

*Footprint in the dust of the Moon
Captured by Apollo 11 astronaut Edwin Aldrin
AS11-40-5878 NASA*



POLARIZATION WALKTHROUGH IN CASA

Africalim, 2024

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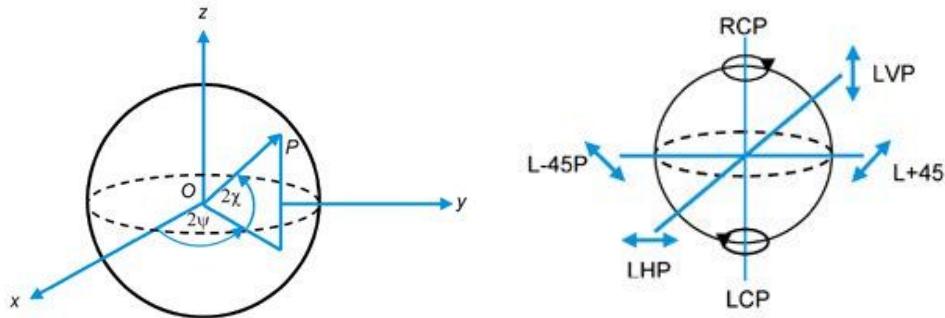
What we will cover (and recap)

- 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

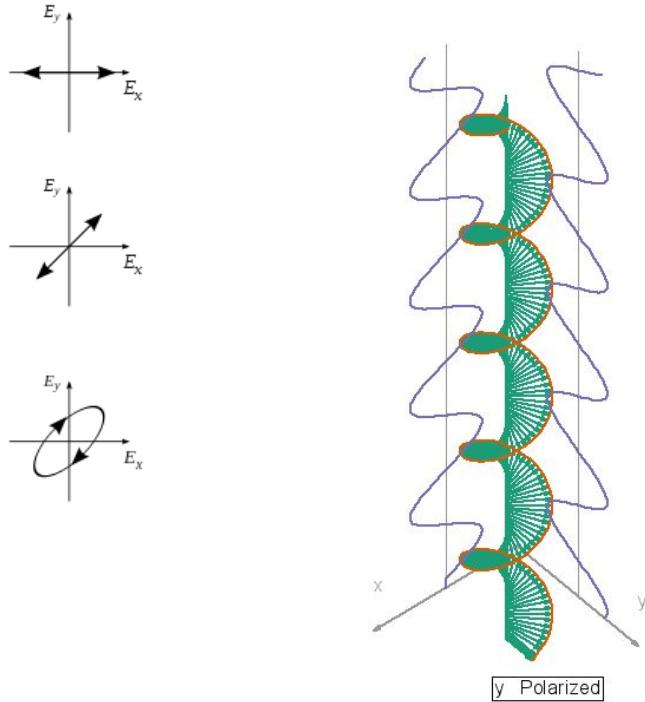


Polarization states - a recap

- 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):



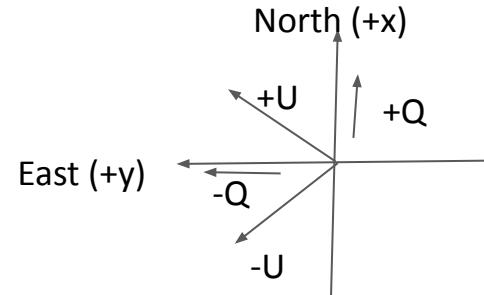
Poincaré description of polarization vector ellipse
[Field Guide to Polarization](#)



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:



$$I = 0.5 \langle e_{px} e_{qx}^* + e_{py} e_{qy}^* \rangle$$

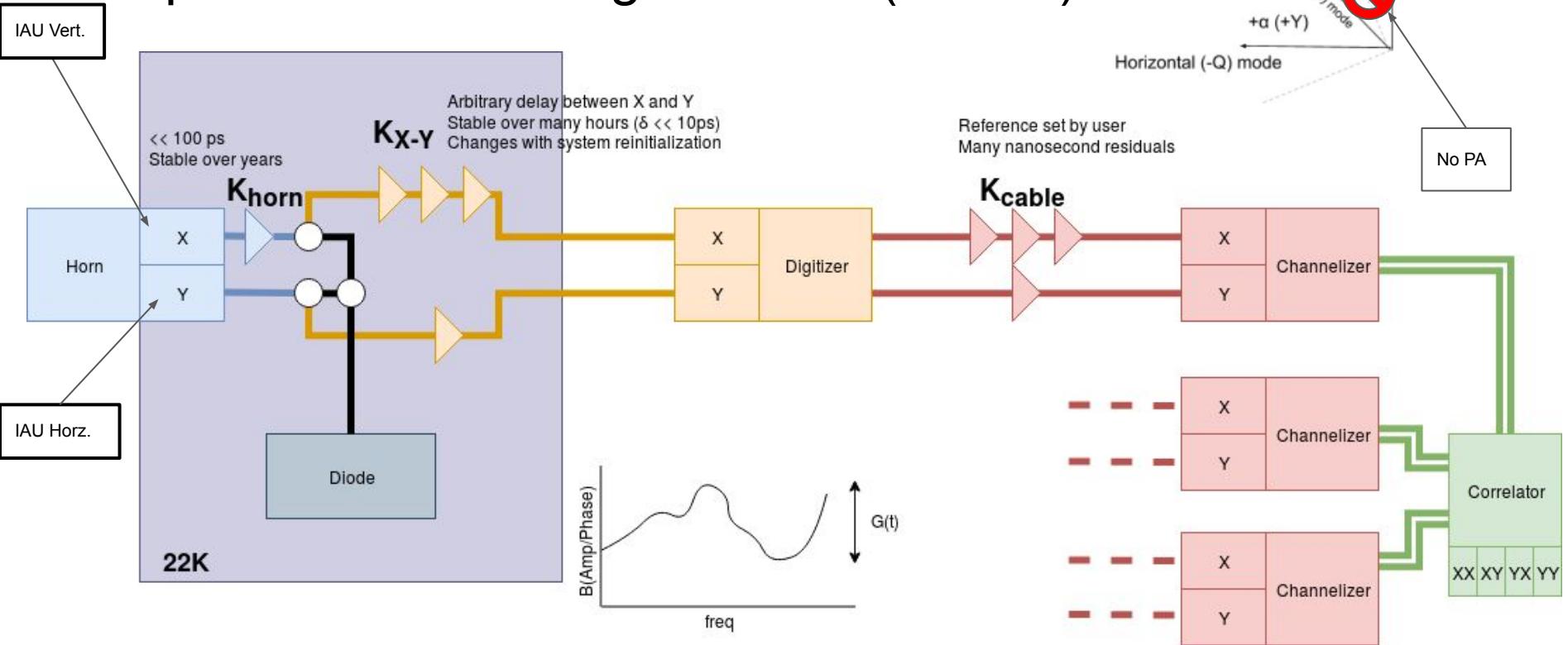
$$Q = 0.5 \langle e_{px} e_{qx}^* - e_{py} e_{qy}^* \rangle$$

$$U = 0.5 \langle e_{px} e_{qy}^* + e_{py} e_{qx}^* \rangle$$

$$V = \mp 0.5i \langle e_{px} e_{qy}^* - e_{py} e_{qx}^* \rangle$$

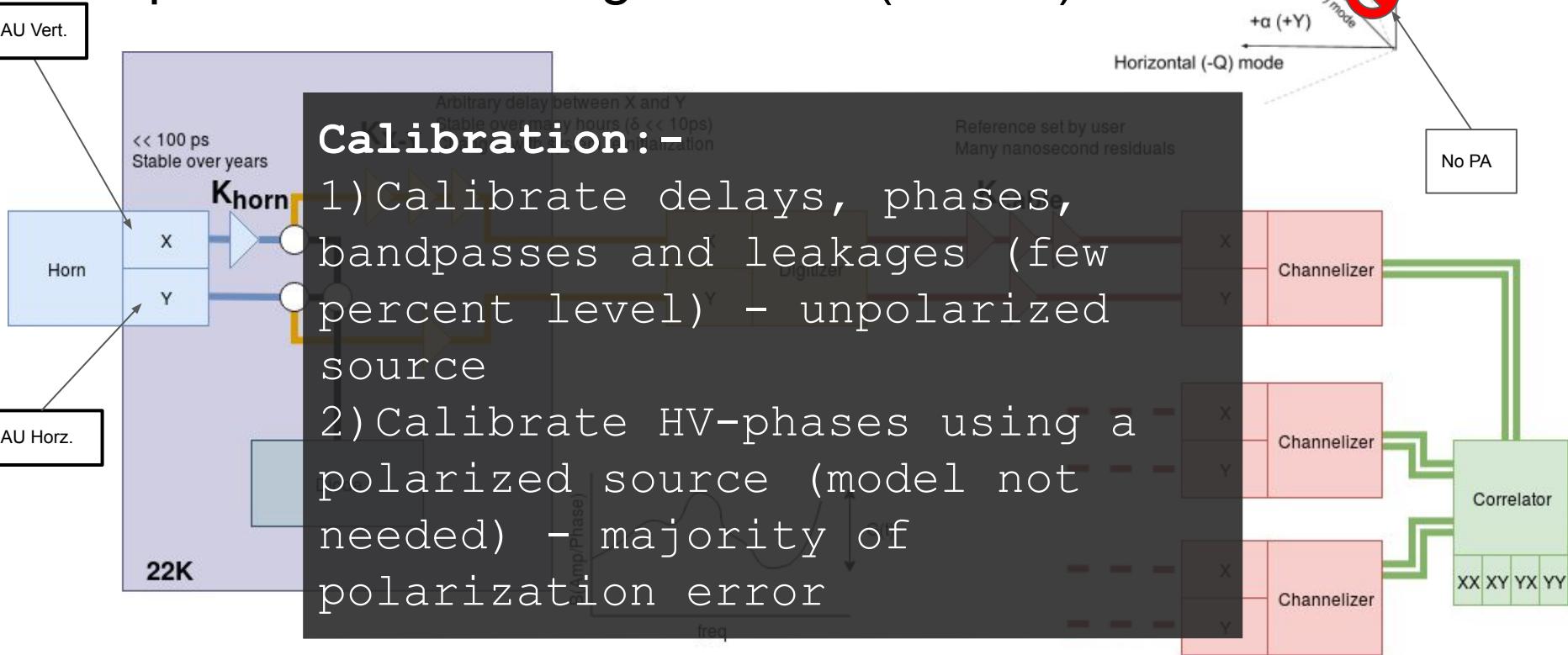
See Hamaker and Bregman (1996)

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)



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.

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

$\underbrace{\mathbf{J}_N \dots \mathbf{J}_1}_{\text{J}} E$



Robert Jones

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

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

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)

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

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



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

Radio Interferometric Measurement Equation

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Cable delay

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

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



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

Radio Interferometric Measurement Equation

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Temporal variable
gain

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

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



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

Radio Interferometric Measurement Equation

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Bandpass (OMT)

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

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



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

Radio Interferometric Measurement Equation

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

Crosshand phase delay

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

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



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

Radio Interferometric Measurement Equation

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

Leakage (non-orthogonality)

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

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



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

Radio Interferometric Measurement Equation

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Antenna response

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

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



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

Radio Interferometric Measurement Equation

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

Parallactic angle (alt-az mount)

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

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



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

Radio Interferometric Measurement Equation

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. It relates the measured field towards a source at cosines l, m

Geometric delay (scalar matrix)

$$e^{2i\pi(\vec{b}_i \cdot (\vec{s} - \vec{s}_0)) / \lambda}$$

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

$$\mathbf{V}_{pq,\text{measured}} = < \mathbf{E}_{p,\text{measured}} \mathbf{E}_{q,\text{measured}}^H >$$

$$= \mathbf{J}_p < E_p E_q^H > \mathbf{J}_q^H$$



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

The Jones family

$d \ll 1$

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

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)

$$\begin{bmatrix} e^{i\theta(\nu,t)} & 0 \\ 0 & 1 \end{bmatrix} \begin{bmatrix} \cos \Psi & -\sin \Psi \\ \sin \Psi & \cos \Psi \end{bmatrix} \begin{bmatrix} \cos(RM\nu^{-2}) & -\sin(RM\nu^{-2}) \\ \sin(RM\nu^{-2}) & \cos(RM\nu^{-2}) \end{bmatrix}$$

Crosshand phase

ParAng (linear)

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) :-

$$X_p X_q^* = (I + Q_\Psi) + U_\Psi(d_{Xp} + d_{Xq}^*)$$

$$X_p Y_q^* = [(U_\Psi + iV) + I(d_{Xp} + d_{Yq}^*) - Q\Psi(d_{Xp} - d_{Yq}^*)] e^{i\rho}$$

$$Y_p X_q^* = [(U_\Psi - iV) + I(d_{Yp} + d_{Xq}^*) + Q\Psi(d_{Yp} - d_{Xq}^*)] e^{-i\rho}$$

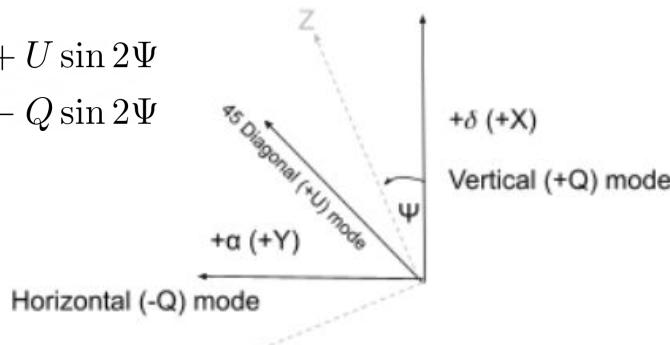
$$Y_p Y_q^* = (I - Q_\Psi) + U_\Psi(d_{Yp} - d_{Xq}^*)$$

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

Psi: Parallactic angle

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

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



Leakages (~few %)

(!) 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)

$$V_{XX} = (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi (d_{Xi} + d_{Xj}^*)$$

$$V_{XY} = [(\mathcal{U}_\psi + i\mathcal{V}) + \mathcal{I}(d_{Xi} + d_{Yj}^*) - \mathcal{Q}_\psi(d_{Xi} - d_{Yj}^*)] e^{i\rho}$$

$$V_{YX} = [(\mathcal{U}_\psi - i\mathcal{V}) + \mathcal{I}(d_{Yi} + d_{Xj}^*) + \mathcal{Q}_\psi(d_{Yi} - d_{Xj}^*)] e^{-i\rho}$$

$$V_{YY} = (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi (d_{Yi} + d_{Yj}^*)$$

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*

$$V_{XX} = (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi (d_{Xi} + d_{Xj}^*)$$

$$V_{XY} = [(\mathcal{U}_\psi + i \mathcal{V}) + \mathcal{I} (d_{Xi} + d_{Yj}^*) - \mathcal{Q}_\psi (d_{Xi} - d_{Yj}^*)] e^{i\rho}$$

$$V_{YX} = [(\mathcal{U}_\psi - i \mathcal{V}) + \mathcal{I} (d_{Yi} + d_{Xj}^*) + \mathcal{Q}_\psi (d_{Yi} - d_{Xj}^*)] e^{-i\rho}$$

$$V_{YY} = (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi (d_{Yi} + d_{Yj}^*)$$

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)

$$V_{XX} = (\mathcal{I} + \mathcal{Q}_\psi) + \mathcal{U}_\psi (d_{Xi} + d_{Xj}^*)$$

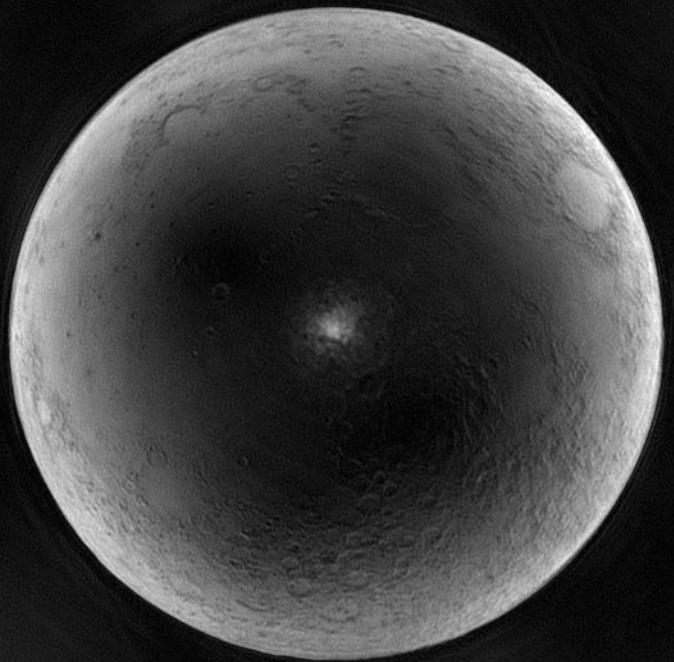
$$V_{XY} = \left[(\mathcal{U}_\psi + i\mathcal{V}) + \mathcal{I} (d_{Xi} + d_{Yj}^*) - \mathcal{Q}_\psi (d_{Xi} - d_{Yj}^*) \right] e^{i\rho}$$

$$V_{YX} = \left[(\mathcal{U}_\psi - i\mathcal{V}) + \mathcal{I} (d_{Yi} + d_{Xj}^*) + \mathcal{Q}_\psi (d_{Yi} - d_{Xj}^*) \right] e^{-i\rho}$$

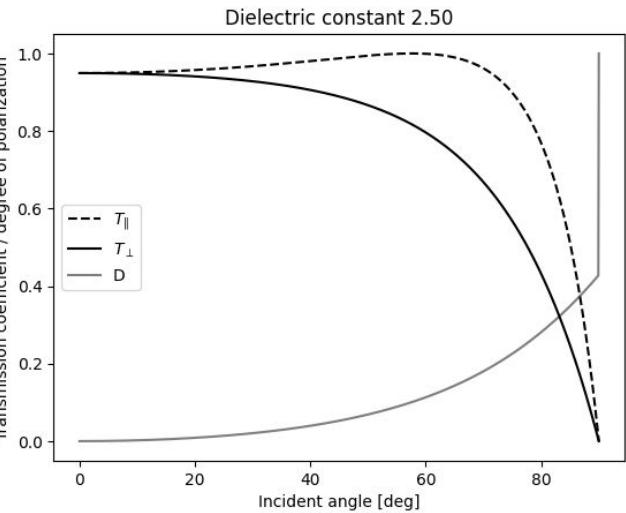
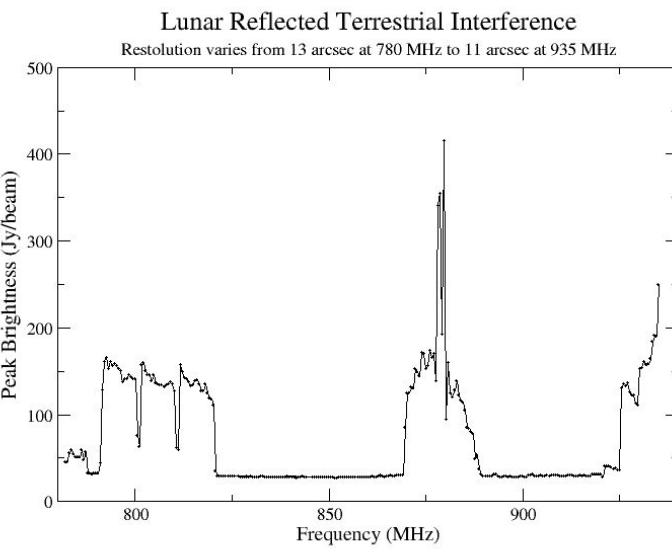
$$V_{YY} = (\mathcal{I} - \mathcal{Q}_\psi) + \mathcal{U}_\psi (d_{Yi} + d_{Yj}^*)$$

Switch to back to unpolarized source (V_{xy} and V_{yx}) consist purely of residual leakage (off diagonal D Jones)

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

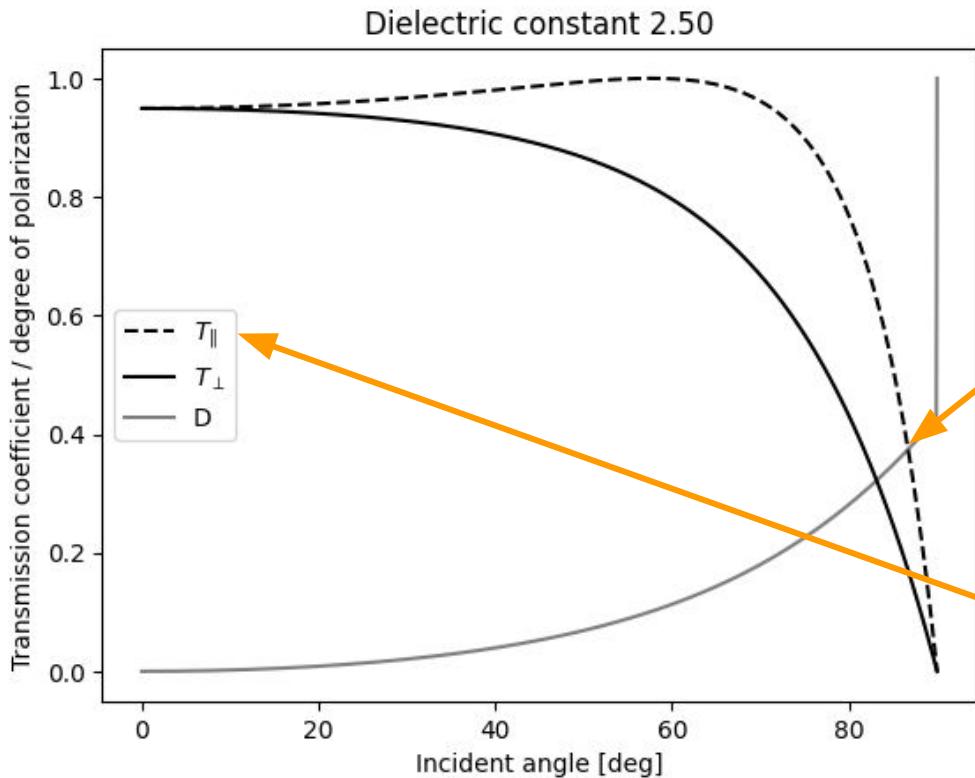


Moon - Total Linear Polarization
815.7 MHz (MeerKAT UHF band) (2021/06/22)



The polarized Moon

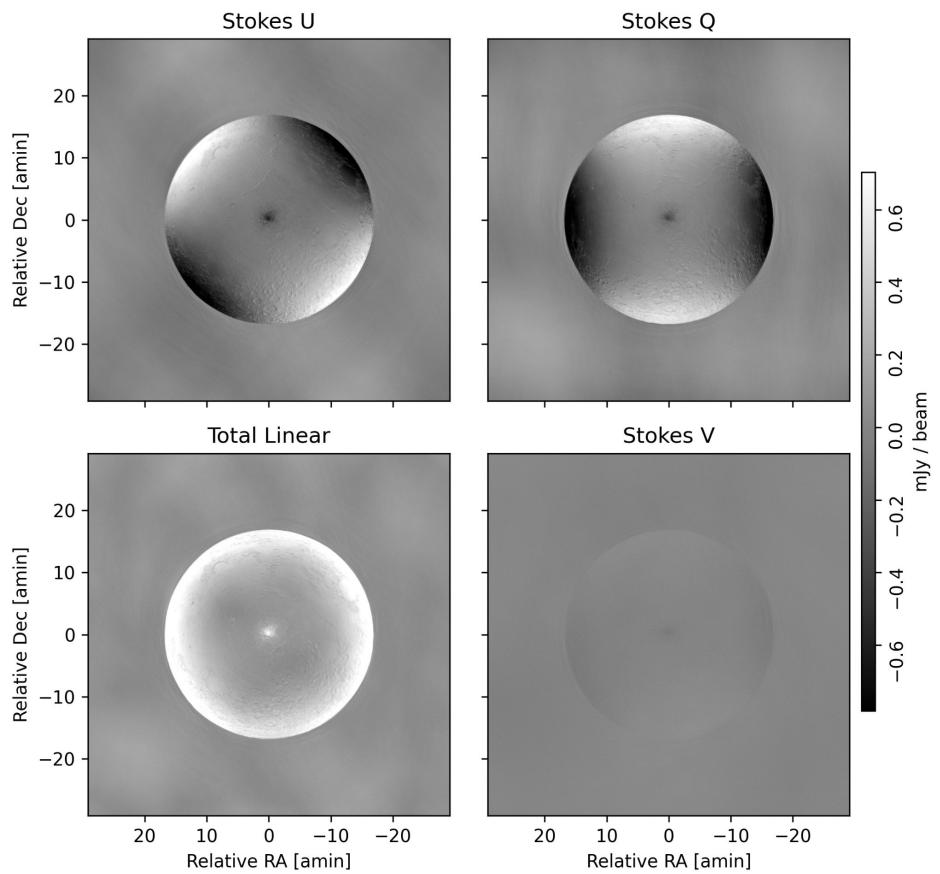
Most light refracted through surface regolith



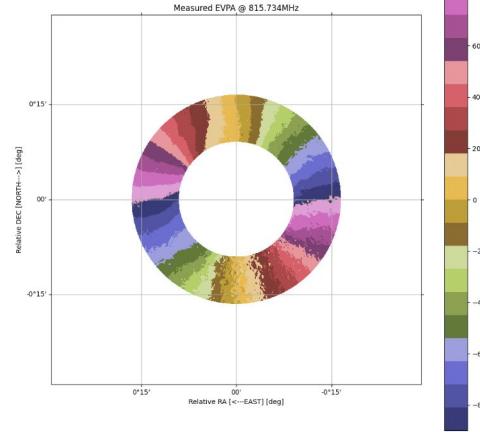
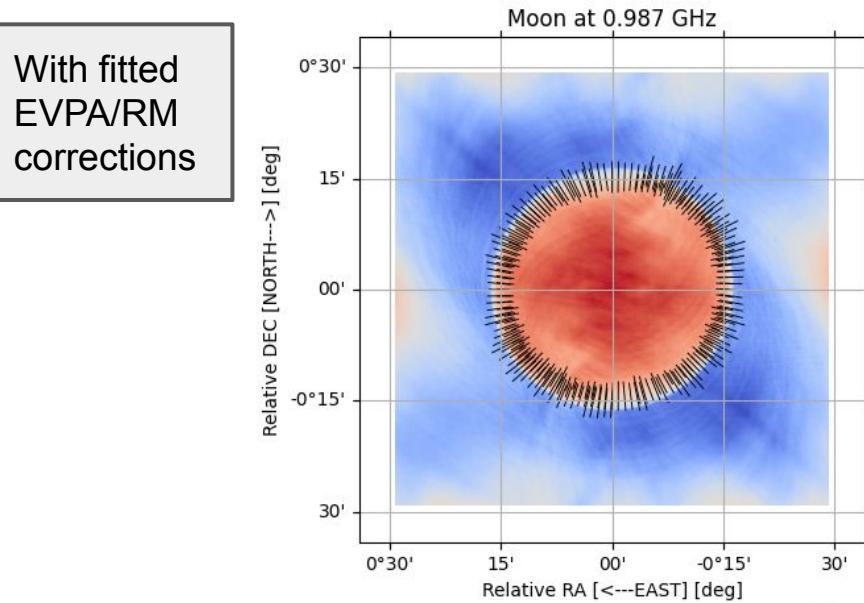
$$R_{\perp}(\theta_i) = \left| \frac{\cos \theta_i - \sqrt{\epsilon - \sin^2 \theta_i}}{\cos \theta_i + \sqrt{\epsilon - \sin^2 \theta_i}} \right|^2$$
$$R_{\parallel}(\theta_i) = \left| \frac{\epsilon \cos \theta_i - \sqrt{\epsilon - \sin^2 \theta_i}}{\epsilon \cos \theta_i + \sqrt{\epsilon - \sin^2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

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

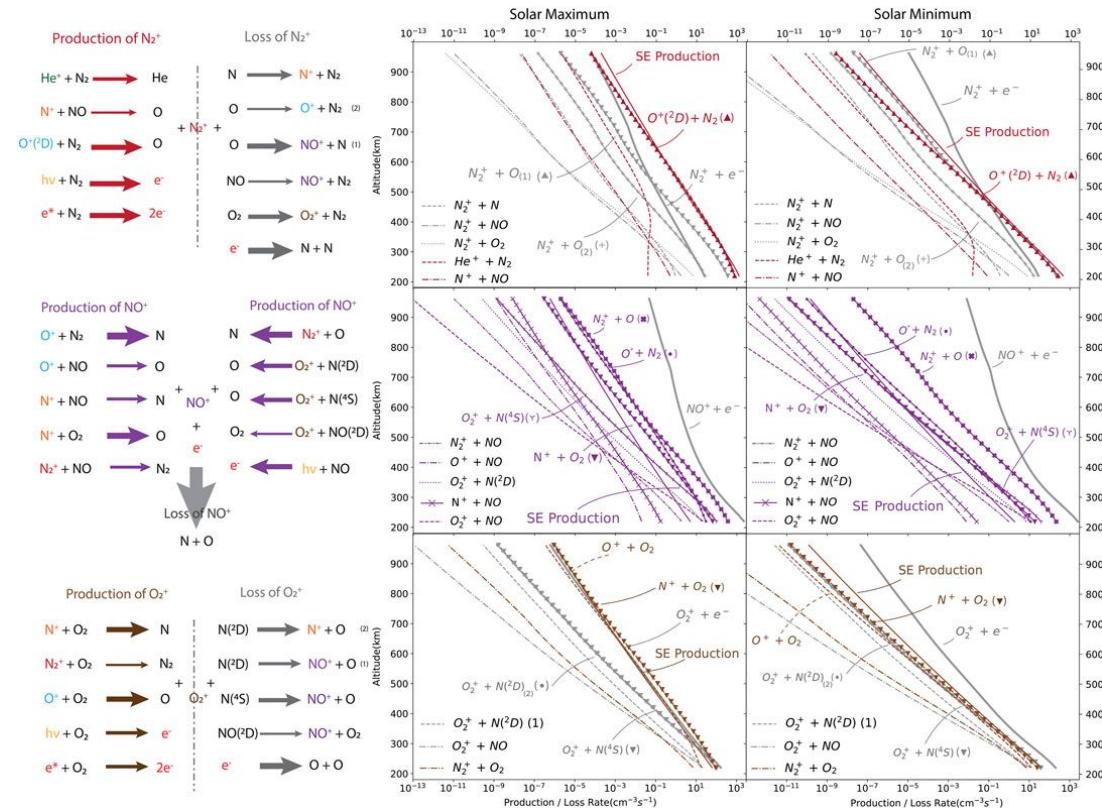
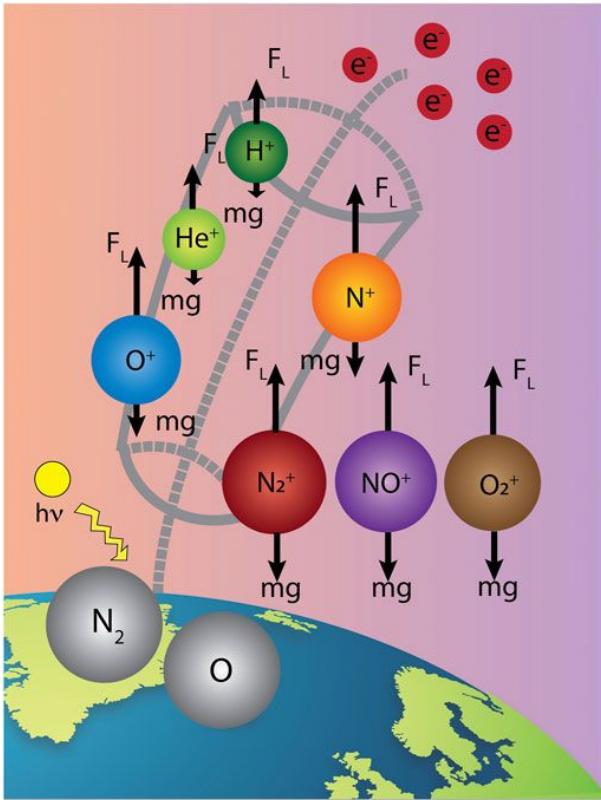
Radial component dominant



(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.)

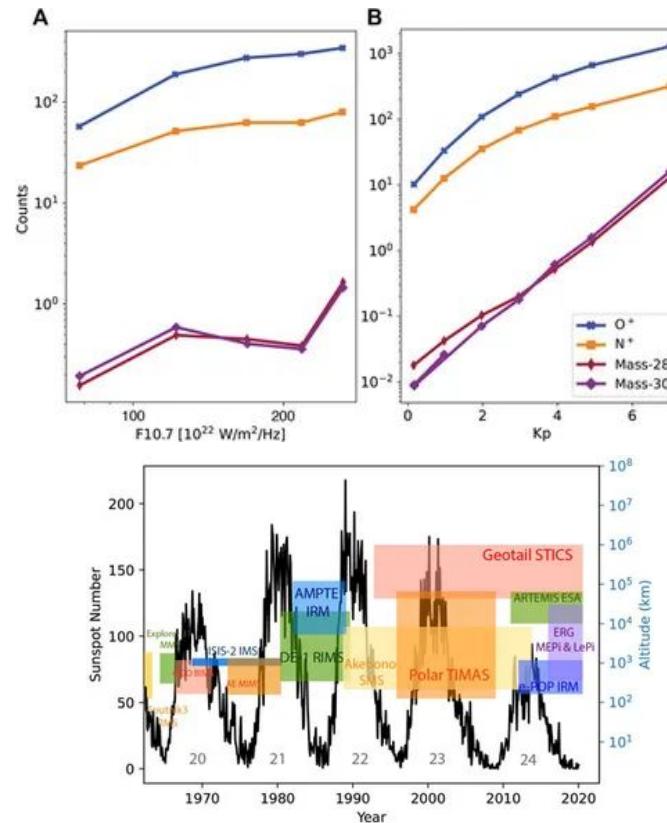
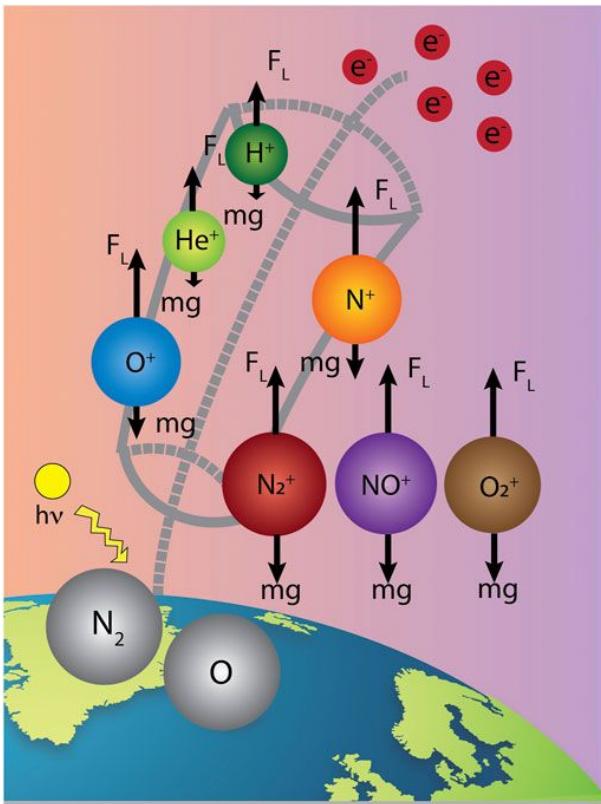


What about the ionosphere?

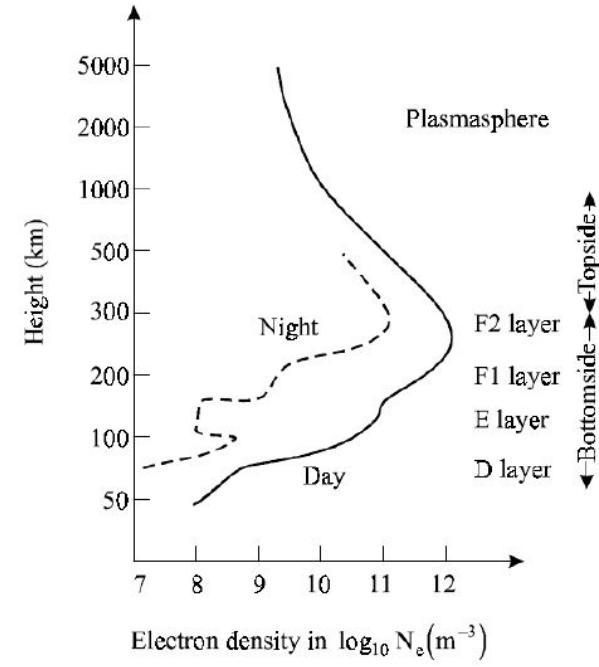
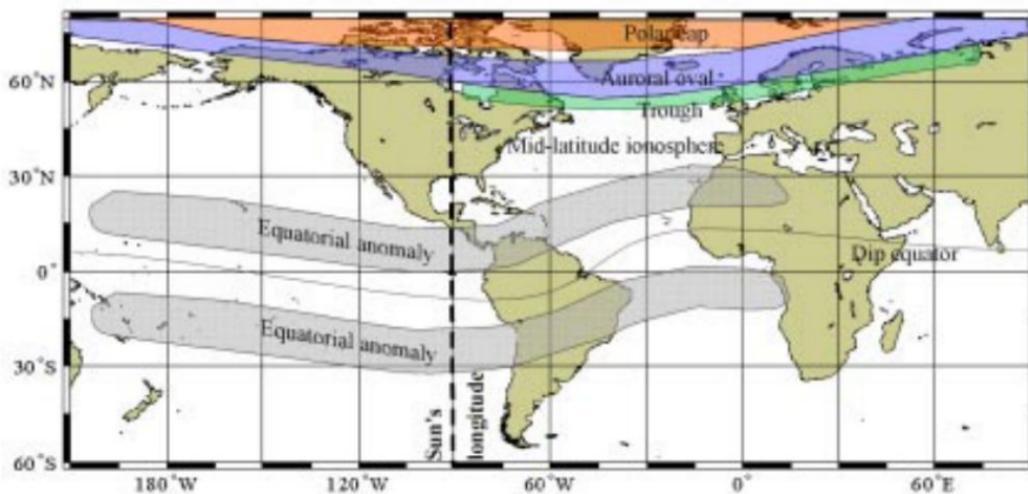


What about the ionosphere?

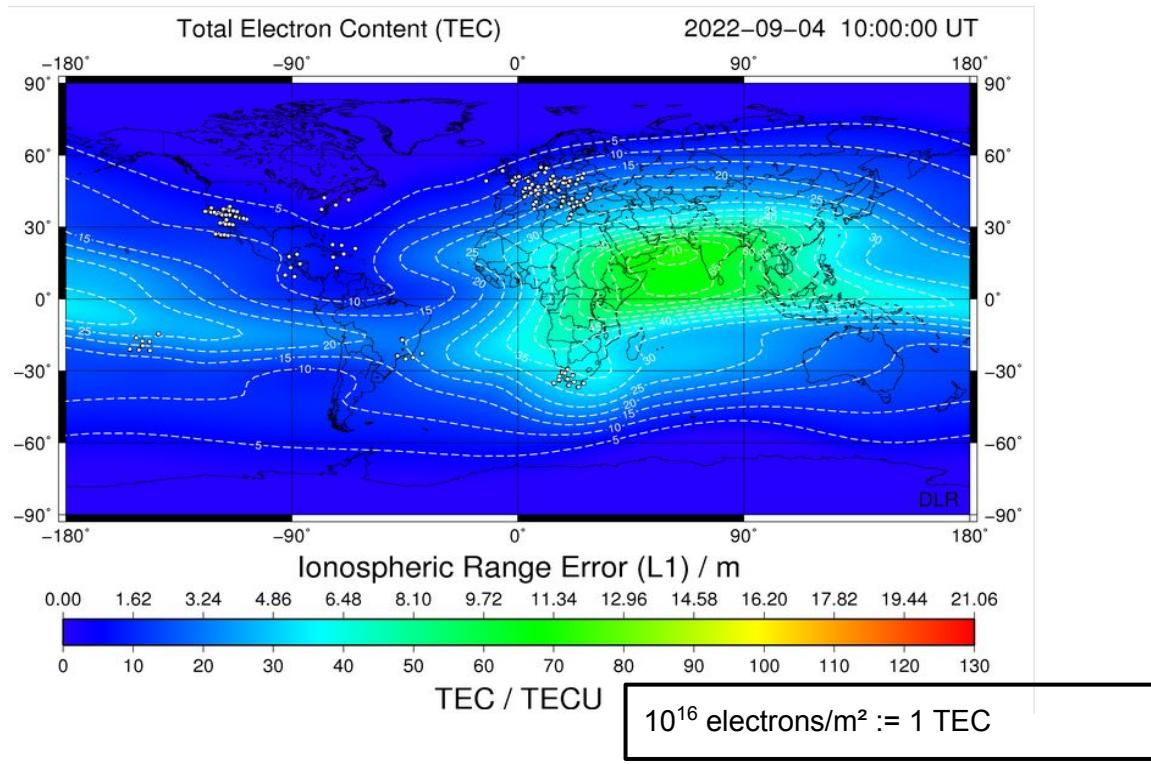
Lin & Llie (2022)



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 ("K_p" 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.



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.

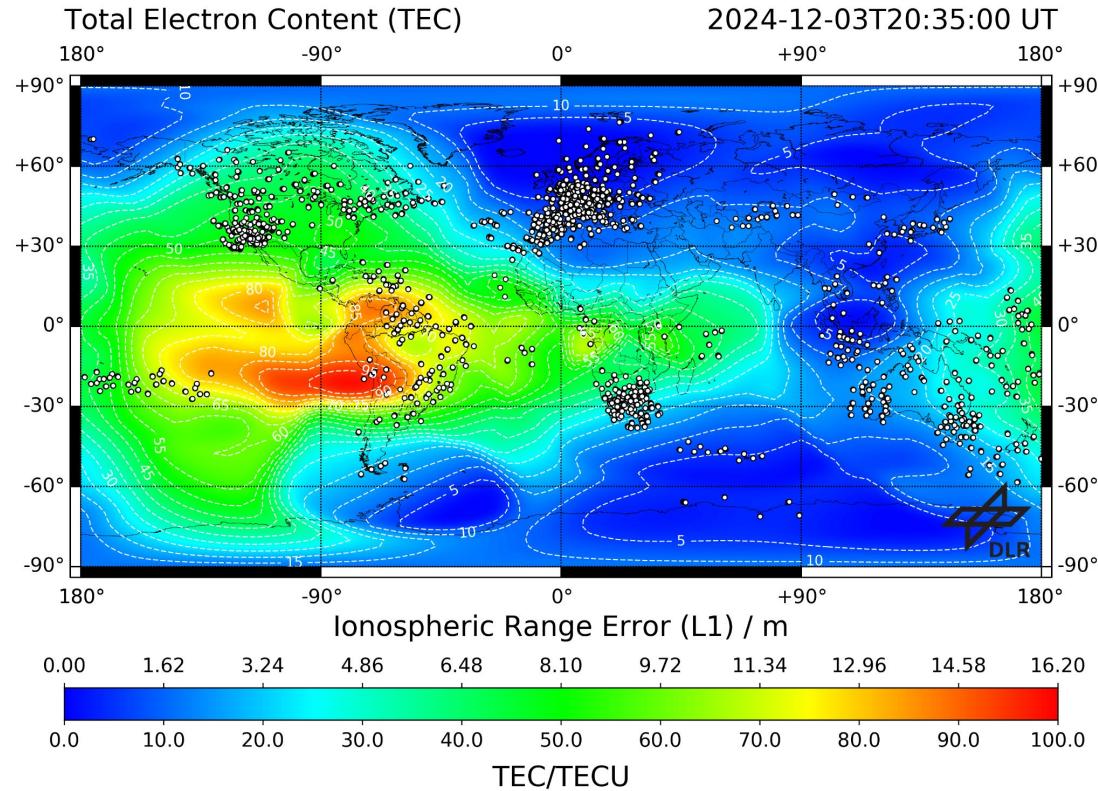
Near real-time map source:
Deutsches Zentrum für Luft- und Raumfahrt e.V. (DLR)
German Aerospace Center

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

Much more active now!



The Ionosphere as dispersive medium - measurement with GNSS

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

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

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

- r is the distance between the receiver and transmitting satellite
- ΔT is the absolute time difference between receiver and transmitter clocks
- v_{L1} and v_{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

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

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

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

The International GNSS Service and TrigNET

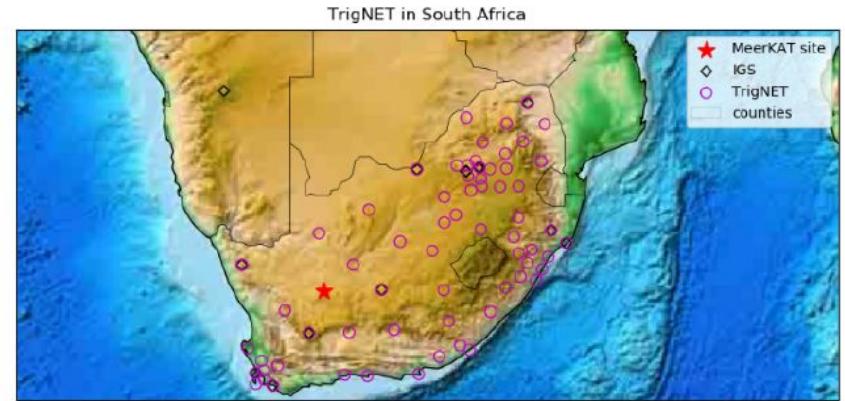
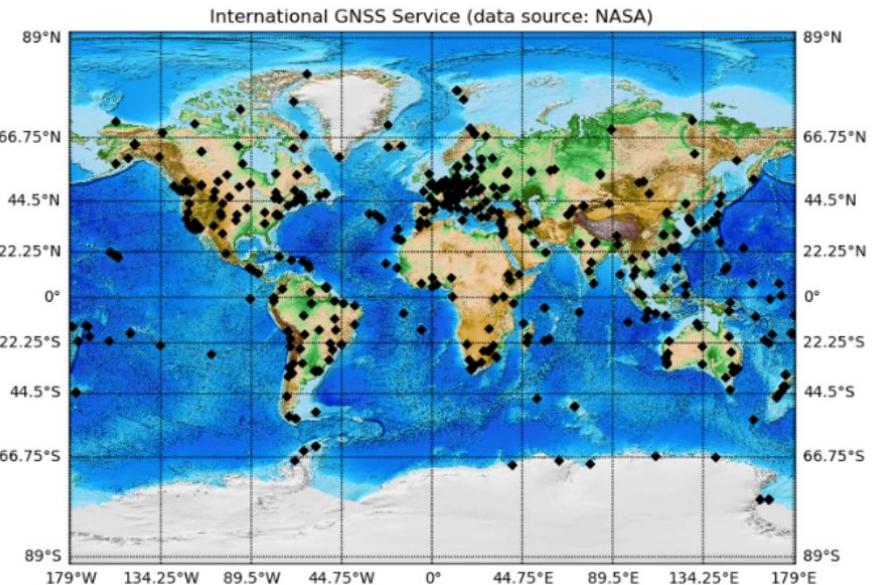


Figure 2.10: All available TrigNET stations in South Africa, as operated by the Department of Agriculture, Land Reform and Rural Development as of 2022.

Strong effects at cm wavelengths: Ionospheric Faraday Rotation

- The ionospheric delay affects astrometry at meter wavelengths as a function of ν^{-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

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

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

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

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 +30.30.33.000000 J2000      0       6760
INFO  listobs::ms::summary+      1   T    J1939-6342      19:39:25.050000 -63.42.43.600000 J2000      1       6760
INFO  listobs::ms::summary+      2   T    J1733-1304      17:33:02.660000 -13.04.49.100000 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?

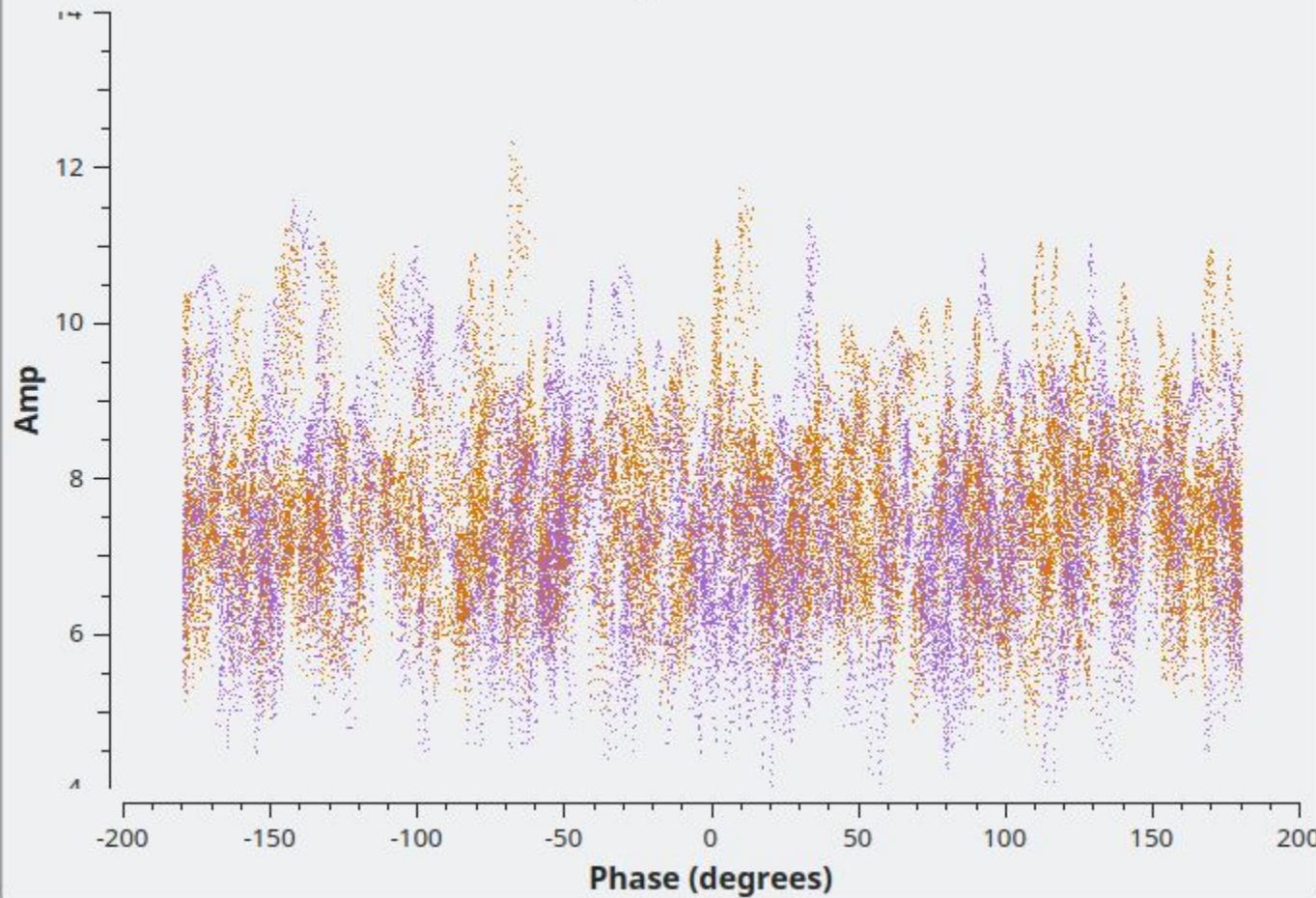
Hint: this GPS source is a ~50 mas (therefore unresolved for MK) source put at the phase centre. Can you say what we should be seeing if the system was well calibrated?

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



(!)ALWAYS(!) do 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::::+      ##### 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.

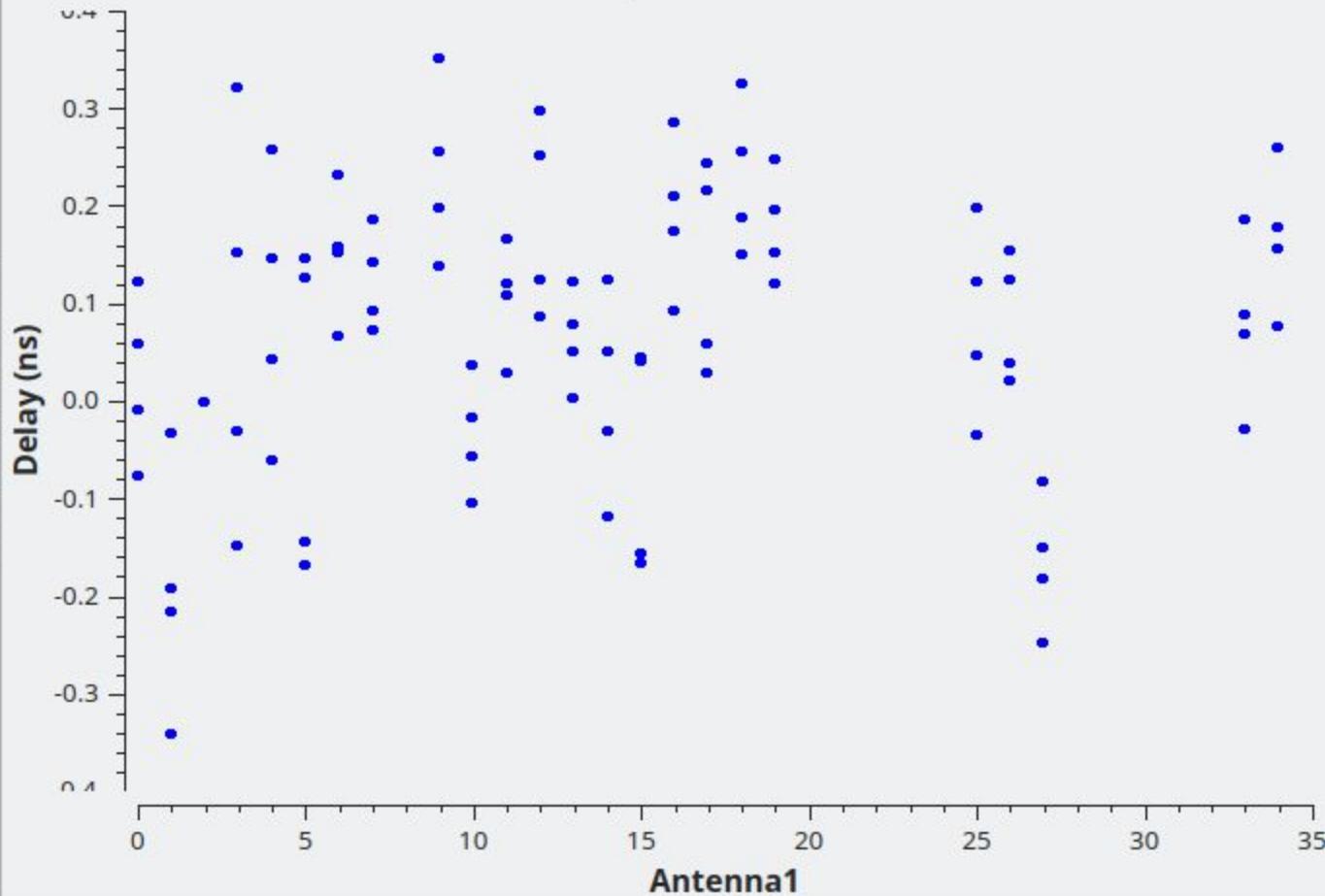
```
INFO  setjy::::
INFO  setjy::::+
INFO  setjy::::+ ##### Begin Task: setjy #####
INFO  setjy::::      setjy(vis="moon_uhf_calibrators.ms",field="J1939-6342",spw="",selectdata=False,timerange="",
INFO  setjy::::          scan="",intent="",observation="",scalebychan=True,standard="Stevens-Reynolds 2016",
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,ismmss=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

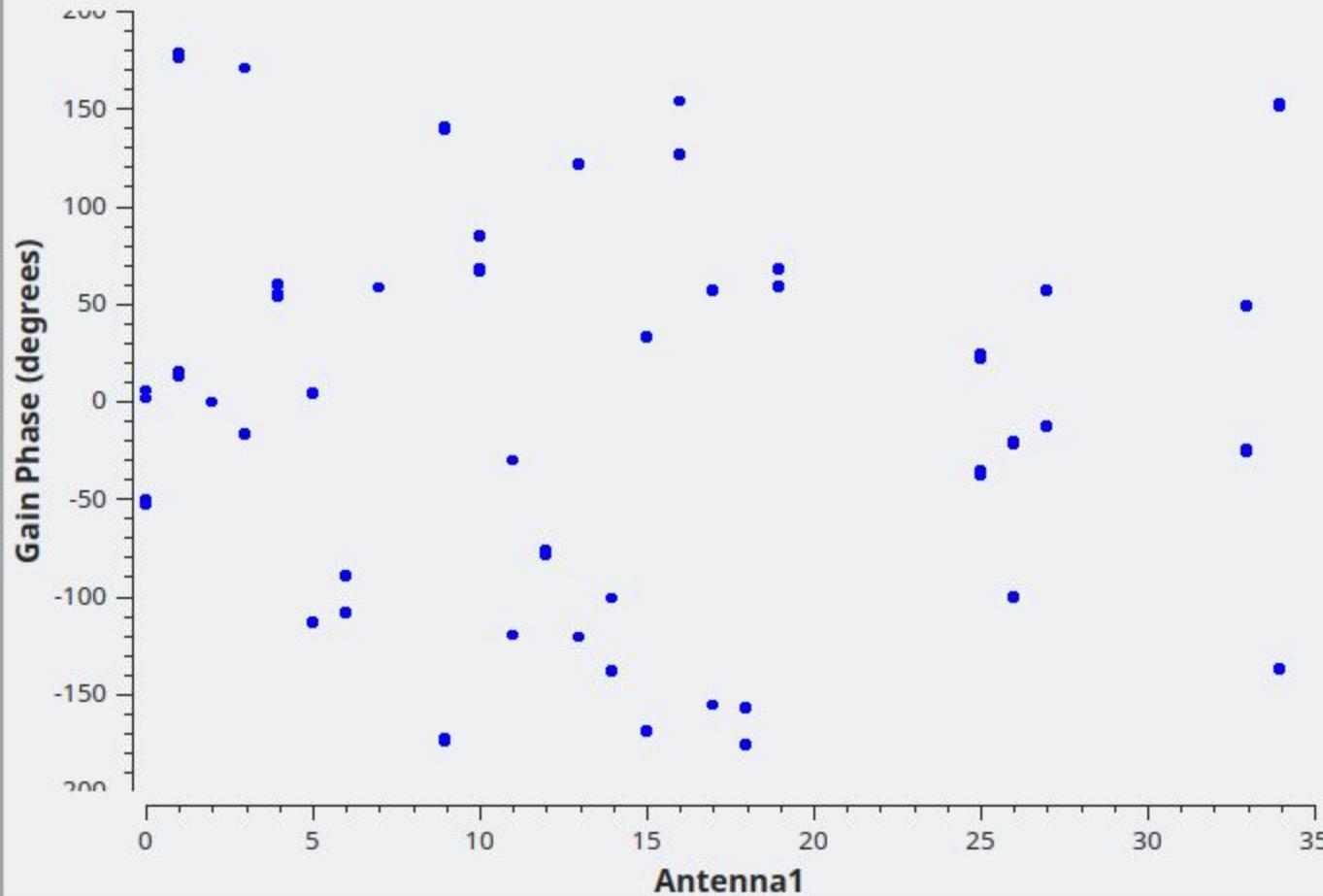
- `gaincal(vis='moon_uhf_calibrators.ms', caltable='bp.K', field='J1939-6342', gaintype='K', solint='inf', combine=",refant='m002')`
- `gaincal(vis='moon_uhf_calibrators.ms', caltable='bp.Gp', field='J1939-6342', gaintype='G', calmode='p', solint='inf', combine=",refant='m002', gaintable=['bp.K'])`
- `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:::+ ##### 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:::calibrator::open ****Using NEW VI2-driven calibrator tool****
INFO gaincal:::calibrator::open Opening MS: moon_uhf_calibrators.ms for calibration.
INFO gaincal:::Calibrator::: Initializing nominal selection to the whole MS.
INFO gaincal::: NB: gaincal automatically excludes auto-correlations.
INFO calibrator::setdata Beginning selectvis--(MSSelection version)-----
INFO calibrator::reset Reseting solve/apply state
INFO Calibrator::selectvis Performing selection on MeasurementSet
INFO Calibrator::selectvis+ Selecting on field: 'J1939-6342'
INFO Calibrator::selectvis+ Selecting with TaQL: 'ANTENNA1!=ANTENNA2'
INFO Calibrator::selectvis By selection 25688 rows are reduced to 5520
INFO Calibrator::selectvis Frequency selection: Selecting all channels in all spws.
INFO calibrator::setdata chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect='ANTENNA1!=ANTENNA2'
INFO calibrator::setsolve Beginning setsolve--(MSSelection version)-----
INFO Calibrator::setsolve Arranging to SOLVE:
INFO Calibrator::setsolve . . K Jones: table=bp.K append=false solint=inf refantmode='flex' refant='m002' minsnr=3 apemode=AP solnorm=false
INFO calibrator::solve Beginning solve-----
INFO Calibrator::solve The following calibration terms are arranged for apply:
INFO Calibrator::solve . (None)
INFO Calibrator::solve The following calibration term is arranged for solve:
INFO Calibrator::solve . . K Jones: table=bp.K append=false solint=inf refantmode='flex' refant='m002' minsnr=3 apemode=AP solnorm=false
INFO Calibrator::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 Calibrator::solve Found good K Jones solutions in 2 solution intervals.
INFO Writing solutions to table: bp.K
INFO calibrator::solve Finished solving.
INFO gaincal::: Calibration solve statistics per spw: (expected/attempted/succeeded):
INFO gaincal::: Spw 0: 2/2
INFO gaincal::: ##### End Task: gaincal #####
INFO gaincal:::+ #####
```

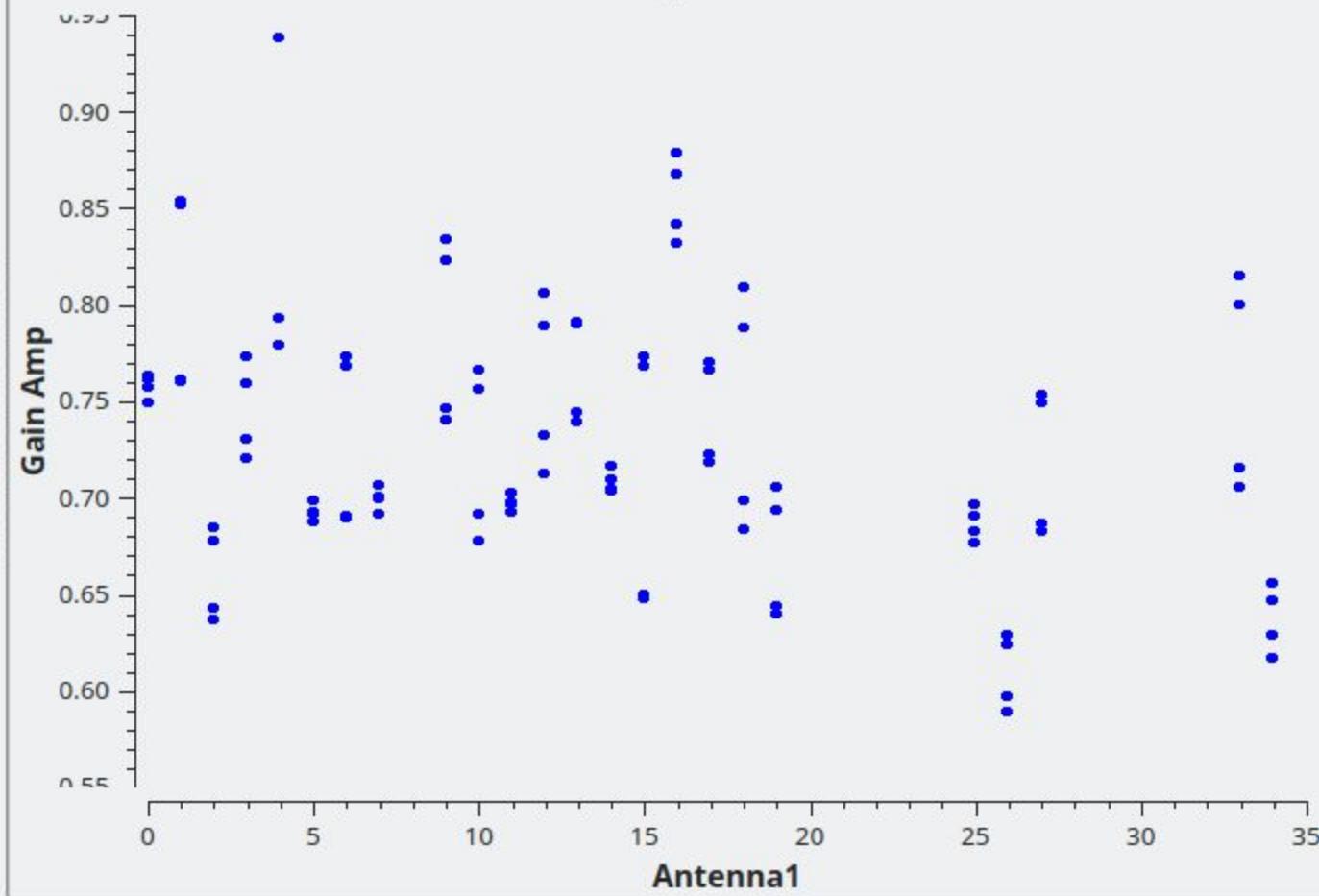
Delay vs. Antenna1



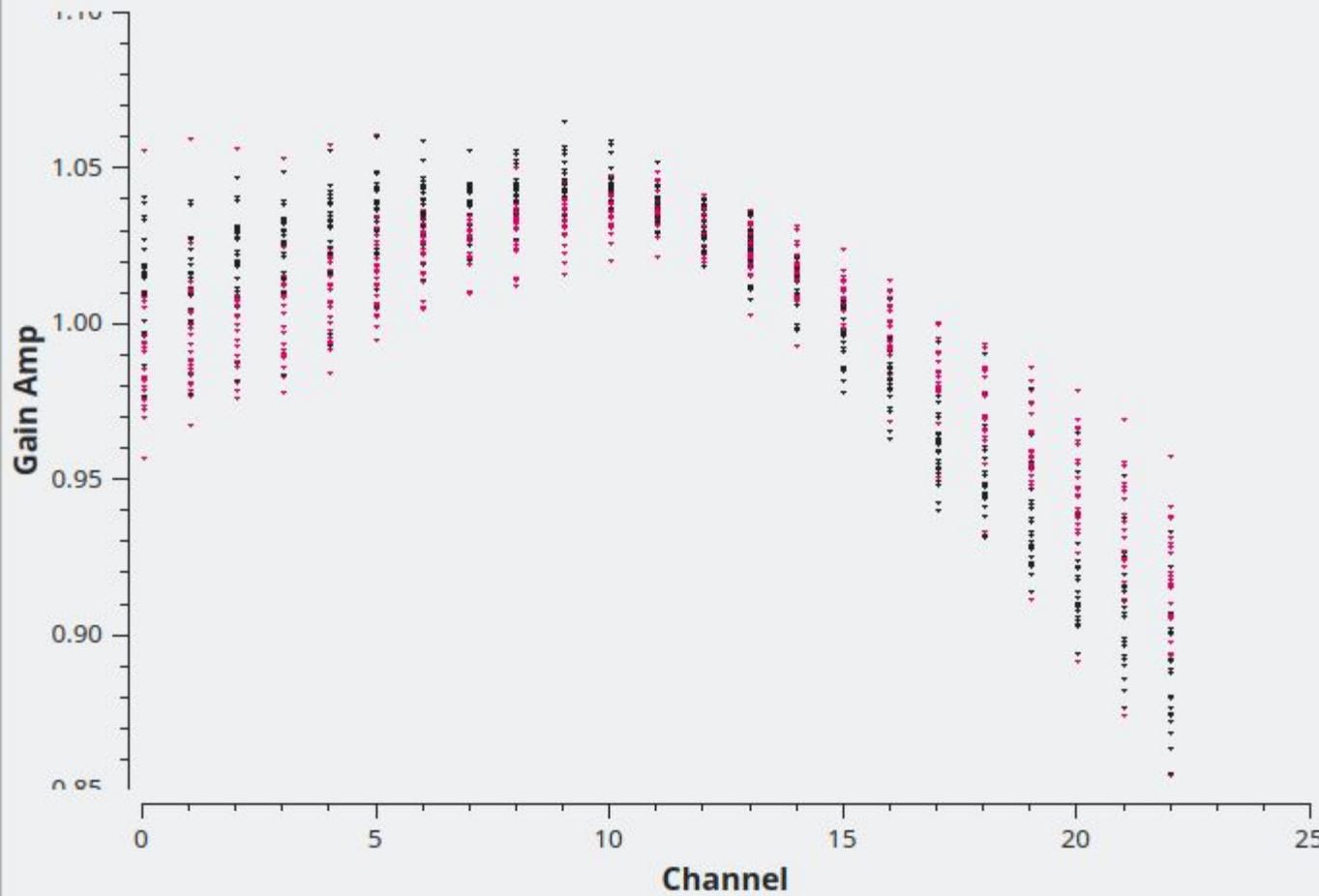
Gain Phase vs. Antenna1



Gain Amp vs. Antenna1



Gain Amp vs. Channel

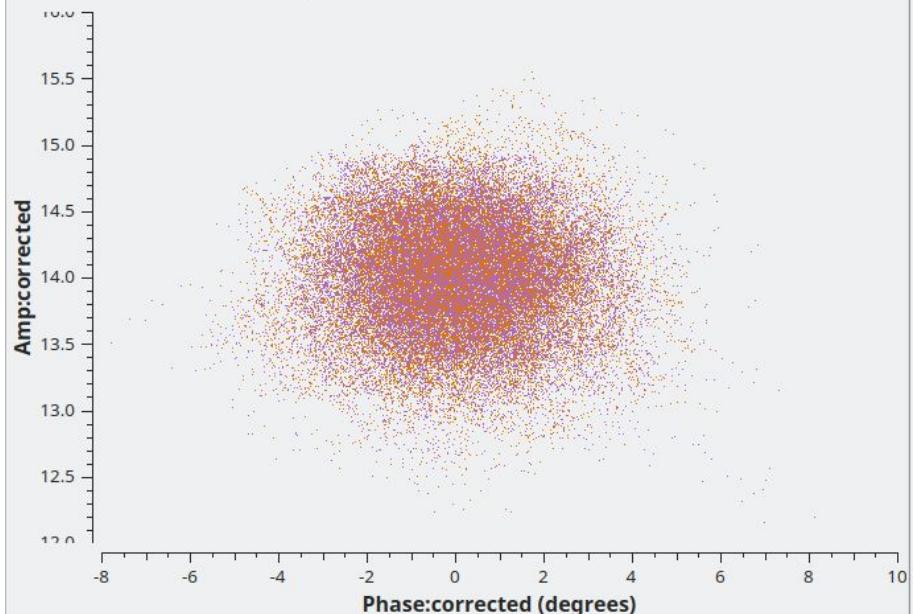


Remarks:

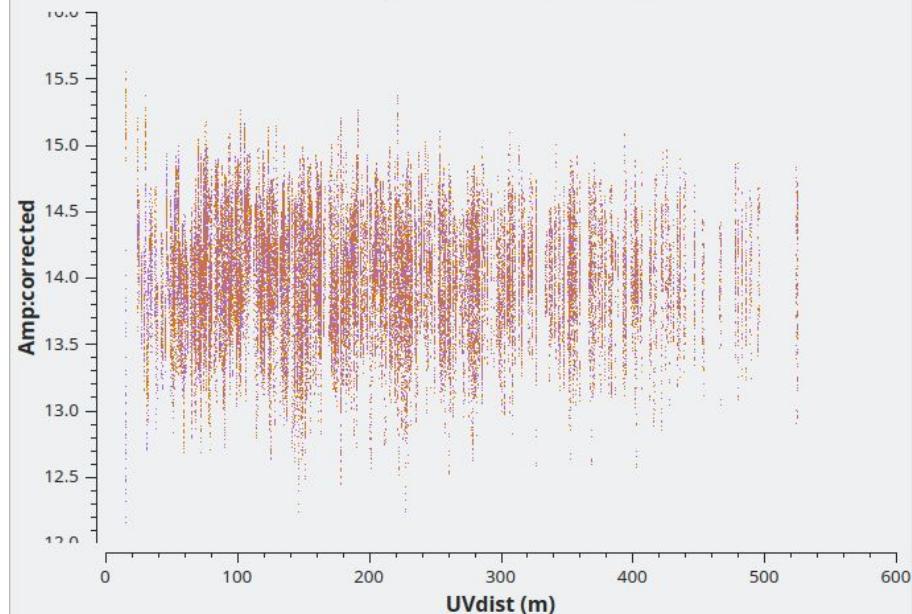
- These delays are residuals -- the MeerKAT science data processor solves for delays before every observation. We expect these to be a few 10s of ns at most, but sometimes the online process fails (due to e.g. RFI). Don't flag solely based on the delay values here.
- Note we only dumped a subset of the 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 stabilized 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 ν^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:::calibrator:::open      ****Using NEW VI2-driven calibrator tool****
INFO applycal:::calibrator:::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:::Calibrator::: Initialize 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 calibrator:::setdata      Beginning selectvis--(MSSelection version)-----
INFO calibrator:::reset      Resetting solve/apply state
INFO Calibrator:::selectvis      Performing selection on MeasurementSet
INFO Calibrator:::selectvis+      Selecting on field: 'J1939-6342'
INFO Calibrator:::selectvis      By selection 25688 rows are reduced to 6760
INFO Calibrator:::selectvis      Frequency selection: Selecting all channels in all spws.
INFO calibrator:::setdata      chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect=''
INFO calibrator:::setapply      Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar)      Arranging to APPLY:
INFO          (K Jones: Enforcing calWt=false for phase/delay-like terms)
INFO Calibrator:::setapply(type, applypar)      . K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO calibrator:::setapply      Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar)      Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar)      . G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator:::setapply      Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar)      Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar)      . G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO calibrator:::setapply      Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar)      Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar)      . B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO calibrator:::correct      Beginning correct-----
INFO Calibrator:::correct2 (VI2/VB2) The following calibration terms are arranged for apply:
INFO Calibrator:::correct2 (VI2/VB2)      . B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO Calibrator:::correct2 (VI2/VB2)      . K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO Calibrator:::correct2 (VI2/VB2)      . G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator:::correct2 (VI2/VB2)      . G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator:::correct2 (VI2/VB2) Found valid WEIGHT_SPECTRUM, correcting it.
INFO calibrator:::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:::      ###### End Task: applycal      ######
INFO applycal:::+      #####
```

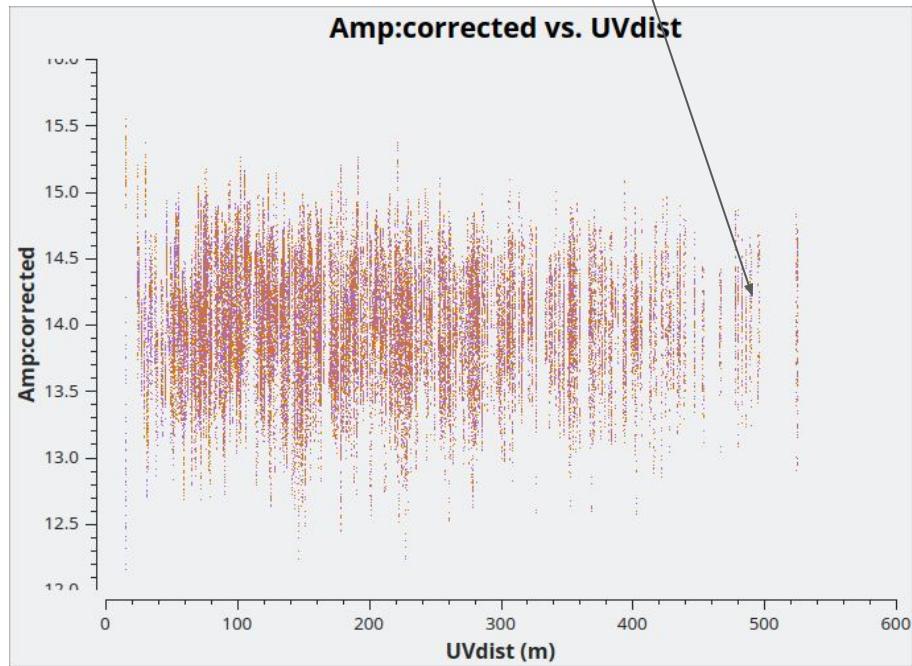
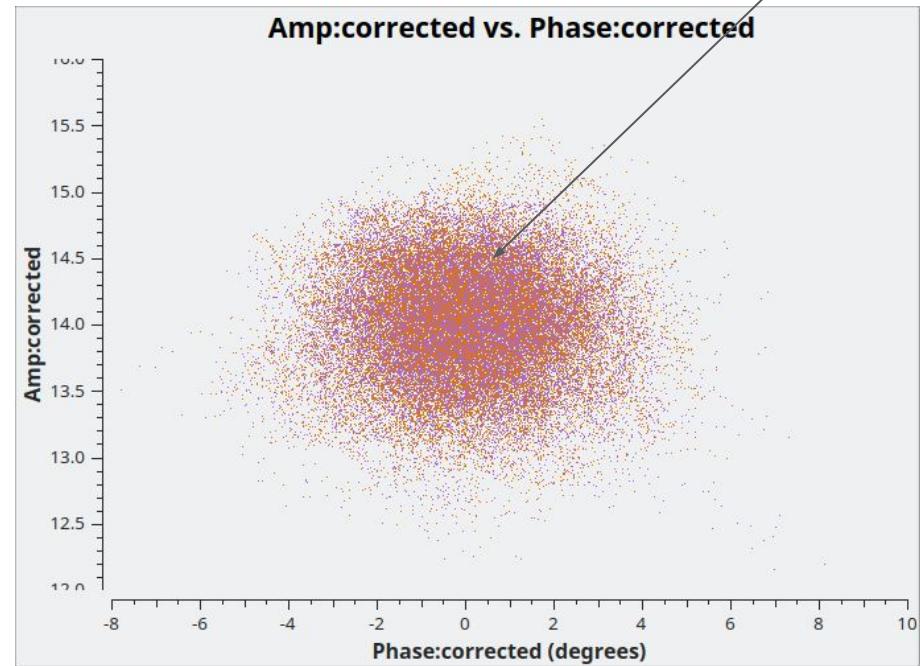
Amp:corrected vs. Phase:corrected



Amp:corrected vs. UVdist



Point-like unresolved source at phase centre

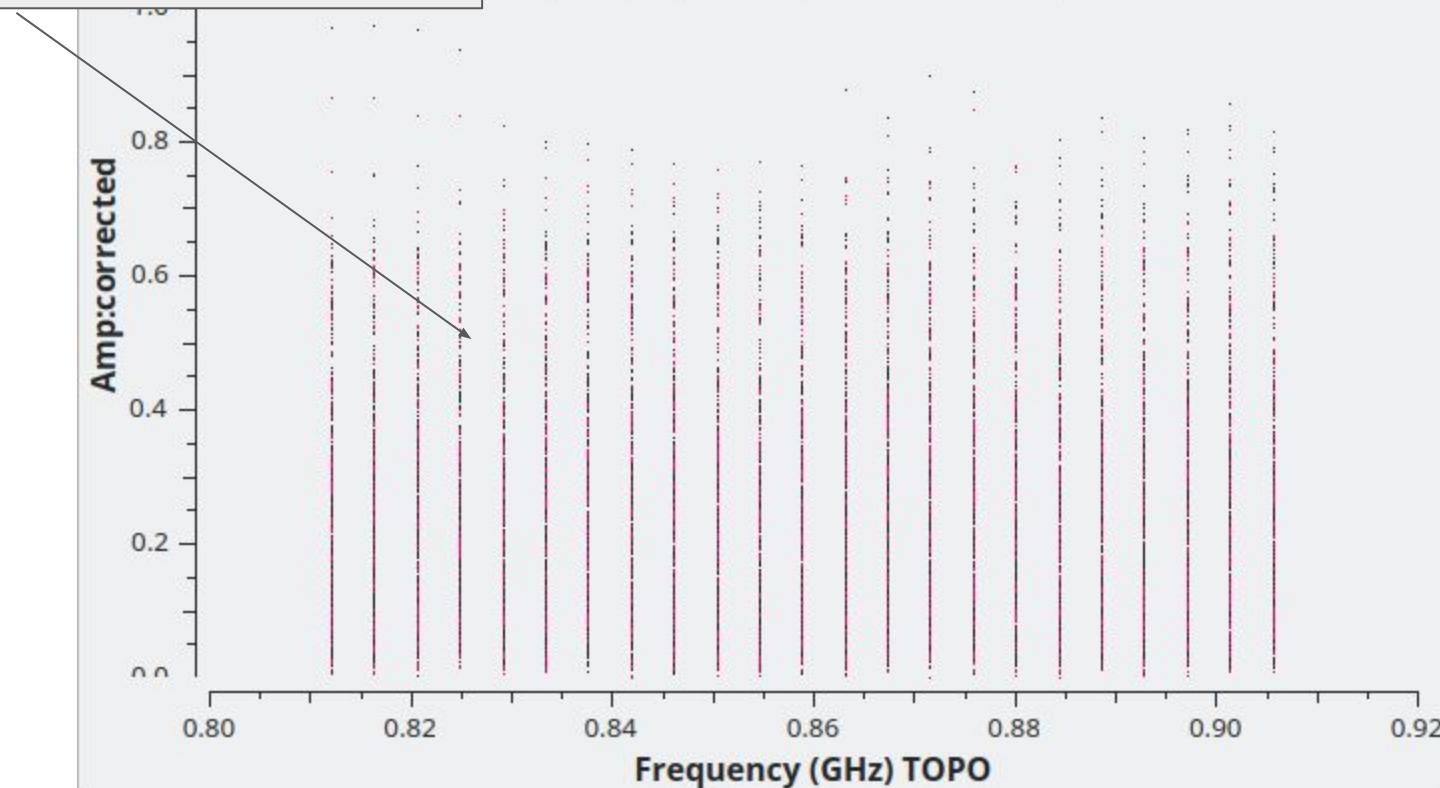


Calibrating Df

- 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', uvrage=">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

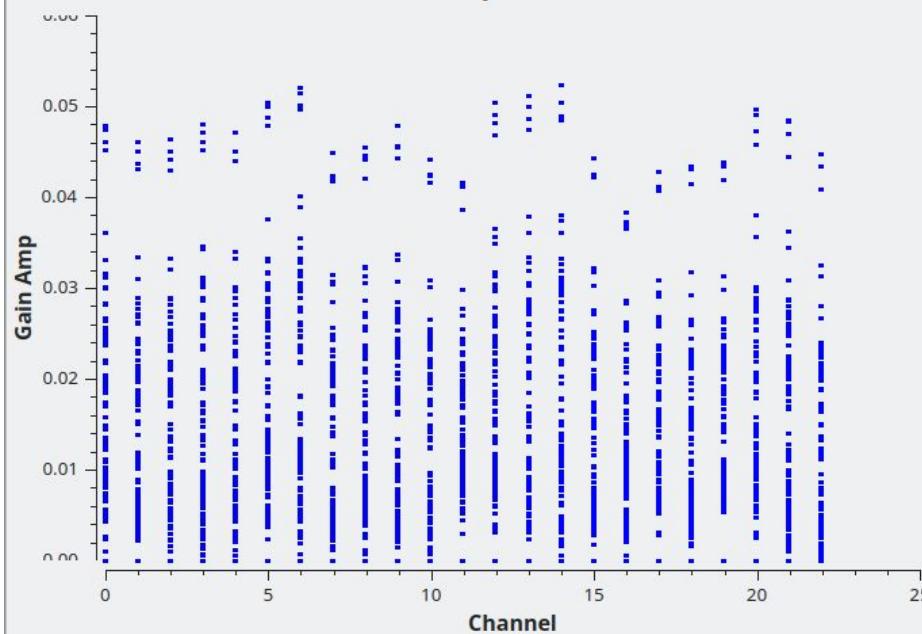
Amp:corrected vs. Frequency

Few percent level

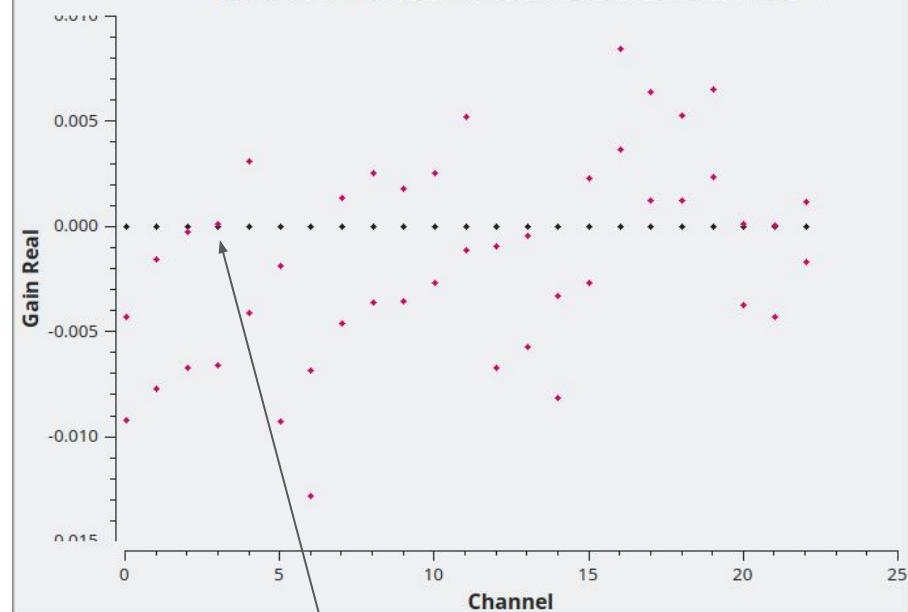


```
INFO polcal:::+
INFO polcal:::+ ###### Begin Task: polcal #####
INFO polcal:::+ polcalvis="moon_uhf_calibrators.ms",caltable="bp.Df",field="J1939-6342",spw="",intent="",
INFO polcal:::+ selectedata=True,timerange="",uvrange="",antenna="" scan="" ,
INFO polcal:::+ observation="",msselect="",solint="inf",combine="",preavg=300.0,
INFO polcal:::+ refant="m002",minblper4=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:::calibrator::open     ***Using NEW VI2-driven calibrator tool***
INFO polcal:::calibrator::open   Opening MS: moon_uhf_calibrators.ms for calibration.
INFO polcal:::Calibrator::: Initializing nominal selection to the whole MS.
INFO polcal:::NB: polcal automatically excludes auto-correlations.
INFO calibrator::setdata Beginning selectvis--(MSSelection version)-----
INFO calibrator::reset Reseting solve/apply state
INFO Calibrator::selectvis Performing selection on MeasurementSet
INFO Calibrator::selectvis+ Selecting on field: 'J1939-6342'
INFO Calibrator::selectvis+ Selecting with Ta0L: 'ANTENNA1!=ANTENNA2'
INFO Calibrator::selectvis By selection 25688 rows are reduced to 5520
INFO Calibrator::selectvis Frequency selection: Selecting all channels in all spws.
INFO calibrator::setdata chanmode=none nchan=1 start=0 step=1 mStart='0km/s' mStep='0km/s' msSelect='ANTENNA1!=ANTENNA2'
INFO calibrator::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator::setapply(type, applypar) Arranging to APPLY:
INFO     (K Jones: Enforcing calWt()=false for phase/delay-like terms)
INFO Calibrator::setapply(type, applypar) . K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO calibrator::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator::setapply(type, applypar) . G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO calibrator::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator::setapply(type, applypar) . G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO calibrator::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator::setapply(type, applypar) . B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO calibrator::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator::setapply(type, applypar) . P Jones <pre-computed>
INFO calibrator::setsolve Beginning setsolve--(MSSelection version)-----
INFO Calibrator::setsolve Arranging to SOLVE:
INFO     Using only cross-hand data for instrumental polarization solution.
INFO Calibrator::setsolve . Df Jones: table=bp.Df append=false solint=inf,none refantmode='flex' refant='m002' minsnr=3 apemode=AP solnorm=false
INFO calibrator::solve Beginning solve-----
INFO Calibrator::solve The following calibration terms are arranged for apply:
INFO Calibrator::solve . B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO Calibrator::solve . K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO Calibrator::solve . G Jones: table=bp.Gp select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator::solve . G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator::solve . P Jones <pre-computed>
INFO Calibrator::solve The following calibration term is arranged for solve:
INFO Calibrator::solve . Df Jones: table=bp.Df append=false solint=inf,none refantmode='flex' refant='m002' minsnr=3 apemode=AP solnorm=false
INFO Calibrator::solve For solint = inf, found 2 solution intervals.
INFO Calibrator::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 calibrator::solve Finished solving.
INFO polcal:::    ##### End Task: polcal #####
INFO polcal:::+ ##### End Task: polcal #####
```

Gain Amp vs. Channel



Gain Real vs. Channel Antenna: m002@m002



Relative feed angle
rotation on sky (real)

$$d_X = \theta_X - i\chi_X$$
$$d_Y = \theta_Y - i\chi_Y$$

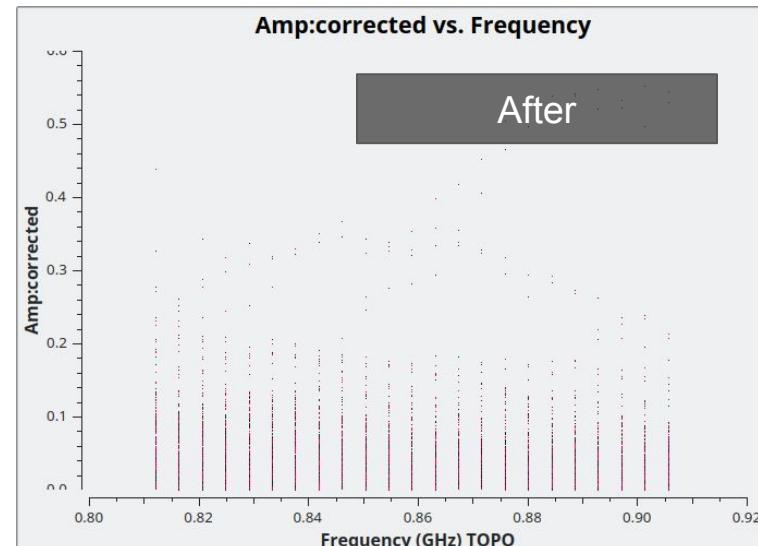
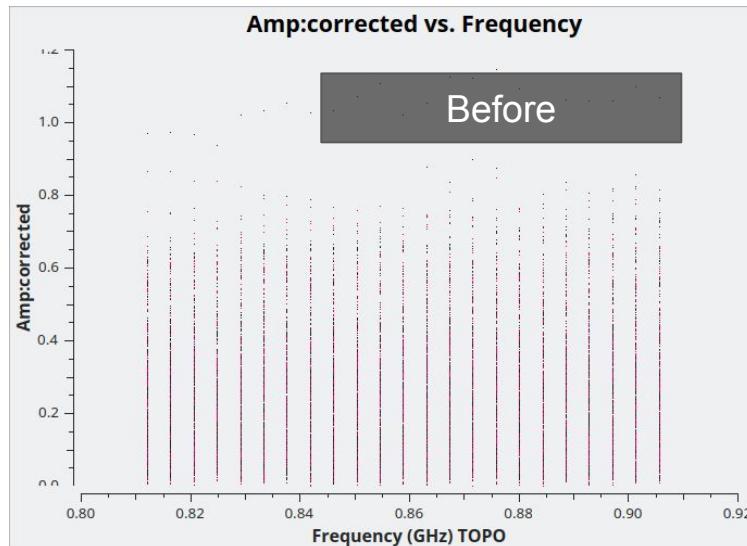
Feed ellipticity (imag)

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**

Df: Proof is in the taste!

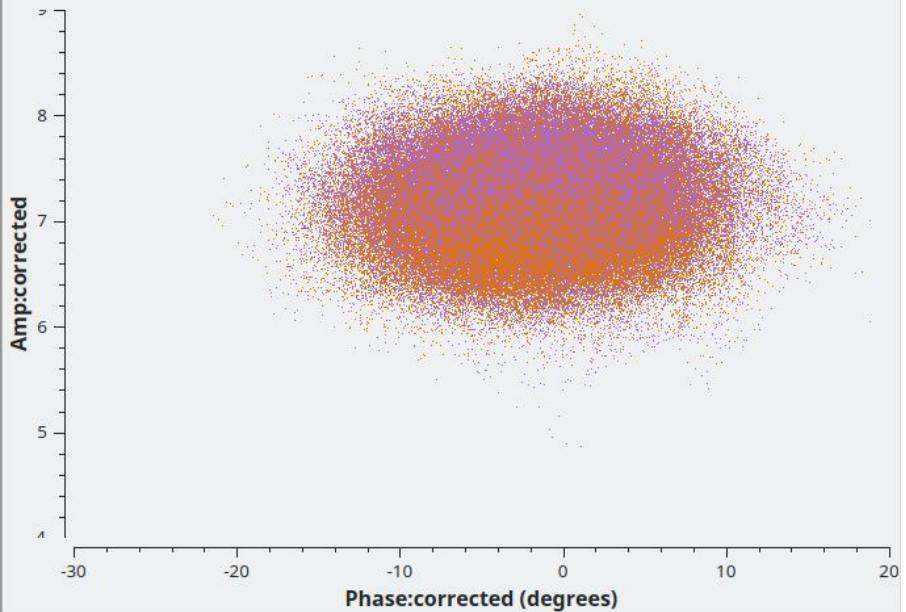
- Apply the solution (add to the chain)
- Plot the XY* and YX* terms afterwards
- If leakage has not gone down something could be wrong on your reference antenna, maybe switch (and start the calibration from scratch!)
- **IMPORTANT:** Applying leakages does not mean that the polarization response of 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)



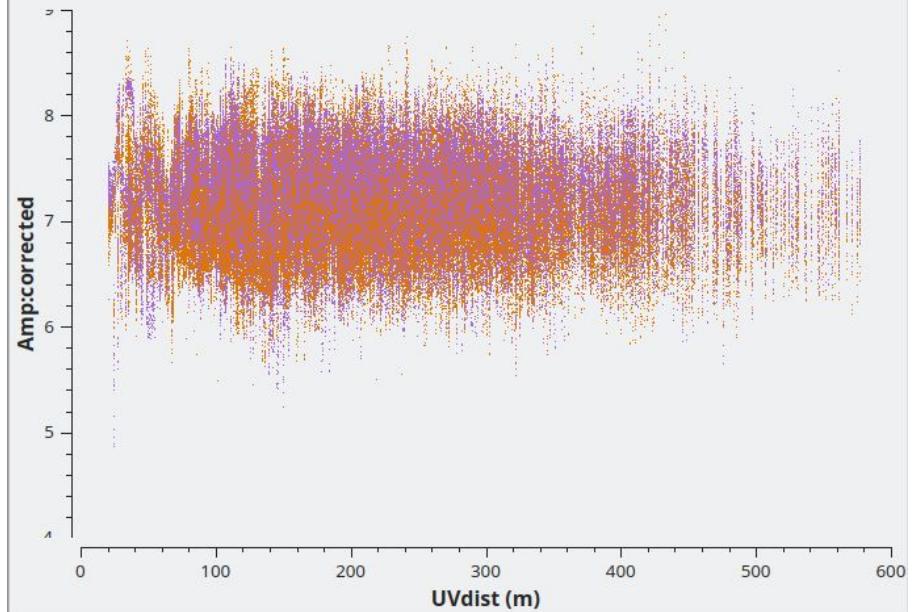
Phase refine for the target using the secondary

- 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', uvrage=">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', uvrage=">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!)

Amp:corrected vs. Phase:corrected



Amp:corrected vs. UVdist

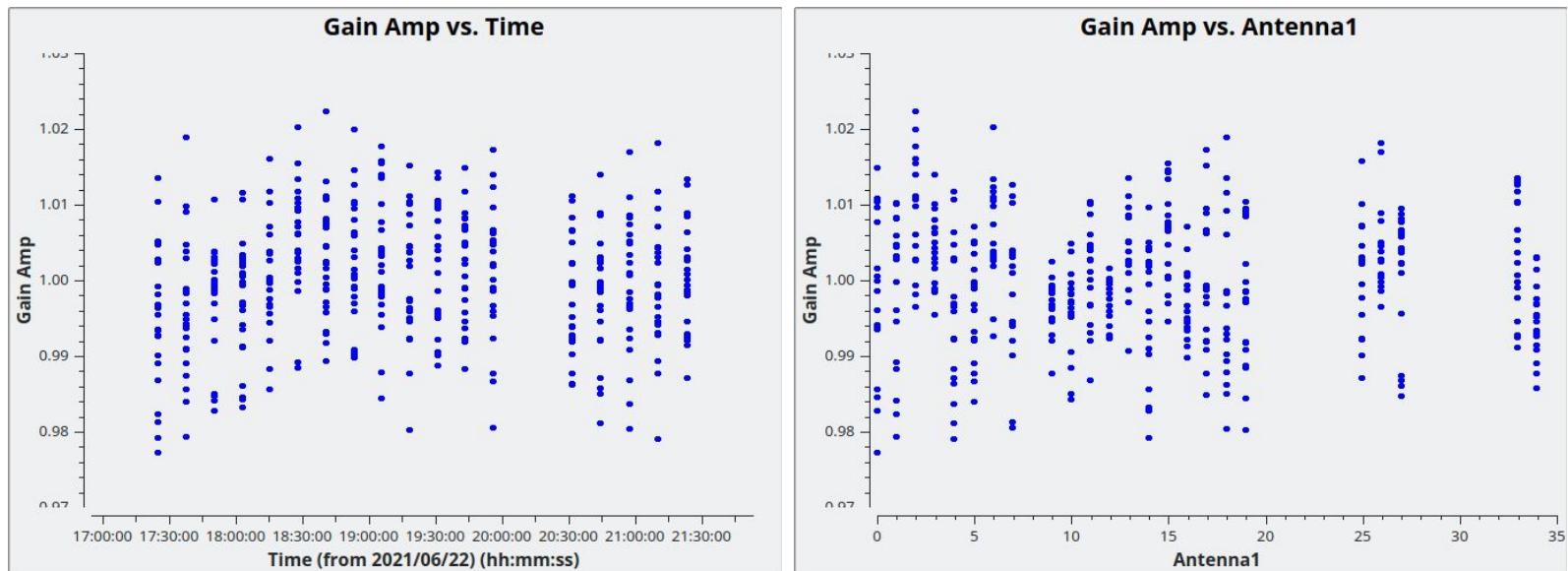


Why is checking this important?

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!

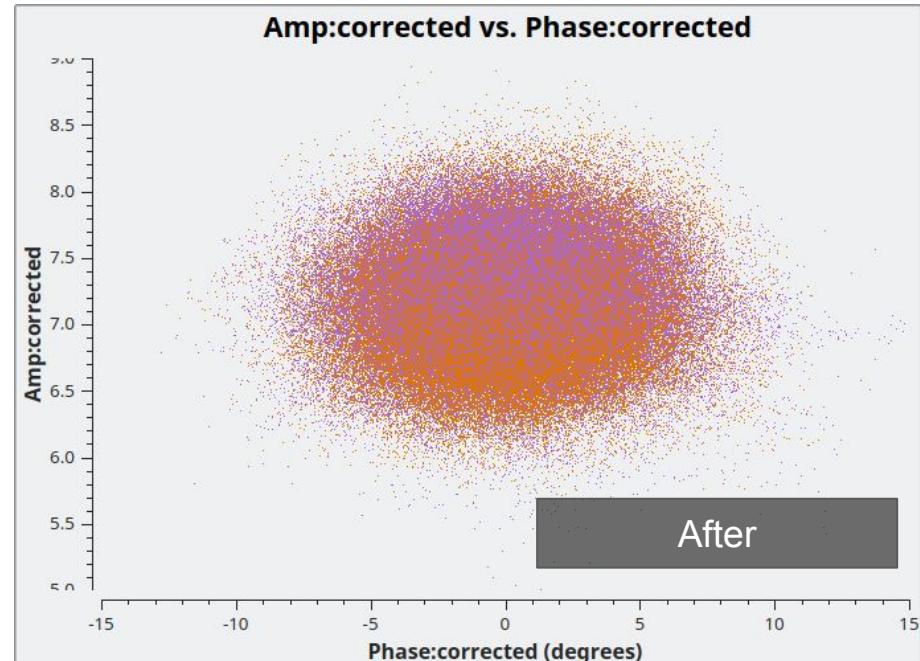
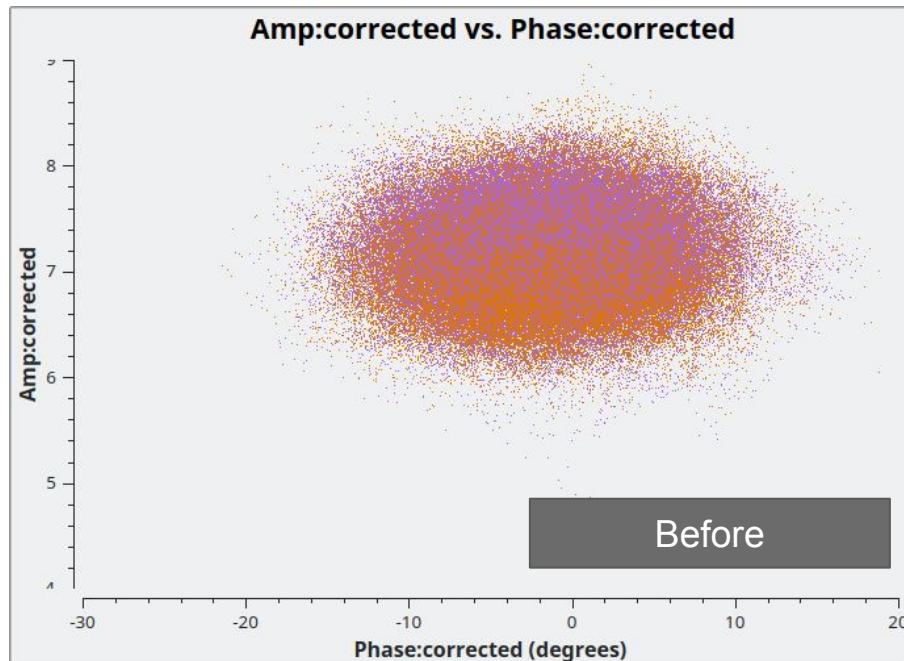
Amplitude variability on the system



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', uvrage=>"1m", avgtime='9999999999', avgchannel='9999999999', avgscan=True, field='Moon', plotrange=[0,300,0,200])`

Repeating the Michelson & Pease experiment on Betelgeuse Moon

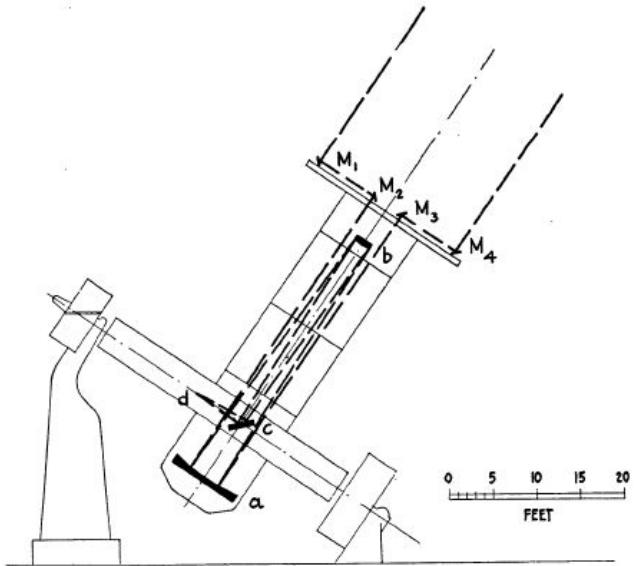
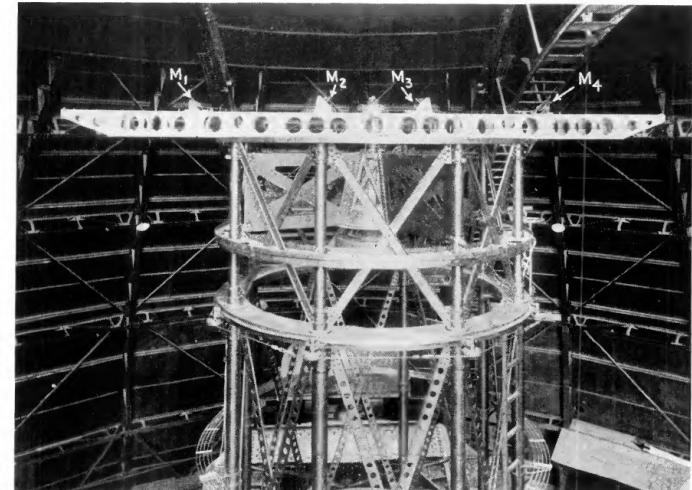


FIG. 1.—Diagram of optical path of interferometer pencils. M_1, M_2, M_3, M_4 , mirrors; a , 100-inch paraboloid; b , convex mirror; c , coudé flat; d , focus.

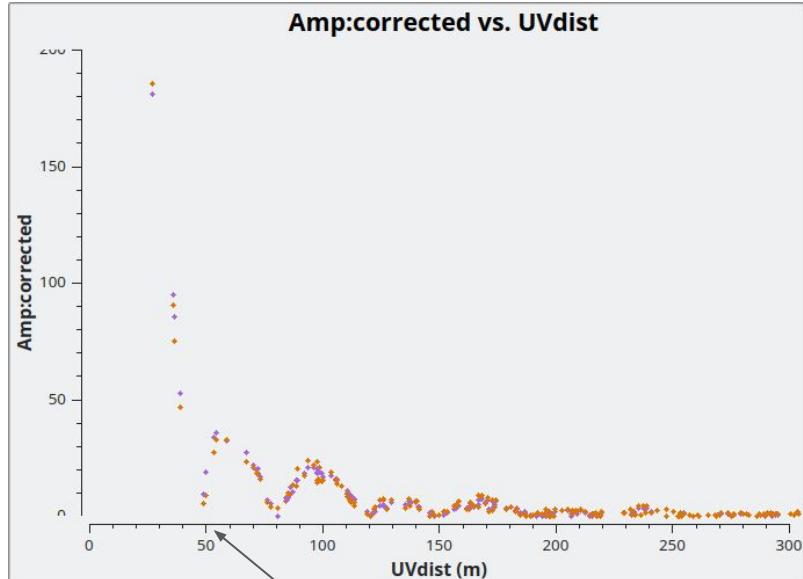
Michelson, Albert A., and Francis G. Pease. "Measurement of the diameter of Alpha-Orionis by the interferometer." *Proceedings of the National Academy of Sciences of the United States of America* 7.5 (1921): 143.

In December 1920 Michelson and Pease measured the apparent size of the stellar disk of Betelgeuse to $0.047'' \pm 10\%$ (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

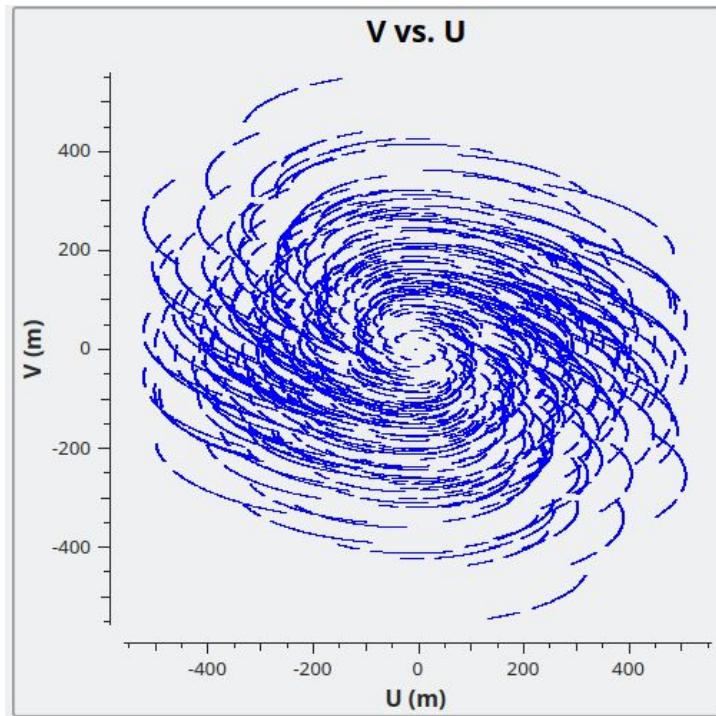
Work out the angular extent of the Moon (a ~flat pillbox):

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

$$l_{\text{radius}} = \frac{3.8317(\lambda = 0.349 \text{ m})}{2\pi(u(m)_{\text{null}} = 50 \text{ m})} \\ \implies l_{\text{radius}} = 0.0042566 \text{ rads} = 14.63 \text{ arcmin}$$

Spot on! :-)

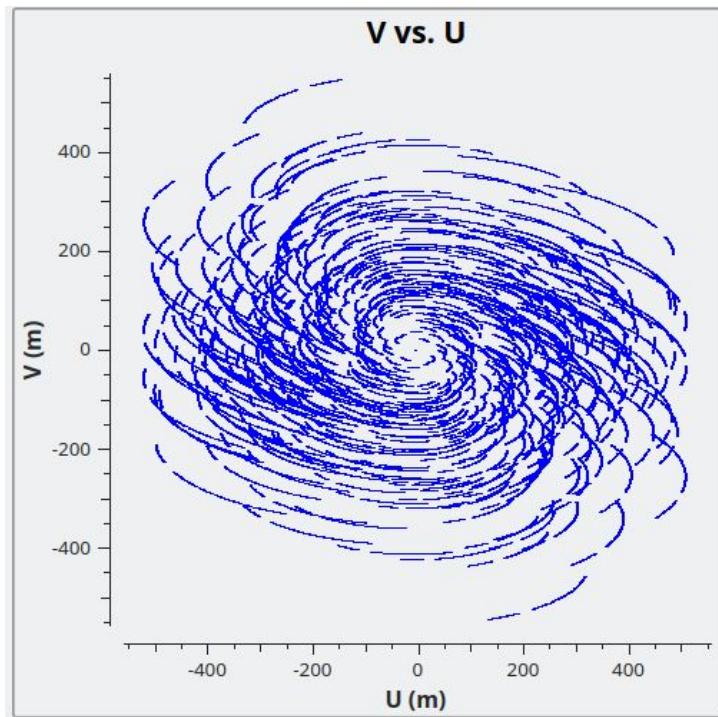
Imaging



- 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):

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

Imaging



Interferometric synthesis imaging is an ill-posed inverse problem - the sampling function for the aperture is incomplete

We will make “Dirty” maps for now

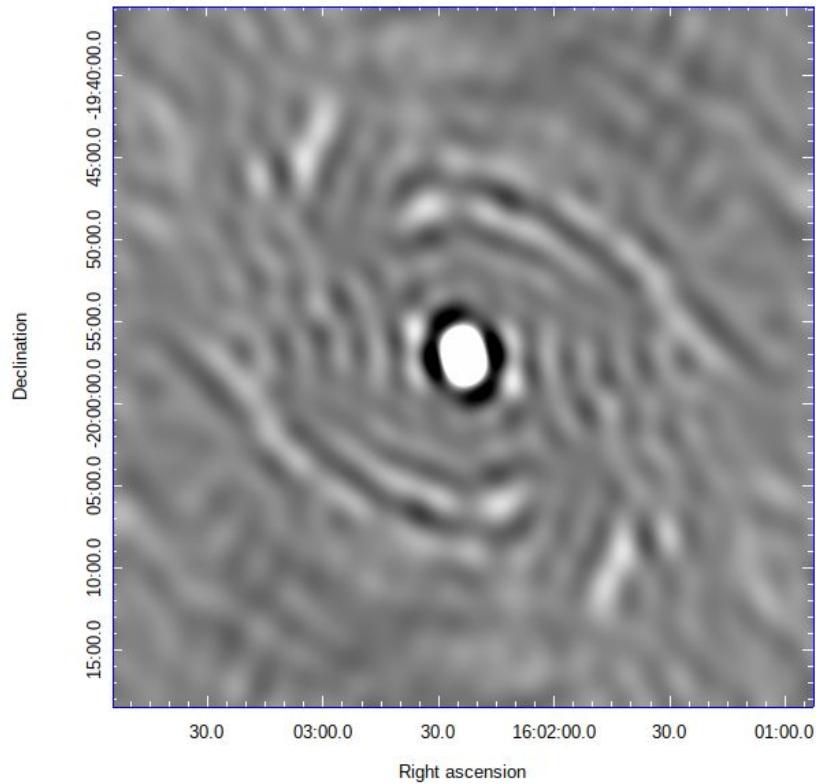
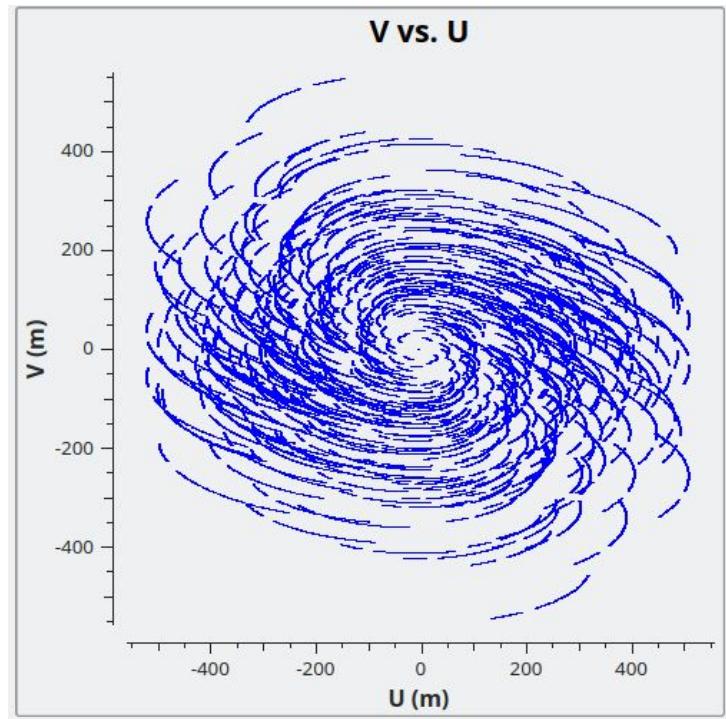
You will see deconvolution (ie. regularizing the problem - and introducing priors!) later this week

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

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

$$\xrightarrow{\mathcal{F}} \bar{I}(l, m) = I(l, m) * \text{PSF}(l, m)$$

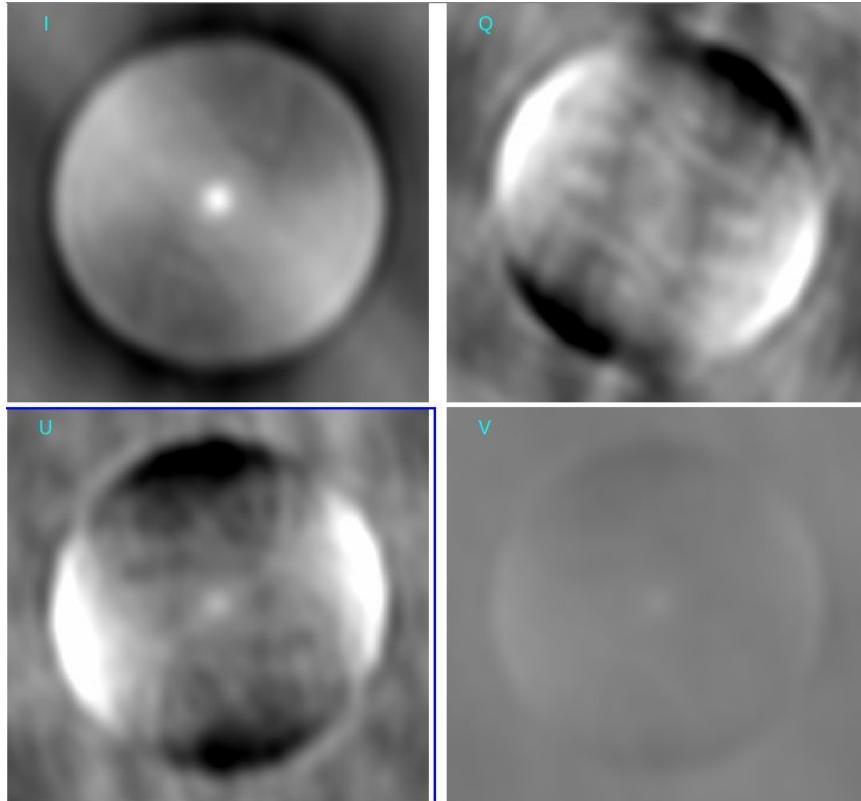
Example PSF for the Moon



Imaging

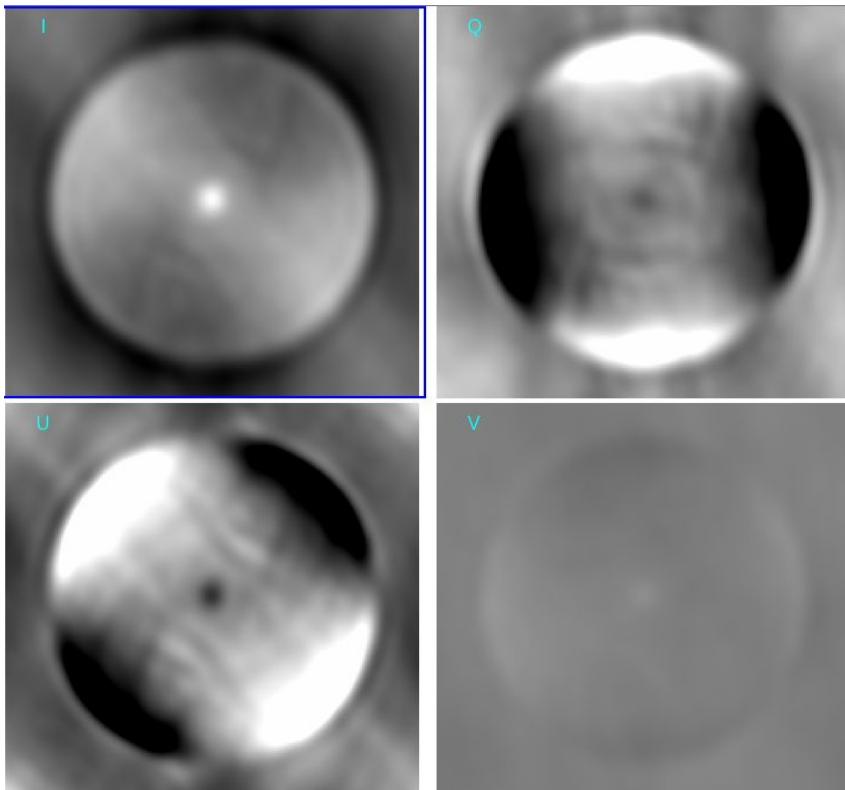
- `clean(vis='moon_uhf.ms', field='Moon', imagename="Moon.noHVphase", imsize=[512], cell=["5arcsec"], stokes="IQUV", weighting='briggs', robust=0.0, facets=3, niter=0)`
- `exportfits(imagename='Moon.noHVphase.image', fitsimage='Moon.noHVphase.image.fits')`
- Open with your favorite FITS viewer

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



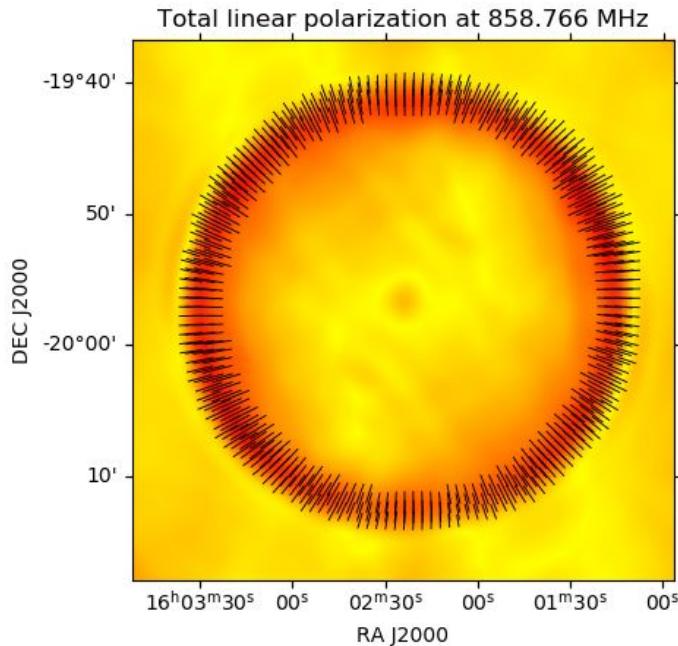
- Q,U,V locked to the same scale
- Aside from the (expected) misalignment of the polarization angle (Q should be positive/white towards positive declination and negative/black east) the handedness does appear to go north->east here
- Induced V is not substantial for this receiver in UHF, however it can 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',
imname="Moon.noHVphase.parang", imsize=[512],
cell=["5arcsec"], stokes="IQUV", weighting='briggs', robust=0.0,
facets=3, niter=0)
exportfits(imname='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  $P \times P^T$  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

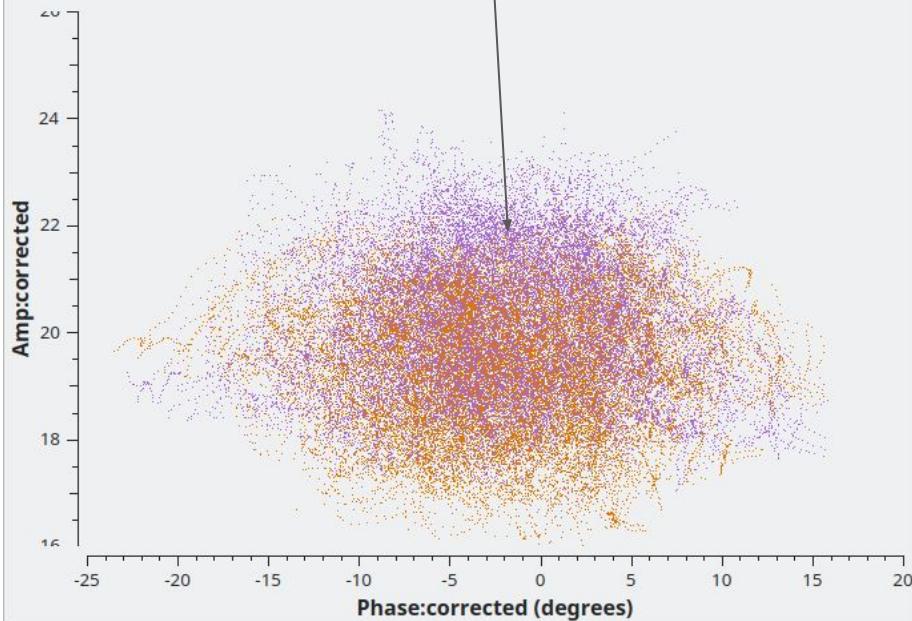
- We must now correct for the ellipticity in the MeerKAT feeds. For this we need a polarized source, e.g. 3C286 or noise diode injected signals (via Bill Cotton's Obit calibration suite) to calibrate this first order effect out.
- First we must refine the phase on 3C286
- Note: 3C286 starts being resolved 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

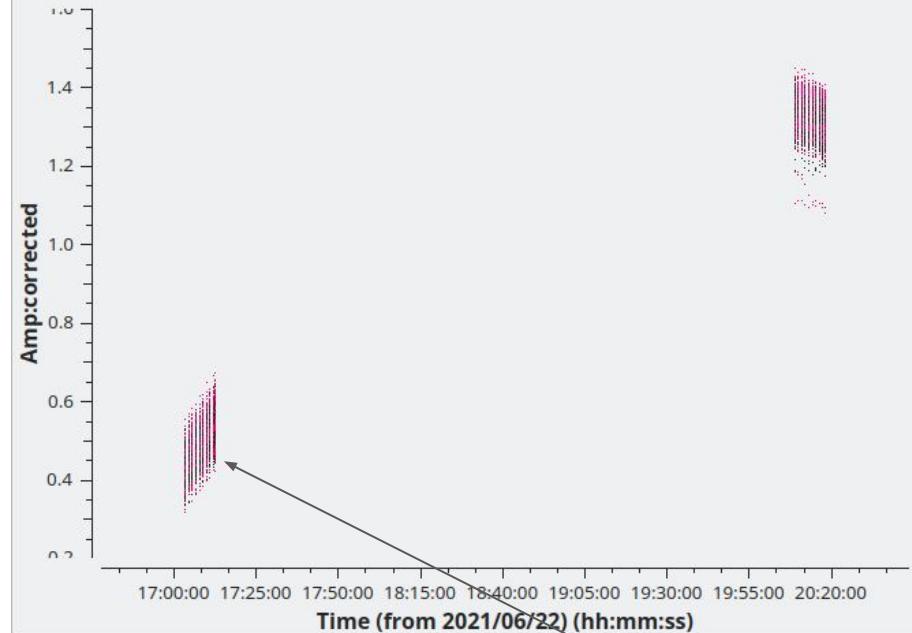
- Let's check the amp x phase and also look at the time variability due to (mainly parallactic angle and ionosphere) on the crosshand correlations XY\* and YX\* - ideally they should be precisely the same and not time variable AFTER we apply HV phase and parallactic angle (modulo ionospheric RM)
  - `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', uvrage">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', uvrage">1m", avgchannel='9999999', field='J1331+3030')`

Phase needs refining (first)

Amp:corrected vs. Phase:corrected



Amp:corrected vs. Time

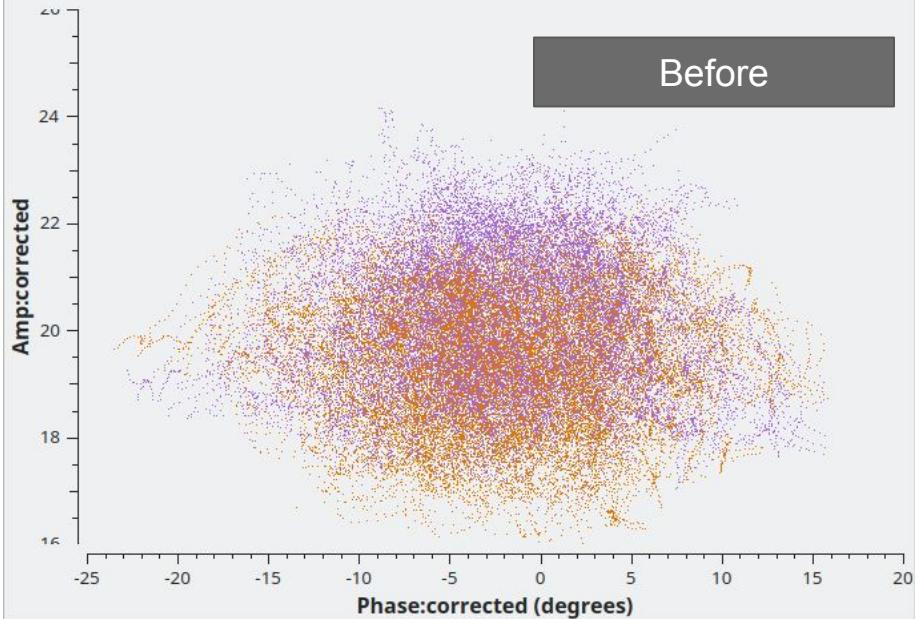


Crosshand ( $XY^*, YX^*$ ) power is low in the first scan due to parallactic angle

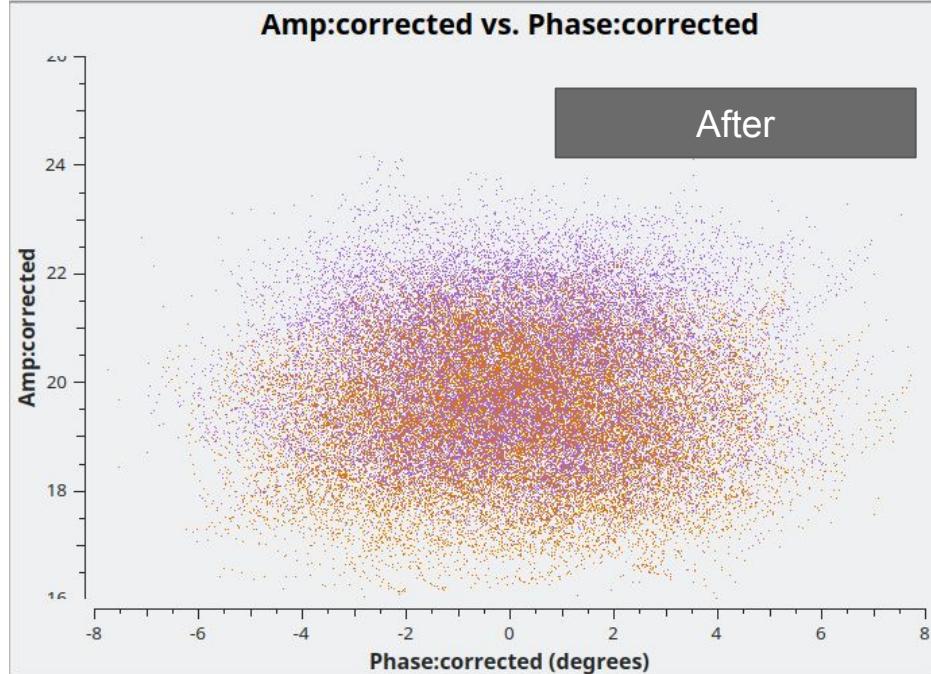
# Phase refinement: 3C286

- 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'])`

**Amp:corrected vs. Phase:corrected**



**Amp:corrected vs. Phase:corrected**



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

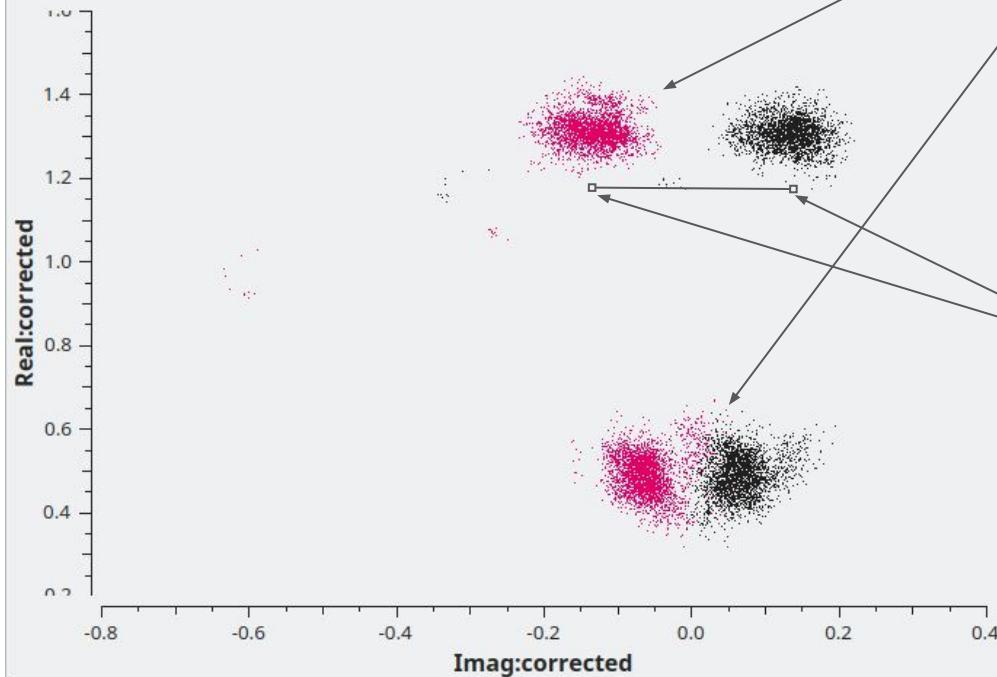
## Now for the HV phase

- 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', uvrage=">1m", avgchannel='9999999', field='J1331+3030')`

# $XY^*$ and $YX^*$

In colour: the (conjugate)  $U \pm iV$   
The change in real axis is due to  
the uncorrected parallactic angle

Real:corrected vs. Imag:corrected



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

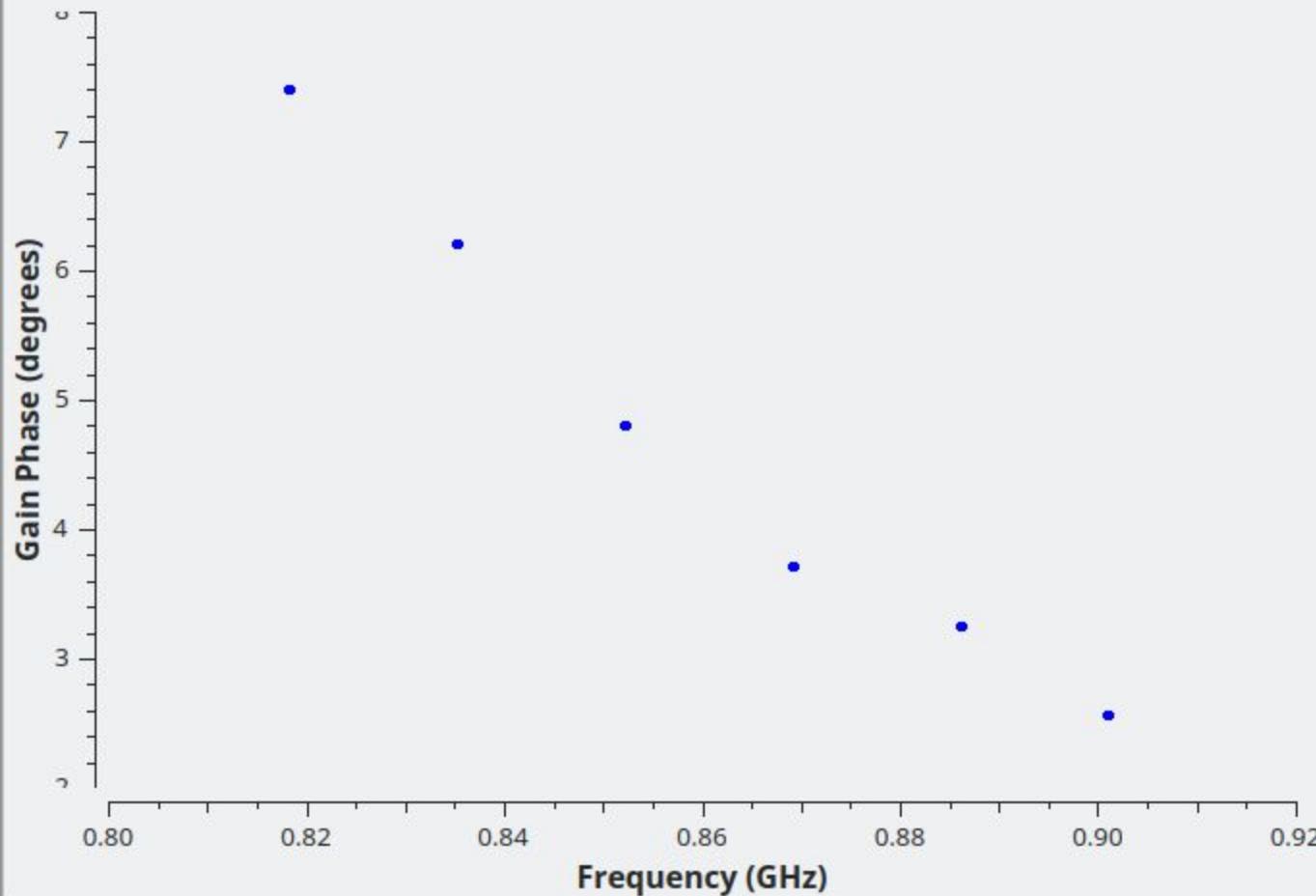
# Calibrating the crosshand phase

- There is fractional V Stokes being picked up here -- the goal is to remove that!
- Underneath the hood we take  $\arctan_2(V/U)$  here, assuming  $V \approx 0$  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 ( $X_f$ ) 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','bp.Df'], 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:::+ ##### Begin Task: polcal #####
INFO polcal:::+ polcalvis="moon_uhf_calibrators.ms",caltable="pol.Xf",field="J1331+3030",spw="",intent="",
INFO polcal:::+ selectdata=True,timerange="",uvrange="",antenna="",scan="",
INFO polcal:::+ observation="",mselect="",solint="inf,20MHz",combine="scan",preavg=300.0,
INFO polcal:::+ refant="m002",minblperant=4,minsnr=3.0,poltype="Xf",smode1=[],
INFO polcal:::+ append=False,docalib=False,callib="",gaintable=['bp.K', 'pol.Gp', 'bp.Ga', 'bp.B'],gainfield=[''],
INFO polcal:::+ interp=[],spwmap=[]

INFO polcal:::calibrator::open ****Using NEW V12-driven calibrator tool****
INFO polcal:::calibrator::open Opening MS: moon_uhf_calibrators.ms for calibration.
INFO polcal:::calibrator::: Initializing nominal selection to the whole MS.
INFO polcal::: NB: polcal automatically excludes auto-correlations.
INFO calibrator:::setdata Beginning selectvis--(MSSelection version)-----
INFO calibrator:::reset Reseting solve/apply state
INFO Calibrator:::selectvis Performing selection on MeasurementSet
INFO Calibrator:::selectvis+ Selecting on field: 'J1331+3030'
INFO Calibrator:::selectvis+ Selecting with TaQL: 'ANTENNA1!=ANTENNA2'
INFO Calibrator:::selectvis By selection 25688 rows are reduced to 5520
INFO Calibrator:::selectvis Frequency selection: Selecting all channels in all spws.
INFO calibrator:::setdata chanmode=hme nchan=1 start=0 step=1 mstart='0km/s' mStep='0km/s' msSelect='ANTENNA1!=ANTENNA2'
INFO calibrator:::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar) Arranging to APPLY:
INFO (K Jones: Enforcing calWt()=false for phase/delay-like terms)
INFO Calibrator:::setapply(type, applypar) . K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO calibrator:::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar) . G Jones: table=pol.Gp select= interp=linear spwmap=[-1] calWt=true
INFO calibrator:::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar) . G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO calibrator:::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar) . B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO calibrator:::setapply Beginning setapply--(MSSelection version)-----
INFO Calibrator:::setapply(type, applypar) Arranging to APPLY:
INFO Calibrator:::setapply(type, applypar) . P Jones <pre-computed>
INFO calibrator:::setsolve Beginning setsolve--(MSSelection version)-----
INFO Calibrator:::setsolve Arranging to SOLVE:
INFO . (Ignoring specified refant for Xf Jones solve.)
INFO Calibrator:::setsolve . Xf Jones: table=pol.Xf append=false solint=inf,20MHz refantmode='flex' refant='none' minsnr=3 apmode=AP solnorm=false
INFO calibrator:::solve Beginning solve-----
INFO Calibrator:::solve The following calibration terms are arranged for apply:
INFO Calibrator:::solve . B Jones: table=bp.B select= interp=linear,linear spwmap=[-1] calWt=true
INFO Calibrator:::solve . K Jones: table=bp.K select= interp=linear spwmap=[-1] calWt=false
INFO Calibrator:::solve . G Jones: table=pol.Gp select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator:::solve . G Jones: table=bp.Ga select= interp=linear spwmap=[-1] calWt=true
INFO Calibrator:::solve . P Jones <pre-computed>
INFO Calibrator:::solve The following calibration term is arranged for solve:
INFO Calibrator:::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 Calibrator:::solve For solint = inf, found 1 solution intervals.
INFO Mean CROSS-HAND PHASE solution for J1331+3030 (spw = 0) = 4.65 deg.
INFO Calibrator:::solve Found good Xf Jones solutions in 1 solution intervals.
INFO Writing solutions to table: pol.Xf
INFO calibrator:::solve Finished solving.
INFO polcal::: ##### End Task: polcal #####
INFO polcal:::+ #####
```

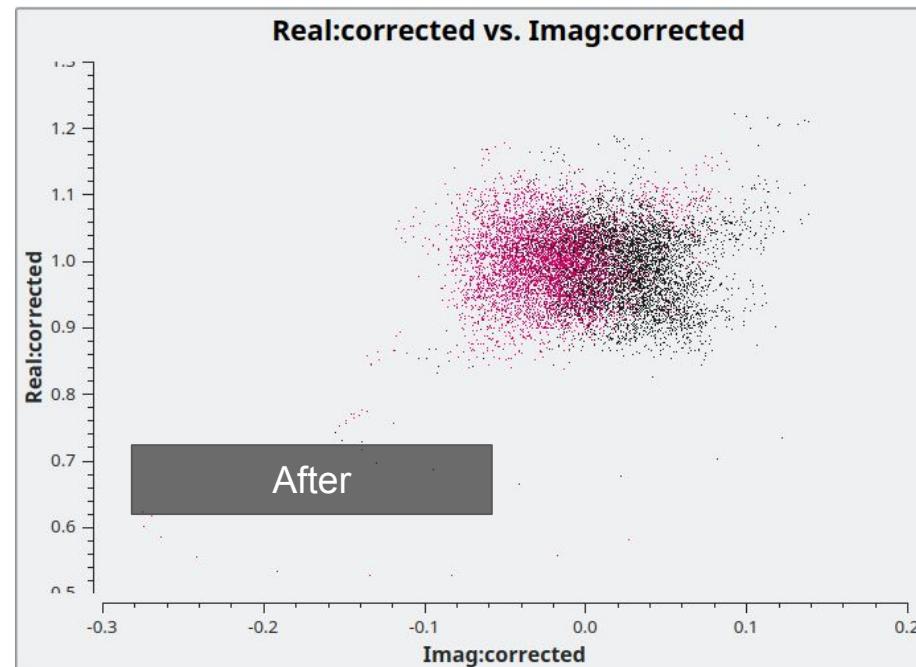
## **Gain Phase vs. Frequency**



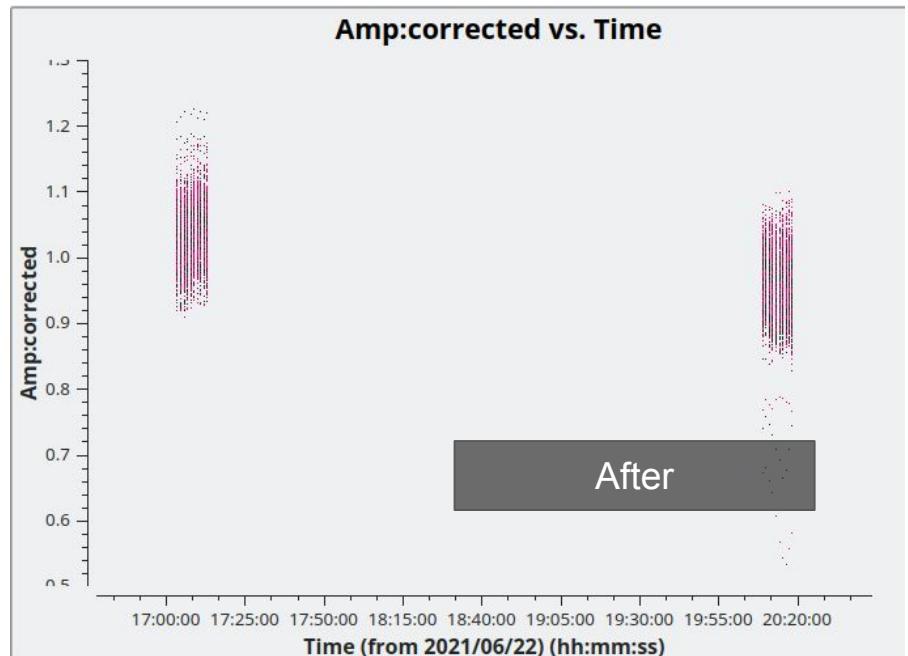
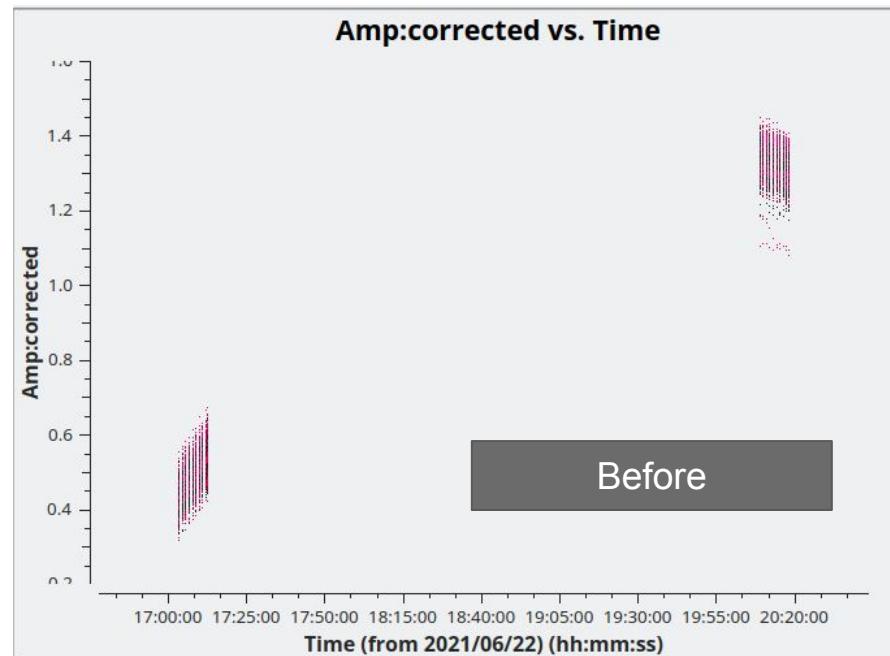
# HV phase: The proof is in the eating!

- 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', uvrage=">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', uvrage=">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!



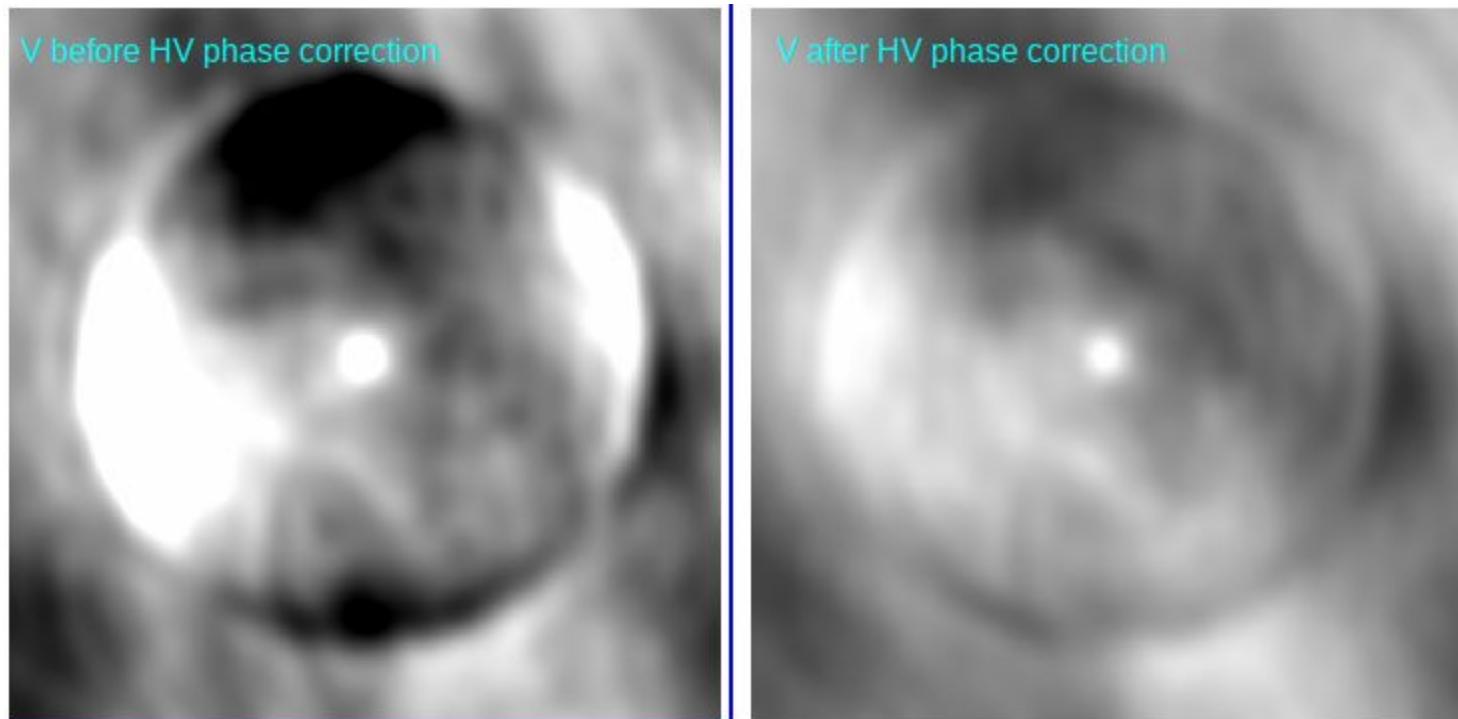
# 3C286: Application of parallactic angle



# 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 impedance 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).

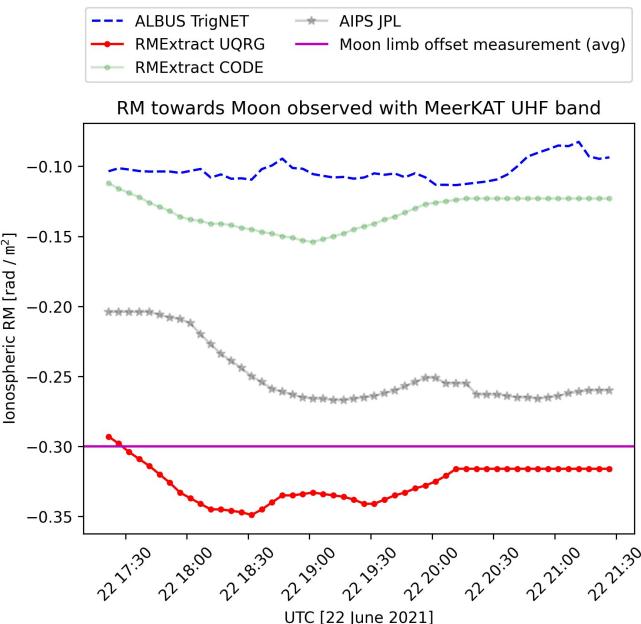
# Improvement in V (scale locked)



# 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 quiescent! 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<sup>2</sup> is common)!

Check out: [https://github.com/twillis449/ALBUS\\_ionosphere](https://github.com/twillis449/ALBUS_ionosphere)



Questions?