Polarization walkthrough in CASA

Africalim, 2024

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SARAO
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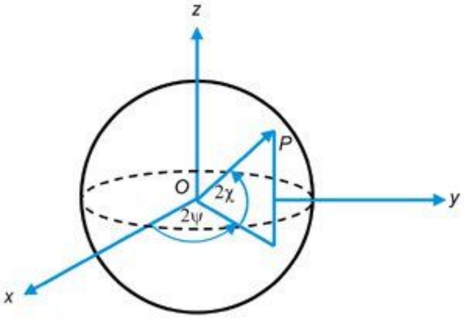
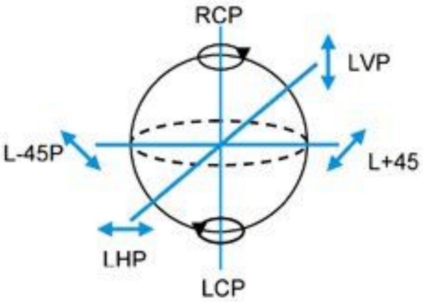
What we will cover (and recap)

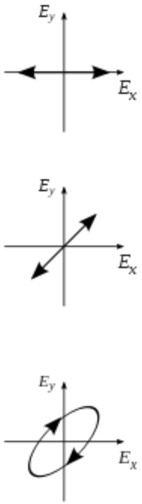
- Definitions and physics needed for this discussion
- Ionospheric variability and its effect on radio polarimetry
- Practical:
    - Basic transfer calibration without HV phase solutions
    - Visibility inspection
    - Leakage and HV phase calibration and common pitfalls
    - Imaging of the Moon in full Stokes

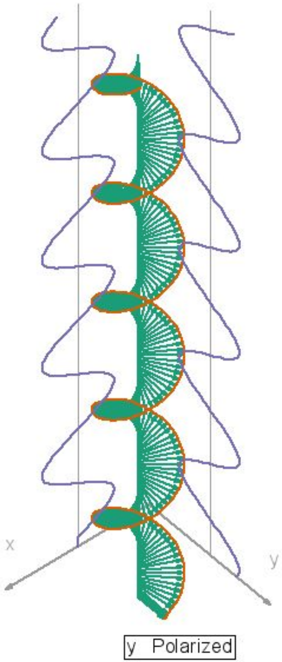
Polarization states - a recap

- The electric field of light is fully described as a transverse (perpendicular to the direction of propagation) wave in a homogenous, uniform and non-impeding medium.
- Most generic propagation vector description is elliptical (of which circular and linear forms are special case). In general this ellipse is fully described by 2 spherical angles (where the fractions lie on a unit sphere):





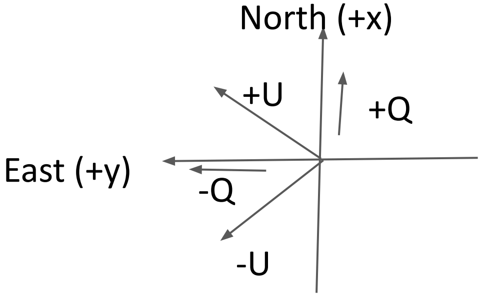




Poincaré description of polarization vector ellipse
Field Guide to Polarization

Source Wikipedia CC SA AT

Relationship to Stokes

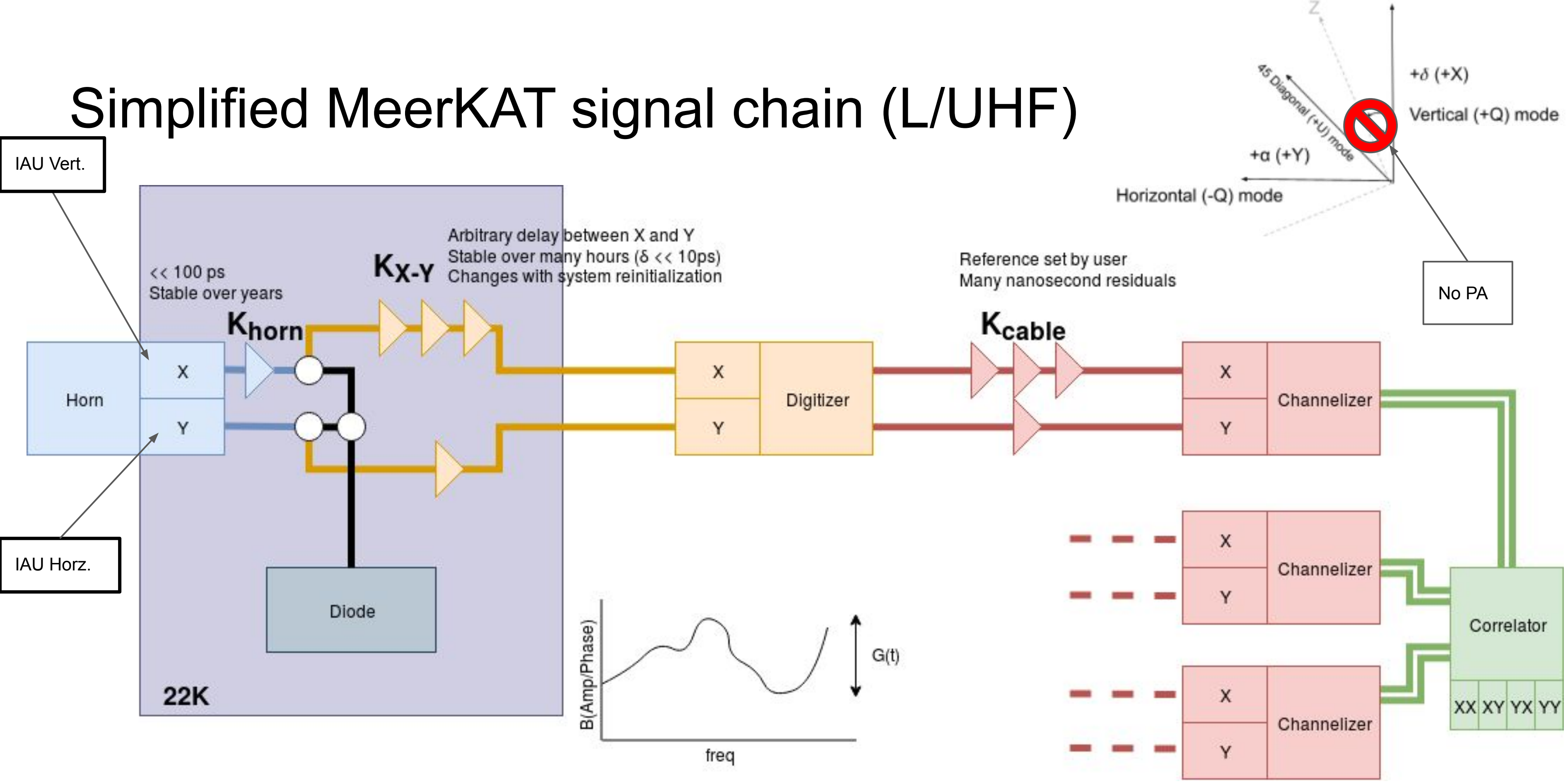


- The IAU convention for linear feeds are defined North through East on the sky sphere as follows:
- An unpolarized source therefore has equal power on xx* and yy*. These terms are added to get the total intensity (I)
- Right circularly polarized source is defined as the y component lagging (phase difference) the x component
- Vertical (+Q) points North (positive x), horizontal (-Q) points East (positive y)
- Software convention stores the correlations for an interferometer pq with a factor of 2, therefore the following equations describe the relationships between the correlations:

$$I = 0.5 < e_{px}e^*_{qx} + e_{py}e^*_{qy} >$$
$$Q = 0.5 < e_{px}e^*_{qx} - e_{py}e^*_{qy} >$$
$$U = 0.5 < e_{px}e^*_{qy} + e_{py}e^*_{qx} >$$
$$V = \mp 0.5i < e_{px}e^*_{qy} - e_{py}e^*_{qx} >$$

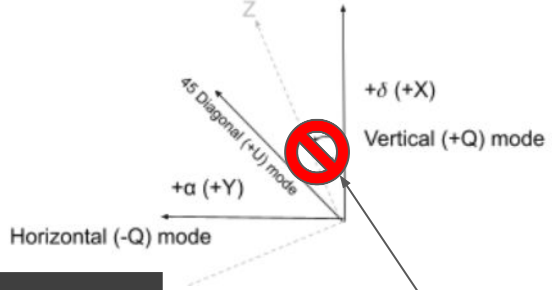
See Hamaker and Bregman (1996)

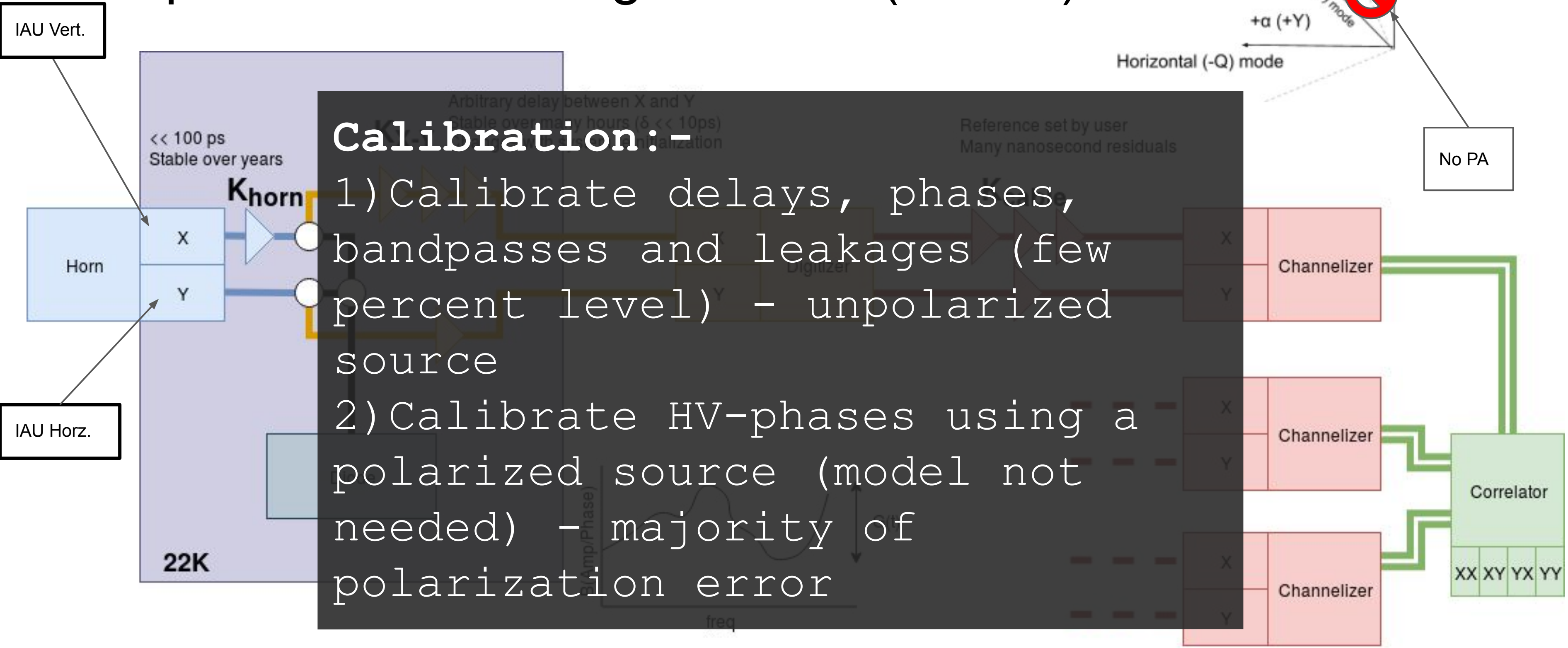
Simplified MeerKAT signal chain (L/UHF)



Note: the digitizer/receiver assembly looks a bit different for the MPIfR-provided S-band system

Simplified MeerKAT signal chain (L/UHF)





Calibration:-

1)Calibrate delays, phases, bandpasses and leakages (few percent level) - unpolarized source

2)Calibrate HV-phases using a polarized source (model not needed) - majority of polarization error

Note: the digitizer/receiver assembly looks a bit different for the MPIfR-provided S-band system

Measurement products

Systematic / environmental effects modifying complex voltage induced on the system is fully described as a series of 2x2 complex Jones terms.

$$(a, b, c, d \in \mathbb{C}) \begin{bmatrix} a & b \\ c & d \end{bmatrix} \begin{bmatrix} I_x e^{i\phi_x} \\ I_y e^{i\phi_y} \end{bmatrix}$$

$$\mathbf{J}_N \ldots \mathbf{J}_1 E$$

Robert Jones

A correlator dumps integrated voltage products between the hands of two antennae p, q of the form (**<u>assuming constant jones effects</u>** over the integration interval):

$$< \mathbf{J}_p E_p \mathbf{J}_q^H E_q^H > = < \mathbf{J}_p E_p E_q^H \mathbf{J}_q^H >$$
$$= \mathbf{J}_p < \begin{bmatrix} I_{xp} e^{i\phi_{xp}} \\ I_{yp} e^{i\phi_{yp}} \end{bmatrix} \begin{bmatrix} I_{xq} e^{-i\phi_{xq}} & I_{yq} e^{-i\phi_{xq}} \end{bmatrix} > \mathbf{J}_q^H$$

Radio Interferometric Measurement Equation

The Radio Interferometric Measurement Equation (RIME) gives us the flexibility to describe the system and environmental effects as a chain of polarizers and therefore describes the calibration problem. The following is an example towards a source at cosines l,m

Corrupted voltage (antenna index i)

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

$$\begin{aligned}\mathbf{V}_{pq,\text{measured}} &=< \mathbf{E}_{p,\text{measured}}\mathbf{E}^H_{q,\text{measured}} > \\ &= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H\end{aligned}$$

Under the assumption that these effects are variable on scales larger than the correlation integration interval

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Cable delay

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

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Temporal variable gain

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

$$\begin{aligned}\mathbf{V}_{pq,\text{measured}} &=< \mathbf{E}_{p,\text{measured}}\mathbf{E}^H_{q,\text{measured}} > \\ &= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H\end{aligned}$$

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Bandpass (OMT)

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

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Crosshand phase delay

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

$$\begin{aligned}\mathbf{V}_{pq,\text{measured}} &=< \mathbf{E}_{p,\text{measured}}\mathbf{E}^H_{q,\text{measured}} > \\ &= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H\end{aligned}$$

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Leakage (non-orthogonality)

$$\mathbf{E}_{i,\mathrm{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

$$\begin{aligned}\mathbf{V}_{pq,\mathrm{measured}} &=< \mathbf{E}_{p,\mathrm{measured}}\mathbf{E}^H_{q,\mathrm{measured}} > \\ &= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H\end{aligned}$$

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Antenna response

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

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Radio Interferometric Measurement Equation

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Parallactic angle (alt-az mount)

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

$$\begin{aligned}\mathbf{V}_{pq,\text{measured}} &=< \mathbf{E}_{p,\text{measured}}\mathbf{E}^H_{q,\text{measured}} > \\ &= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H\end{aligned}$$

Under the assumption that these effects are variable on scales larger than the correlation integration interval

Radio Interferometric Measurement Equation

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Geometric delay (scalar matrix)

$$e^{2i\pi(\vec{b_i}.(\vec{s}-\vec{s}_0)/\lambda)}$$

$$\mathbf{E}_{i,\text{measured}} = \mathbf{K}_i(\nu)\mathbf{G}_i(t)\mathbf{B}_i(\nu)\mathbf{X}_i(\nu)\mathbf{D}_i(\nu)\mathbf{A}_i(l,m,\nu)\mathbf{P}_i(t)\mathbf{K}_i(l,m,\nu)[I_x e^{i\phi_x}, I_y e^{i\phi_y}]^T$$

$$\begin{aligned}\mathbf{V}_{pq,\text{measured}} &=< \mathbf{E}_{p,\text{measured}}\mathbf{E}^H_{q,\text{measured}} > \\ &= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H\end{aligned}$$

Under the assumption that these effects are variable on scales larger than the correlation integration interval

The Jones family

d << 1

$$\begin{bmatrix} g_x & 0 \\ 0 & g_y \end{bmatrix}$$

Complex gain matrix

$$\begin{bmatrix} 1 & d_x \\ d_y & 1 \end{bmatrix}$$

Feed non-orthogonality (leakage)

$$\begin{bmatrix} e^{i\phi_x} & 0 \\ 0 & e^{i\phi_y} \end{bmatrix}$$

Phasor (e.g. cable delay - frequency slope)

$$\begin{bmatrix} e^{i\theta(\nu,t)} & 0 \\ 0 & 1 \end{bmatrix}$$

Crosshand phase

$$\begin{bmatrix} \cos\Psi & -\sin\Psi \\ \sin\Psi & \cos\Psi \end{bmatrix}$$

ParAng (linear)

$$\begin{bmatrix} \cos\left(\mathrm{RM}\nu^{-2}\right) & -\sin\left(\mathrm{RM}\nu^{-2}\right) \\ \sin\left(\mathrm{RM}\nu^{-2}\right) & \cos\left(\mathrm{RM}\nu^{-2}\right) \end{bmatrix}$$

Faraday rotation (linear)

These 2x2 matrices do not generally commute, except special cases like constant matrices and axial rotation matrices (amongst themselves only).
Take care!

Radio Interferometric Measurement Equation

After KGB calibration the following (first order) errors remain (low-moderate linear point-like source) :-

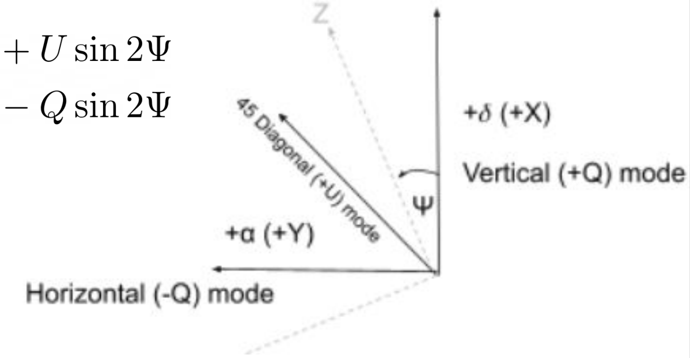
$$X_pX_q^* = (I + Q_\Psi) + U_\Psi(d_{Xp} + d^*_{Xq})$$
$$X_pY_q^* = \left[(U_\Psi + iV) + I(d_{Xp} + d^*_{Yq}) - Q\Psi(d_{Xp} - d^*_{Yq})\right] e^{i\rho}$$
$$Y_pX_q^* = \left[(U_\Psi - iV) + I(d_{Yp} + d^*_{Xq}) + Q\Psi(d_{Yp} - d^*_{Xq})\right] e^{-i\rho}$$
$$Y_pY_q^* = (I - Q_\Psi) + U_\Psi(d_{Yp} - d^*_{Xq})$$

Crosshand phasor (can be quite large -- >>50% of the error on U if left uncorrected)

Leakages (~few %)

Psi: Parallactic angle

$$Q_\Psi := Q\cos 2\Psi + U\sin 2\Psi$$
$$U_\Psi := U\cos 2\Psi - Q\sin 2\Psi$$



(!) Note -- this method **does not correct the absolute angle** which may still have unaccounted ionospheric, ref. receiver/dipole rotations, etc.

Equations for: nominally aligned linear system responding to a low polarized intensity source

In circular polarisation the angle is just a further rotation on parallactic angle (phasor matrix in circular feeds) and absorbed into X(f) solutions. This is not the case for linear systems

On-axis leakage transfer calibration (post KGB)

$$
\begin{aligned}
V_{XX} &= (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Xi} + d^*_{Xj}) \\
V_{XY} &= \left[(\mathcal{U}_\psi + i\,\mathcal{V}) + \mathcal{I}\,(d_{Xi} + d^*_{Yj}) - \mathcal{Q}_\psi\,(d_{Xi} - d^*_{Yj})\right] e^{i\rho} \\
V_{YX} &= \left[(\mathcal{U}_\psi - i\,\mathcal{V}) + \mathcal{I}\,(d_{Yi} + d^*_{Xj}) + \mathcal{Q}_\psi\,(d_{Yi} - d^*_{Xj})\right] e^{-i\rho} \\
V_{YY} &= (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Yi} + d^*_{Yj})
\end{aligned}
$$

Calibrate frequency and slow time variable response (diagonal KGB) using a source with no linear or circular polarization

(See Christopher Hales' 2017 paper for an excellent summary.)

On-axis leakage transfer calibration (post KGB)

Instantaneous U is dependent on parallactic angles => at some hour angles you may have insufficient SNR on XY* and YX*

$$
\begin{aligned}
V_{XX} &= (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi \left(d_{Xi} + d^*_{Xj}\right) \\
V_{XY} &= \left[(\mathcal{U}_\psi + i\,\mathcal{V}) + \mathcal{I}\left(d_{Xi} + d^*_{Yj}\right) - \mathcal{Q}_\psi \left(d_{Xi} - d^*_{Yj}\right)\right] e^{i\rho} \\
V_{YX} &= \left[(\mathcal{U}_\psi - i\,\mathcal{V}) + \mathcal{I}\left(d_{Yi} + d^*_{Xj}\right) + \mathcal{Q}_\psi \left(d_{Yi} - d^*_{Xj}\right)\right] e^{-i\rho} \\
V_{YY} &= (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi \left(d_{Yi} + d^*_{Yj}\right)
\end{aligned}
$$

Switch to a linearly polarized source with a known polarization angle to calibrate circular polarization response (must be highly polarized). (X Jones)

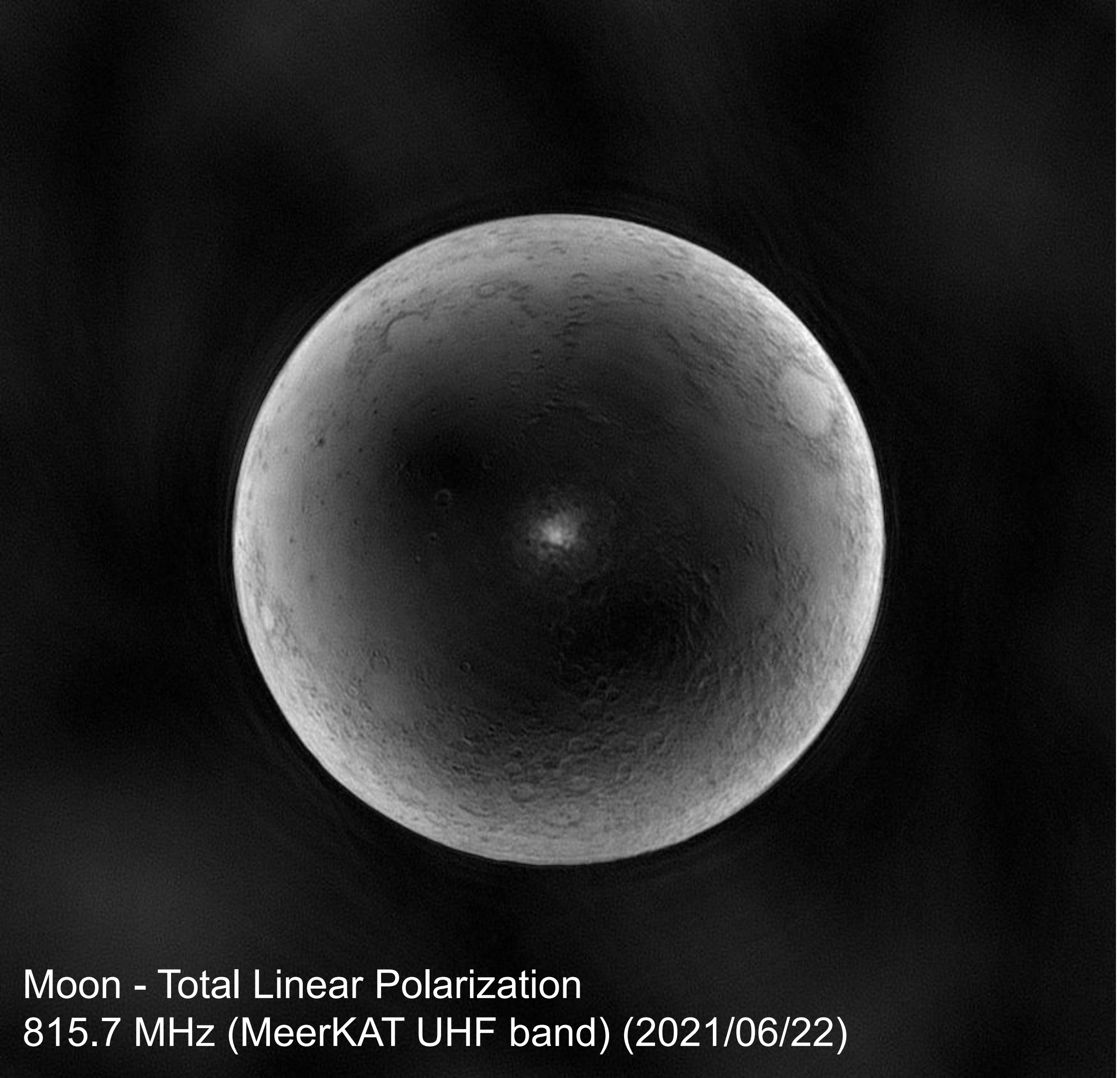
(See Christopher Hales' 2017 paper for an excellent summary.)

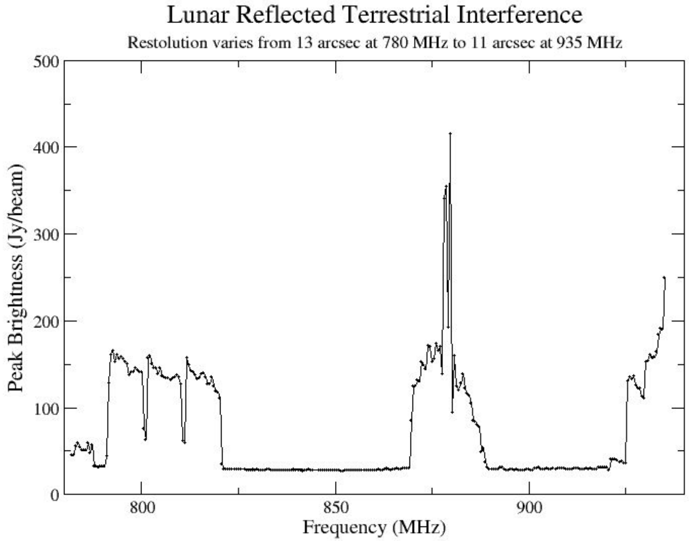
On-axis leakage transfer calibration (post KGB)

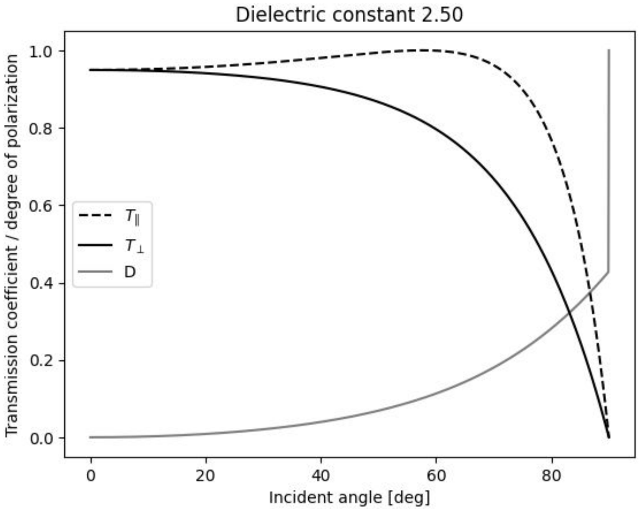
$$
\begin{aligned}
V_{XX} &= (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Xi} + d^*_{Xj})\\
V_{XY} &= \left[(\mathcal{U}_\psi + i\,\mathcal{V}) + \mathcal{I}\,(d_{Xi} + d^*_{Yj}) - \mathcal{Q}_\psi\,(d_{Xi} - d^*_{Yj})\right] e^{i\rho}\\
V_{YX} &= \left[(\mathcal{U}_\psi - i\,\mathcal{V}) + \mathcal{I}\,(d_{Yi} + d^*_{Xj}) + \mathcal{Q}_\psi\,(d_{Yi} - d^*_{Xj})\right] e^{-i\rho}\\
V_{YY} &= (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi\,(d_{Yi} + d^*_{Yj})
\end{aligned}
$$

Switch to back to unpolarized source (Vxy and Vyx) consist purely of residual leakage (off diagonal D Jones)

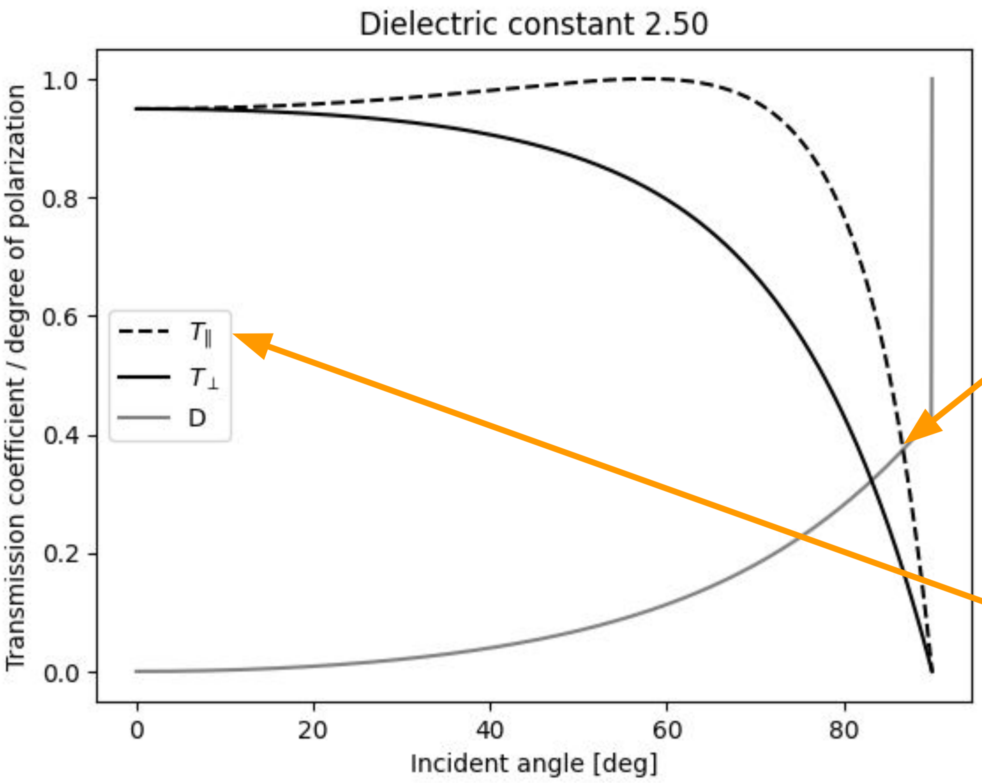
(See Christopher Hales' 2017 paper for an excellent summary.)


Moon - Total Linear Polarization
815.7 MHz (MeerKAT UHF band) (2021/06/22)


Lunar Reflected Terrestrial Interference
Restolution varies from 13 arcsec at 780 MHz to 11 arcsec at 935 MHz
Peak Brightness (Jy/beam)
Frequency (MHz)
0
100
200
300
400
500
800
850
900


Dielectric constant 2.50
Transmission coefficient / degree of polarization
Incident angle [deg]
$T_{\parallel}$
$T_{\perp}$
D
0.0
0.2
0.4
0.6
0.8
1.0
0
20
40
60
80

The polarized Moon



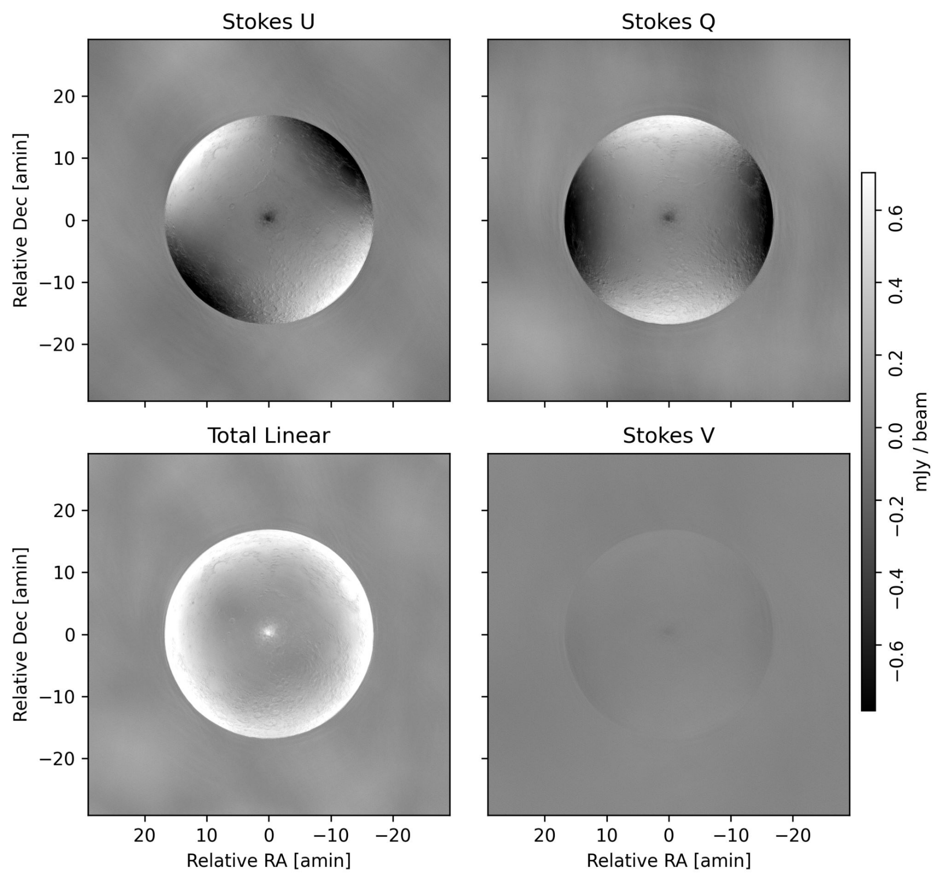
Most light refracted through surface regolith

$$R_\perp(\theta_i) = \left| \frac{\cos\theta_i - \sqrt{\varepsilon - \sin^2\theta_i}}{\cos\theta_i + \sqrt{\varepsilon - \sin^2\theta_i}} \right|^2$$

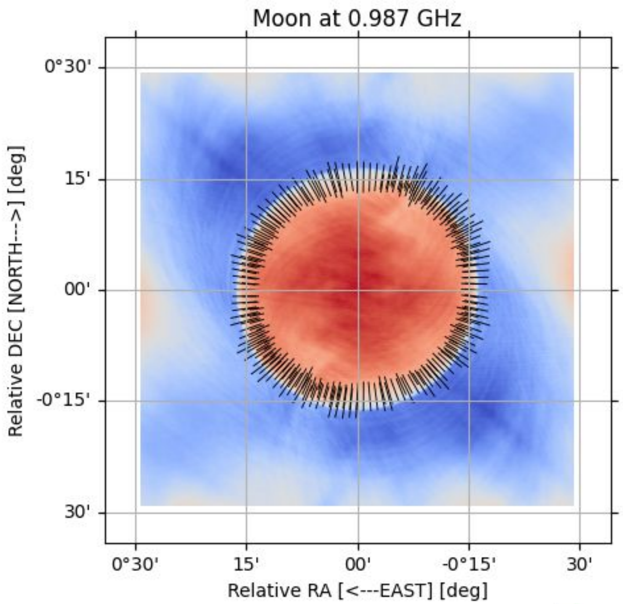
$$R_\parallel(\theta_i) = \left| \frac{\varepsilon\cos\theta_i - \sqrt{\varepsilon - \sin^2\theta_i}}{\varepsilon\cos\theta_i + \sqrt{\varepsilon - \sin^2\theta_i}} \right|^2$$

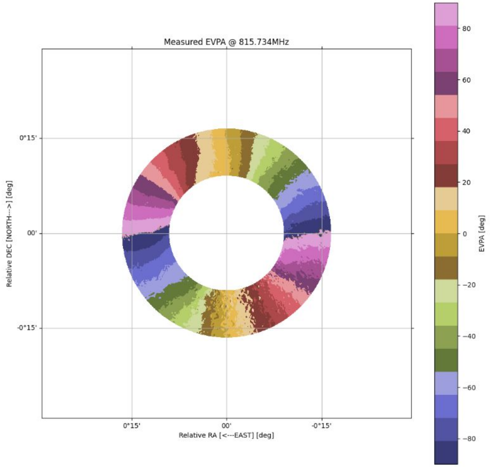
$$D = \frac{\frac{1}{2}(R_\parallel - R_\perp)}{1 - \frac{1}{2}(R_\perp + R_\parallel)}$$

Radial component dominant



With fitted EVPA/RM corrections

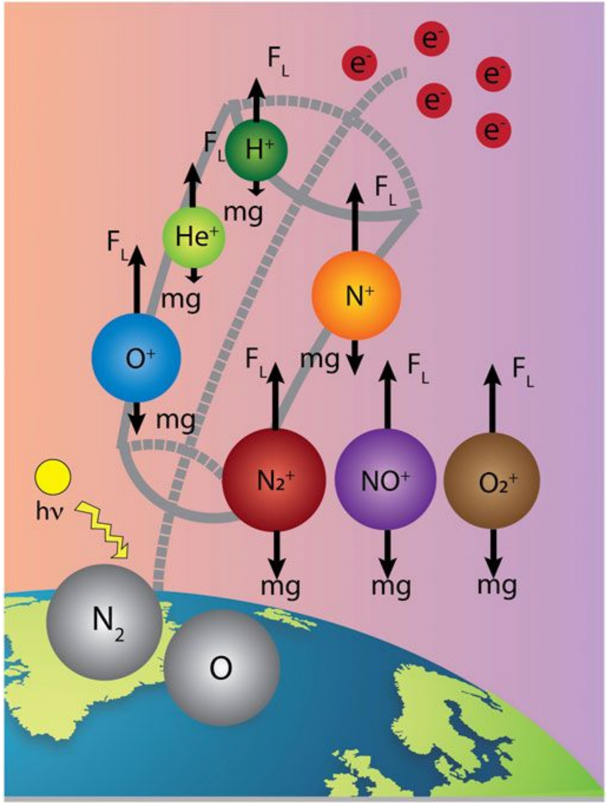


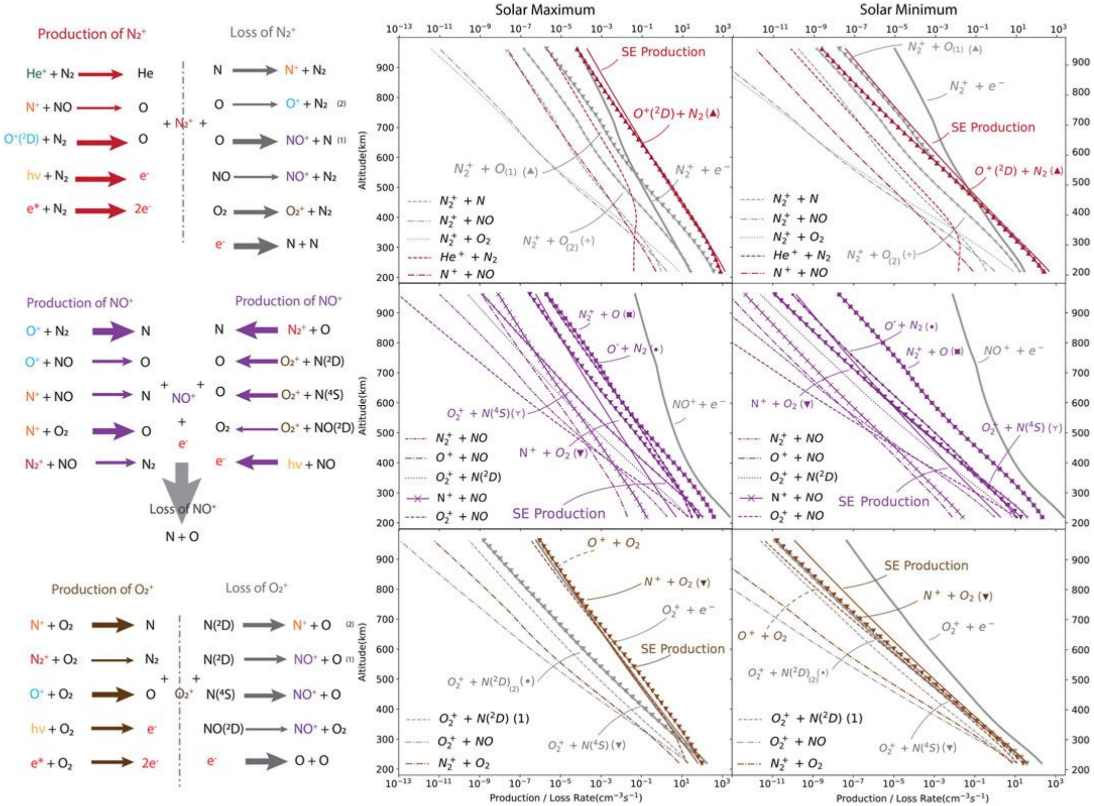


(Locked to scale)
Stokes V should be zero - ***CASA-calibrated residual*** system HV phase effects shown (1-2 orders of magnitude below Q and U)
Black (-) to white (+) scale shown --- +Q (vert.), -Q (horiz.)

What about the ionosphere?

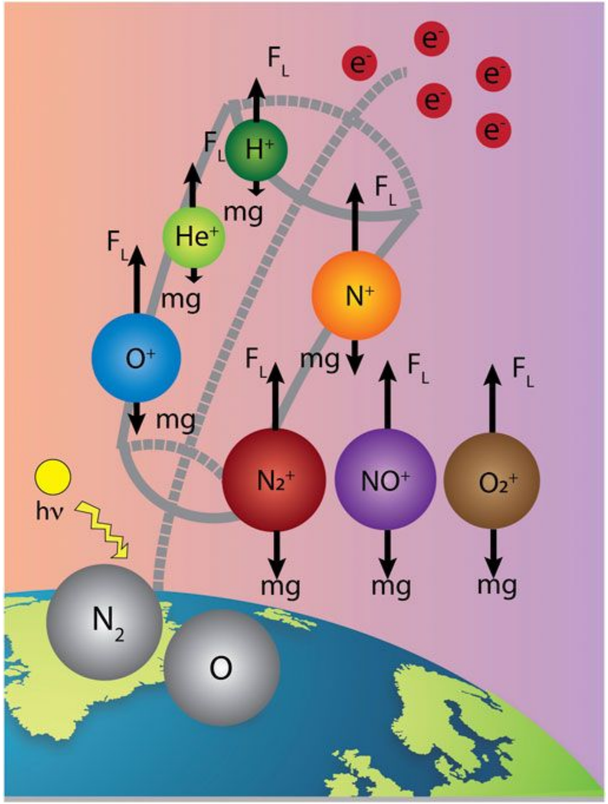
Lin & Llie (2022)

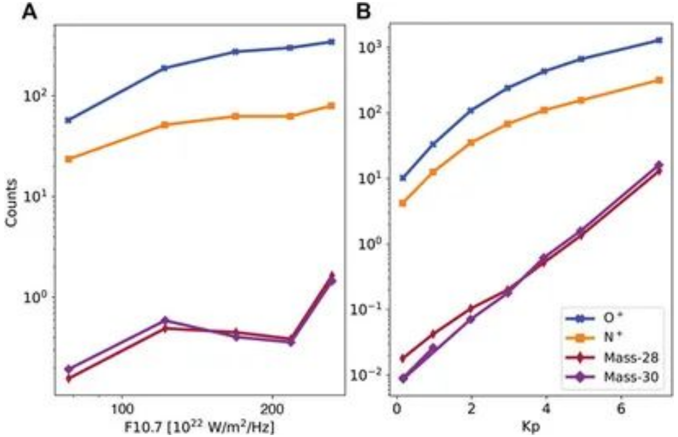


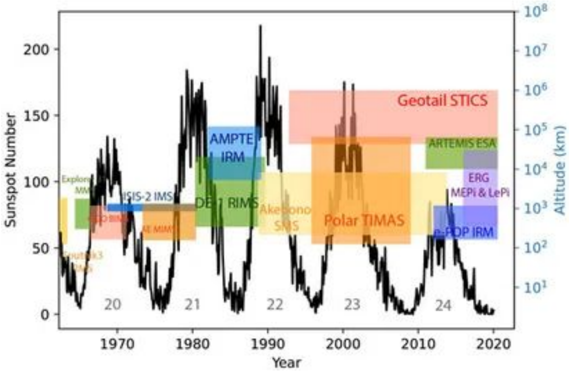


What about the ionosphere?

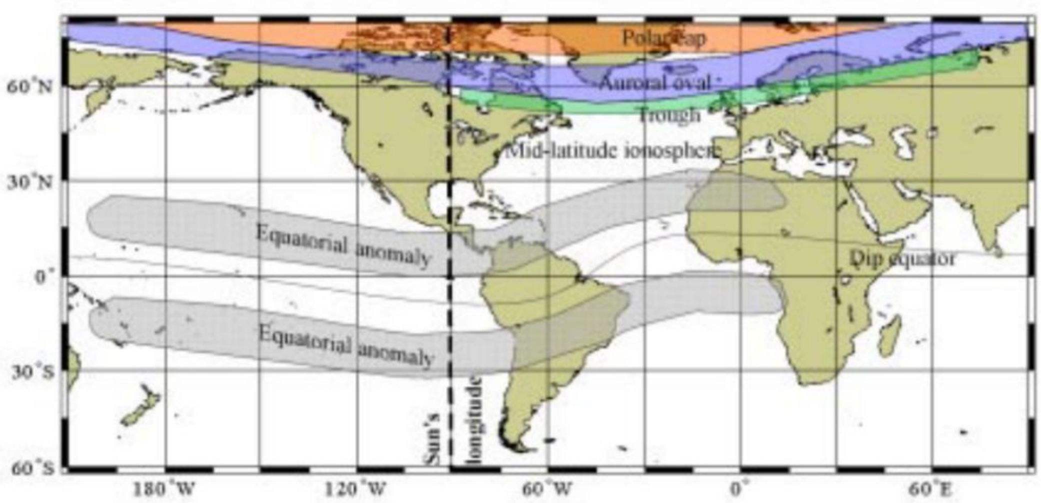
Lin & Llie (2022)

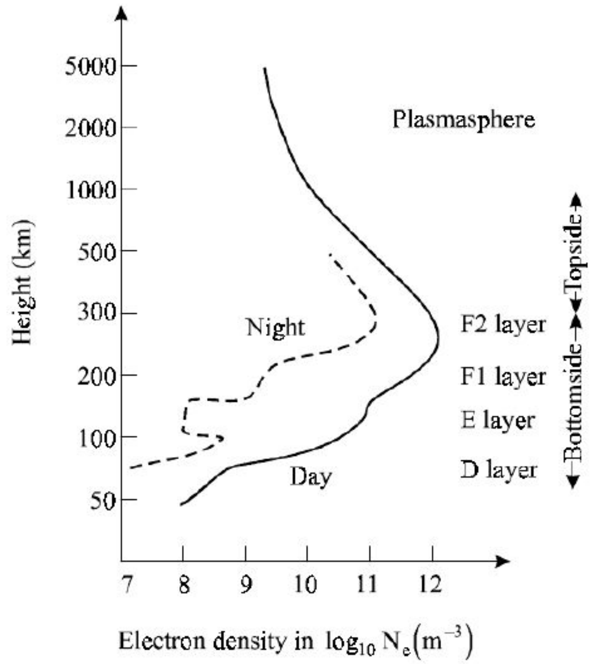




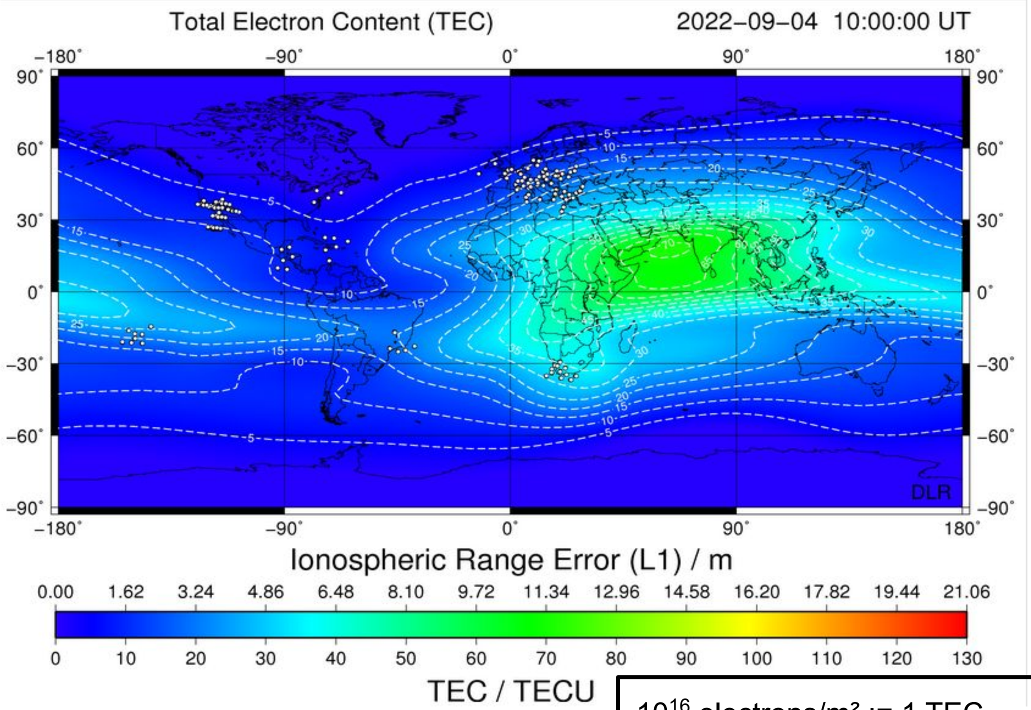


The 3D variable ionosphere





- In equatorial regions the ionized content travels horizontally and is the most sensitive to the solar zenith angle and variable during day time. Here the F1 (and lower layers have markedly higher densities than other latitudes)
- Mid-latitudes are generally markedly stable. It has some seasonal variability
- The full impact of solar activity on the 3D profile in polar regions are not well understood at present. It is known that densities of molecular gasses increase even out into the magnetosphere in this region during high solar activity and associated increases in the magnetic field strength ("Kp" indexes - up to about 500 nT in higher latitudes and up to 2000nT at mid-latitudes) due to compression by solar winds
- Plasmaspheric electron content can be up to 60% of total profile content at night. F layer generally contains 50-60% during daytime. Plasmaspheric electron content has a minor impact on RM due to the (mainly) dipole magnetic field strength at higher altitudes.
- For reference - dipole field strength at the magnetic poles are about 50 000nT (see the IGRS) at an altitude of 450 km above the planet mean geoid.



10^{16} electrons/m² := 1 TEC

Near real-time map source:
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
German Aerospace Center

Ionosphere Monitoring and Prediction Center

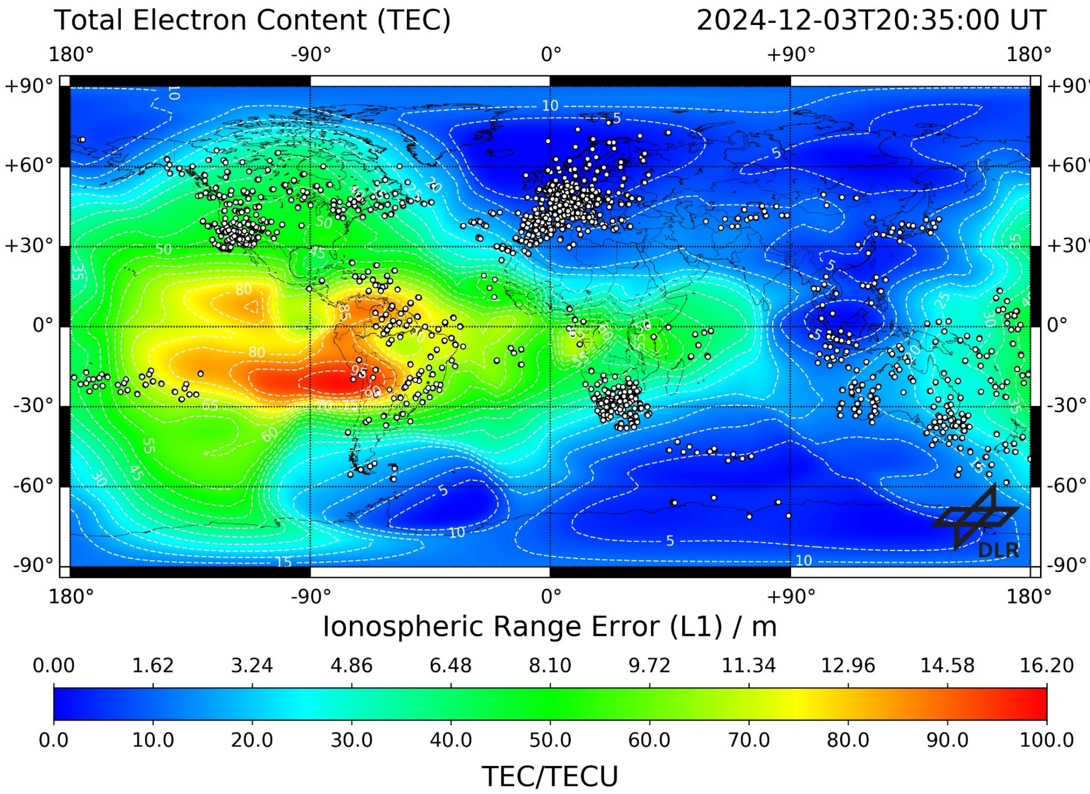
https://swe.ssa.esa.int/impc-federated
https://swe.ssa.esa.int/

(!) Data on e.g. the NASA public portal is of low spatial / temporal cadence -- not all that useful in highly disturbed environments

Variability:

- long-term variability during 11yr cycles,
- diurnal variability (due to the relative motion of the Sun on the celestial sphere), and
- periodicities of 27d due to Solar rotations.

Much more active now!



The Ionosphere as dispersive medium - measurement with GNSS

$$P_1 = r + c.\Delta T + d_{\text{ion}} + d_{\text{trop}} + b_{s_i,L1} + b_{r_j,L1} + m_{P1} + \varepsilon_{P1}$$

$$P_2 = r + c.\Delta T + \left(\frac{\nu_{L1}}{\nu_{L2}}\right)^2 d_{\text{ion}} + d_{\text{trop}} + b_{s_i,L2} + b_{r_j,L2} + m_{P2} + \varepsilon_{P2}$$

$$P_1 - P_2 \approx \left[1 - \left(\frac{\nu_{L1}}{\nu_{L2}}\right)^2\right] d_{\text{ion}} + \left[b_{s_i,L1} - b_{s_i,L2} + b_{r_j,L1} - b_{r_j,L2}\right] + \ldots$$

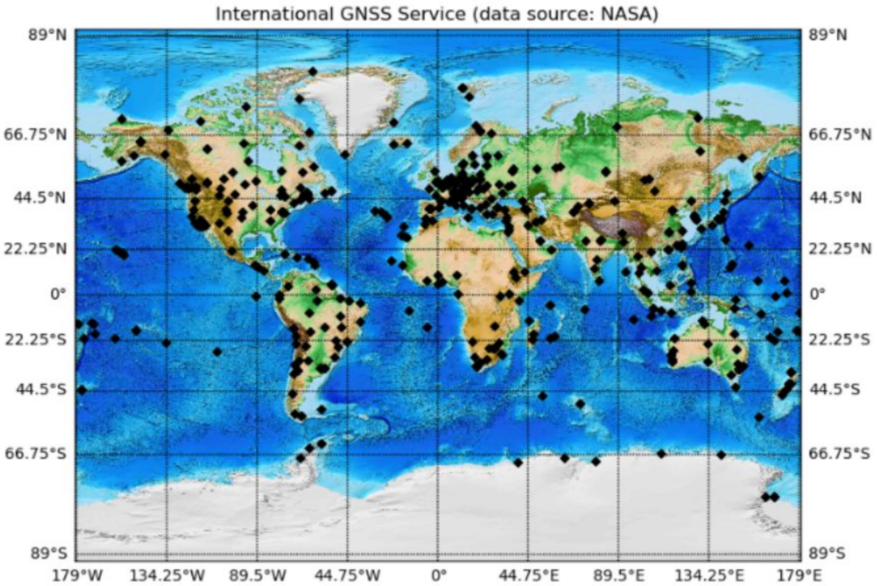
- r is the distance between the receiver and transmitting satellite
- ΔT is the absolute time difference between receiver and transmitter clocks
- ν_{L1} and ν_{L2} are the operating frequencies of the bands
- d_{ion} is the ionospheric dispersive delay
- d_{trop} is the Tropospheric delay
- b_{r_j} is the j^{th} receiver instrumental delay per band
- b_{s_i} is the i^{th} satellite instrumental delay per band
- m is the multipath (ground reflection) error near the horizon on the pseudo-range
- ε is the receiver noise on the pseudo-range

$$\text{TEC}_P = 9.52(P_2 - P_1)$$

$$\Delta r = 40.3\text{TEC}/\nu^2$$

GNSS are at MEO circular orbits - 20000 km for GPS, slightly higher for Galileo

The International GNSS Service and TrigNET



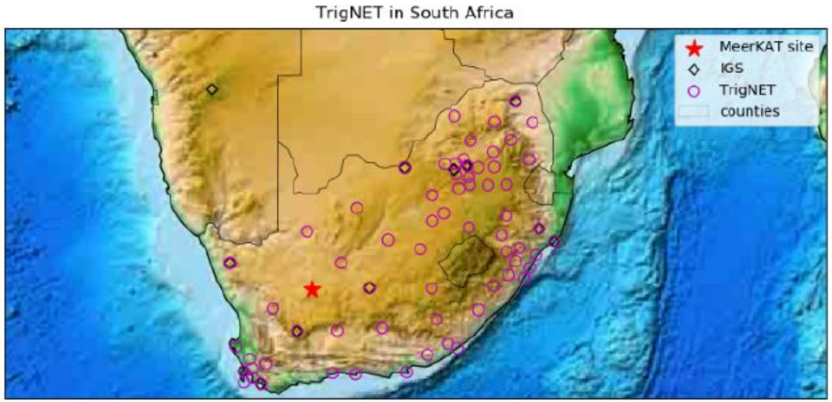


Figure 2.10: All available TrigNET stations in South Africa, as operated by the Department of Agriculture, Land Reform and Rural Development as of 2022.

Strong effects at cm wavelengths: Ionospheric Faraday Rotation

- The ionospheric delay affects astrometry at meter wavelengths as a function of nu^{-2}
- **At cm wavelengths the main effect is to rotate the linear polarization angle of a plane-polarized signal (negligible effect on circular polarization)**
- At very low frequencies Hz - 10s Hz the ionosphere induces a delay between the vertical and horizontal component of the wave (induces ellipticity -- not necessary for discussion here)
- Rotation measure (single Faraday screen) is generally negative in the southern hemisphere and positive in the north due to the sign of the parallel magnetic field component

$$P(\lambda^2) = \frac{\iint_{\text{source}} I(\vec{r},\lambda)\,p(\vec{r})\,e^{2i(\mathrm{EVPA}(\vec{r})+F(\vec{r})\lambda^2)}\,dr\,d\Omega}{\iint_{\text{source}} I(\vec{r},\lambda)\,dr\,d\Omega}$$

$$F(\vec{r}) := \frac{e^3}{2\pi m_e^2 c^4}\int_{\text{source}}^{\text{observer}} n_e(\vec{r})B_{|}(\vec{r})\,d\vec{r}$$

$$\mathrm{EVPA}(\vec{r}) := 0.5\arctan\left(\frac{U}{Q}\right), \mathrm{EVPA}(\vec{r}) \in [-90^\circ, 90^\circ)$$

Hands-on

Info

- CASA recipe can be found here. Follow along as a team - interrupt if you are stuck!!!

  https://github.com/africalim/Polcal-Primer/blob/master/recipe.casa.py

- Data available under:

  https://github.com/africalim/Polcal-Primer/tree/master/data

- We will do the following:

  - KGB Jones recap

  - Df Jones using primary

  - Phase refinement on secondary

  - Phase refinement on polcal and ambiguous HV-phase derivation

  - Application of parallactic angle and HV phase - before and after Stokes imaging of the Moon

This reduction will use CASA 5.6 - you are welcome to use CASA 6.x or CASA 4.7. If you run into issues between CASA versions let us know!

Listobs

- Two datasets:

  listobs(vis="moon_uhf_calibrators.ms")

  listobs(vis="moon_uhf.ms")

- What bandwidth is being observed?
- Date/duration of this observation
- What fields are in this dataset?

```
INFO     listobs::ms::summary    ================================================================================
INFO     listobs::ms::summary+             MeasurementSet Name:  /home/bhugo/workspace/moon_uhf_100MHz_mkcore_checkreduce/moon_uhf_calibrators.ms      MS Version 2
INFO     listobs::ms::summary+   ================================================================================
INFO     listobs::ms::summary+      Observer: B Hugo     Project: 20210622-0005
INFO     listobs::ms::summary+   Observation: MeerKAT
INFO     listobs::MSMetaData::_computeScanAndSubScanProperties   Computing scan and subscan properties...
INFO     listobs::ms::summary    Data records: 25688       Total elapsed time = 15646.1 seconds
INFO     listobs::ms::summary+      Observed from   22-Jun-2021/17:02:42.2   to   22-Jun-2021/21:23:28.3 (UTC)
INFO     listobs::ms::summary
INFO     listobs::ms::summary+      ObservationID = 0         ArrayID = 0
INFO     listobs::ms::summary+     Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)    ScanIntent
INFO     listobs::ms::summary+     22-Jun-2021/17:02:42.2 - 17:12:34.4     1      0 J1331+3030               3380  [0]  [59.2] [CALIBRATE_BANDPASS,CALIBRATE_FLUX]
INFO     listobs::ms::summary+                 17:14:02.5 - 17:23:54.7     2      1 J1939-6342               3380  [0]  [59.2] [CALIBRATE_BANDPASS,CALIBRATE_FLUX]
INFO     listobs::ms::summary+                 17:24:42.7 - 17:26:02.7     3      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 17:37:15.0 - 17:38:35.0     4      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 17:49:47.3 - 17:51:07.3     5      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 18:02:19.6 - 18:03:39.6     6      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 18:14:51.9 - 18:16:19.9     7      2 J1733-1304                676  [0]  [44] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 18:27:24.2 - 18:28:52.2     8      2 J1733-1304                676  [0]  [44] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 18:39:56.5 - 18:41:24.5     9      2 J1733-1304                676  [0]  [44] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 18:52:28.7 - 18:53:56.8    10      2 J1733-1304                676  [0]  [44] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 19:05:01.0 - 19:06:29.1    11      2 J1733-1304                676  [0]  [44] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 19:17:33.3 - 19:18:53.4    12      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 19:30:05.6 - 19:31:25.7    13      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 19:42:37.9 - 19:43:57.9    14      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 19:55:02.2 - 19:56:30.2    15      2 J1733-1304                676  [0]  [44] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 20:08:06.5 - 20:18:06.7    16      0 J1331+3030               3380  [0]  [60] [CALIBRATE_BANDPASS,CALIBRATE_FLUX]
INFO     listobs::ms::summary+                 20:19:50.8 - 20:29:43.0    17      1 J1939-6342               3380  [0]  [59.2] [CALIBRATE_BANDPASS,CALIBRATE_FLUX]
INFO     listobs::ms::summary+                 20:30:47.0 - 20:32:07.1    18      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 20:43:27.3 - 20:44:47.4    19      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 20:56:15.6 - 20:57:35.7    20      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 21:09:11.9 - 21:10:32.0    21      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary+                 21:22:08.2 - 21:23:28.3    22      2 J1733-1304                676  [0]  [40] [CALIBRATE_AMPLI,CALIBRATE_PHASE]
INFO     listobs::ms::summary              (nRows = Total number of rows per scan)
INFO     listobs::ms::summary    Fields: 3
INFO     listobs::ms::summary+     ID   Code Name                RA               Decl           Epoch   SrcId      nRows
INFO     listobs::ms::summary+     0    T    J1331+3030          13:31:08.290000 +30.30.33.00000 J2000   0           6760
INFO     listobs::ms::summary+     1    T    J1939-6342          19:39:25.050000 -63.42.43.60000 J2000   1           6760
INFO     listobs::ms::summary+     2    T    J1733-1304          17:33:02.660000 -13.04.49.10000 J2000   2          12168
INFO     listobs::ms::summary    Spectral Windows:  (1 unique spectral windows and 1 unique polarization setups)
INFO     listobs::ms::summary+     SpwID  Name   #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz)  Corrs
INFO     listobs::ms::summary+     0      none      23   TOPO     812.016      4250.000     97750.0    858.7656   XX  XY  YX  YY
```

```
INFO    listobs::ms::summary   ================================================================================
INFO    listobs::ms::summary+            MeasurementSet Name:  /home/bhugo/workspace/moon_uhf_100MHz_mkcore_checkreduce/moon_uhf.ms      MS Version 2
INFO    listobs::ms::summary+  ================================================================================
INFO    listobs::ms::summary+     Observer: B Hugo     Project: 20210622-0005
INFO    listobs::ms::summary+  Observation: MeerKAT
INFO    listobs::MSMetaData::_computeScanAndSubScanProperties   Computing scan and subscan properties...
INFO    listobs::ms::summary   Data records: 57460       Total elapsed time = 14077.5 seconds
INFO    listobs::ms::summary+     Observed from   22-Jun-2021/17:26:42.7   to   22-Jun-2021/21:21:20.2 (UTC)
INFO    listobs::ms::summary
INFO    listobs::ms::summary+     ObservationID = 0         ArrayID = 0
INFO    listobs::ms::summary+    Date        Timerange (UTC)          Scan  FldId FieldName             nRows     SpwIds   Average Interval(s)    ScanIntent
INFO    listobs::ms::summary+    22-Jun-2021/17:26:42.7 - 17:36:35.0     1      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                17:39:15.0 - 17:49:07.3     2      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                17:51:47.3 - 18:01:39.6     3      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                18:04:19.6 - 18:14:11.9     4      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                18:16:51.9 - 18:26:44.1     5      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                18:29:24.2 - 18:39:16.4     6      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                18:41:56.5 - 18:51:48.7     7      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                18:54:28.8 - 19:04:21.0     8      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                19:07:01.1 - 19:16:53.3     9      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                19:19:33.4 - 19:29:25.6    10      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                19:32:05.7 - 19:41:57.9    11      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                19:44:38.0 - 19:54:30.2    12      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                19:57:02.2 - 20:07:02.5    13      0 Moon                      3380  [0]  [60] [TARGET]
INFO    listobs::ms::summary+                20:32:47.1 - 20:42:39.3    14      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                20:45:27.4 - 20:55:27.6    15      0 Moon                      3380  [0]  [60] [TARGET]
INFO    listobs::ms::summary+                20:58:23.7 - 21:08:15.9    16      0 Moon                      3380  [0]  [59.2] [TARGET]
INFO    listobs::ms::summary+                21:11:20.0 - 21:21:20.2    17      0 Moon                      3380  [0]  [60] [TARGET]
INFO    listobs::ms::summary           (nRows = Total number of rows per scan)
INFO    listobs::ms::summary   Fields: 1
INFO    listobs::ms::summary+    ID   Code Name                RA               Decl           Epoch   SrcId      nRows
INFO    listobs::ms::summary+    0    T    Moon                16:02:23.524142 -19.57.04.42223 J2000   0          57460
INFO    listobs::ms::summary   Spectral Windows:  (1 unique spectral windows and 1 unique polarization setups)
INFO    listobs::ms::summary+    SpwID  Name   #Chans   Frame   Ch0(MHz)  ChanWid(kHz)  TotBW(kHz) CtrFreq(MHz)  Corrs
INFO    listobs::ms::summary+    0      none      23   TOPO     812.016      4250.000     97750.0    858.7656   XX  XY  YX  YY
INFO    listobs::ms::summary   Sources: 1
INFO    listobs::ms::summary+    ID   Name                SpwId RestFreq(MHz)
INFO    listobs::ms::summary+    0    Moon                0     -
INFO    listobs::ms::summary+    NB: No systemic velocity information found in SOURCE table.
```

Intent

- J1331+3030 - polarization
- J1939-6342 - primary
- J1733-1304 - phase calibrator (very important - cannot self-calibrate the lunar phase due to lack of power on longer spacings)
- Moon - target
- Observed from 22-Jun-2021/17:02:42.2 to 22-Jun-2021/21:23:28.3 (UTC)
- Bandwidth: 812.016->909.766MHz, channelization: 4.250 MHz

Looking at the (primary) calibrator field

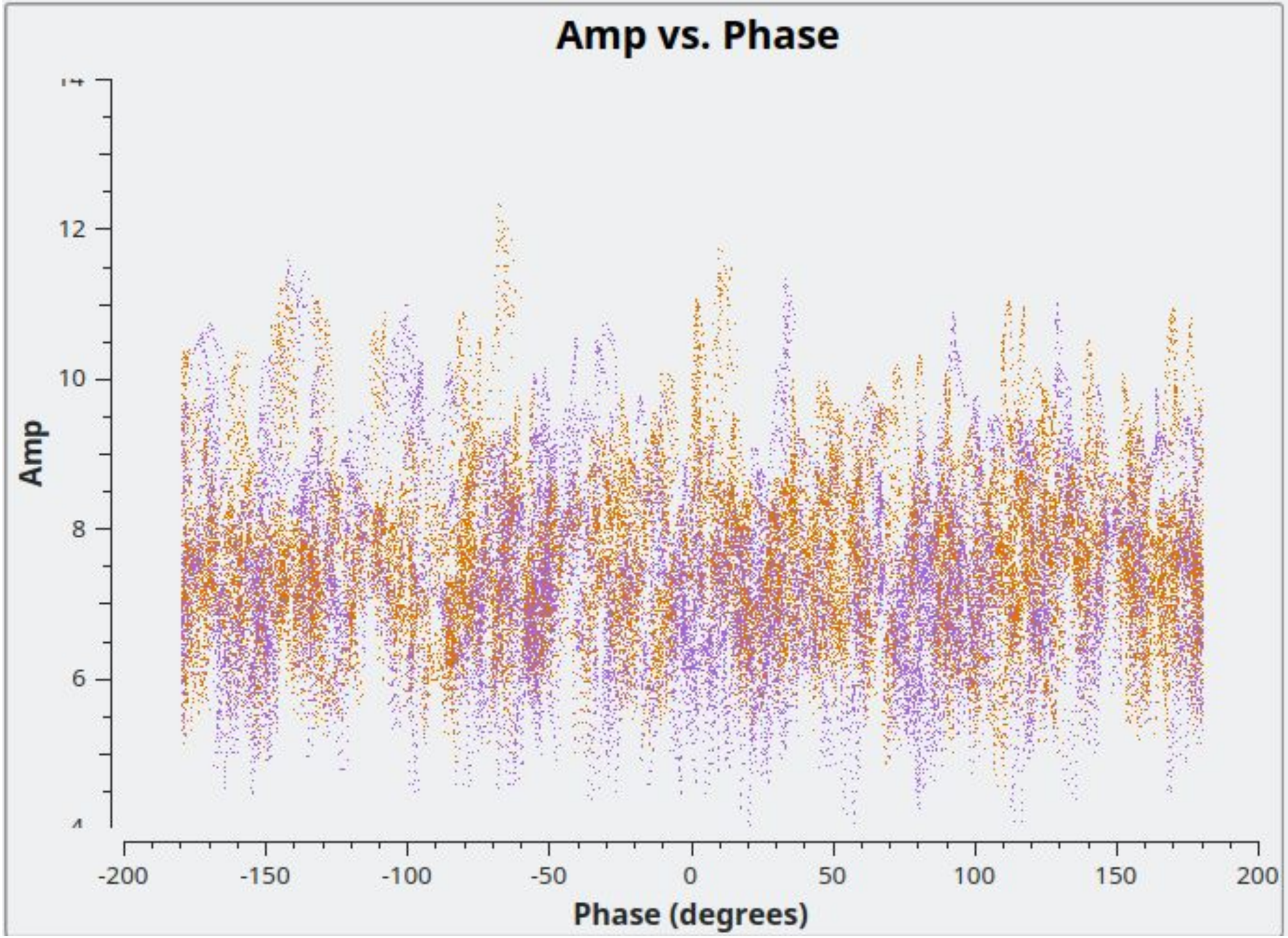
Q: what are we expecting to see?

Hint: this GPS source is a ~50 mas (therefore unresolved for MK) source put at the phase centre. Can you say what we should be seeing if the system was well calibrated?

Compare this with uncalibrated data:

- plotms(vis='moon_uhf_calibrators.ms', xaxis='phase', yaxis='amplitude', xdatacolumn='data', ydatacolumn='data', correlation='XX,YY', coloraxis='corr', uvrange=">1m", avgtime='300', field='J1939-6342')

Clearly our work is cut out for us!



Amp vs. Phase
Amp
Phase (degrees)
4
6
8
10
12
14
-200
-150
-100
-50
0
50
100
150
200

(!)ALWAYS(!) do your your flag backup before calibration

- flagmanager(vis='moon_uhf_calibrators.ms/', versionname='observatory', mode='save')
- flagmanager(vis='moon_uhf.ms/', versionname='observatory', mode='save')

Before we set off we will backup our flags. Every time we either apply gains or perform flagging operations we must keep backups of our flag state so that we can roll back as needed should things (inevitably!) not succeed!

```
INFO    flagmanager::::
INFO    flagmanager::::+        ##########################################
INFO    flagmanager::::+        ##### Begin Task: flagmanager        #####
INFO    flagmanager:::: flagmanager(vis="moon_uhf_calibrators.ms/",mode="save",versionname="observatory",oldname="",comment="",
INFO    flagmanager::::+                merge="replace")
INFO    flagmanager::AgentFlagger::open Table type is Measurement Set
INFO    flagmanager:::: Save current flagversions to observatory
INFO    FlagVersion::saveFlagVersion    Creating new backup flag file called observatory
INFO    flagmanager:::: ##### End Task: flagmanager          #####
INFO    flagmanager::::+        ##########################################
INFO    flagmanager::::
INFO    flagmanager::::+        ##########################################
INFO    flagmanager::::+        ##### Begin Task: flagmanager        #####
INFO    flagmanager:::: flagmanager(vis="moon_uhf.ms/",mode="save",versionname="observatory",oldname="",comment="",
INFO    flagmanager::::+                merge="replace")
INFO    flagmanager::AgentFlagger::open Table type is Measurement Set
INFO    flagmanager:::: Save current flagversions to observatory
INFO    FlagVersion::saveFlagVersion    Creating new backup flag file called observatory
INFO    flagmanager:::: ##### End Task: flagmanager          #####
INFO    flagmanager::::+        ##########################################
```

Goal: KGB, starting with primary

We have the following calibration errors to remove:

- We will set and transfer the flux scale and the spectral (bandpass response) of the system using PKS B 1934 here
- We remove the delay (K Jones - frequency slope), and average gain (constant offset) before doing the (normalized) bandpass.
- We solve for the amplitudes (mainly) and the leakages (non-orthogonality of the feeds) using this unpolarized source

To simplify things for now we will use a single component spectral model for this unresolved source. Run

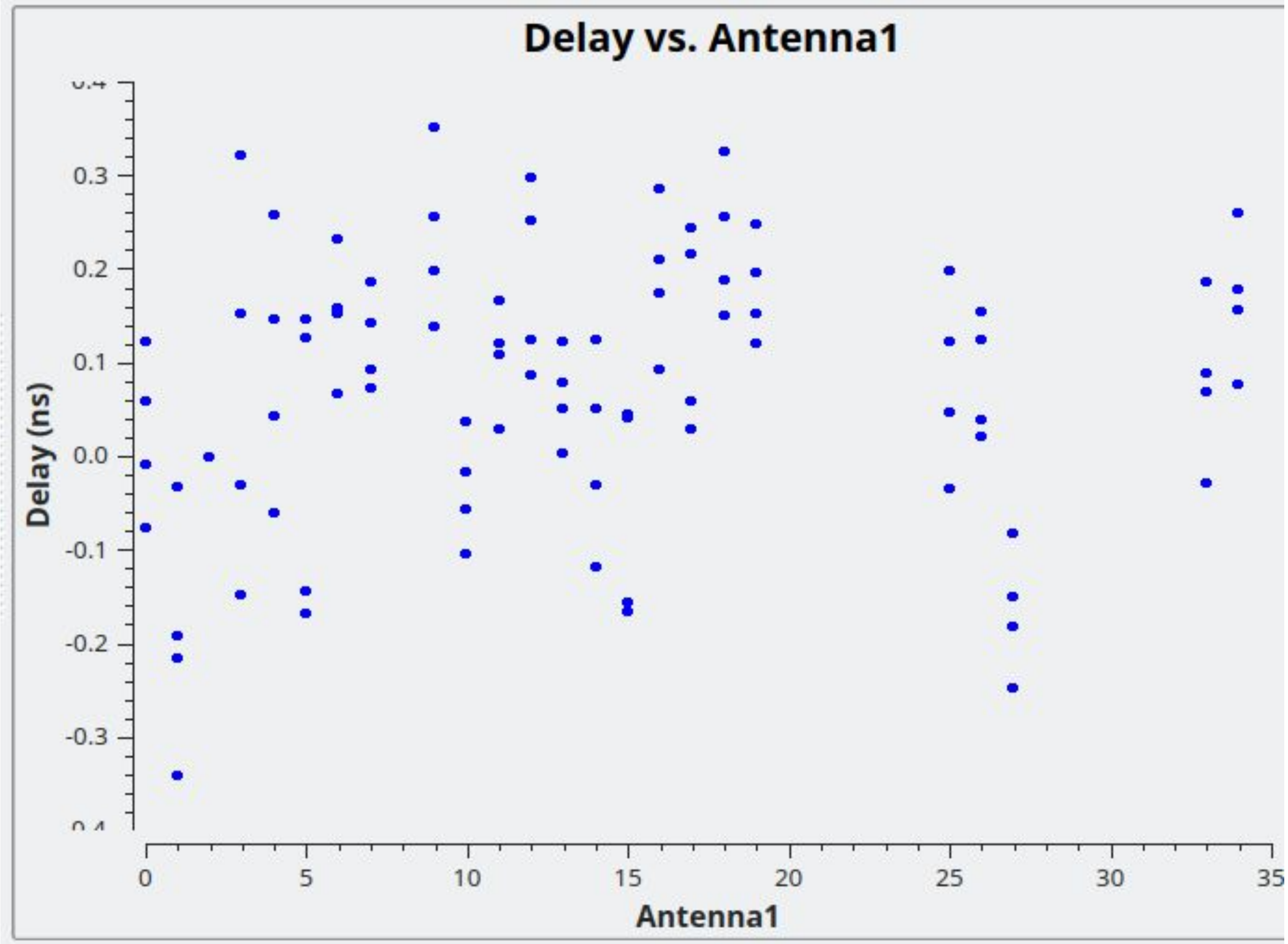
- setjy(vis='moon_uhf_calibrators.ms', standard='Stevens-Reynolds 2016', field='J1939-6342',usescratch=True)
- For calibration note that we are using m002 as reference antenna THROUGHOUT! Switching reference antenna will bias polarization calibration.

```
INFO    setjy::::
INFO    setjy::::+      ##########################################
INFO    setjy::::+      ##### Begin Task: setjy             #####
INFO    setjy::::       setjy(vis="moon_uhf_calibrators.ms",field="J1939-6342",spw="",selectdata=False,timerange="",
INFO    setjy::::+              scan="",intent="",observation="",scalebychan=True,standard="Stevens-Reynolds 2016",
INFO    setjy::::+              model="",modimage="",listmodels=False,fluxdensity=-1,spix=0.0,
INFO    setjy::::+              reffreq="1GHz",polindex=[],polangle=[],rotmeas=0.0,fluxdict={},
INFO    setjy::::+              useephemdir=False,interpolation="nearest",usescratch=True,ismms=False)
INFO    setjy::::       {'field': 'J1939-6342'}
INFO    Imager::open()  Opening MeasurementSet /home/bhugo/workspace/moon_uhf_100MHz_mkcore_checkreduce/moon_uhf_calibrators.ms
INFO            Clearing all model records in MS header.
INFO    VisSetUtil::addScrCols  Adding MODEL_DATA column(s).
INFO    VisSetUtil::initScrCols Initializing MODEL_DATA to (unity).
INFO    VisSetUtil::initScrCols Initialized 25688 rows.
INFO            Clearing all model records in MS header.
INFO    setjy::::       CASA Version 5.6.0-60
INFO    setjy::::
INFO    imager::setjy() Using channel dependent flux densities
INFO            Clearing all model records in MS header.
INFO    imager::data selection  Selected 6760 out of 25688 rows.
INFO    imager::setjy()   J1939-6342 (fld ind 1) spw 0  [I=13.614, Q=0, U=0, V=0] Jy @ 8.1202e+08Hz, (Stevens-Reynolds 2016)
INFO            Clearing all model records in MS header.
INFO    imager::data selection  Selected 6760 out of 25688 rows.
INFO    imager::ft()    Fourier transforming: replacing MODEL_DATA column
INFO    imager::createSkyEquation()     Processing after subtracting componentlist /home/bhugo/workspace/moon_uhf_100MHz_mkcore_checkreduce/moon_uh
INFO    imager::createFTMachine()       Performing interferometric gridding...
INFO    setjy::::       ##### End Task: setjy               #####
INFO    setjy::::+      ##########################################
```

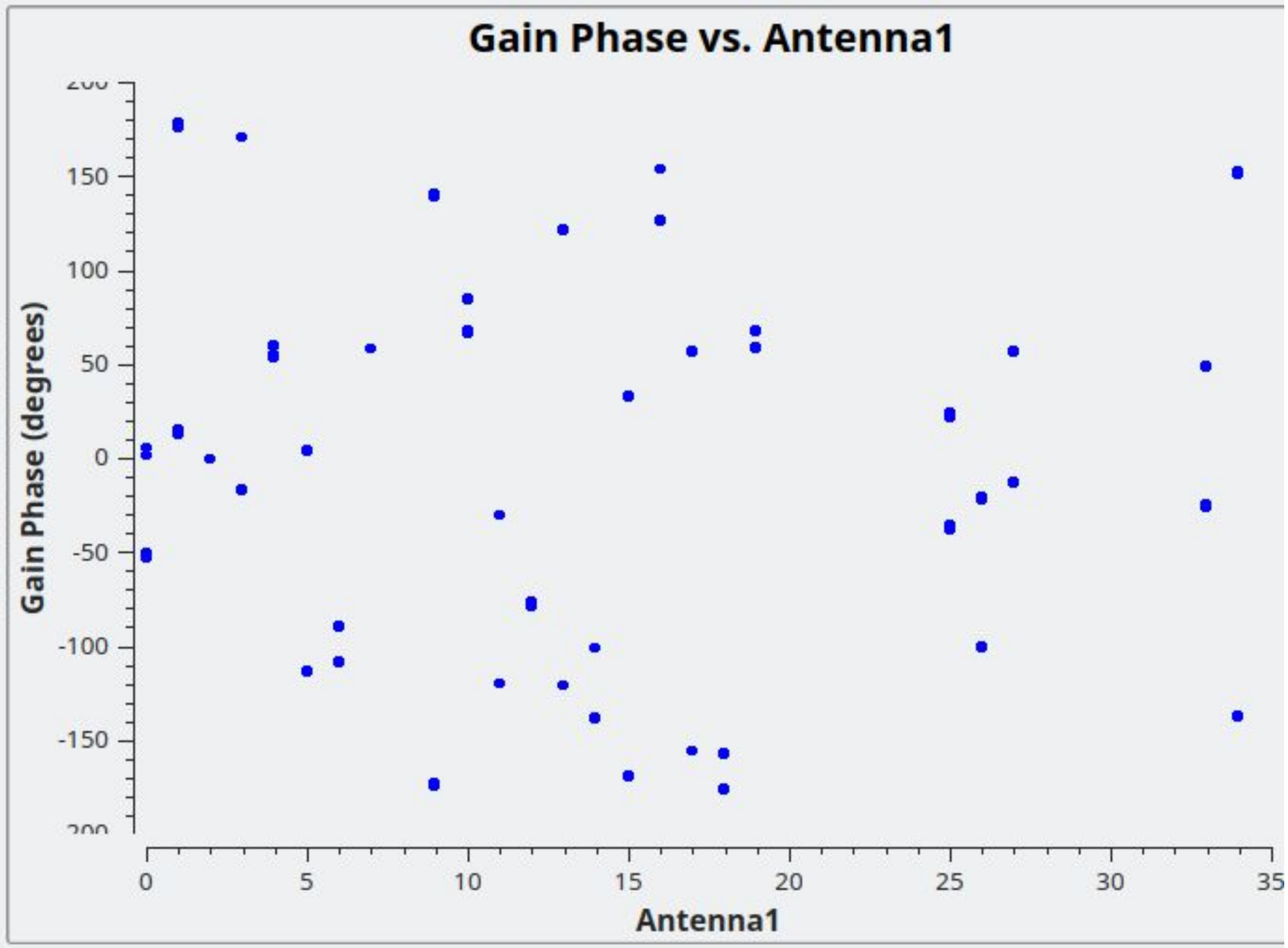
KGB

- gaincal(vis='moon_uhf_calibrators.ms', caltable='bp.K', field='J1939-6342', gaintype='K', solint='inf', combine='',refant='m002')
- gaincal(vis='moon_uhf_calibrators.ms', caltable='bp.Gp', field='J1939-6342', gaintype='G', calmode='p', solint='inf', combine='',refant='m002', gaintable=['bp.K'])
- gaincal(vis='moon_uhf_calibrators.ms', caltable='bp.Ga', field='J1939-6342', gaintype='G', calmode='a', solint='inf', combine='',refant='m002', gaintable=['bp.K', 'bp.Gp'])
- bandpass(vis='moon_uhf_calibrators.ms', caltable='bp.B', field='J1939-6342', solint='inf', combine='scan',refant='m002', gaintable=['bp.K', 'bp.Gp', 'bp.Ga'])
- Plot up the gain tables e.g. plotms(vis='bp.Gp',yaxis='phase')

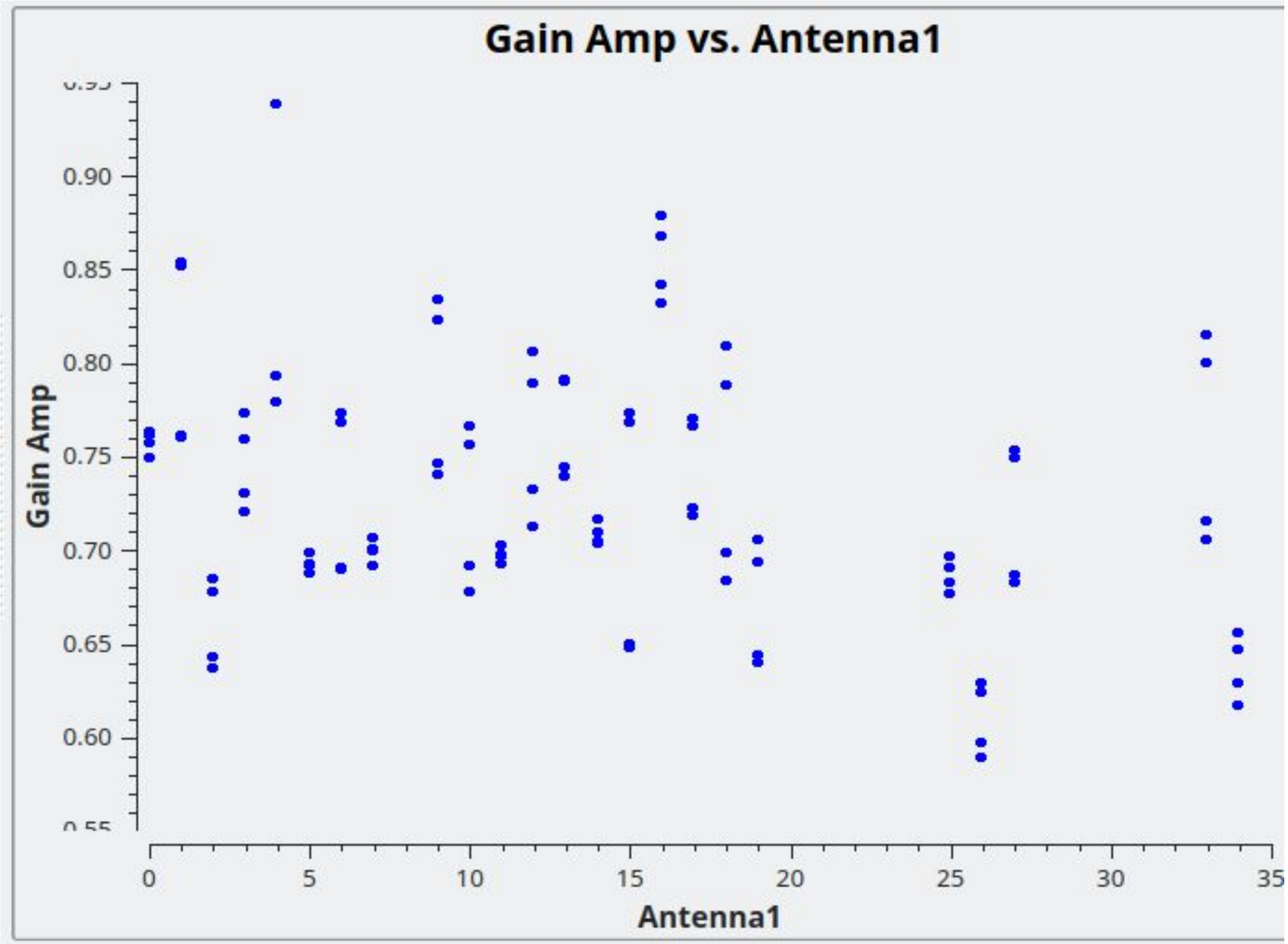
```
INFO    gaincal::::
INFO    gaincal::::+    ##########################################
INFO    gaincal::::+    ##### Begin Task: gaincal            #####
INFO    gaincal::::     gaincal(vis="moon_uhf_calibrators.ms",caltable="bp.K",field="J1939-6342",spw="",intent="",
INFO    gaincal::::+            selectdata=True,timerange="",uvrange="",antenna="",scan="",
INFO    gaincal::::+            observation="",msselect="",solint="inf",combine="",preavg=-1.0,
INFO    gaincal::::+            refant="m002",refantmode="flex",minblperant=4,minsnr=3.0,solnorm=False,
INFO    gaincal::::+            normtype="mean",gaintype="K",smodel=[],calmode="ap",solmode="",
INFO    gaincal::::+            rmsthresh=[],append=False,splinetime=3600.0,npointaver=3,phasewrap=180.0,
INFO    gaincal::::+            docallib=False,callib="",gaintable=[''],gainfield=[''],interp=[],
INFO    gaincal::::+            spwmap=[],parang=False)
INFO    gaincal::calibrater::open       ****Using NEW VI2-driven calibrater tool****
INFO    gaincal::calibrater::open       Opening MS: moon_uhf_calibrators.ms for calibration.
INFO    gaincal::Calibrater::   Initializing nominal selection to the whole MS.
INFO    gaincal::::     NB: gaincal automatically excludes auto-correlations.
INFO    calibrater::setdata     Beginning selectvis--(MSSelection version)-------
INFO    calibrater::reset       Reseting solve/apply state
INFO    Calibrater::selectvis   Performing selection on MeasurementSet
INFO    Calibrater::selectvis+   Selecting on field: 'J1939-6342'
INFO    Calibrater::selectvis+   Selecting with TaQL: 'ANTENNA1!=ANTENNA2'
INFO    Calibrater::selectvis   By selection 25688 rows are reduced to 5520
INFO    Calibrater::selectvis   Frequency selection: Selecting all channels in all spws.
INFO    calibrater::setdata     chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect='ANTENNA1!=ANTENNA2'
INFO    calibrater::setsolve    Beginning setsolve--(MSSelection version)-------
INFO    Calibrater::setsolve    Arranging to SOLVE:
INFO    Calibrater::setsolve    .   K Jones: table=bp.K append=false solint=inf refantmode='flex' refant='m002' minsnr=3 apmode=AP solnorm=false
INFO    calibrater::solve       Beginning solve-----------------------------
INFO    Calibrater::solve       The following calibration terms are arranged for apply:
INFO    Calibrater::solve       .   (None)
INFO    Calibrater::solve       The following calibration term is arranged for solve:
INFO    Calibrater::solve       .   K Jones: table=bp.K append=false solint=inf refantmode='flex' refant='m002' minsnr=3 apmode=AP solnorm=false
INFO    Calibrater::solve       For solint = inf, found 2 solution intervals.
SEVERE  MeasTable::dUTC(Double) (file ../../measures/Measures/MeasTable.cc, line 4290)  Leap second table TAI_UTC seems out-of-date.
SEVERE  MeasTable::dUTC(Double) (file ../../measures/Measures/MeasTable.cc, line 4290)+ Until the table is updated (see the CASA documentation or your system admin),
SEVERE  MeasTable::dUTC(Double) (file ../../measures/Measures/MeasTable.cc, line 4290)+ times and coordinates derived from UTC could be wrong by 1s or more.
INFO    Calibrater::solve         Found good K Jones solutions in 2 solution intervals.
INFO            Writing solutions to table: bp.K
INFO    calibrater::solve       Finished solving.
INFO    gaincal::::     Calibration solve statistics per spw:  (expected/attempted/succeeded):
INFO    gaincal::::       Spw 0: 2/2/2
INFO    gaincal::::     ##### End Task: gaincal              #####
INFO    gaincal::::+    ##########################################
```



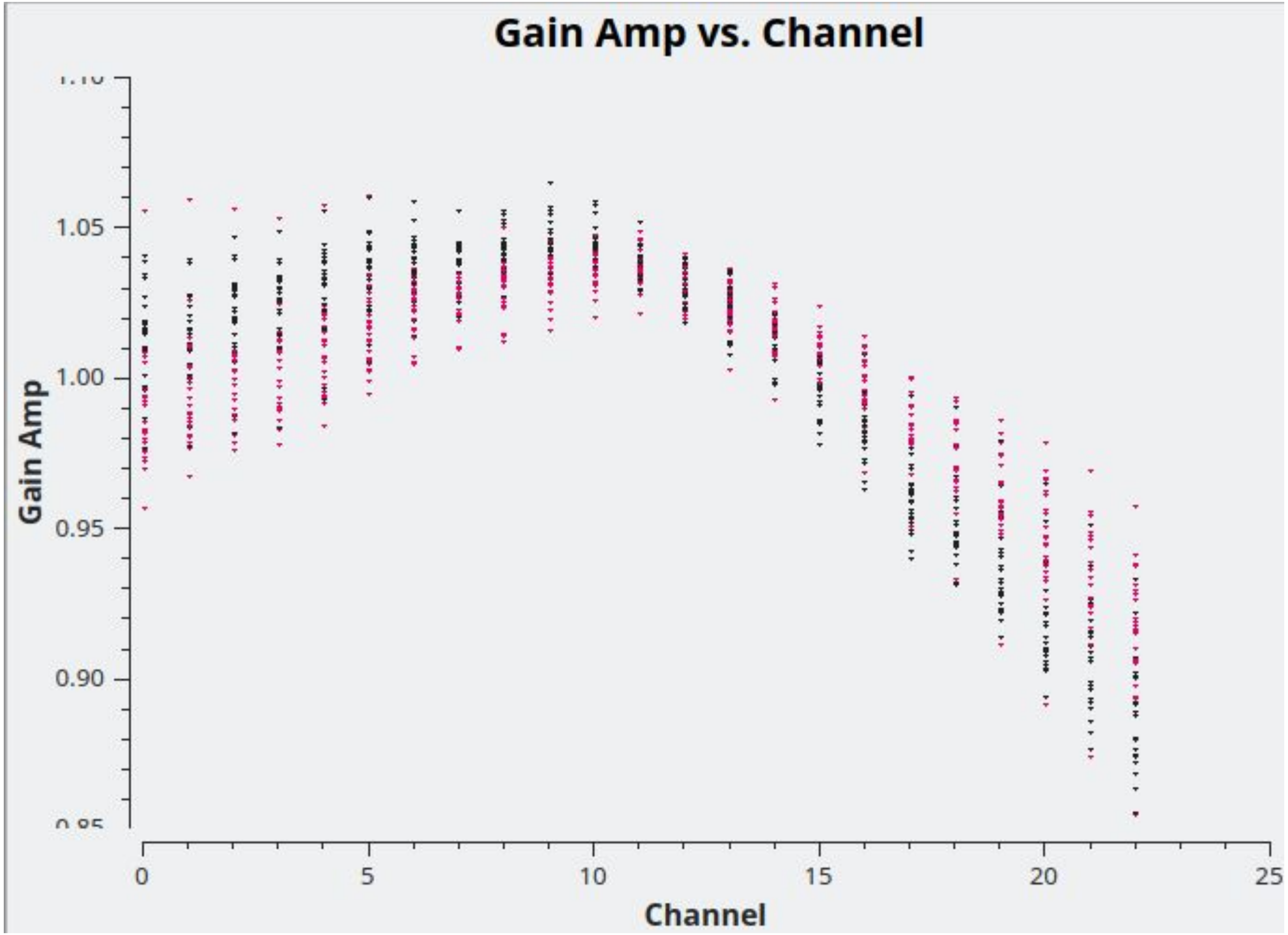
Delay vs. Antenna1
Delay (ns)
0.3
0.2
0.1
0.0
-0.1
-0.2
-0.3
0
5
10
15
20
25
30
35
Antenna1



Gain Phase vs. Antenna1
Gain Phase (degrees)
200
150
100
50
0
-50
-100
-150
-200
0
5
10
15
20
25
30
35
Antenna1



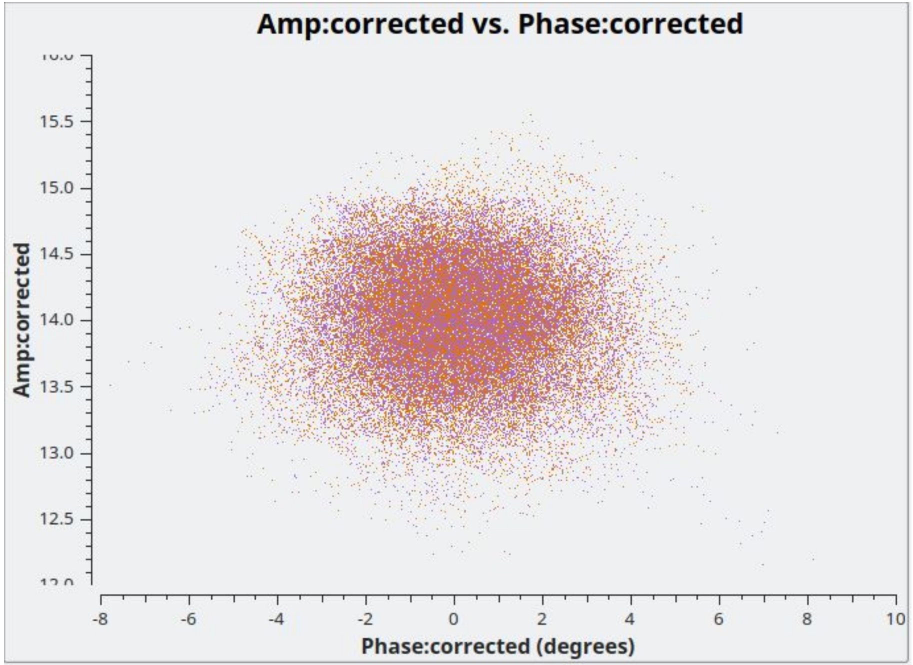
Gain Amp vs. Antenna1
Gain Amp
0.90
0.85
0.80
0.75
0.70
0.65
0.60
0
5
10
15
20
25
30
35
Antenna1


Gain Amp vs. Channel
Gain Amp
1.05
1.00
0.95
0.90
Channel
0
5
10
15
20
25

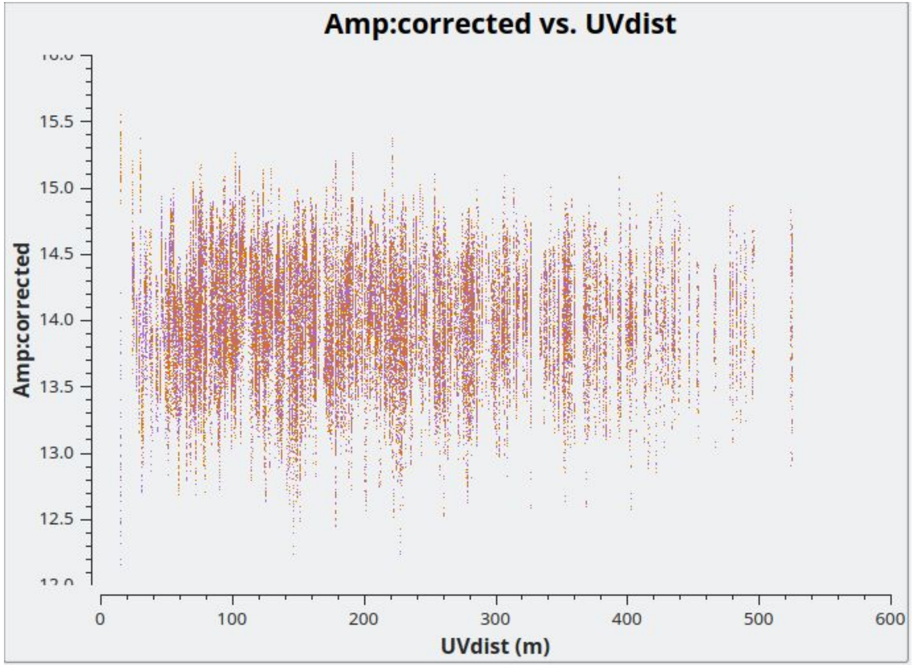
Remarks:

- These delays are residuals -- the MeerKAT science data processor solves for delays before every observation. We expect these to be a few 10s of ns at most, but sometimes the online process fails (due to e.g. RFI). Don't flag solely based on the delay values here.
- Note we only dumped a subset of the original spacings in this small dataset to conserve space and interactiveness. Some of the antennas are therefore fully flagged!
- Same goes for calibrating the phase and the amplitude. We split the two because the phase component is highly variable across the hemisphere, whereas the system amplitude is temperature stablized and should not vary too much. The amplitude term here is solved for both X (vertical) and Y (horizontal) feeds and has to be done on an unpolarized source because it is sensitive to I +/- Q stokes.
- You can also check that when solved for a time-variable bandpass, the bandpass does not substantially slope with time in amplitude - a variable pointing error or frequency-dependent phases changing as nu^2 - indicative of a highly variable ionosphere
- Any of your own?
- Apply using: applycal(vis='moon_uhf_calibrators.ms', field='J1939-6342', gaintable=['bp.K','bp.Gp','bp.Ga','bp.B'])
- Next rerun the plotms command on corrected data to see how the phase vs. amplitude balls of x(/y)datacolumn=’corrected’ look!

```
INFO    applycal::calibrater::open      ****Using NEW VI2-driven calibrater tool****
INFO    applycal::calibrater::open      Opening MS: moon_uhf_calibrators.ms for calibration.
INFO    applycal::VisSetUtil::addScrCols        Adding CORRECTED_DATA column(s).
INFO    applycal::VisSetUtil::addScrCols        Start copying column keyword(s) of CORRECTED_DATA from DATA
INFO    applycal::Calibrater::  Initializing nominal selection to the whole MS.
INFO    applycal::AgentFlagger::open    Table type is Measurement Set
INFO    FlagVersion::saveFlagVersion    Creating new backup flag file called applycal_1
INFO    calibrater::setdata     Beginning selectvis--(MSSelection version)-------
INFO    calibrater::reset       Reseting solve/apply state
INFO    Calibrater::selectvis   Performing selection on MeasurementSet
INFO    Calibrater::selectvis+   Selecting on field: 'J1939-6342'
INFO    Calibrater::selectvis   By selection 25688 rows are reduced to 6760
INFO    Calibrater::selectvis   Frequency selection: Selecting all channels in all spws.
INFO    calibrater::setdata     chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect=''
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO             (K Jones: Enforcing calWt()=false for phase/delay-like terms)
INFO    Calibrater::setapply(type, applypar)    .   K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO    calibrater::correct     Beginning correct---------------------------
INFO    Calibrater::correct2 (VI2/VB2)  The following calibration terms are arranged for apply:
INFO    Calibrater::correct2 (VI2/VB2)  .   B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO    Calibrater::correct2 (VI2/VB2)  .   K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO    Calibrater::correct2 (VI2/VB2)  .   G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO    Calibrater::correct2 (VI2/VB2)  .   G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO    Calibrater::correct2 (VI2/VB2)  Found valid WEIGHT_SPECTRUM, correcting it.
INFO    calibrater::correct     Finished correcting.
INFO    applycal::::    Calibration apply flagging statistics (among calibrateable spws):
INFO    applycal::::      Total visibilities selected for correction (ncorr x nchan x nrow summed over spws) = 621920
INFO    applycal::::      Flags:
INFO    applycal::::       B Jones: In: 0 / 621920   (0.0%) --> Out: 69920 / 621920   (11.2426035503%) (bp.B)
INFO    applycal::::       K Jones: In: 69920 / 621920   (11.2426035503%) --> Out: 69920 / 621920   (11.2426035503%) (bp.K)
INFO    applycal::::       G Jones: In: 69920 / 621920   (11.2426035503%) --> Out: 69920 / 621920   (11.2426035503%) (bp.Gp)
INFO    applycal::::       G Jones: In: 69920 / 621920   (11.2426035503%) --> Out: 69920 / 621920   (11.2426035503%) (bp.Ga)
INFO    applycal::::    CASA Version 5.6.0-60
INFO    applycal::::
INFO    applycal::::    ##### End Task: applycal             #####
INFO    applycal::::+   ##########################################
```

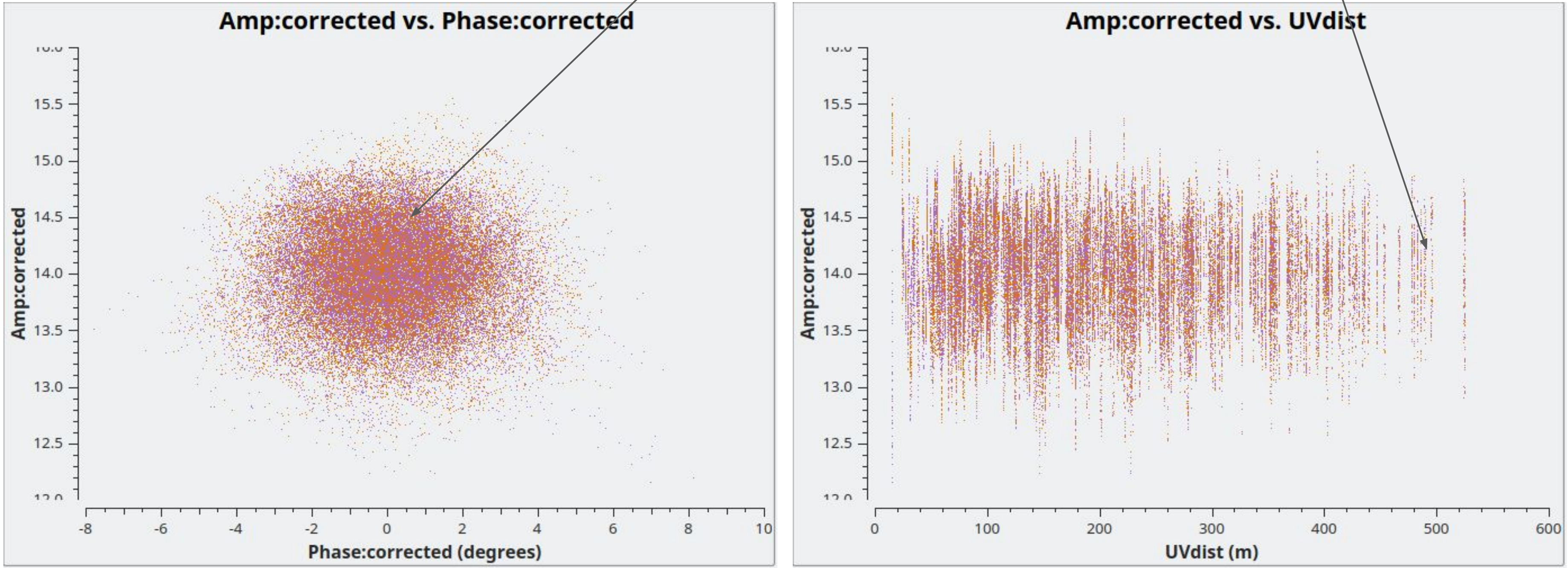


Amp:corrected vs. Phase:corrected
Amp:corrected
Phase:corrected (degrees)
15.5
15.0
14.5
14.0
13.5
13.0
12.5
-8
-6
-4
-2
0
2
4
6
8
10



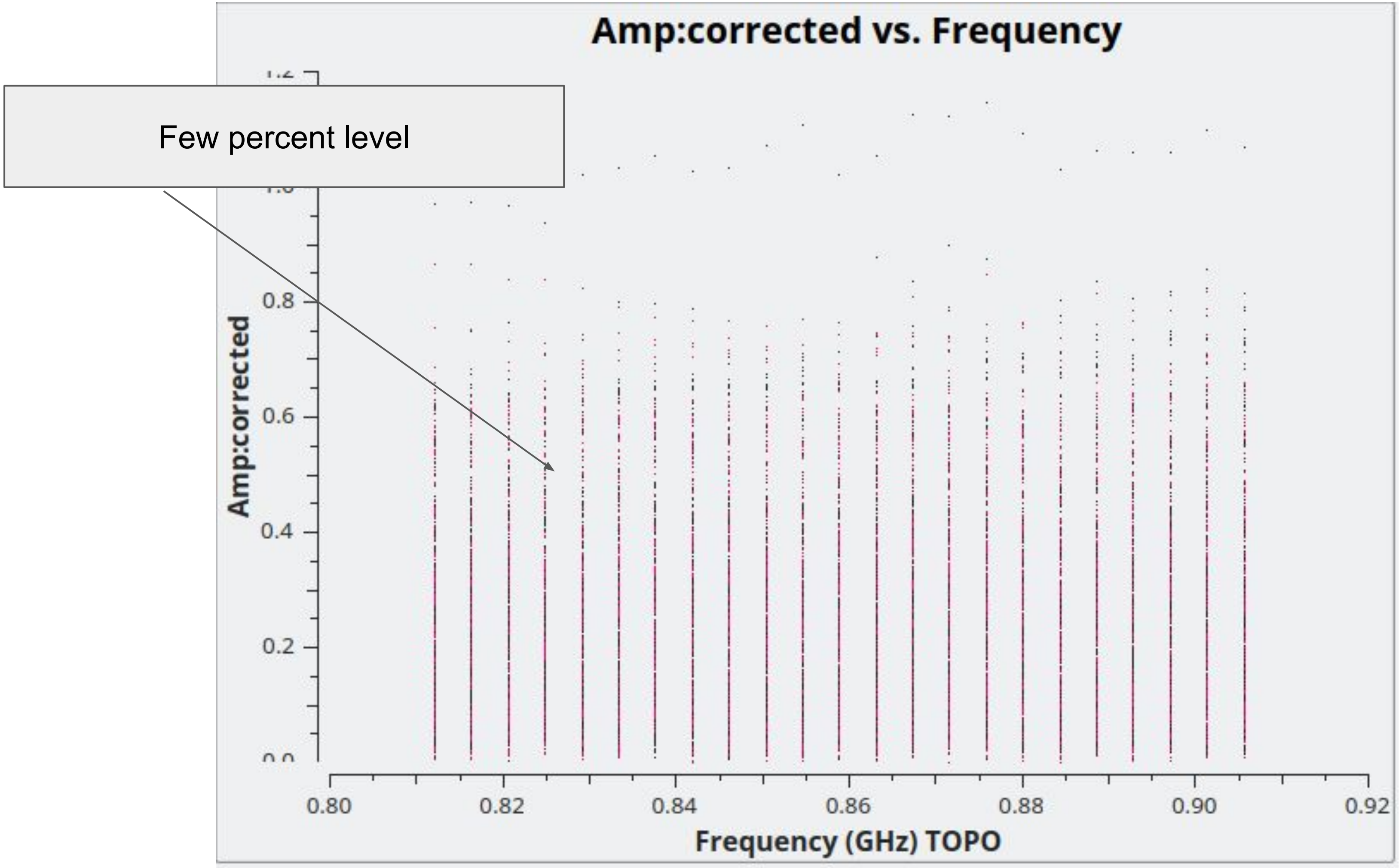
Amp:corrected vs. UVdist
Amp:corrected
UVdist (m)
15.5
15.0
14.5
14.0
13.5
13.0
12.5
0
100
200
300
400
500
600

Point-like unresolved source at phase centre

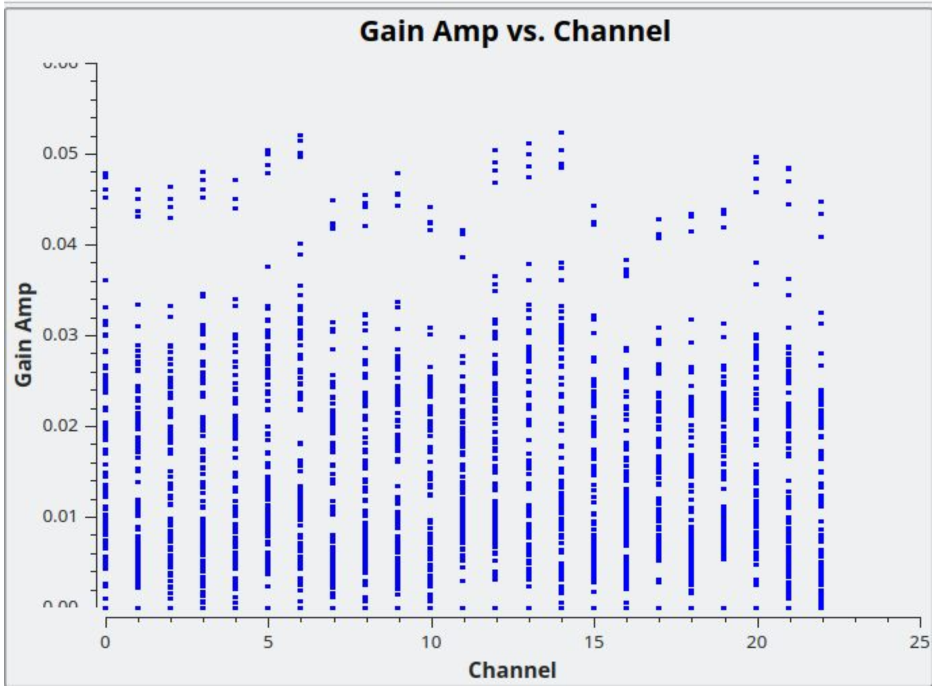


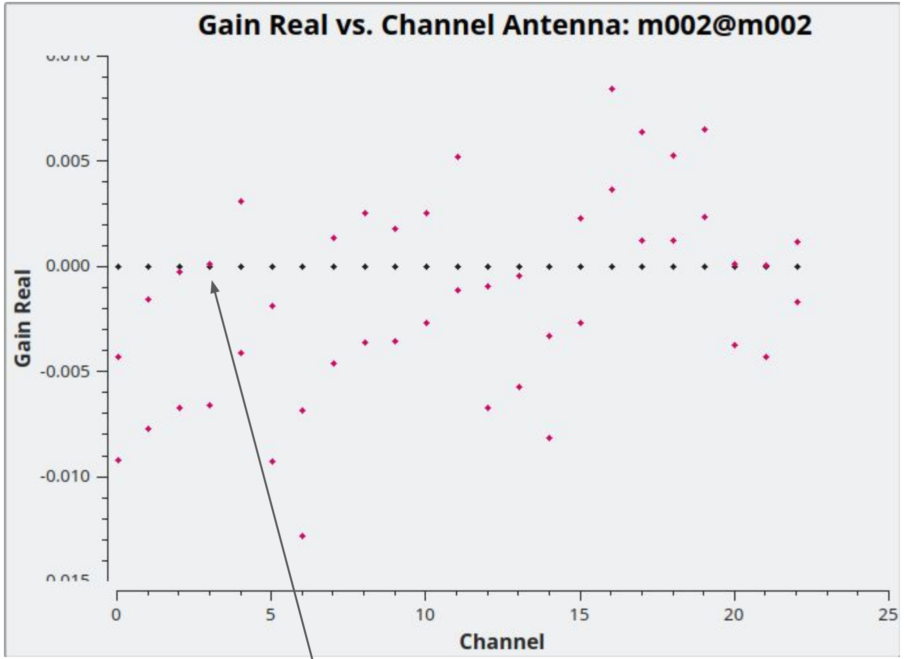
Calibrating Df

- Let’s first inspect the XY* and YX* correlations for this source
- plotms(vis='moon_uhf_calibrators.ms', xaxis='frequency', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XY,YX', coloraxis='corr', uvrange=">1m", avgtime='999999999999', avgscan=True, field='J1939-6342')
- polcal(vis='moon_uhf_calibrators.ms', field='J1939-6342', caltable='bp.Df', refant='m002', gaintable=['bp.K','bp.Gp','bp.Ga','bp.B'], combine='', poltype='Df', solint='inf')
- Check the levels by plotting the solutions.
- Warning: these solutions are extremely sensitive to residual RFI. You may need to clip the solutions (in which case CASA interpolates from the neighbouring solutions)
- These solutions should be stable up to about 70~80+ degrees elevation


Amp:corrected vs. Frequency
Few percent level
Amp:corrected
0.8
0.6
0.4
0.2
0.80
0.82
0.84
0.86
0.88
0.90
0.92
Frequency (GHz) TOPO

```
INFO    polcal::::
INFO    polcal::::+     ##########################################
INFO    polcal::::+     ##### Begin Task: polcal             #####
INFO    polcal::::      polcal(vis="moon_uhf_calibrators.ms",caltable="bp.Df",field="J1939-6342",spw="",intent="",
INFO    polcal::::+             selectdata=True,timerange="",uvrange="",antenna="",scan="",
INFO    polcal::::+             observation="",msselect="",solint="inf",combine="",preavg=300.0,
INFO    polcal::::+             refant="m002",minblperant=4,minsnr=3.0,poltype="Df",smodel=[],
INFO    polcal::::+             append=False,docallib=False,callib="",gaintable=['bp.K', 'bp.Gp', 'bp.Ga', 'bp.B'],gainfield=[''],
INFO    polcal::::+             interp=[],spwmap=[])
INFO    polcal::calibrater::open        ****Using NEW VI2-driven calibrater tool****
INFO    polcal::calibrater::open        Opening MS: moon_uhf_calibrators.ms for calibration.
INFO    polcal::Calibrater::    Initializing nominal selection to the whole MS.
INFO    polcal::::      NB: polcal automatically excludes auto-correlations.
INFO    calibrater::setdata     Beginning selectvis--(MSSelection version)-------
INFO    calibrater::reset       Reseting solve/apply state
INFO    Calibrater::selectvis   Performing selection on MeasurementSet
INFO    Calibrater::selectvis+   Selecting on field: 'J1939-6342'
INFO    Calibrater::selectvis+   Selecting with TaQL: 'ANTENNA1!=ANTENNA2'
INFO    Calibrater::selectvis   By selection 25688 rows are reduced to 5520
INFO    Calibrater::selectvis   Frequency selection: Selecting all channels in all spws.
INFO    calibrater::setdata     chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect='ANTENNA1!=ANTENNA2'
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO            (K Jones: Enforcing calWt()=false for phase/delay-like terms)
INFO    Calibrater::setapply(type, applypar)    .   K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   P Jones <pre-computed>
INFO    calibrater::setsolve    Beginning setsolve--(MSSelection version)-------
INFO    Calibrater::setsolve    Arranging to SOLVE:
INFO            Using only cross-hand data for instrumental polarization solution.
INFO    Calibrater::setsolve    .   Df Jones: table=bp.Df append=false solint=inf,none refantmode='flex' refant='m002' minsnr=3 apmode=AP solnorm=false
INFO    calibrater::solve       Beginning solve-----------------------------
INFO    Calibrater::solve       The following calibration terms are arranged for apply:
INFO    Calibrater::solve       .   B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO    Calibrater::solve       .   K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO    Calibrater::solve       .   G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO    Calibrater::solve       .   G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO    Calibrater::solve       .   P Jones <pre-computed>
INFO    Calibrater::solve       The following calibration term is arranged for solve:
INFO    Calibrater::solve       .   Df Jones: table=bp.Df append=false solint=inf,none refantmode='flex' refant='m002' minsnr=3 apmode=AP solnorm=false
INFO    Calibrater::solve       For solint = inf, found 2 solution intervals.
INFO    Calibrater::solve         Found good Df Jones solutions in 2 solution intervals.
INFO            Applying refant: m002 refantmode = flex (hold alternate refants' phase constant) when refant flagged
INFO            Writing solutions to table: bp.Df
INFO    calibrater::solve       Finished solving.
INFO    polcal::::      ##### End Task: polcal               #####
INFO    polcal::::+     ##########################################
```





Real part on one of the hands set to 0 on ref antenna?
This is relative leakage calibration - the **global orientation** of the feeds (and polarization angle) **is NOT calibrated**

Relative feed angle rotation on sky (real)

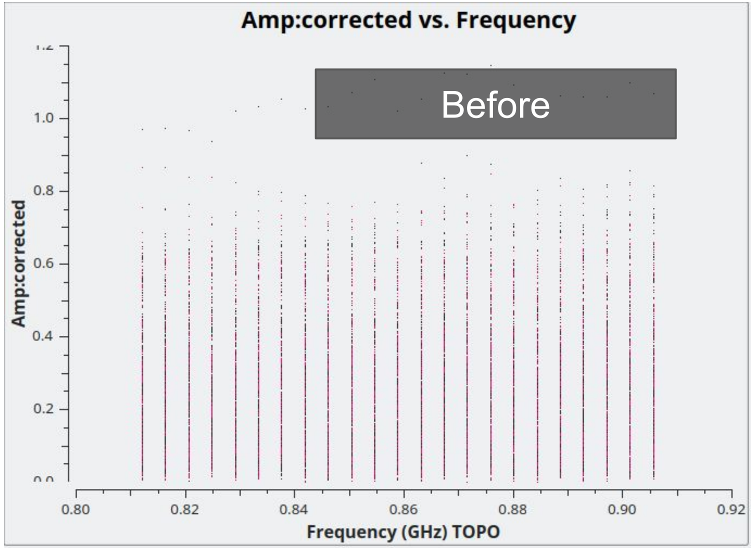
$$d_X = \theta_X - i\chi_X$$

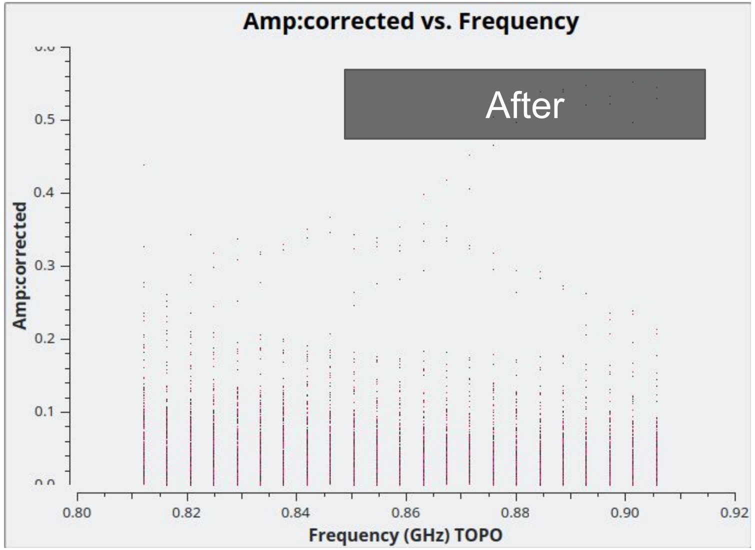
$$d_Y = \theta_Y - i\chi_Y$$

Feed ellipticity (imag)

Df: Proof is in the taste!

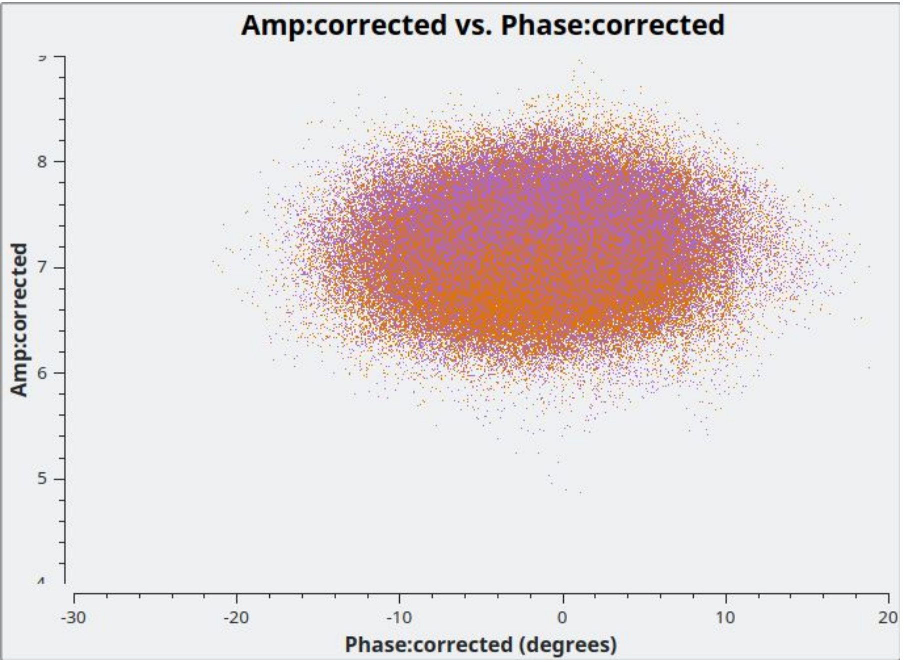
- Apply the solution (add to the chain)
- Plot the XY* and YX* terms afterwards
- If leakage has not gone down something could be wrong on your reference antenna, maybe switch (and start the calibration from scratch!)
- IMPORTANT: Applying leakages does not mean that the polarization response of the system is fixed. The vast majority of the error (by an order of magnitude) is calibrating the differential (ambiguous) impedance phase between the X and Y hands which turns a linearly polarized signal into an elliptical one on our system. This HV phase calibration will be done later and must be done on a linearly polarized source (ie. emitting coherently on both X and Y feeds)

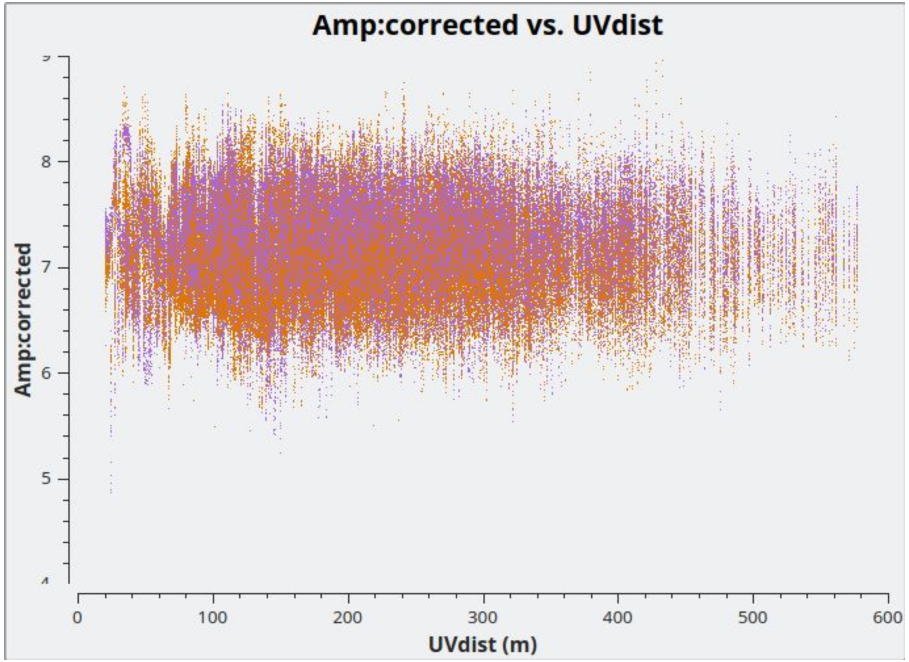




Phase refine for the target using the secondary

- The primary is usually far away from the target - we can transfer everything except the constant phase (both the troposphere [high frequencies] and ionosphere [low frequencies]) act as a dispersive medium delaying the signal. At cm-wavelengths the constant gain phase is mostly affected by the ionosphere.
- Bootstrap the secondary: applycal(vis='moon_uhf_calibrators.ms', field='J1733-1304', gaintable=['bp.K','bp.Gp','bp.Ga','bp.B','bp.Df'])
- plotms(vis='moon_uhf_calibrators.ms', xaxis='phase', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XX,YY', coloraxis='corr', uvrange=">1m", avgtime='300', field='J1733-1304')
- plotms(vis='moon_uhf_calibrators.ms', xaxis='uvdist', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XX,YY', coloraxis='corr', uvrange=">1m", avgtime='300', field='J1733-1304')
- You should see that the transferred phase looks reasonable for a first pass. We can refine it through self calibrating the field (we will show you that tomorrow. In practice you **REALLY SHOULD** phase self calibrate both your secondary and your polarization calibrator before transferring their solutions onto your target field, especially for wideband datasets!)



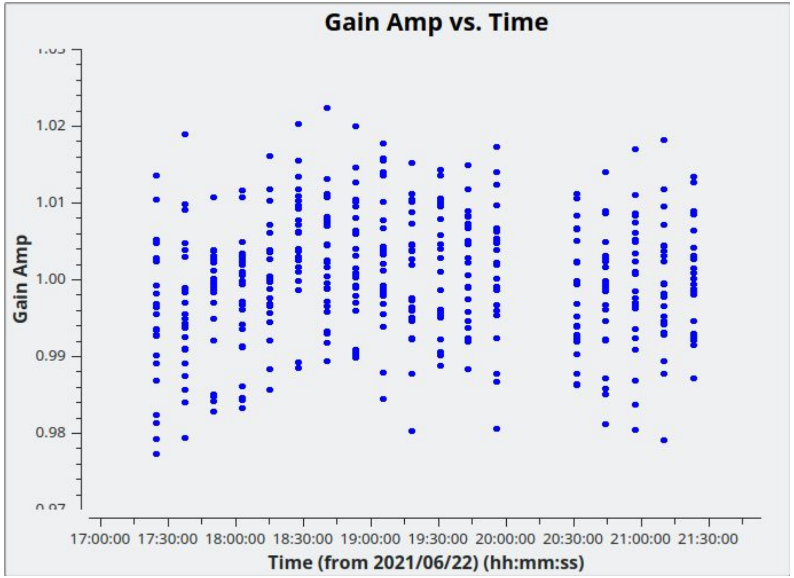


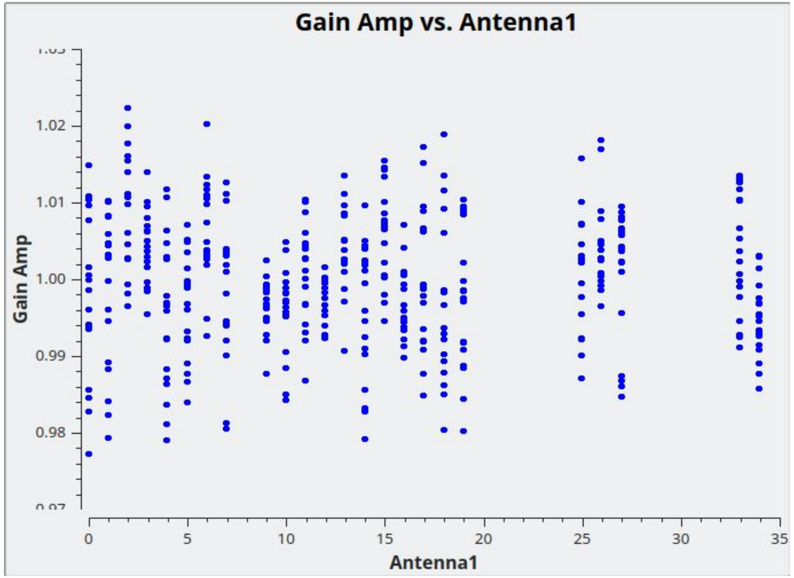
Why is checking this important?

Phase refinement - we can do better!

- The spread in phase for this unresolved (almost) unpolarized secondary source can be improved. Let’s swap out the primary (bp) phase for new solutions assuming a point model (as an exercise you should try phase selfcal this field). We will also solve for a constant matrix “Tropospheric” (mode T) amplitude and phase that is insensitive to any unmodelled polarization of the source
- gaincal(vis='moon_uhf_calibrators.ms', caltable='sec.Gp', field='J1733-1304', gaintype='G', calmode='p', solint='inf', combine='',refant='m002', gaintable=['bp.K', 'bp.Ga', 'bp.B', 'bp.Df'])
- gaincal(vis='moon_uhf_calibrators.ms', caltable='sec.T', field='J1733-1304', gaintype='T', calmode='ap', solnorm=True, solint='inf', combine='',refant='m002', gaintable=['bp.K', 'sec.Gp', 'bp.Ga', 'bp.B', 'bp.Df'])
- **Note:** that we normalize the amplitude solution to unity - we don’t have a model of the secondary, just a unitary flat spectrum model (default - no need to specify). All the more reason to image the secondary and self calibrate!

Amplitude variability on the system



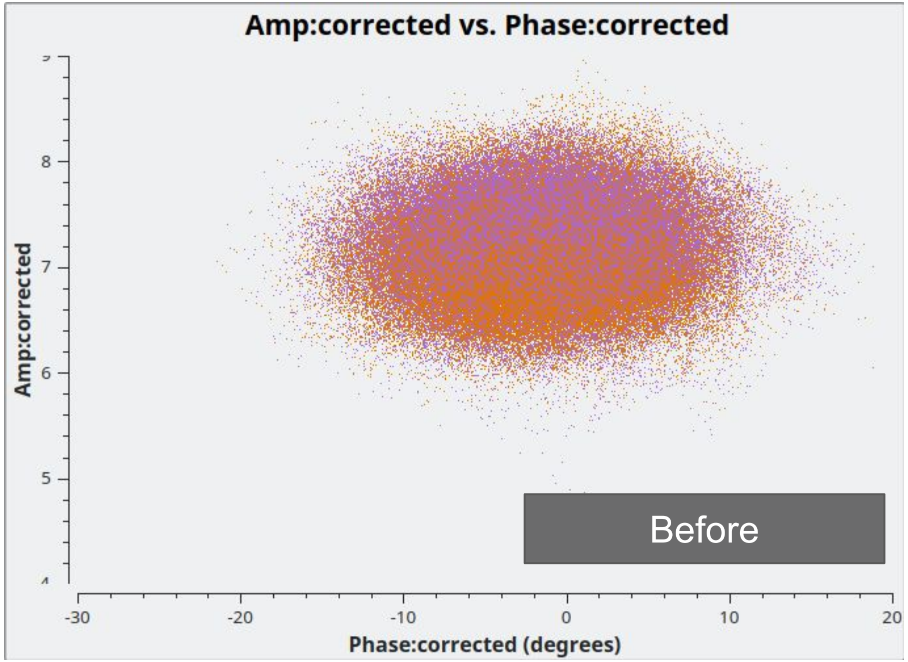


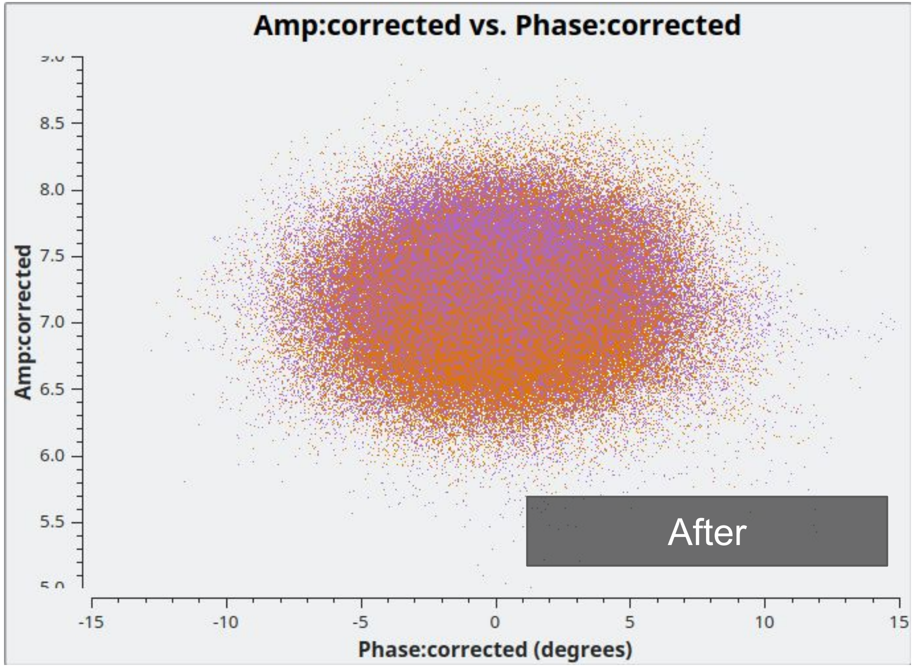
A high degree of variability here may indicate severe variable pointing error or LNA cycling on one or both of the receiver feeds.

FLAG THE ANTENNA!

Secondary: before and after phase refinement

Apply and replot: applycal(vis='moon_uhf_calibrators.ms', field='J1733-1304', gaintable=['bp.K','sec.Gp','bp.Ga','bp.B','sec.T','bp.Df'])





Pitstop - the Moon before HV phase and P Jones

- Thus far we have:
  - System’s cable delays (K Jones) per feed
  - System/environment’s phase and amplitude gains (G Jones), with phase refined on secondary
  - System’s passband (frequency dependent) response (B Jones), due to reflections in the analog components and OMT (mainly)
  - System’s non-orthogonality (leakage) response (D(f) Jones - frequency dependent)
- Let’s look at corrected Lunar data
  - Transfer: applycal(vis='moon_uhf.ms', field='Moon', gaintable=['bp.K','sec.Gp','bp.Ga','bp.B','sec.T','bp.Df'])
  - Plot amp vs. uvdist: plotms(vis='moon_uhf.ms', xaxis='uvdist', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XX,YY', coloraxis='corr', uvrange=">1m", avgtime='9999999999', avgchannel='99999999999', avgscan=True, field='Moon', plotrange=[0,300,0,200])

Repeating the Michelson & Pease experiment on ~~Betelgeuse~~ Moon

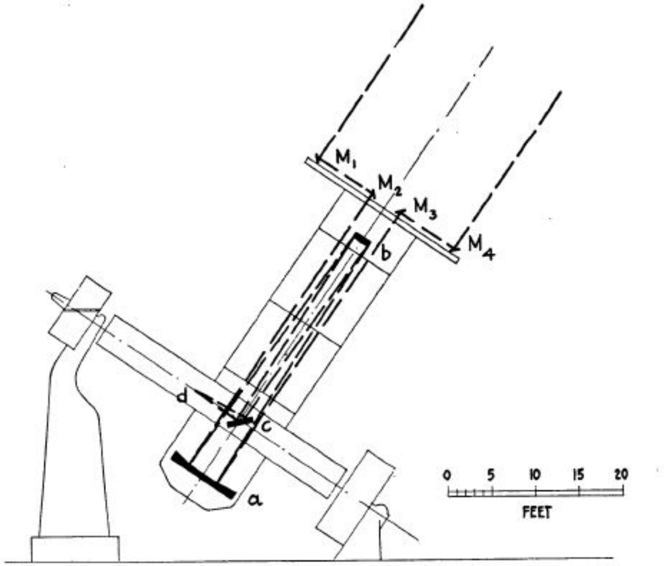
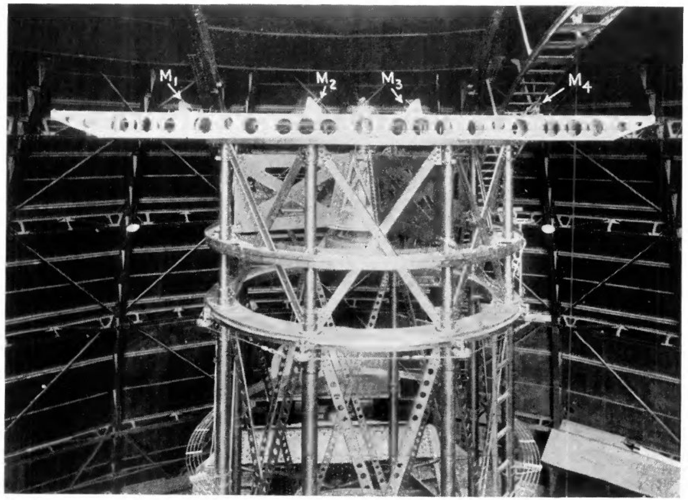


FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4, mirrors; *a*, 100-inch paraboloid; *b*, convex mirror; *c*, coudé flat; *d*, focus.

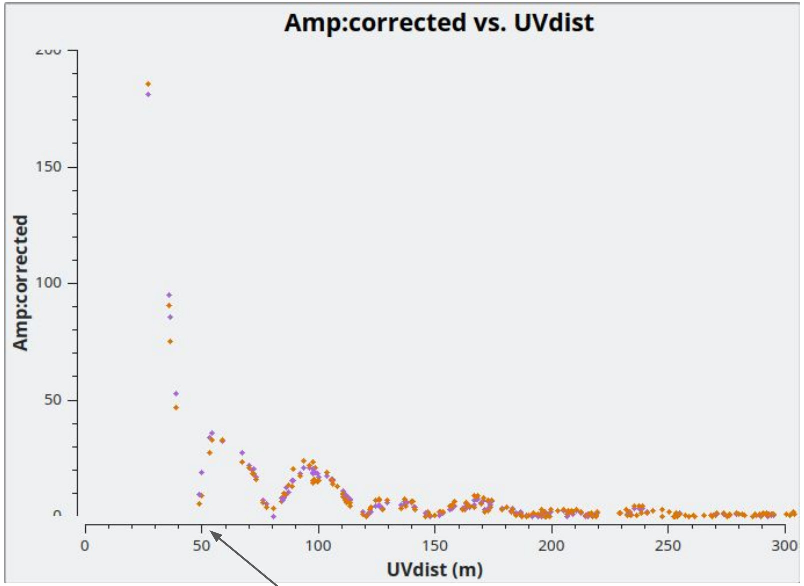
Michelson, Albert A., and Francis G. Pease. "Measurement of the diameter of Alpha-Orionis by the interferometer." *Proceedings of the National Academy of Sciences of the United States of America* 7.5 (1921): 143.

In December 1920 Michelson and Pease measured the apparent size of the stellar disk of Betelgeuse to 0.047” +/- 10% (corresponding to a diameter of 386×10^6 km at a parallax of 0.018” wavelength of 575nm) using an adjustable 20 foot interferometer at the Mt Wilson observatory.

Let’s repeat a similar experiment with a radio interferometer



How *visible* is the Moon?



First null at ~50m

Work out the angular extent of the Moon (a ~flat pillbox):

$$\mathcal{J}_1(2\pi u(\lambda)_{\text{null}} l_{\text{radius}}) = \mathcal{J}_1(3.8317) = 0$$

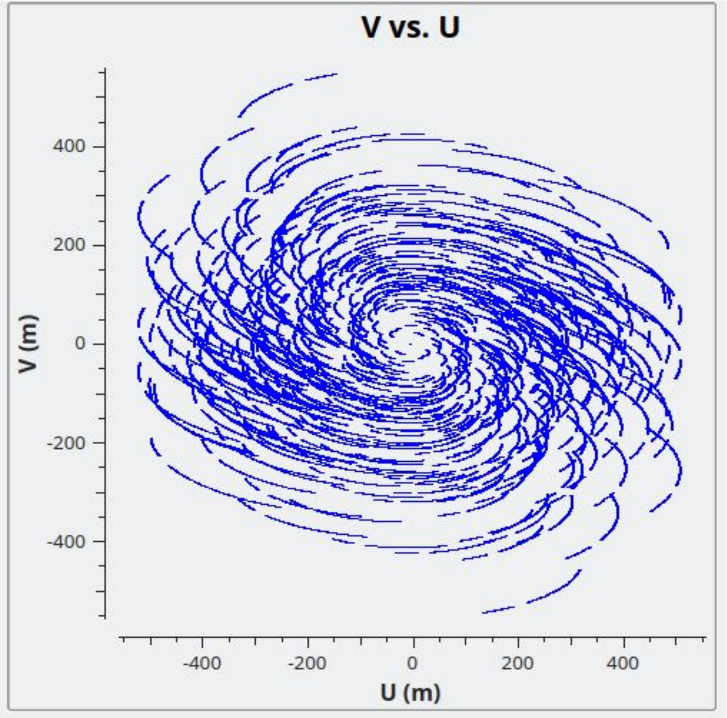
$$\implies 2\pi u(\lambda)_{\text{null}} l_{\text{radius}} = 3.8317$$

$$l_{\text{radius}} = \frac{3.8317(\lambda = 0.349 \text{ m})}{2\pi(u(m)_{\text{null}} = 50 \text{ m})}$$

$$\implies l_{\text{radius}} = 0.0042566 \text{ rads} = 14.63 \text{ arcmin}$$

Spot on! :-)

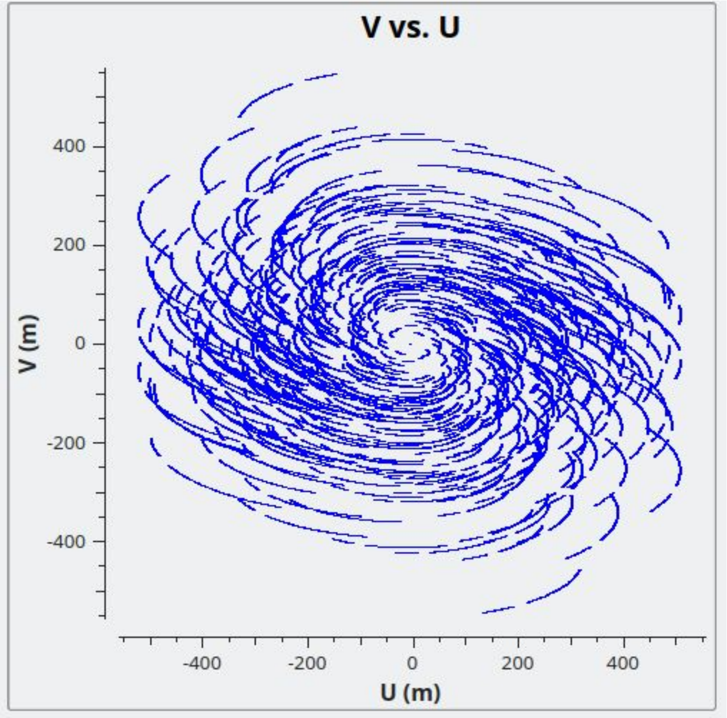
Imaging



- Left: aperture sampling function (uv) for this MeerKAT core measurement of the Moon.
- Outer samples set the highest spatial frequency sampled by the interferometer - finest scale structure
- Inner samples sets the largest spatial scale that the interferometer is sensitive to.
- Note: u,v=0 (DC) component is discarded -- correlated noise
- Nyquist (spatial) sampling rate sets the achievable resolution of the data - sampling should be higher than this (we will use factor 20, 5-10 will do):

$$
\begin{aligned}
\theta &\approx 1.22\lambda/uv_{\mathrm{max}} \\
&\approx 1.22 \times 0.349 \mathrm{~m}/550 \mathrm{~m} \\
&\approx 0.000774 \mathrm{~rads} = 2.66 \mathrm{~arcmin}
\end{aligned}
$$

Imaging



RA is an ill-posed inverse problem - the sampling function for the aperture is incomplete

We will make "Dirty" maps for now

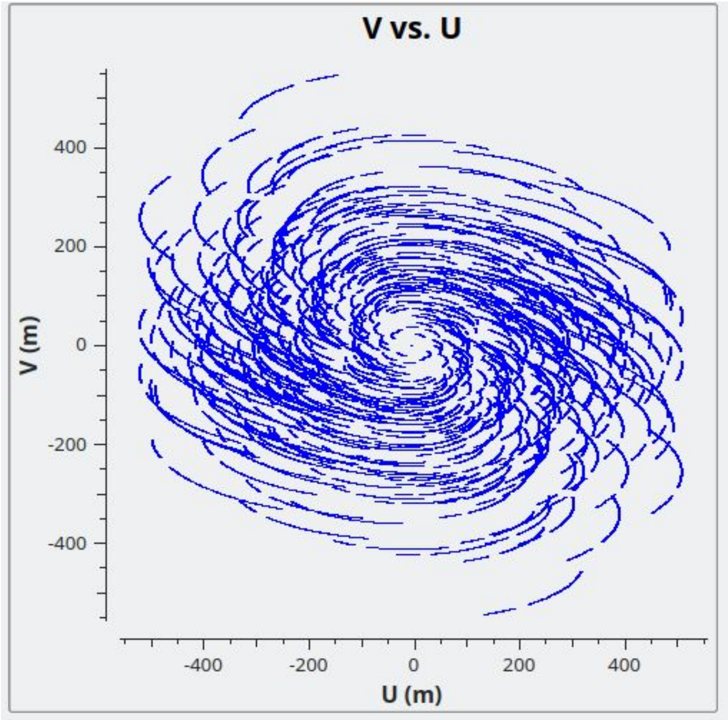
You will see deconvolution (ie. regularizing the problem - and introducing priors!) later this week

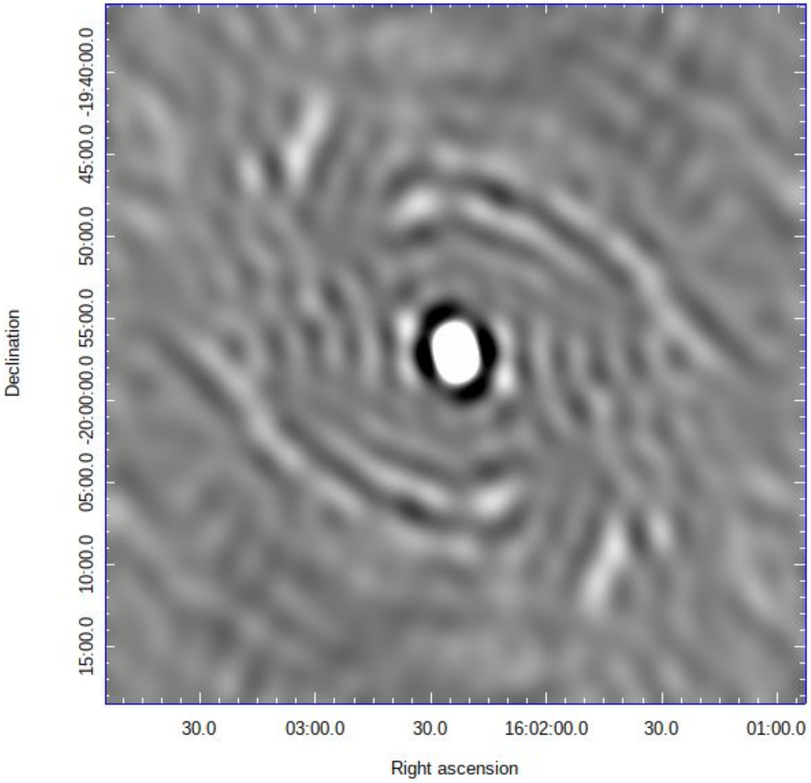
$$V(u, v, w = 0) \approx \int_{2\pi} I(l, m) \exp\left(-2i\pi/\lambda[ul + vm]\right) dl dm$$

$$\text{Let } \bar{V}(u, v) := V(u, v) \cdot S(u, v)$$

$$\underset{\mathcal{F}}{\Longrightarrow} \quad \bar{I}(l, m) = I(l, m) * \mathrm{PSF}(l, m)$$

Example PSF for the Moon

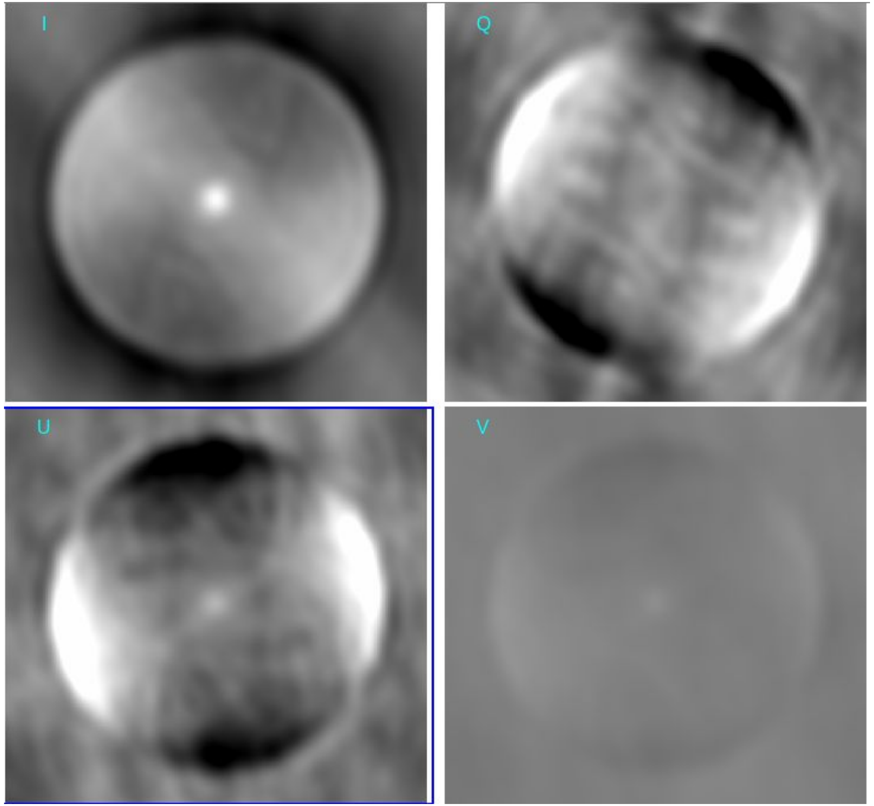




Imaging

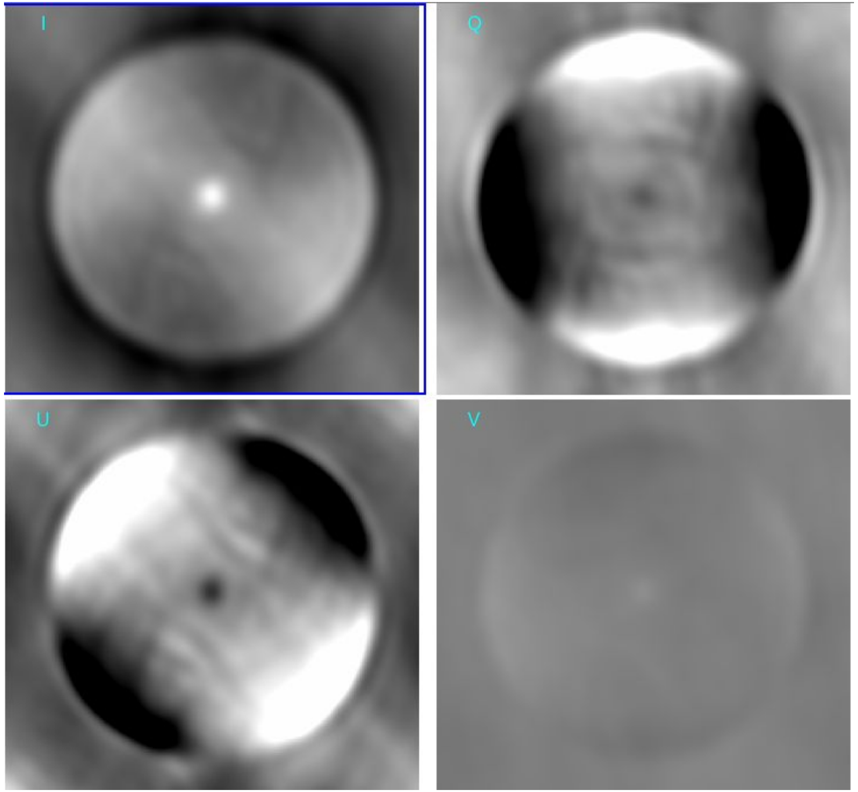
- clean(vis='moon_uhf.ms', field='Moon', imagename="Moon.noHVphase", imsize=[512], cell=["5arcsec"], stokes="IQUV", weighting='briggs', robust=0.0, facets=3, niter=0)
- exportfits(imagename='Moon.noHVphase.image', fitsimage='Moon.noHVphase.image.fits')
- Open with your favorite FITS viewer

The Moon (no parallactic angle derotation of Q and U)



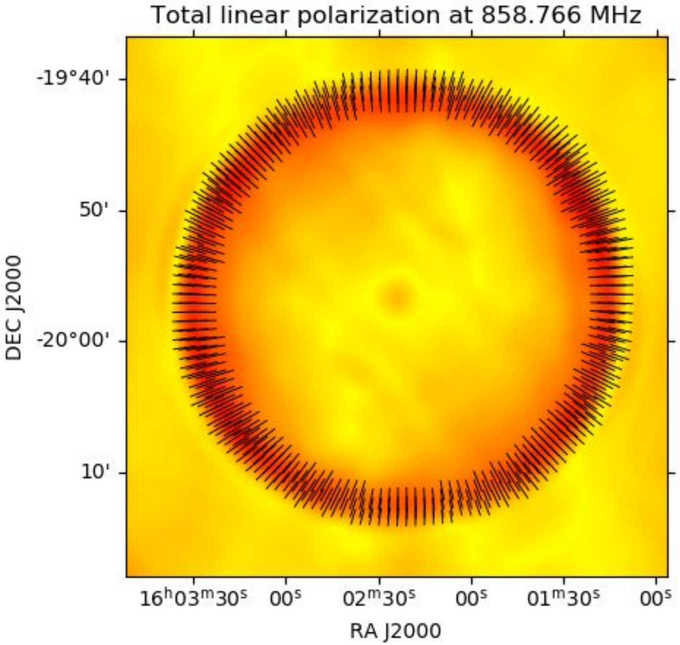
- Q,U,V locked to the same scale
- Aside from the (expected) misalignment of the polarization angle (Q should be positive/white towards positive declination and negative/black east) the handedness does appear to go north->east here
- Induced V is not substantial for this receiver in UHF, however it can be much more substantial (50%+ one some receivers). It can still be improved by several fold as we will see later!
- Let's additionally apply P Jones next to take out the parallactic angle, now that we know the handedness "goes the right way around". WARNING: this is not the case for S-band receivers and some UHF receivers due to phasing!
- applycal(vis='moon_uhf.ms', field='Moon', gaintable=['bp.K','sec.Gp','bp.Ga','bp.B','sec.T','bp.Df'], parang=True)
- clean(vis='moon_uhf.ms', field='Moon', imagename="Moon.noHVphase.parang", imsize=[512], cell=["5arcsec"], stokes="IQUV", weighting='briggs', robust=0.0, facets=3, niter=0)
- exportfits(imagename='Moon.noHVphase.parang.image', fitsimage='Moon.noHVphase.parang.image.fits')

The Moon (with parallactic angle derotation)



- Nearly spot on! +Q vertical towards NCP at PA=0, -Q horizontal towards east
- Notice V hasn’t changed - the P Jones matrix hasn’t influenced it at all? Exercise to the reader - apply P X P^T where P is a 2x2 Euclidean rotation matrix and convince yourself that V should not be influenced!

The Moon (with parallactic angle derotation)



- Left: Linear (radially polarized) polarization angles overlaid on total linear polarization raster map
- Towards the edge of the limb the Moon is polarized 30+%!
- The vectors here are very well aligned - very quiescent ionosphere (more about that later)
- Up next: HV phase calibration

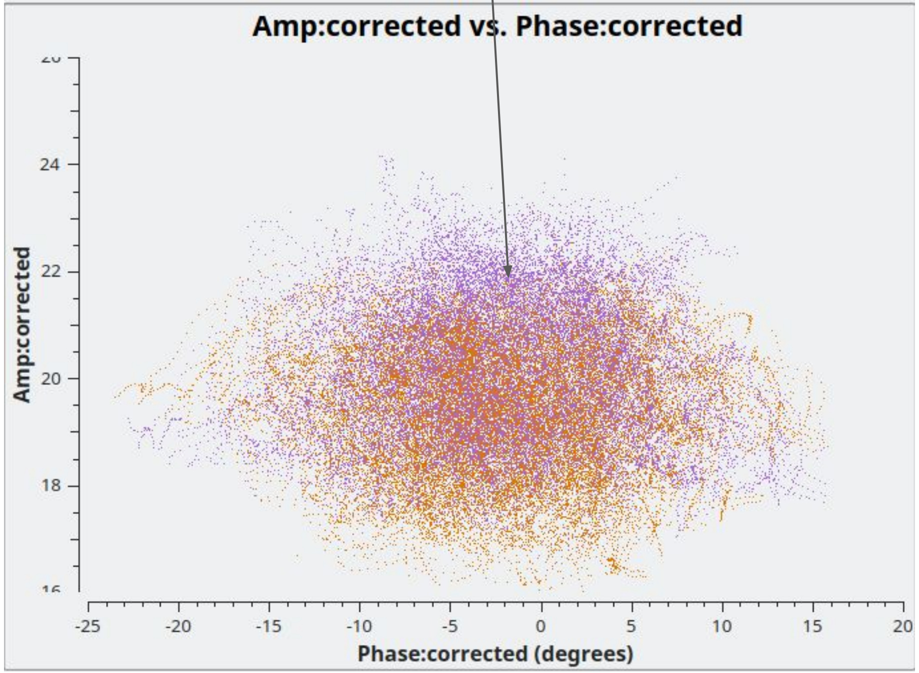
Polcal - calibrating the HV phase

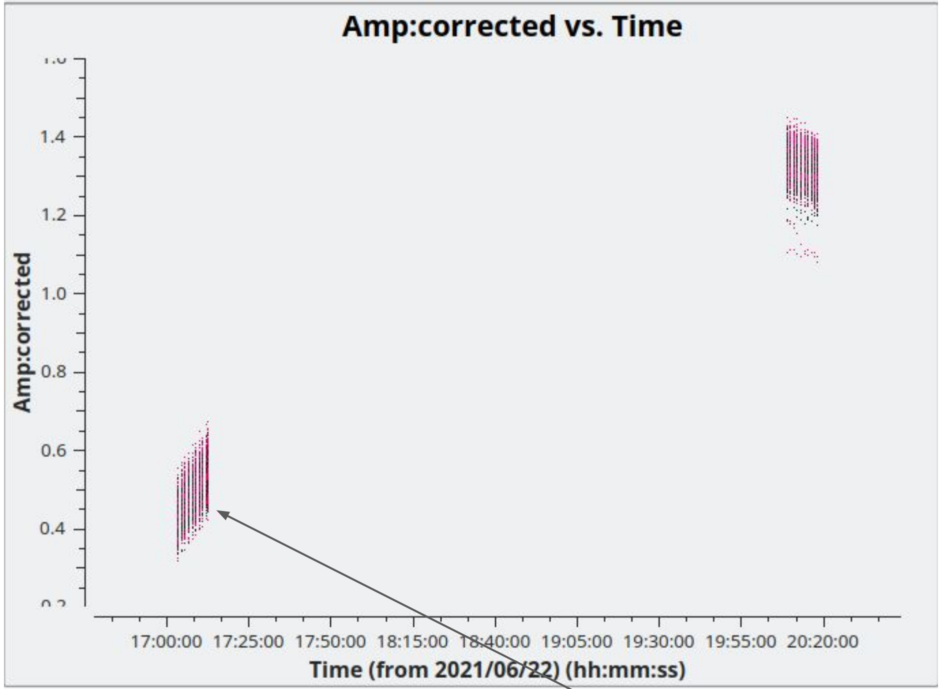
- We must now correct for the ellipticity in the MeerKAT feeds. For this we need a polarized source, e.g. 3C286 or noise diode injected signals (via Bill Cotton's Obit calibration suite) to calibrate this first order effect out.
- First we must refine the phase on 3C286
- Note: 3C286 starts being resolved at higher frequencies (S) with the longer spacings, but as we don't have those here we can safely assume it is point like. It is ideal to self-calibrate the phase component of 3C286 at cadences finer than scan level before solving for the ambiguous HV phase here, but we will do a rough calibration for now.
- We start by bootstrapping with the phase of the primary and then refine the phase, for now we leave the parallactic angle unapplied
- (!) Pitfall: When the parallactic angle is close to -30 for this source there is no power on XY* and YX* correlations (U+/-iV) so those scans should be deselected in your solving step. You should plan your observations with sufficient short scans on 3C286 to cover a reasonably wide range of parallactic angles so that you are assured of instantaneous power on U to solve for the ambiguous HV phase!! The MeerKAT OPT will help you plan

Pre-calibration inspection

- Let’s check the amp x phase and also look at the time variability due to (mainly parallactic angle and ionosphere) on the crosshand correlations XY* and YX* - ideally they should be precisely the same and not time variable AFTER we apply HV phase and parallactic angle (modulo ionospheric RM)
  - applycal(vis='moon_uhf_calibrators.ms', field='J1331+3030', gaintable=['bp.K','bp.Gp','bp.Ga','bp.B','sec.T','bp.Df'])
  - plotms(vis='moon_uhf_calibrators.ms', xaxis='phase', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XX,YY', coloraxis='corr', uvrange=">1m", avgtime='300', field='J1331+3030')
  - plotms(vis='moon_uhf_calibrators.ms', xaxis='time', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XY,YX', coloraxis='corr', uvrange=">1m", avgchannel='9999999', field='J1331+3030')

Phase needs refining (first)

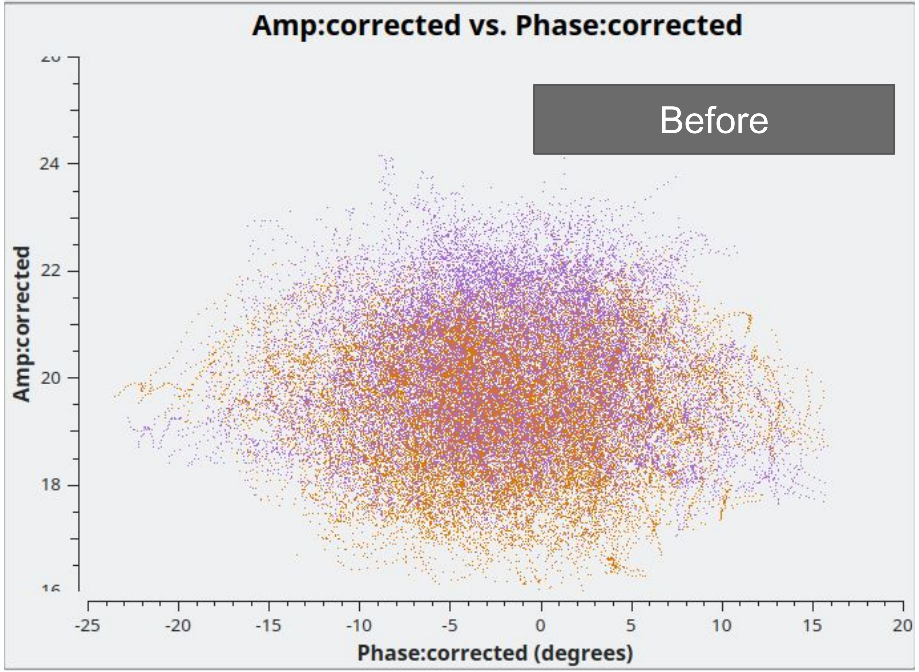


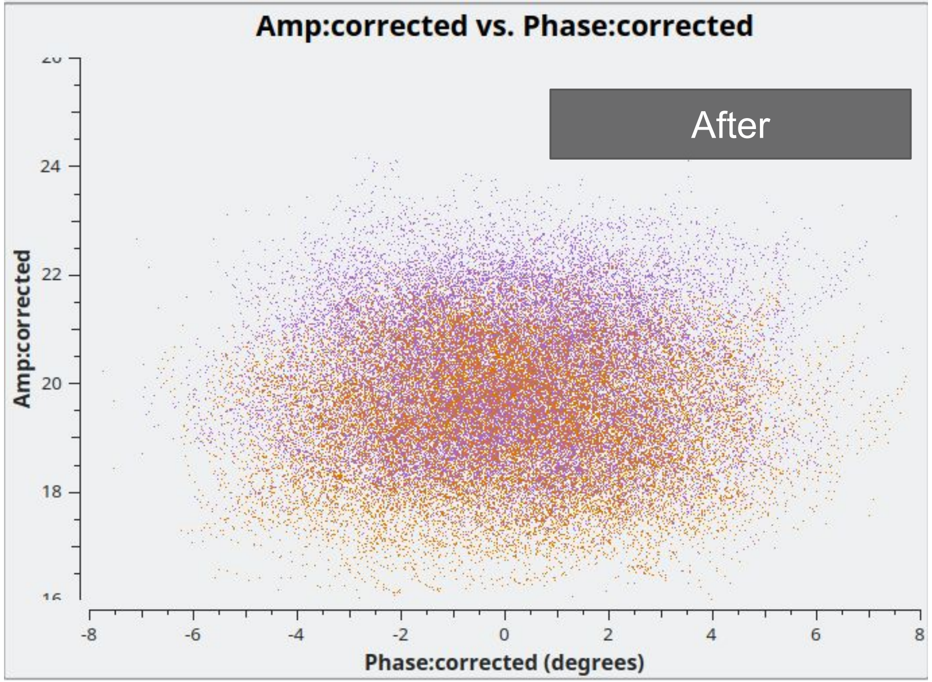


Crosshand (XY*,YX*) power is low in the first scan due to parallactic angle

Phase refinement: 3C286

- Let’s refine the phase -- obviously this source is quite polarized (10% at L-band dropping to <2% at the bottom of UHF at 600MHz).
- (!!) IMPORTANT: MAKE SURE YOU CALIBRATE ONLY THE PHASE --- otherwise you will absorb the source's unmodelled polarization into your transfer solutions and bias your entire target field as a result!
    - gaincal(vis='moon_uhf_calibrators.ms', caltable='pol.Gp', field='J1331+3030', gaintype='G', calmode='p', solint='inf', combine='',refant='m002', gaintable=['bp.K', 'bp.Ga', 'bp.B', 'bp.Df'])
    - applycal(vis='moon_uhf_calibrators.ms', field='J1331+3030', gaintable=['bp.K','pol.Gp','bp.Ga','bp.B','sec.T','bp.Df'])



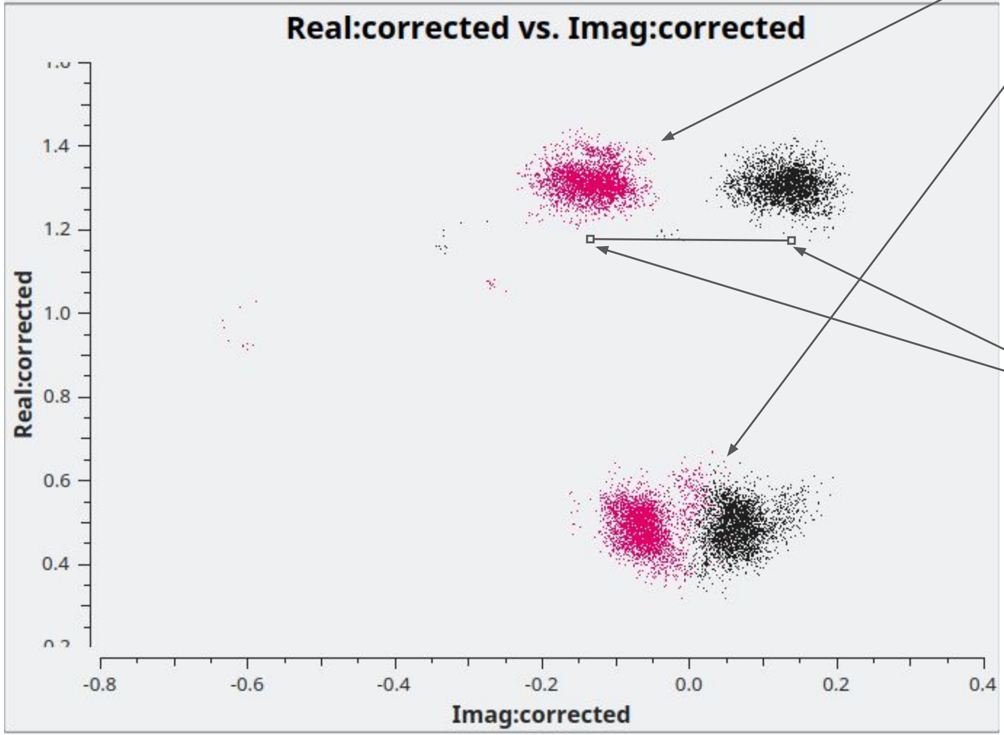


We can further refine this phase through self calibration (and I leave this as an exercise to the reader!) which is especially important on wideband data, but let's continue solving for the HV phase here. Before we do let’s closely look at the crosshands

Now for the HV phase

- 3C286 is a quasar with a polarized jet. Generally speaking these strong quasars are not circularly polarized (notably things like pulsars and solar flares can be highly circularly polarized -- BEWARE!)
- We therefore expect the crosshands to be real-value dominated for this strong pointlike object at phase centre. The imaginary component is a good estimate therefore of the receiver systems' induced ellipticity
  - plotms(vis='moon_uhf_calibrators.ms', xaxis='imag', yaxis='real', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XY,YX', coloraxis='corr', uvrange=">1m", avgchannel='9999999', field='J1331+3030')

XY* and YX*



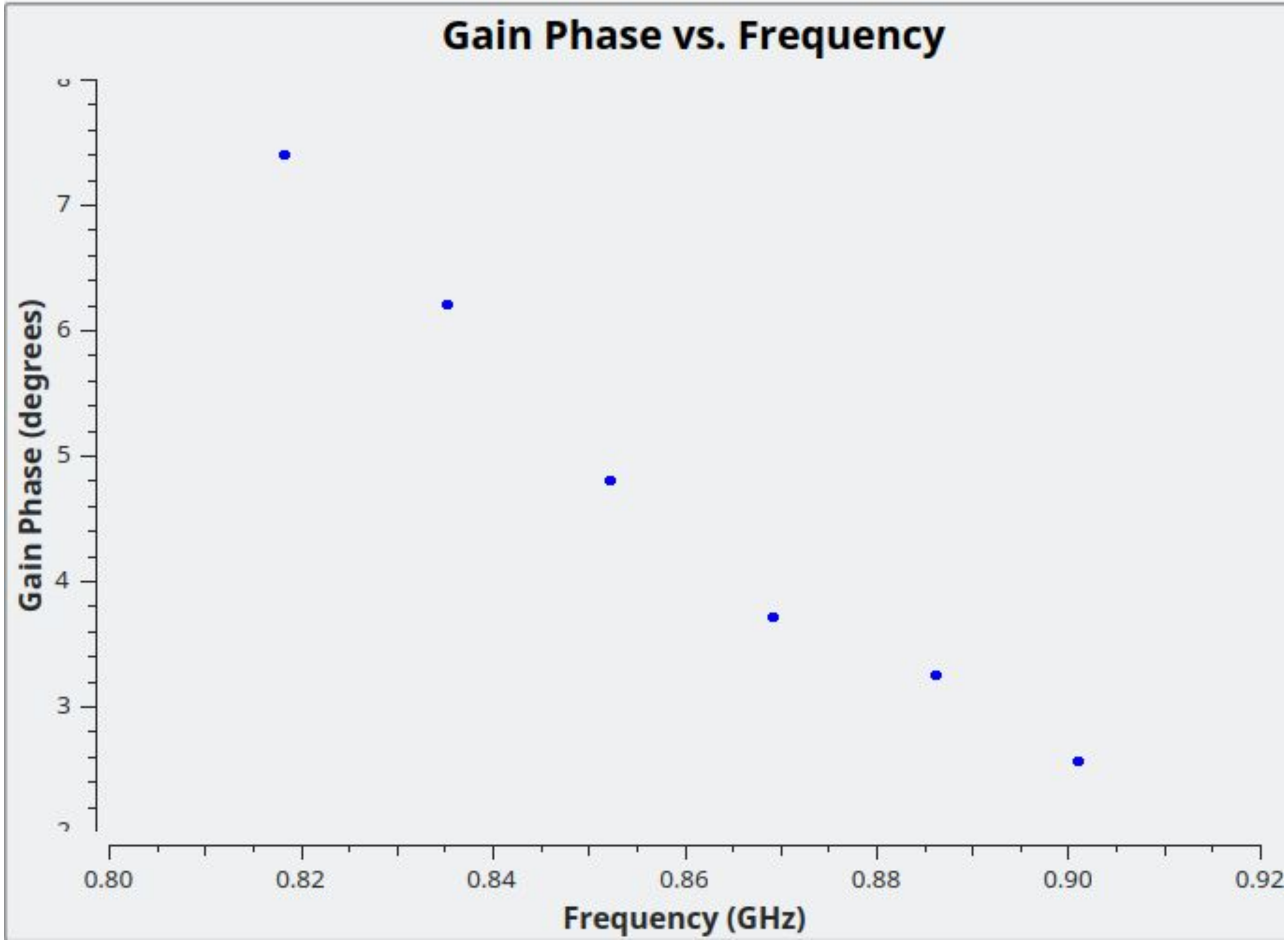
In colour: the (conjugate) U +/- iV
The change in real axis is due to the uncorrected parallactic angle

The spread in the imaginary component for this compact source (ie. +/- iV) indicates that the receiver impedance between X and Y is inducing ellipticity to (what should be) a plane polarized wave

Calibrating the crosshand phase

- There is fractional V Stokes being picked up here -- the goal is to remove that!
- Underneath the hood we take arctan2(V/U) here, assuming V~=0 Jy
- We can also solve for a crosshand delay (mode KCROSS in gaincal). This is necessary at lower ranges in UHF especially due to SNR concerns but this frequency dependent slope is stable at few ps level so we will just absorb it into crosshand phase (Xf) solutions here
- We combine scans to increase SNR on the crosshand phase here and solve for a coarse frequency dependent solution, for the same reason.
- WARNING: these solutions are very sensitive to unflagged RFI!
    - polcal(vis='moon_uhf_calibrators.ms', field='J1331+3030', caltable='pol.Xf', refant='m002', gaintable=['bp.K','pol.Gp','bp.Ga','bp.B'], combine='scan', poltype='Xf', solint='inf,20MHz')
    - plotms(vis='pol.Xf', xaxis='freq', yaxis='phase')
    - Should see a few tens of picosecond phase slope (very stable with time)

```
INFO    polcal::::
INFO    polcal::::+     ##########################################
INFO    polcal::::+     ##### Begin Task: polcal             #####
INFO    polcal::::      polcal(vis="moon_uhf_calibrators.ms",caltable="pol.Xf",field="J1331+3030",spw="",intent="",
INFO    polcal::::+             selectdata=True,timerange="",uvrange="",antenna="",scan="",
INFO    polcal::::+             observation="",msselect="",solint="inf,20MHz",combine="scan",preavg=300.0,
INFO    polcal::::+             refant="m002",minblperant=4,minsnr=3.0,poltype="Xf",smodel=[],
INFO    polcal::::+             append=False,docallib=False,callib="",gaintable=['bp.K', 'pol.Gp', 'bp.Ga', 'bp.B'],gainfield=[''],
INFO    polcal::::+             interp=[],spwmap=[])
INFO    polcal::calibrater::open        ****Using NEW VI2-driven calibrater tool****
INFO    polcal::calibrater::open        Opening MS: moon_uhf_calibrators.ms for calibration.
INFO    polcal::Calibrater::    Initializing nominal selection to the whole MS.
INFO    polcal::::      NB: polcal automatically excludes auto-correlations.
INFO    calibrater::setdata     Beginning selectvis--(MSSelection version)-------
INFO    calibrater::reset       Reseting solve/apply state
INFO    Calibrater::selectvis   Performing selection on MeasurementSet
INFO    Calibrater::selectvis+   Selecting on field: 'J1331+3030'
INFO    Calibrater::selectvis+   Selecting with TaQL: 'ANTENNA1!=ANTENNA2'
INFO    Calibrater::selectvis   By selection 25688 rows are reduced to 5520
INFO    Calibrater::selectvis   Frequency selection: Selecting all channels in all spws.
INFO    calibrater::setdata     chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect='ANTENNA1!=ANTENNA2'
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO             (K Jones: Enforcing calWt()=false for phase/delay-like terms)
INFO    Calibrater::setapply(type, applypar)    .   K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   G Jones: table=pol.Gp select= interp=linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO    calibrater::setapply    Beginning setapply--(MSSelection version)-------
INFO    Calibrater::setapply(type, applypar)    Arranging to APPLY:
INFO    Calibrater::setapply(type, applypar)    .   P Jones <pre-computed>
INFO    calibrater::setsolve    Beginning setsolve--(MSSelection version)-------
INFO    Calibrater::setsolve    Arranging to SOLVE:
INFO            .   (Ignoring specified refant for Xf Jones solve.)
INFO    Calibrater::setsolve    .   Xf Jones: table=pol.Xf append=false solint=inf,20MHz refantmode='flex' refant='none' minsnr=3 apmode=AP solnorm=false
INFO    calibrater::solve       Beginning solve-----------------------------
INFO    Calibrater::solve       The following calibration terms are arranged for apply:
INFO    Calibrater::solve       .   B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO    Calibrater::solve       .   K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO    Calibrater::solve       .   G Jones: table=pol.Gp select= interp=linear spwmap=[-1] calWt=true
INFO    Calibrater::solve       .   G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO    Calibrater::solve       .   P Jones <pre-computed>
INFO    Calibrater::solve       The following calibration term is arranged for solve:
INFO    Calibrater::solve       .   Xf Jones: table=pol.Xf append=false solint=inf,20MHz refantmode='flex' refant='none' minsnr=3 apmode=AP solnorm=false
INFO             Frequency solint parsing:
INFO            .  Spw 0:  (freq solint: 2e+07 Hz) / (data width: 4.25e+06 Hz) = 4 data channels per solution channel.
INFO    ChannelAverageTVI::parseConfiguration   Channel bin is [4]
INFO    Calibrater::solve       For solint = inf, found 1 solution intervals.
INFO            Mean CROSS-HAND PHASE solution for J1331+3030 (spw = 0) = 4.65 deg.
INFO    Calibrater::solve         Found good Xf Jones solutions in 1 solution intervals.
INFO            Writing solutions to table: pol.Xf
INFO    calibrater::solve       Finished solving.
INFO    polcal::::      ##### End Task: polcal               #####
INFO    polcal::::+     ##########################################
```

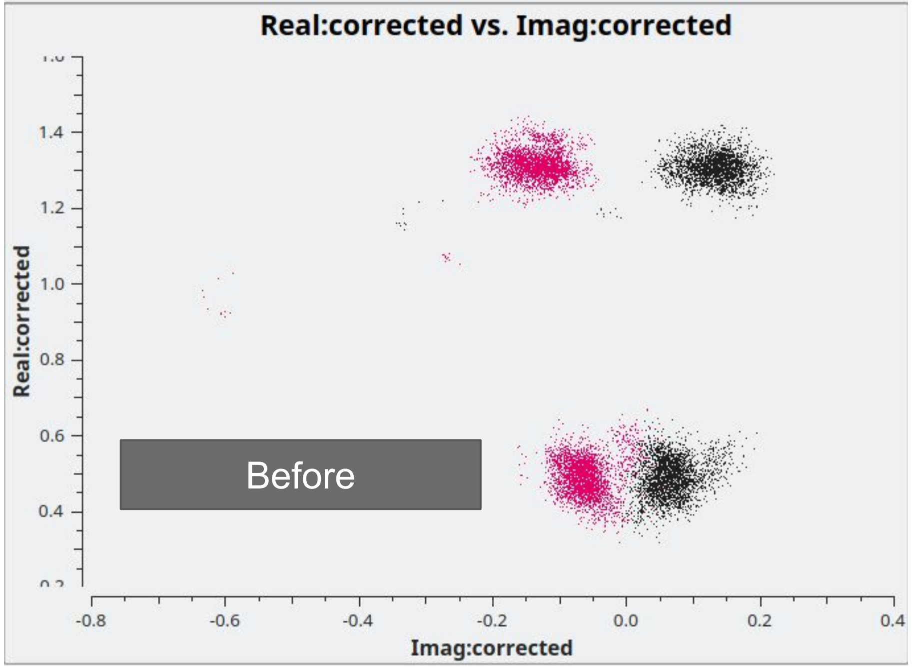


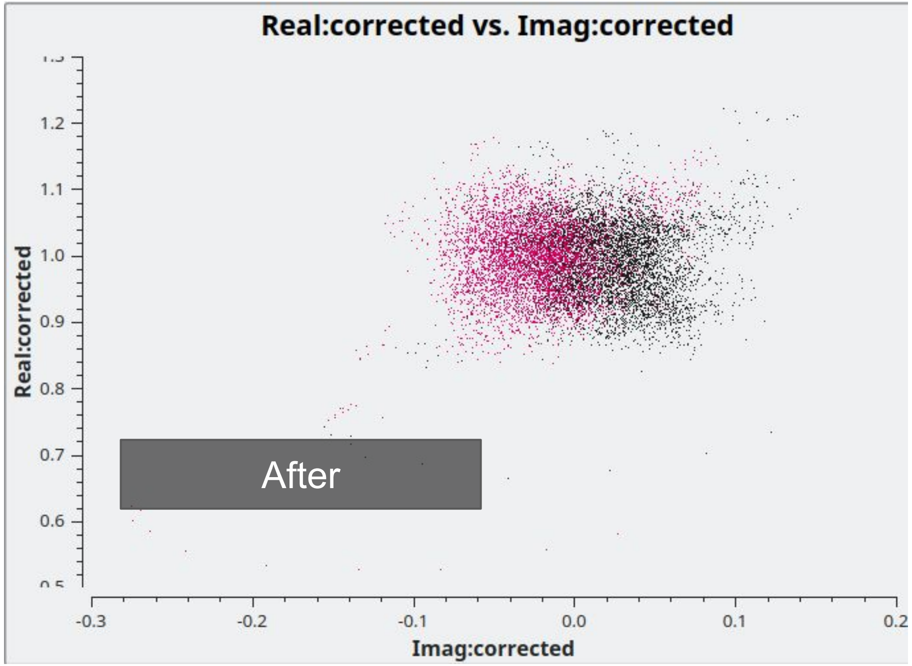
Gain Phase vs. Frequency
Gain Phase (degrees)
8
7
6
5
4
3
2
0.80
0.82
0.84
0.86
0.88
0.90
0.92
Frequency (GHz)

HV phase: The proof is in the eating!

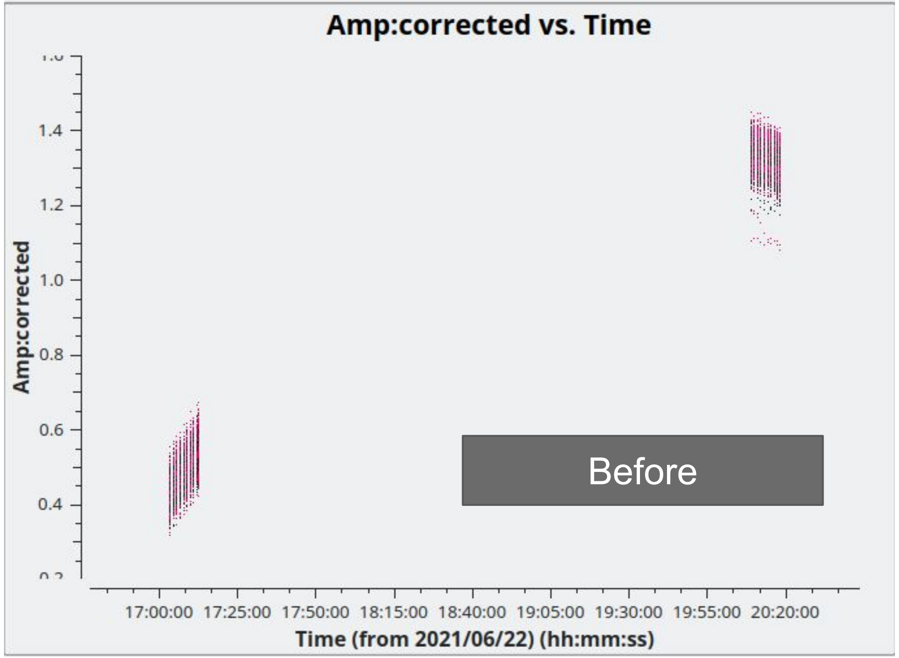
- Apply and inspect the net result on 3C286, time variability should be mostly gone (modulo ionosphere) and real-dominated as discussed
    - applycal(vis='moon_uhf_calibrators.ms', field='J1331+3030', gaintable=['bp.K','pol.Gp','bp.Ga','bp.B','sec.T','bp.Df','pol.Xf'], parang=True)
    - plotms(vis='moon_uhf_calibrators.ms', xaxis='imag', yaxis='real', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XY,YX', coloraxis='corr', uvrange=">1m", avgchannel='9999999', field='J1331+3030')
    - plotms(vis='moon_uhf_calibrators.ms', xaxis='time', yaxis='amplitude', xdatacolumn='corrected', ydatacolumn='corrected', correlation='XY,YX', coloraxis='corr', uvrange=">1m", avgchannel='9999999', field='J1331+3030')
- All that is left is transfer of the full chain onto the Moon and verifying that the V goes down on the Lunar maps!

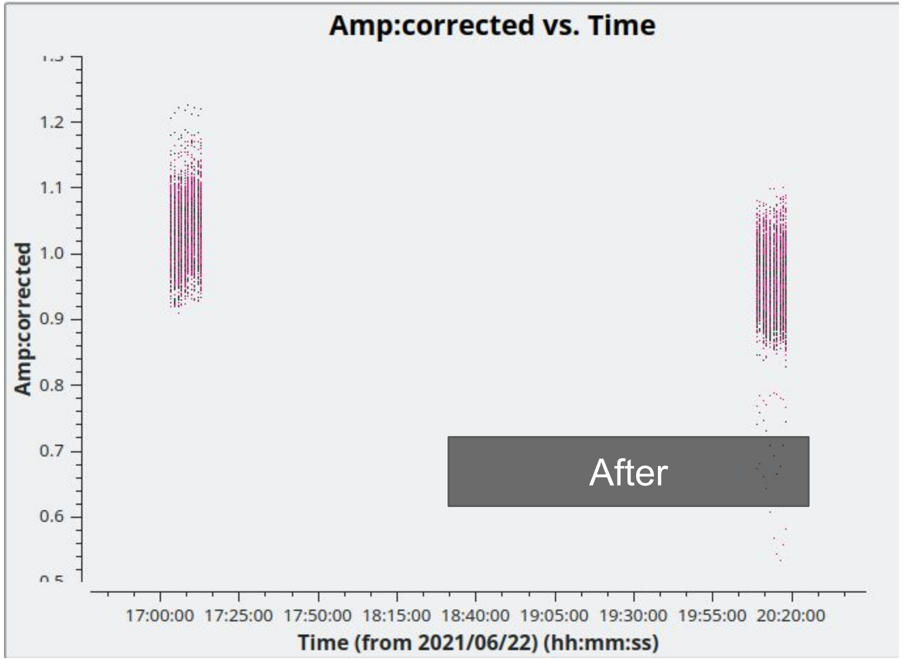
HV phase: The proof is in the eating!





3C286: Application of parallactic angle

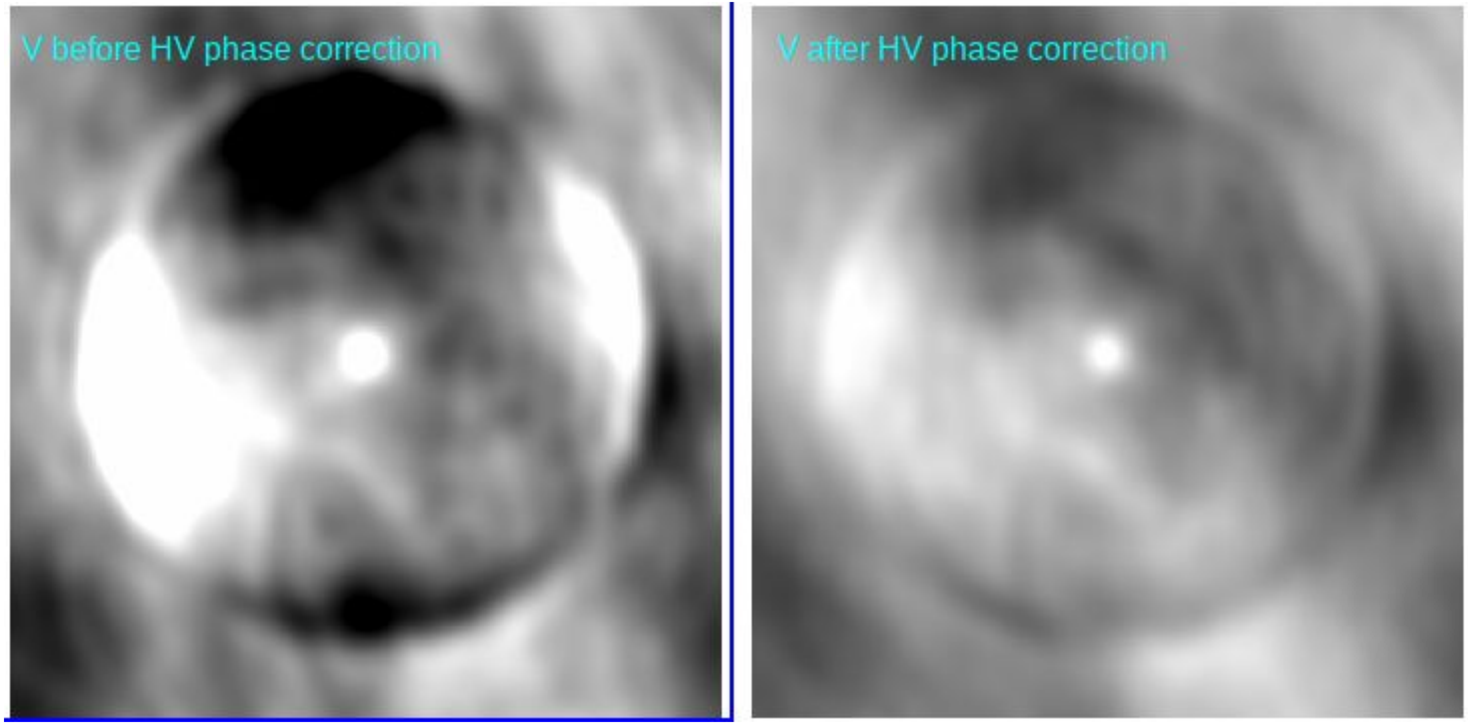




Finally!

- All that is left is transfer of the full chain onto the Moon and verifying that the V goes down on the Lunar maps!
  - applycal(vis='moon_uhf.ms', field='Moon', gaintable=['bp.K','sec.Gp','bp.Ga','bp.B','sec.T','bp.Df','pol.Xf'], parang=True)
  - clean(vis='moon_uhf.ms', field='Moon', imagename="Moon.HVphase.parang", imsize=[512], cell=["5arcsec"], stokes="IQUV", weighting='briggs', robust=0.0, facets=3, niter=0)
  - exportfits(imagename='Moon.HVphase.parang.image', fitsimage='Moon.HVphase.parang.image.fits')
- Depending on the impedence on the refant this ellipticity can be more than half the signal of U so it is one of the more important terms to calibrate!
- Additional terms to correct is ionospheric spatio-temporal variability (must be done per target, not inferring variability on 3C286, which is low on the horizon).

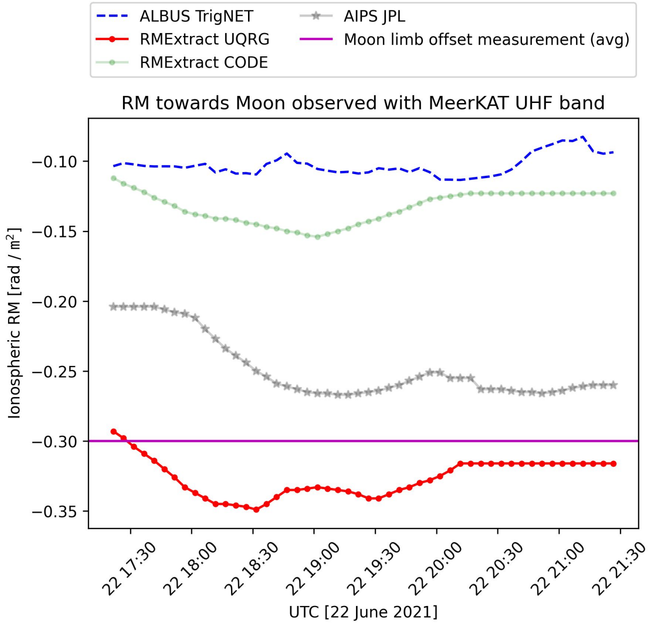
Improvement in V (scale locked)



Ionosphere

- Included in the repo is two text files containing the GNSS predicted RM measurements for the Moon and 3C286. I leave it as an exercise to you to plot these
- I show to the right a comparison of the ionosphere as measured from the offset of the linear polarization of the Lunar limb, compared to various International GNSS Service-derived models and models derived locally from TrigNET using ALBUS
- The ionosphere was markedly quiescant! This is not always the case - you should check these measurements carefully for your observations. Strong diurnal effects may be present day to night! These can offset your polarization angles by many 10s of degrees at the low part of UHF (-5 to -6 rad/m^2 is common)!

Check out: https://github.com/twillis449/ALBUS_ionosphere



Questions?