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

$$\begin{aligned} T_{ant} &= T_{bg} \\ &+ T_{sky} \sim \eta_f (1 - \exp(-\tau_{atm}) T_{atm} \\ &+ T_{spill} \sim (1 - \eta_f - \eta_{loss}) T_{ground} \\ &+ T_{loss} \sim \eta_{loss} T_{cabin} \\ &+ T_{rec} \end{aligned}$$

- At mm wavelength, we are dominated by the atmosphere.
- 35K < Trec < 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 Tsys and Ta* requires knowledge of:
  - Atmosphere and ground temperature: meteo station

System temperature

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  - Receiver temperature: chopper wheel method

System temperature

- Determination of Tsys and Ta* requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
    - Assume linearity of the receiving chain:

$$\begin{aligned} P_{chop} &= K \times (T_{chop} + T_{rec}) \\ P_{cold} &= K \times (T_{cold} + T_{rec}) \end{aligned}$$

$$T_{rec} = \frac{P_{cold} \times T_{hot} - P_{hot} \times T_{cold}}{P_{hot} - P_{cold}}$$

    - 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 Tsys and Ta* requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips

System temperature

- Determination of Tsys and Ta* requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
    - Measurement on the sky and a load:

$$
\begin{aligned}
P_{chop} &= K \times (T_{chop} + T_{rec}) \\
P_{sky} &= K \times (\eta_f \, (1 - \exp(-\tau_{atm}) \, T_{atm}) + (1 - \eta_f T_{ground}) + T_{rec})
\end{aligned}
$$

System temperature

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  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
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\end{aligned}
$$

    - Optically thin atmosphere (for simplicity, not required):

$$
(1 - \exp(-\tau_{atm})) \sim \tau_{atm} \sim \mathrm{Airmass} \times \tau_{zenith}
$$

System temperature

- Determination of Tsys and Ta* requires knowledge of:
  - Atmosphere and ground temperature: meteo station
  - Receiver temperature: chopper wheel method
  - Forward efficiency: skydips
    - Measurement on the sky and a load:

$$\begin{aligned} P_{chop} &= K \times (T_{chop} + T_{rec}) \\ P_{sky} &= K \times (\eta_f\,(1 - \exp(-\tau_{atm})\,T_{atm}) + (1 - \eta_f T_{ground}) + T_{rec}) \end{aligned}$$

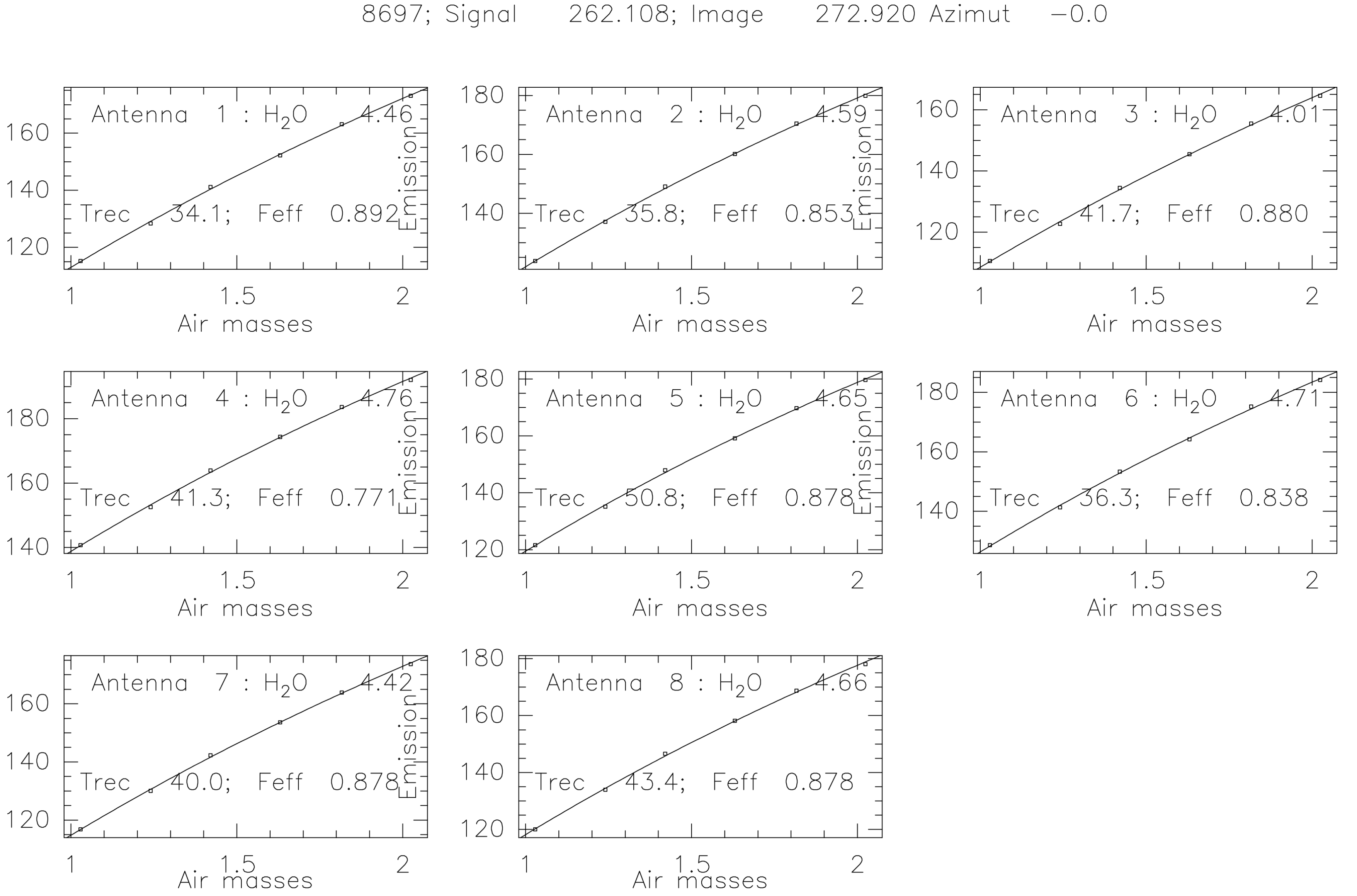
    - Optically thin atmosphere (for simplicity, not required):

$$(1 - \exp(-\tau_{atm})) \sim \tau_{atm} \sim \mathrm{Airmass} \times \tau_{zenith}$$

    - So we have:

$$(T_{chop} + T_{rec}) \times \frac{P_{sky}}{P_{chop}} - T_{rec} = \eta_f \times \mathrm{Airmass} \times \tau_{zenith} + (1 - \eta_f)T_{ground}$$

Skydips


8697; Signal 262.108; Image 272.920 Azimut −0.0
Antenna 1 : H_2O 4.46
Trec 34.1; Feff 0.892
Antenna 2 : H_2O 4.59
Trec 35.8; Feff 0.853
Antenna 3 : H_2O 4.01
Trec 41.7; Feff 0.880
Antenna 4 : H_2O 4.76
Trec 41.3; Feff 0.771
Antenna 5 : H_2O 4.65
Trec 50.8; Feff 0.878
Antenna 6 : H_2O 4.71
Trec 36.3; Feff 0.838
Antenna 7 : H_2O 4.42
Trec 40.0; Feff 0.878
Antenna 8 : H_2O 4.66
Trec 43.4; Feff 0.878
Emission
Air masses

System temperature

- Determination of Tsys and Ta* 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 Tsys and Ta* 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:

ψ_1	Signal
0	$V_1 = A_\mathrm{U} e^{i\varphi_\mathrm{U}} + A_\mathrm{L} e^{-i\varphi_\mathrm{L}}$
$\pi/2$	$V_2 = A_\mathrm{U} e^{i(\varphi_\mathrm{U} - \pi/2)} + A_\mathrm{L} e^{i(-\varphi_\mathrm{L} + \pi/2)}$

System temperature

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  - Atmosphere and ground temperature: meteo station
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$\pi/2$	$V_2 = A_U e^{i(\varphi_U - \pi/2)} + A_L e^{i(-\varphi_L + \pi/2)}$

    - And compute the visibilities in each sideband:

$$A_U e^{i\varphi_U} = (V_1 + iV_2)/2$$
$$A_L e^{-i\varphi_L} = (V_1 - iV_2)/2$$

System temperature

- Determination of Tsys and Ta* 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
  - Forward efficiency: skydips
  - Receiver temperature: chopper wheel method
  - Receiver gain (sideband attenuation): measurement on a quasar
    - Add a frequency offset to LO1 and LO2:

$$\omega_1 = \omega_1^{ref} + \delta\omega$$
$$\omega_2 = \omega_2^{ref} - \delta\omega$$

    - Fringes will be stopped in the signal SB but rotate in image SB

$$\begin{aligned}\psi(USB) &= \psi_U - \delta\omega\tau_g + \delta\omega\tau_g \\ &= \psi_U\end{aligned}$$

$$\psi(LSB) = -\psi_L + 2\delta\omega\tau_g$$

System temperature

- Determination of Tsys and Ta* 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
  - Atmosphere opacity: use of an atmospheric model

Using an atmospheric model

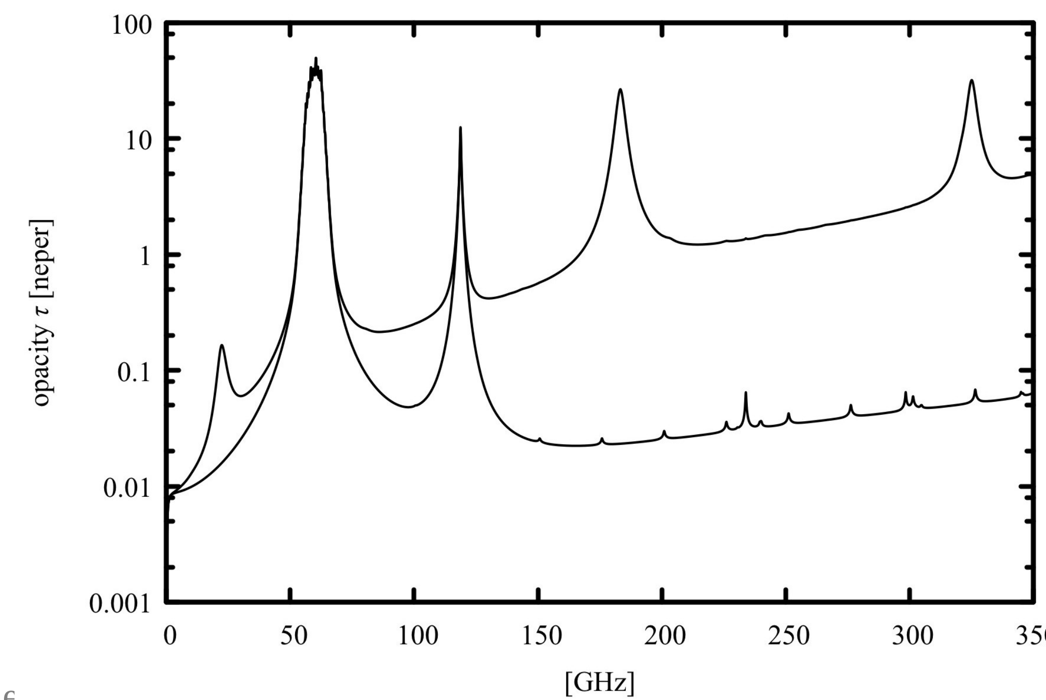
- Use of an atmospheric model. NOEMA and ALMA uses different flavour of the ATM model (J. Cernicharo, J. Pardo). E.g.

IEEE TRANSACTIONS ON ANTENNAS AND PROPAGATION, VOL. 49, NO. 12, DECEMBER 2001 1683

Atmospheric Transmission at Microwaves (ATM): An Improved Model for Millimeter/Submillimeter Applications

Juan R. Pardo, José Cernicharo, and Eugene Serabyn

- 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

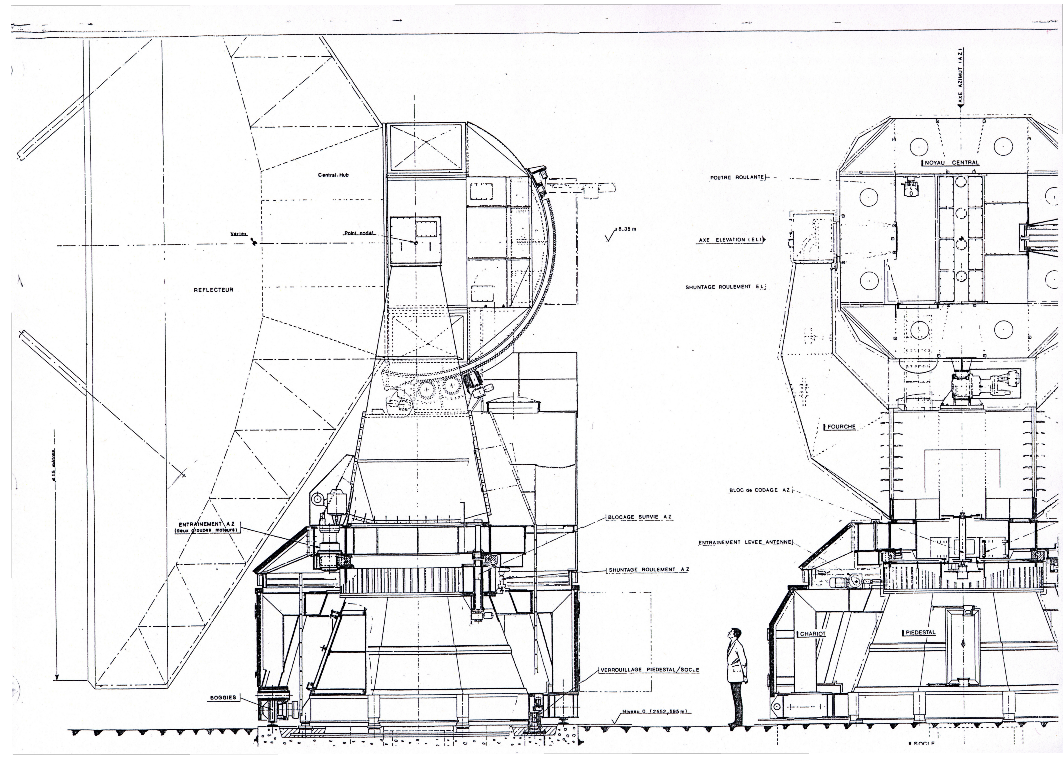
Radiometers calibration

- 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.

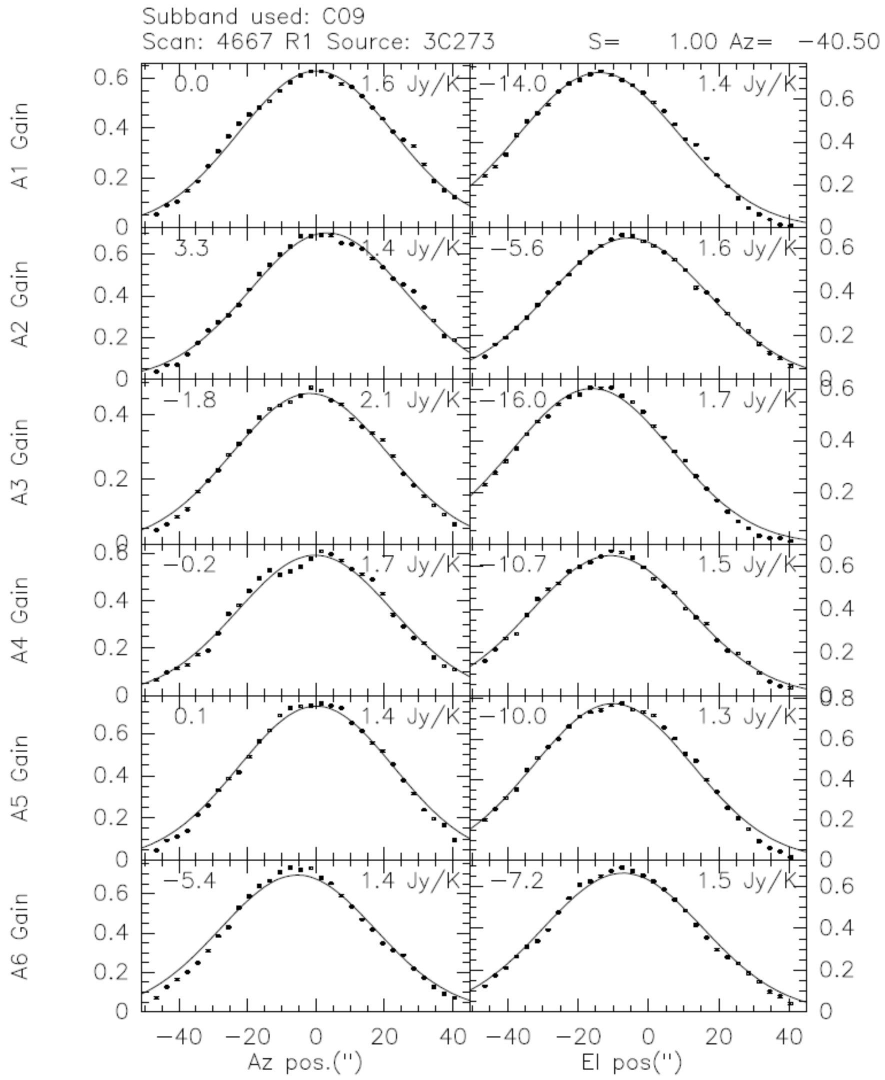
Pointing

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

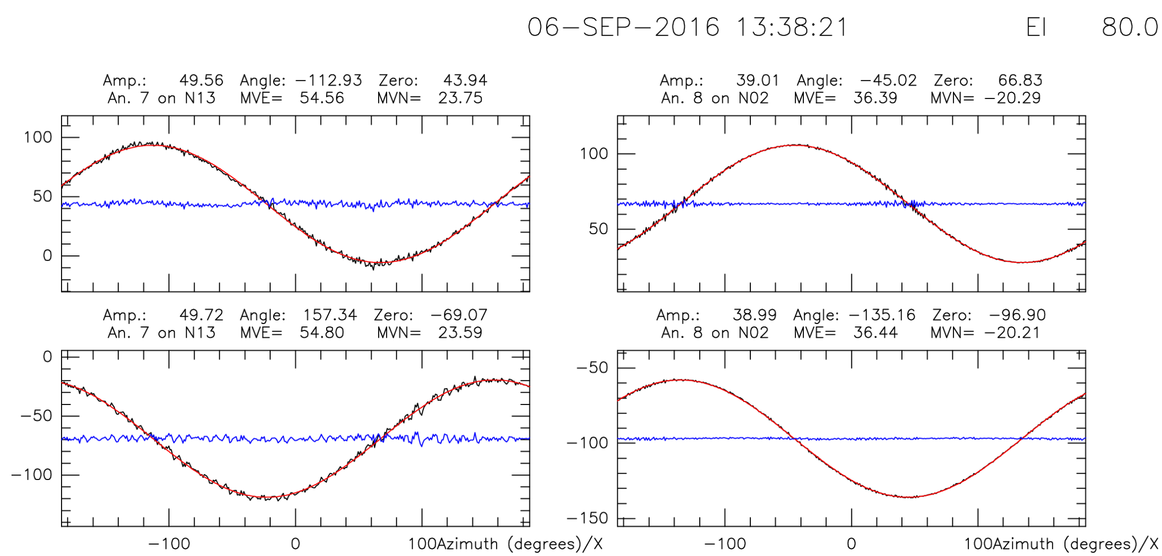
```
IAZ     azimuth encoder zero
        dX = IAZ*cos(El)               dY = 0
IEL     elevation encoder zero
        dX = 0                         dY = IEL
COH     telescope azimuth collimation
        dX = cos(El)*asin(COH/cos(El)) dY = -asin(sin(El)/sqrt(1-COH**2))
        for COH << cos(El), equivalent to
        dX = COH                       dY = 0,
COV     telescope vertical collimation
        dX = 0                         dY = COV
MVE     Azimuth axis tilt towards East
        dX =  MVE*cos(Az)*sin(El)      dY = -MVE*sin(Az)
MVN     Azimuth axis tilt towards North
        dX = -MVN*sin(Az)*sin(El)      dY = -MVN*cos(Az)
NPE     Elevation axis tilt (axis non perpendicularity)
        dX = -NPE*sin(El)              dY = 0
        (assuming small NPE and COH in practice.)
REF0    First order refraction coefficient
        dX = 0                         dY = -REF0/tan(El)
REF1    Second order refraction coefficient
        dX = 0                         dY = -REF1/tan(El)**3
ELES    gravity+eccentricity of Elevation encoder
        dX = 0                         dY =  ELES*sin(El)
ELEC    gravity+eccentricity of Elevation encoder
        dX = 0                         dY =  ELEC*cos(El)
AZES    eccentricity of Azimuth encoder
        dX = AZES*sin(Az)*cos(El)      dY = 0
AZEC    eccentricity of Azimuth encoder
        dX = AZEC*cos(Az)*cos(El)      dY = 0
HEL     Homology elevation bending (cos(El))
        dX = 0                         dY = -HEL*cos(El)
```

Derive pointing model parameters

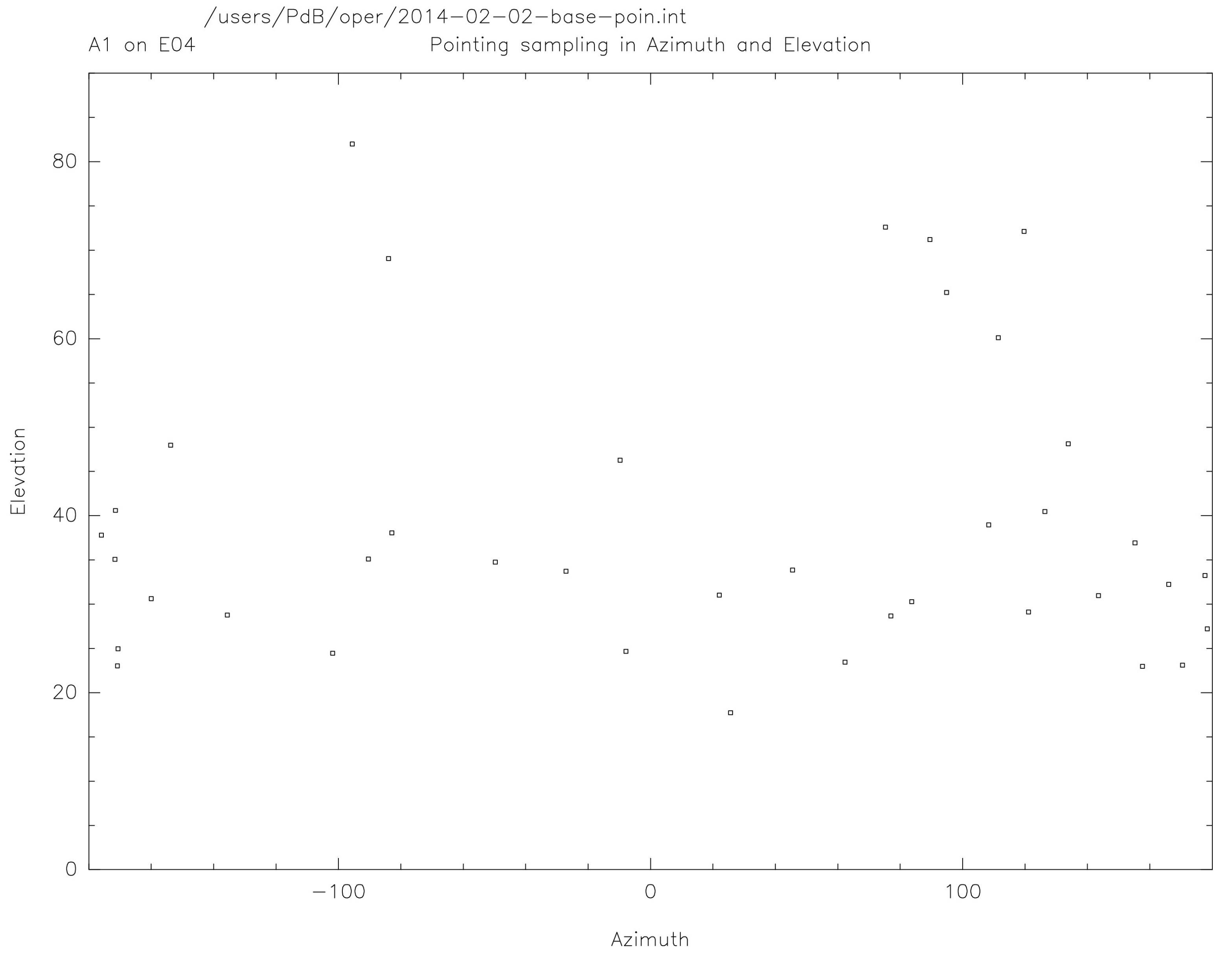
- Corrections:

```
dX = IAZ.cos(El) + COH + sin(El) * (MVE*cos(Az)-MVN*sin(Az)-NPE)
       + cos(El) * (AZES*sin(Az)+AZEC*cos(Az))
dY = IEL+COV - (MVE*sin(Az)+MVN*cos(Az))
       + (ELES*sin(El)+(ELEC-HEL)*cos(El))
       - REF0/tan(El) - REF1/tan(El)**3 - REF2/tan(El)**5
```

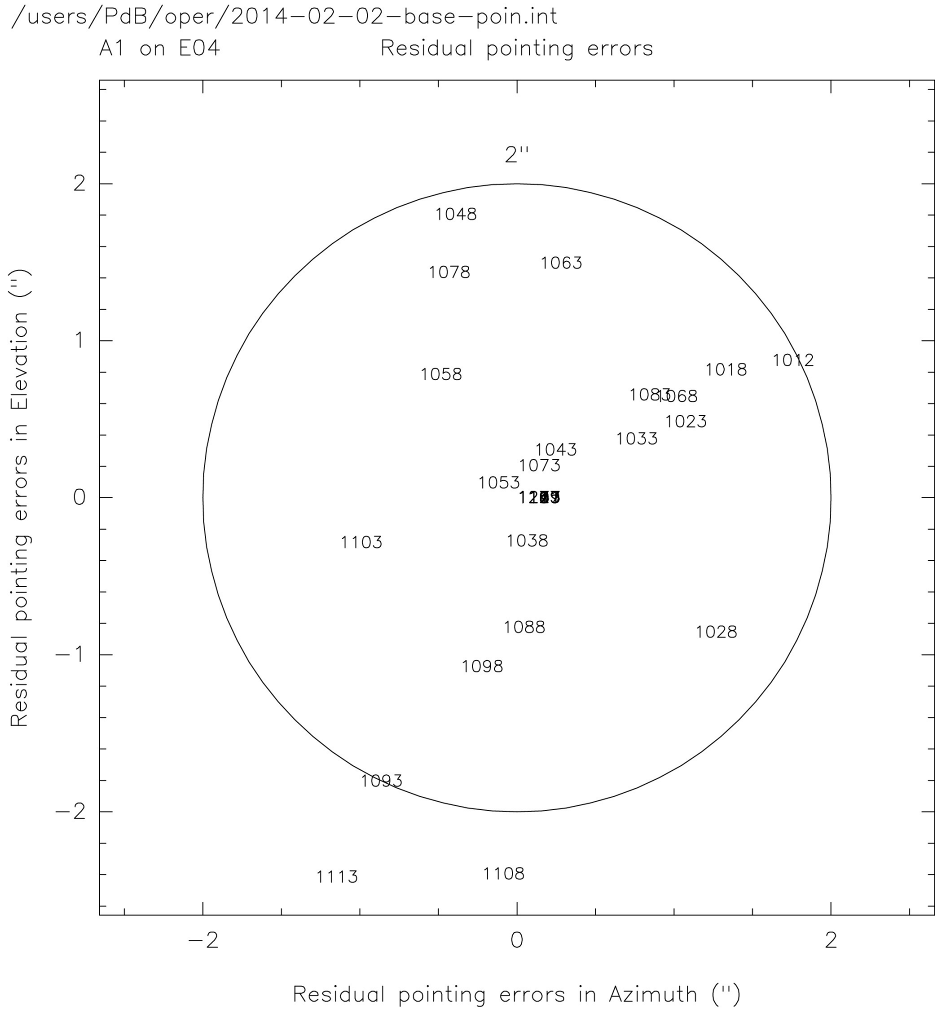
- Parameters playing the larger role:
  - IAZ, IEL+COV, COH, MVE, MVN, HEL
  - Depending on antenna or antenna+station
  - We use inclinometers to monitor the antenna tilt.
  - Corrected for the local gravity vector (attraction of the Alps).

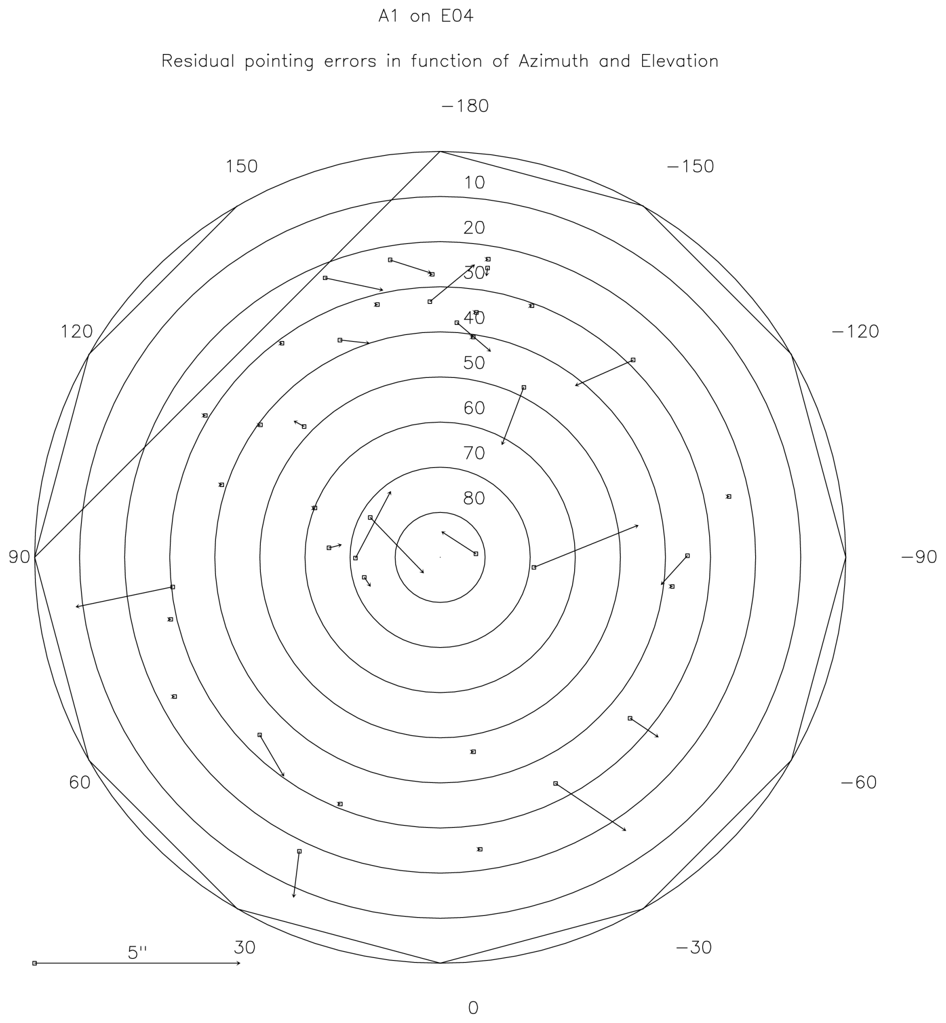


Do pointing all-over the sky



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 asymetric 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.*

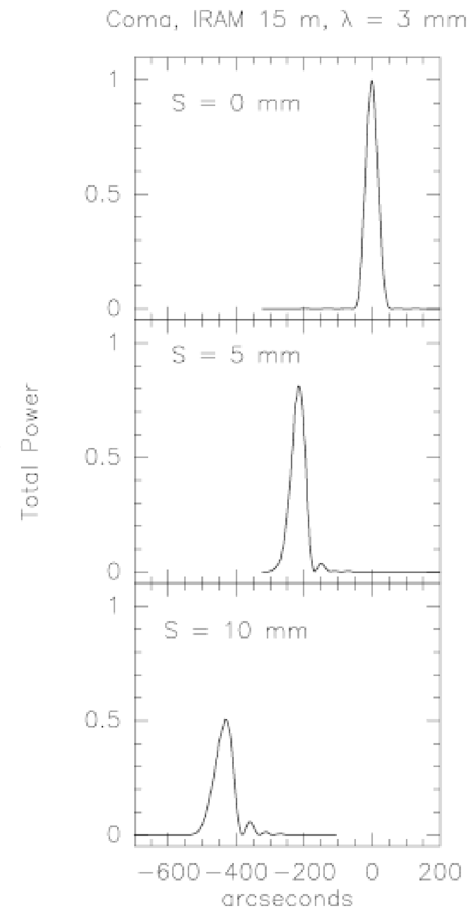
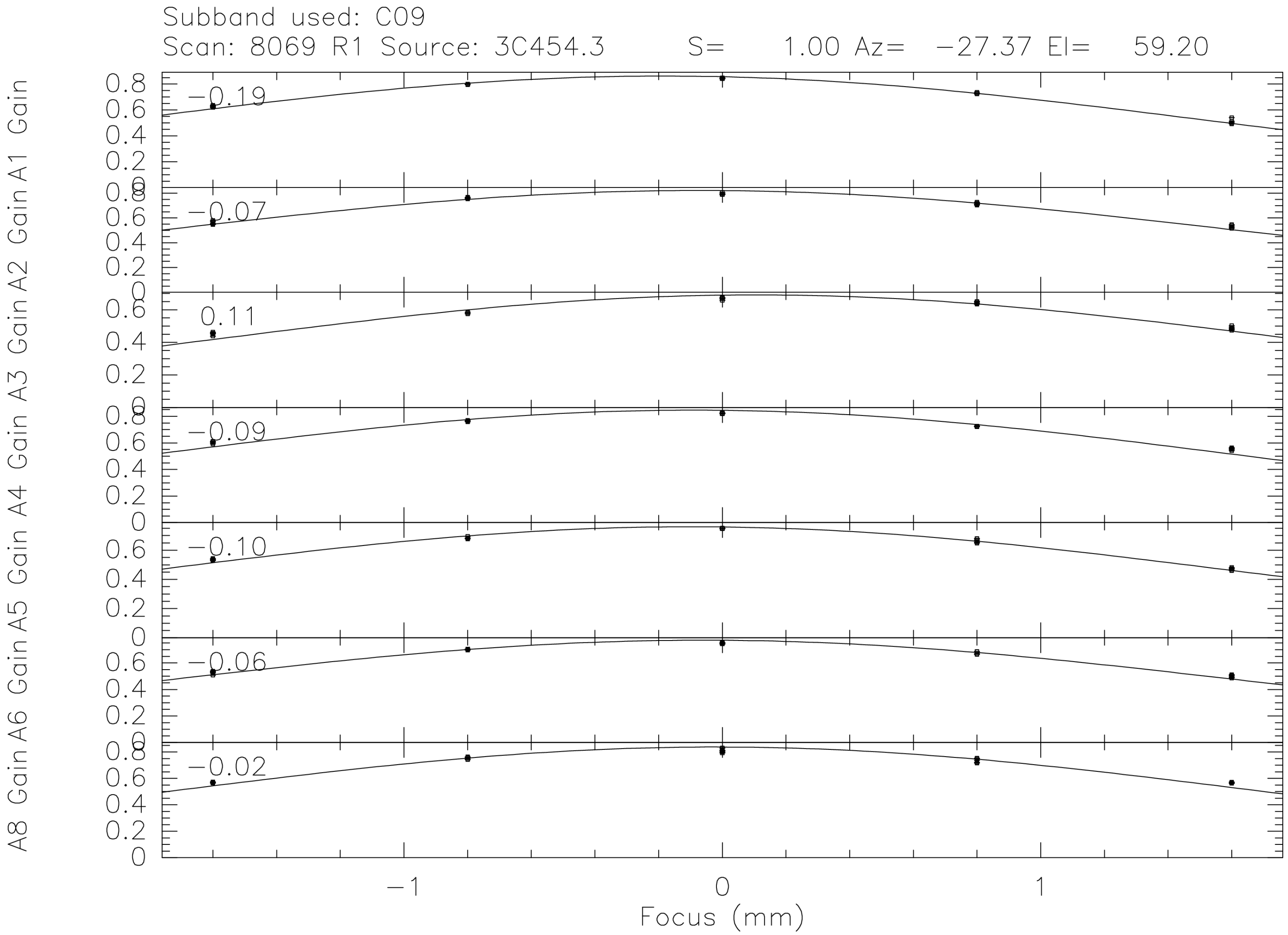


Figure 1.8: Illustration of a comatic beam (scanned in the direction of the coma) especially produced on the IRAM 15–m telescope. The shift of the subreflector is indicated by S. The beam pattern is perfect at S = 0. Note the shift of the beam (pointing error) when the subreflector is shifted.

NOEMA focus measurement

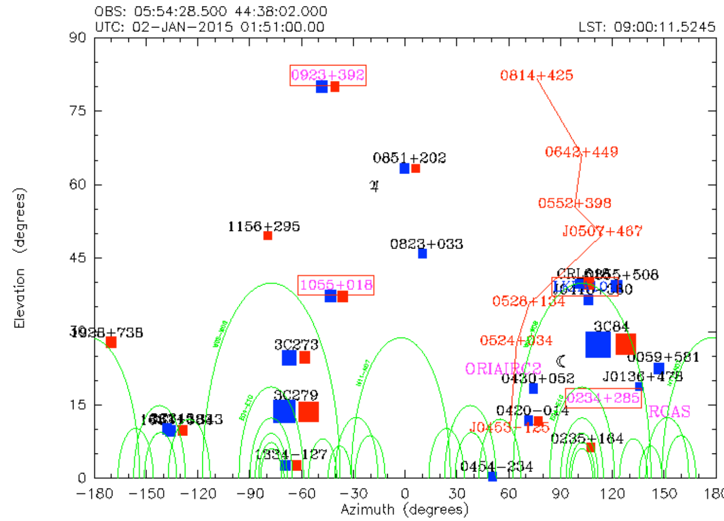


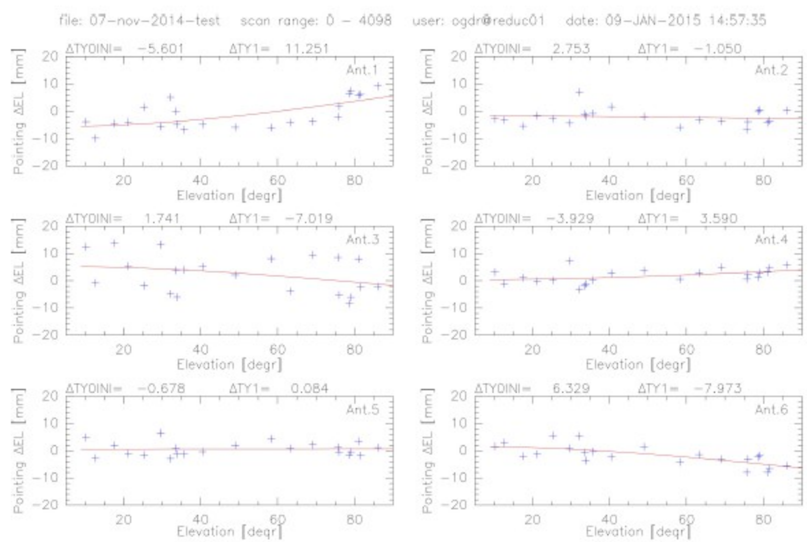
Focus model

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

defocus component	symbol	pointing error
translation primary	y_p	$-K_p(y_p/f)$
rotation primary	ϵ	$(1+K_p)\,\epsilon$
translation secondary	y_s	$(y_s/f)\,(K_p - K_s/M)$
rotation secondary (vertex)	α	$-\alpha\,(2\,c/f)\,(K_p+K_s)/(M+1)$
rotation secondary (focus)	α	$-\alpha\,(2\,c/f)\,(K_s/M)$
translation feed (in sec. focus)	y_f	$(y_f/f)\,(K_s/M)$

- Knowing the beam deviation factor (BDF) Kp, we can derive the lateral shift we are interested in.





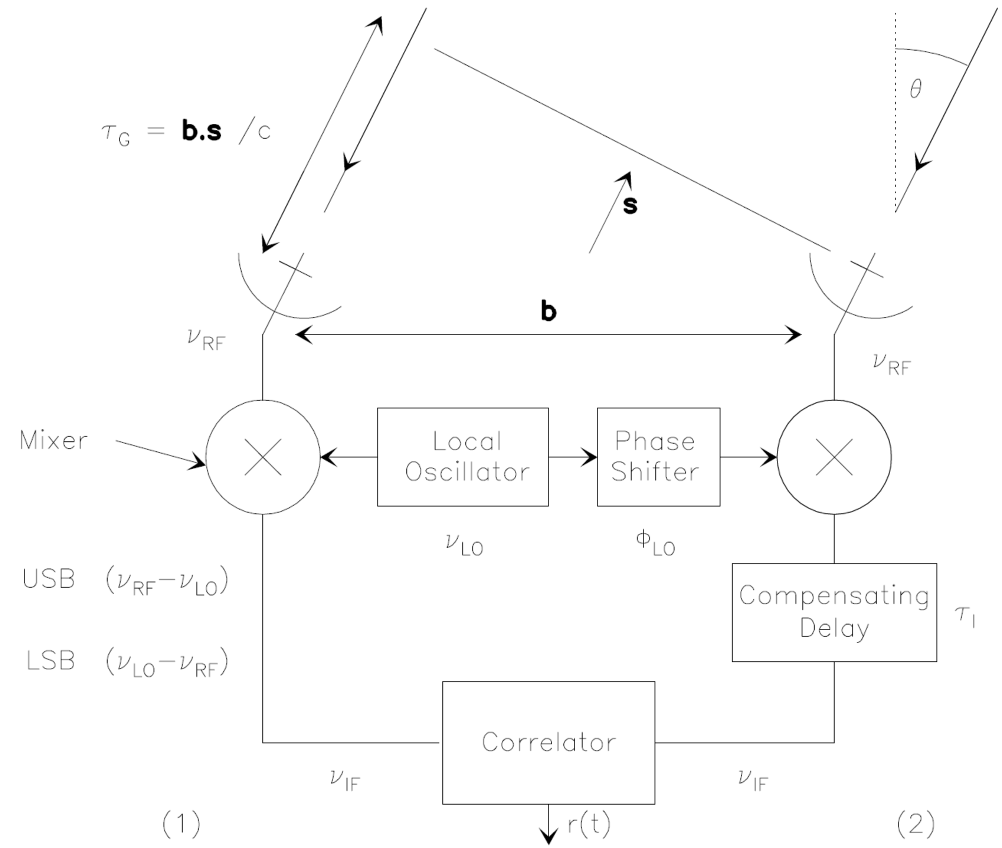
Delay

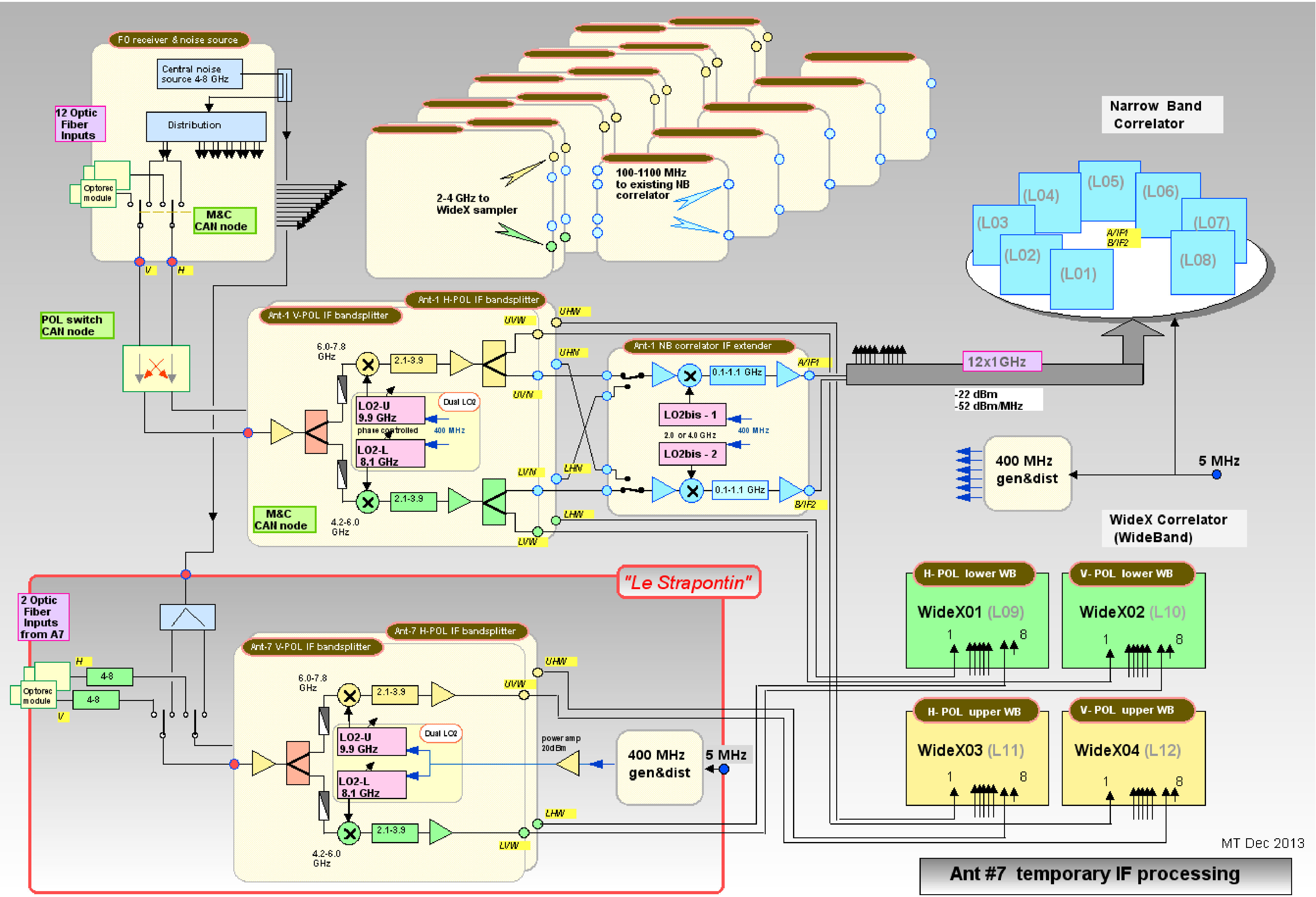
Delay calibration

- An uncorrected (constant) delay introduce a phase slope as a function of frequency:

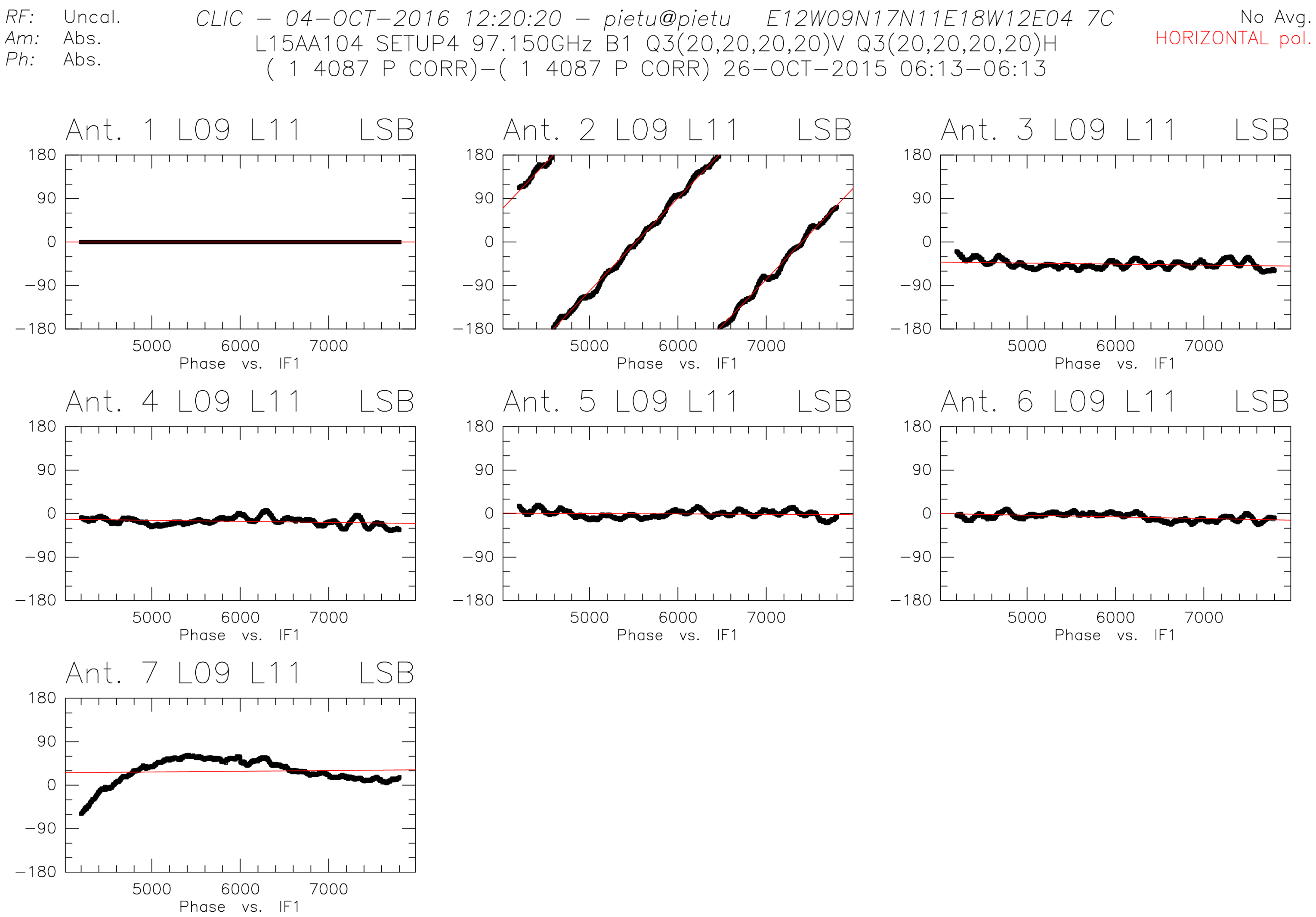
$$\Phi(\nu_{IF}) = \pm 2\pi\nu_{IF}\Delta\tau$$

- 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.

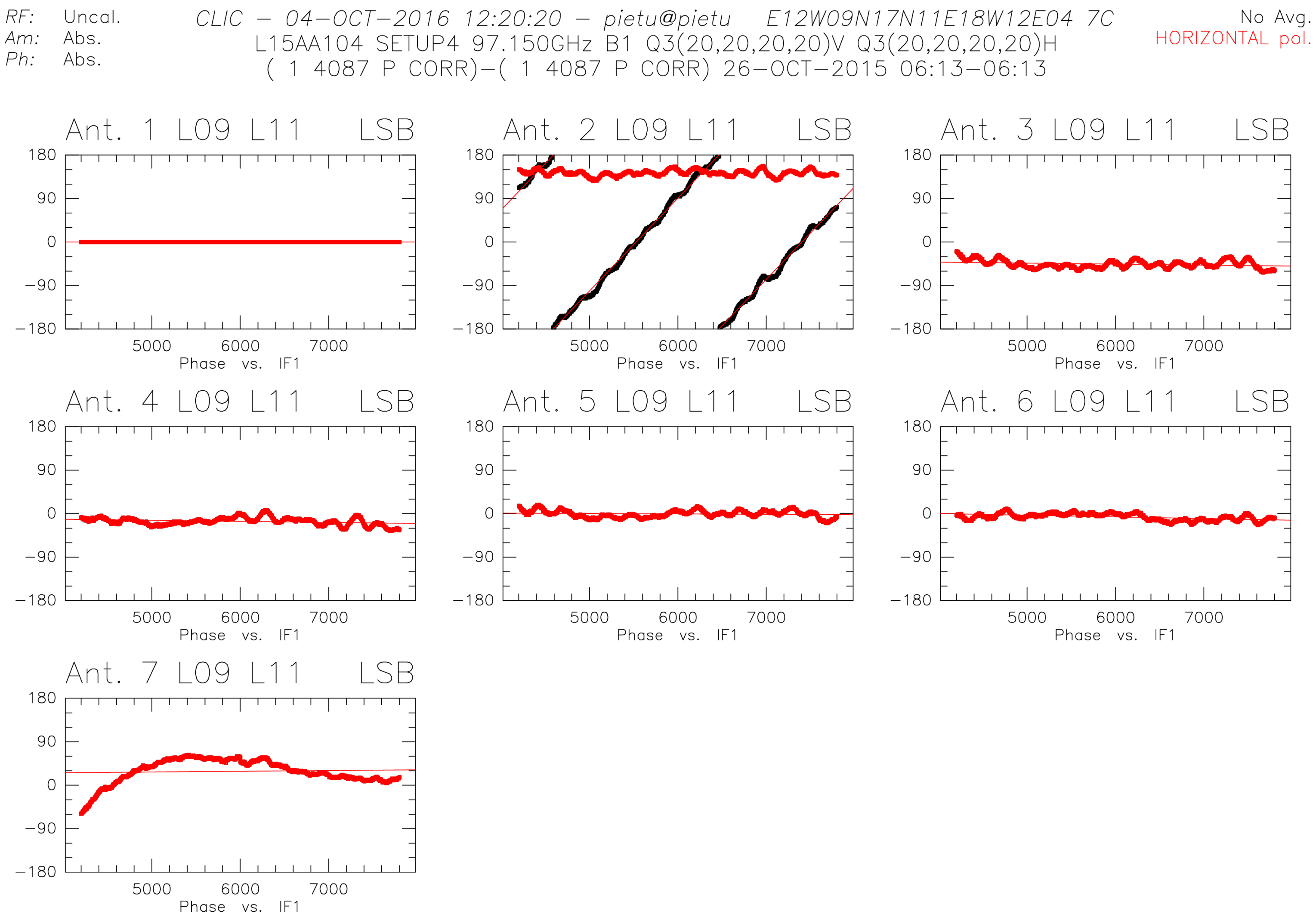




F0 receiver & noise source
Central noise source 4-8 GHz
Distribution
12 Optic Fiber Inputs
Optorec module
M&C CAN node
POL switch CAN node
2-4 GHz to WideX sampler
100-1100 MHz to existing NB correlator
Narrow Band Correlator
(L01)
(L02)
(L03
(L04)
(L05)
(L06)
(L07)
(L08)
A/IF1 B/IF2
Ant-1 H-POL IF bandsplitter
Ant-1 V-POL IF bandsplitter
Ant-1 NB correlator IF extender
6.0-7.8 GHz
4.2-6.0 GHz
2.1-3.9
LO2-U 9.9 GHz
LO2-L 8.1 GHz
Dual LO2
phase controlled
400 MHz
LO2bis - 1
LO2bis - 2
2.0 or 4.0 GHz
0.1-1.1 GHz
UHW
UVW
UHN
UVN
LHN
LVN
LHW
LVW
A/IF1
B/IF2
12x1GHz
-22 dBm
-52 dBm/MHz
400 MHz gen&dist
5 MHz
WideX Correlator (WideBand)
"Le Strapontin"
2 Optic Fiber Inputs from A7
Ant-7 H-POL IF bandsplitter
Ant-7 V-POL IF bandsplitter
4-8
power amp 20dBm
H- POL lower WB
WideX01 (L09)
V- POL lower WB
WideX02 (L10)
H- POL upper WB
WideX03 (L11)
V- POL upper WB
WideX04 (L12)
MT Dec 2013
Ant #7 temporary IF processing



RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC – 04–OCT–2016 12:20:20 – pietu@pietu E12W09N17N11E18W12E04 7C
L15AA104 SETUP4 97.150GHz B1 Q3(20,20,20,20)V Q3(20,20,20,20)H
(1 4087 P CORR)–(1 4087 P CORR) 26–OCT–2015 06:13–06:13
No Avg.
HORIZONTAL pol.
Ant. 1 L09 L11 LSB
Ant. 2 L09 L11 LSB
Ant. 3 L09 L11 LSB
Ant. 4 L09 L11 LSB
Ant. 5 L09 L11 LSB
Ant. 6 L09 L11 LSB
Ant. 7 L09 L11 LSB
180
90
0
–90
–180
5000
6000
7000
Phase vs. IF1


RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC − 04−OCT−2016 12:20:20 − pietu@pietu E12W09N17N11E18W12E04 7C
L15AA104 SETUP4 97.150GHz B1 Q3(20,20,20,20)V Q3(20,20,20,20)H
(1 4087 P CORR)−(1 4087 P CORR) 26−OCT−2015 06:13−06:13
No Avg.
HORIZONTAL pol.
Ant. 1 L09 L11 LSB
Ant. 2 L09 L11 LSB
Ant. 3 L09 L11 LSB
Ant. 4 L09 L11 LSB
Ant. 5 L09 L11 LSB
Ant. 6 L09 L11 LSB
Ant. 7 L09 L11 LSB
180
90
0
−90
−180
5000
6000
7000
Phase vs. IF1

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 offfline 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:

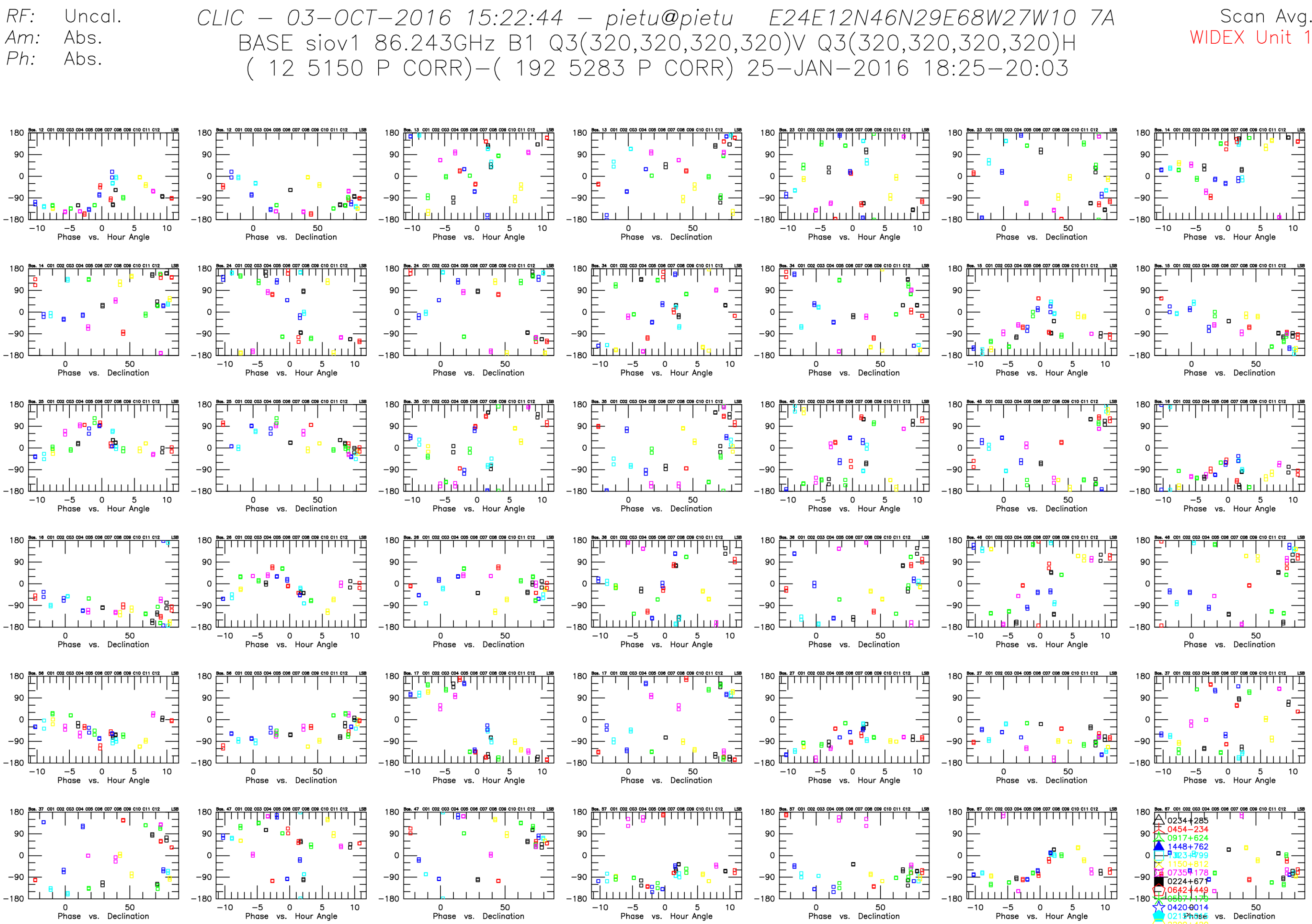
$$\phi^g_{ij} = \phi^s_{ij} + \phi^a_{ij} = 2\pi\, w =$$

$$= \frac{2\pi}{\lambda} \underbrace{(X_{ij}, Y_{ij}, Z_{ij})}_{b} \cdot \underbrace{\begin{pmatrix} cosH cos\delta \\ -sinH cos\delta \\ sin\delta \end{pmatrix}}_{s} + \phi^a_{ij}$$

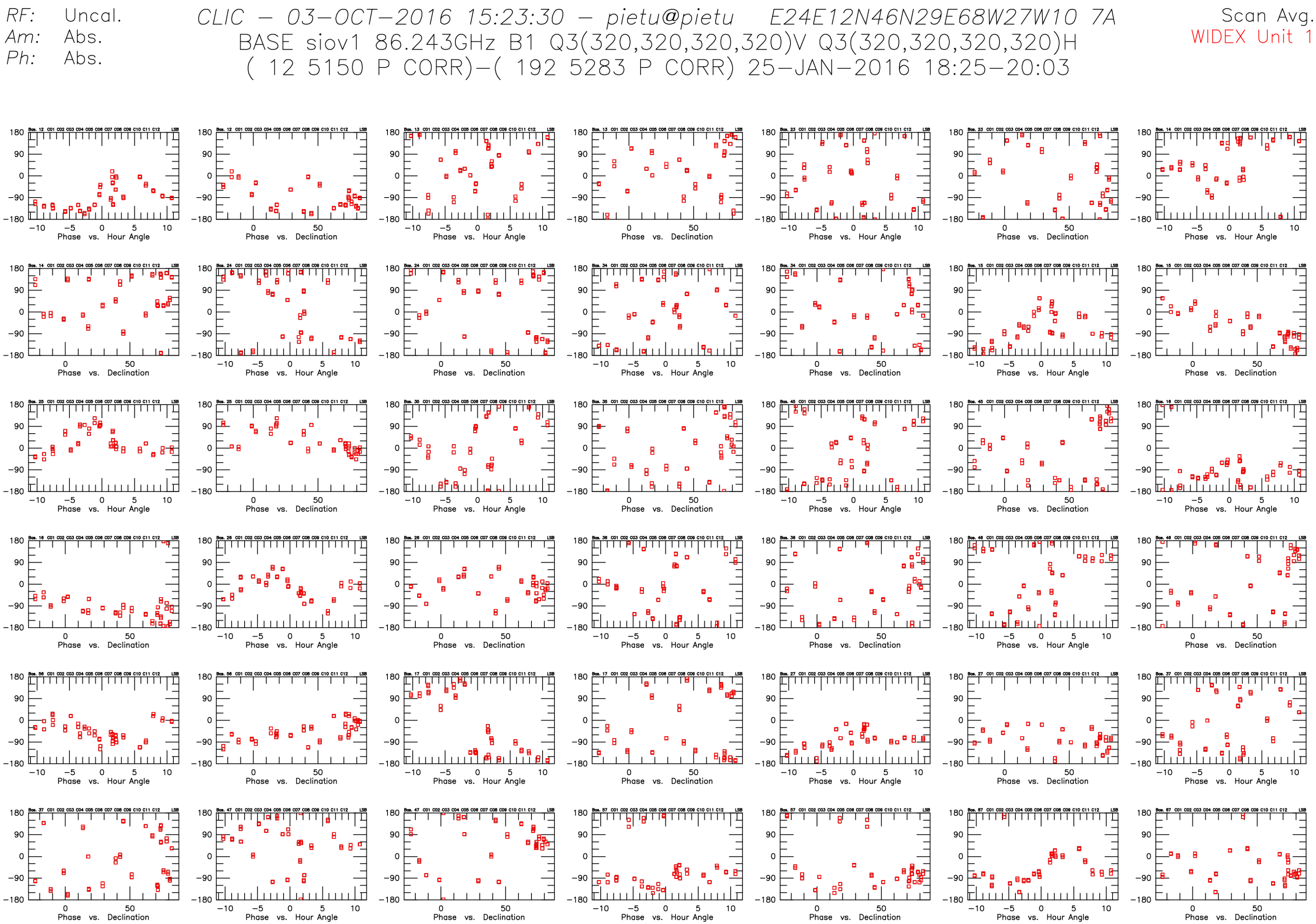
$$\longrightarrow \quad \Delta\phi^g_{ijk} = \frac{2\pi}{\lambda} (\Delta b_{ij} \cdot s_k + \underbrace{b_{ij} \cdot \Delta s_k}_{\simeq 0}) + \Delta\phi^a_{ijk}$$

- 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

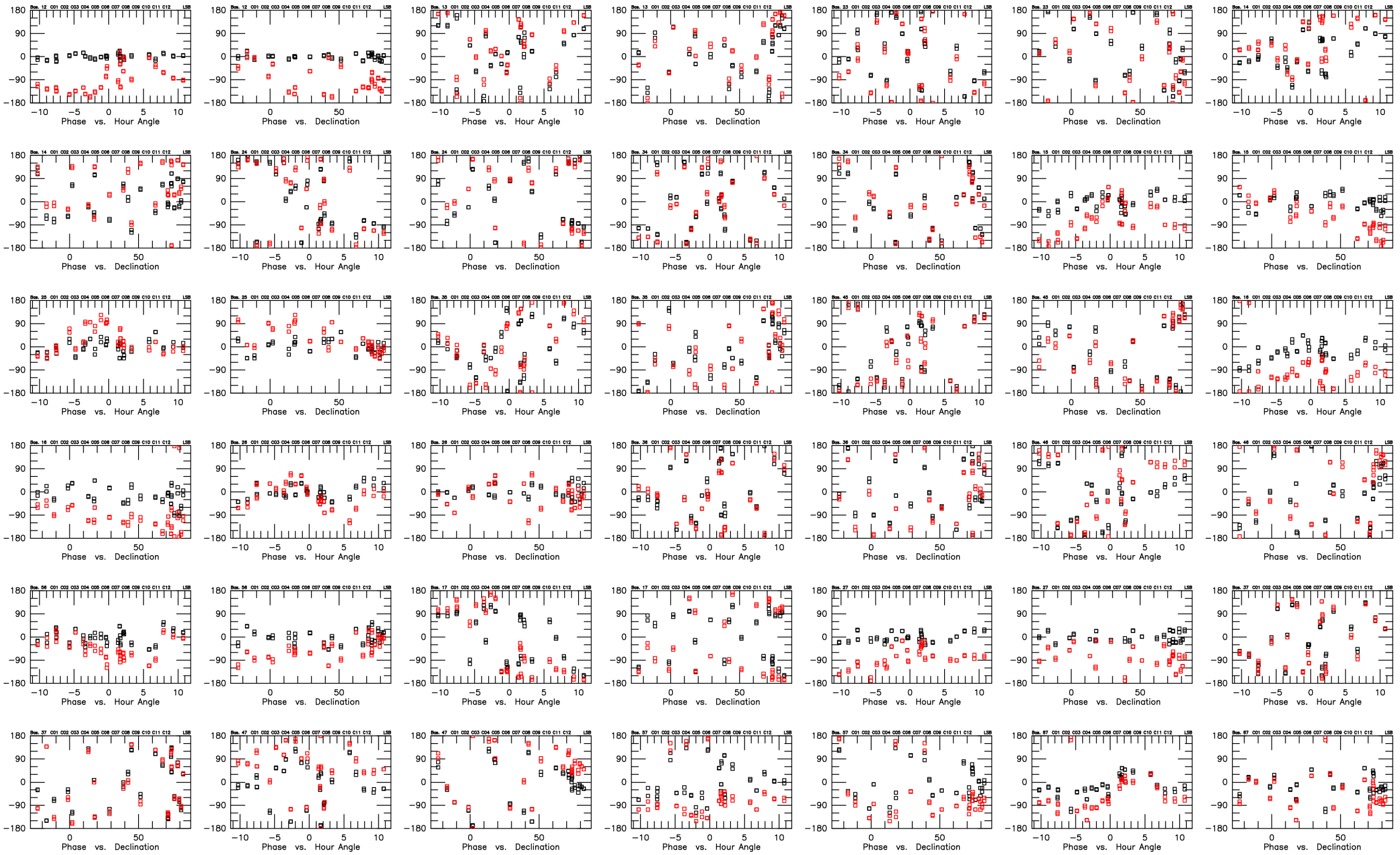

RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC – 03–OCT–2016 15:23:30 – pietu@pietu E24E12N46N29E68W27W10 7A
BASE siov1 86.243GHz B1 Q3(320,320,320,320)V Q3(320,320,320,320)H
(12 5150 P CORR)–(192 5283 P CORR) 25–JAN–2016 18:25–20:03
Scan Avg.
WIDEX Unit 1
Phase vs. Hour Angle
Phase vs. Declination

After baseline fit

RF: Uncal.
Am: Abs.
Ph: Abs.

CLIC – 03–OCT–2016 15:23:46 – pietu@pietu E24E12N46N29E68W27W10 7A
BASE siov1 86.243GHz B1 Q3(320,320,320,320)V Q3(320,320,320,320)H
(12 5150 P CORR)–(192 5283 P CORR) 25–JAN–2016 18:25–20:03

Scan Avg.
WIDEX Unit 1



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

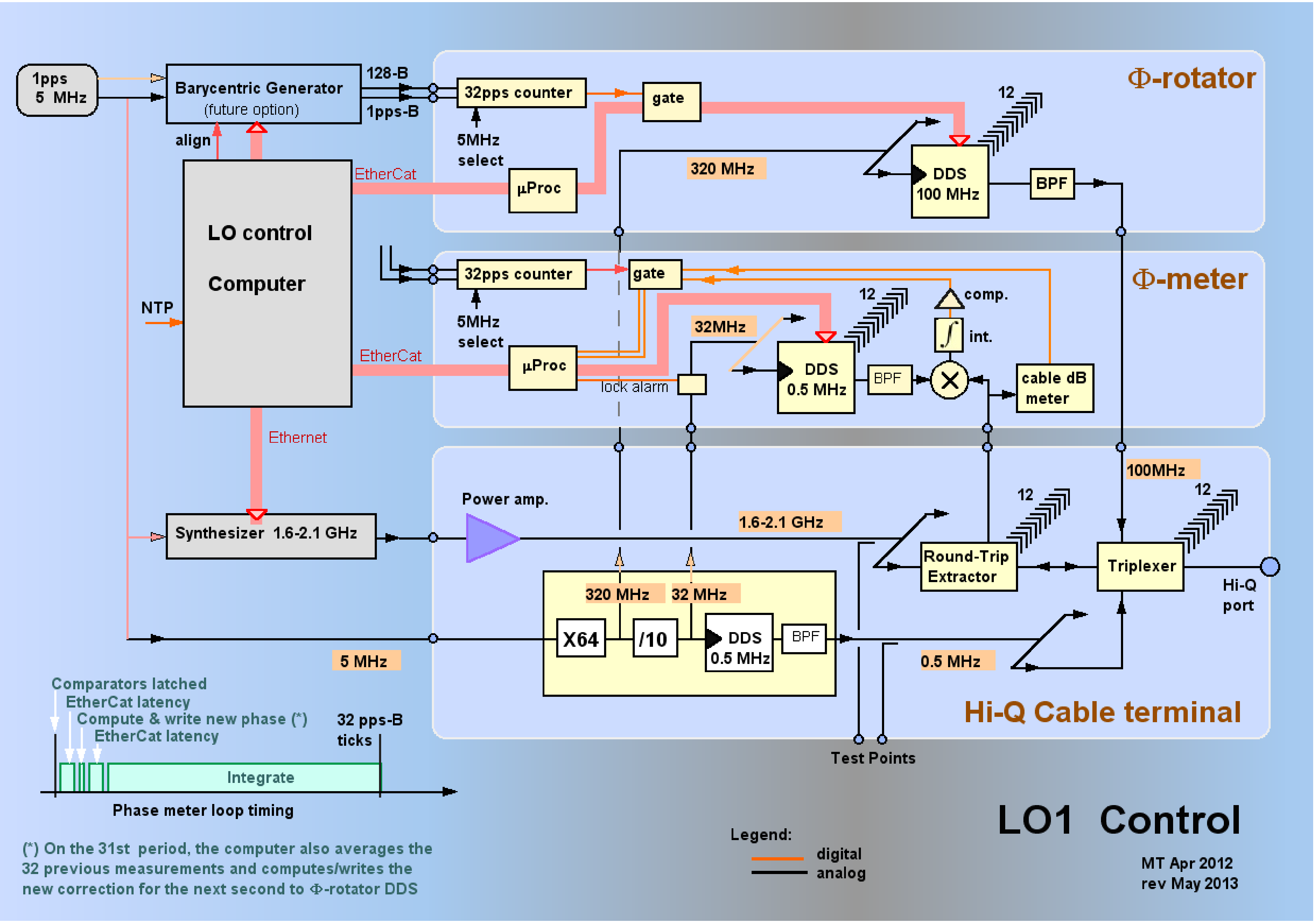
  (e.g. To correct for the position of a phase calibrator).

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
NTP
EtherCat
EtherCat
Ethernet
32pps counter
5MHz
select
gate
µProc
320 MHz
DDS
100 MHz
BPF
12
Φ-rotator
32pps counter
5MHz
select
gate
µProc
32MHz
12
comp.
int.
lock alarm
DDS
0.5 MHz
BPF
cable dB
meter
Φ-meter
Synthesizer 1.6-2.1 GHz
Power amp.
1.6-2.1 GHz
100MHz
12
12
Round-Trip
Extractor
Triplexer
Hi-Q
port
320 MHz
32 MHz
X64
/10
DDS
0.5 MHz
BPF
5 MHz
0.5 MHz
Hi-Q Cable terminal
Test Points
Comparators latched
EtherCat latency
Compute & write new phase (*)
EtherCat latency
32 pps-B
ticks
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
Legend:
digital
analog
LO1 Control
MT Apr 2012
rev May 2013

Holography

Holography

- Far-field approximation (Fraunhofer region):

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

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

- Near-field approximation (Fresnel region):

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

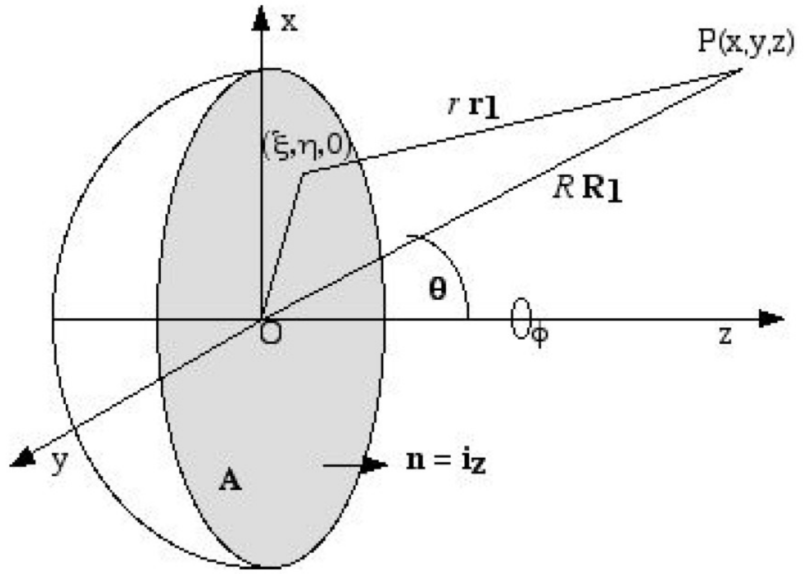


Fig. 1. Geometry of the aperture integration method for finite distance to the field point P.

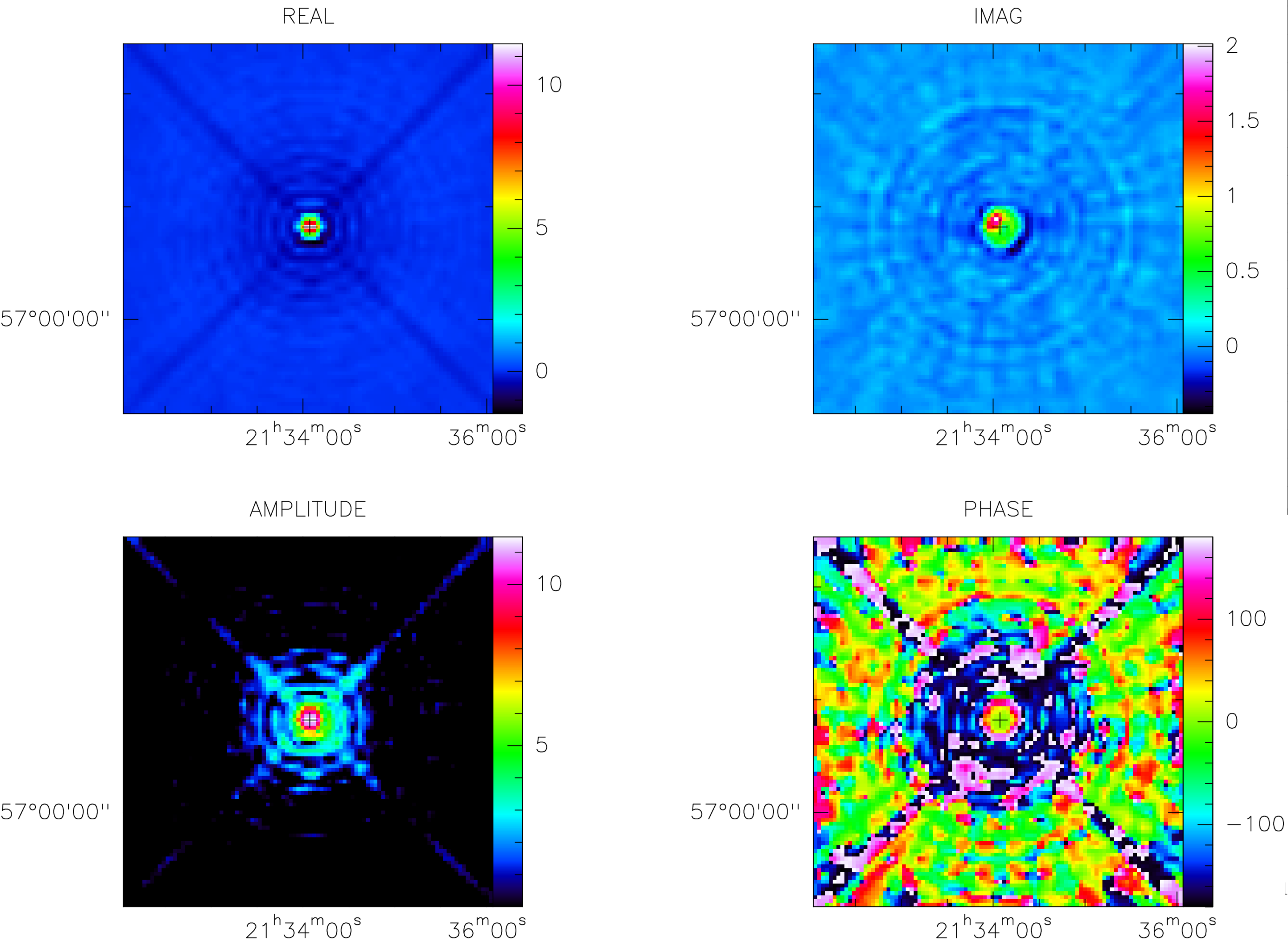
Baars et al. 2007

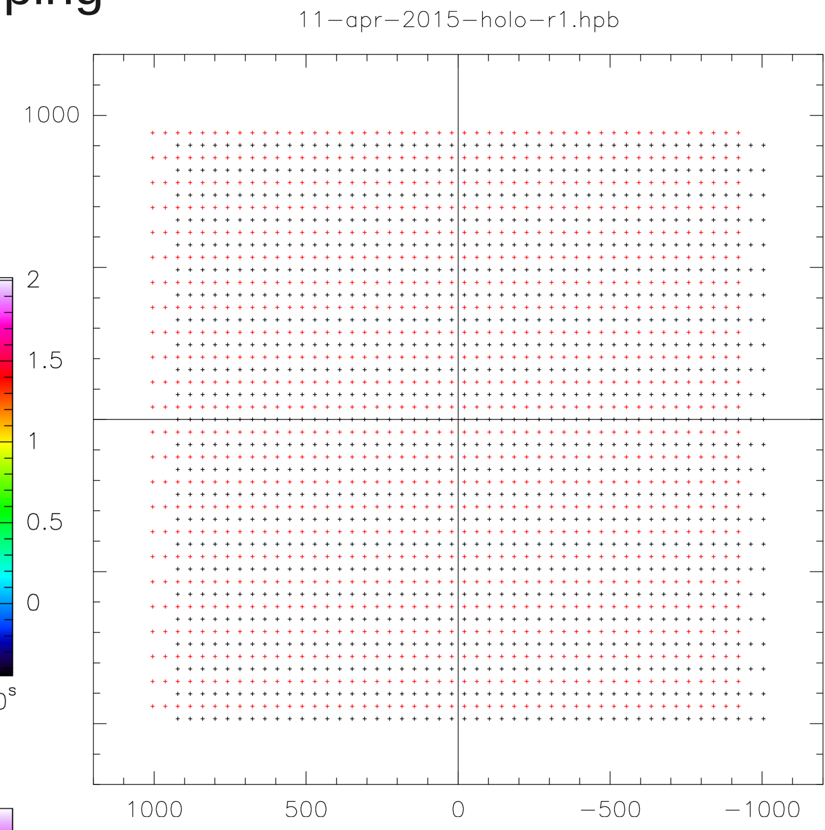
- A Fourier transform relationship between the far-field pattern and the complex aperture field distribution (and almost in the near-field case).
- Far field:

$$D_{ff} > 2d^2/\lambda$$

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.





11−apr−2015−holo−r1

RF: Fr.(B) CLIC − 29−SEP−2016 13:41:06 − pietu@pietu − Ant 3 − W09E04W12N17N13E10N07

Am: Rel.(B) 3C454.3 7ant−Special scans 1025 to 1099 11−APR−2015 07:56UT El: 57.14

Ph: Rel.(B)

rms	Pha.
13	3.07
23	7.35
34	7.23
35	7.42
36	7.00
37	5.25

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_A(86.243 GHz) = 0.739; η_A(230.0 GHz) = 0.537; η_A(345.0 GHz) = 0.340

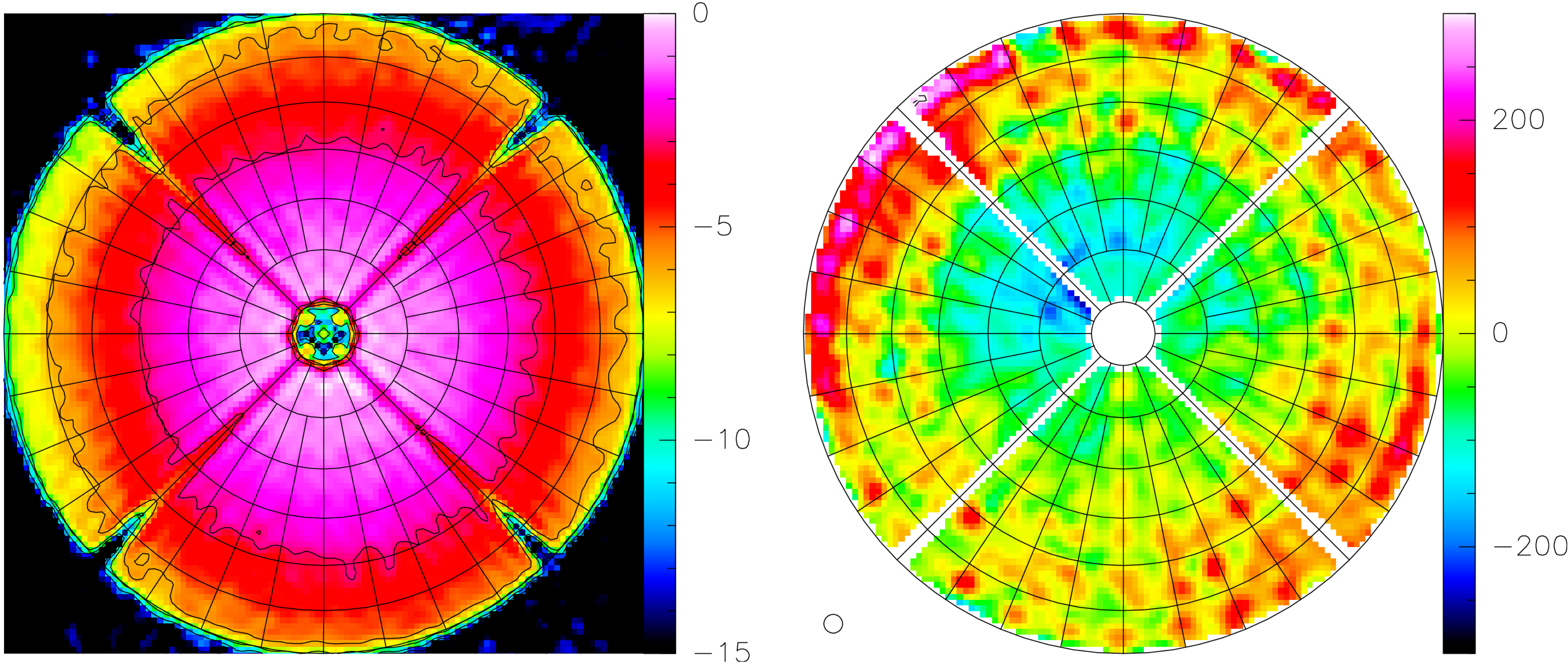
S/T(86.243 GHz)= 21.141 Jy/K; S/T(230GHz)= 29.064 Jy/K; S/T(345 GHz)= 45.909 Jy/K

η_I= 0.779 −η_S= 0.780 −η_P(86.243 GHz)= 0.949 −η_P(230 GHz)= 0.690 −η_P(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:

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

Baars et al. 2007

11−apr−2015−holo−r1

CLIC − 29−SEP−2016 13:41:06 − pietu@pietu − Ant 3 − W09E04W12N17N13E10N07

3C454.3 7ant−Special scans 1025 to 1099 11−APR−2015 07:56UT El: 57.14

RF:	Fr.(B)
Am:	Rel.(B)
Ph:	Rel.(B)

rms	Pha.
13	3.07
23	7.35
34	7.23
35	7.42
36	7.00
37	5.25

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_A(86.243 GHz) = 0.739; η_A(230.0 GHz) = 0.537; η_A(345.0 GHz) = 0.340

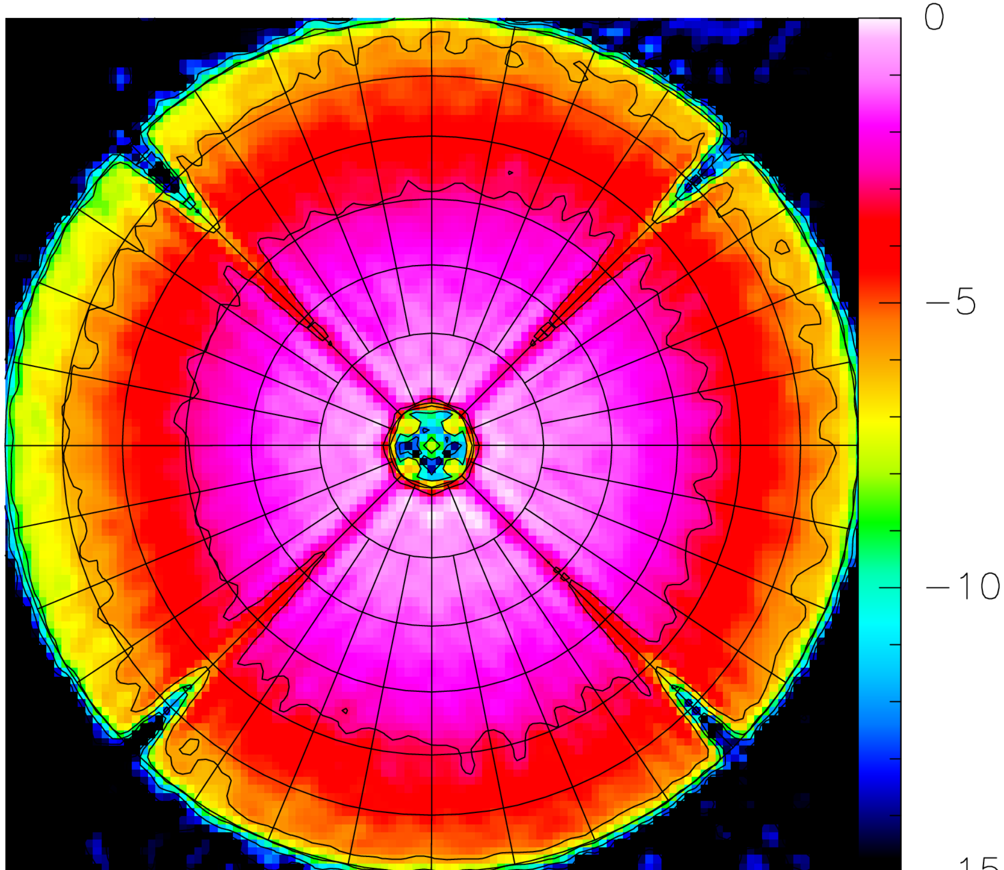
S/T(86.243 GHz)= 21.141 Jy/K; S/T(230GHz)= 29.064 Jy/K; S/T(345 GHz)= 45.909 Jy/K

η_I= 0.779 −η_S= 0.780 −η_P(86.243 GHz)= 0.949 −η_P(230 GHz)= 0.690 −η_P(345 GHz)= 0.437

Rms/ring: 42.8 41.5 39.4 46.4 44.9 70.4

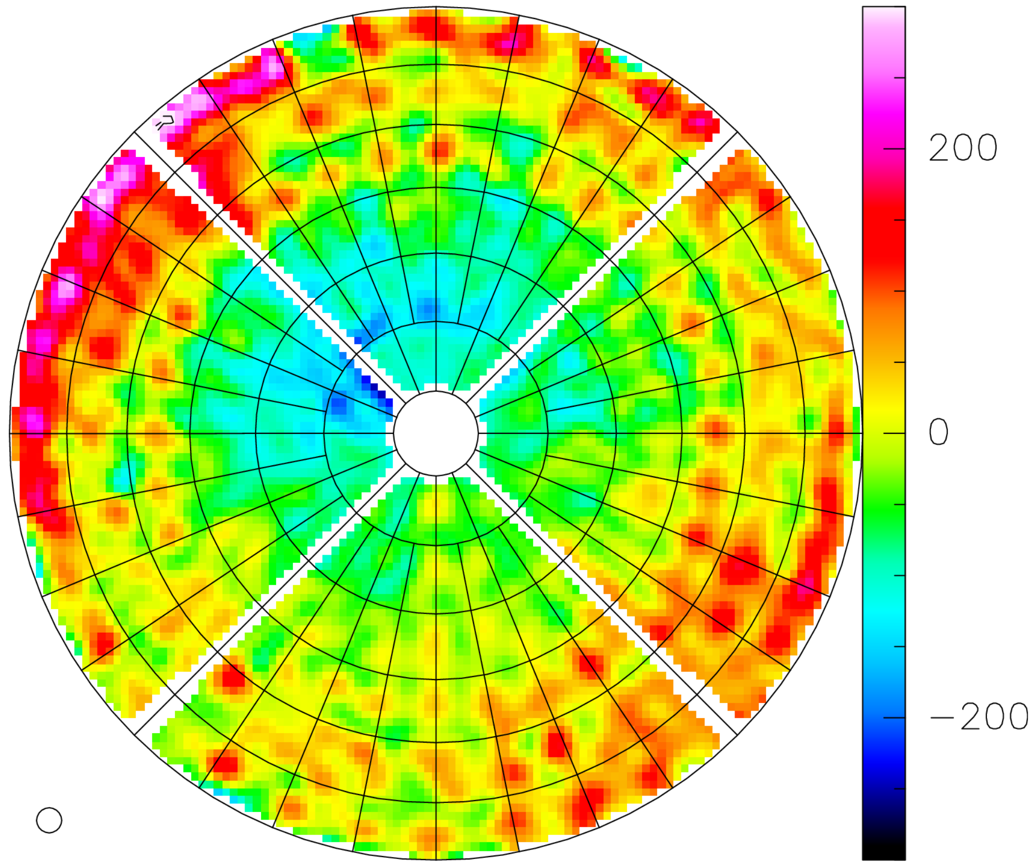
Amplitude (back view)

−15.000 to 0.000 by 3.000



Normal errors (back view)

−300.000 to 300.000 by 300.000



11−apr−2015−holo−r1

RF: Fr.(B) *CLIC − 29−SEP−2016 13:41:28 − pietu@pietu − Ant 3 − W09E04W12N17N13E10N07*

Am: Rel.(B)

Ph: Rel.(B) 3C454.3 7ant−Special scans 1025 to 1099 11−APR−2015 07:56UT El: 57.14

rms Pha.

13	3.07
23	7.35
34	7.23
35	7.42
36	7.00
37	5.25

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 (180.0deg.)

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

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

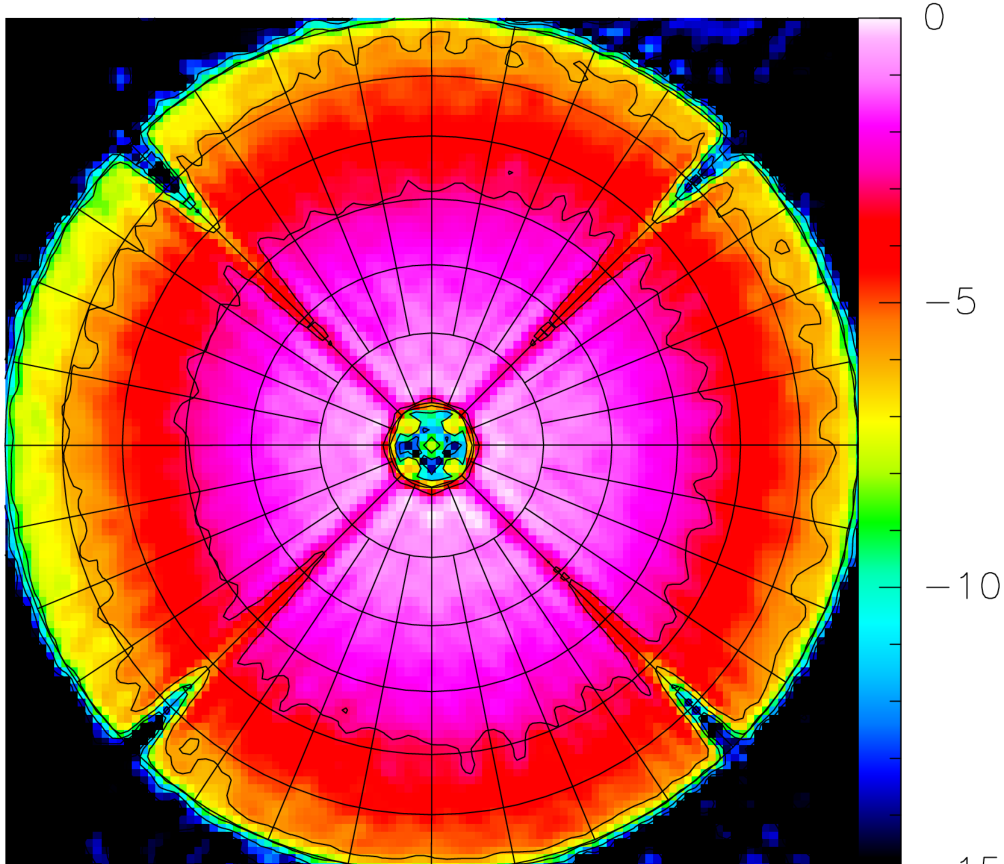
η_A(86.243 GHz) = 0.761; η_A(230.0 GHz) = 0.662; η_A(345.0 GHz) = 0.542

S/T(86.243 GHz)= 20.525 Jy/K; S/T(230GHz)= 23.585 Jy/K; S/T(345 GHz)= 28.799 Jy/K

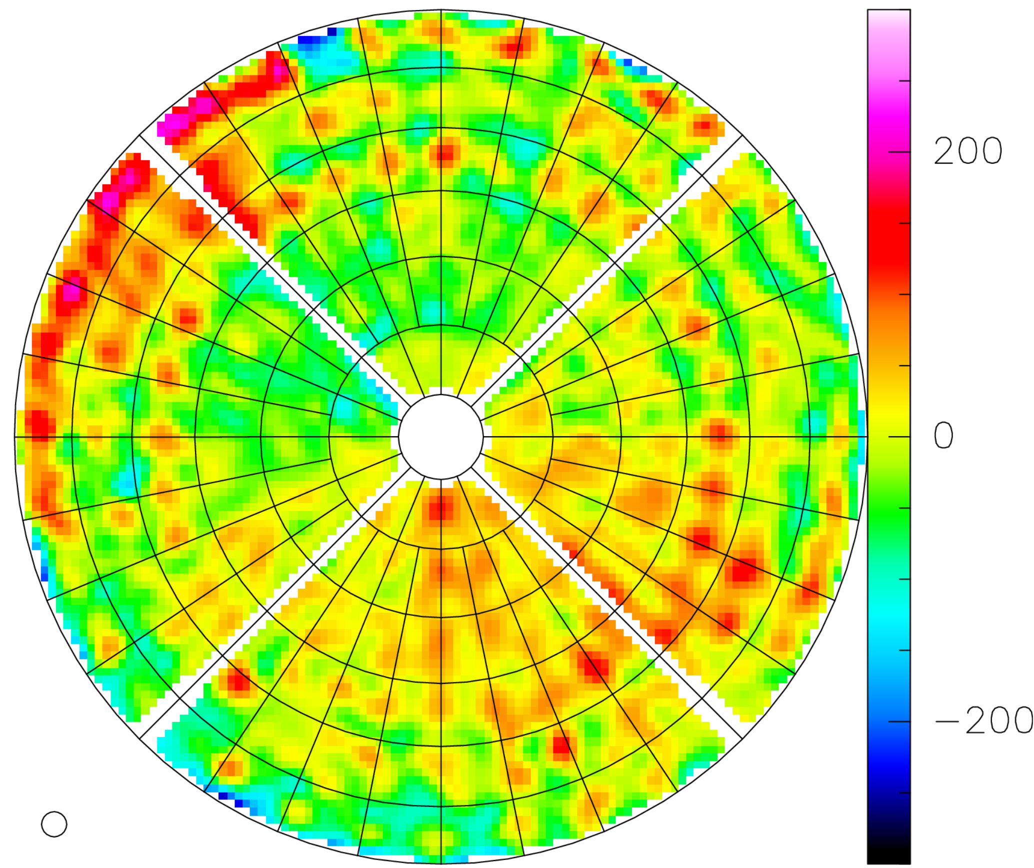
η_I= 0.779 $-\eta_S$= 0.780 $-\eta_P$(86.243 GHz)= 0.977 $-\eta_P$(230 GHz)= 0.851 $-\eta_P$(345 GHz)= 0.697

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



11-apr-2015-holo-r1

CLIC - 29-SEP-2016 13:41:44 - pietu@pietu - Ant 3 - W09E04W12N17N13E10N07

3C454.3 7ant-Special scans 1025 to 1099 11-APR-2015 07:56UT El: 57.14

RF: Fr.(B)
Am: Rel.(B)
Ph: Rel.(B)

rms	Pha.
13	3.07
23	7.35
34	7.23
35	7.42
36	7.00
37	5.25

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 = 0.0 μm (180.0deg.)

Phase rms (unweighted)= 0.143 (weighted)= 0.126 radians

Surface rms (unweighted)= 46.54 - (weighted)= 40.01 μm

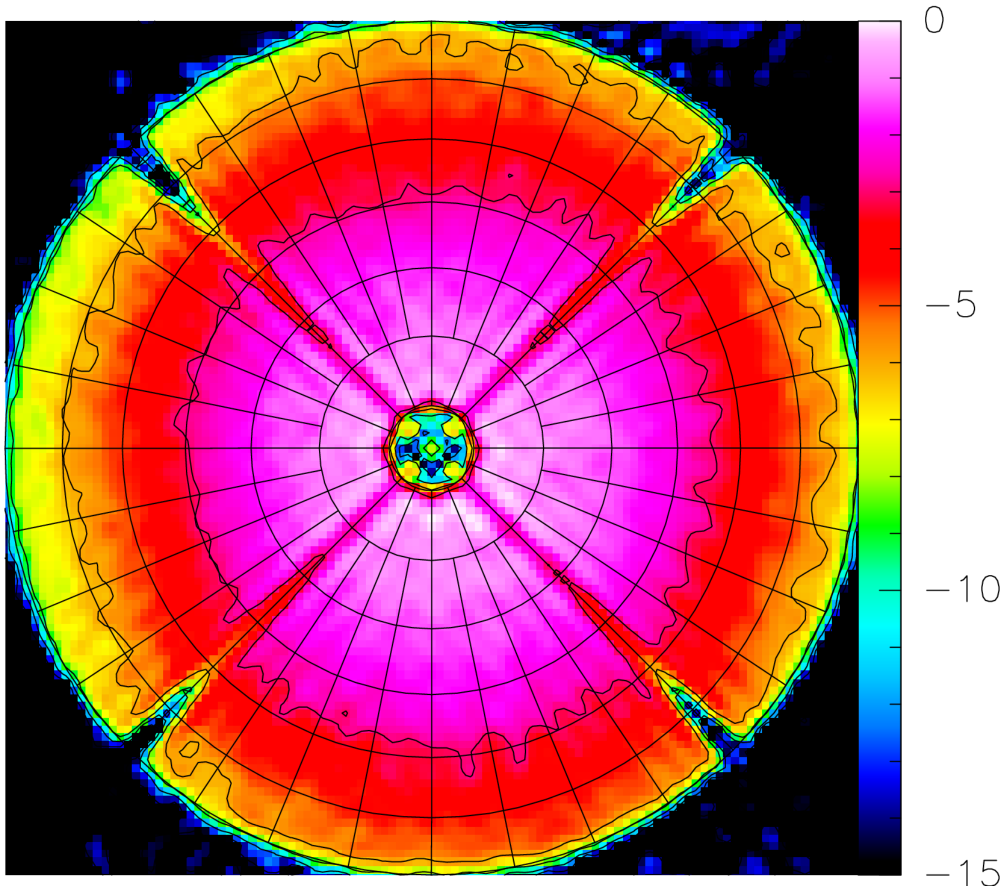
η_A(86.243 GHz) = 0.766; η_A(230.0 GHz) = 0.697; η_A(345.0 GHz) = 0.609

S/T(86.243 GHz)= 20.382 Jy/K; S/T(230GHz)= 22.422 Jy/K; S/T(345 GHz)= 25.636 Jy/K

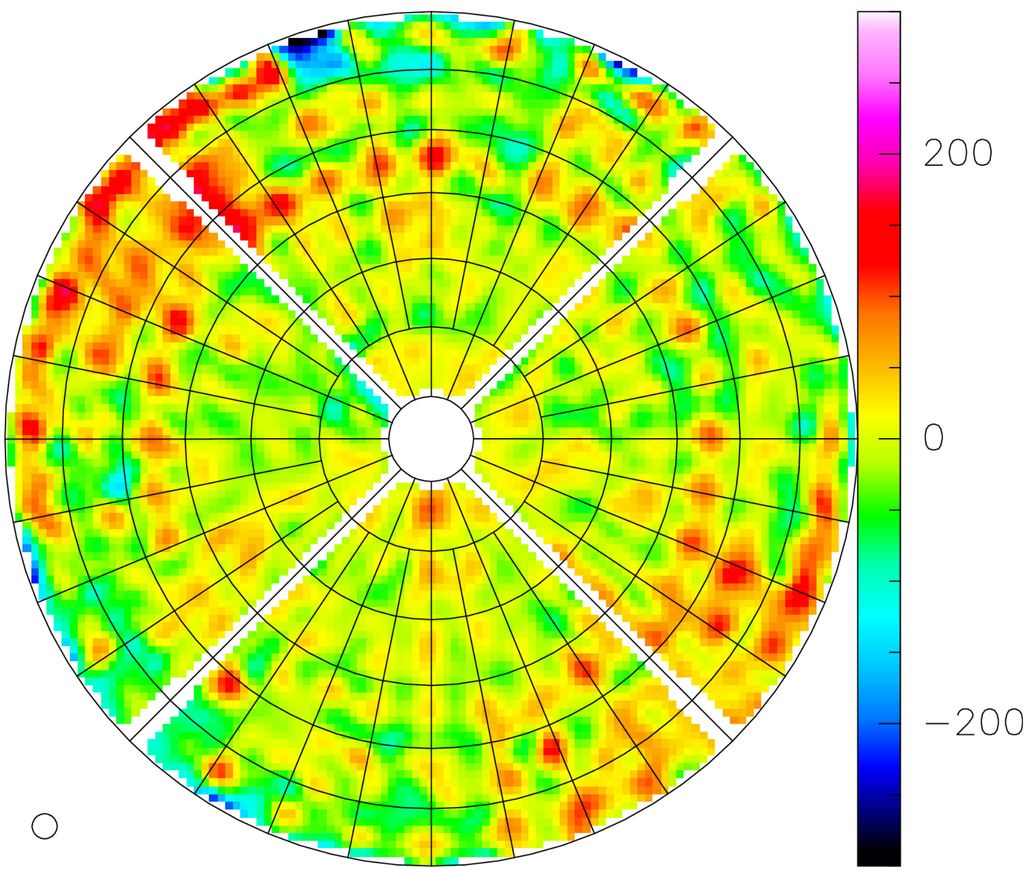
η_I= 0.779 $-\eta_S$= 0.780 $-\eta_P$(86.243 GHz)= 0.984 $-\eta_P$(230 GHz)= 0.895 $-\eta_P$(345 GHz)= 0.783

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



11−apr−2015−holo−r1

RF: Fr.(B)
Am: Rel.(B)
Ph: Rel.(B)

CLIC − 29−SEP−2016 13:42:05 − pietu@pietu − Ant 3 − W09E04W12N17N13E10N07

3C454.3 7ant−Special scans 1025 to 1099 11−APR−2015 07:56UT El: 57.14

rms Pha.	
13	3.07
23	7.35
34	7.23
35	7.42
36	7.00
37	5.25

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 (35.1deg.)

Phase rms (unweighted)= 0.131 (weighted)= 0.119 radians

Surface rms (unweighted)= 42.14 − (weighted)= 37.34 μm

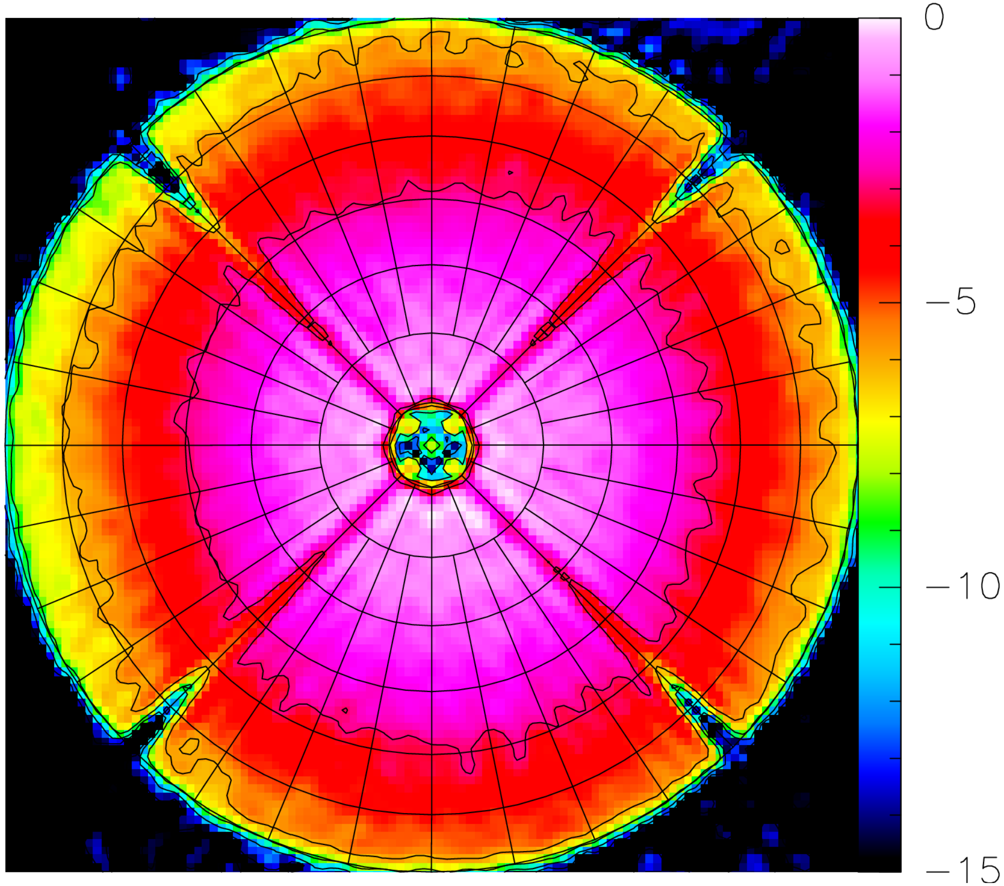
η_A(86.243 GHz) = 0.768; η_A(230.0 GHz) = 0.705; η_A(345.0 GHz) = 0.626

S/T(86.243 GHz)= 20.345 Jy/K; S/T(230GHz)= 22.142 Jy/K; S/T(345 GHz)= 24.941 Jy/K

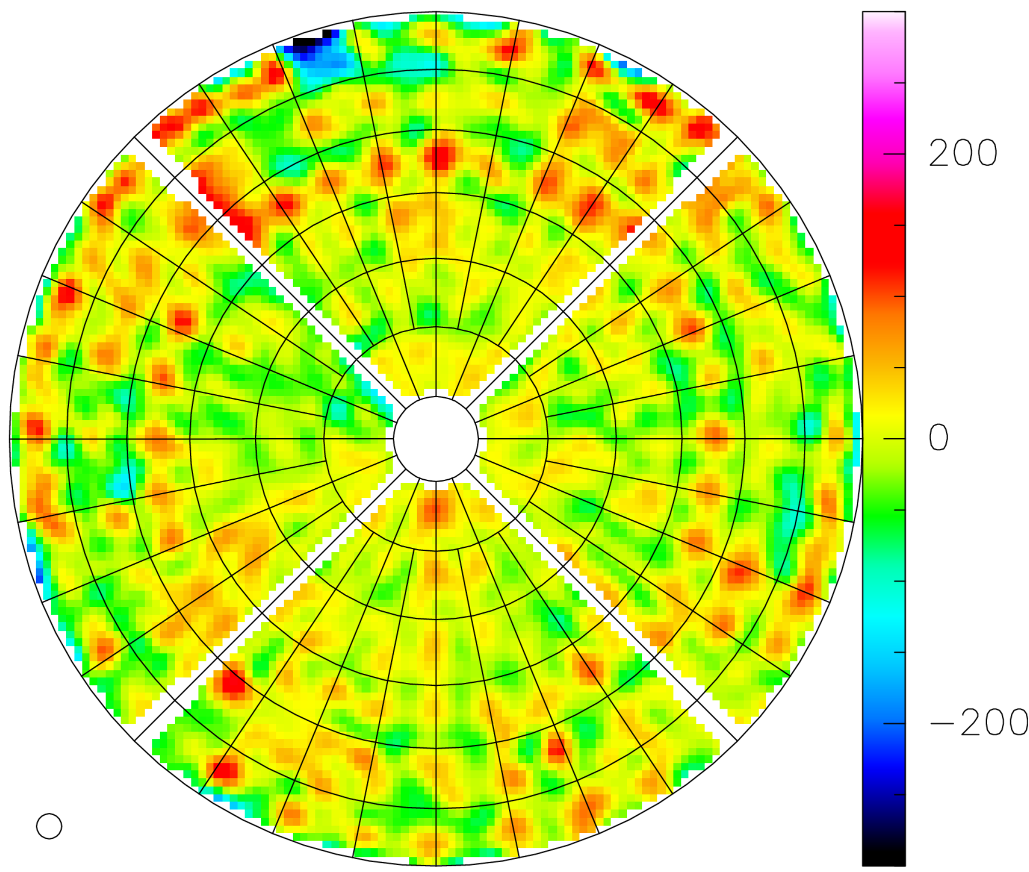
η_I= 0.779 −η_S= 0.780 −η_P(86.243 GHz)= 0.986 −η_P(230 GHz)= 0.906 −η_P(345 GHz)= 0.804

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



11-apr-2015-holo-r1

RF: Fr.(B)
Am: Rel.(B)
Ph: Rel.(B)

CLIC - 29-SEP-2016 13:42:29 - pietu@pietu - Ant 3 - W09E04W12N17N13E10N07

3C454.3 7ant-Special scans 1025 to 1099 11-APR-2015 07:56UT El: 57.14

rms	Pha.
13	3.07
23	7.35
34	7.23
35	7.42
36	7.00
37	5.25

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 (35.1deg.)

Phase rms (unweighted)= 0.131 (weighted)= 0.119 radians

Surface rms (unweighted)= 42.14 - (weighted)= 37.34 μm

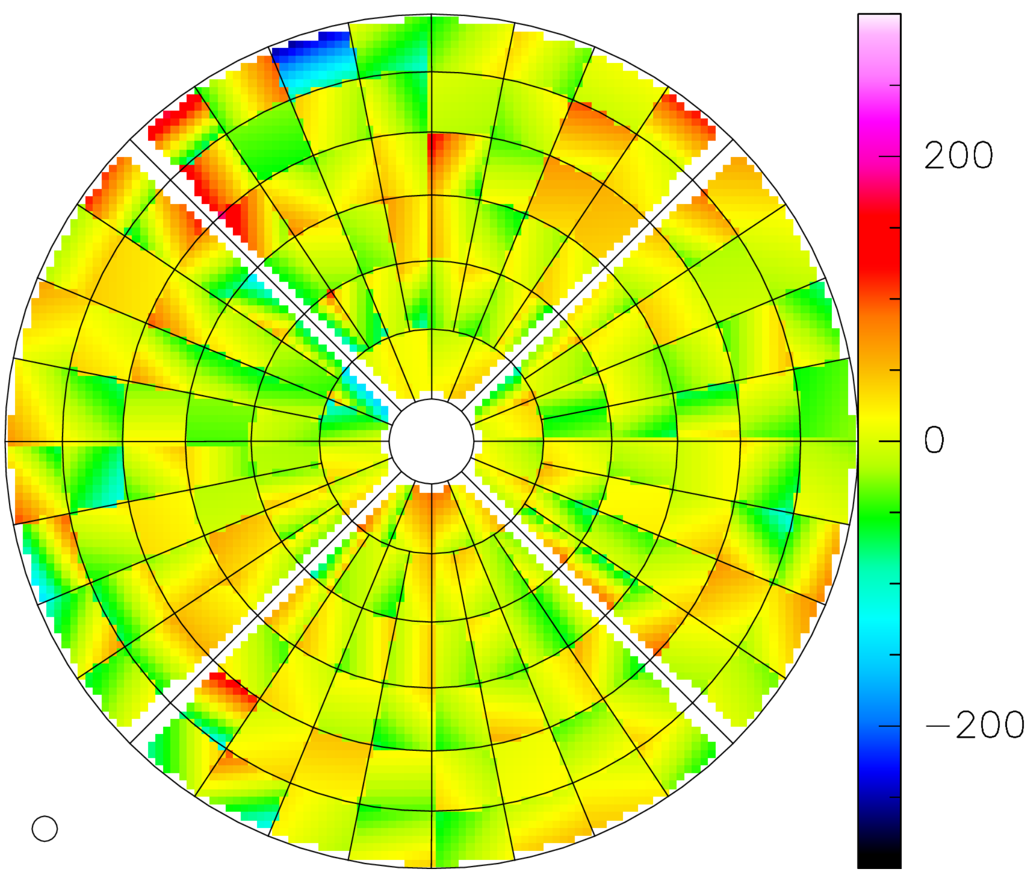
η_A(86.243 GHz) = 0.768; η_A(230.0 GHz) = 0.705; η_A(345.0 GHz) = 0.626

S/T(86.243 GHz)= 20.345 Jy/K; S/T(230GHz)= 22.142 Jy/K; S/T(345 GHz)= 24.941 Jy/K

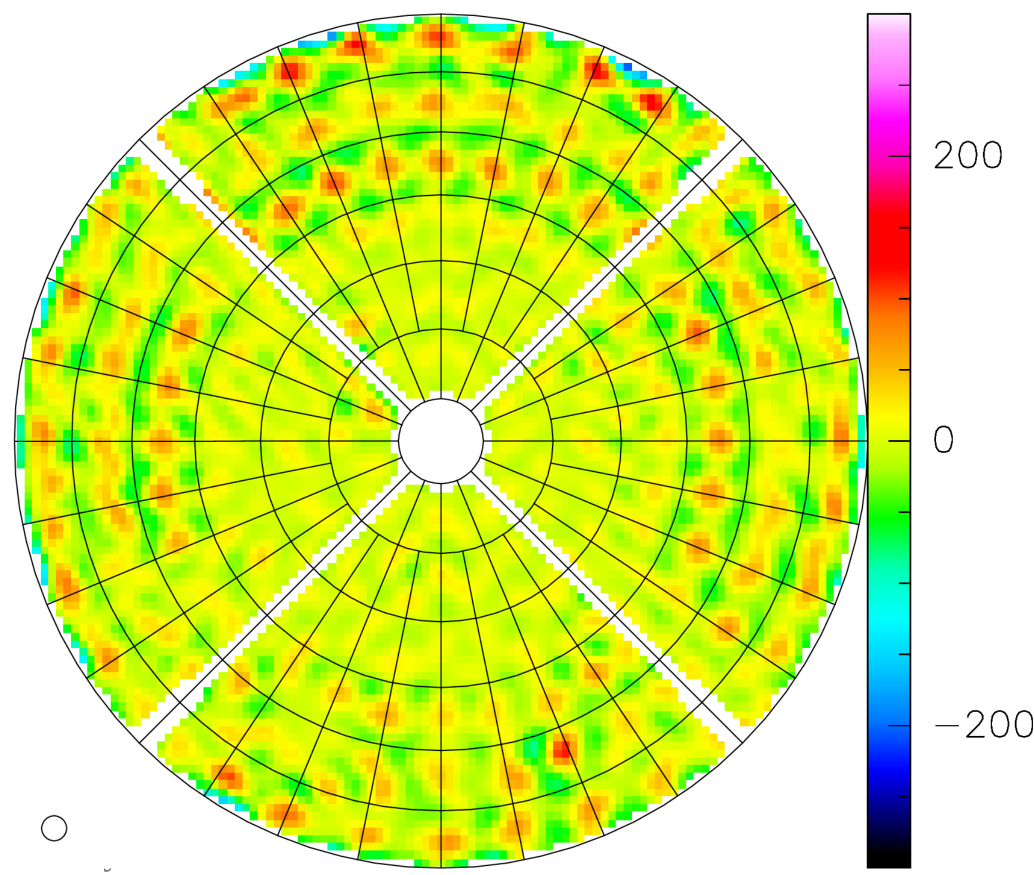
η_I= 0.779 $-\eta_S$= 0.780 $-\eta_P$(86.243 GHz)= 0.986 $-\eta_P$(230 GHz)= 0.906 $-\eta_P$(345 GHz)= 0.804

Rms/ring: 31.5 23.6 26.6 40.4 39.7 55.8

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

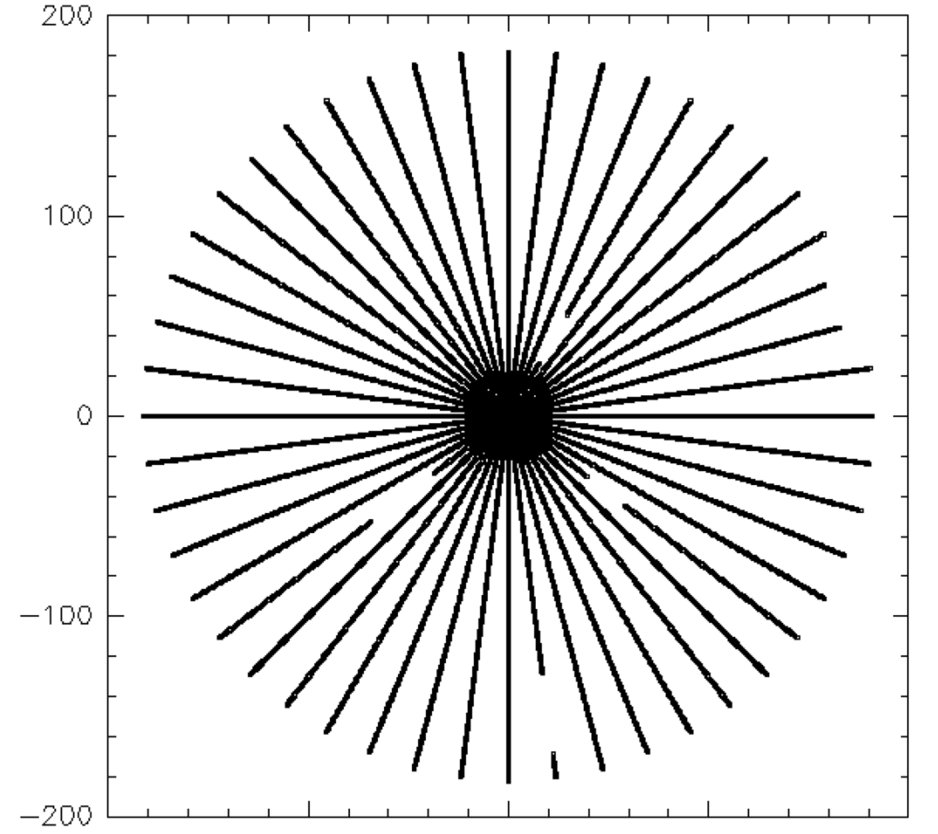


Holography

- After Fourier transform:
  - Transform the amplitude in dB
  - Fit a parabola to the amplitude:
    - Measure feed taper
    - Receiver alignement
  - 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.*



Robert Lucas presentation

Summary

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