ALMA/VLA Polarization Data Reduction

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NRAO Community Day IRyA-UNAM

28-29 September 2023, Morelia

Take Home Message

- Polarimetry is a little complicated, but do not be afraid!
- The polarized state of EM radiation gives valuable insights into magnetic fields and the physics of the emission.
- Understanding polarization improves calibration and imaging even in the unpolarized case.

- As a final note: polarization calibration is *now* in the ALMA Pipeline - hifa_selfcal

Thanks to Frank Schinzel Rick Perley & Michiel Brentjens from whom I extensively borrowed and/or adapted presented materials.

Outline of Talk

Electromagnetic Waves Refresher

Astrophysical Motivation

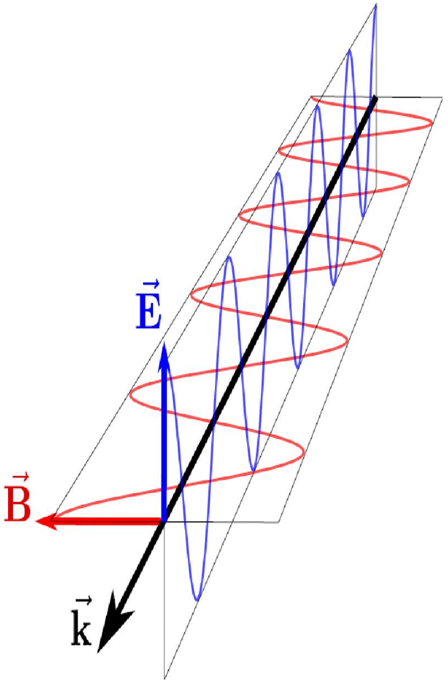
Polarimetry of Interferometers

- Monochromatic vs Quasi-monochromatic
- Circular vs Linear Bases
- Stokes Visibilities
- Interferometer Response to Polarized Emission

Theory meets real-world

- Calibrating Polarimetry Observations
- A Simple Example of Interpreting Images

Plane Electromagnetic (EM) Wave

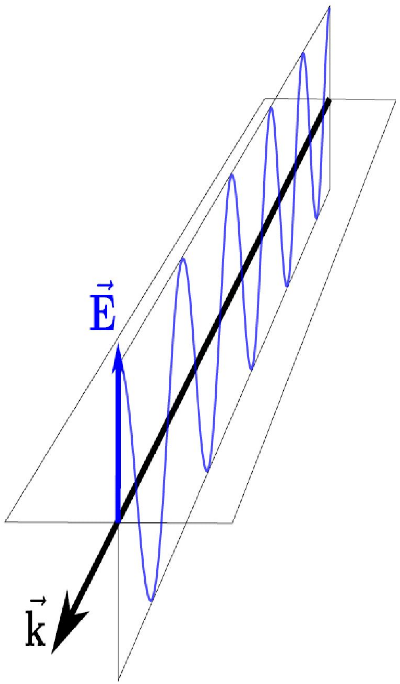


Vector fields describe EM waves

Applying Maxwell's equations for plane monochromatic waves (far field):

Wave vector: $\vec{k} = \vec{E} \times \vec{B}$

Plane Electromagnetic (EM) Wave



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Applying Maxwell's equations for plane monochromatic waves (far field):

Wave vector: $\vec{k} = \vec{E} \times \vec{B}$

Typically easiest to measure $\vec{E}$

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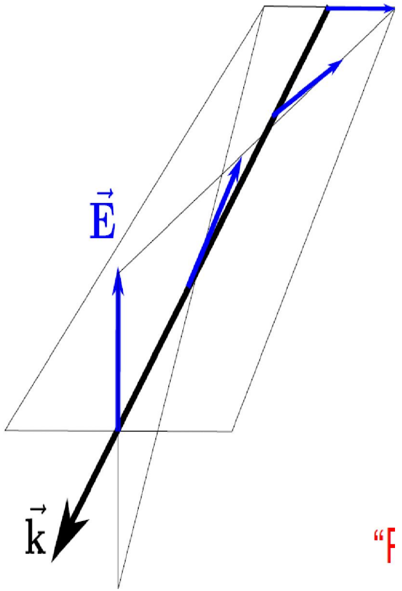


Vector fields describe EM waves

Applying Maxwell's equations for plane monochromatic waves (far field):

Wave vector: $\vec{k} = \vec{E} \times \vec{B}$

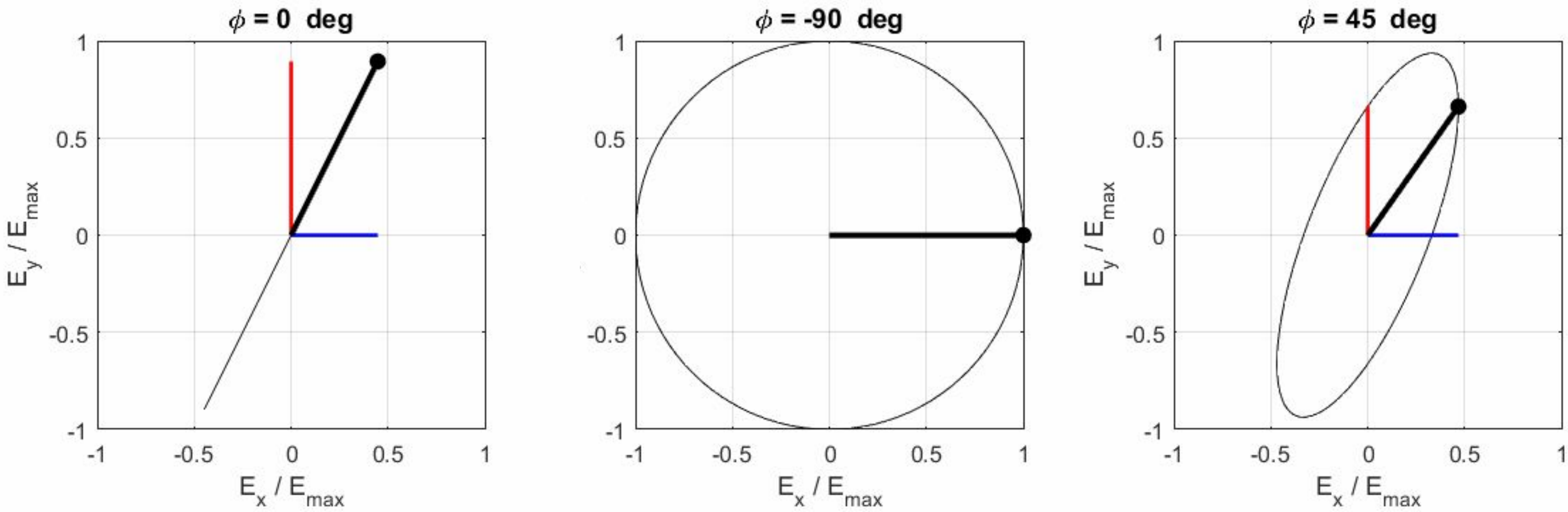
Typically easiest to measure $\vec{E}$

Single $\vec{E}$ field vector breaks down into an x/y component for mono-chromatic waves:

$$E_x = A_x \cos(kz - \omega t + \delta_1)$$
$$E_y = A_y \cos(kz - \omega t + \delta_2)$$
$$k = \frac{2\pi}{\lambda};\ \omega = 2\pi\nu;\ \mathrm{Phase} = \delta_{1/2}$$

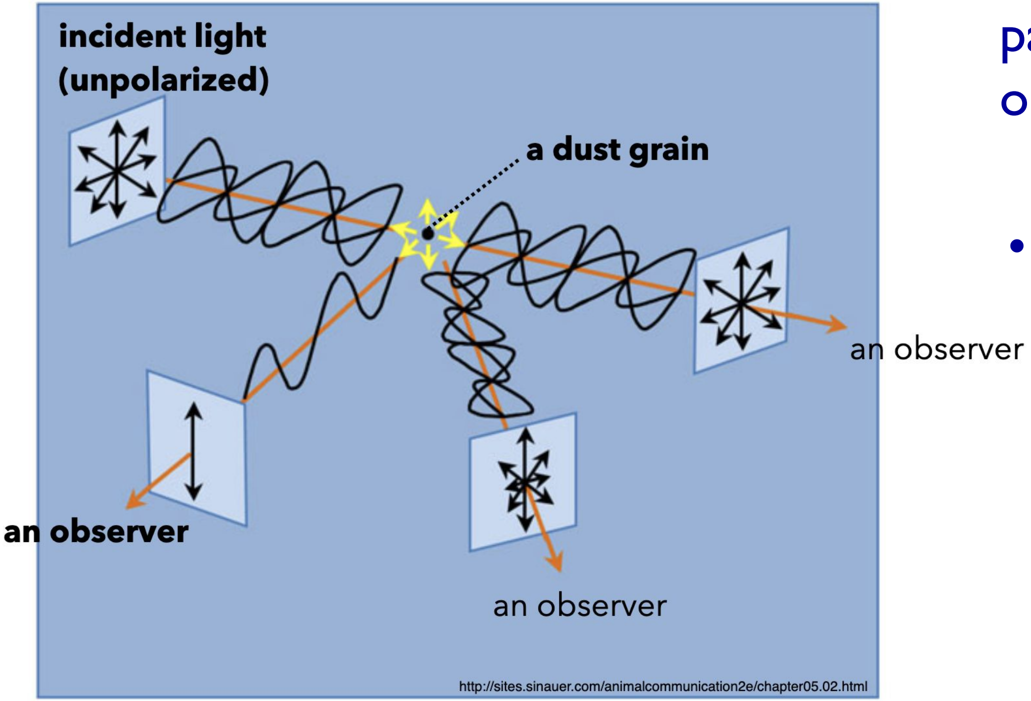
Plane Polarized EM Wave

Linearly Polarized Circularly Polarized Elliptically Polarized



Polarized Radio Emission

Scattering/reflection



Unpolarized EM wave scattered by particles; the scattered wave is partially or completely polarized.

- Modifies polarization state

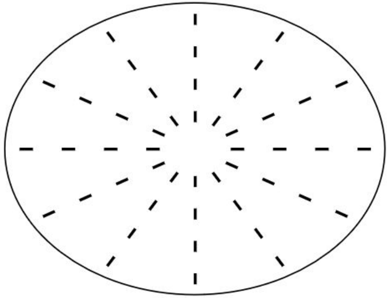
Polarimetry provides:

- Electron densities in cool gas
- Dust properties
- B-field direction
- B-field strength (estimate)
- Lunar dielectric constant

Polarized Radio Emission

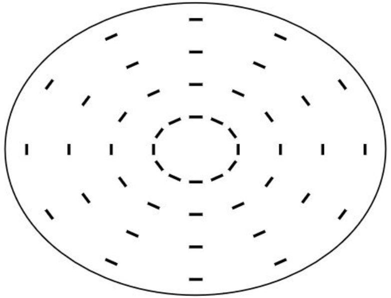
Scattering/reflection

alignment with B-fields



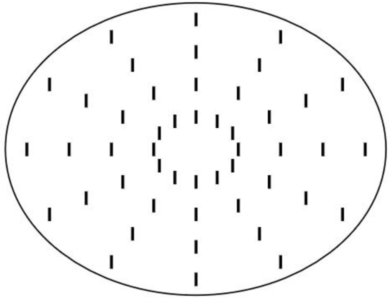
- **depends on magnetic field components**

alignment with radiation

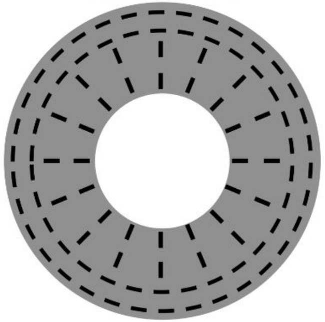


(alignment with gas flow)

self-scattering



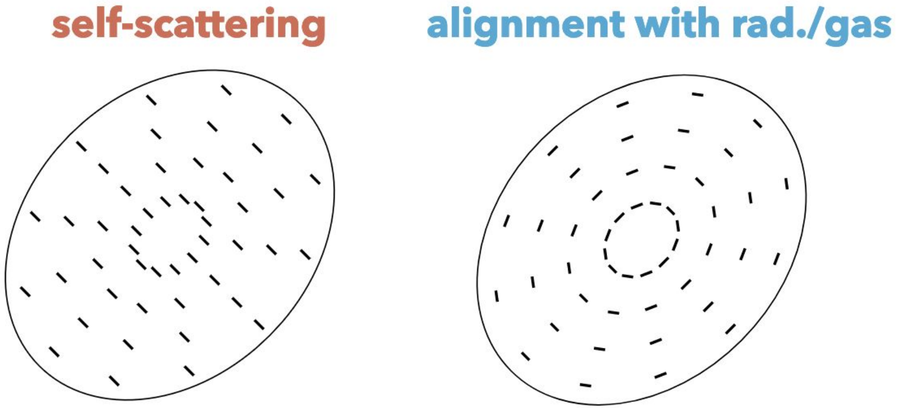
(a) self-scattering

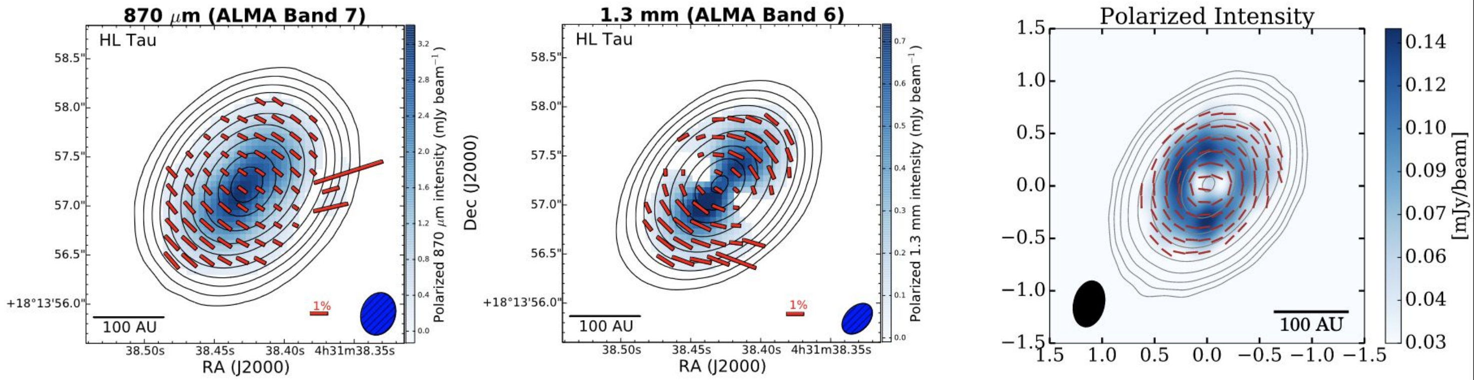


wavelength independent ⟷ **wavelength dependent**

Polarized Radio Emission

Scattering/reflection

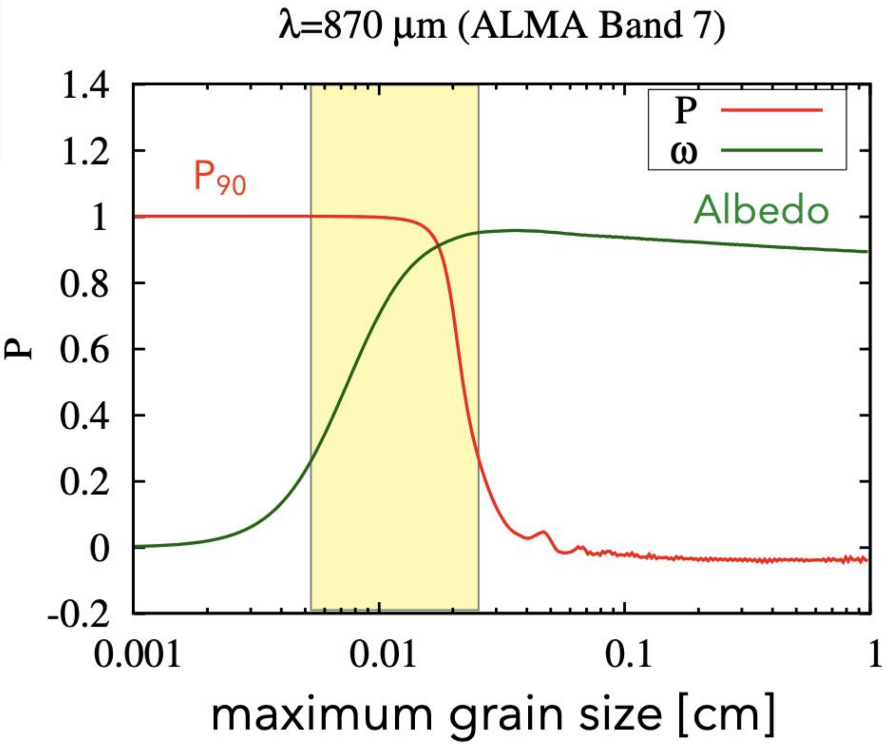


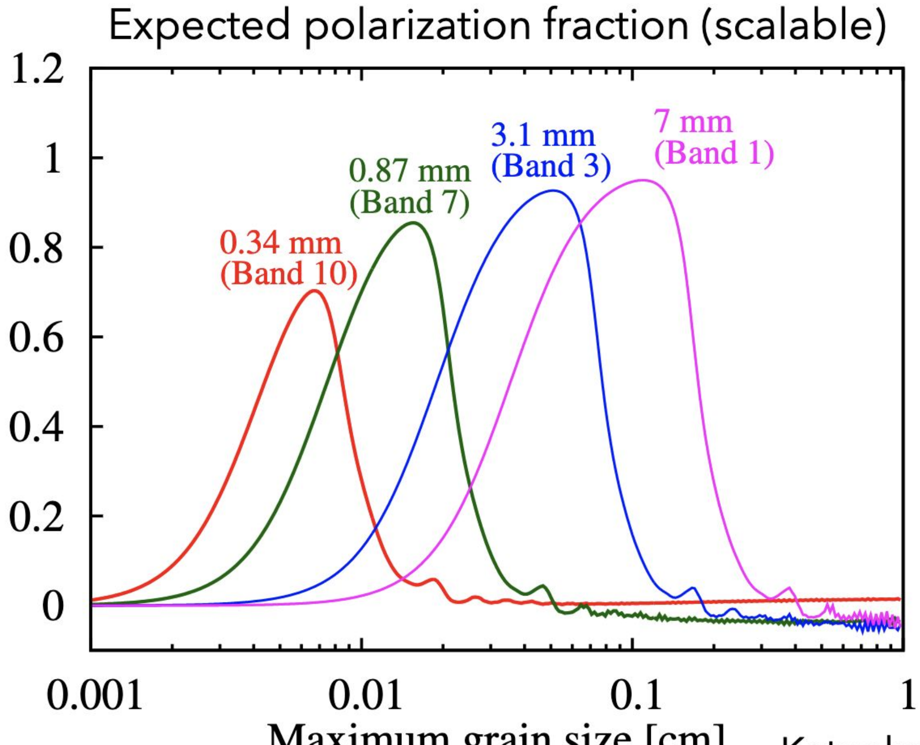


Stephens,…, Kataoka, et al. 2017

Kataoka et al. 2017

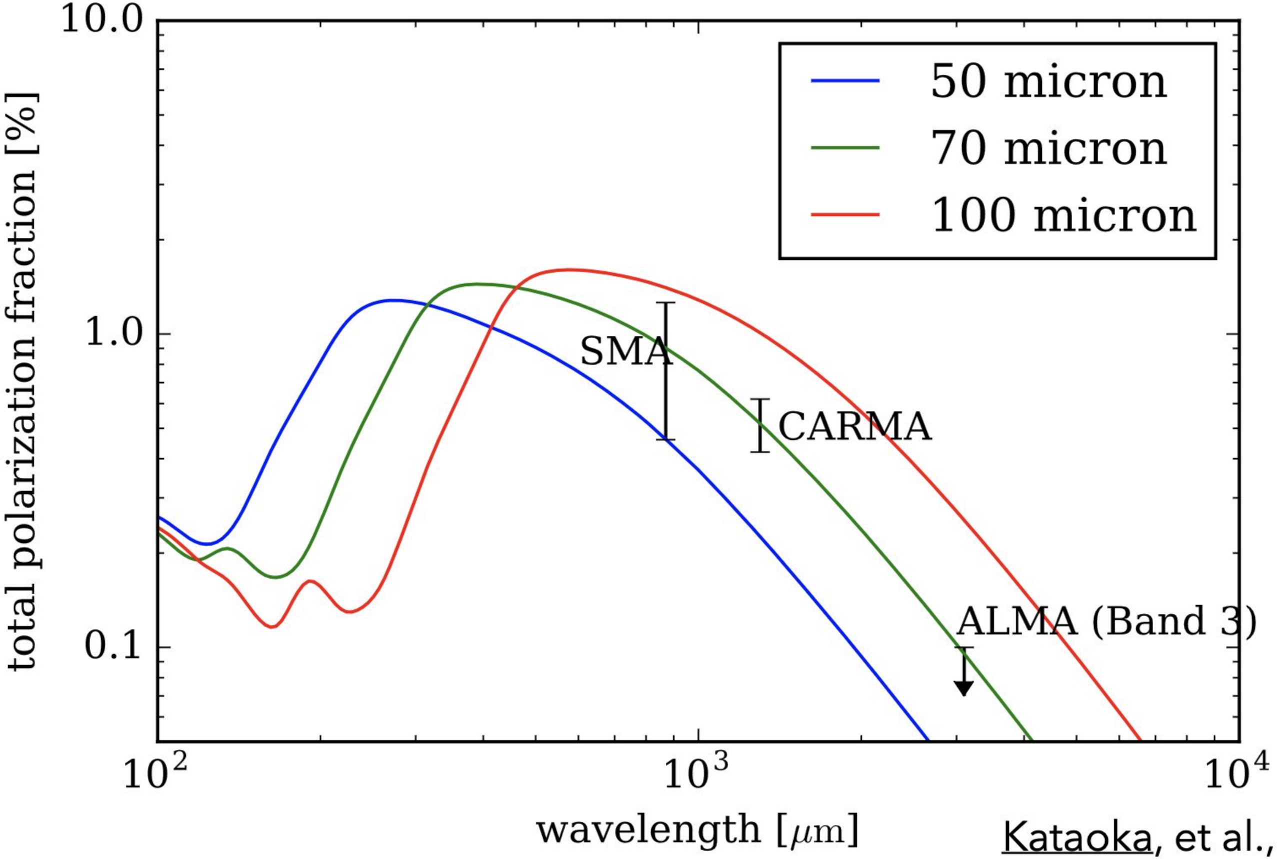
Polarized Radio Emission
Scattering/reflection





Polarized Radio Emission

Scattering/reflection



Kataoka, et al., 2017

Polarized Radio Emission

Synchrotron Emission

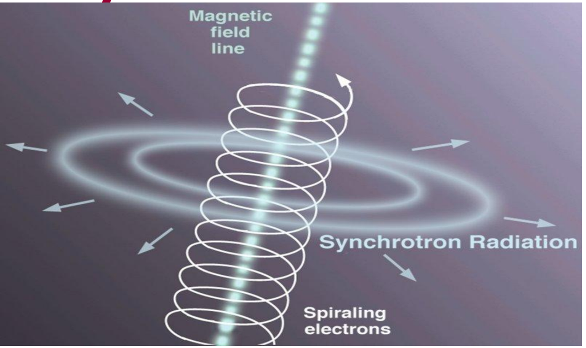


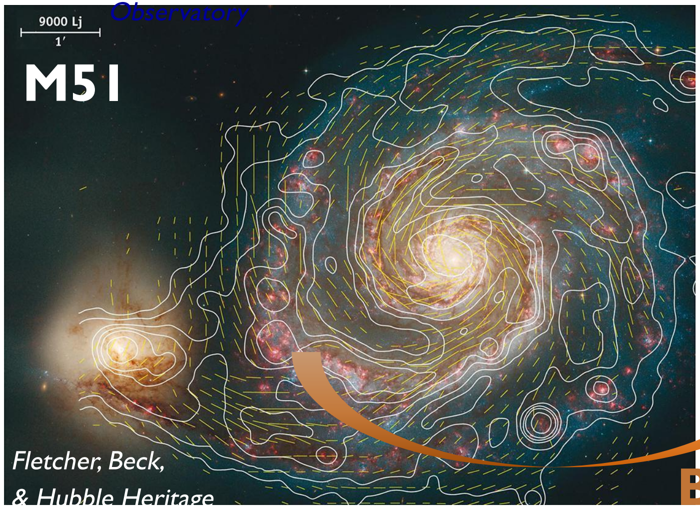
Image Credit: Gemini Observatory

Generates polarized emission

Main emission mechanism at cm-m wavelength

Up to 80% linearly polarized (no circular pol.)

$$< \vec{E}_{\text{source}} > \perp \vec{B}_{\text{source}}$$



Fletcher, Beck, & Hubble Heritage

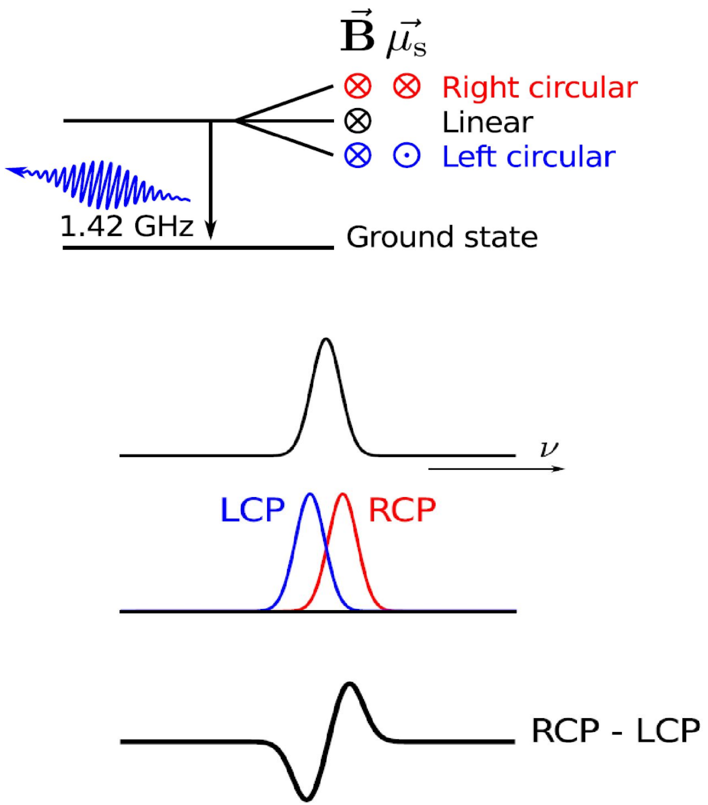
B-vectors

Polarimetry provides

- B-field direction
- Turbulence
- Indirectly: B-field strength

Polarized Radio Emission

Zeeman splitting



Generates polarized emission only in spectral lines

If magnetic moment:

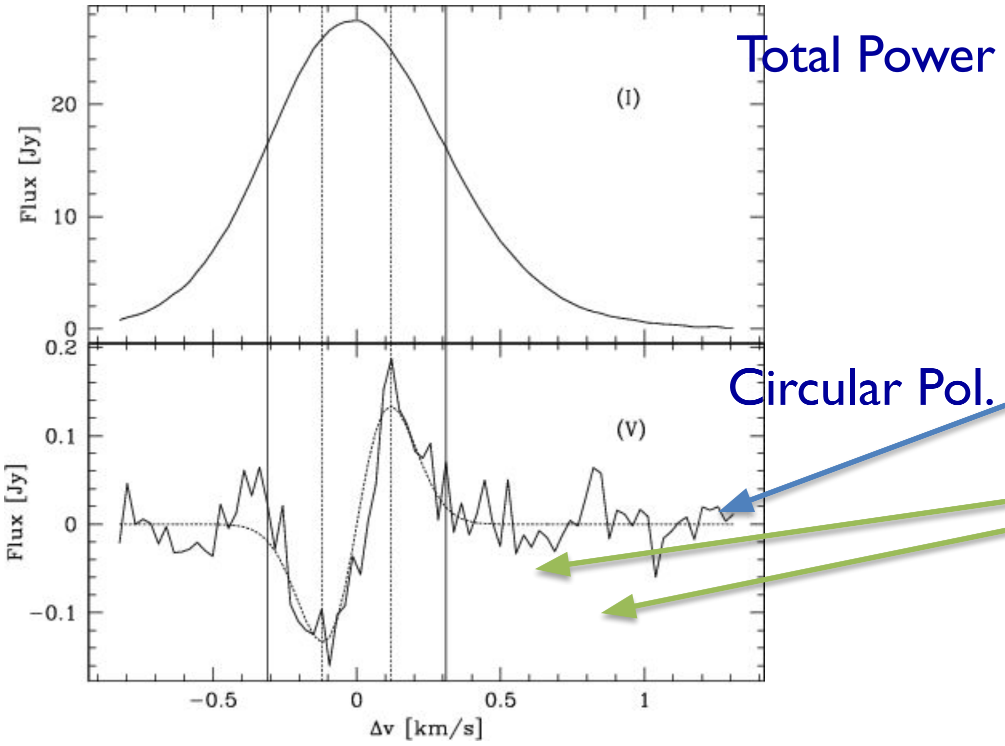
e.g. HI, OH, CN, H2O

B-field splits RCP and LCP

Separation: 2.8 Hz/mG

Polarimetry provides (if detectable) B-field strength at source

Zeeman splitting example
Vlemmings, Diamond, & van Lengevelde (2001)



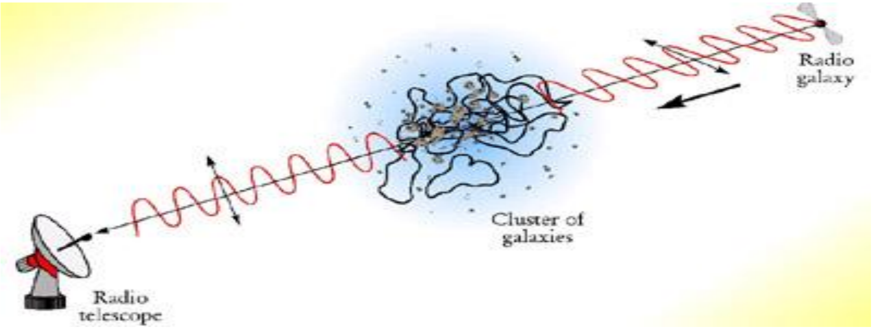
The brightest H_2O maser feature around the late type star S Per (VLBA Observation).

The dashed line is the fit of the synthetic circularly polarized spectrum to the observed spectrum.

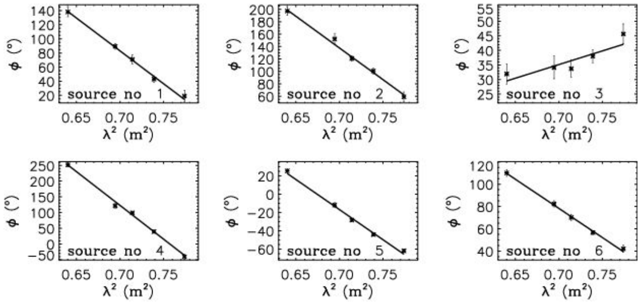
Also shown are the observed (dashed) and expected (solid) positions of the minimum and maximum of the circular polarization spectrum.

Narrowing of V-spectrum attributed to overlap of multiple hyperfine components.

Faraday rotation



λ^2 law



Graphs of polarization angle against wavelength squared for polarized extragalactic sources in the field (Haverkorn, Katgert, & de Bruyn 2003).

Process

- Modifies polarization state
- Delay between LCP and RCP
- Rotates linear pol. angle
- $\Delta\chi = \chi_0 + \phi\lambda^2$

$$\phi = 0.812 \int_{\text{there}}^{\text{here}} n_e \vec{B} \cdot d\vec{l}$$

Polarimetry provides

- Source plasma properties
- Intervening plasma properties
- Rare cases: 3D tomography

Stokes Parameters - Monochromatic

In radio astronomy, we use the parameters defined by George Stokes (1852; *ABCD*), and introduced to astronomy by Chandrasekhar (1946; *IQUV*):

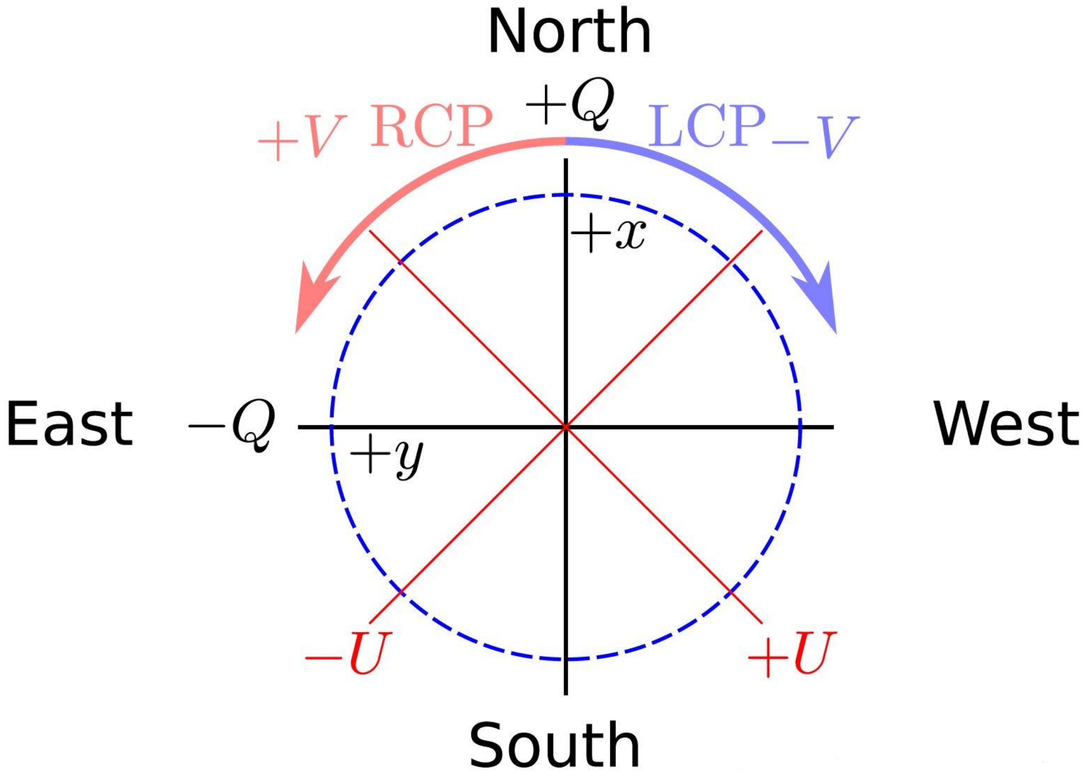
$$
\left.\begin{aligned}
I &= A_x^2 + A_y^2 &&= A_R^2 + A_L^2 \\
Q &= A_x^2 - A_y^2 &&= 2A_R A_L \cos\delta_{RL} \\
U &= 2A_x A_y \cos\delta_{xy} &&= 2A_R A_L \sin\delta_{RL} \\
V &= 2A_x A_y \sin\delta_{xy} &&= A_R^2 - A_L^2
\end{aligned}\right\}
$$

Units of power:
Jy, or Jy/beam

Monochromatic radiation is 100% polarized:

$$I^2 = Q^2 + U^2 + V^2$$

Stokes Parameters:
IAU convention (since 1973)



Stokes Parameters - Quasi-monochromatic

In reality, monochromatic radiation does not exist and 100% polarization is not possible. Instead we deal with averages in time:

$$\begin{aligned}
I &= \langle A_x^2 \rangle + \langle A_y^2 \rangle & &= \langle A_R^2 \rangle + \langle A_L^2 \rangle \\
Q &= \langle A_x^2 \rangle - \langle A_y^2 \rangle & &= \langle 2A_R A_L \cos\delta_{RL} \rangle \\
U &= \langle 2A_x A_y \cos\delta_{xy} \rangle & &= \langle 2A_R A_L \sin\delta_{RL} \rangle \\
V &= \langle 2A_x A_y \sin\delta_{xy} \rangle & &= \langle A_R^2 \rangle - \langle A_L^2 \rangle
\end{aligned}$$

Quasi-monochromatic radiation is 100% polarized: $I^2 > Q^2 + U^2 + V^2$

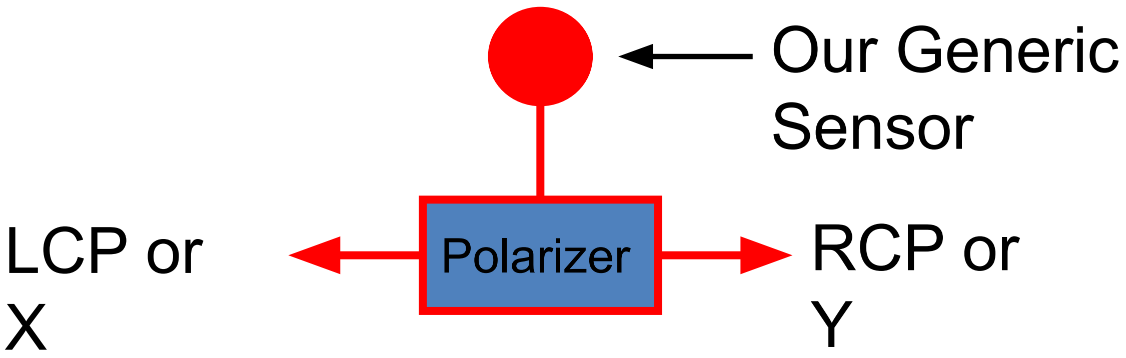
Fractional Linear Polarization: $p = \frac{\sqrt{Q^2+U^2}}{I}$

Polarization Angle: $\chi = \tan^{-1}\frac{U}{Q}$

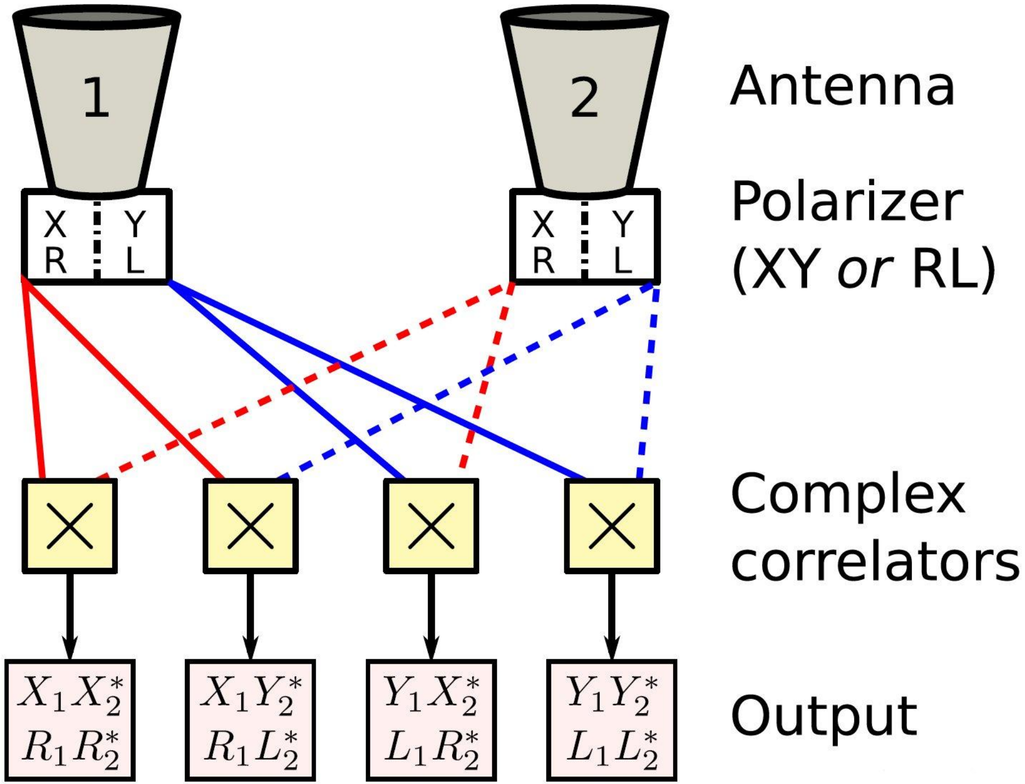
Fractional Circular Polarization: $v = \frac{|V|}{I}$

Relation to Sensors

- What is the relation to real sensors (antennas)?
- Antennas are polarized – they provide two simultaneous voltage signals whose values are (ideally) representations of the two electric field components – either in circular or linear basis.



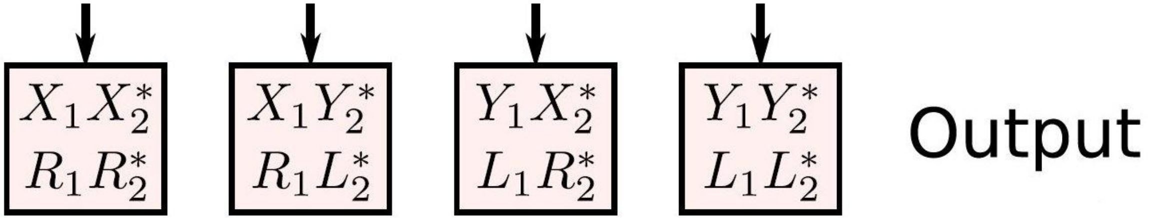
Relation to Sensors



Two antennas, each with two differently polarized outputs, produce four complex correlations.

From these four outputs, we want to generate the four complex Stokes' visibilities I, Q, U, V .

Relating the Products to Stokes' Visibilities



We can work out from the earlier definitions that the outputs of an interferometer are related to the stokes parameters by:

Linear

$$V_{xx} = \langle X_1X_2^* \rangle = (I + Q)/2$$
$$V_{xy} = \langle X_1Y_2^* \rangle = (U + iV)/2$$
$$V_{yx} = \langle Y_1X_2^* \rangle = (U - iV)/2$$
$$V_{yy} = \langle Y_1Y_2^* \rangle = (I - Q)/2$$

Circular

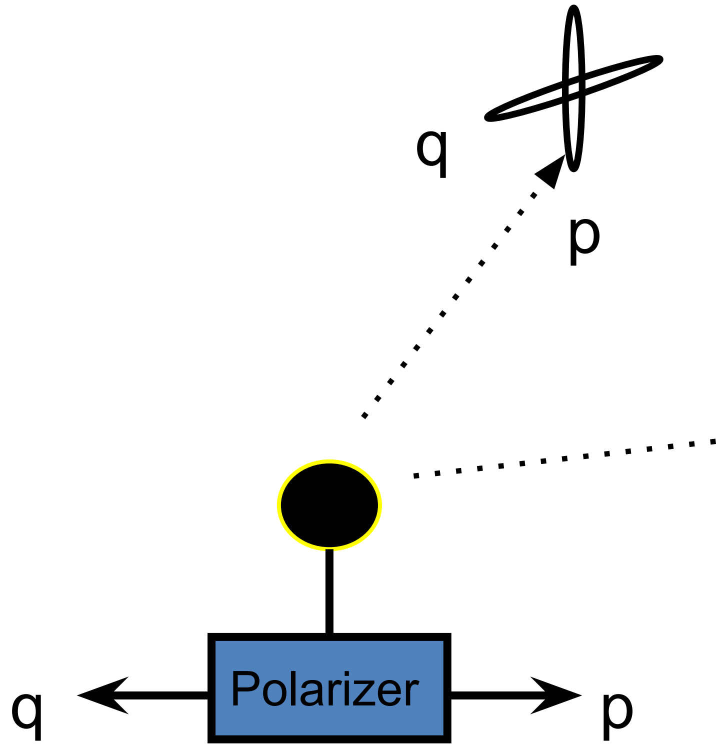
$$V_{RR} = (I + V)/2$$
$$V_{LL} = (I - V)/2$$
$$V_{LR} = (Q + iU)/2$$
$$V_{RL} = (Q - iU)/2$$

Real Sensors

Sadly real sensors are:

1. Imperfectly polarized. Typically, the cross-polarization for circularly polarized systems is ~5% or ~1% for linear.
2. Misaligned with the sky frame. Alt-Az antennas rotate w.r.t. the sky frame as they track a celestial source. The angle describing the misalignment is called the 'parallactic angle'.

How do these imperfections affect the polarimetry?



Real Telescope Response - Linear

For linear polarization receivers:

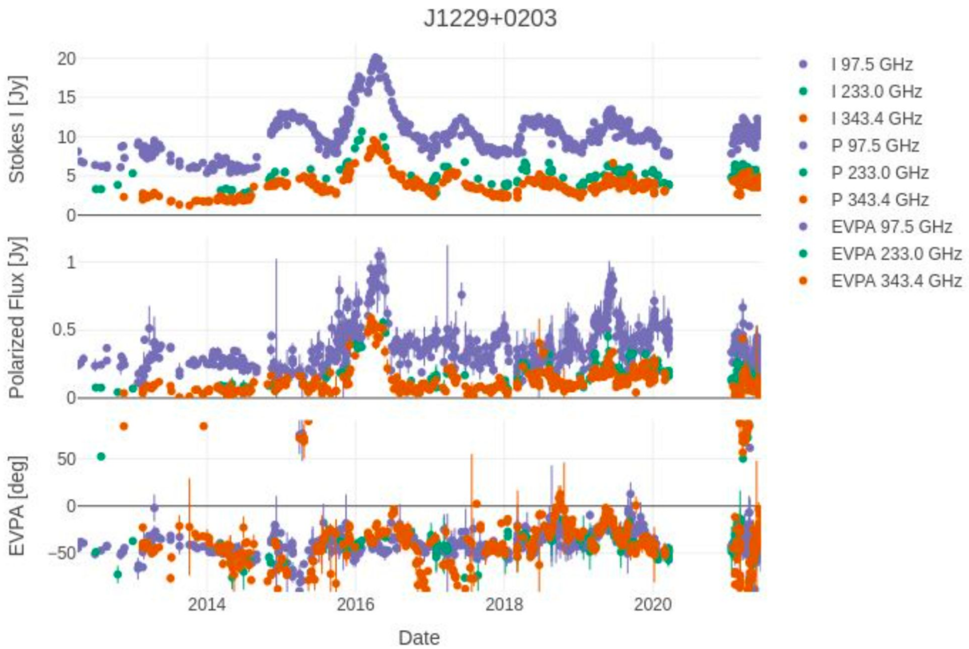
$$
\begin{aligned}
V_{xx} &= \frac{1}{2} g_{xj} g_{xj}^* (I \; + Q \cos 2\chi \; + U \sin 2\chi) \\
V_{xy} &= \frac{1}{2} g_{xi} g_{yj}^* \left(I \left(d_{xi} - d_{yj}^*\right) - Q \sin 2\chi \; + U \cos 2\chi \; + iV\right) \\
V_{yx} &= \frac{1}{2} g_{yi} g_{xj}^* \left(I \left(d_{xj}^* - d_{yi}\right) - Q \sin 2\chi \; + U \cos 2\chi \; - iV\right) \\
V_{yy} &= \frac{1}{2} g_{yi} g_{yj}^* (I \; - Q \cos 2\chi \; + U \sin 2\chi)
\end{aligned}
$$

The *d* terms represent the "leakages" from one polarization to the other due to the misalignment of the polarized receivers.

Calibration - Linear

Calibrators typically have negligible circular polarization, i.e. V = 0…

… but also frequently have small amounts, a few %, of unknown and variable linear polarization.



Calibration - Linear

Calibrators typically have negligible circular polarization, i.e. V = 0…

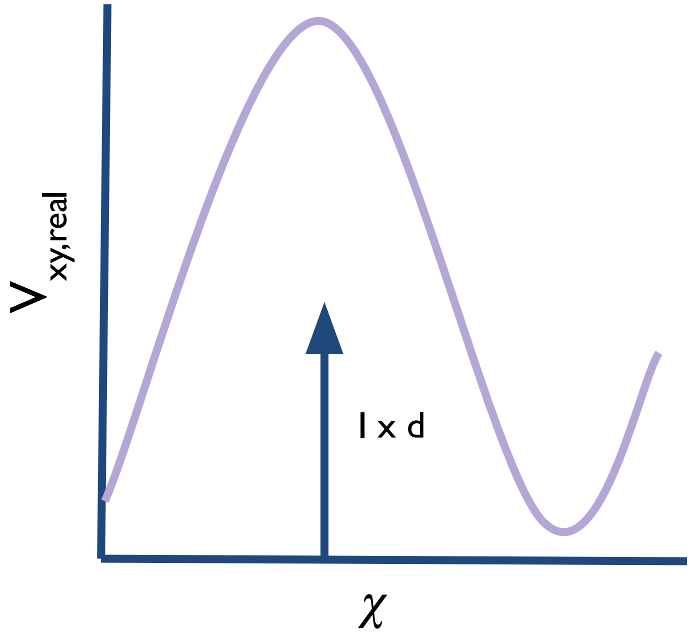
… but also frequently have small amounts, a few %, of unknown and variable linear polarization.

Moreover, gain calibration typically sets the per-polarization gains of the reference antenna to 0, meaning there's a remnant phase delay between cross polarizations.

$$
\begin{aligned}
V_{xx} &= \frac{1}{2} g_{xi} g_{xj}^{*} (I + Q\cos 2\chi + U \sin 2\chi) \\
V_{xy} &= \frac{1}{2} g_{xi} g_{yj}^{*} \left(I \left(d_{xi} - d_{yj}^{*}\right) - Q \sin 2\chi + U \cos 2\chi\right) e^{-i\phi_{xy}} \\
V_{yx} &= \frac{1}{2} g_{yi} g_{xj}^{*} \left(I \left(d_{xj}^{*} - d_{yi}\right) - Q \sin 2\chi + U \cos 2\chi\right) e^{i\phi_{xy}} \\
V_{yy} &= \frac{1}{2} g_{yi} g_{yj}^{*} (I - Q\cos 2\chi + U \sin 2\chi)
\end{aligned}
$$

Calibration - Linear

Fortunately, this can be separate into a constant leakage term, and a term that only depends on calibrator polarization properties that varies with time.

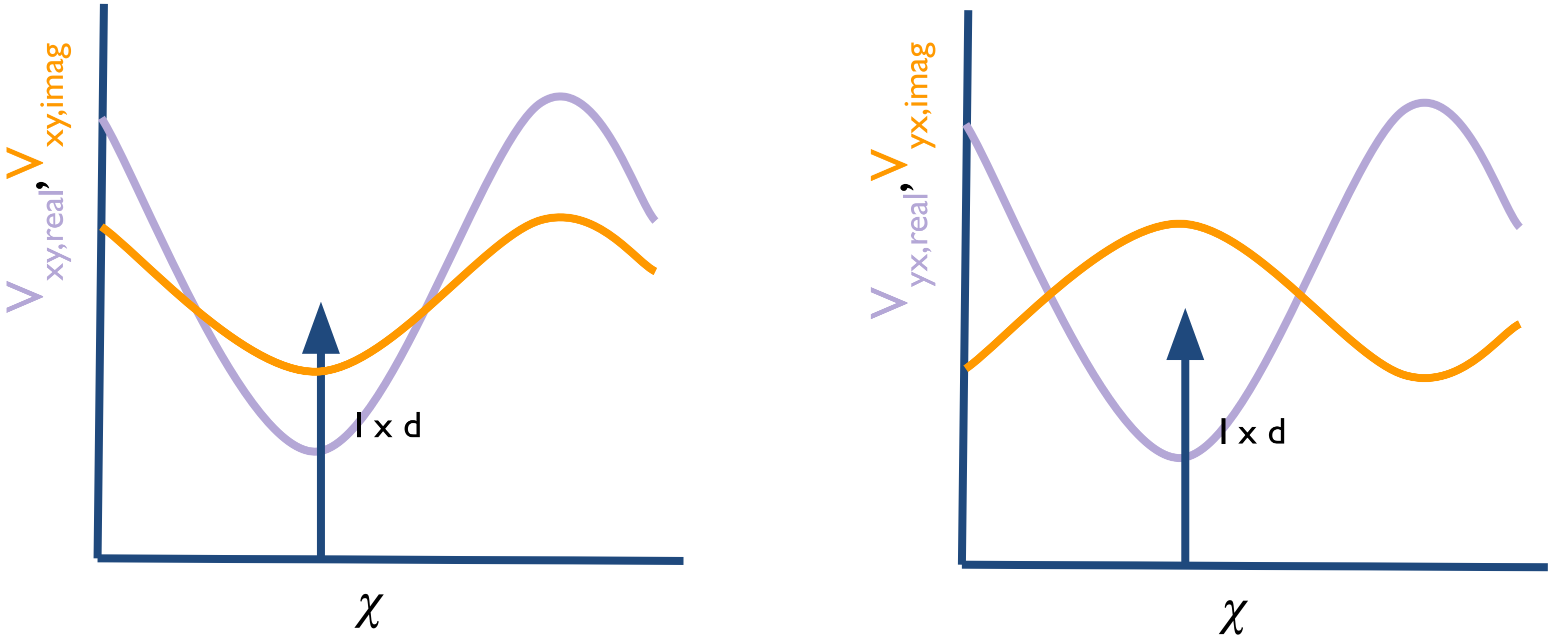


$$V_{xy} = \frac{1}{2} g_{xi} g_{yj}^{*} \left(I \left(d_{xi} - d_{yj}^{*} \right) - Q \sin 2\chi + U \cos 2\chi \right) e^{-i\phi_{xy}}$$

$$V_{yx} = \frac{1}{2} g_{yi} g_{xj}^{*} \left(I \left(d_{xj}^{*} - d_{yi} \right) - Q \sin 2\chi + U \cos 2\chi \right) e^{i\phi_{xy}}$$

Calibration - Linear

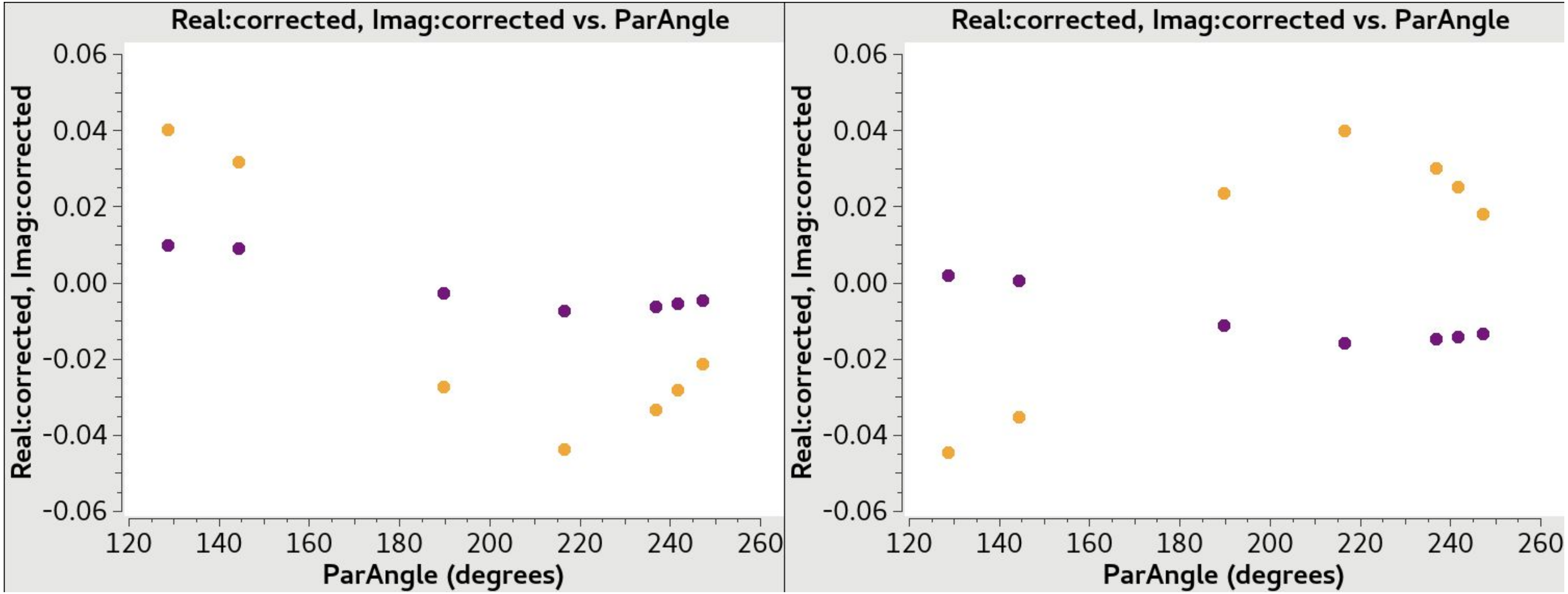
And the phase delay pushes some of the signal into the imaginary component



We can solve for phase delay, unknown source polarization, and leakages

In Real Data

And the phase delay pushes some of the signal into the imaginary component



We can solve for phase delay, unknown source polarization, and leakages

Linear Calibration Steps

1. Observe science target(s) as usual, but with an additional polarization calibrator observed over a range of parallactic angle => usually multiple tracks with ALMA
2. Use the cross-hand terms to solve for the XY phase delay and calibrator polarization model (i.e. Q, U)

```
gaincal(vis='3c286_Band6.ms',caltable='3c286_Band6.ms.XY0amb', field='0',
            gaintype='XYf+QU', solint='inf', combine='scan,obs', preavg=300,
            refant=refant, refantmode='strict', smodel=[1,0,1,0],
            gaintable=['3c286_Band6.ms.Bscan','3c286_Band6.ms.G1',
            '3c286_Band6.ms.Kcrs'], interp=['nearest','linear','nearest'])
```

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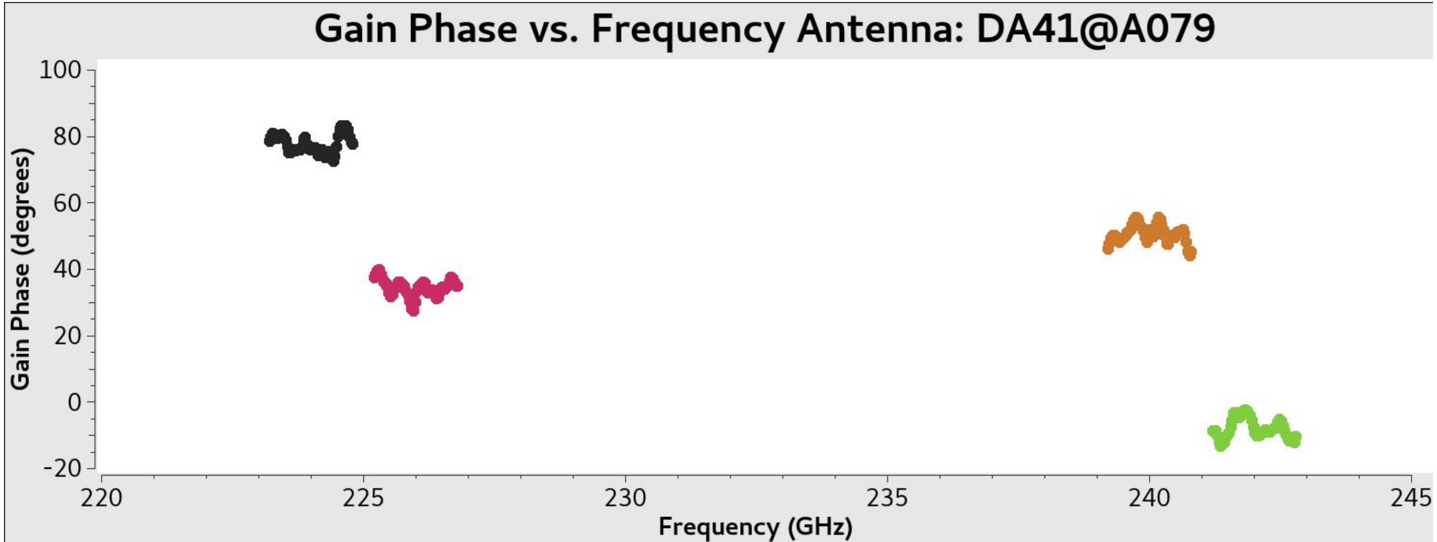

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$$V_{xy} = \frac{1}{2} g_{xi} g_{yj}^* \left(I \left(d_{xi} - d_{yj}^* \right) - Q \sin 2\chi + U \cos 2\chi \right) \cancel{e^{-i\phi_{xy}}}$$
$$V_{yx} = \frac{1}{2} g_{yi} g_{xj}^* \left(I \left(d_{xj}^* - d_{yi} \right) - Q \sin 2\chi + U \cos 2\chi \right) \cancel{e^{i\phi_{xy}}}$$

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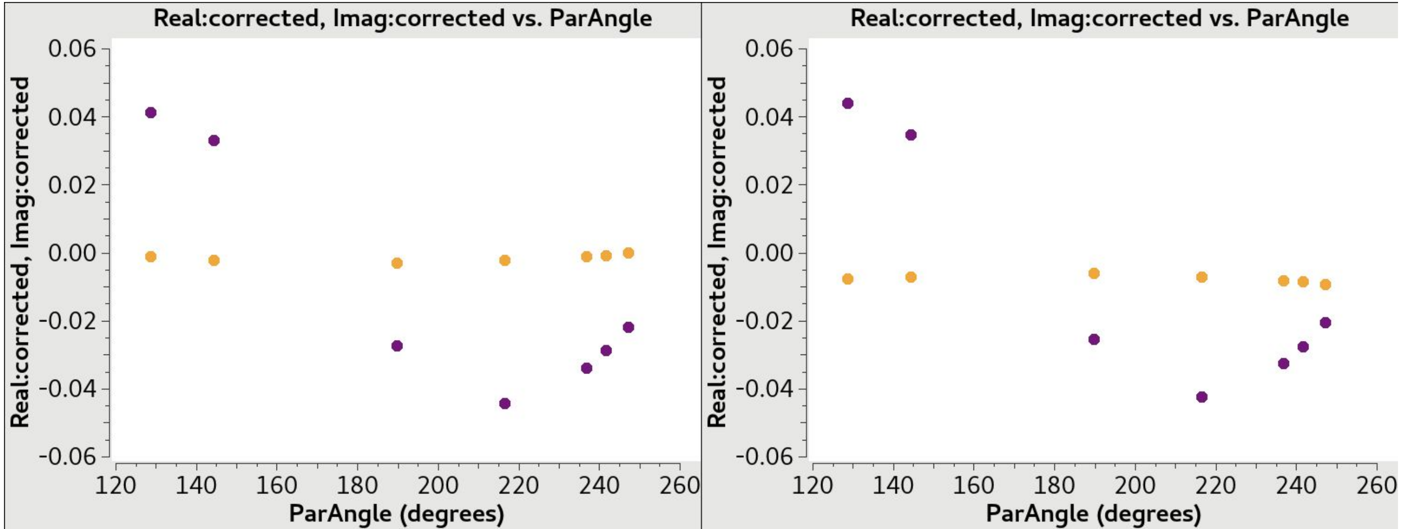

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3. Re-solve for the gains of the polarization calibrator, accounting for parallactic angle

```
gaincal(vis='3c286_Band6.ms', caltable='3c286_Band6.ms.G2.polcal',
        field='0', solint='int', refant=refant, refantmode='strict',
        smodel=S, gaintable=['3c286_Band6.ms.Bscan'],interp=['nearest'],
        parang=True)
```

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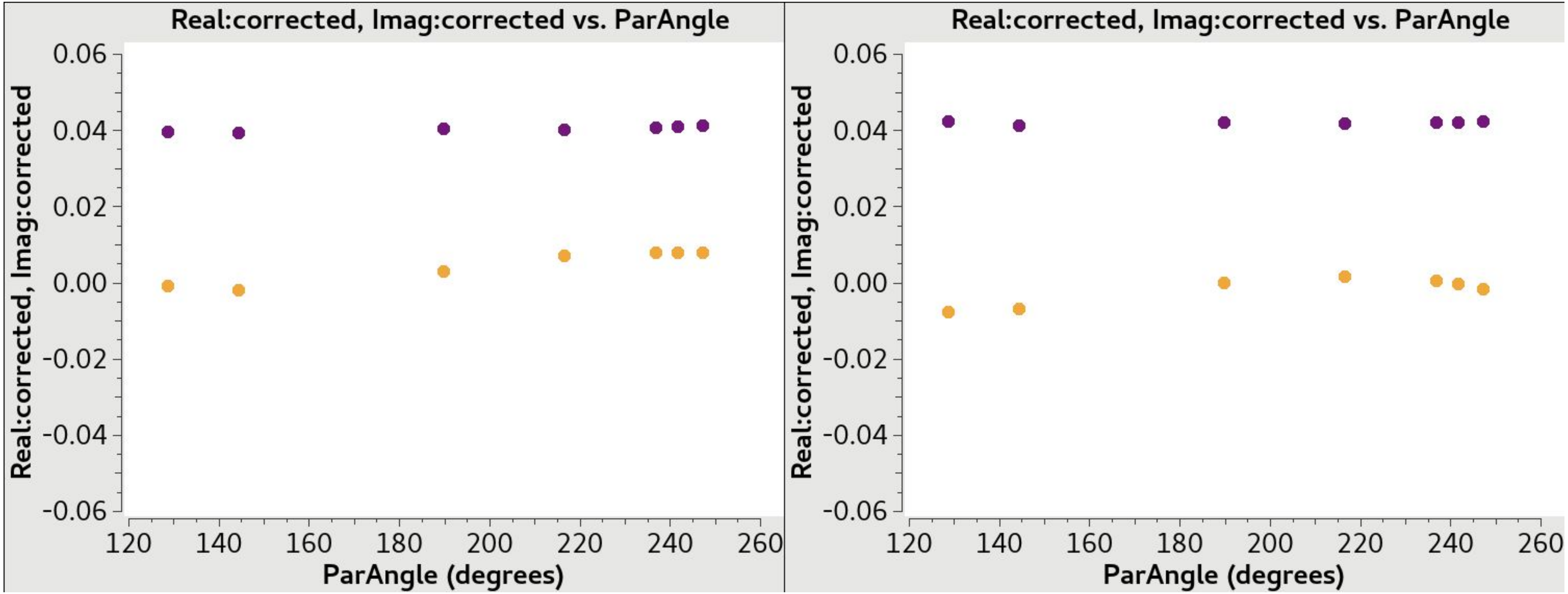
$$
\begin{aligned}
V_{xy} &= \frac{1}{2}\cancel{g_{xi}}g^*_{yj}\left(I\left(d_{xi} - d^*_{yj}\right) - \cancel{Q\sin 2\chi} + U\cancel{\cos 2\chi}\right) \\
V_{yx} &= \frac{1}{2}\cancel{g_{yi}}g^*_{xj}\left(I\left(d^*_{xj} - d_{yi}\right) - \cancel{Q\sin 2\chi} + U\cancel{\cos 2\chi}\right)
\end{aligned}
$$

Linear Calibration Steps

3. Re-solve for the gains of the polarization calibrator, accounting for parallactic angle



Linear Calibration Steps

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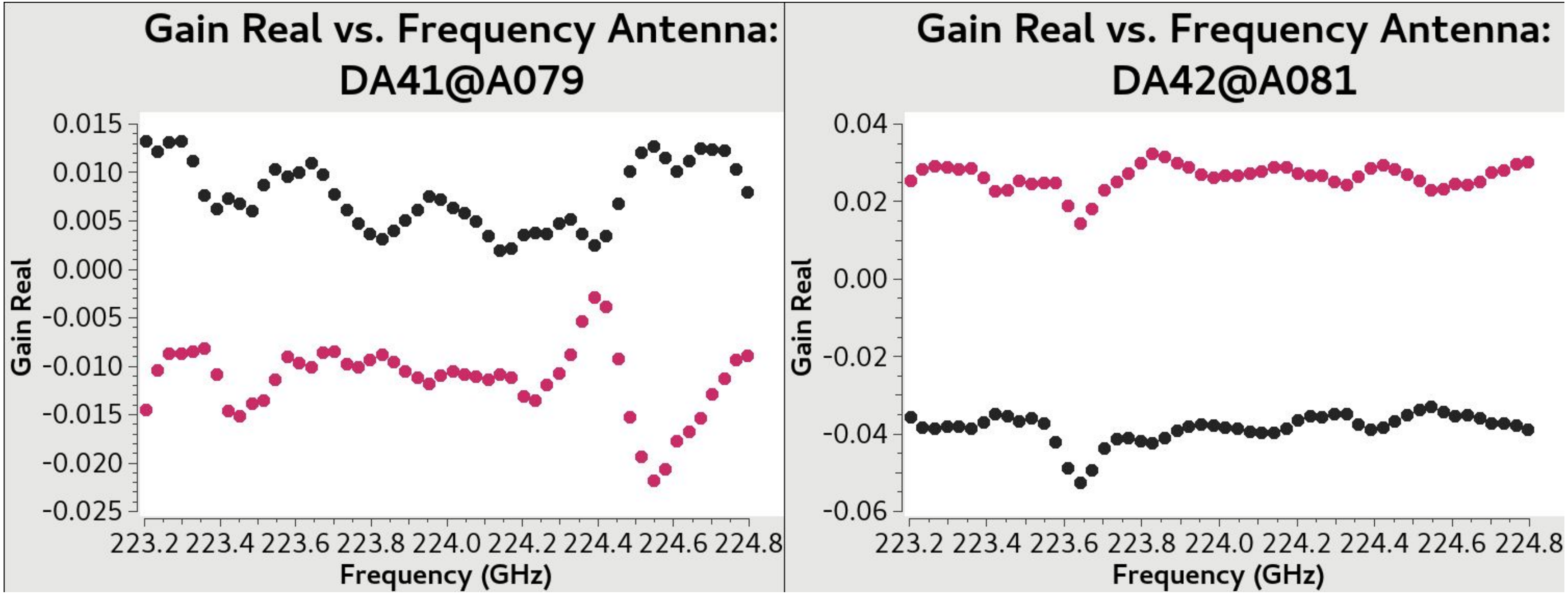
2. Use the cross-hand terms to solve for the XY phase delay and calibrator polarization model (i.e. Q, U)
3. Re-solve for the gains of the polarization calibrator, accounting for parallactic angle
4. Solve for the instrumental polarization leakage

```
polcal(vis='3c286_Band6.ms', caltable='3c286_Band6.ms.Df0', field='0',
        solint='inf',combine='obs,scan', preavg=300, poltype='Dflls',
        refant='', smodel=S, gaintable=['3c286_Band6.ms.Bscan',
        '3c286_Band6.ms.G2.polcal', '3c286_Band6.ms.Kcrs',
        '3c286_Band6.ms.XY0'], gainfield=['', '', '', ''],
        interp=['nearest','linear','nearest','nearest'])
```

Linear Calibration Steps

4. Solve for the instrumental polarization leakage



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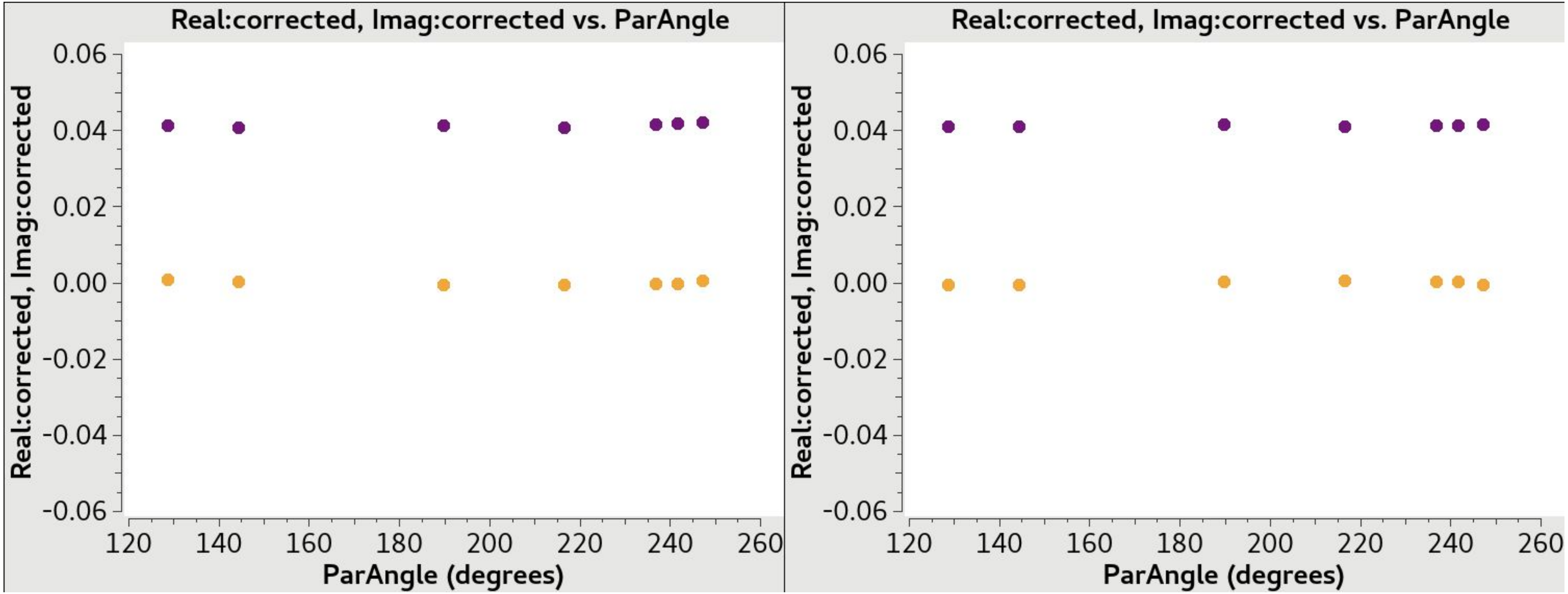
$$
\begin{aligned}
V_{xy} &= \frac{1}{2}\left(\cancel{I\left(d_{xi} - d_{yj}^*\right)} + U\right) \\
V_{yx} &= \frac{1}{2}\left(\cancel{I\left(d_{xj}^* - d_{yi}\right)} + U\right)
\end{aligned}
$$

Linear Calibration Steps

4. Solve for the instrumental polarization leakage



Real Telescope Response - Circular

For linear polarization receivers:

$$
\begin{aligned}
V_{rr} &= \frac{1}{2} g_{ri} g_{rj}^{*} (I + V) \\
V_{rl} &= \frac{1}{2} g_{ri} g_{lj}^{*} \left(I \left(d_{ri} - d_{lj}^{*} \right) + (Q + iU)\, e^{-2i\chi} \right) \\
V_{lr} &= \frac{1}{2} g_{li} g_{rj}^{*} \left(I \left(d_{rj}^{*} - d_{li} \right) + (Q - iU)\, e^{2i\chi} \right) \\
V_{ll} &= \frac{1}{2} g_{li} g_{lj}^{*} (I - V)
\end{aligned}
$$

Real Telescope Response - Circular

Or, assuming that calibrators have no/minimal circular polarization and including the residual phase delay between polarizations:

$$
\begin{aligned}
V_{rr} &= \frac{1}{2} g_{ri} g_{rj}^{*} I \\
V_{rl} &= \frac{1}{2} g_{ri} g_{lj}^{*} \left(I \left(d_{ri} - d_{lj}^{*} \right) + \left(Q + iU \right) e^{-2i\chi} \right) e^{-i\phi} \\
V_{lr} &= \frac{1}{2} g_{li} g_{rj}^{*} \left(I \left(d_{rj}^{*} - d_{li} \right) + \left(Q - iU \right) e^{2i\chi} \right) e^{i\phi} \\
V_{ll} &= \frac{1}{2} g_{li} g_{lj}^{*} I
\end{aligned}
$$

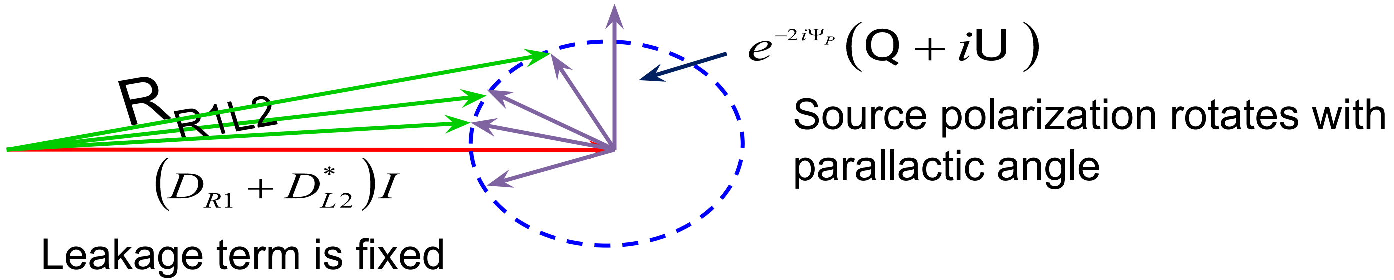
The good news: gains for the parallel hands can be calibrated entirely independently of polarization properties.

Real Telescope Response - Circular

Also good news: we again have a term that is constant and a term that depends on parallactic angle, so they can be separated:

$$V_{rl} = \frac{1}{2} g_{ri} g_{lj}^{*} \left(I \left(d_{ri} - d_{lj}^{*} \right) + \left(Q + iU \right) e^{-2i\chi} \right) e^{-i\phi}$$

$$V_{lr} = \frac{1}{2} g_{li} g_{rj}^{*} \left(I \left(d_{rj}^{*} - d_{li} \right) + \left(Q - iU \right) e^{2i\chi} \right) e^{i\phi}$$



Measuring Cross-Polarization Terms

There are two standard ways to proceed (circular base):

1. Observe a calibrator source of known polarization (preferably zero!)
2. Observe a calibrator of unknown polarization over an extended period.

Case 1: Calibrator source known to have zero polarization

$$
\begin{aligned}
V_{rl} &= \frac{1}{2} I \left(d_{ri} - d_{lj}^* \right) e^{-i\phi} \\
V_{lr} &= \frac{1}{2} I \left(d_{rj}^* - d_{li} \right) e^{i\phi}
\end{aligned}
$$

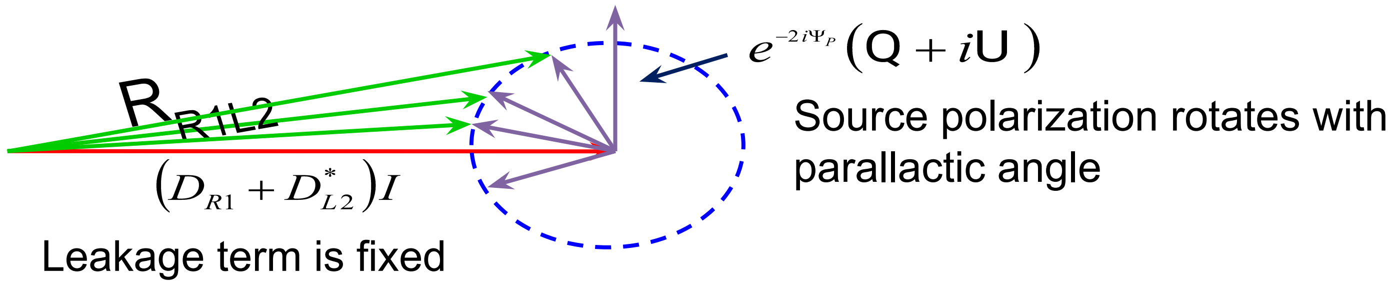
Single observation should suffice to measure leakage terms.

Measuring Cross-Polarization Terms

Case 2: Calibrator with significant (or unknown) polarization.

You can simultaneously determine both the D terms and the calibrator by observing a calibrator over a sufficiently wide range of parallactic angle:

$$V_{rl} = \frac{1}{2} g_{ri} g^*_{lj} \left(I \left(d_{ri} - d^*_{lj} \right) + \left(Q + iU \right) e^{-2i\chi} \right) e^{-i\phi}$$
$$V_{lr} = \frac{1}{2} g_{li} g^*_{rj} \left(I \left(d^*_{rj} - d_{li} \right) + \left(Q - iU \right) e^{2i\chi} \right) e^{i\phi}$$

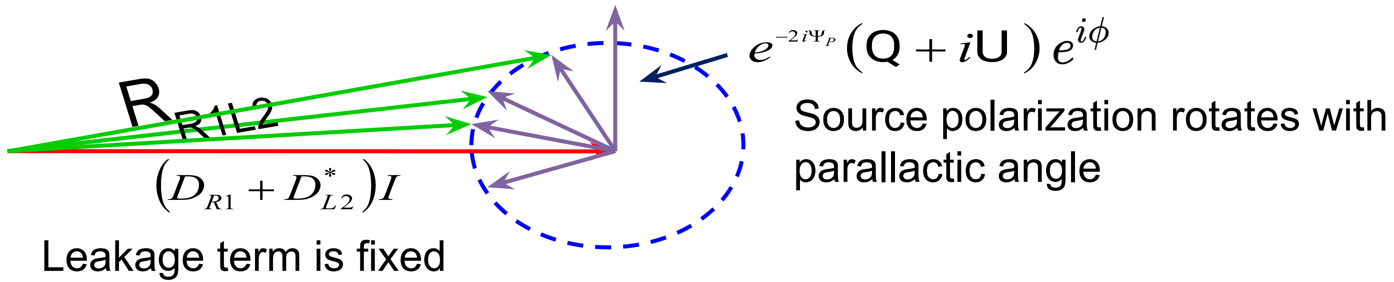


Measuring RL Phase Offset

In either case, the phase delay between R and L feeds leads to an overall uncertainty in the position angle of the polarization.

- **Case 1:** Only leakage terms (can be) solved for
- **Case 2:** Phase delay is degenerate with parallactic angle

In either case, a calibrator with known polarization is needed.



Circular Calibration Steps

1. Observe science target(s) as usual, but with both (a) either a polarization calibrator with 0 polarization once or unknown polarization over a range of parallactic angles, and (b) a calibrator with known polarization properties
2. Use the cross-hand terms for (a) to solve for the leakage terms and calibrator polarization model (i.e. Q, U)

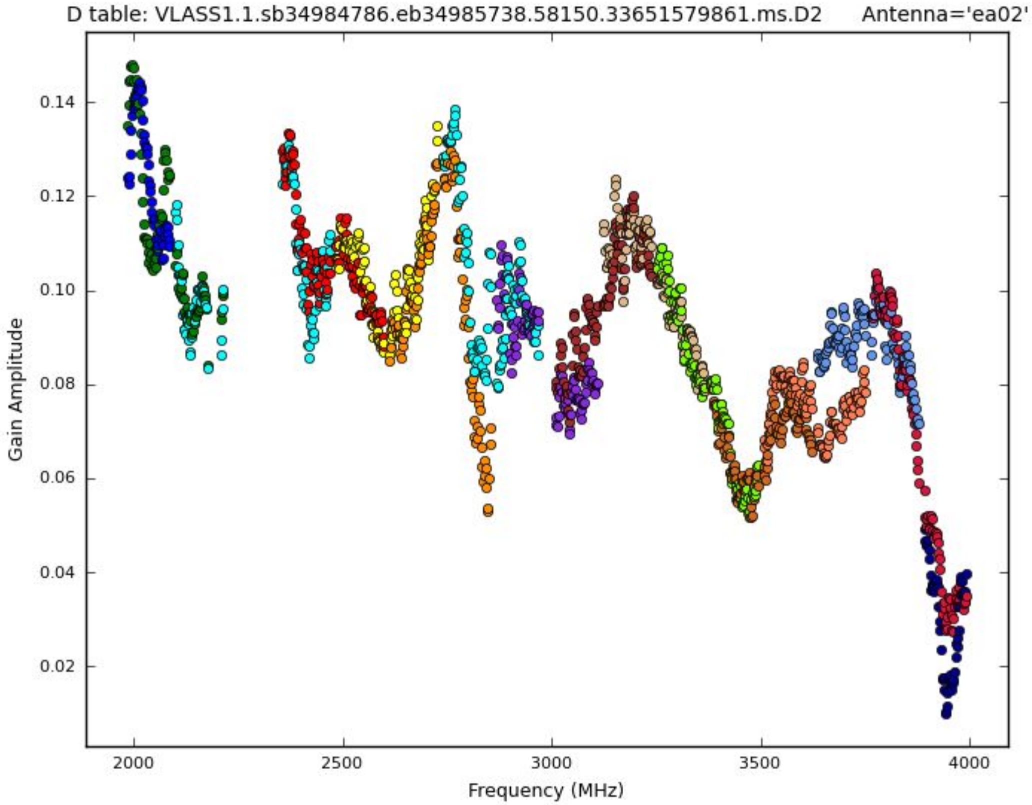
0 Polarization

```
polcal(vis='TDRW0001_calibrated.ms',
       caltable=dtab_J2355,
       field='J2355+4950', spw='0~7',refant='ea10',
       poltype='Df', solint='inf,2MHz',
       combine='scan', gaintable=[kcross_mbd],
       gainfield=[''], spwmap=[[0,0,0,0,0,0,0,0]])
```

Unknown Polarization

```
polcal(vis='TDRW0001_calibrated.ms',
       caltable=dtab_J0259, spw='0~7',
       refant='ea10', poltype='Df+QU',
       solint='inf,2MHz',combine='scan',
       gaintable=[kcross_mbd],
       gainfield=[''],
       spwmap=[[0,0,0,0,0,0,0,0]])
```

Example VLA D-terms



Real VLA S-band D-term amplitudes.

Significant frequency structure (2-4 MHz scale).

Antenna polarization ~8-10% for this particular VLA antenna w.r.t. the reference antenna.

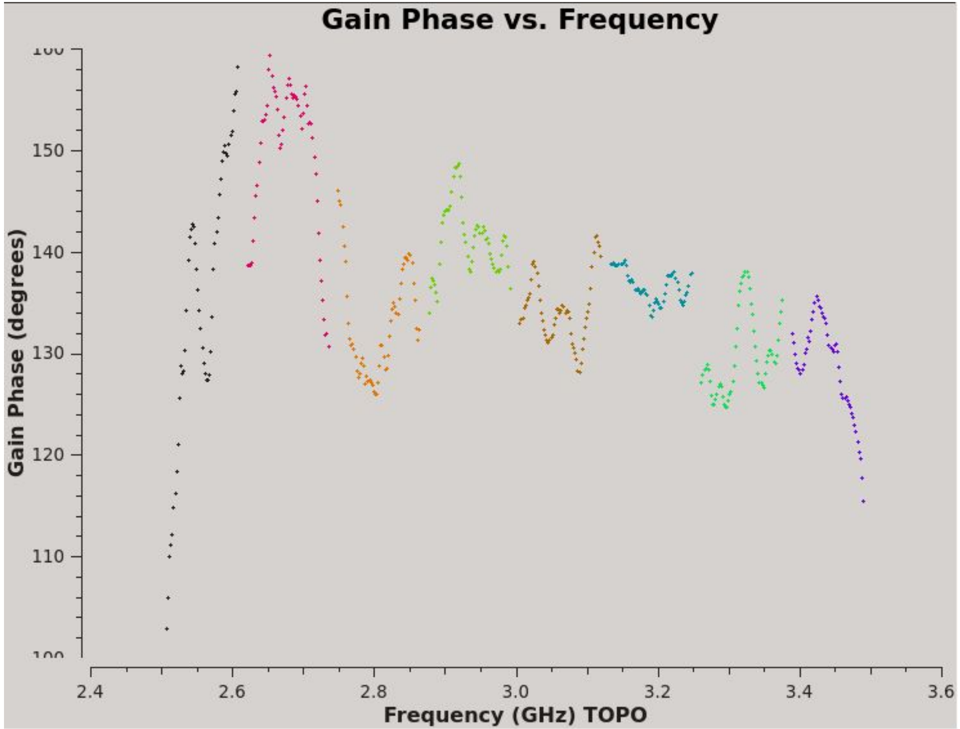
Circular Calibration Steps

1. Observe science target(s) as usual, but with both (a) either a polarization calibrator with 0 polarization once or unknown polarization over a range of parallactic angles, and (b) a calibrator with known polarization properties
2. Use the cross-hand terms for (a) to solve for the leakage terms and calibrator polarization model (i.e. Q, U)
3. Use (b) with the calculated leakage terms to calibrate the RL phase delay

```
polcal(vis='TDRW0001_calibrated.ms', caltable=xtab, spw='0~7',
       field='0137+331=3C48', solint='inf,2MHz', combine='scan',
       poltype='Xf', refant = 'ea10', gaintable=[kcross_mbd,dtab_J0259],
       gainfield=['',''], spwmap=[[0,0,0,0,0,0,0,0],[]], append=False)
```

RL Delays/Phase – real examples

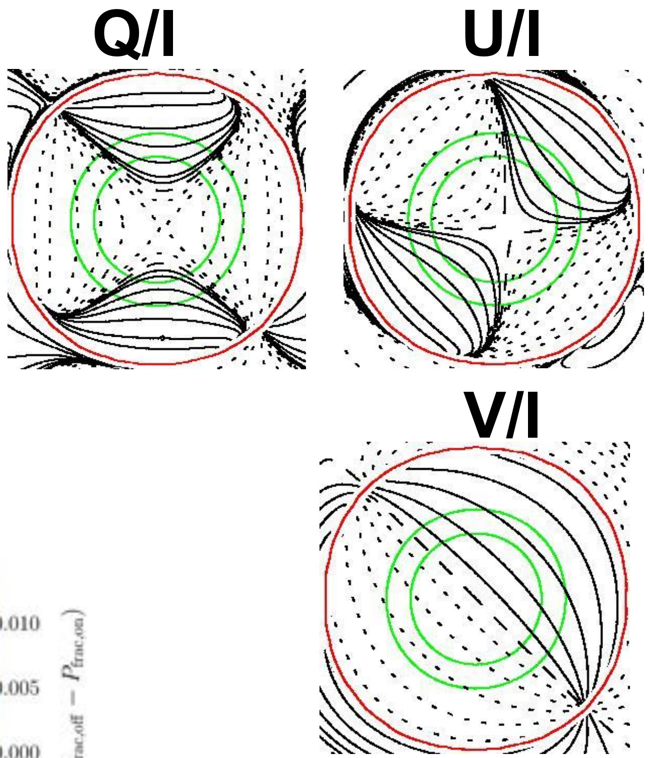
Instrumental delay between polarizations due to e.g. differences in signal path lengths.



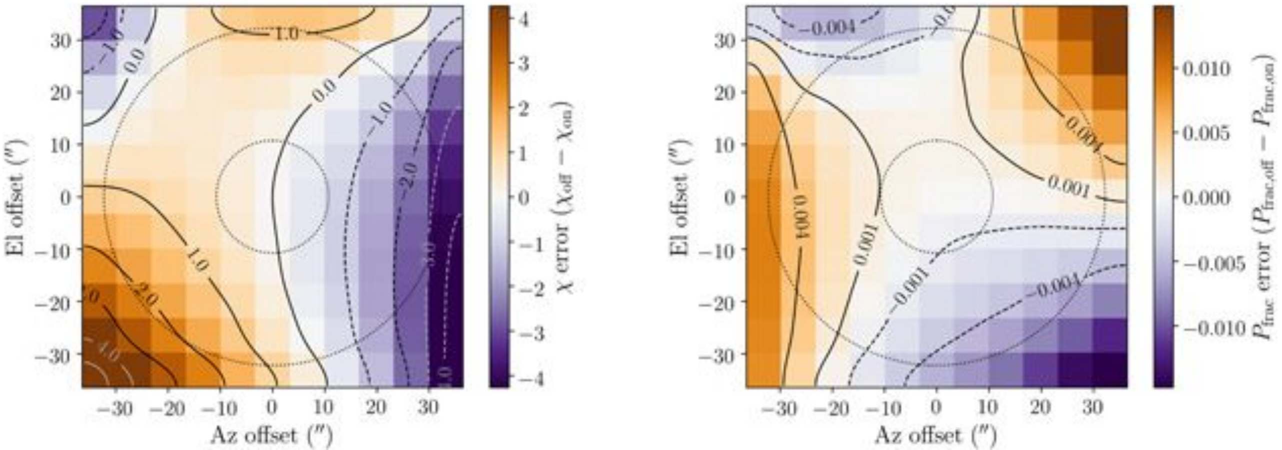
Beam Polarization

- The beam polarization is due to the antenna and feed geometry.
- The beam polarizations can be removed in software – if antenna patterns are known – at considerable computational cost.

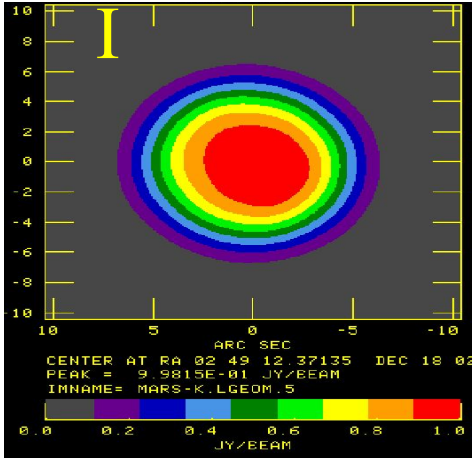
VLA

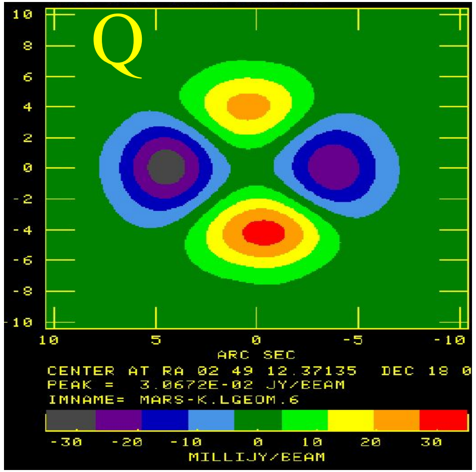


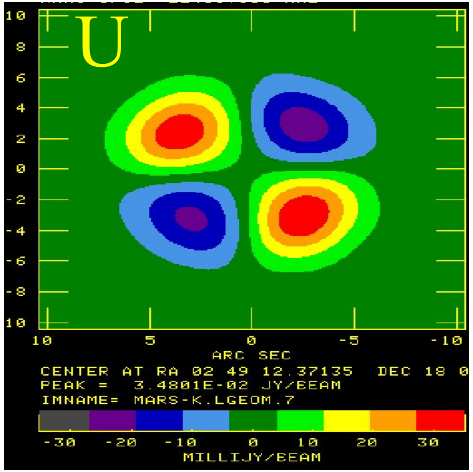
ALMA



In Practice: Stokes Imaging of Mars

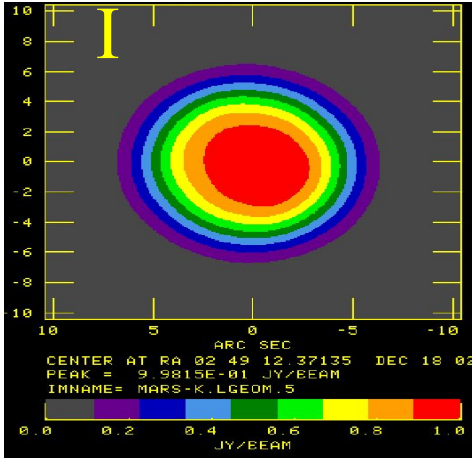


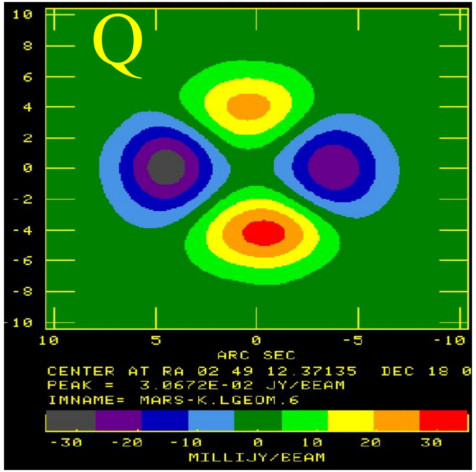


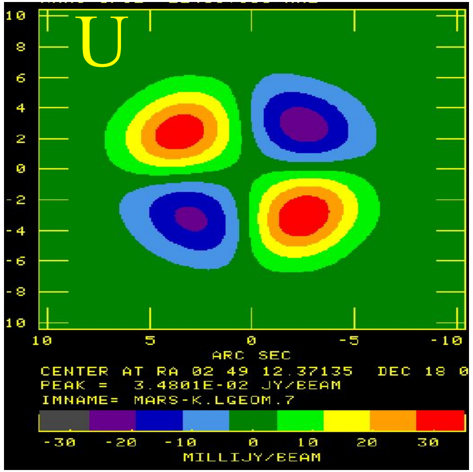


- Shown are false-color coded I,Q,U,P images.
- V is not shown – all noise – no circular polarization.
- Resolution is 3.5”, Mars’ diameter is ~10”
- From the Q and U images alone, we can deduce the polarization is radial, around the limb.

In Practice: Stokes Imaging of Mars







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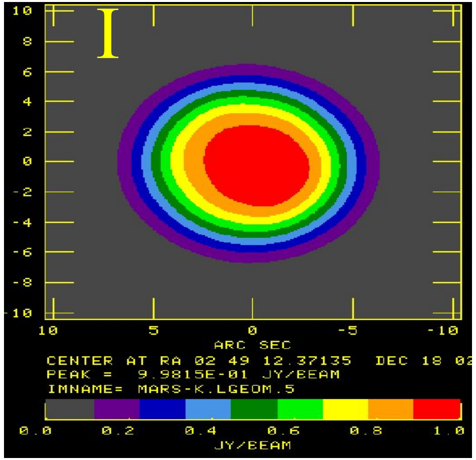

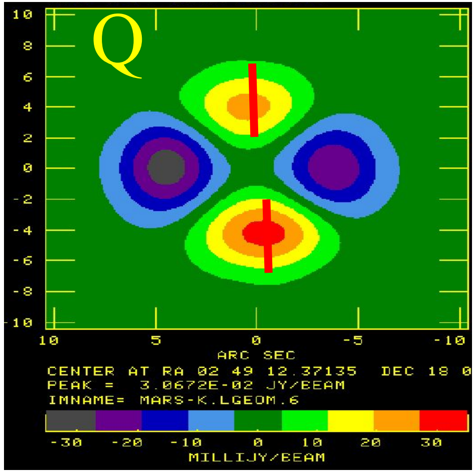

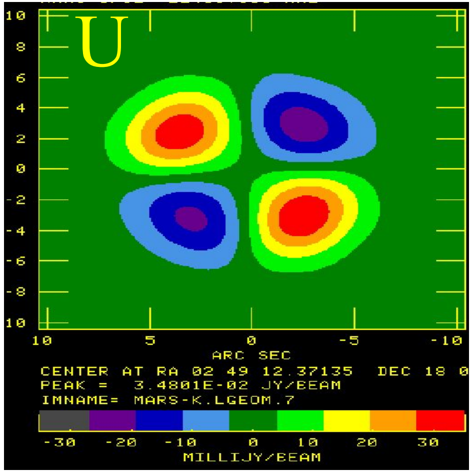

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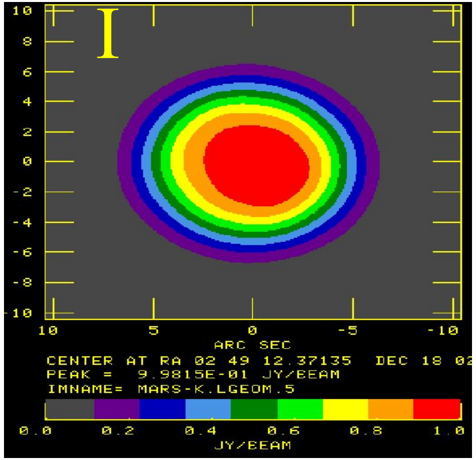

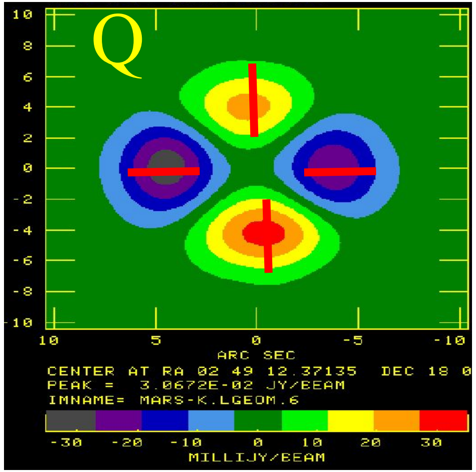

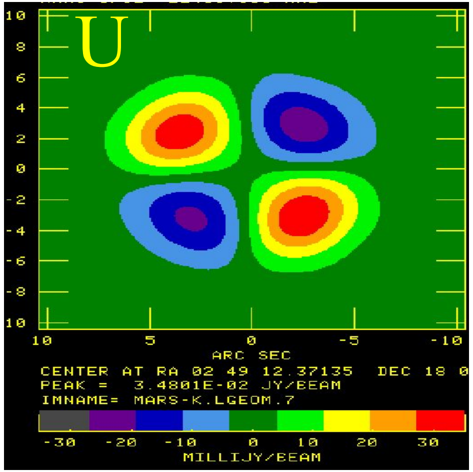

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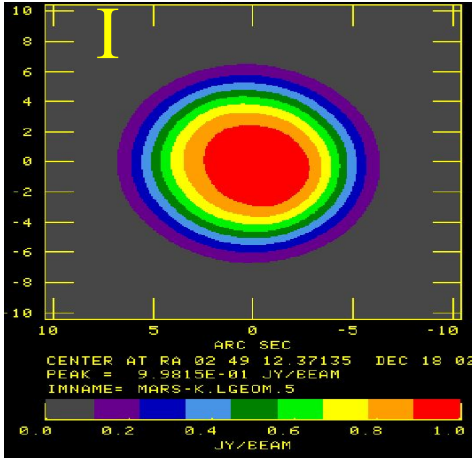

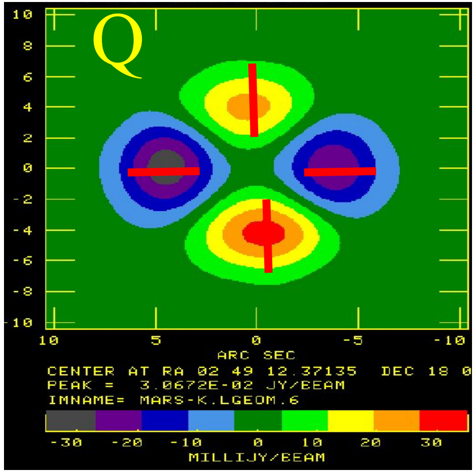

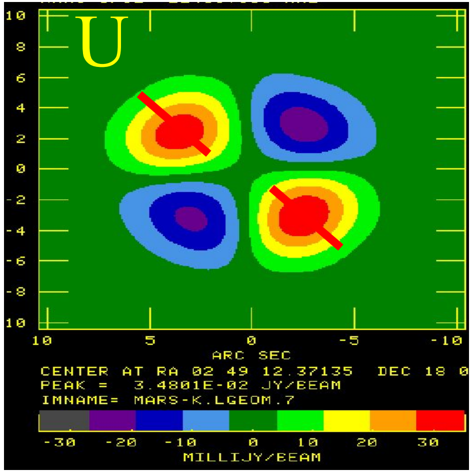

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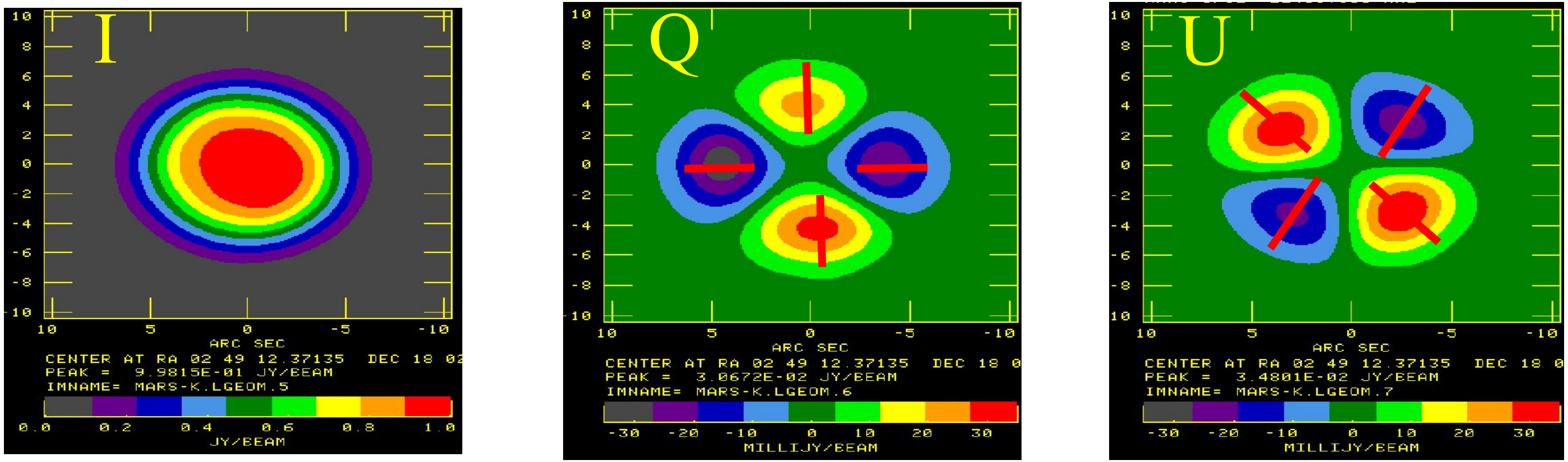

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Mars – A Traditional Representation

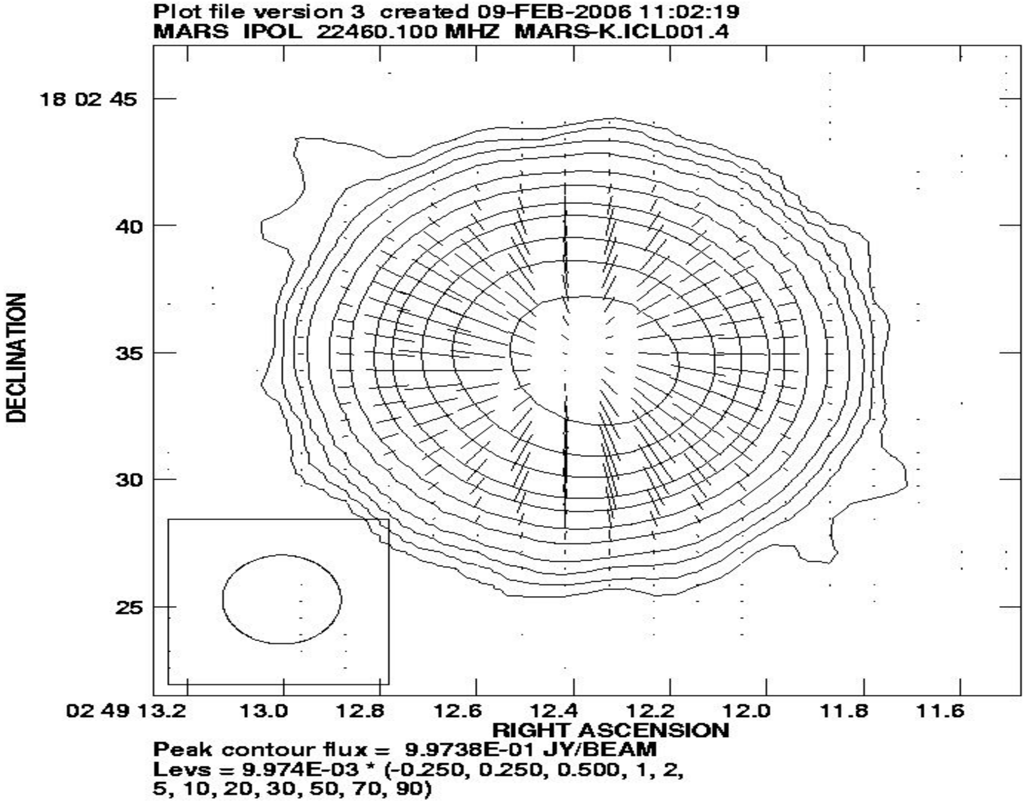
Here I, Q, and U are combined to make a more realizable map of the total and linearly polarized emission from Mars.

The dashes show the direction of the E-field.

The dash length is proportional to the polarized intensity.

$$P = \frac{\sqrt{Q^2 + U^2}}{I}$$

$$\chi = 0.5\ \tan^{-1}\left(\frac{U}{Q}\right)$$



Further Reading

- K. Rohlfs & T.L. Wilson: *Tools of Radio Astronomy (Chapters 2 & 3)*
- Thompson, Moran & Swenson: *Inteferometry and Synthesis in Radio Astronomy*
- Taylor, Carilli, & Perley: *Snythesis Imaging in Radio Astronomy II*
- Bracewell: *The Fourier Transform & Its Applications*
- Hamaker/Bregman/Sault*: Understanding radio polarimetry: papers I - V (1996-2006)*
- Brentjens & de Bruyn: *Faraday rotation measure synthesis (2005)*
- *EVLA Memos by Perley & Sault (#131, #134, #135, #141, #151, #170, #178)*
- *Guide to Observing with the VLA - Polarimetry (https://science.nrao.edu/facilities/vla/docs/manuals/obsguide/modes/pol)*
- *Hales EVLA Memo #201; Schinzel EVLA Memo #205*
- *Perley EVLA Memos #207, #210*
- *Polarization Calibration (8th VLA Data Reduction Workshop) https://science.nrao.edu/science/meetings/2021/vla-data-reduction/presentations/Schinzel_Polarization.pdf*

Take Home Message

- Polarimetry is a little complicated, but do not be afraid!
- The polarized state of EM radiation gives valuable insights into magnetic fields and the physics of the emission.
- Understanding polarization improves calibration and imaging even in the unpolarized case.

- As a final note: polarization calibration is *now* in the ALMA Pipeline - hifa_selfcal

Thanks to Frank Schinzel Rick Perley & Michiel Brentjens from whom I extensively borrowed and/or adapted presented materials.