Polarization calibration of the Phased ALMA for mm VLBI

Algorithms for calibration and test simulations

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The ALMA Phasing Team

(Incomplete list. Arbitrary order)

- Haystack
  - Shep Doeleman (PI), Mike Hecht (PM), Geoff Crew, Vincent Fish, Victor Pankratius, Chet Ruszczyk, Chip Coldwell, ...
- NRAO
  - Rich Lacasse, Ray Escoffier, Joseph Greenberg, Bill Shillue, Bob Treacy, Rafael Hiriart, Matias Mora, ...
- MPIfR
  - Walter Alef, Alan Roy, Helge Rottman, James Anderson, ...
- Onsala
  - Michael Lindqvist, Iván Martí-Vidal, Tobia Carozzi, ...

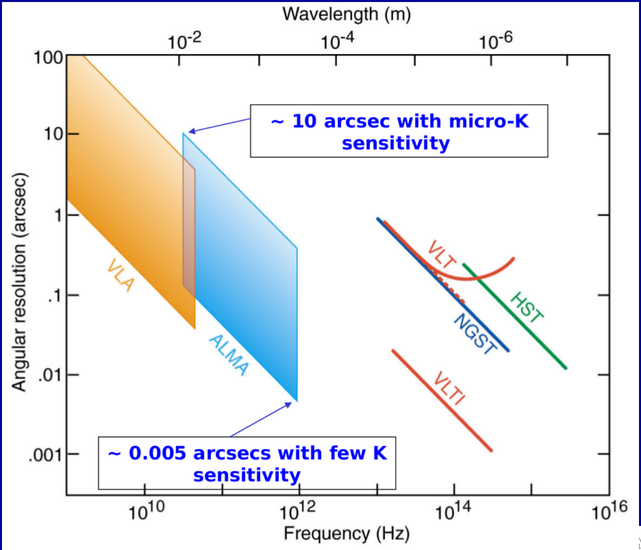
..., Alan Baudry (ESO), Mareki Honma (NAOJ), Tomoaki Oyama (NAOJ), Makoto Inoue (ASIAA), Nicolas Pradel (ASIAA), Robert Lucas (UJF), Neil Nagar (UDEC), Alejandro Sáez (ALMA), Bernhard López (ALMA) Jonathan Weintroub (CfA), ...

The Atacama Large mm/submm Array

Located in the desert of Chajnantor (Chilean Andes), the driest region on Earth, at 5000 meters over the sea level, ALMA is, by far, the most **powerful** and **sensitive** telescope in the mm/submm wavelength regime.

- Operated by the Joint ALMA Observatory (JAO),a partnership of ESO (EU), NRAO (USA), and NAOJ (East Asia).

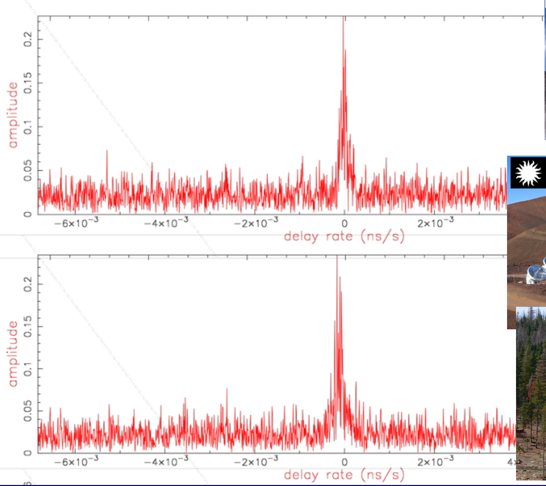
A new window


Wavelength (m)
10^{-2}
10^{-4}
10^{-6}
100
10
1
.1
.01
.001
Angular resolution (arcsec)
~ 10 arcsec with micro-K sensitivity
VLA
ALMA
VLT
HST
NGST
VLTI
~ 0.005 arcsecs with few K sensitivity
10^{10}
10^{12}
10^{14}
10^{16}
Frequency (Hz)

The mm-VLBI Window

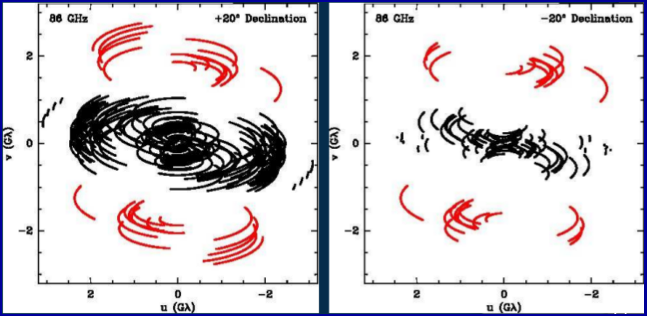
- The highest spatial resolution (Event Horizon Telescope)
- APEX, SMA, and ARO-SMT at 1.3mm ($\sim 30\mu$as!)

Wagner et al. (submitted)



The ALMA Phasing Project

- Use the whole ALMA as one single (VLBI) station.
- Large increase in sensitivity (and image fidelity) for mm-VLBI.
- Will reach a few 10s of μas resolution!



UV Coverage of Global VLBI at 3mm (ALMA in red)

See Fish et al. (arXiv:1309.3519)

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	PdBu P.	Pico V.	Onsala	VLBA	ALMA
Bonn	0.038	0.049	0.143	0.082	0.014
PdBu P.	0.000	0.031	0.090	0.051	0.009
Pico V.	0.000	0.000	0.116	0.066	0.011
Onsala	0.000	0.000	0.000	0.195	0.033
VLBA	0.000	0.000	0.000	0.122	0.019

Baseline sensitivity (Jy) at 3mm for 20s int. time

See Fish et al. (arXiv:1309.3519)

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	PdB	CARMA	SMTO	APEX	ALMA
P. Veleta	0.063	0.076	0.201	0.169	0.024
PdB	-	0.058	0.153	0.129	0.019
CARMA	-	-	0.185	0.155	0.022
SMTO	-	-	-	0.413	0.059
APEX	-	-	-	-	0.050

Baseline sensitivity (Jy) at 1mm for 10s int. time

See Fish et al. (arXiv:1309.3519)

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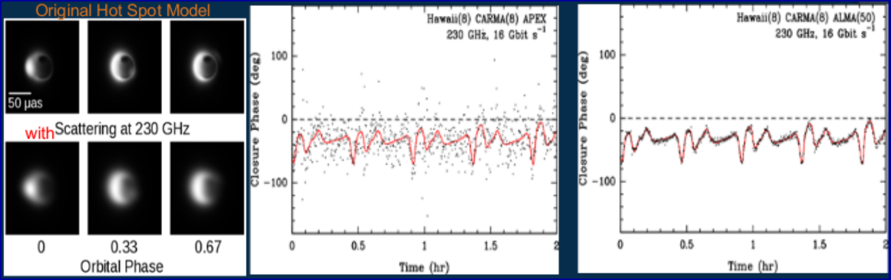

Closure phase simulation (Doeleman et al. 2009)

See Fish et al. (arXiv:1309.3519)

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High-quality phasing in the mm/submm regime is challenging, especially for VLBI use. We need state-of-the-art solutions for some important problems, e.g.

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- Different frequency sampling in digitizer (2^n MHz sub-bands for VLBI; 62.5 MHz sub-bands for ALMA).
- Polarization compatibility (ALMA registers in X/Y base; VLBI stations register in RCP/LCP base).

ALMA polarization for VLBI

Roy et al. (2013). *APP polarization White Paper*

Final strategy is

- Record X/Y phased-up streams at ALMA.
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The main advantages are

- Minimum hardware implementation.
- Flexibility for post-processing.
- Easy adaptability for future X/Y-based stations.

Mixed-polarization conversion (ideal case)

- Electric vectors: $e_r = \frac{1}{\sqrt{2}}(e_x + e_y) \quad ; \quad e_l = \frac{1}{\sqrt{2}}(e_x - e_y)$

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- Conversion matrix: $C_{\odot+} = \frac{1}{\sqrt{2}} \begin{pmatrix} 1 & -i \\ 1 & +i \end{pmatrix}$ and $C_{+\odot} = C_{\odot+}^H$

Mixed-polarization conversion (with gains)

The Measurement Equation formulation (Smirnov 2011) allows us to solve the calibration problem easily

- Calibrate using gains in X/Y basis: $B^{cal}_{+\odot} = D_+ G_+ B_{+\odot}$
  - $G_+ = \begin{pmatrix} G_x & 0 \\ 0 & G_y \end{pmatrix} \qquad D_+ = \begin{pmatrix} 1 & D_x \\ D_y & 1 \end{pmatrix}$

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Mixed-polarization conversion (phased array)

Each antenna has independent corrections in X/Y base, *but all streams are added equally*

- $B^{obs}_{\odot +} = \frac{1}{N}\sum_i^N B^{cal}_{\odot +} K^i_+$, where K^i_+ is the overall gain matrix for antenna i (i.e., with bandpass, amplitude, and phase corrections).

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- $K_+ = \begin{pmatrix} \langle B_x \rangle & \langle D_x\, B_x \rangle \\ \langle D_y\, B_y\, e^{j\alpha} \rangle & \langle B_y\, e^{j\alpha} \rangle \end{pmatrix}$ so that $B^{cal}_{\odot\odot} = B^{obs}_{\odot +}\,(K_+)^{-1}\, C_{+\odot}$

Software implementation: PolConvert

- Written in C++. Can be used in multi-threaded environment.
- Uses `casacore` to interact with measurement sets and CASA tables.
- Reads and converts SWIN (i.e., DifX) formatted data.

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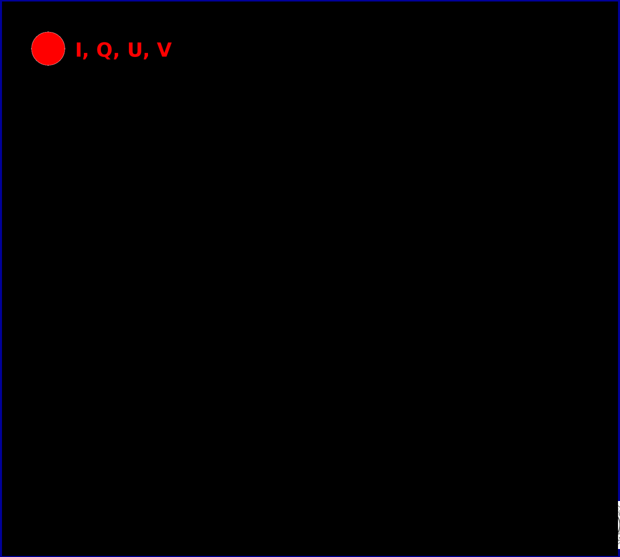
- The cross-correlations among ALMA antennas are used to derive K_+^i.
- Bandpass, gain, X/Y phase, X/Y delay, and leakage are taken into account (for each ALMA antenna).
- Reads the DifX output (in mixed-pol basis).
- interpolates the K_+^i matrices and computes $(K_+)^{-1}$.
- Applies the matrices, converts the VLBI visibilities to a pure circular basis, and writes a new DifX file.

Software implementation: PolSimulate

Multi-threaded realistic simulator of APP observations



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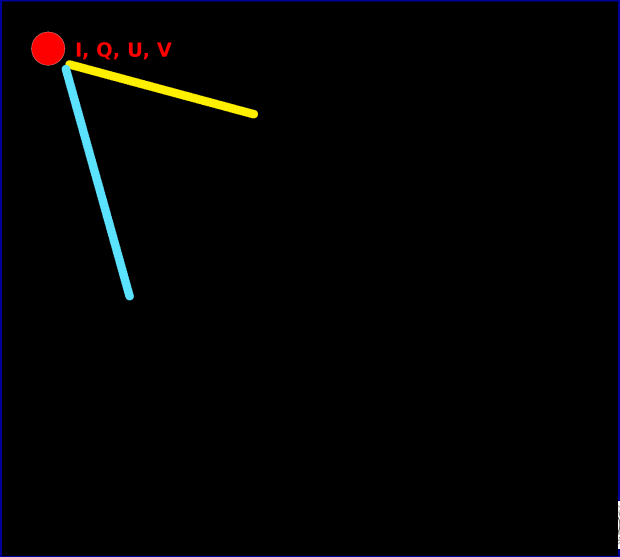

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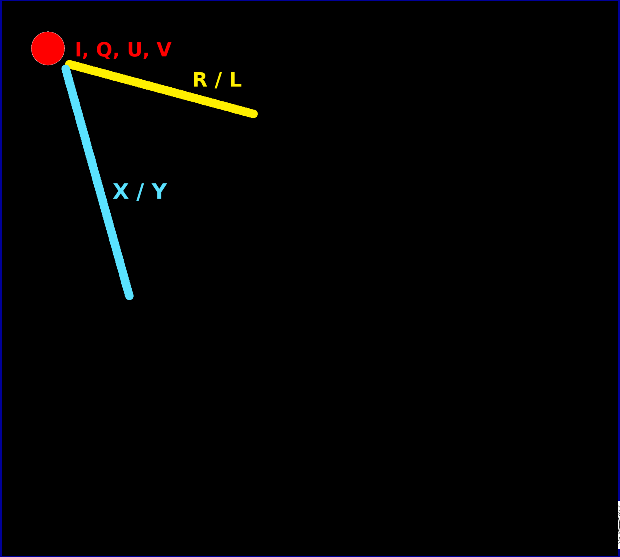

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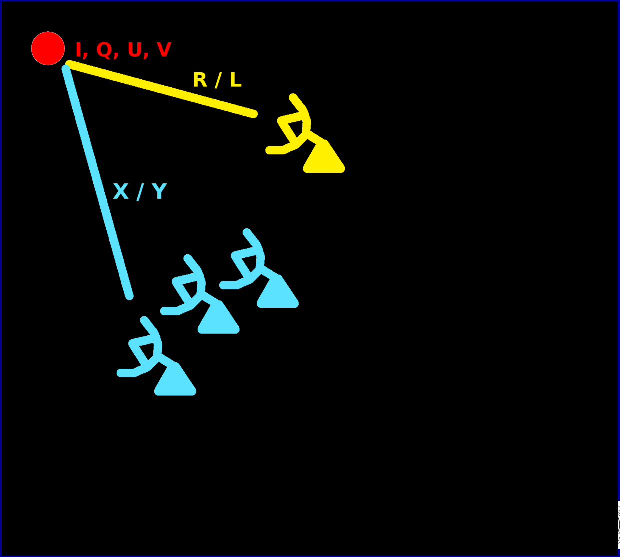

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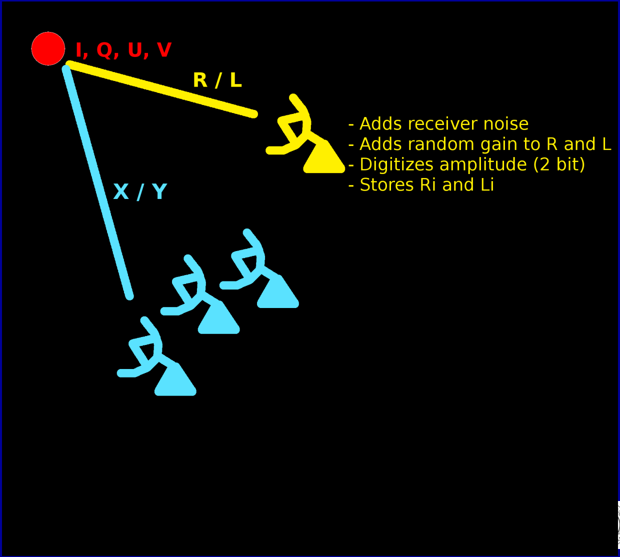

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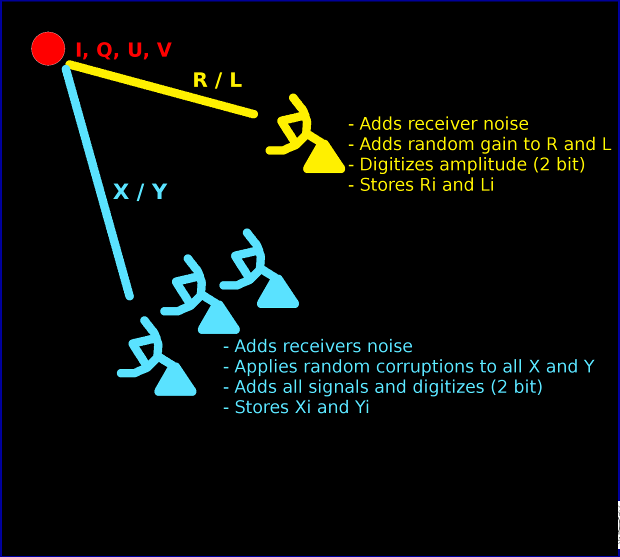

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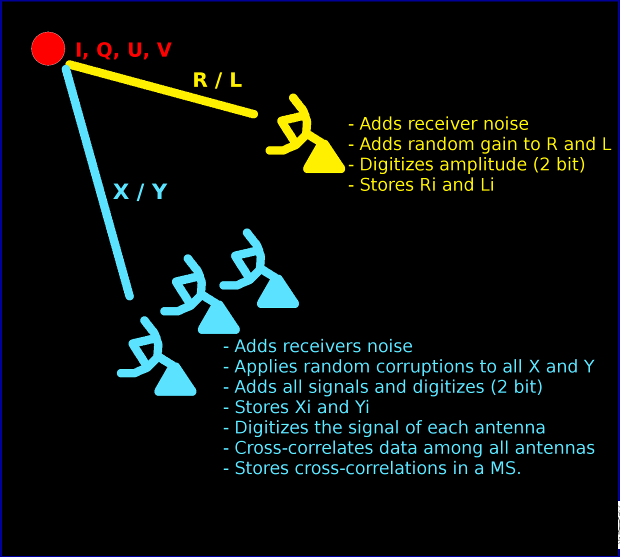

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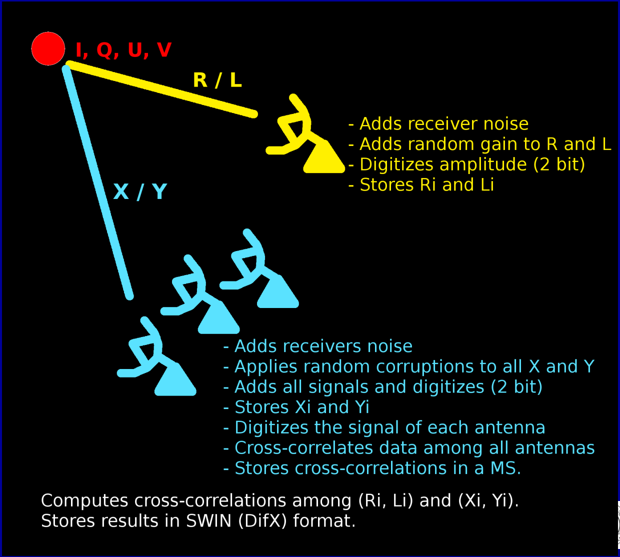

Simulation results I. Unpolarized source

- Observing frequency: $\nu = 100\,\mathrm{GHz}$.
- Bandwidth: $\Delta\nu = 100\,\mathrm{MHz}$.
- Number of ALMA antennas: $N_{ant} = 10$.
- Receiver noise: $T_{ant}/T_{sys} = 0.1$.
- Integration time: $t_{int} = 1\,\mathrm{s}$.
- Scan duration: $t_{sc} = 25\,\mathrm{s}$.
- Number of scans: $N_{sc} = 5$.
- Declination: $\delta = -60^\circ$.
- Maximum hour angle: $H_M = 6\,\mathrm{h}$.
- Maximum leakage (amp & phase): $D_{max} = 3\%$.
- Maximum bandpass correction (amplitude): $B_M^A = 10\%$.
- Maximum bandpass correction (phase): $B_M^P = 20^\circ$.
- Maximum differential X-Y gain: $G_M = 40\%$.
- Amplitude calib. (Jy): $I = 1.0$, $Q = U = 0.0$, $V = 0.0$.
- Polarization calib. (Jy): $I = 1.0$, $Q = 0.1$, $U = 0.0$, $V = 0.0$.

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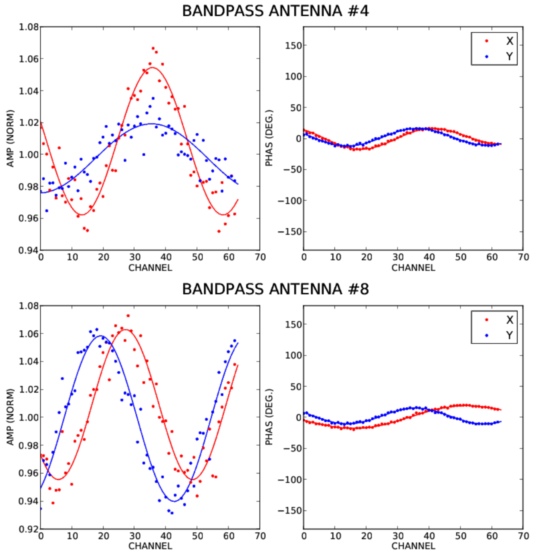
PolSimulate gains vs. CASA estimates (from calibration of the ALMA-only MS)



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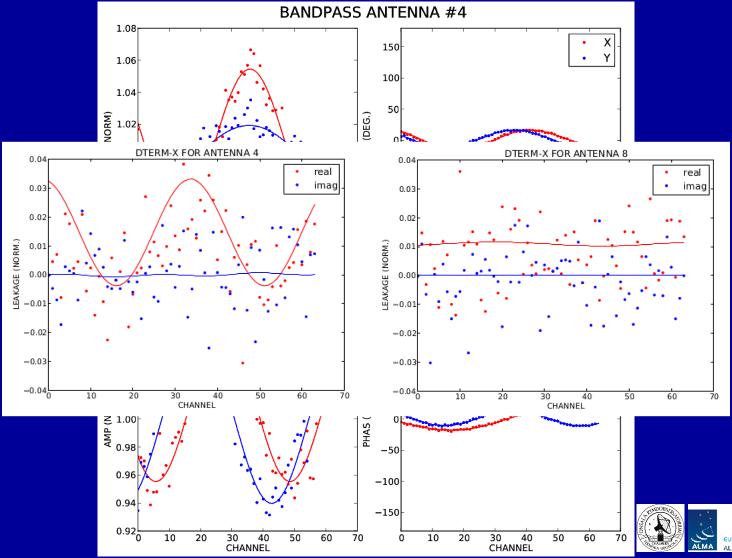
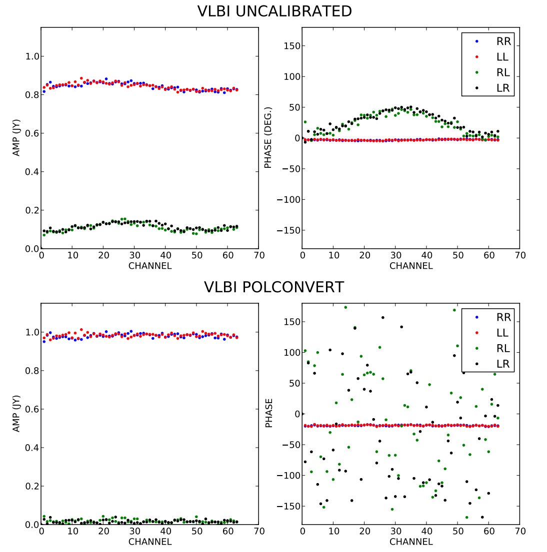


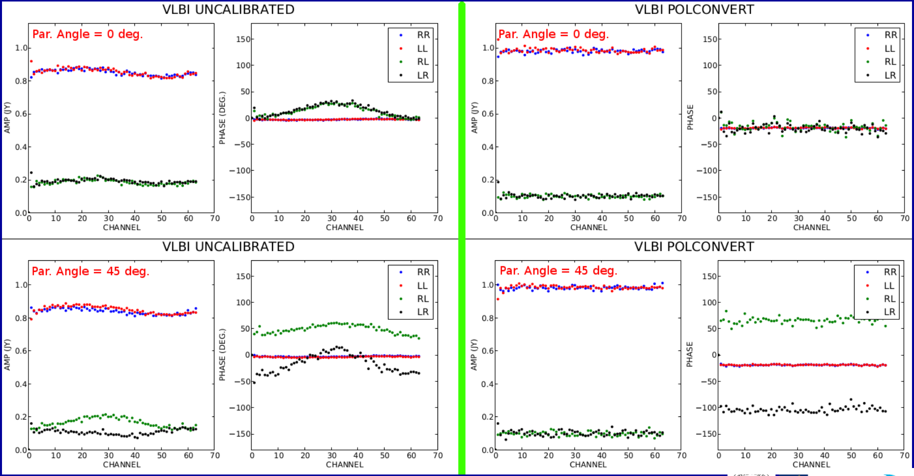
Simulation results I. Unpolarized source

Visibilities converted into pure circular basis (using K_+ derived from the MS calibration)



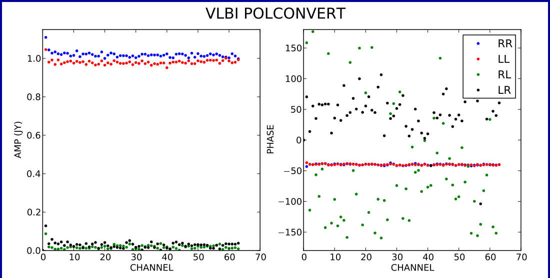
Simulation results II. Linearly polarized source

Stokes parameters (Jy): $I = 1.0,\ Q = 0.1,\ U = 0.0,\ V = 0.0$



Simulation results III. Circularly polarized source

Stokes parameters (Jy): $I = 1.0$, $Q = 0.0$, $U = 0.0$, $V = 0.03$



Small contamination from V into RL/LR, due to deviations in the estimates of the D-terms

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- Pilot observations in mixed basis will be performed soon (Onsala/Effelsberg) at 3mm, to test *PolConvert* with real data.