Instrumental calibrations

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IRAM
Why instrumental calibration

- A number of effects will reduce amplitude:
  - This leads to unrecoverable signal-to-noise loss.
  - Needs to be calibrated out in any case.
- Phase information as a dramatic effect on images.
  - Need as good as possible control of the phases.
- Need to setup the system for optimal performances:
  - Receiver alignments.
  - Panel adjustment.
- This can only be obtained by either:
  - Dedicated observing session
  - Long term monitoring
- Most effects need to be correct at the time of observing and cannot be corrected later on.
Outline

- Amplitude:
  - Atmospheric
    - Astronomical observations calibration.
    - WVR calibration.
  - Pointing.
  - Focusing.
- Phase:
  - Delay calibration.
  - Baselines measurements.
  - Cable phase correction.
- Holography.
Atmospheric calibration
System temperature

\[ T_{ant} = T_{bg} \]
\[ + \quad T_{sky} \sim \eta_f (1 - \exp(-\tau_{atm})T_{atm} \]
\[ + \quad T_{spill} \sim (1 - \eta_f - \eta_{loss})T_{ground} \]
\[ + \quad T_{loss} \sim \eta_{loss}T_{cabin} \]
\[ + \quad T_{rec} \]

- At mm wavelength, we are dominated by the atmosphere.
- 35K < T_{rec} < 100 K
- Taking into account receiver rejection and referring to a perfect antenna outside atmosphere, one gets:

\[ T_{sys} = (1 + g) \frac{\exp(\tau_{atm})}{\eta_f} T_{ant} \]

- Opacity correction allows to have sources on a scale proportional to their intensities (no more elevation dependent)
System temperature

- Determination of $T_{sys}$ and $T_{a^*}$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
System temperature

- Determination of $T_{sys}$ and $T_{a^*}$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
System temperature

- Determination of $T_{sys}$ and $T_a^*$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
    - Assume linearity of the receiving chain:
      \[
      P_{\text{chop}} = K \times (T_{\text{chop}} + T_{\text{rec}}) \\
      P_{\text{cold}} = K \times (T_{\text{cold}} + T_{\text{rec}}) \\
      T_{\text{rec}} = \frac{P_{\text{cold}} \times T_{\text{hot}} - P_{\text{hot}} \times T_{\text{cold}}}{P_{\text{hot}} - P_{\text{cold}}}
      \]
    - NOEMA: we use an ambient temperature load and mirror looking back at the 15K stage of the cryostat.
    - ALMA: ambient and hot load (350K).
System temperature

- Determination of $T_{sys}$ and $T_{a^*}$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
System temperature

- Determination of $T_{sys}$ and $T_{a^*}$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
    - Measurement on the sky and a load:
      \[
      P_{chop} = K \times (T_{chop} + T_{rec})
      \]
      \[
      P_{sky} = K \times (\eta_f (1 - \exp(-\tau_{atm}) T_{atm}) + (1 - \eta_f T_{ground}) + T_{rec})
      \]
System temperature

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  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
    - Measurement on the sky and a load:
      \[
      P_{chop} = K \times (T_{chop} + T_{rec}) \\
      P_{sky} = K \times (\eta_f (1 - \exp(-\tau_{atm}) T_{atm}) + (1 - \eta_f T_{ground}) + T_{rec})
      \]
    - Optically thin atmosphere (for simplicity, not required):
      \[
      (1 - \exp(-\tau_{atm})) \sim \tau_{atm} \sim \text{Airmass} \times \tau_{zenith}
      \]
System temperature

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  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
    - Measurement on the sky and a load:
      \[
      P_{\text{chop}} = K \times (T_{\text{chop}} + T_{\text{rec}}) \\
      P_{\text{sky}} = K \times (\eta_f (1 - \exp(-\tau_{\text{atm}})T_{\text{atm}}) + (1 - \eta_f T_{\text{ground}}) + T_{\text{rec}})
      \]
    - Optically thin atmosphere (for simplicity, not required):
      \[
      (1 - \exp(-\tau_{\text{atm}})) \sim \tau_{\text{atm}} \sim \text{Airmass} \times \tau_{\text{zenith}}
      \]
    - So we have:
      \[
      (T_{\text{chop}} + T_{\text{rec}}) \times \frac{P_{\text{sky}}}{P_{\text{chop}}} - T_{\text{rec}} = \eta_f \times \text{Airmass} \times \tau_{\text{zenith}} + (1 - \eta_f)T_{\text{ground}}
      \]
Skydips

Determination of $T_{sys}$ and $T_a^*$ requires knowledge of:

1. Atmosphere and ground temperature: meteo station
2. Forward efficiency: skydips
System temperature

• Determination of $T_{sys}$ and $T_{a^*}$ requires knowledge of:
  • Atmosphere and ground temperature: meteo station
  • Forward efficiency: skydips
  • Receiver temperature: chopper wheel method
  • Receiver gain (sideband attenuation): measurement on a quasar
System temperature

- Determination of $T_{sys}$ and $T_a^*$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Forward efficiency: skydips
  - Receiver temperature: chopper wheel method
  - Receiver gain (sideband attenuation): measurement on a quasar
    - Add an offset to LO1 phase:

$$
\begin{array}{c|c}
\psi_1 & \text{Signal} \\
0 & V_1 = A_U e^{i\varphi_u} + A_L e^{-i\varphi_L} \\
\pi/2 & V_2 = A_U e^{i(\varphi_u - \pi/2)} + A_L e^{i(-\varphi_L + \pi/2)} \\
\end{array}
$$
System temperature

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  - Atmosphere and ground temperature: meteo station
  - Forward efficiency: skydips
  - Receiver temperature: chopper wheel method
  - Receiver gain (sideband attenuation): measurement on a quasar
    - Add an offset to LO1 phase:
      $$\psi_1$$
      | Signal |
      |------------------|
      | $V_1 = A_U e^{i\psi_U} + A_L e^{-i\psi_L}$ |
      | $V_2 = A_U e^{i(\psi_U - \pi/2)} + A_L e^{i(-\psi_L + \pi/2)}$ |
    - And compute the visibilities in each sideband:
      $$A_U e^{i\psi_U} = \frac{(V_1 + iV_2)}{2}$$
      $$A_L e^{-i\psi_L} = \frac{(V_1 - iV_2)}{2}$$
System temperature

- Determination of $T_{sys}$ and $T_a^*$ requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Forward efficiency: skydips
  - Receiver temperature: chopper wheel method
  - Receiver gain (sideband attenuation): measurement on a quasar
    - Add a frequency offset to LO1 and LO2:
      \[
      \omega_1 = \omega_1^{ref} + \delta \omega \\
      \omega_2 = \omega_2^{ref} - \delta \omega
      \]
System temperature

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  - Atmosphere and ground temperature: meteo station
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  - Receiver temperature: chopper wheel method
  - Receiver gain (sideband attenuation): measurement on a quasar
    - Add a frequency offset to LO1 and LO2:
      $$
      \omega_1 = \omega_{1}^{ref} + \delta \omega
      $$
      $$
      \omega_2 = \omega_{2}^{ref} - \delta \omega
      $$
    - Fringes will be stopped in the signal SB but rotate in image SB
      $$
      \psi(USB) = \psi_U - \delta \omega \tau_g + \delta \omega \tau_g = \psi_U
      $$
      $$
      \psi(LSB) = -\psi_L + 2 \delta \omega \tau_g
      $$
System temperature

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  - Atmosphere and ground temperature: meteo station
  - Forward efficiency: skydips
  - Receiver temperature: chopper wheel method
  - Receiver gain (sideband attenuation): measurement on a quasar
  - Atmosphere opacity: use of an atmospheric model
Using an atmospheric model

- Use of an atmospheric model. NOEMA and ALMA uses different flavour of the ATM model (J. Cernicharo, J. Pardo). E.g.

- SMA uses am (S. Paine).
- Allow to derive water vapor
Atmospheric calibration

- At NOEMA, atmospheric calibration is done with one value per baseband.
- Actually two operations are performed:
  - 1. Data are scaled by Tsys so that they are on a Ta* temperature scale.
  - 2. In addition crosscorrelation spectra are divided by the square-root of the product of the autocorrelation spectra to correct bandpass (amplitude only).
- Data are then stored in a file.
- This can be redone (except 2.) using CLIC\ATMOSPHERE.
- At ALMA, only 2. is done online, and “raw” data are stored in the asdm file. Multiplication by Tsys is done later on.
Radiometers
Radiometers calibration

- We just have one usable load.
- Using skydips to compute radiometer receiver temperatures.
- Compute a calibration factor using receiver temperature and observation of the hot load (commuted during the regular astronomical atmospheric calibration).
- Compute the derivative of the optical path with respect to the radiometer brightness temperature.
- Update scaling factors used to compute a phase.
- The correlator software uses these scaling factors and the raw counts to compute a correction (including time averaging if needed).
- The average spectrum is computed with and without correction, and both are kept in the files so that a non-working correction does not harm otherwise good data. Pipeline later chooses which data to use.
- This calibration can be redone using CLIC\WVR.
Pointing
Pointing

- With an aperture taper, primary beam is roughly gaussian.
- 10% loss at 0.2 FWHM.
- Knowledge of the beam (including offsets) crucial for large-scale imaging (mosaics, on-the-fly imaging).
- We need to have a sufficiently good pointing. For NOEMA:
  - 0.5” tracking accuracy
  - 2” pointing accuracy
- Unlike in the optical, strong sources are scare, so we cannot use guide stars.
Pointing

- We slew the antenna over a point source (in azimuth and in elevation), fit a gaussian, and derive corrections which are entered in the system regularly.
- A (really) bad pointing leads to unrecoverable loss of signal-to-noise and tricky to impossible corrections to the amplitude.
- Possible to fit total power (not requiring to have fringes) or amplitude.
- Other pattern are possible (e.g. ALMA using 5 points pointing).
NOEMA pointing model

IAZ azimuth encoder zero
\[ dX = IAZ \cdot \cos(El) \quad dY = 0 \]

IEL elevation encoder zero
\[ dX = 0 \quad dY = IEL \]

COH telescope azimuth collimation
\[ dX = \cos(El) \cdot \arcsin(COH/\cos(El)) \quad dY = -\arcsin(\sin(El)/\sqrt{1-COH^2}) \]
for \( COH << \cos(El) \), equivalent to
\[ dX = COH \quad dY = 0, \]

COV telescope vertical collimation
\[ dX = 0 \quad dY = COV \]

MVE Azimuth axis tilt towards East
\[ dX = MVE \cdot \cos(Az) \cdot \sin(El) \quad dY = -MVE \cdot \sin(Az) \]

MVN Azimuth axis tilt towards North
\[ dX = -MVN \cdot \sin(Az) \cdot \sin(El) \quad dY = -MVN \cdot \cos(Az) \]

NPE Elevation axis tilt (axis non perpendicularity)
\[ dX = -NPE \cdot \sin(El) \quad dY = 0 \]
(assuming small NPE and COH in practice.)

REFO First order refraction coefficient
\[ dX = 0 \quad dY = -REFO/\tan(El) \]

REF1 Second order refraction coefficient
\[ dX = 0 \quad dY = -REF1/\tan(El)^3 \]

ELES gravity+eccentricity of Elevation encoder
\[ dX = 0 \quad dY = ELES \cdot \sin(El) \]

ELEC gravity+eccentricity of Elevation encoder
\[ dX = 0 \quad dY = ELEC \cdot \cos(El) \]

AZES eccentricity of Azimuth encoder
\[ dX = AZES \cdot \sin(Az) \cdot \cos(El) \quad dY = 0 \]

AZEC eccentricity of Azimuth encoder
\[ dX = AZEC \cdot \cos(Az) \cdot \cos(El) \quad dY = 0 \]

HEL Homology elevation bending (\cos(El))
\[ dX = 0 \quad dY = -HEL \cdot \cos(El) \]
Derive pointing model parameters

- Corrections:

\[
\begin{align*}
\Delta X &= IAZ \cdot \cos(El) + COH \cdot \sin(El) \cdot (MVE \cdot \cos(Az) - MVN \cdot \sin(Az) - NPE) \\
&\quad + \cos(El) \cdot (AZES \cdot \sin(Az) + AZEC \cdot \cos(Az)) \\
\Delta Y &= IEL + COV - (MVE \cdot \sin(Az) + MVN \cdot \cos(Az)) \\
&\quad + (ELES \cdot \sin(El) + (ELEC-HEL) \cdot \cos(El)) \\
&\quad - \frac{REF0}{\tan(El)} - \frac{REF1}{\tan(El)^2} - \frac{REF2}{\tan(El)^3}
\end{align*}
\]

- Parameters playing the larger role:
  - IAZ, IEL+COV, COH, MVE, MVN, HEL
  - Depending on antenna or antenna+station
  - We use inclinometers to monitor the antenna tilt.
  - Corrected for the local gravity vector (attraction of the Alps).
Do pointing all-over the sky

Pointing sampling in Azimuth and Elevation

Azimuth

Elevation
Derive pointing model parameters
Focus
Focus

- An error in the positioning of the subreflector causes an unrecoverable loss of signal-to-noise and/or pointing errors and/or primary beam deformations (e.g. Coma with asymmetric sidelobes).
- Homological design need to have a focus model as well: variation of focus position as a function of elevation (X, Z directions).
- Thermal variation of focus (sunset, sunrise)
- NOEMA make focus measurement (Z only) every hour or so.
- **ALMA makes XYZ focus and tabulates focus value as a function of elevation and temperature and applies it.**

![Figure 1.8: Illustration of a coma}\text{\textit{ic beam (scanned in the direction of the coma) especially produced on the IRAM 15-m telescope. The shift of the subreflector is indicated by S. The beam pattern is perfect at S = 0. Note the shift of the beam (pointing error) when the subreflector is shifted.}}
NOEMA focus measurement

Subband used: C09
Scan: 8069 R1 Source: 3C454.3


Focus (mm)

0 0.2 0.4 0.6 0.8
-1 -0.2 -0.4 -0.6 -0.8

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IRAM millimeter interferometry summerschool
Focus model

- Dependence on elevation only: observe a “strip” at a given azimuth.
- We do not (yet) directly measure X and Y focus.
- But a lateral defocus gives a pointing error:

<table>
<thead>
<tr>
<th>defocus component</th>
<th>symbol</th>
<th>pointing error</th>
</tr>
</thead>
<tbody>
<tr>
<td>translation primary</td>
<td>$y_p$</td>
<td>$- K_p (y_p / f)$</td>
</tr>
<tr>
<td>rotation primary</td>
<td>$\epsilon$</td>
<td>$(1 + K_p) \epsilon$</td>
</tr>
<tr>
<td>translation secondary</td>
<td>$y_s$</td>
<td>$(y_s / f) (K_p - K_s / M)$</td>
</tr>
<tr>
<td>rotation secondary (vertex)</td>
<td>$\alpha$</td>
<td>$- \alpha (2 c / f) (K_p + K_s) / (M + 1)$</td>
</tr>
<tr>
<td>rotation secondary (focus)</td>
<td>$\alpha$</td>
<td>$- \alpha (2 c / f) (K_s / M)$</td>
</tr>
<tr>
<td>translation feed (in sec. focus)</td>
<td>$y_f$</td>
<td>$(y_f / f) (K_s / M)$</td>
</tr>
</tbody>
</table>

- Knowing the beam deviation factor (BDF) $K_p$, we can derive the lateral shift we are interested in.
Delay
Delay calibration

- An uncorrected (constant) delay introduce a phase slope as a function of frequency:
  \[ \Phi(\nu_{IF}) = \pm 2\pi \nu_{IF} \Delta \tau \]
- Geometrical delay can be computed with accurate baselines, positions and timing.
- However, despite good engineering, small instrumental delays, depending on the instrumental setup remain.
- Part is done online, using a noise source, allowing to coherently add all the spectral windows connected to it.
Delay measurement

- Measured delay are added to the known instrumental delay (length of fiber optics) and to the geometrical delay and corrected for in the correlator/correlator software.

- Correlator has a given time resolution (inverse of the sampling frequency), allowing only to correct delays down to that resolution. Fine delays are corrected in software.

- Having corrected delays allows averaging of spectra needed to get the continuum sensitivity required for calibration.

- Can however be corrected offline using **CLIC\MODIFY DELAY**

- At ALMA, this is done automatically on phase calibrator (INTENT=CALIBRATE_DELAY). Use of a much more complex delay server (have to take into account propagation time to the antenna, dry component due to possible altitude difference between stations, etc.)
Baseline
Measuring phases

- Measured phase are:

\[\phi_{ij}^g = \phi_{ij}^s + \phi_{ij}^o = 2\pi w = \]

\[= \frac{2\pi}{\lambda} \left[ X_{ij}, Y_{ij}, Z_{ij} \right] \cdot \begin{pmatrix} \cos H \cos \delta \\ -\sin H \cos \delta \\ \sin \delta \end{pmatrix} + \phi_{ij}^o\]

\[\rightarrow \Delta \phi_{ij,k}^g = \frac{2\pi}{\lambda} \left( \Delta b_{ij} \cdot s_k + b_{ij} \cdot \Delta s_k \right) + \Delta \phi_{ij,k}^o \approx 0\]

- Observing sources distributed in hour-angle and declination, with a stable atmospheric phase allow to derive positions (wrt an reference position).

- We need of course to know accurately the position of the observed sources.

- At ALMA, possibility to fit differential delays between sources.
Measuring baselines
Raw phases
After baseline fit
Baseline measurements

- Usually done after configuration change.
- Needs
  - accurate source positions.
  - Excellent weather conditions.
- Can be redone offline using:
  - CLIC\MODIFY ANTENNA
  or
  - CLIC\MODIFY BASELINE
- Position can also be updated offline with:
  - CLIC\MODIFY POSITION
  (e.g. To correct for the position of a phase calibrator).
Cable phase
Need to control cable phase

- At NOEMA, reference signal are transported through an HiQ cable. LO1 reference frequency is transported in the 1.6-2.1 GHz range. This frequency is hence multiplied by a factor 50-150, depending on the frequency band.

- For 1km cable, with a linear expansion coefficient of 1e-5, a 1K gradient lengthen the cable by 10mm, or 10 turns at 1mm !

- We monitor the length of the cable by sending forth the reference frequency plus 500 kHz, and back the reference frequency, the difference of these being compared to a reference 500 kHz oscillator.

- Data are corrected in real-time in the correlator software for this “cable phase”.

- At ALMA, reference is from photonics LO, and cable phase is corrected physically in the LLC (line-length corrector) by mechanically stretching a fiber optic.
LO1 control

1pps 5 MHz
Barycentric Generator (future option)

128-B
1pps-B
align

LO control
Computer

32pps counter
5 MHz

μProc

320 MHz

DDS
100 MHz

BPF

Φ-rotator

32pps counter
5 MHz

μProc

32MHz

DDS
0.5 MHz

BPF

Φ-meter

Power amp.

1.6-2.1 GHz

320 MHz

32 MHz

1.6-2.1 GHz

Round-Trip
Extractor

Triplexer

Hi-Q Cable terminal

Test Points

Legend: digital analog

Comparators latched EtherCat latency
Compute & write new phase (*) EtherCat latency
Integrate

Phase meter loop timing

(*) On the 31st period, the computer also averages the 32 previous measurements and computes/writes the new correction for the next second to Φ-rotator DDS

LO1 Control
MT Apr 2012 rev May 2013
Holography
Holography

- Far-field approximation (Fraunhofer region):

\[ f(u, v) = \frac{i}{\lambda} \frac{e^{-ikR}}{R} \int F(\xi, \eta) \exp\{-ik(\xi u + \eta v)\} d\xi d\eta \]

\[ F(\xi, \eta) = \frac{1}{4\pi} \frac{e^{ikR}}{R} \int f(u, v) \exp\{ik(u\xi + v\eta)\} dudv \]

- Near-field approximation (Fresnel region):

\[ f(u, v) = \frac{i}{\lambda} \frac{e^{ikR}}{R} \int F(\xi, \eta) \exp \left\{ ik \left[ -(u\xi + v\eta) + \frac{\xi^2 + \eta^2}{2R} \right] \right\} d\xi d\eta \]

- A Fourier transform relationship between the far-field pattern and the complex aperture field distribution (and almost in the near-field case).

- Far field:

\[ D_{f.f} > 2d^2 / \lambda \]

Fig. 1. Geometry of the aperture integration method for finite distance to the field point P.

Baars et al. 2007
Holography

- We scan a source with one antenna while keeping a reference antenna pointing at the source.
- We grid the data, we (Fast)-Fourier transform back them.
Edge taper = 14.76x 12.15 dB - offset X= 0.32 Y= -0.26 m
Focus offsets (X,Y,Z) = 0.00 0.00 0.00 mm; Astigmatism = 0.0 μm (180.0deg.)
Phase rms (unweighted)= 0.238 (weighted)= 0.239 radians
Surface rms (unweighted)= 74.78 - (weighted)= 69.91 μm
η(86.243 GHz) = 0.739; η(230.0 GHz) = 0.537; η(345.0 GHz) = 0.340
S/T(86.243 GHz)= 21.141 Jy/K; S/T(230GHz)= 29.064 Jy/K; S/T(345 GHz)= 45.909 Jy/K
η = 0.779 -ηs = 0.780 -ηp(86.243 GHz) = 0.949 -ηp(230 GHz) = 0.690 -ηp(345 GHz) = 0.437
Rms/ring: 42.8 41.5 39.4 46.4 44.9 70.4
Amplitude (back view) -15.000 to 0.000 by 3.000
Normal errors (back view) -300.000 to 300.000 by 300.000
Effect of defocusing

- An axial defocus induces the following path-length error:

\[
\delta p_z = \delta z \left\{ 1 - \frac{1 - \frac{\xi^2 + \eta^2}{4f^2} + \frac{\delta f}{f}}{\sqrt{\frac{\xi^2 + \eta^2}{4f^2} + \left(1 - \frac{\xi^2 + \eta^2}{4f^2} + \frac{\delta f}{f}\right)^2}} \right\}
\]

- An transverse offset will produce:

\[
\delta p_x = \delta x \frac{\xi}{f} \left\{ \frac{1}{1 + \frac{\delta f}{f}} - \frac{1}{\sqrt{\frac{\xi^2 + \eta^2}{f^2} + \left(1 - \frac{\xi^2 + \eta^2}{4f^2} + \frac{\delta f}{f}\right)^2}} \right\}
\]

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Baars et al. 2007
Edge taper = 14.76x 12.15 dB - offset X= 0.32 Y= -0.26 m

Focus offsets (X,Y,Z) = 0.00 0.00 0.48 mm; Astigmatism = 0.0 μm (180.0 deg.)

Phase rms (unweighted) = 0.163 (weighted) = 0.151 radians

Surface rms (unweighted) = 52.35 μm (weighted) = 47.04 μm

\( \eta_A(86.243 \text{ GHz}) = 0.761; \eta_A(230.0 \text{ GHz}) = 0.662; \eta_A(345.0 \text{ GHz}) = 0.542 \)

\( \frac{S}{T}(86.243 \text{ GHz}) = 20.525 \text{ Jy/K}; \frac{S}{T}(230 \text{ GHz}) = 23.585 \text{ Jy/K}; \frac{S}{T}(345 \text{ GHz}) = 28.799 \text{ Jy/K} \)

\( \eta_I = 0.779; -\eta_S = 0.780; -\eta_P(86.243 \text{ GHz}) = 0.977; -\eta_P(230 \text{ GHz}) = 0.851; -\eta_P(345 \text{ GHz}) = 0.697 \)

Rms/ring: 43.0 40.7 38.5 44.7 44.7 69.6

Amplitude (back view) -15.000 to 0.000 by 3.000

Normal errors (back view) -300.000 to 300.000 by 300.000
Edge taper = 14.76x 12.15 dB – offset X = 0.32 Y = -0.26 m

Phase rms (unweighted) = 0.143 (weighted) = 0.126 radians
Surface rms (unweighted) = 46.54 μm (weighted) = 40.01 μm

η_A(86.243 GHz) = 0.766; η_A(230.0 GHz) = 0.697; η_A(345.0 GHz) = 0.609
S/T(86.243 GHz) = 20.382 Jy/K; S/T(230 GHz) = 22.422 Jy/K; S/T(345 GHz) = 25.636 Jy/K

η_I = 0.779 - η_S = 0.780 - η_P(86.243 GHz) = 0.984 - η_P(230 GHz) = 0.895 - η_P(345 GHz) = 0.783

Rms/ring: 31.1 23.2 24.8 42.3 43.8 65.0

Amplitude (back view)
-15.000 to 0.000 by 3.000

Normal errors (back view)
-300.000 to 300.000 by 300.000
Am: Rel.(B)  3C454.3  7ant–Special scans 1025 to 1099 11–APR–2015  07:56UT El: 57.14
Ph: Rel.(B)  

Edge taper = 14.76x 12.15 dB – offset X= 0.32 Y= -0.26 m

Focus offsets (X,Y,Z) = -0.38 0.62 0.48 mm; Astigmatism = 13.3 μm ( 35.1 deg.)

Phase rms (unweighted) = 0.131 (weighted) = 0.119 radians
Surface rms (unweighted) = 42.14 (weighted) = 37.34 μm

η_A(86.243 GHz) = 0.768; η_A(230.0 GHz) = 0.705; η_A(345.0 GHz) = 0.626
S/T(86.243 GHz)= 20.345 Jy/K; S/T(230GHz)= 22.142 Jy/K; S/T(345 GHz)= 24.941 Jy/K
η_I= 0.779 -η_S= 0.780 -η_P(86.243 GHz)= 0.986 -η_P(230 GHz)= 0.906 -η_P(345 GHz)= 0.804

Rms/ring: 31.5 23.6 26.6 40.4 39.7 55.8

Amplitude (back view)
-15.000 to 0.000 by 3.000

Normal errors (back view)
-300.000 to 300.000 by 300.000
Edge taper = 14.76x 12.15 dB - offset X= 0.32 Y= -0.26 m
focus offsets (X,Y,Z) = -0.38 0.62 0.48 mm; Astigmatism = 13.3 μm (35.1 deg.)
Phase rms (unweighted)= 0.131 (weighted)= 0.119 radians
Surface rms (unweighted)= 42.14 - (weighted)= 37.34 μm

η_A(86.243 GHz) = 0.768; η_A(230.0 GHz) = 0.705; η_A(345.0 GHz) = 0.626
S/T(86.243 GHz) = 20.345 Jy/K; S/T(230GHz) = 22.142 Jy/K; S/T(345 GHz) = 24.941 Jy/K

η_I = 0.779 -η_S = 0.780 -η_P(86.243 GHz) = 0.986 -η_P(230 GHz) = 0.906 -η_P(345 GHz) = 0.804

Panel fit (back view)
-300.000 to 300.000 by 300.000

Residual after panel fit: 23.75μm (back view)
-300.000 to 300.000 by 300.000
Holography

- After Fourier transform:
  - Transform the amplitude in dB
  - Fit a parabola to the amplitude:
    - Measure feed taper
    - Receiver alignment
  - Fit the phases for:
    - Constant phase
    - Phase slope (constant pointing error)
    - x,y,z focus
    - Astigmatism
    - Panels
- This allow to compute aperture efficiency and illumination efficiency.
Other pattern: ALMA

- On can do a radial scanning.
  - Does not need inter-scan boresight measurements
  - Give more weight to the central part (large scales in the aperture)
    - Ideal for beam shape measurement, focus measurement etc.
- Was tested and is used at ALMA.
## Summary

<table>
<thead>
<tr>
<th>Calibration</th>
<th>Can be corrected</th>
<th>When is it done</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pointing</td>
<td>No</td>
<td>Every 1/2h</td>
</tr>
<tr>
<td>Focusing</td>
<td>No</td>
<td>Every 1h</td>
</tr>
<tr>
<td>Delay</td>
<td>Yes</td>
<td>Once per track</td>
</tr>
<tr>
<td>Baseline</td>
<td>Yes</td>
<td>Once per config</td>
</tr>
<tr>
<td>Cable phase</td>
<td>No</td>
<td>Always</td>
</tr>
<tr>
<td>WVR phase corr.</td>
<td>No</td>
<td>Always</td>
</tr>
<tr>
<td>Holography</td>
<td>No</td>
<td>When needed</td>
</tr>
<tr>
<td>Atm. calibration</td>
<td>Yes</td>
<td>Every source change</td>
</tr>
</tbody>
</table>