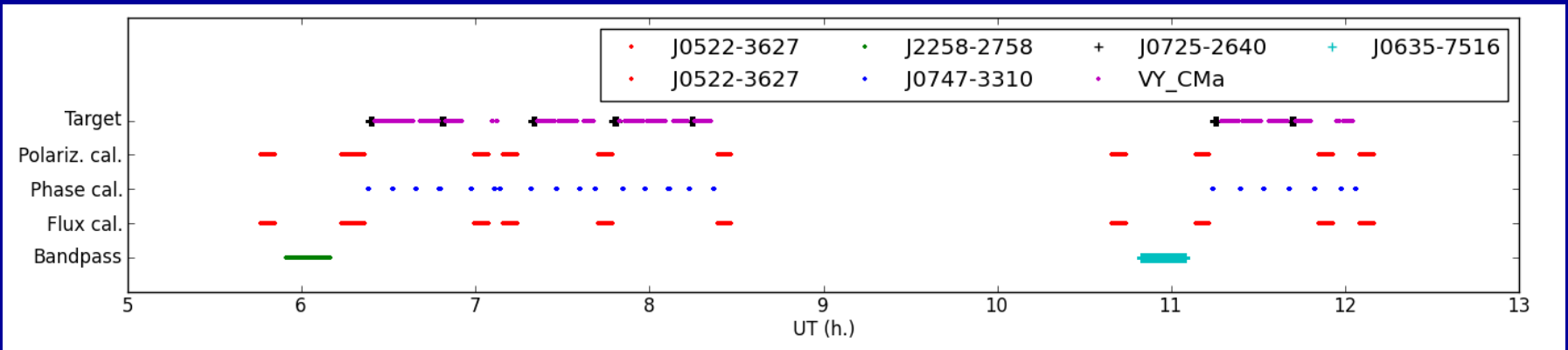
Polarization Calibration Tutorial
ALMA Band 5: Understand



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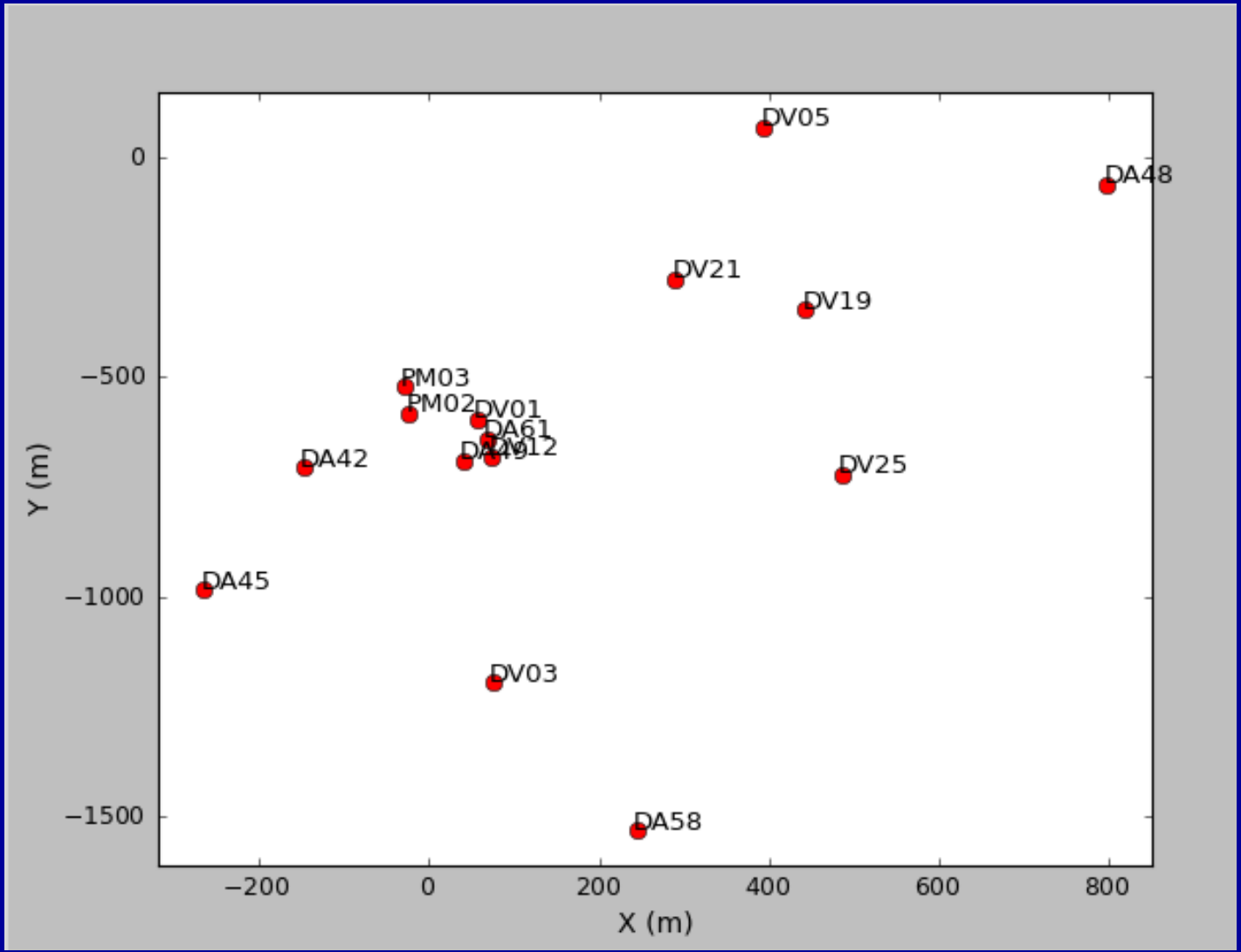
ALMA Band 5: Understand



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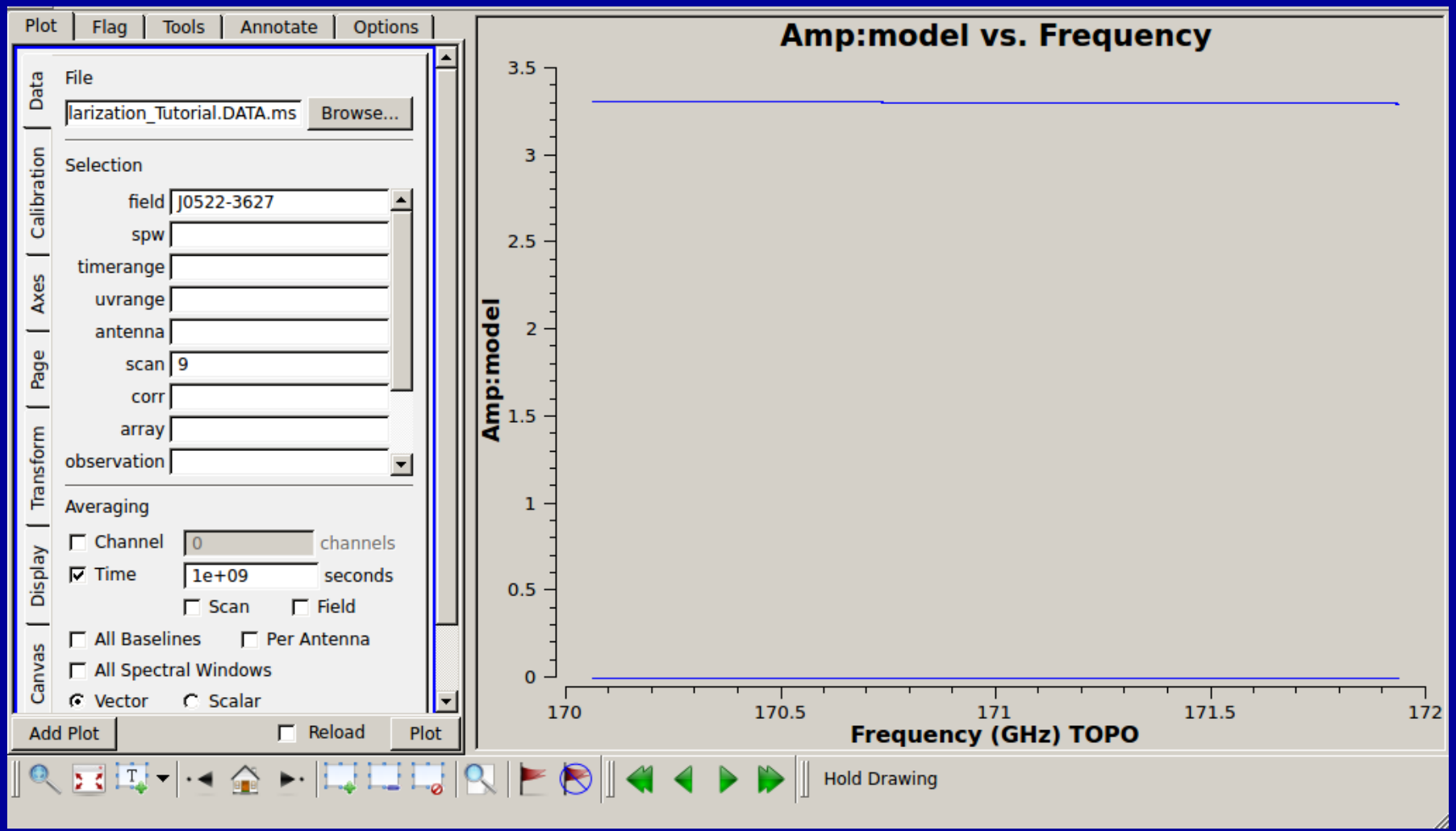
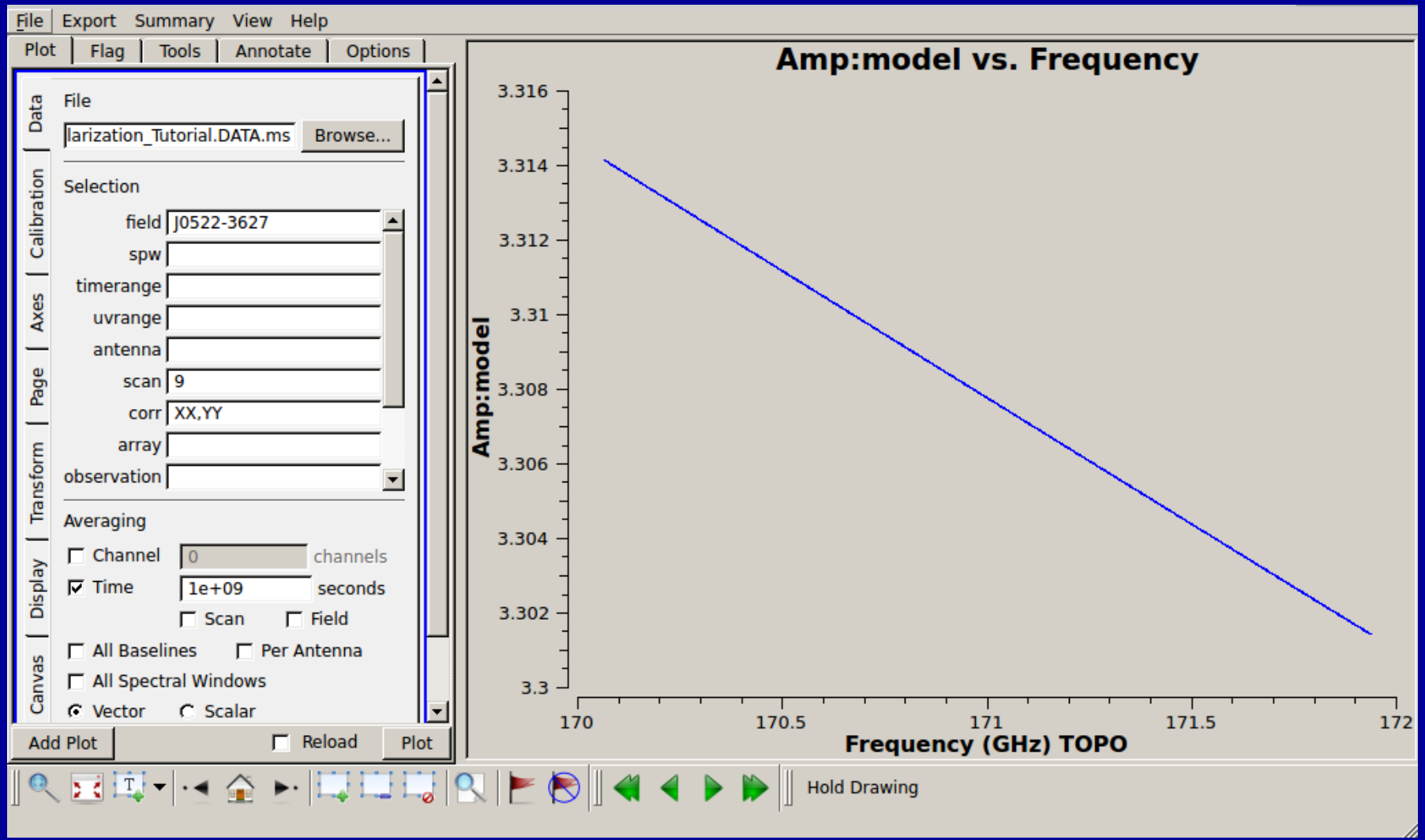
Polarization Calibration Tutorial
ALMA Band 5: Flux Cal.



Polarization Calibration Tutorial
ALMA Band 5: Flux Cal.



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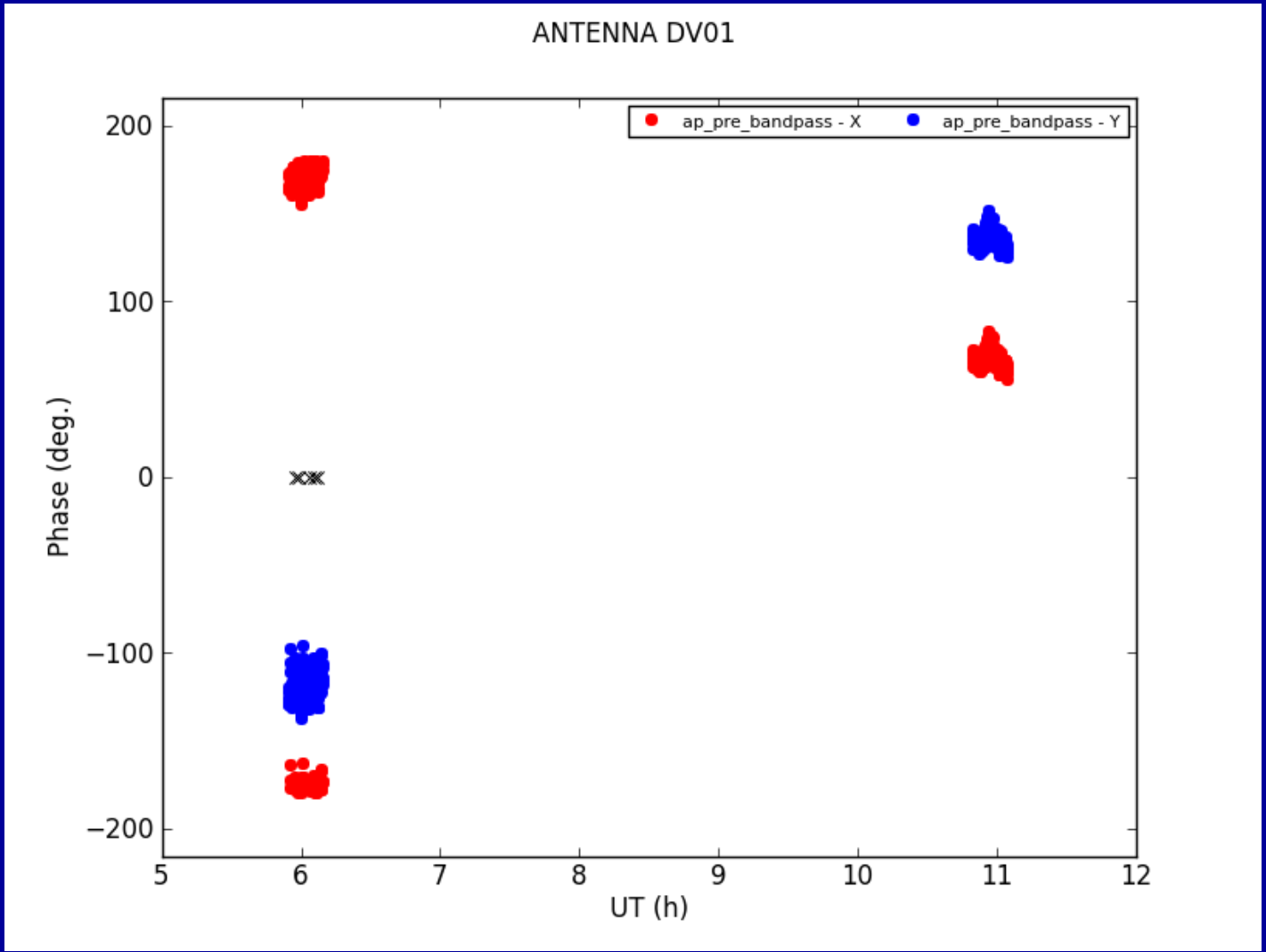
Polarization Calibration Tutorial
ALMA Band 5: Bandpass



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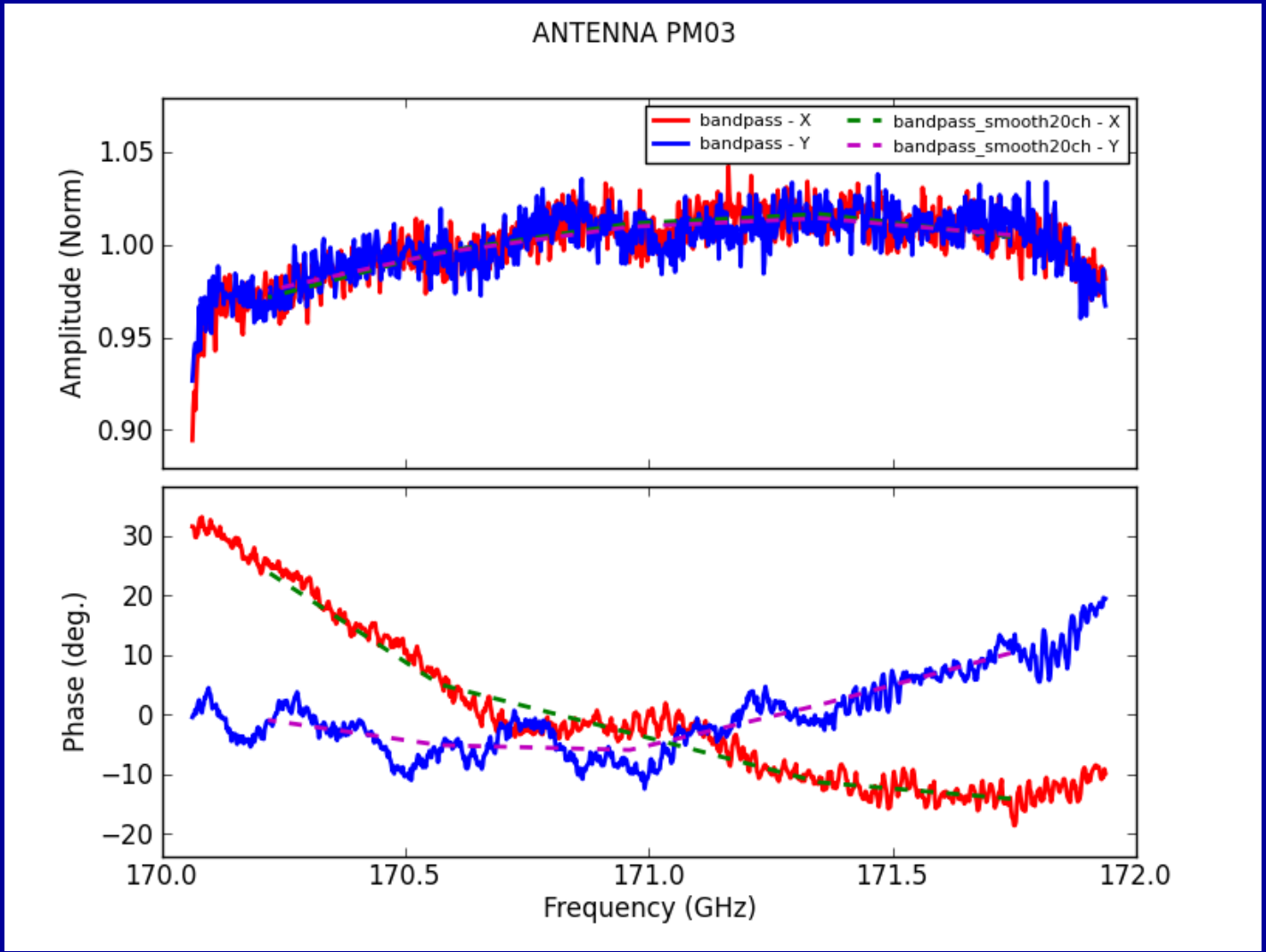
ALMA Band 5: Bandpass



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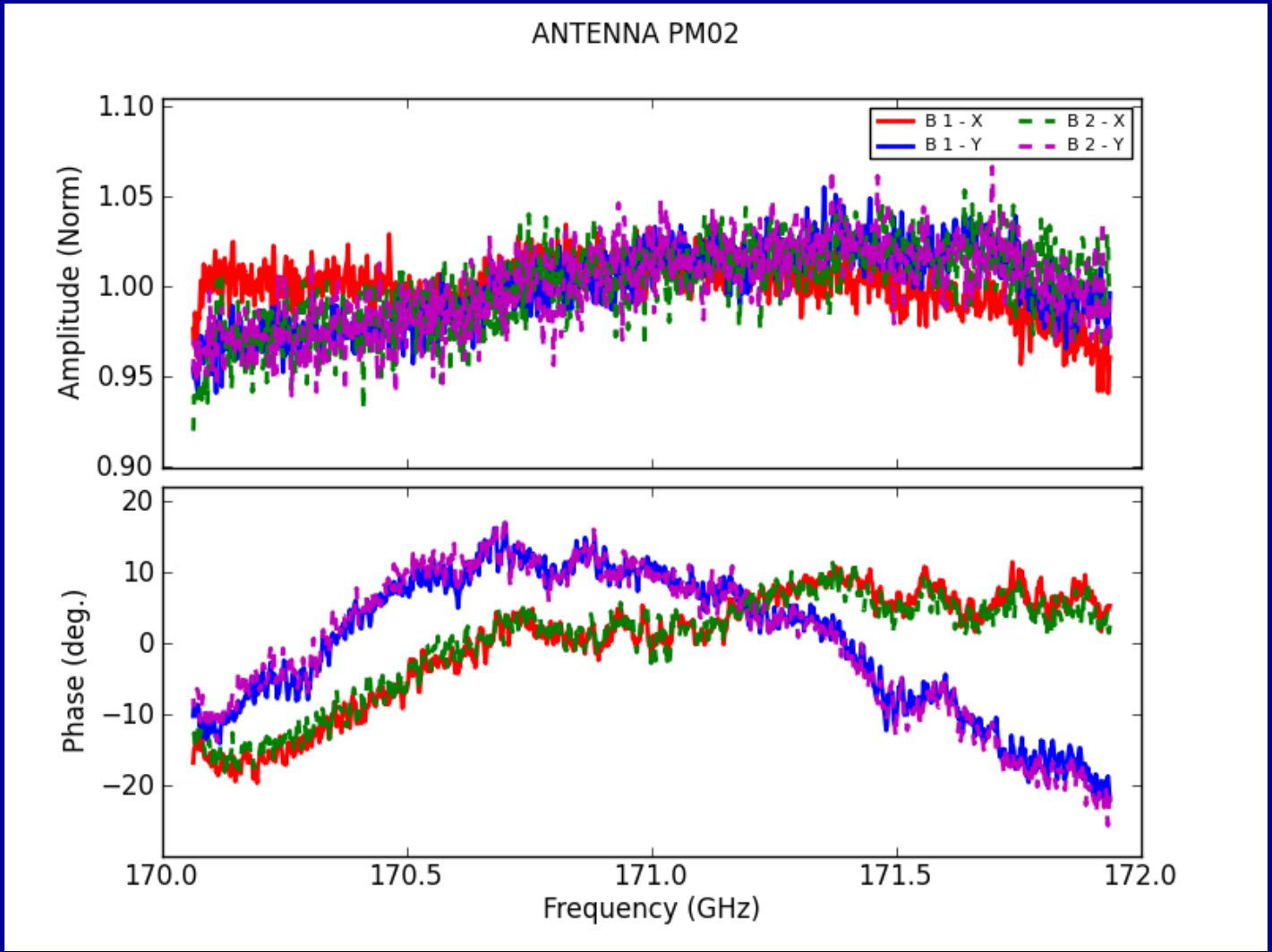

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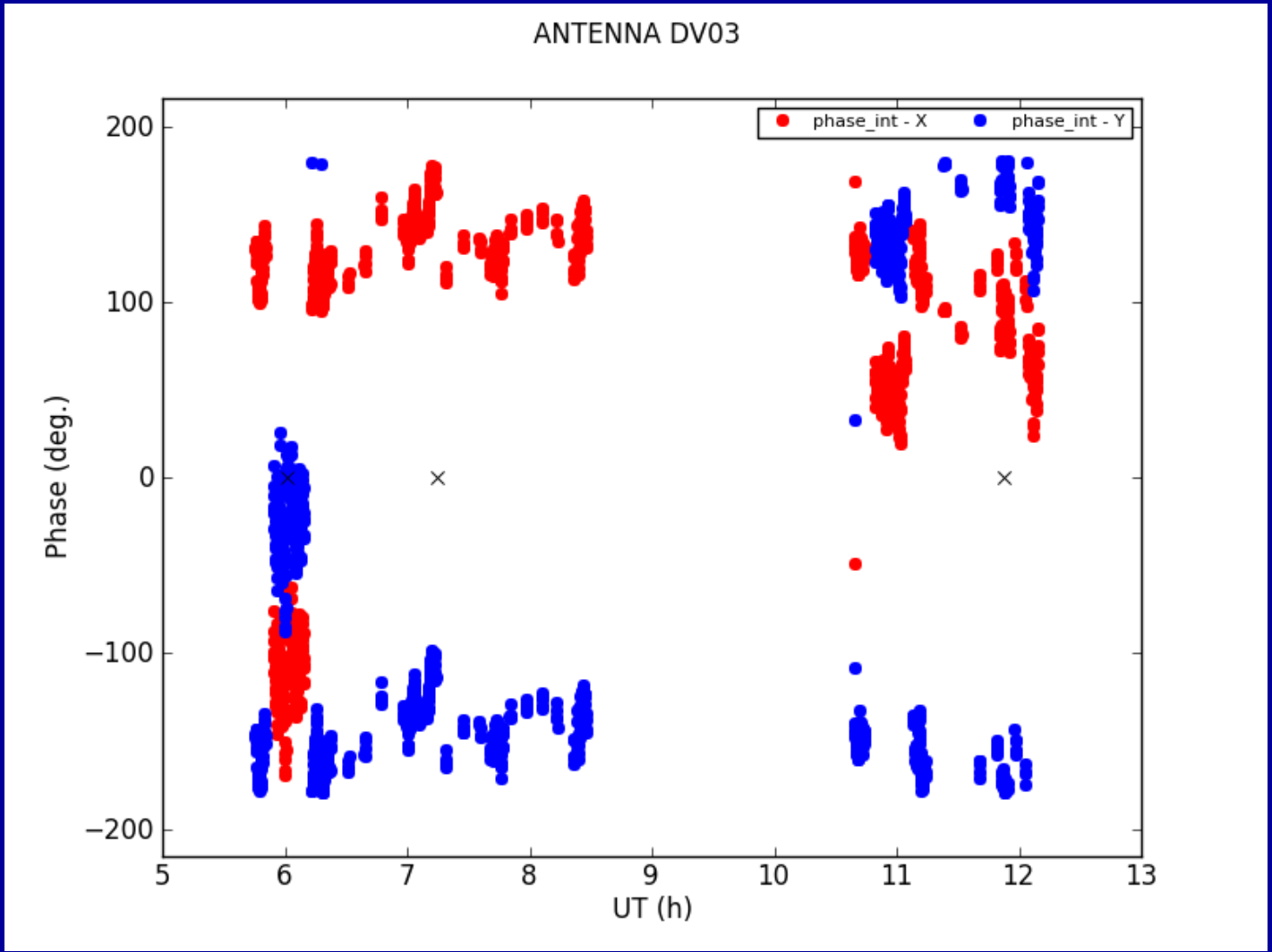
ALMA Band 5: Gain Cal.



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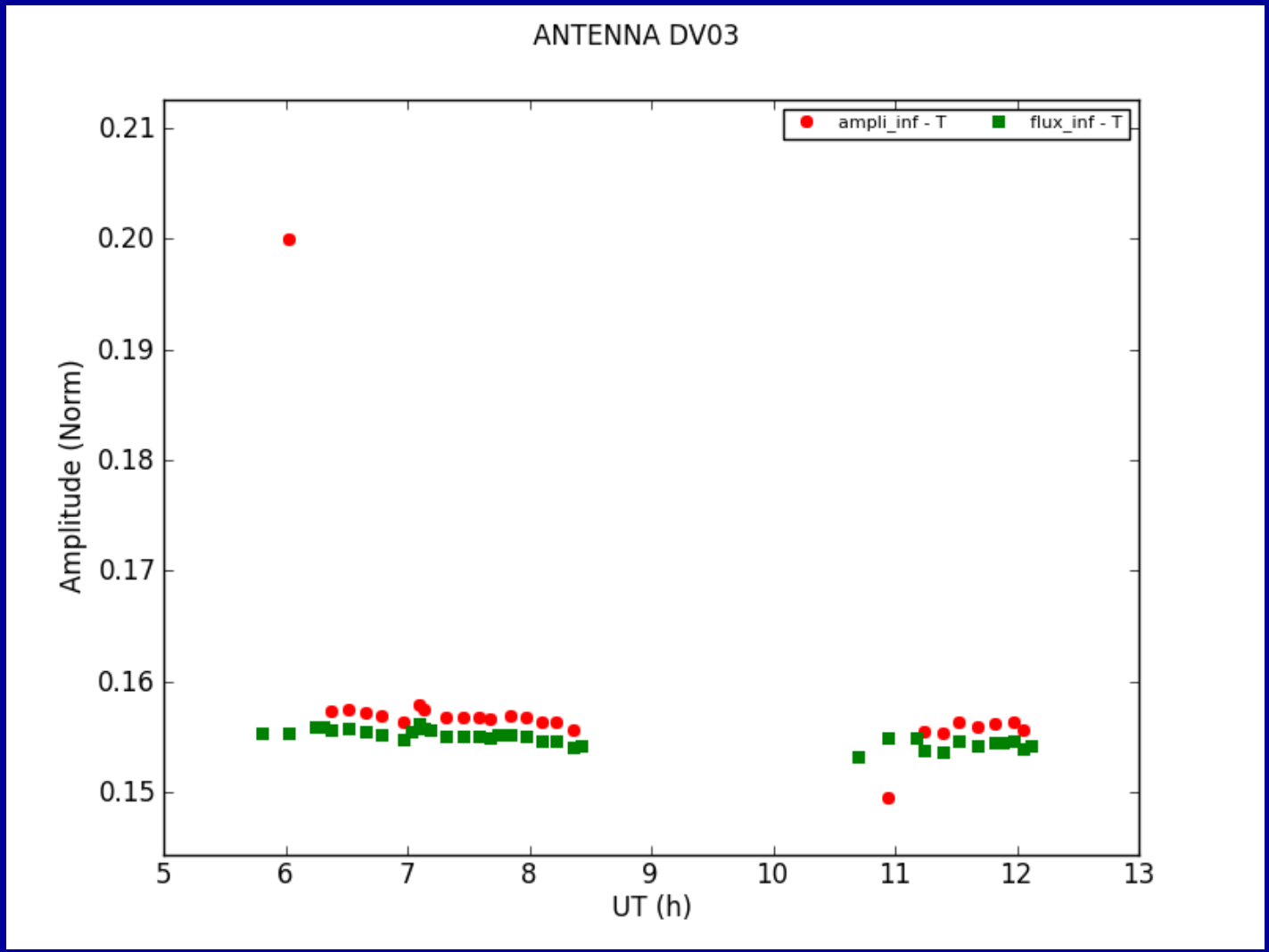

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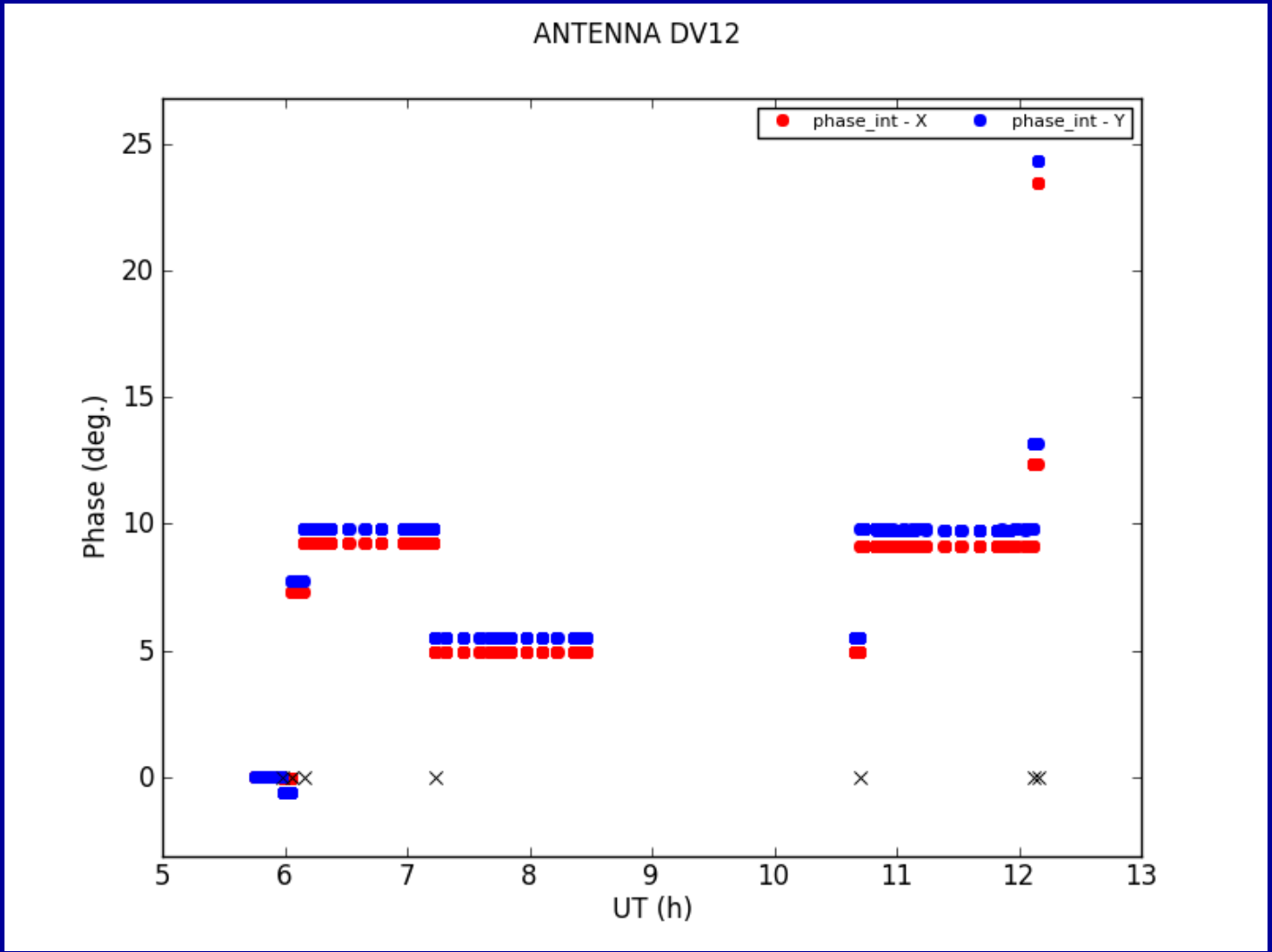

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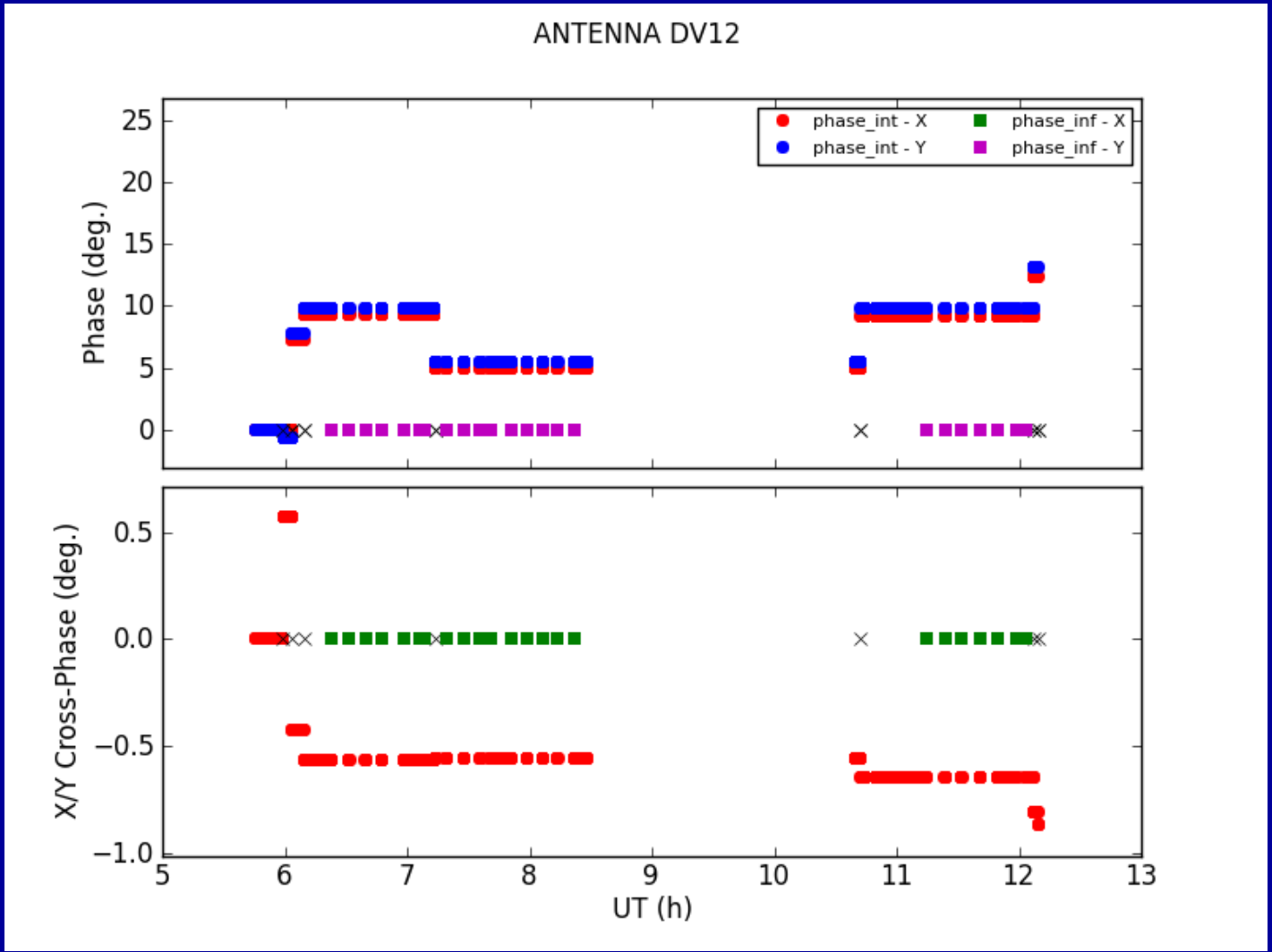

Polarization Calibration Tutorial
ALMA Band 5

PART II: Polarization Calibration

- X/Y gain ratio for the Pol. calibrator (Q effect on XX/YY).
- Cross-delay calibration (take a look at the data)
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- Cross-phase calibration ambiguity
- Polarization leakage
- Amplitude cross-polarization ratios

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Polarization Calibration Tutorial
ALMA Band 5: Q/U from Gain

- Remember the brightness matrix in linear-polarization basis:

$$S = \begin{pmatrix} I + Q_{ant} & U_{ant} + j\,V \\ U_{ant} - j\,V & I - Q_{ant} \end{pmatrix}$$

where $Q_{ant} = Q_{sky} \cos 2\psi + U_{sky} \sin 2\psi$

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- So: $\frac{G_x}{G_y} \rightarrow \frac{I + Q_{ant}}{I - Q_{ant}} = f(\psi)$.

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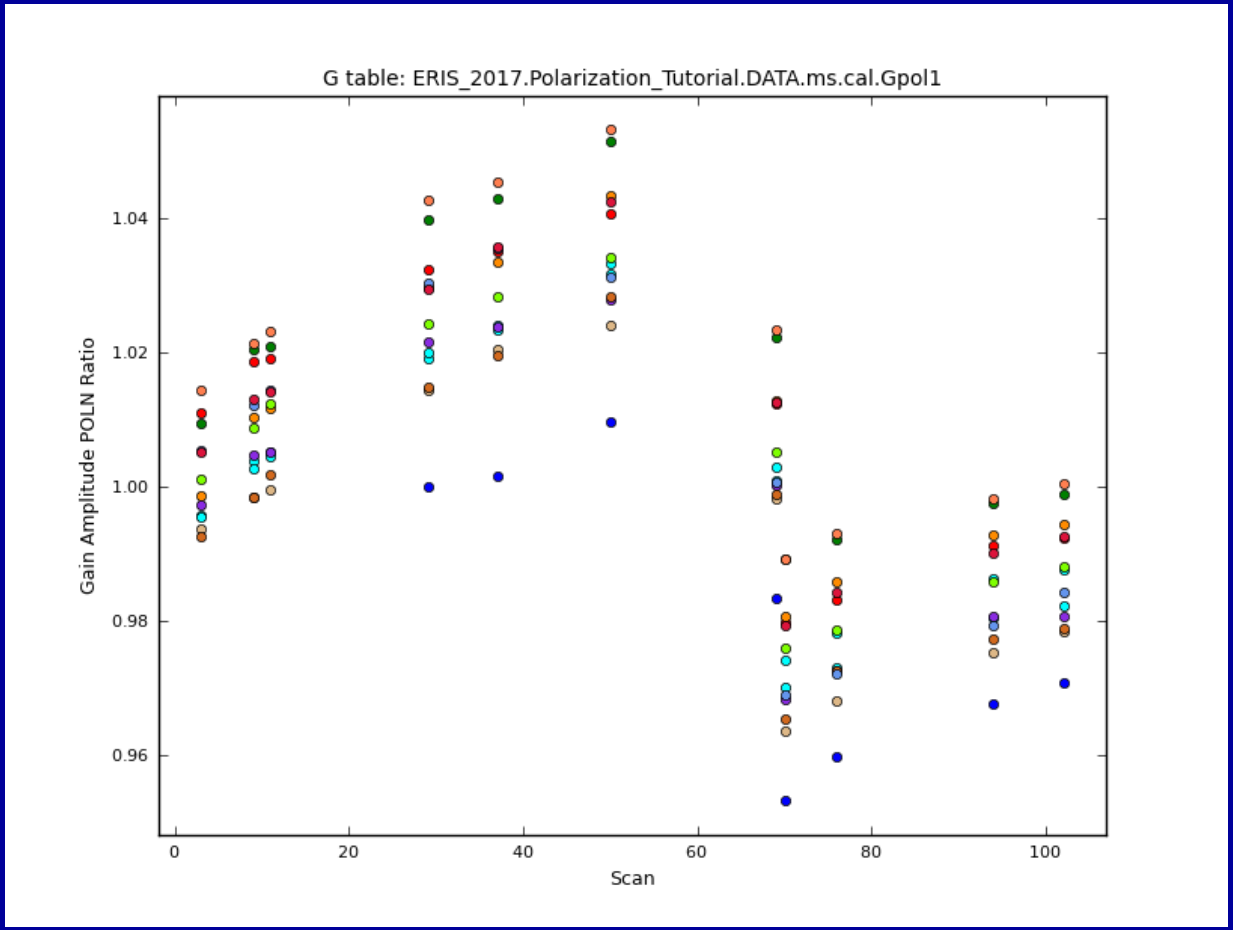
ALMA Band 5: Q/U from Gain



We estimate Q_{sky} and U_{sky} from $\frac{G_x}{G_y}$ vs. ψ

Polarization Calibration Tutorial
ALMA Band 5: Q/U from Gain

```
Latitude =  -23.0285840963
Found as many as 6 fields.
Found as many as 1 spws.
Fld= 0 Spw= 0 (B=05, PA offset=-45.0deg) Gx/Gy= 1.00386895757

Q= -0.0256329086095 U= -0.014657685591 P= 0.0295278470374 X= -75.1188751681

For field id =  0  there are  1 good spws.

Spw mean: Fld= 0 Q= -0.0256329086095 U= -0.014657685591 (rms= 0.0 0.0 )
P= 0.0295278470374 X= -75.1188751681
```

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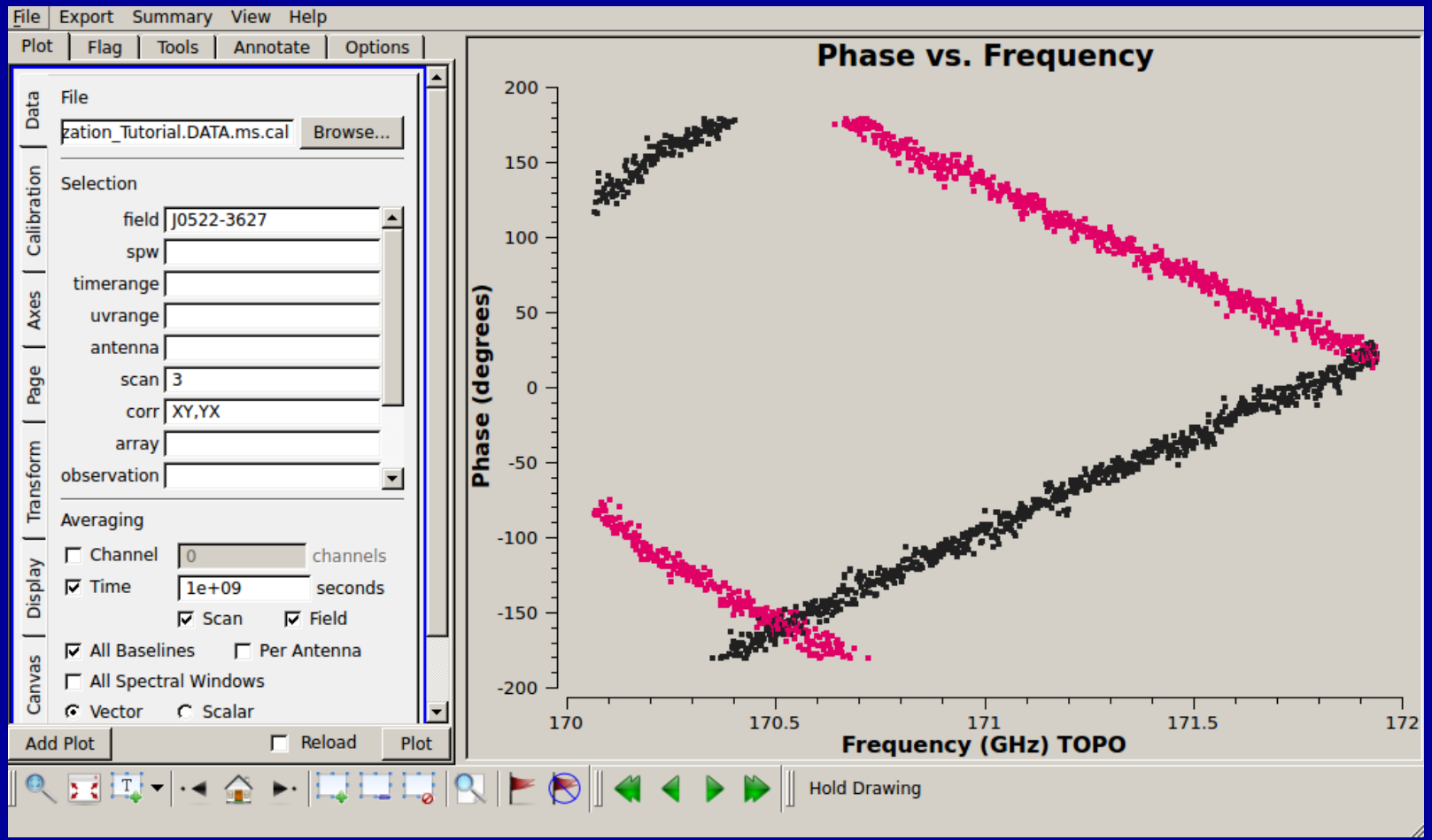
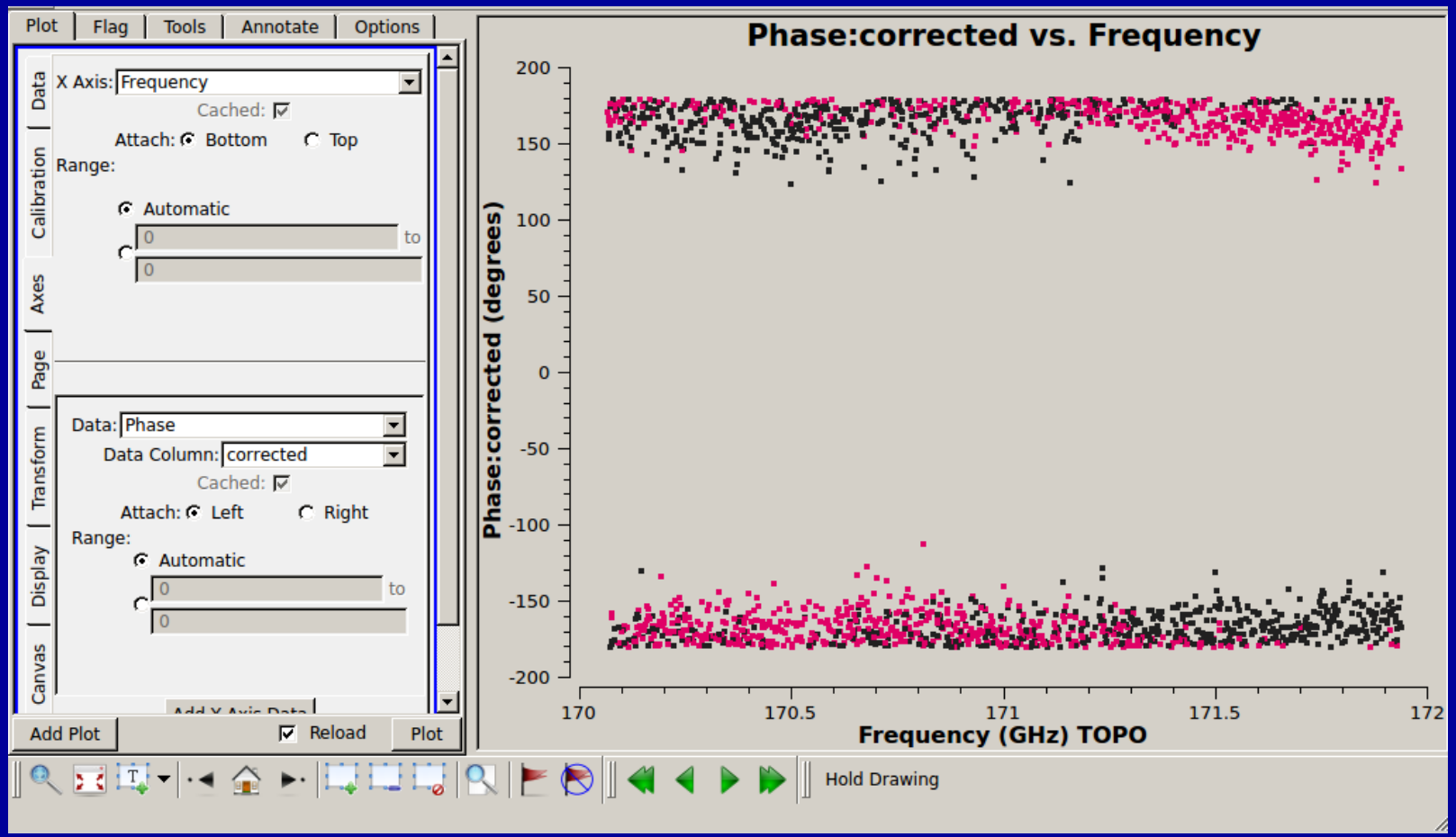
Polarization Calibration Tutorial
ALMA Band 5: X-Y Delay



Polarization Calibration Tutorial
ALMA Band 5: X-Y Delay



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Polarization Calibration Tutorial
ALMA Band 5: X-Y Phase

- Let's add a cross-polarization phase to the brightness matrix:

$$S = \begin{pmatrix} I + Q_{ant} & (U_{ant} + j\,V)e^{-j\Delta} \\ (U_{ant} - j\,V)e^{+j\Delta} & I - Q_{ant} \end{pmatrix}$$

where $G_x = 1$ and $G_y = e^{+j\Delta}$ at all antennas.

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- So the cross-polarization visibilities are:
  $XY^* = (U_{sky}\cos 2\psi - Q_{sky}\sin 2\psi + jV)e^{j\Delta}$.

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- Real vs. Imag:
  - $Re(XY^*) = (U_{sky}\cos 2\psi - Q_{sky}\sin 2\psi)\cos\Delta - V\sin\Delta$
  - $Im(XY^*) = (U_{sky}\cos 2\psi - Q_{sky}\sin 2\psi)\sin\Delta + V\sin\Delta$

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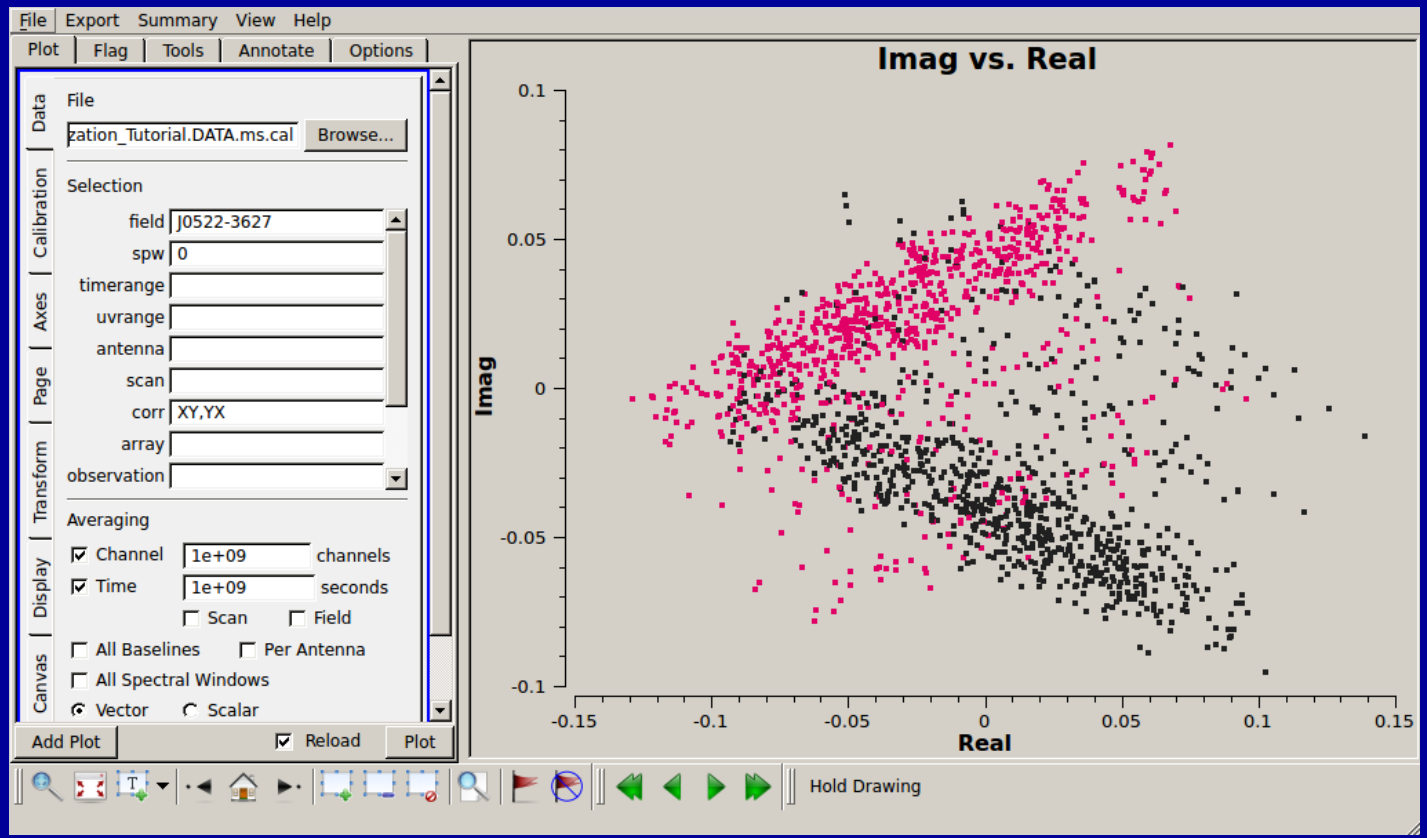
  - $Im(XY^*) = (U_{sky}\cos 2\psi - Q_{sky}\sin 2\psi)\sin\Delta + V\sin\Delta$

- If we plot $Re(XY^*)$ vs. $Im(XY^*)$, we will see a straight line (as long as V is negligible) with a slope proportional to $\tan(\Delta)$.

Polarization Calibration Tutorial
ALMA Band 5: X-Y Phase



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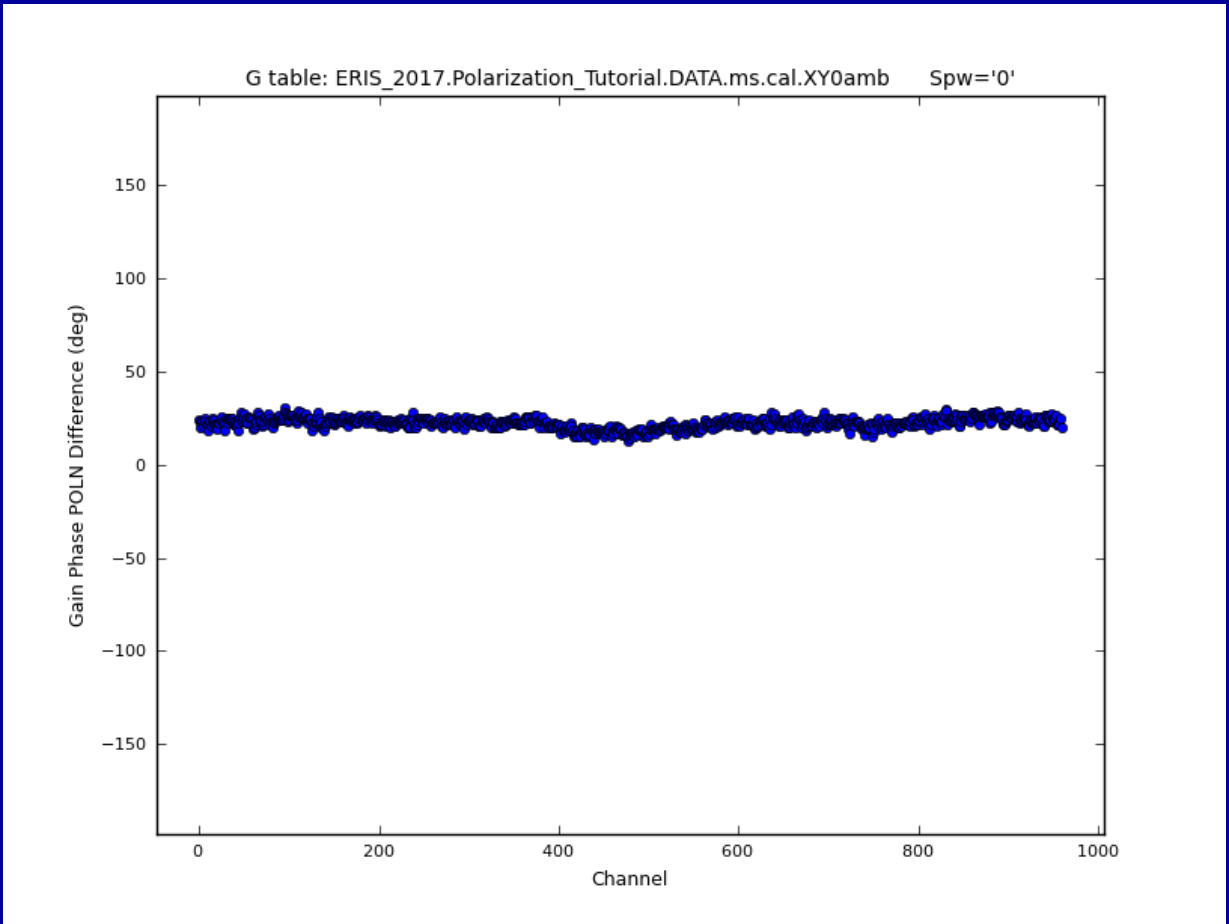

Polarization Calibration Tutorial
ALMA Band 5: X-Y Phase Ambiguity

- We fit for Q_{sky}, U_{sky}, and Δ using XY^* and XY^* as data.

Polarization Calibration Tutorial
ALMA Band 5: X-Y Phase Ambiguity

- We fit for Q_{sky}, U_{sky}, and Δ using XY^* and XY^* as data.
- BUT notice that

  $XY^* = (U_{sky}\cos 2\psi - Q_{sky}\sin 2\psi + jV)e^{j\Delta}$

  has an ambiguity.
  - $(Q_{sky},\ U_{sky},\ \Delta) \rightarrow (-Q_{sky},\ -U_{sky},\ \Delta + \pi)$

Polarization Calibration Tutorial
ALMA Band 5: X-Y Phase Ambiguity

ERIS_2017.Polarization_Tutorial.DATA.ms.cal.QUfromGain.txt (~/WORKAREA/ERIS_2017) - GVIM2

File Edit Tools Syntax Buffers Window Help

```
Latitude =  -23.0285840963
Found as many as 6 fields.
Found as many as 1 spws.
Fld= 0 Spw= 0 (B=05, PA offset=-45.0deg) Gx/Gy= 1.00386895757 Q= -0.0256329086095 U= -0.014657685591 P= 0.0295278470374 X= -75.1188751681
For field id =  0  there are  1 good spws.
Spw mean: Fld= 0 Q= -0.0256329086095 U= -0.014657685591 (rms= 0.0 0.0 ) P= 0.0295278470374 X= -75.1188751681
```

ERIS_2017.Polarization_Tutorial.DATA.ms.cal.XY-Ambiguity.txt (~/WORKAREA/ERIS_2017) - GVIM3

File Edit Tools Syntax Buffers Window Help

```
Expected QU =  (-0.025632908609475556, -0.014657685591015343)
Spw = 0: Found QU = [-0.0288661  -0.01583534]
      ...KEEPING X-Y phase 22.4312378423 deg
Ambiguity resolved (spw mean): Q= -0.0288661047816 U= -0.0158353354782 (rms= 0.0 0.0 ) P= 0.0329243049277 X= -75.6258787305
Returning the following Stokes vector: [1.0, -0.028866104781627655, -0.015835335478186607, 0.0]
~
```

Polarization Calibration Tutorial
ALMA Band 5

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Polarization Calibration Tutorial
ALMA Band 5: Leakage

- Effect of the Dterms on the XY^* cross-correlations:

$$XY^* \rightarrow XY^* + D_x^a YY^* + (D_y^b)^* XX^*$$

Polarization Calibration Tutorial
ALMA Band 5: Leakage

- Effect of the Dterms on the XY^* cross-correlations:

$$XY^* \rightarrow XY^* + D_x^a YY^* + (D_y^b)^* XX^*$$

- In terms of the brightness matrix (i.e., assuming a point source):

$$XY^* \rightarrow U_{ant} + jV + D_x^a(I - Q_{ant}) + (D_y^b)^*(I + Q_{ant})$$

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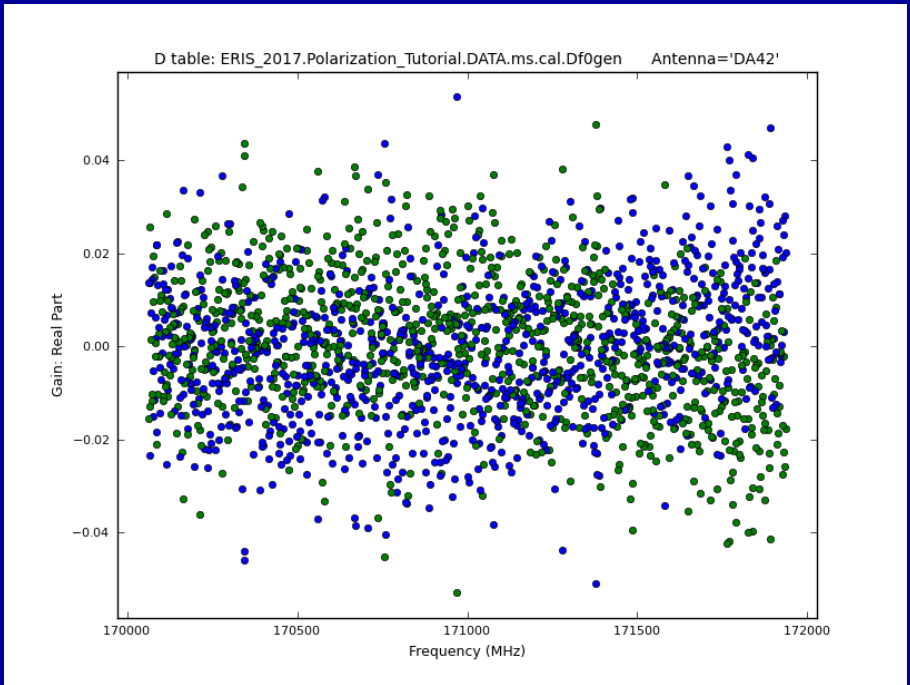
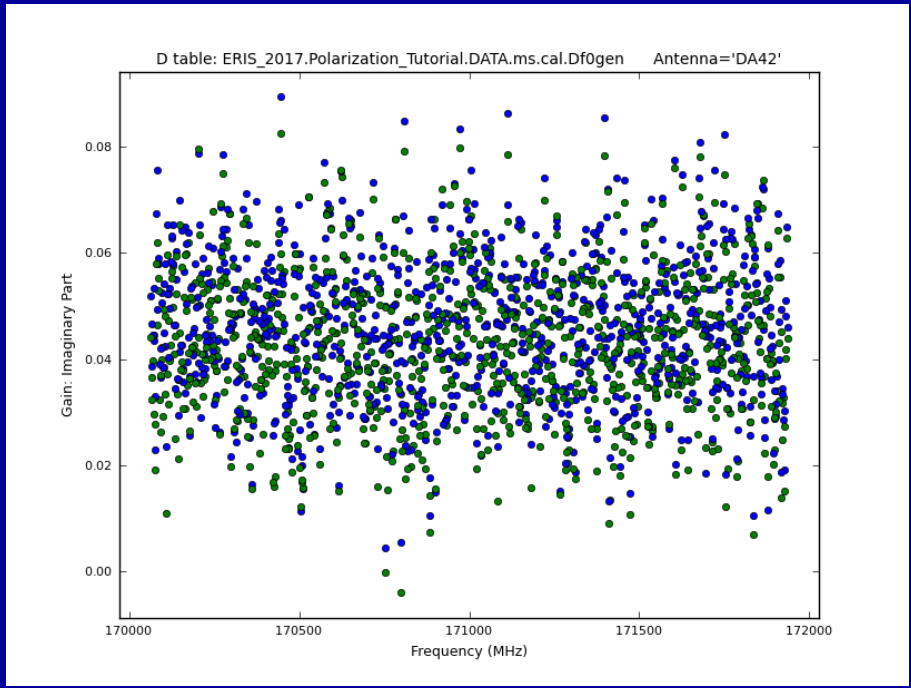
- Re-arranging terms:

$$XY^* \rightarrow U_{ant} + Q_{ant}\left((D_y^b)^* - D_x^a\right) + jV + I(D_x^a + (D_y^b)^*)$$

Polarization Calibration Tutorial
ALMA Band 5: Leakage





By knowing U_{ant} and Q_{ant}, we can solve for D_x and D_y for all antennas.

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Polarization Calibration Tutorial
ALMA Band 5: X-Y Amp. Ratio

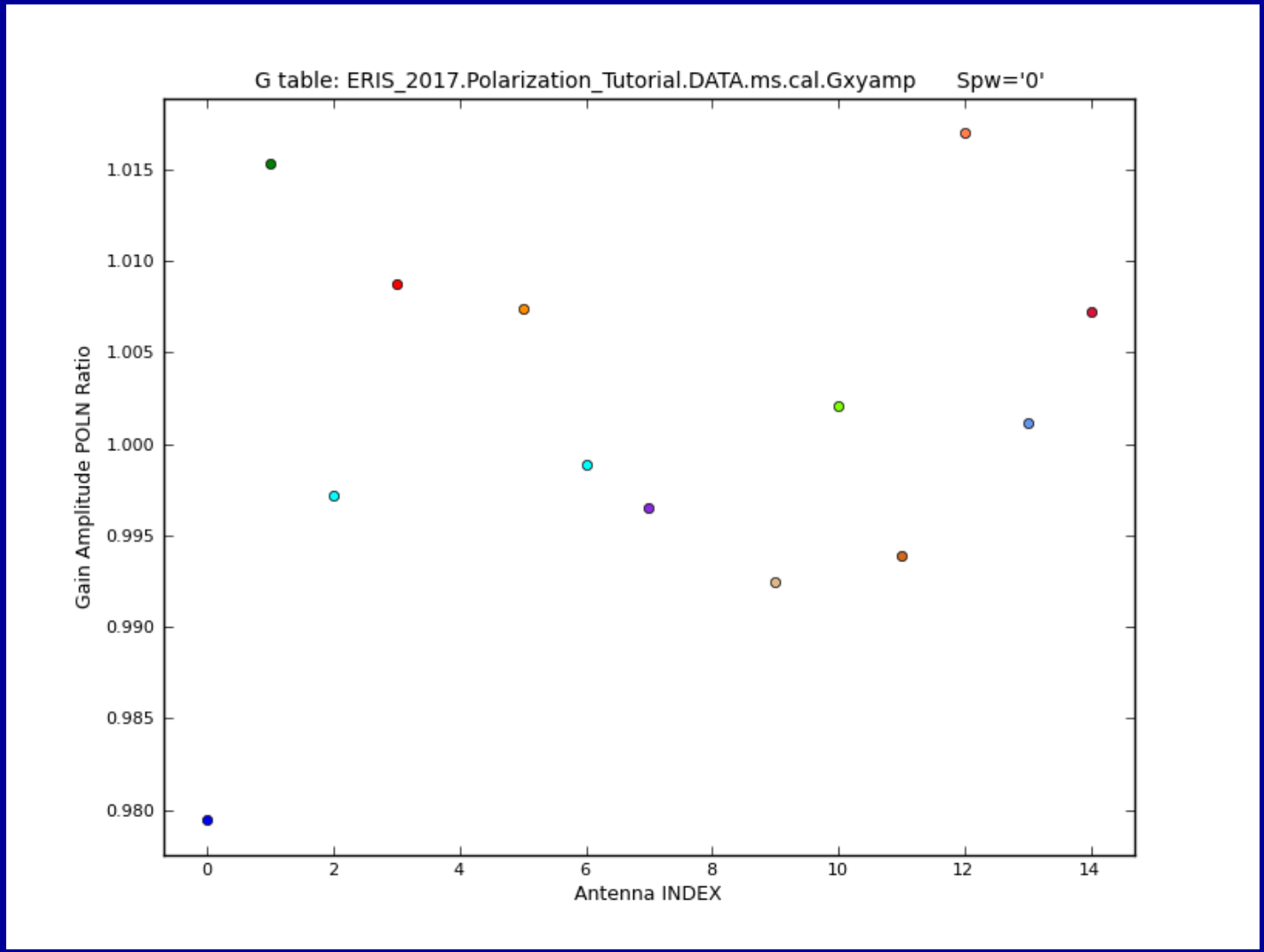
- Let's add a cross-polarization amplitude ratio to the brightness matrix:

$$\mathcal{F}[V_{ab}] \rightarrow \begin{pmatrix} I + Q_{ant} & (U_{ant} + j\,V)\rho_b \\ (U_{ant} - j\,V)\rho_a & (I - Q_{ant})\rho_a\rho_b \end{pmatrix}$$

  where $G^i_x = 1$ and $G^i_y = \rho_i$.

- Changes in the amplitudes vs. ψ allow us to solve for ρ_i.

Polarization Calibration Tutorial
ALMA Band 5: X-Y Amp. Ratio



FINISHED!

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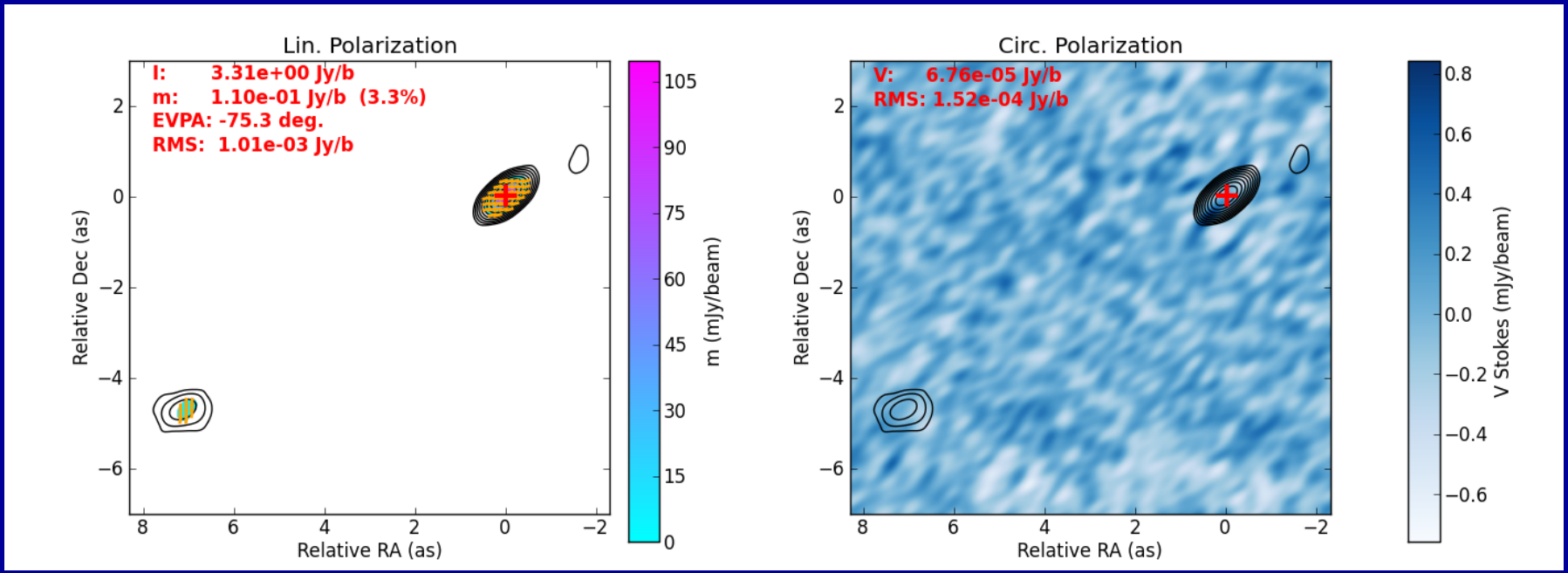
LET'S PLAY NOW!

Polarization Calibration Tutorial
ALMA Band 5: Pol. Calib. Image



Polarization Calibration Tutorial
ALMA Band 5: Hacking Tables!

- The function "`finetune_G`" allows you to change any calibration table in many different ways.
- Make a backup of your tables, run "`finetune_G`" and repeat steps 9, 11, and 12 of the polarization calibration script.
- You can load the different images with the "`plotPolImage`" function to compare!
- Some ideas:
  - Add an offset to the imaginary parts of the Dterms (different sign for each polarization).
  - Same as above, but add it to the real parts.
  - Repeat both previous items by using the same signs for both polarizations.
  - Add an offset to the X-Y cross-polarization phase.
  - Add a ratio to the X-Y amplitude-ratio gains.
  - Add a cross-polarization delay.
  - Any combination of the above.

BONUS:
Leakage calibration on circular polarizers

- Calibrate R/L phase offset using pol. calibrator.

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Leakage calibration on circular polarizers

- Calibrate R/L phase offset using pol. calibrator.
  - $V^{obs} = D_a\, X\, V^{true}_{ab}\, X^H\, D_b^H \quad ; \quad X = \begin{pmatrix} 1 & 0 \\ 0 & e^{j\alpha} \end{pmatrix} \quad ; \quad D_a = \begin{pmatrix} 1 & D_a^L \\ D_a^R & 1 \end{pmatrix}$

$$V^{obs}_{RL} = ((D_a^R + (D_b^L)^*)\, I + P)\, e^{-j\alpha} + O(D^2)$$
$$V^{obs}_{LR} = ((D_a^L + (D_b^R)^*)\, I + P^*)\, e^{j\alpha} + O(D^2)$$

BONUS:
Leakage calibration on circular polarizers

- Calibrate R/L phase offset using pol. calibrator.
  - $V^{obs} = D_a\, X\, V^{true}_{ab}\, X^H\, D_b^H \quad ; \quad X = \begin{pmatrix} 1 & 0 \\ 0 & e^{j\alpha} \end{pmatrix} \quad ; \quad D_a = \begin{pmatrix} 1 & D_a^L \\ D_a^R & 1 \end{pmatrix}$

$$V^{obs}_{RL} = ((D_a^R + (D_b^L)^*)\, I + P)\, e^{-j\alpha} + O(D^2)$$
$$V^{obs}_{LR} = ((D_a^L + (D_b^R)^*)\, I + P^*)\, e^{j\alpha} + O(D^2)$$

  - **Unpolarized** calibrator:
    $(D_a^L,\ D_a^R,\ e^{j\alpha}) \rightarrow (D_a^L\, e^{j\Delta} + jK,\ D_a^R\, e^{-j\Delta} + jK,\ e^{j(\alpha-\Delta)})$
  - **Polarized** calibrator:
    $(D_a^L,\ D_a^R,\ e^{j\alpha}) \rightarrow (D_a^L + jK,\ D_a^R + jK,\ e^{j(\alpha)})$