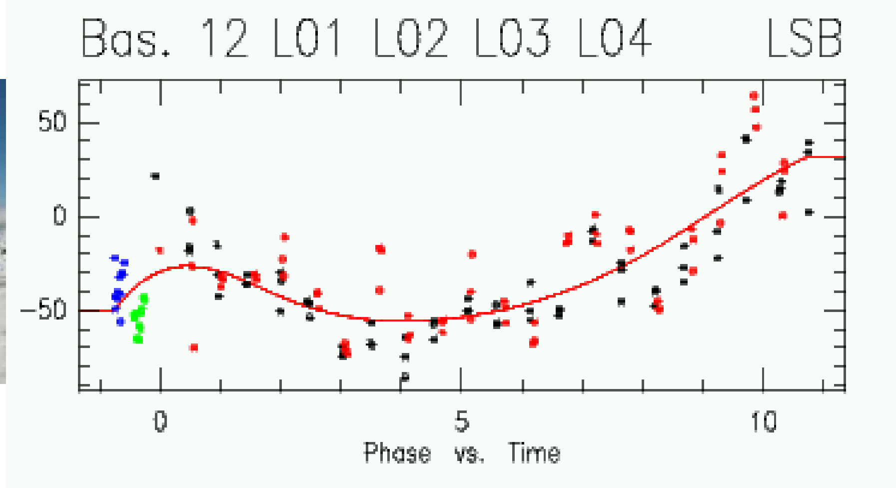


Calibration principles

Frédéric Gueth, IRAM Grenoble

9th IRAM Millimeter Interferometry School
Grenoble, 10—14 October 2016

Data calibration
Outline

- **Introduction**
- **The atmosphere** — our best enemy
- **Formalism** — deriving antenna gains

- **Bandpass** — phase and amplitude vs freq
- **Phase** — phase vs time
- **Amplitude** — amplitude vs time
- **Flux** — absolute flux scale

Introduction
Measurements

- At any time t, the interferometer provides:
  - **V(nu,t)** = spectrum
  - **V(t)** = continuum data = spectrum average
- We do not consider (u,v) dependence, only t

- Need various **calibrations** because
  - electronics have variable gains (both amp. and phase, both frequency and time)
  - atmosphere absorption and path length fluctuations

Introduction
Telescope calibration

- Pointing
- Focus
- IF filters band pass

Real-time calibrations

- Atmospheric calibration
- Antenna positions
- Delay

Done real-time but new values can be entered off-line if necessary

- Atmospheric phase correction

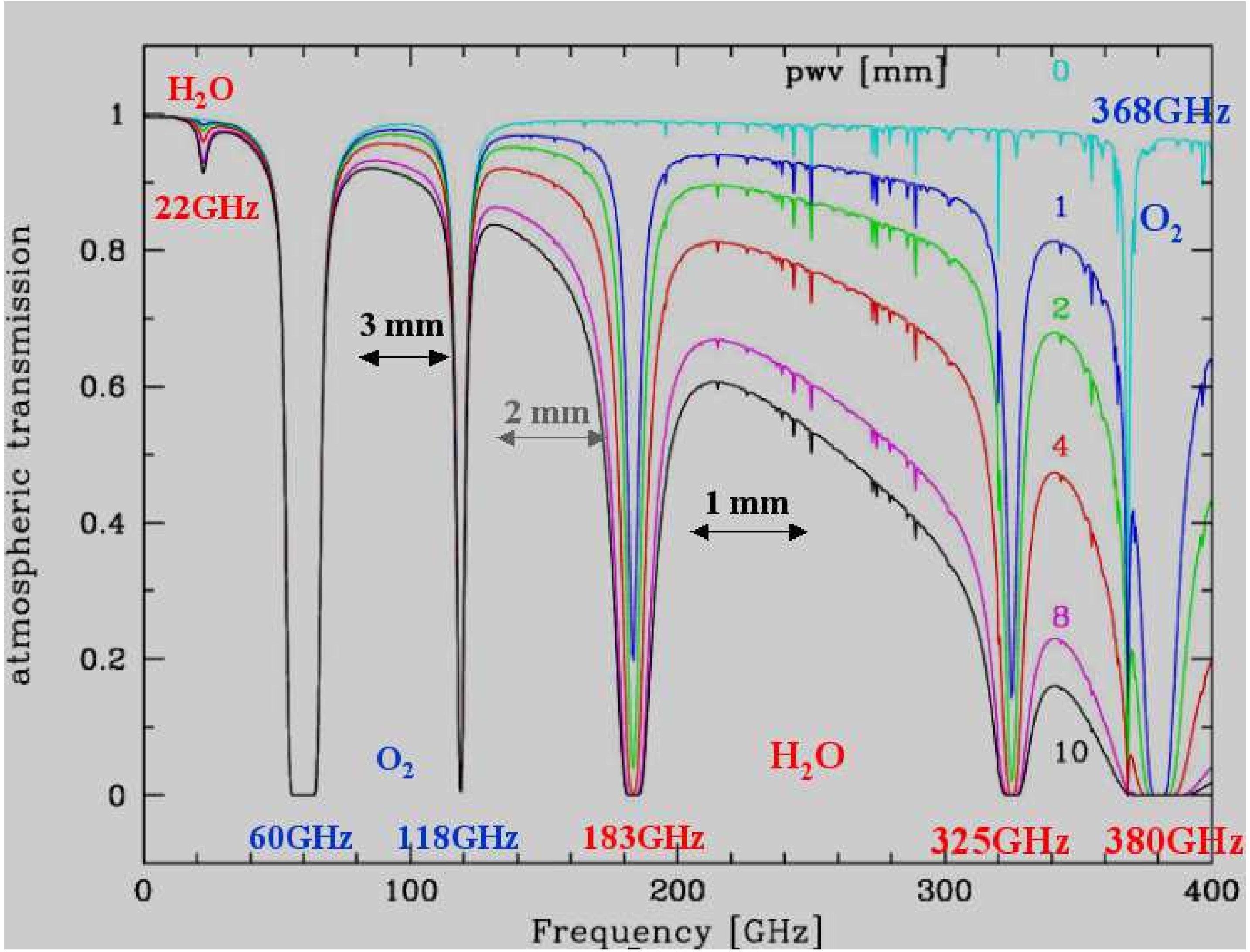
Done real-time but uncorrected data are also stored

The atmosphere
Our best enemy

- Thermal emission → **noise**
- **Absorption of incoming signal** → attenuation
- Time- and position- dependent **phase error**
  → Radio "seeing"
  → Amplitude decorrelation

- Amount of **water vapor is highly variable** in time
  – Need real-time calibration of signal attenuation
  – Need real-time calibration of phase fluctuations

The atmosphere
Absorption



The atmosphere
Absorption calibration

- Goals

  1. Correct for atmospheric absorption

  2. Backend counts → Temperature (Kelvin)

- At mm wavelengths, this **must be done very often** (20 min) because
  - Receiver gain drift
  - Atmosphere fluctuations

The atmosphere
Absorption calibration

- Assume linear answer of receiving system

$$\text{Counts} = \alpha\,(Te^{-\tau} + \mathbf{Tsys})$$

- Observe sky, cold (4K), and warm (273 K) loads
- Compute:
  - System temperature **Tsys**
  - Receiver gain α
  - Atmosphere opacity τ (**using atm. model**)

The atmosphere
Phase correction

- Timescale of phase fluctuations: seconds to hours
- Need **real-time correction** of fluctuations during basic integration time (< 1 min) to avoid
  - loss of amplitude = **decorrelation** by $\exp(-\sigma^2/2)$
  - "**seeing**" (phase $\leftrightarrow$ position)
- This is conceptually similar to **piston correction** in adaptative optics in optical/IR domain

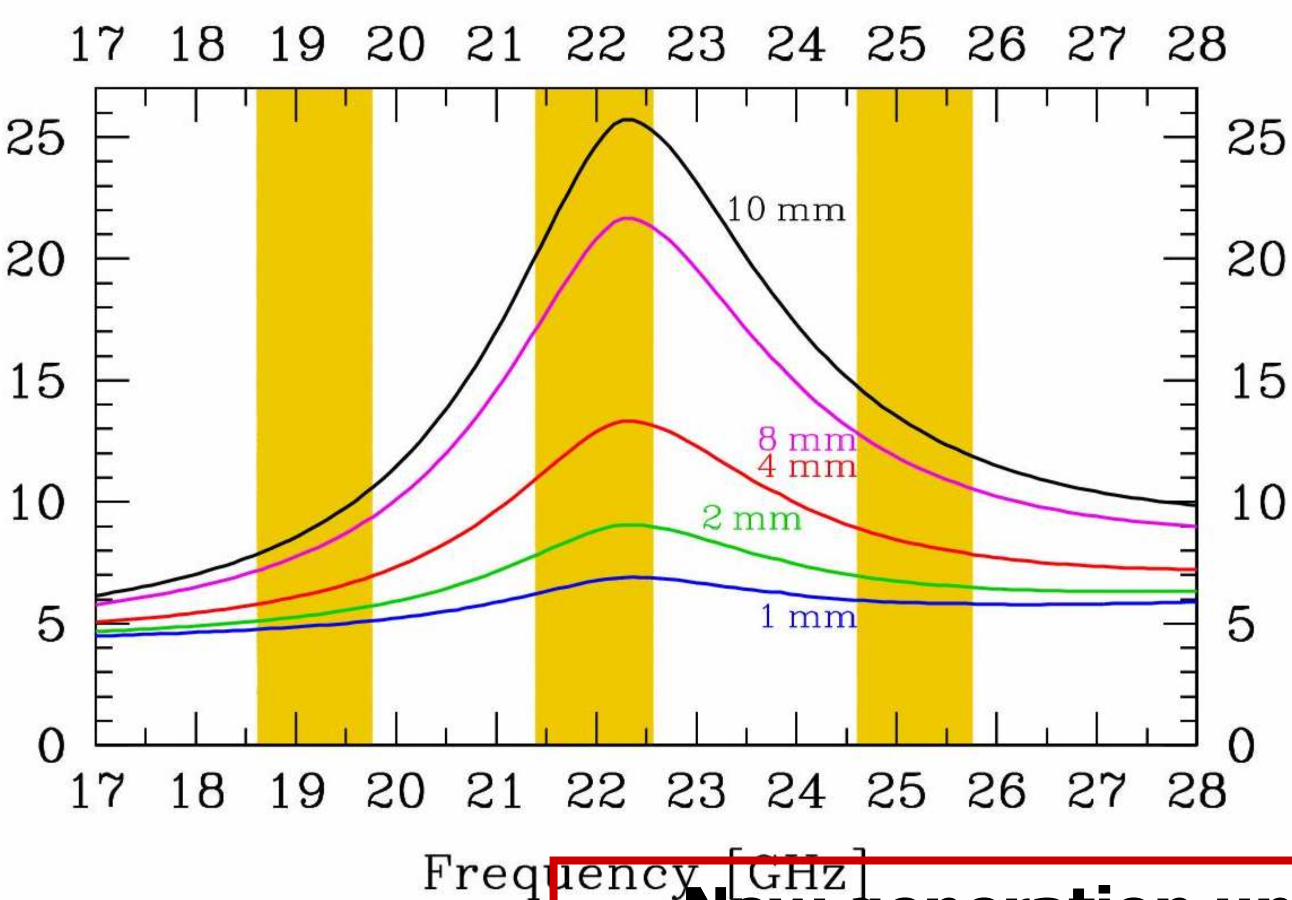
The atmosphere
Phase correction

- Predict amount of water from **water line at 22 GHz (NOEMA) or 183 GHz (ALMA)** using dedicated receivers (Water Vapor Radiometers = WVR)

- Measurement → Atmospheric **model** → Water vapor content → Path delay → Atmospheric phase → Real-time correction

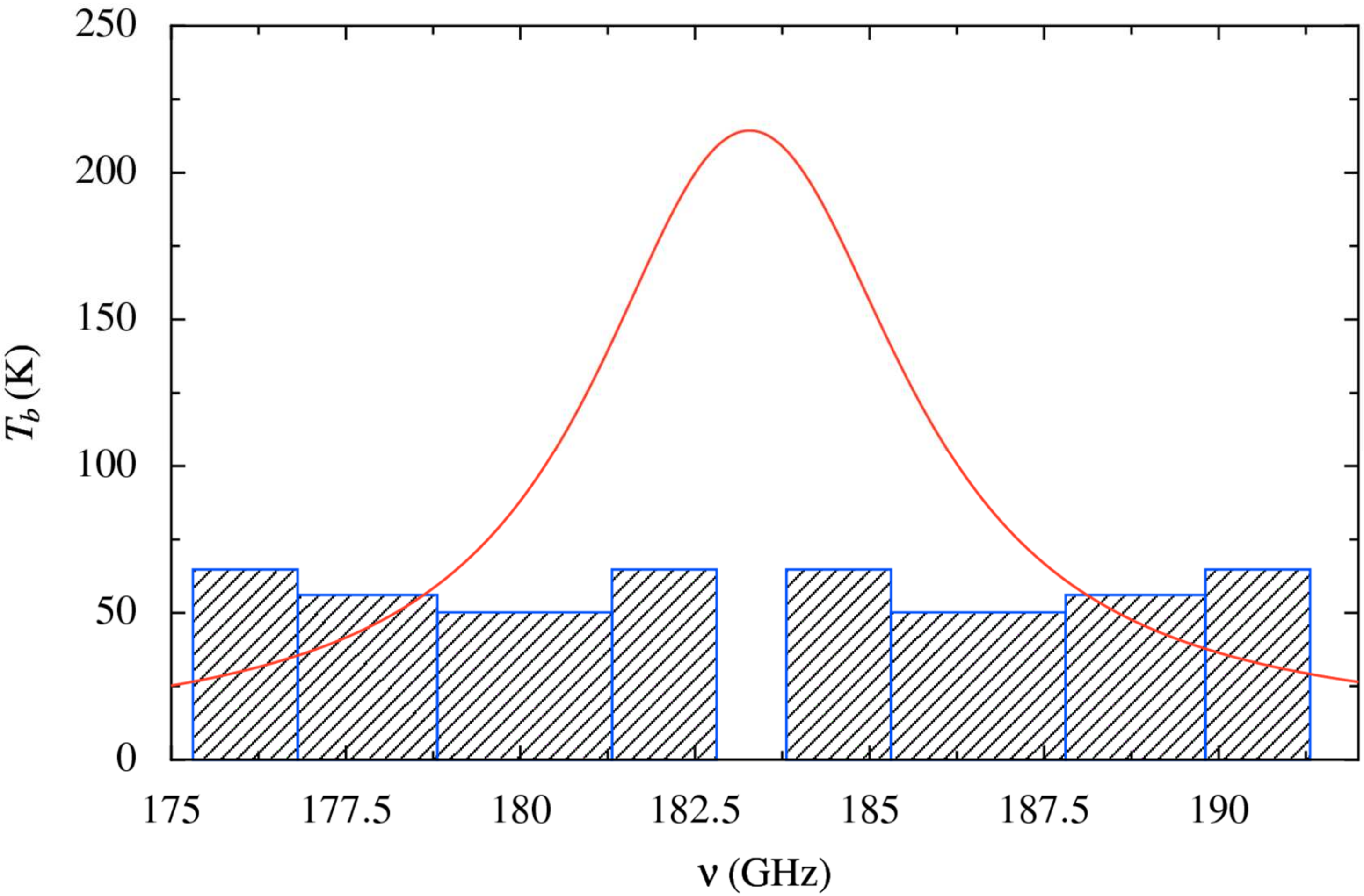
- Done **every few second** at NOEMA
- Keep both corrected and not corrected data

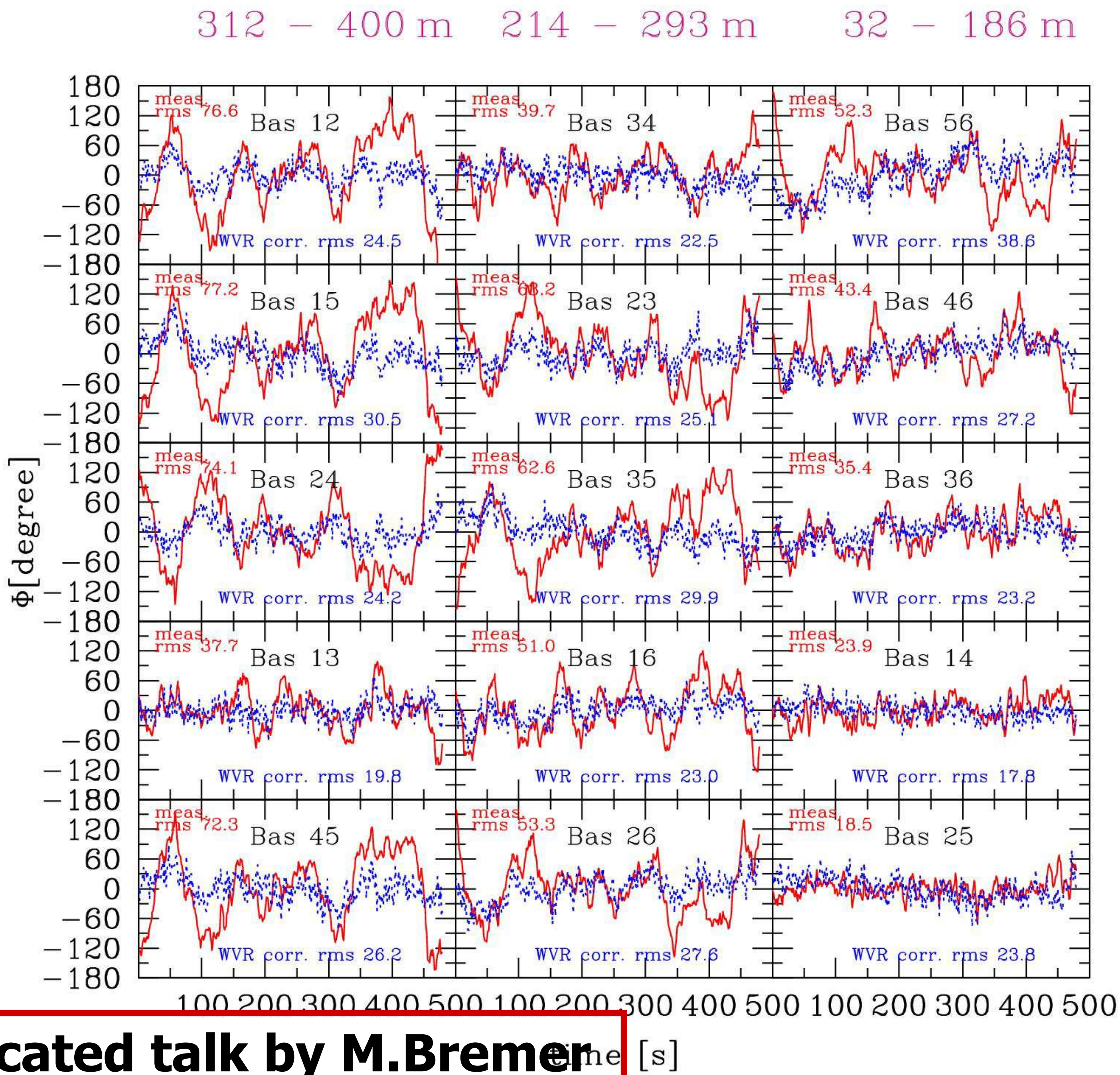
The atmosphere
22 GHz WVR (PdBI)



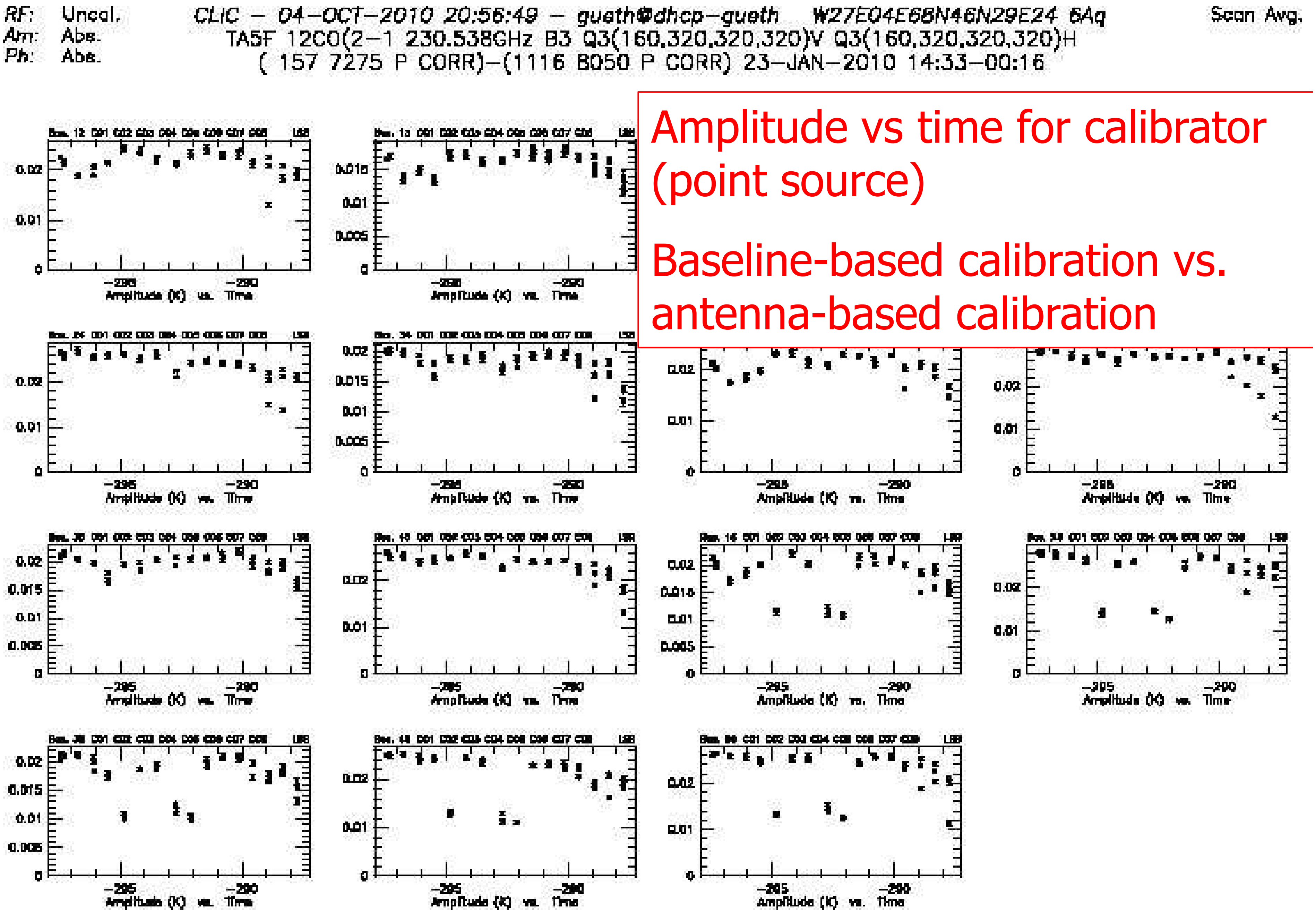
New generation under development

The atmosphere
183 GHz WVR (ALMA)





Dedicated talk by M.Bremer



Amplitude vs time for calibrator (point source)

Baseline-based calibration vs. antenna-based calibration

Formalism
Visibilities

- Calibrate only temporal or frequency effects, do not consider dependence on (u,v)
- True visibility: $\mathbf{V_{ij}(\nu,t)}$ (baseline ij)
- Observed visibility:

$$\boxed{\mathbf{Vobs_{ij}(\nu,t) = G_{ij}(\nu,t)\, V_{ij}(\nu,t) + noise}}$$

- $\mathbf{G_{ij}}$ = complex gain (amplitude & phase)
- Scalar description – no polarization

Formalism
Gain decomposition

- **Most of the effects are antenna-based**
  – Pointing, Focus, Antenna position, Atmosphere, Receivers noise, Receivers bandpass…

- **Gain decomposition:** $\boxed{Vobs_{ij} = G_{ij}\,V_{ij} = g_i\,g_j\,V_{ij}}$

- Baseline-based effect?
  – Correlator bandpass → real-time calibration
  – Time and frequency averaging → **decorrelation**

Formalism
Antenna-based gains

- Observation of a **point source** of flux S:

$$Vobs = G_{ij}\, V \qquad V = S \qquad Vobs = G_{ij}\, S$$

- Antenna –based gains: $\boxed{Vobs = g_i g_j\, S}$

- Can solve for antenna gains with 3 antennas

$$(\mathbf{g_1})^2 = \frac{\mathbf{Vobs_{12}\, Vobs31}}{\mathbf{S\, Vobs23}}$$

Formalism
Antenna-based gains

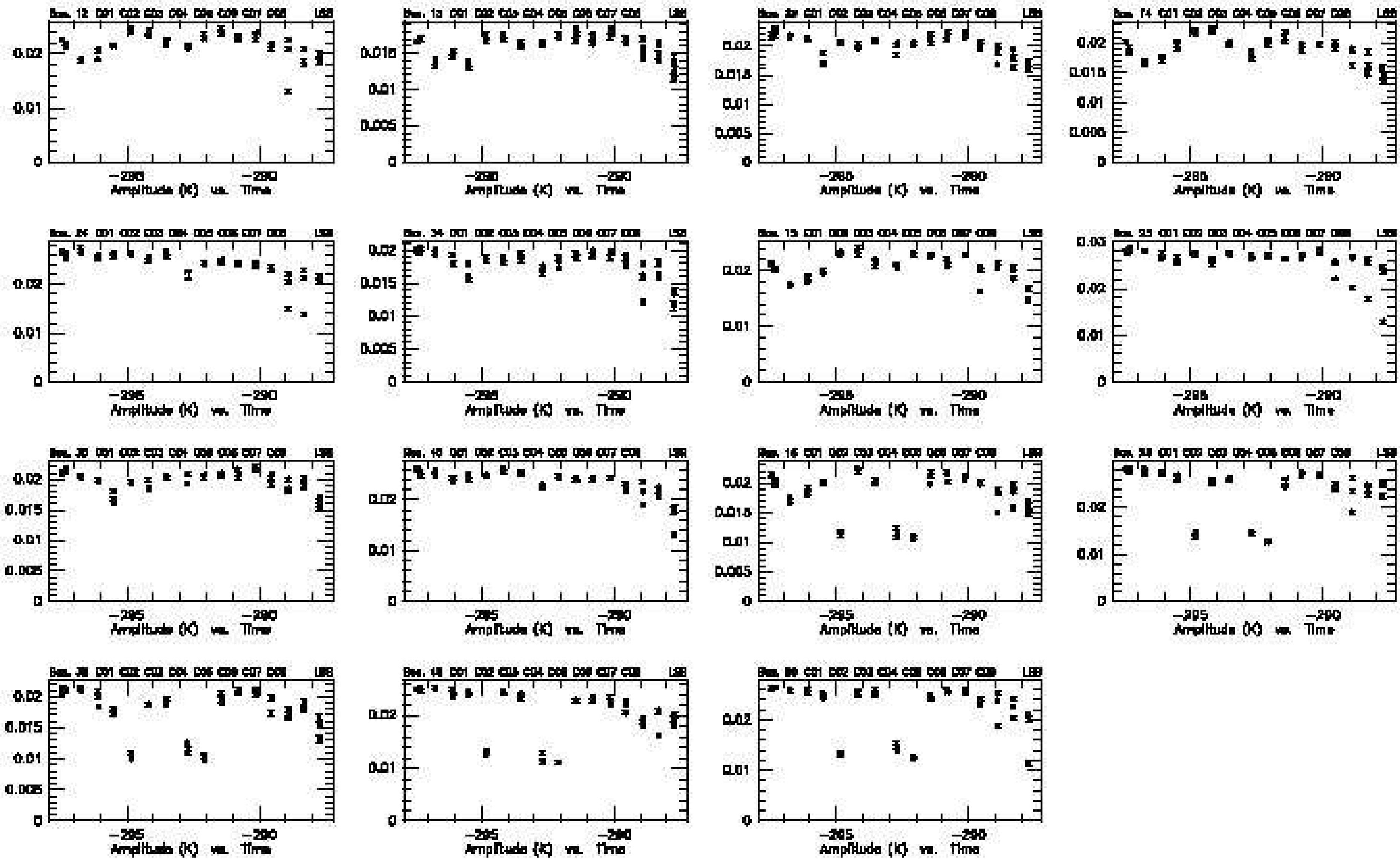
- Observation of a **point source** of flux S:

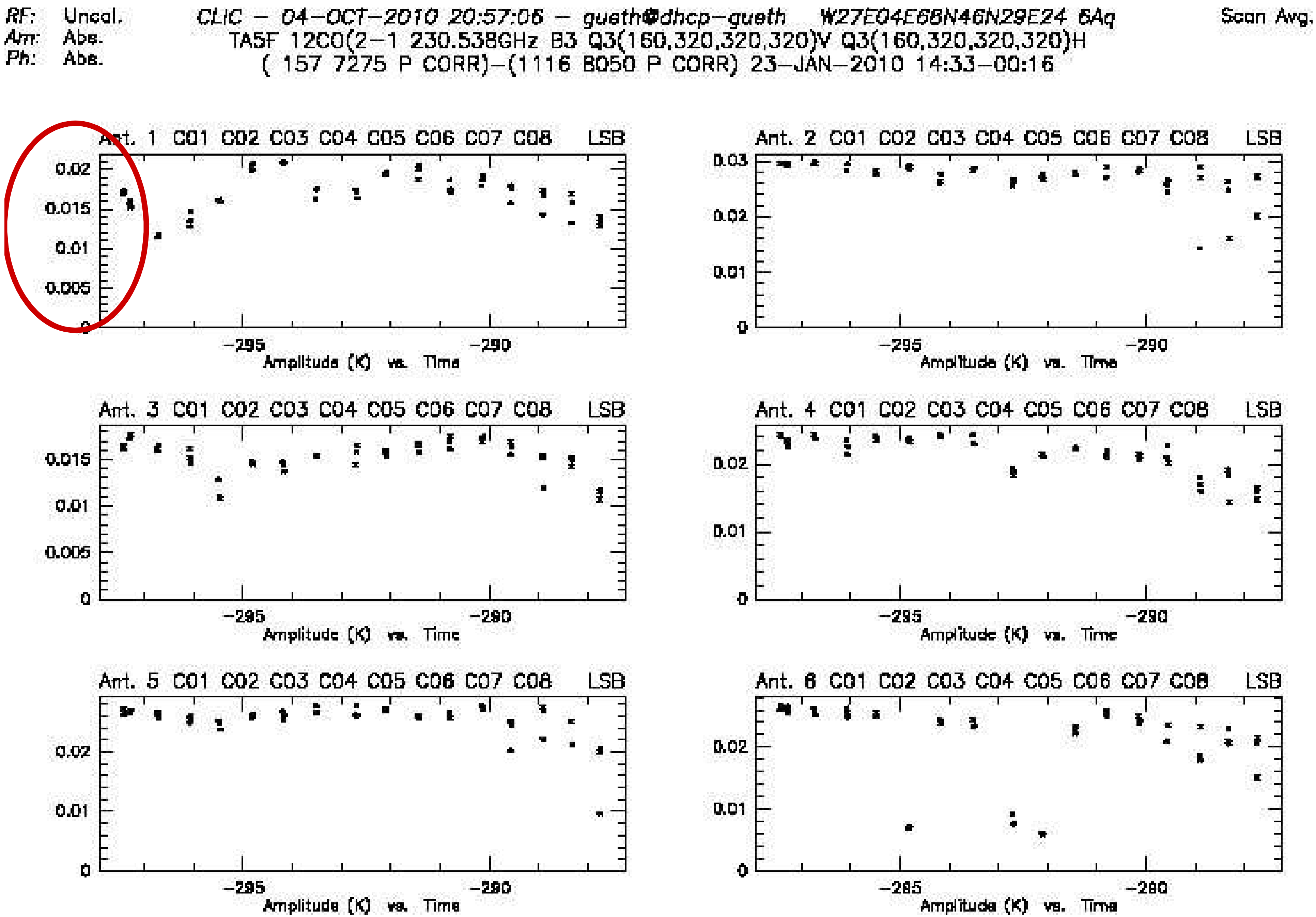
$$Vobs = G_{ij}\, V \qquad V = S \qquad Vobs = G_{ij}\, S$$

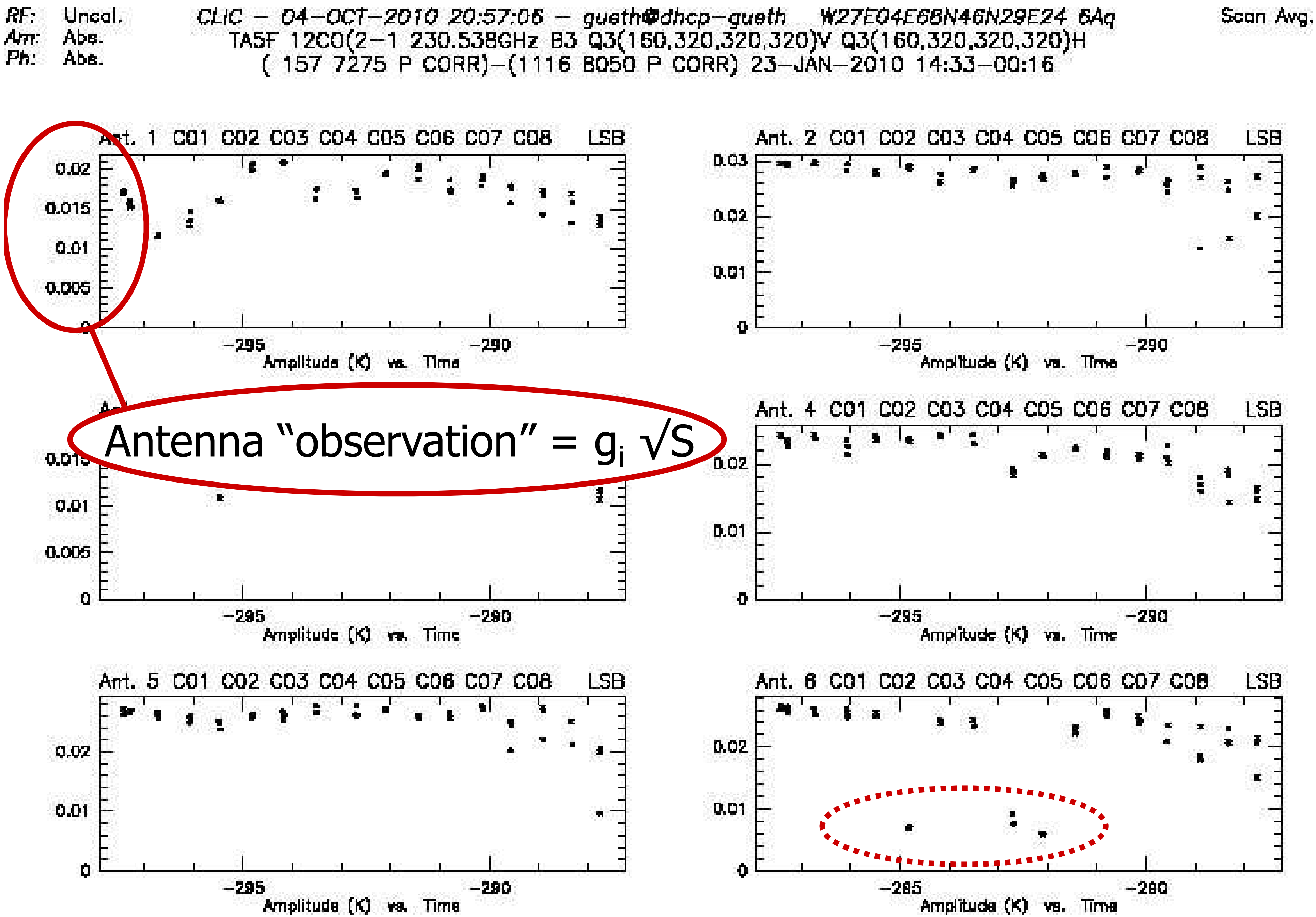
- Antenna –based gains: $\boxed{Vobs = g_i g_j\, S}$

- N complex unknown (one g_i per antenna)
- N(N-1)/2 equations (one per baseline)
- **System is over-determined** and may be solved by a method of **least squares**

RF: Uncal. CLIC – 04-OCT-2010 20:56:49 – gueth@dhcp-gueth W27E04E68N46N29E24 6Aq Scan Avg.
Am: Abs. TA5F 12CO(2-1 230.538GHz B3 Q3(160,320,320,320)V Q3(160,320,320,320)H
Ph: Abs. (157 7275 P CORR)-(1116 8050 P CORR) 23-JAN-2010 14:33-00:16

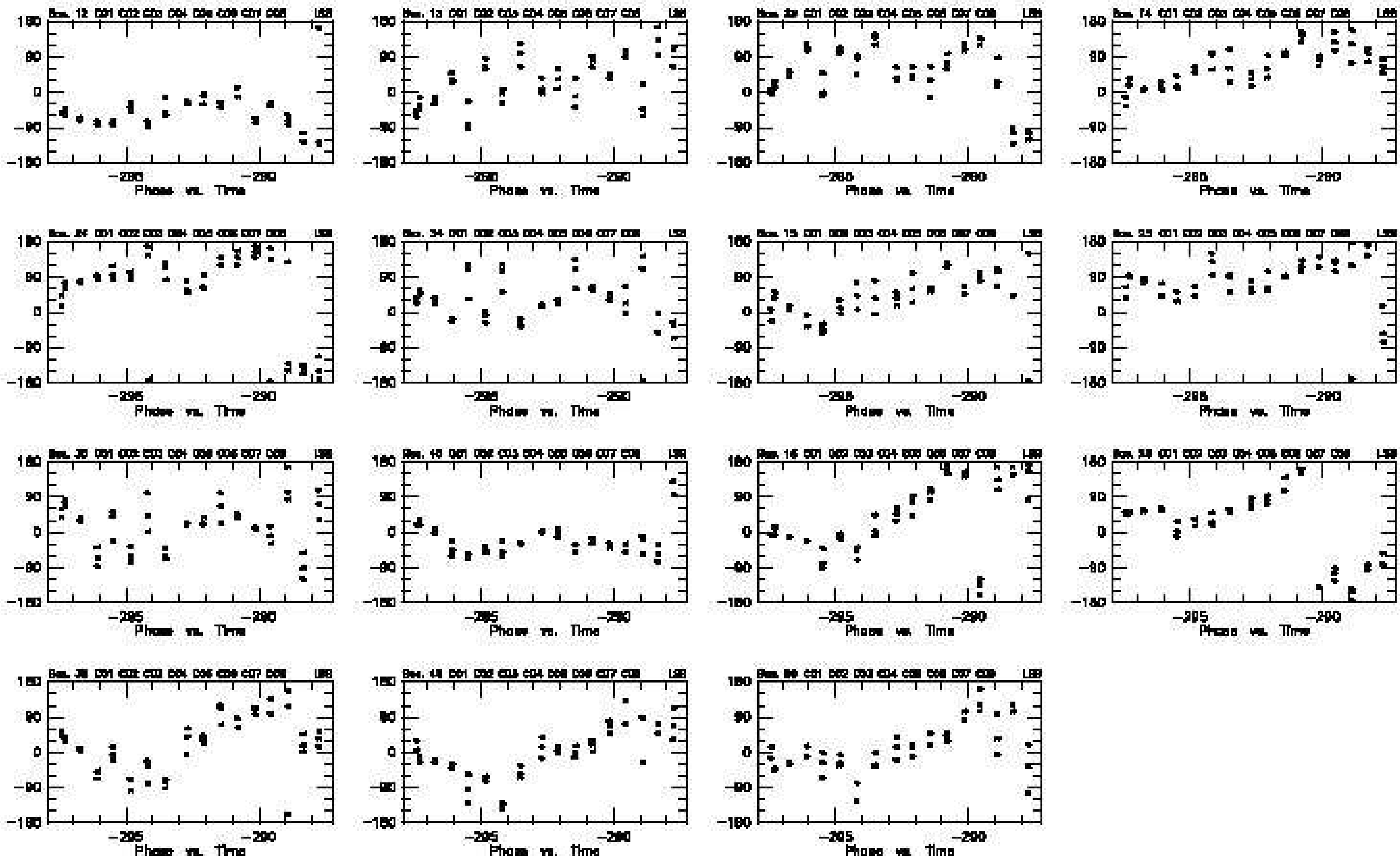


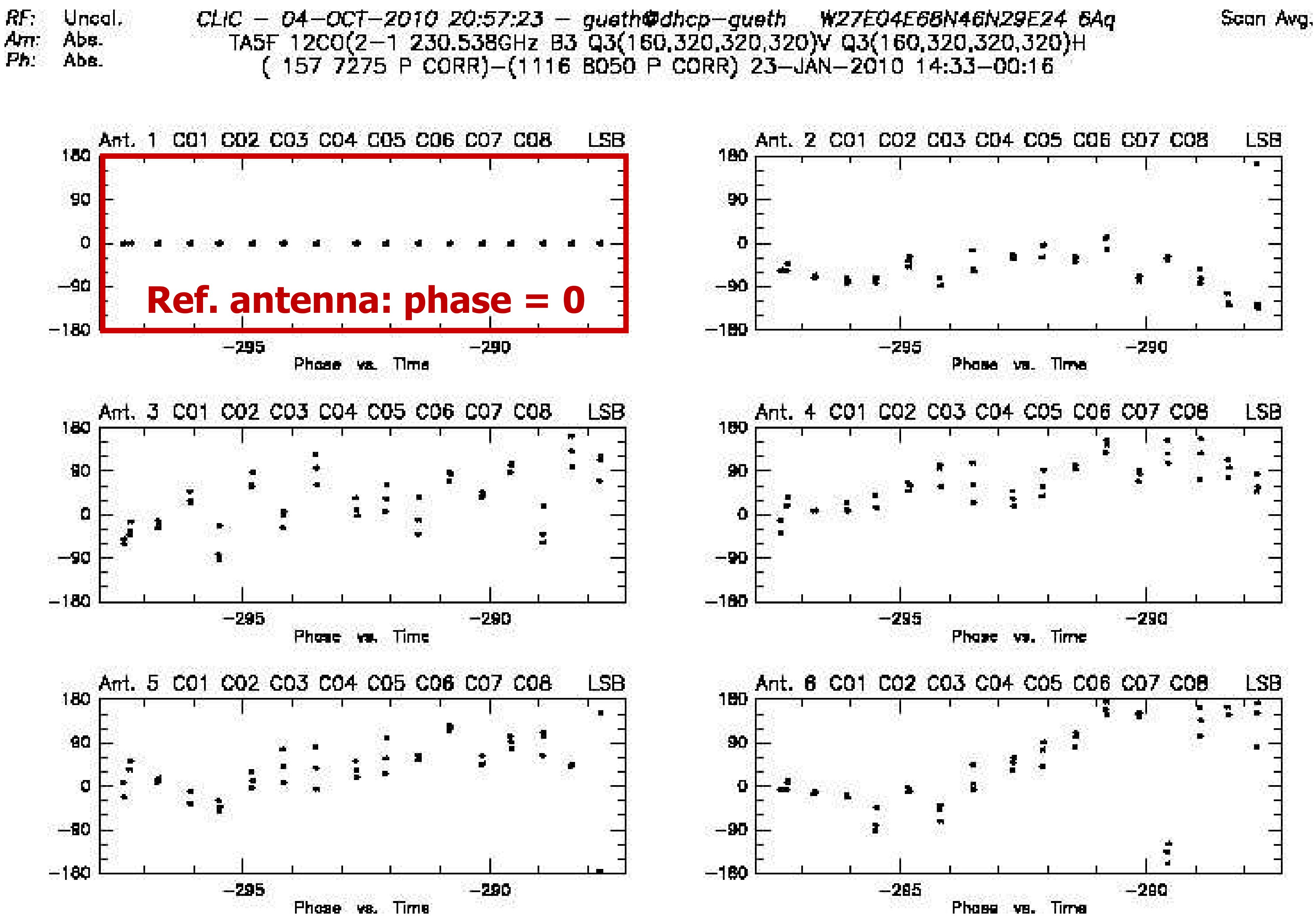

RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC – 04-OCT-2010 20:57:06 – gueth@dhcp-gueth W27E04E68N46N29E24 6Aq
TA5F 12CO(2-1 230.538GHz B3 Q3(160,320,320,320)V Q3(160,320,320,320)H
(157 7275 P CORR)-(1116 8050 P CORR) 23-JAN-2010 14:33-00:16
Scan Avg.
Ant. 1 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 2 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 3 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 4 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 5 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 6 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Amplitude (K) vs. Time



RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC – 04-OCT-2010 20:57:06 – gueth@dhcp-gueth W27E04E68N46N29E24 6Aq
TA5F 12CO(2-1 230.538GHz B3 Q3(160,320,320,320)V Q3(160,320,320,320)H
(157 7275 P CORR)-(1116 8050 P CORR) 23-JAN-2010 14:33-00:16
Scan Avg.
Ant. 1 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 2 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 4 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 5 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 6 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Amplitude (K) vs. Time
Antenna "observation" = $g_i \sqrt{S}$

RF: Uncal. CLIC – 04-OCT-2010 20:57:35 – gueth@dhcp-gueth W27E04E68N46N29E24 6Aq Scan Avg.
Am: Abs. TA5F 12CO(2–1 230.538GHz B3 Q3(160,320,320,320)V Q3(160,320,320,320)H
Ph: Abs. (157 7275 P CORR)–(1116 8050 P CORR) 23-JAN-2010 14:33–00:16




RF: Uncal.
Am: Abs.
Ph: Abs.
CLIC – 04–OCT–2010 20:57:23 – gueth@dhcp–gueth W27E04E68N46N29E24 6Aq
TA5F 12CO(2–1 230.538GHz B3 Q3(160,320,320,320)V Q3(160,320,320,320)H
(157 7275 P CORR)–(1116 8050 P CORR) 23–JAN–2010 14:33–00:16
Scan Avg.
Ant. 1 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ref. antenna: phase = 0
Ant. 2 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 3 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 4 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 5 C01 C02 C03 C04 C05 C06 C07 C08 LSB
Ant. 6 C01 C02 C03 C04 C05 C06 C07 C08 LSB
180
90
0
–90
–180
–295
–290
Phase vs. Time

Formalism
Gain decomposition

<u>Advantages of using the antenna-based gains</u>:

1. most of the effects are **truly antenna-based**
   example: pointing, focus, …

2. precision to which antenna gains are determined is **improved by a factor √N** over the precision of the measurement of baseline gains

Formalism
Closure relations

- Phase closure relation (point source):
  - Antenna-based decomposition: $\varphi12 = \varphi1 - \varphi2$
  - Phase closure: **$\varphi12 + \varphi23 + \varphi31 = 0$**

- Very useful relation when phases are too unstable to be directly measured (VLBI, optics)
- Similar relations exists for amplitude ratios

- **The decomposition in antenna-based gains implicitly takes into account the closure relations**

Data calibration
Time/Frequency

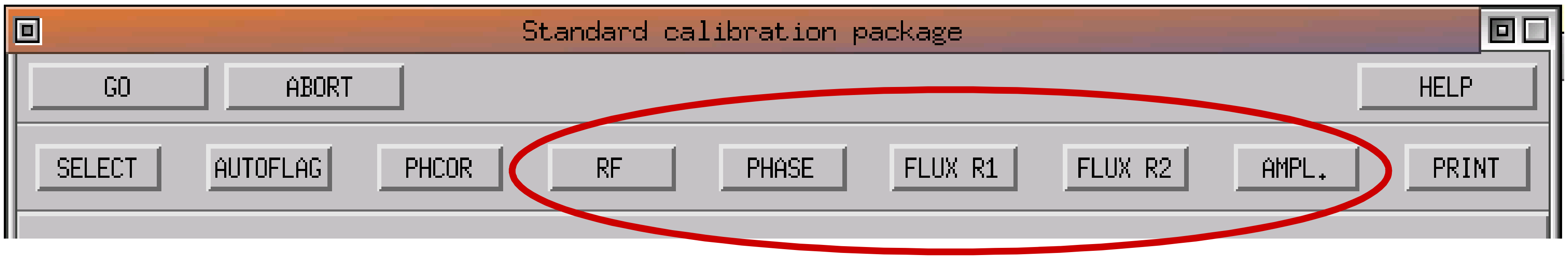
- **Basic assumption: time- and frequency-variations are decoupled**

- Quite robust:
  - Frequency response mostly due to receivers; stable until retuning
  - Time variations (atmosphere, antennas, …) mostly achromatic

Data calibration
Steps

<u>Millimeter interferometers</u>

- **Bandpass** (amplitude and phase vs. frequency)
- **Phase** vs. time
- **Flux** scale
- **Amplitude** vs. time



Bandpass calibration
The problems

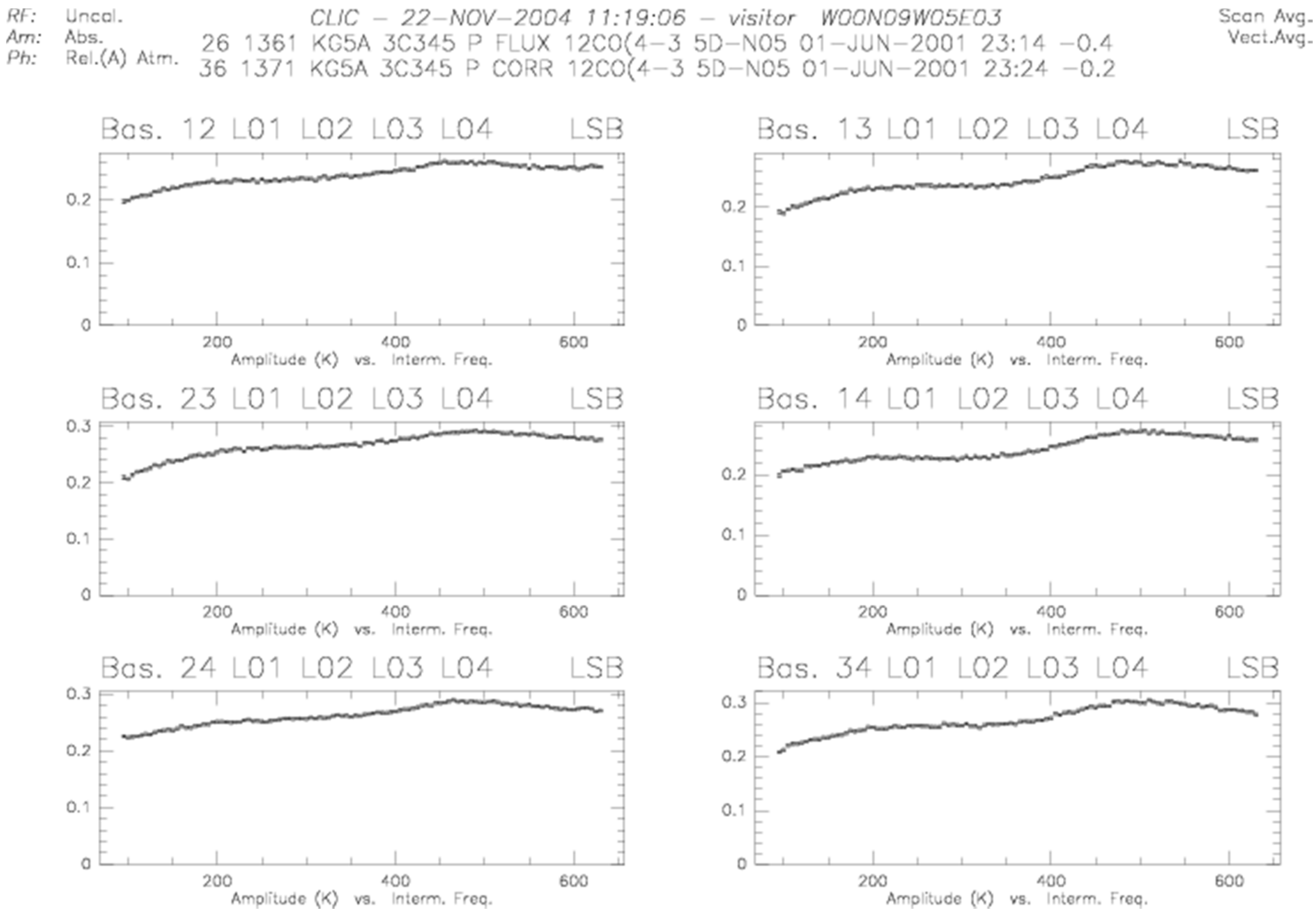
- Frequency dependence of the interferometer response arises from:
  - Receivers intrinsic response
  - Delay offsets (slope on phase)
  - Coaxial cables attenuation
  - Antenna chromatism
  - Atmosphere (O2, O3 lines)
  - …

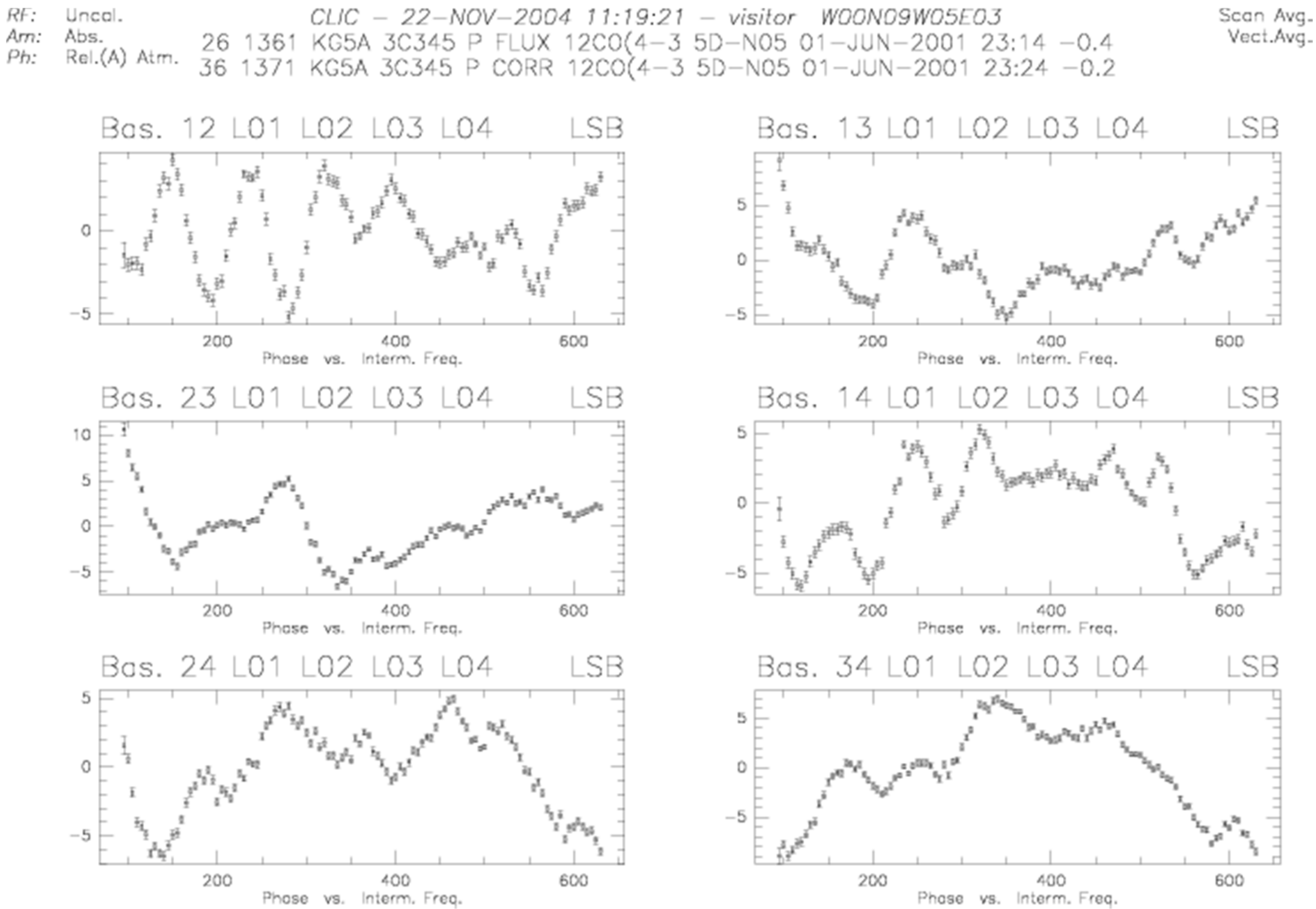
Bandpass calibration
Method

- A strong quasar is observed at the beginning of each project

- **Phase should be zero** (point source)
  Amplitude vs. frequency should be constant (continuum source)

- Potential problem: spectral index of quasars over large bandwidth


RF: Uncal.
Am: Abs.
Ph: Rel.(A) Atm.
CLIC – 22-NOV-2004 11:19:06 – visitor W00N09W05E03
26 1361 KG5A 3C345 P FLUX 12CO(4-3 5D-N05 01-JUN-2001 23:14 -0.4
36 1371 KG5A 3C345 P CORR 12CO(4-3 5D-N05 01-JUN-2001 23:24 -0.2
Scan Avg.
Vect.Avg.
Bas. 12 L01 L02 L03 L04 LSB
Bas. 13 L01 L02 L03 L04 LSB
Bas. 23 L01 L02 L03 L04 LSB
Bas. 14 L01 L02 L03 L04 LSB
Bas. 24 L01 L02 L03 L04 LSB
Bas. 34 L01 L02 L03 L04 LSB
Amplitude (K) vs. Interm. Freq.


RF: Uncal.
Am: Abs.
Ph: Rel.(A) Atm.
CLIC – 22-NOV-2004 11:19:21 – visitor W00N09W05E03
26 1361 KG5A 3C345 P FLUX 12CO(4-3 5D-N05 01-JUN-2001 23:14 -0.4
36 1371 KG5A 3C345 P CORR 12CO(4-3 5D-N05 01-JUN-2001 23:24 -0.2
Scan Avg.
Vect.Avg.
Bas. 12 L01 L02 L03 L04 LSB
Bas. 13 L01 L02 L03 L04 LSB
Bas. 23 L01 L02 L03 L04 LSB
Bas. 14 L01 L02 L03 L04 LSB
Bas. 24 L01 L02 L03 L04 LSB
Bas. 34 L01 L02 L03 L04 LSB
Phase vs. Interm. Freq.

Bandpass calibration
Method

- Time calibration + average (improve the SNR)
- **Solve for antenna-based gains**
- **Fit as a function of frequency** (polynom)
- NB: gains defined such that integral = 1
- Apply the bandpass to all data

- Assume bandpass is constant with time
- Must be recalibrated if receivers are retuned

Bandpass calibration
Accuracy

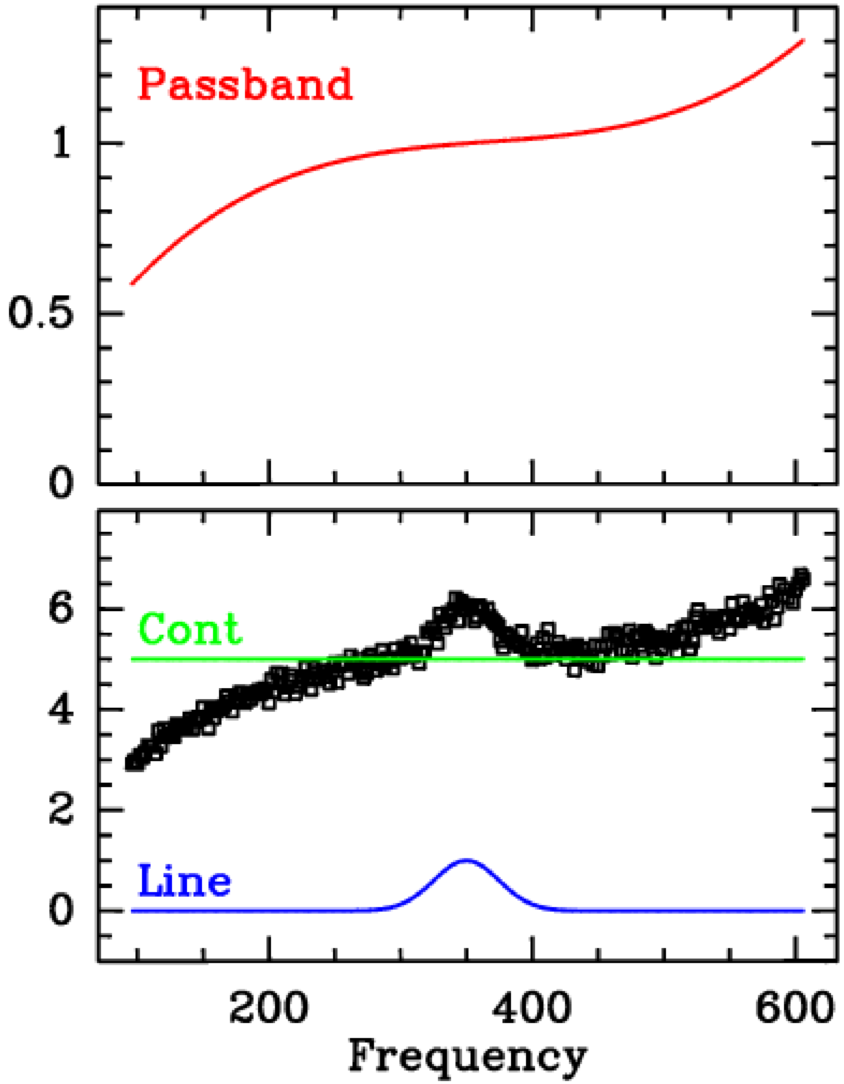
- RF bandpass phase accuracy → uncertainty on relative positions of spectral features

- Rule of thumb:

$$\boxed{\textbf{Position error / Beam} = \Delta\Phi / 360}$$

- **1″ resolution observations, $\Delta\Phi$ = 5 deg, error = 0.015″**

Bandpass calibration
Accuracy



- RF bandpass <u>amplitude</u> accuracy → may be important to detect **weak line on a strong continuum**

- Bandpass curve is a multiplicative factor

Phase calibration
The problems

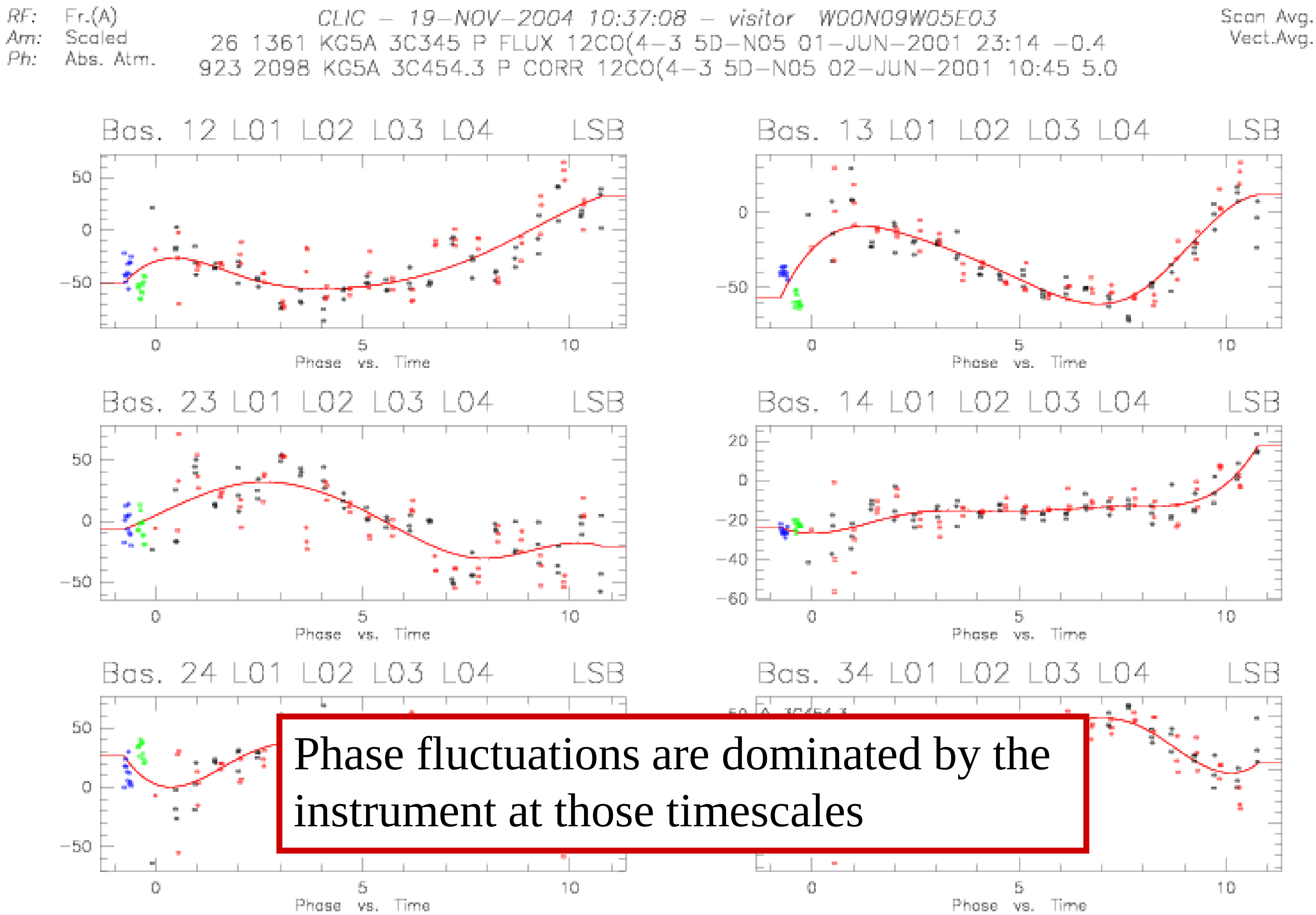
- **Short-term time variation** of the phase is caused by the atmosphere

- **Long-term** time variation:
  - Antenna position errors (period 24 h)
  - Atmosphere up to ~1h
  - Antenna/electronics drifts

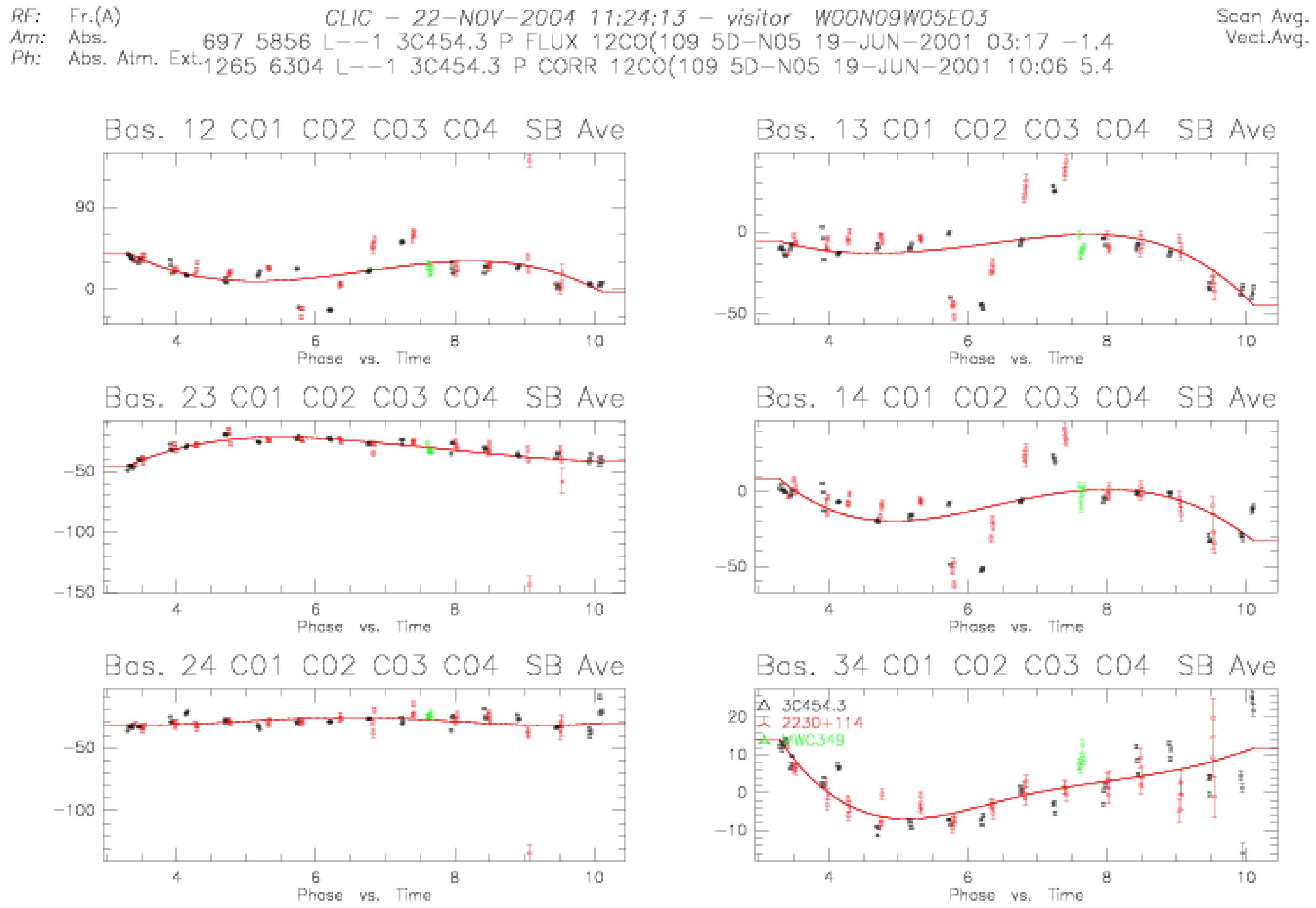
Phase calibration critical for final image quality

Phase calibration
Method

- Calibration
  - A point source (quasar) is observed every few min
  - **Its phase must be zero**
  - **Solve for antenna-based gains**
  - **Fit as a function of time** (spline)
  - Better: use two calibrators
  - Apply to all data
  - Plot per baseline: measurements + combination of antenna-based fits



Phase fluctuations are dominated by the instrument at those timescales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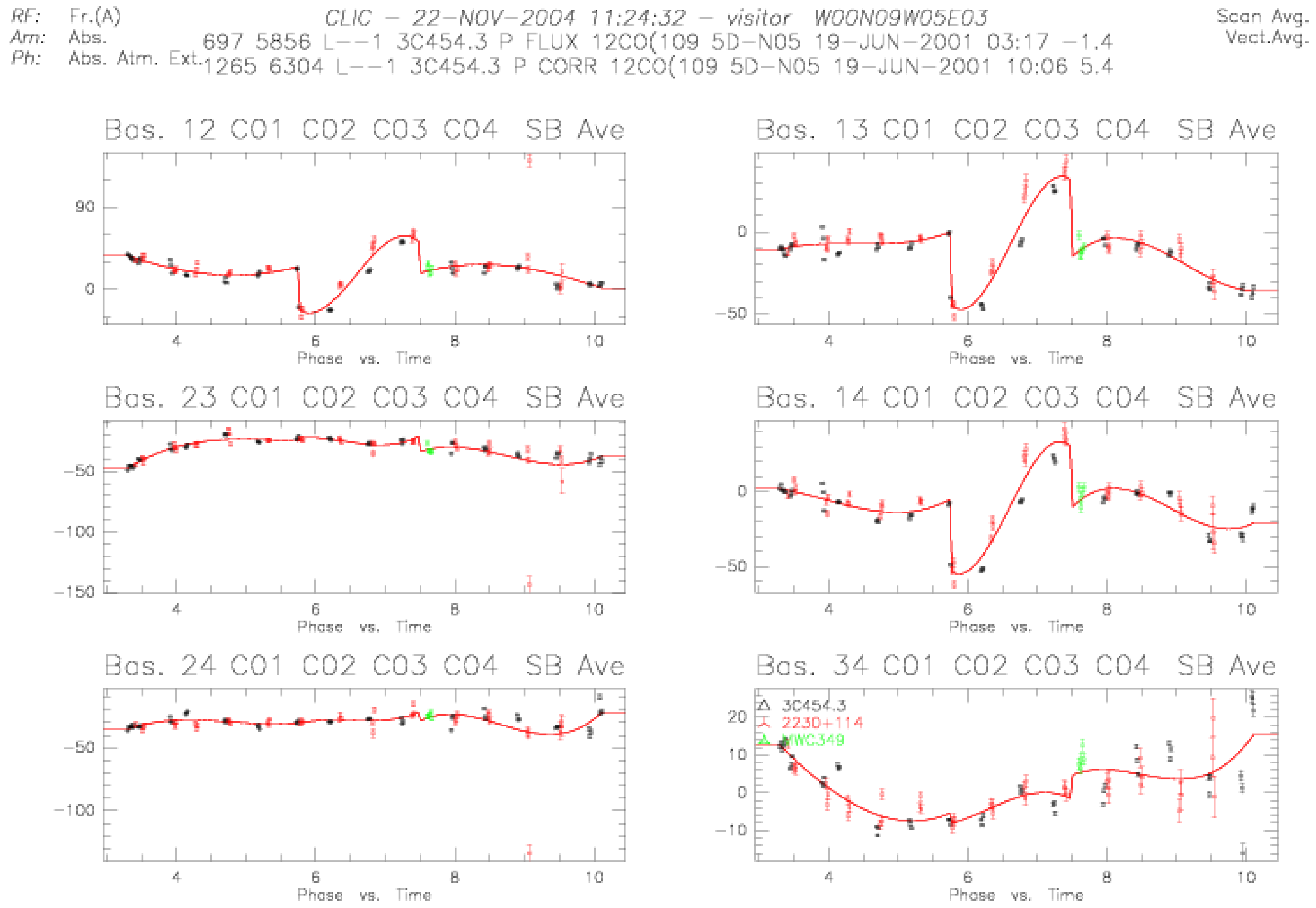
Am: Abs.
Ph: Abs. Atm. Ext.
CLIC – 22-NOV-2004 11:24:13 – visitor W00N09W05E03
697 5856 L--1 3C454.3 P FLUX 12CO(109 5D-N05 19-JUN-2001 03:17 -1.4
1265 6304 L--1 3C454.3 P CORR 12CO(109 5D-N05 19-JUN-2001 10:06 5.4
Scan Avg.
Vect.Avg.
Bas. 12 C01 C02 C03 C04 SB Ave
Bas. 13 C01 C02 C03 C04 SB Ave
Bas. 23 C01 C02 C03 C04 SB Ave
Bas. 14 C01 C02 C03 C04 SB Ave
Bas. 24 C01 C02 C03 C04 SB Ave
Bas. 34 C01 C02 C03 C04 SB Ave
Phase vs. Time
3C454.3
2230+114
MWC349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Ph: Abs. Atm. Ext.
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697 5856 L--1 3C454.3 P FLUX 12CO(109 5D-N05 19-JUN-2001 03:17 -1.4
1265 6304 L--1 3C454.3 P CORR 12CO(109 5D-N05 19-JUN-2001 10:06 5.4
Scan Avg.
Vect.Avg.
Bas. 12 C01 C02 C03 C04 SB Ave
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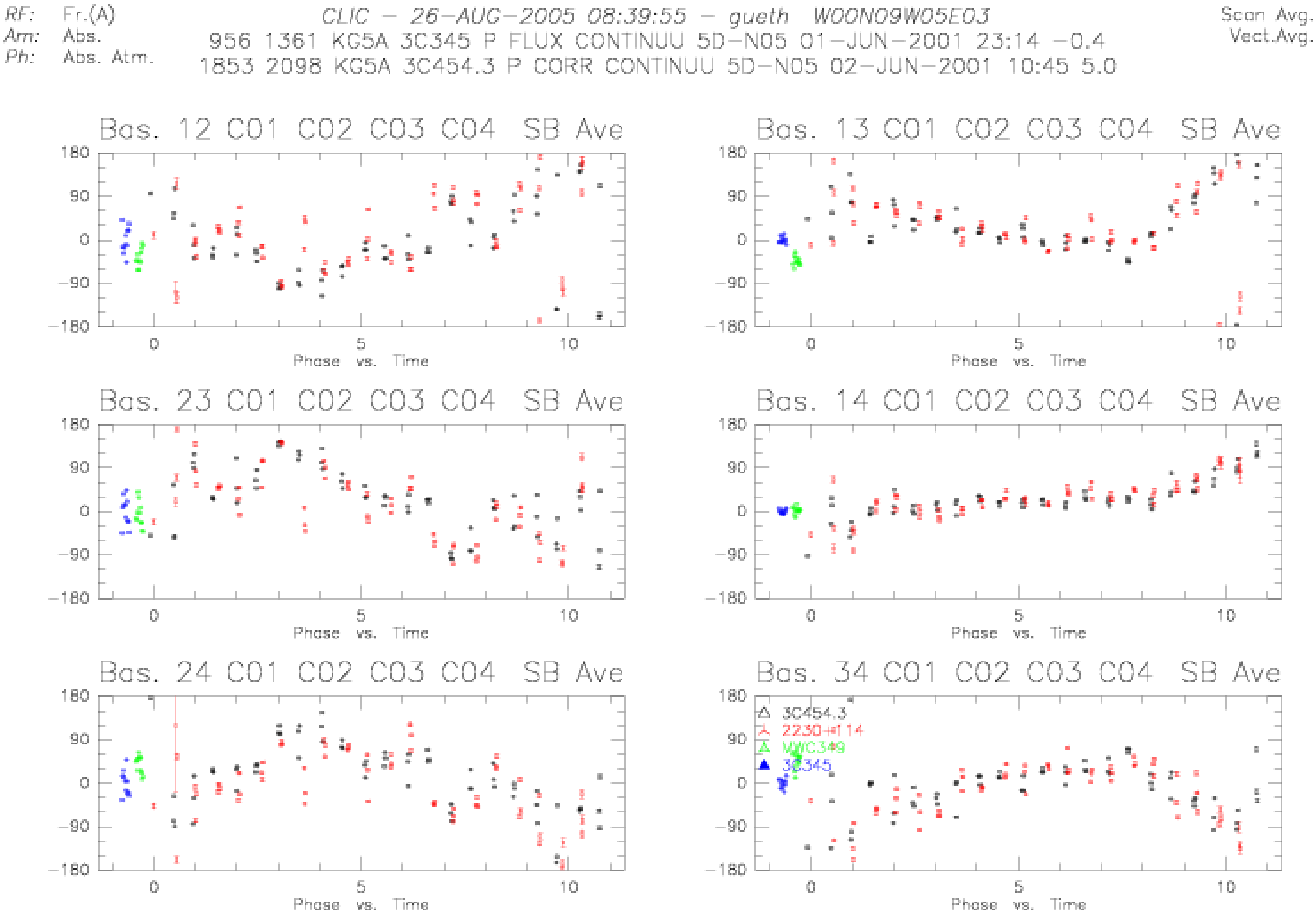
Bas. 23 C01 C02 C03 C04 SB Ave
Bas. 14 C01 C02 C03 C04 SB Ave
Bas. 24 C01 C02 C03 C04 SB Ave
Bas. 34 C01 C02 C03 C04 SB Ave
3C454.3
2230+114
MWC349
Phase vs. Time

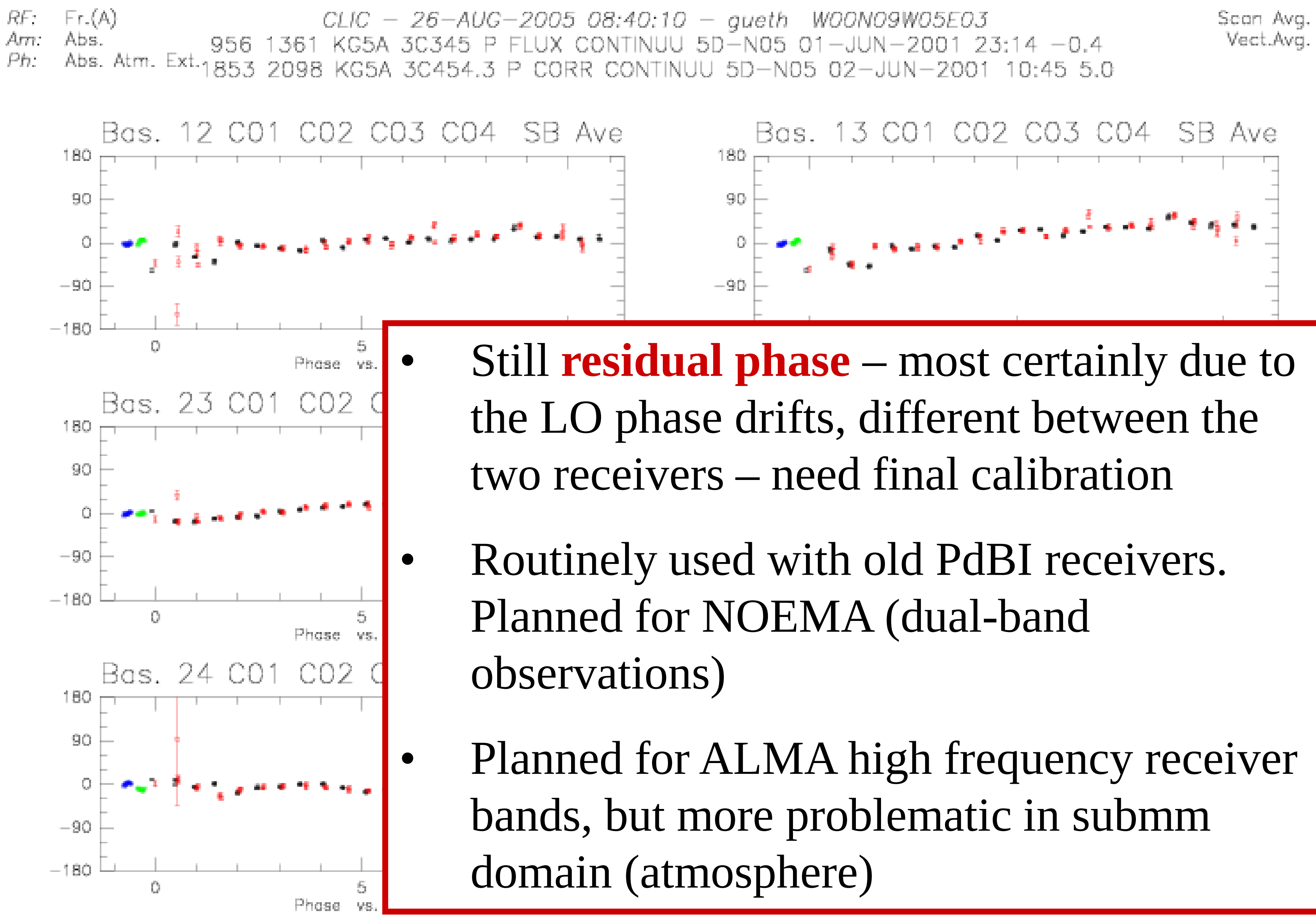
Phase calibration
Phase transfer

- Atmosphere and most of the instrumental fluctuations **scale with frequency**
- **Phase transfer:**
  1. use low-frequency data (highest SNR) to derive phase curve
  2. scale according to frequency ratio
  3. correct the high frequency data

230 GHz data, no phase transfer



230 GHz, with phase transfer



- Still **residual phase** – most certainly due to the LO phase drifts, different between the two receivers – need final calibration
- Routinely used with old PdBI receivers. Planned for NOEMA (dual-band observations)
- Planned for ALMA high frequency receiver bands, but more problematic in submm domain (atmosphere)

Phase calibration
Strategies

<u>Phase calibration strategies</u>:

effect of the noise on calibrators measurements?

interpolation from calibrators to source?

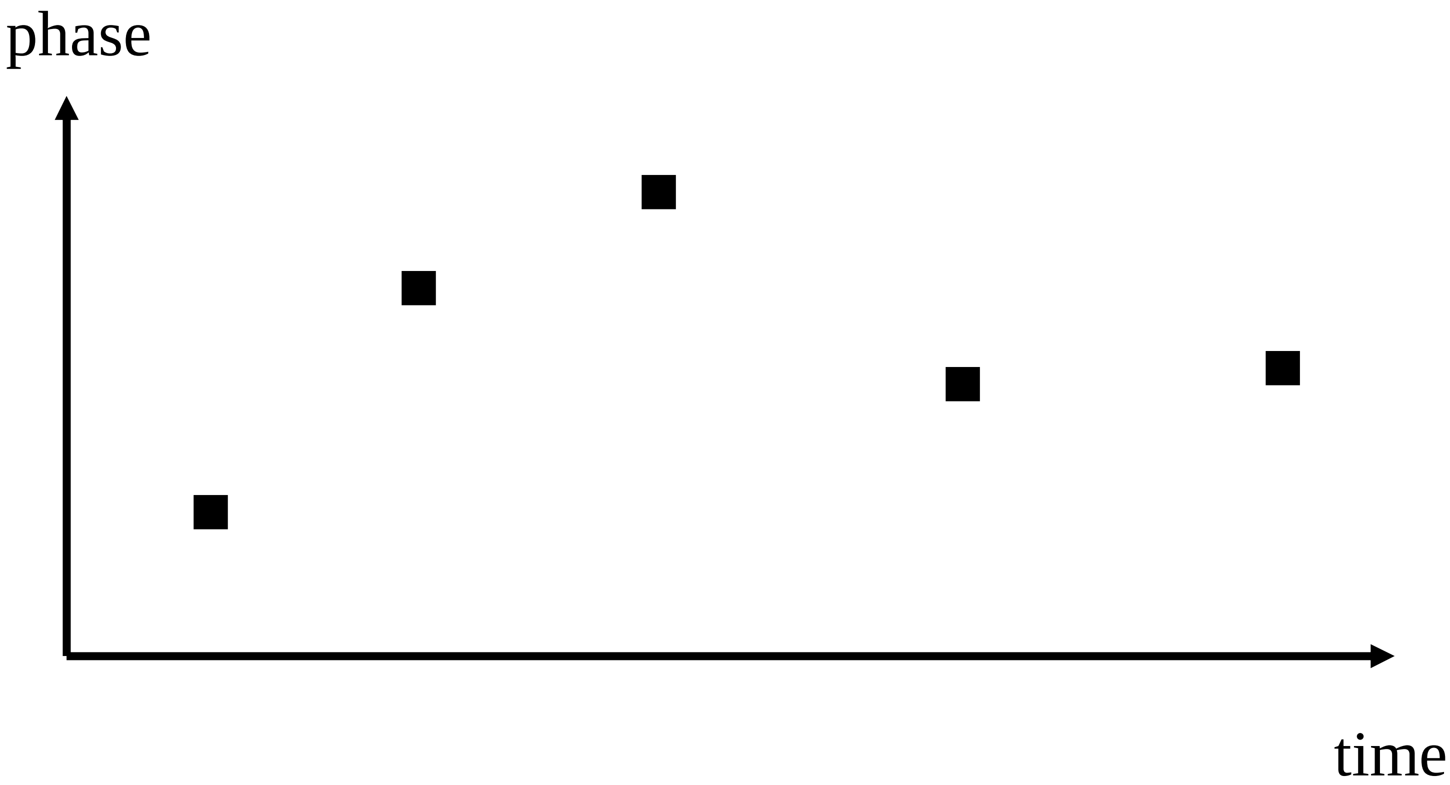
Fits

1. Derive antenna phase
2. Fit continuus curve (e.g. spline)
3. Use that curve to correct source data in between calibrators

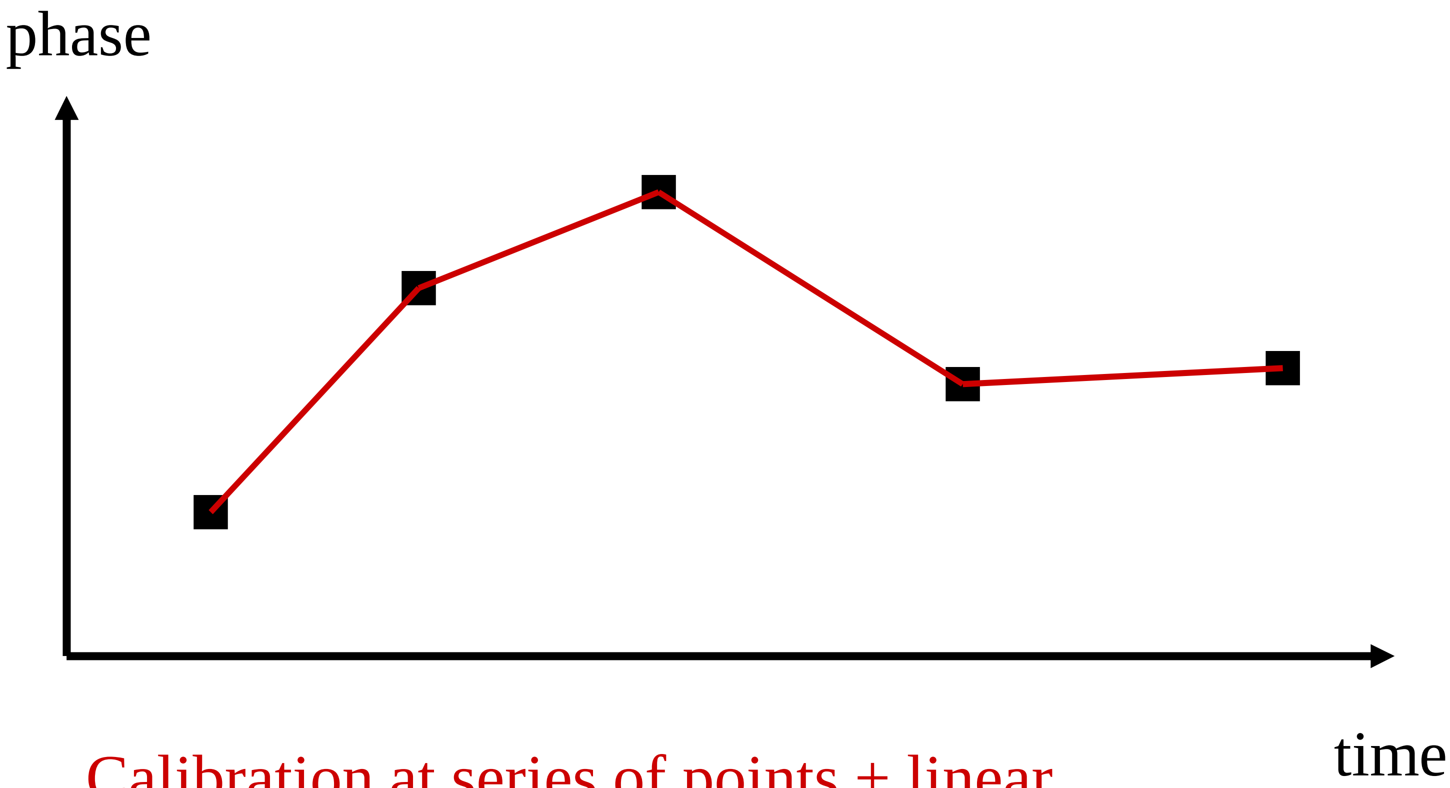
Points

1. Derive antenna phase
2. Trust it: use that value as calibration
3. Interpolate between the calibrators

Phase calibration
Strategies

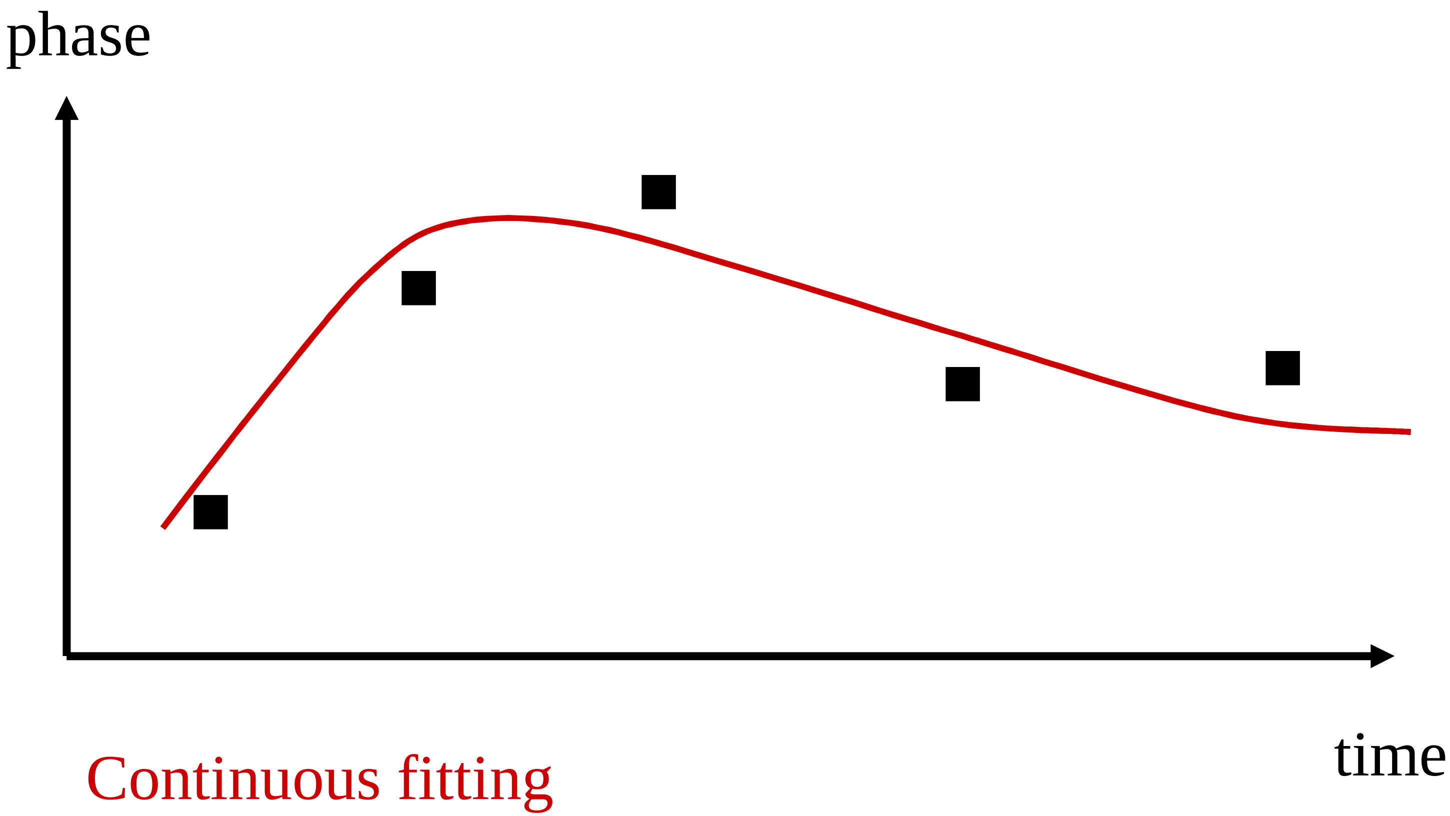


Phase calibration
Strategies

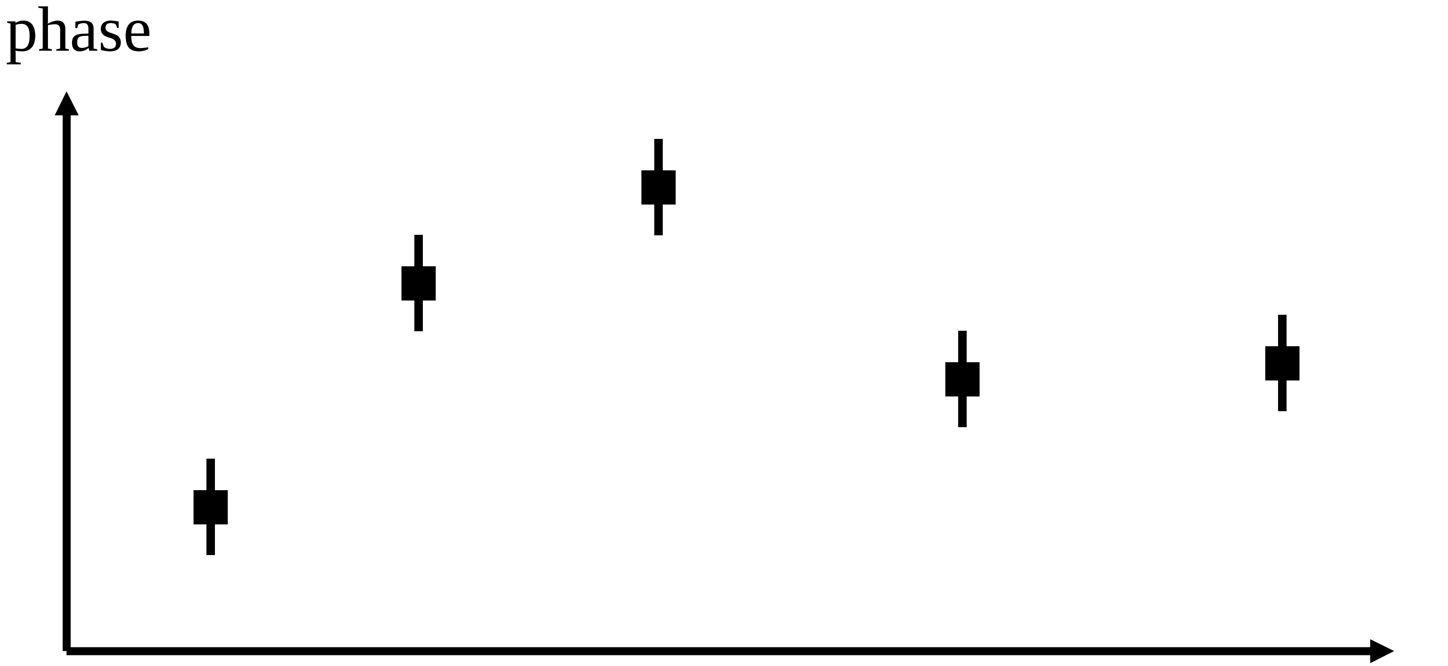


Calibration at series of points + linear interpolation

Phase calibration
Strategies

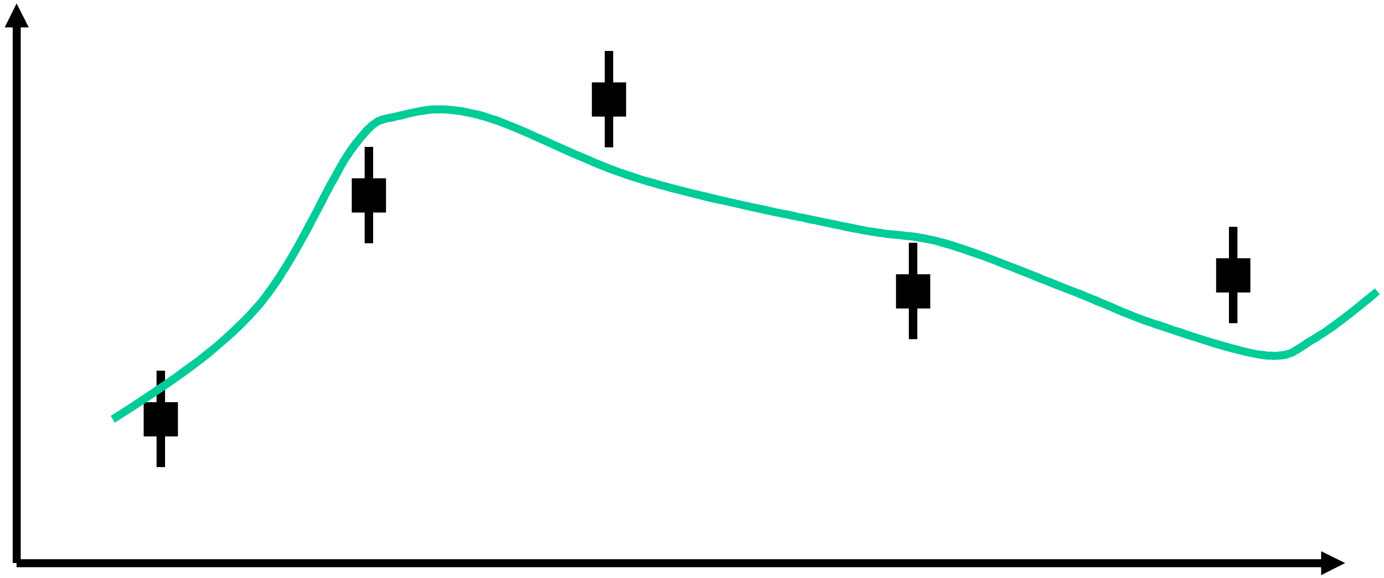


Phase calibration
Strategies



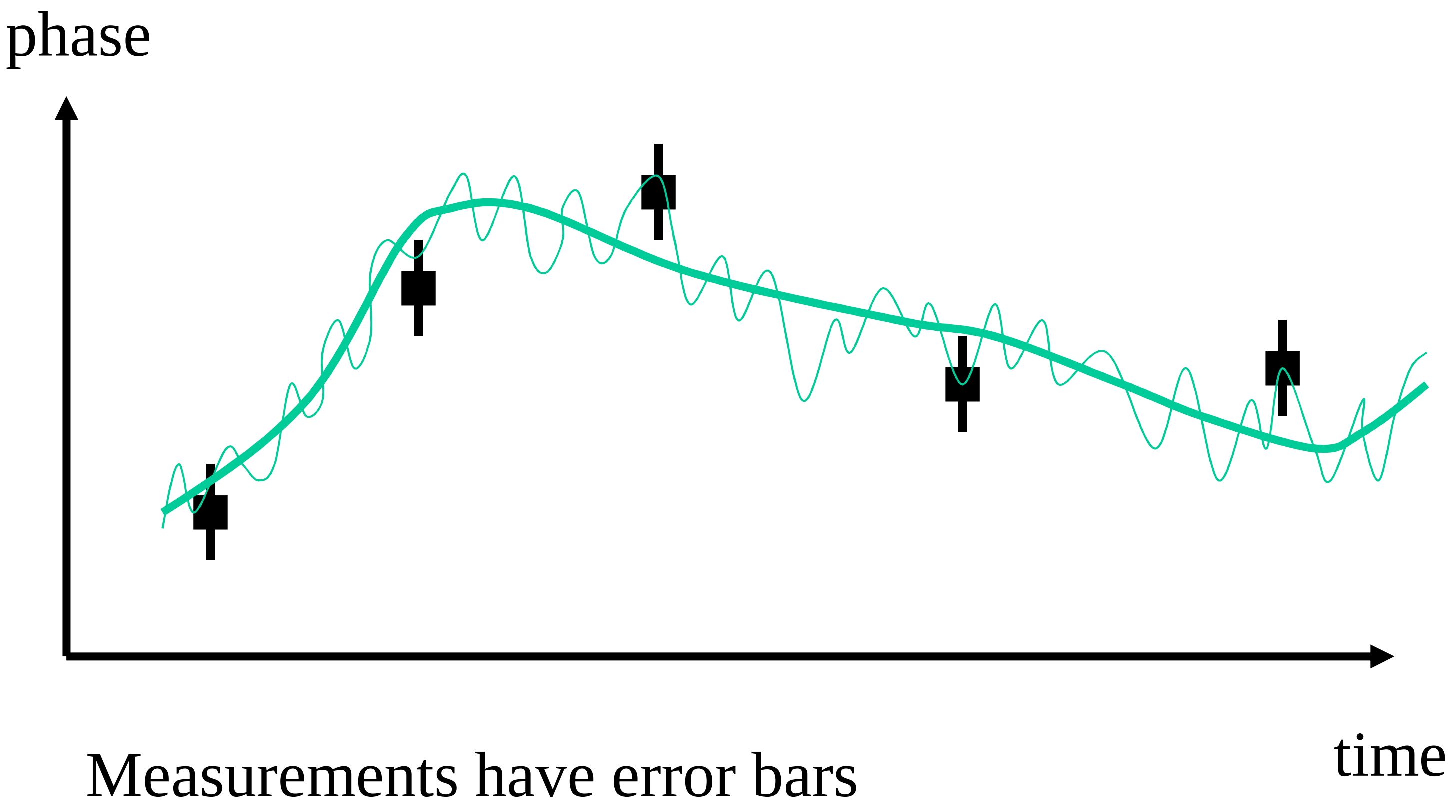
Measurements have error bars

Phase calibration
Strategies



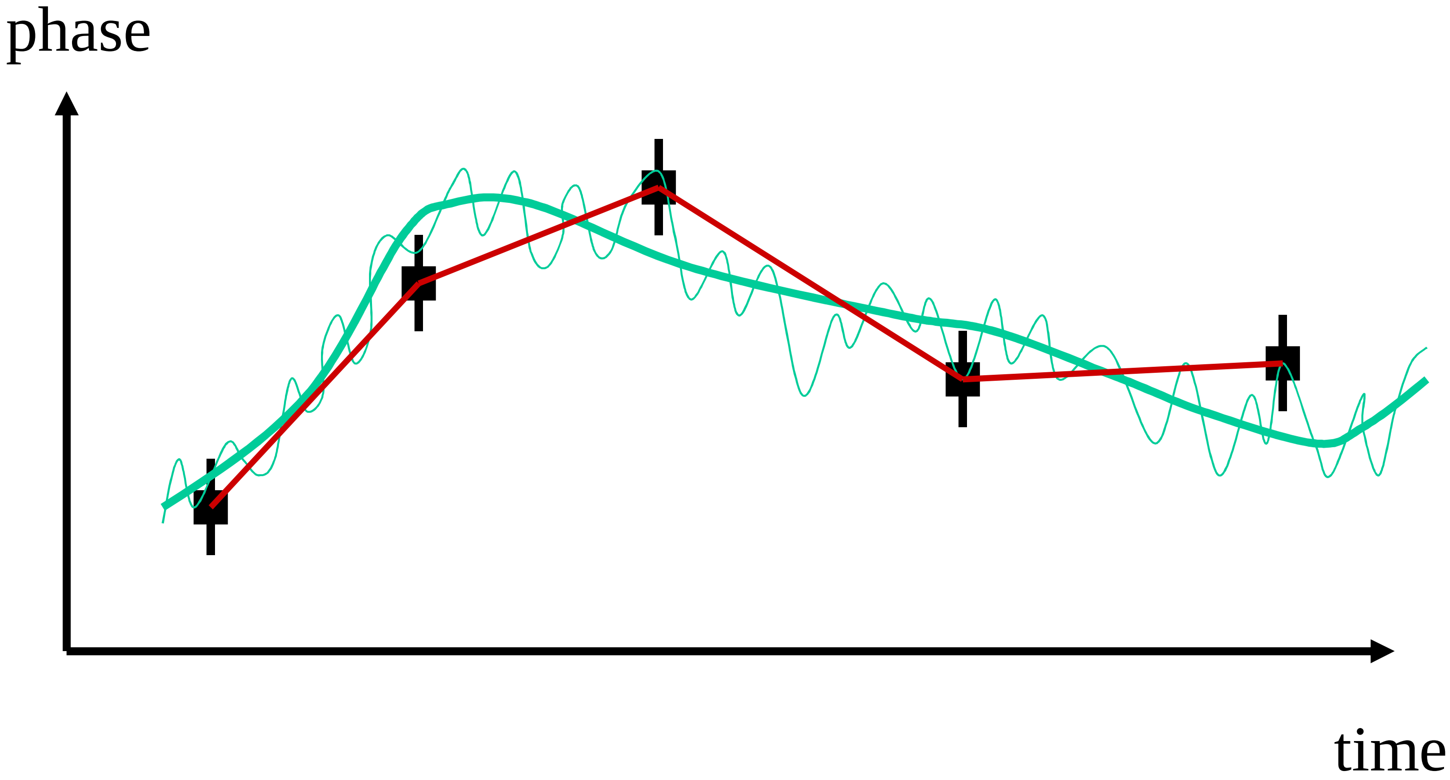
Measurements have error bars
Real phase: slow component

Phase calibration
Strategies

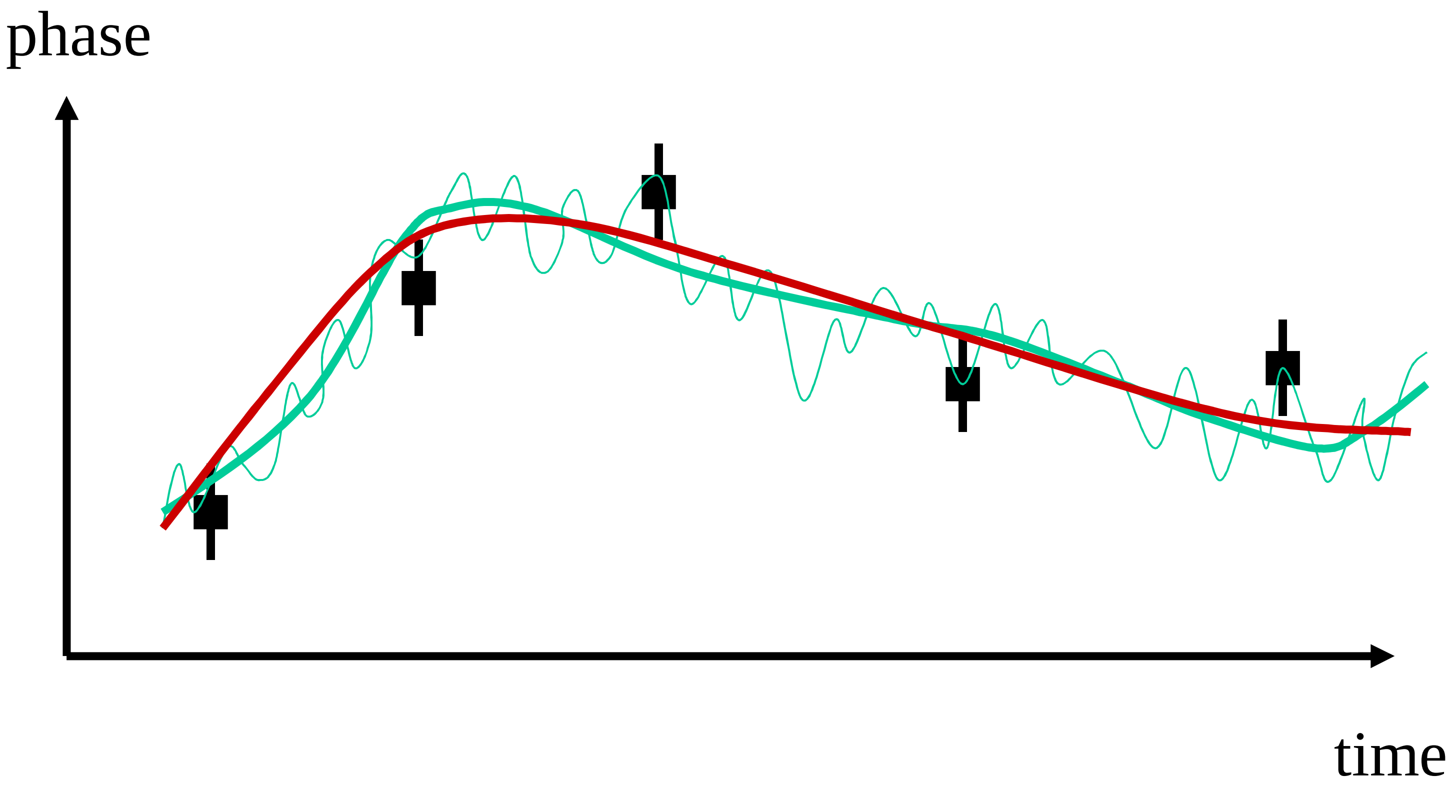


Measurements have error bars
Real phase: slow + fast component

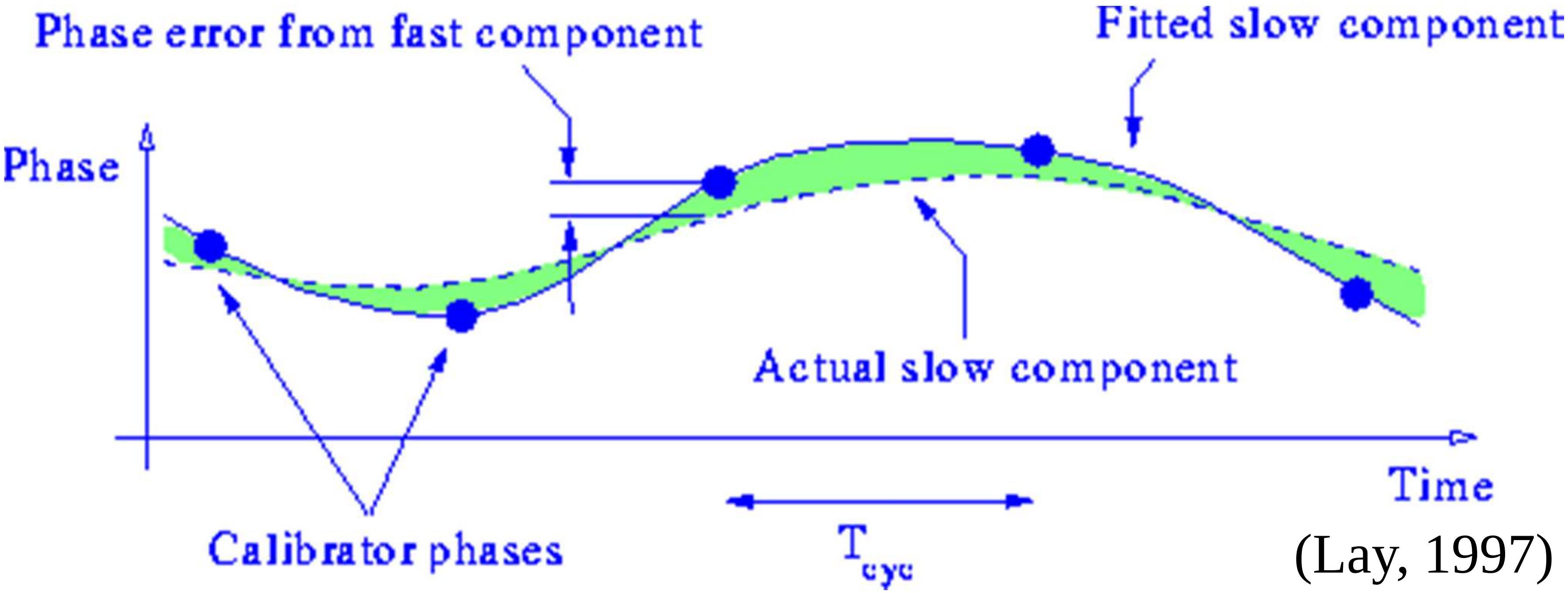
Phase calibration
Strategies



Phase calibration
Strategies



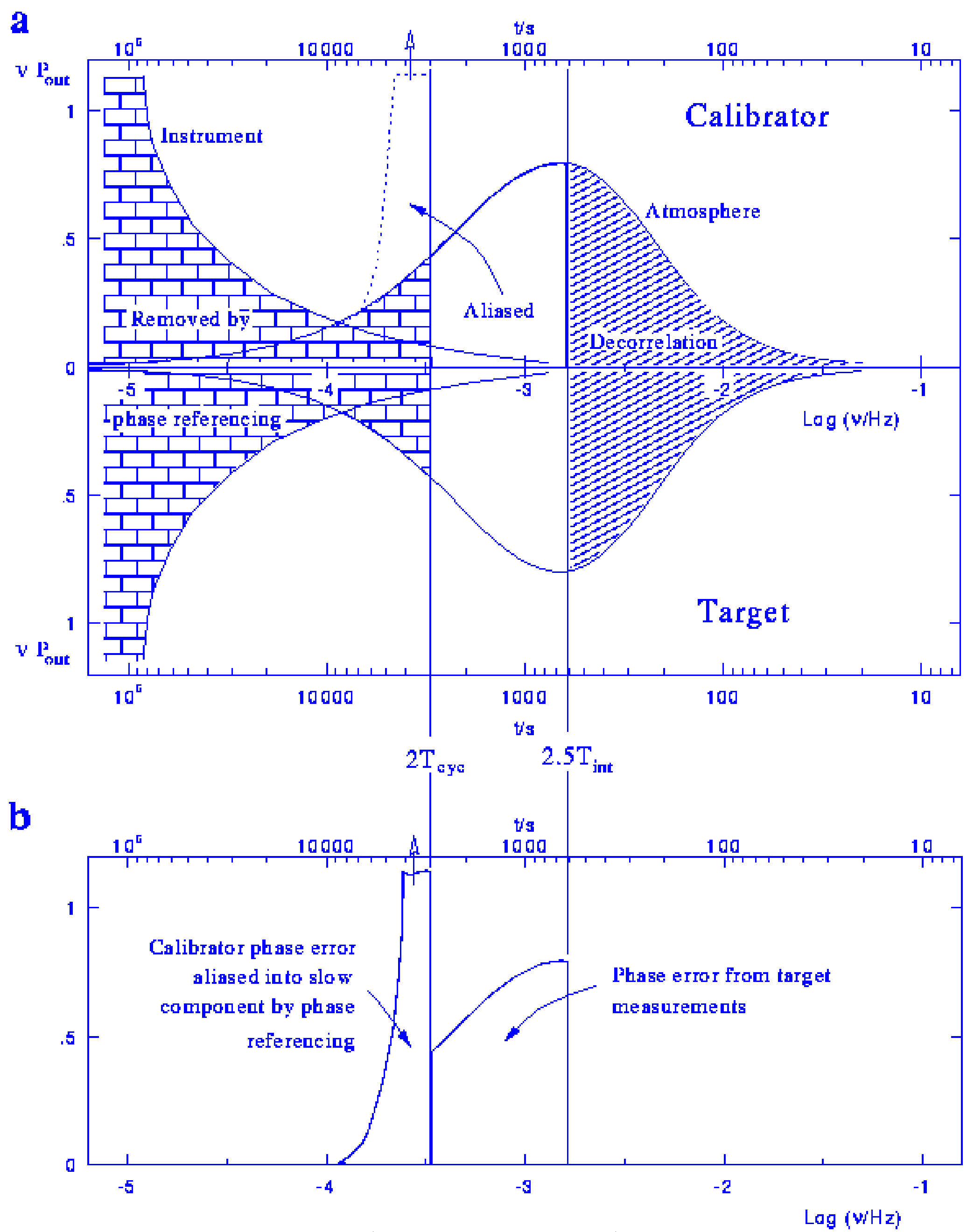
Phase calibration
Strategies



(Lay, 1997)

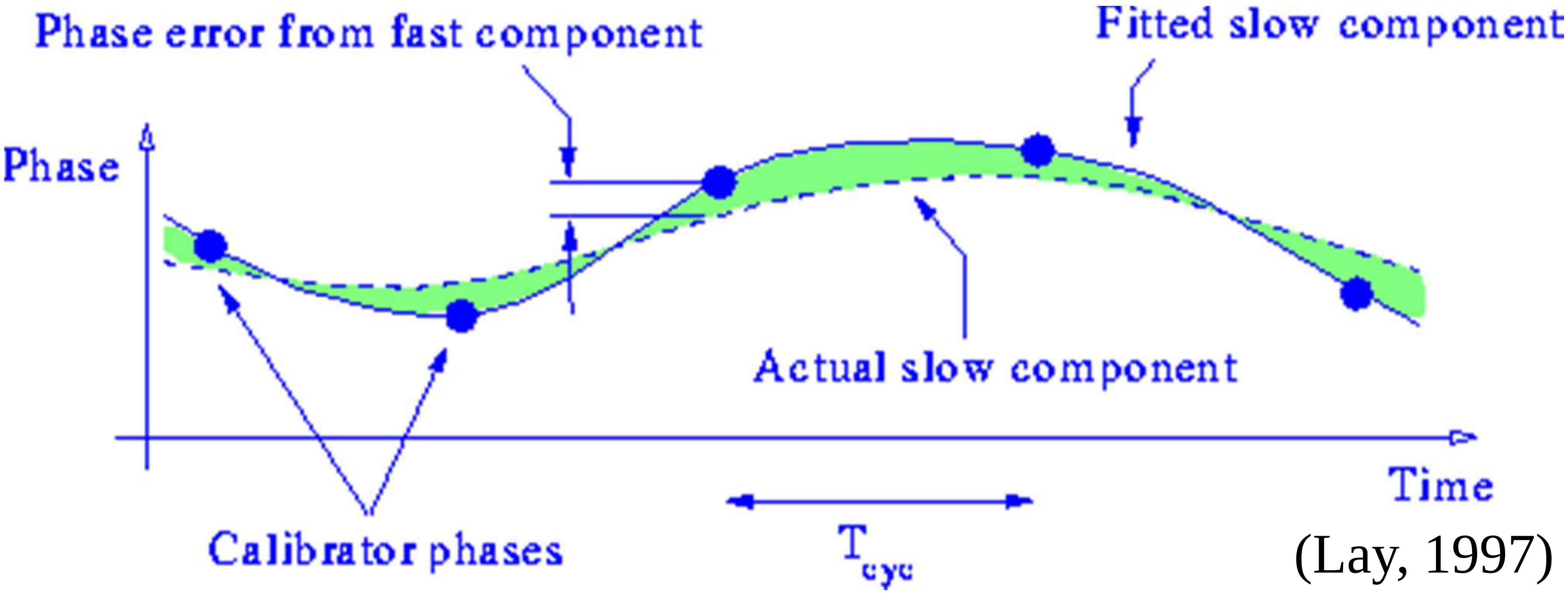
Phase is sampled at intervals Tc → fit is sensitive to errors due to the presence of the fast component (<2Tc), which can be large

Equivalent to **aliasing** of fast component into slow component



(Lay, 1997)

Phase calibration
Strategies



(Lay, 1997)

It is actually recommended to fit a curve that does **not** go through all points

Phase calibration
Strategies

<u>Phase calibration strategies</u>:

effect of the noise on calibrators measurements?

interpolation from calibrators to source?

Fits

1. Derive antenna phase
2. Fit continuus curve (e.g. spline)
3. Use that curve to correct source data in between calibrators

Points

1. Derive antenna phase
2. Trust it: use that value as calibration
3. Interpolate between the calibrators

Phase calibration
Strategies

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Fits → **Limited SNR & phase noise**

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Points → **OK if excellent SNR & no atmospheric phase noise**

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Strategies

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NOEMA, ALMA high freq

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VLA, ALMA low freq

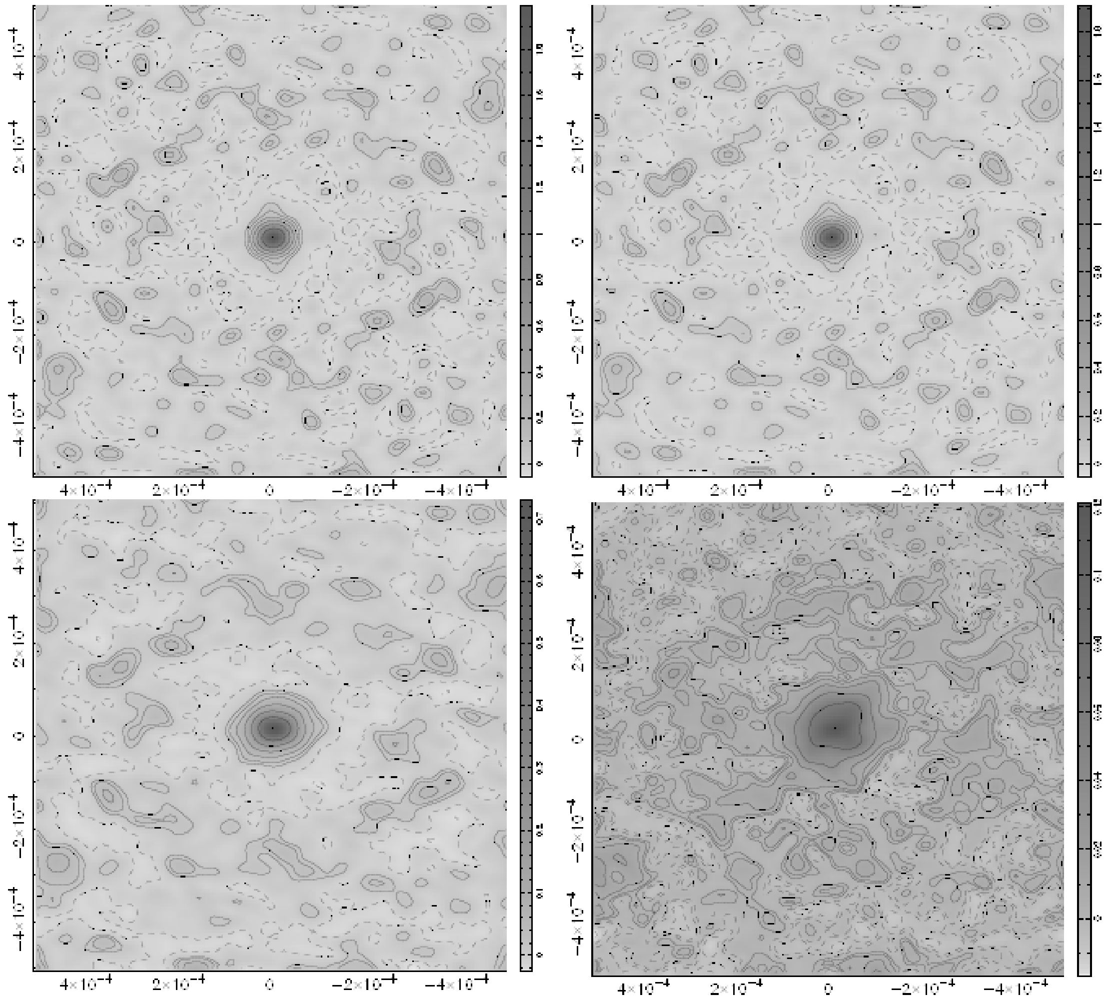
Phase calibration
Radio seeing

- Phase fluctuations timescales:

< 1 min	real-time (WVR) phase correction
1 min – 20min	→ **not corrected**
>20 min	off-line phase calibration

- Can be estimated by rms of phase calibration fit
- Translate into a **radio seeing** ~ phase rms / baseline
- Can be a fraction of the beam ➔ larger effective beam…

Seeing



Simulations:
increasing the phase
noise 3:10:50:100
(Nikolic et al. 2008)

Phase calibration
Fast switching

- **Reduce the switching time** calibrator-source down to 10 seconds
- <u>Advantages</u>: Remove a larger part of the atmospheric fluctuations spectrum. Perfect complement to the WVR corrections (second timescale)
- <u>Drawbacks</u>: Observing efficiency is decreased. Puts very strong constrains on the antennas and acquisition system.
- Planned for ALMA?

Phase calibration
Auto-calibration

- Simple case where the field **contains a strong point source**
- Can be used to calibrate out almost all phase fluctuations at periods > integration time (30 sec)
- Excellent results but for **very specific projects**
  - Absorption lines in quasars
  - Stars with strong maser lines

Phase calibration
Self-calibration

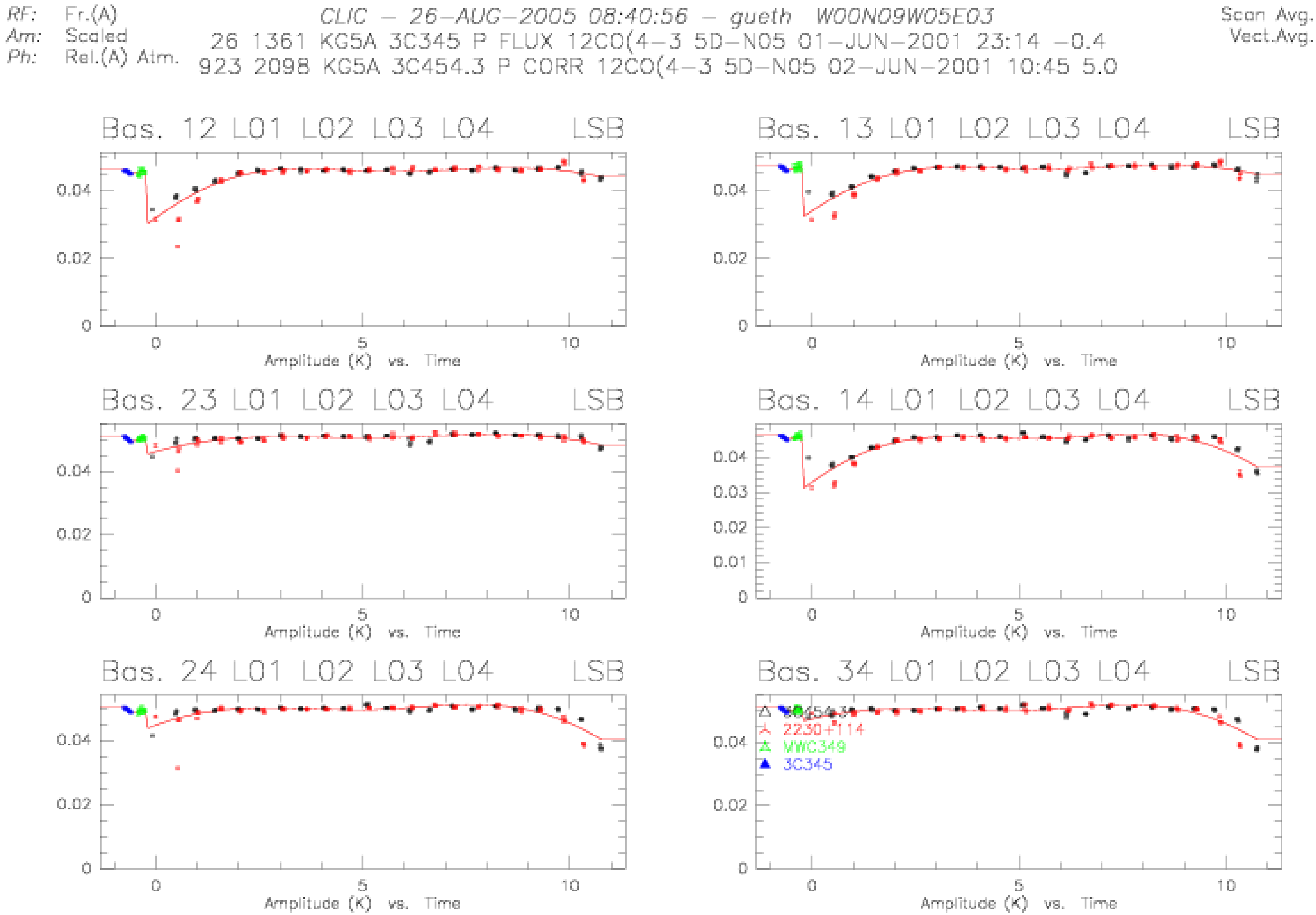
- **Extended (but simple) bright source?**
  1. Classical calibration with calibrators
  2. Source imaging & deconvolution
  3. Predicted visibilities (“model”)
  4. Divide observed source visibilities by model
  5. Calibrate remaining variations
  6. Go to 2

- Can work because N ant < N baseline
- Requires enough SNR on source in each individual integration

Amplitude calibration
The problems

- Temperature (K) → Flux (Jansky)
  - Scaling by **antenna efficiency** (Jy/K)
  - **Not enough for mm-interferometers** because
    - Amplitude loss due to decorrelation
    - Variation of the antenna gain (pointing, focus)

- Need **amplitude referencing to a point source** (quasar) to calibrate out the temporal variation of the antenna efficiency – just like phase calibration


RF: Fr.(A)
Am: Scaled
Ph: Rel.(A) Atm.
CLIC - 26-AUG-2005 08:40:56 - gueth W00N09W05E03
26 1361 KG5A 3C345 P FLUX 12CO(4-3 5D-N05 01-JUN-2001 23:14 -0.4
923 2098 KG5A 3C454.3 P CORR 12CO(4-3 5D-N05 02-JUN-2001 10:45 5.0
Scan Avg.
Vect.Avg.
Bas. 12 L01 L02 L03 L04 LSB
Bas. 13 L01 L02 L03 L04 LSB
Bas. 23 L01 L02 L03 L04 LSB
Bas. 14 L01 L02 L03 L04 LSB
Bas. 24 L01 L02 L03 L04 LSB
Bas. 34 L01 L02 L03 L04 LSB
Amplitude (K) vs. Time
2230+114
MWC349
3C345

Flux calibration
The problems

- Problem: **all quasars have varying fluxes** (several 10% in a few weeks) and varying spectral indexes
- **Cannot rely on a priori antenna efficiency** to measure their fluxes (decorrelation…)
- Need to measure the quasar fluxes against
  - Planets
  - Strong quasars (RF)
  - MWC349, CRL618, …
- Can be **difficult** if a good accuracy is required

Flu... The...

Caution: terminology "(Absolute) Flux calibration" vs "Amplitude calibration"

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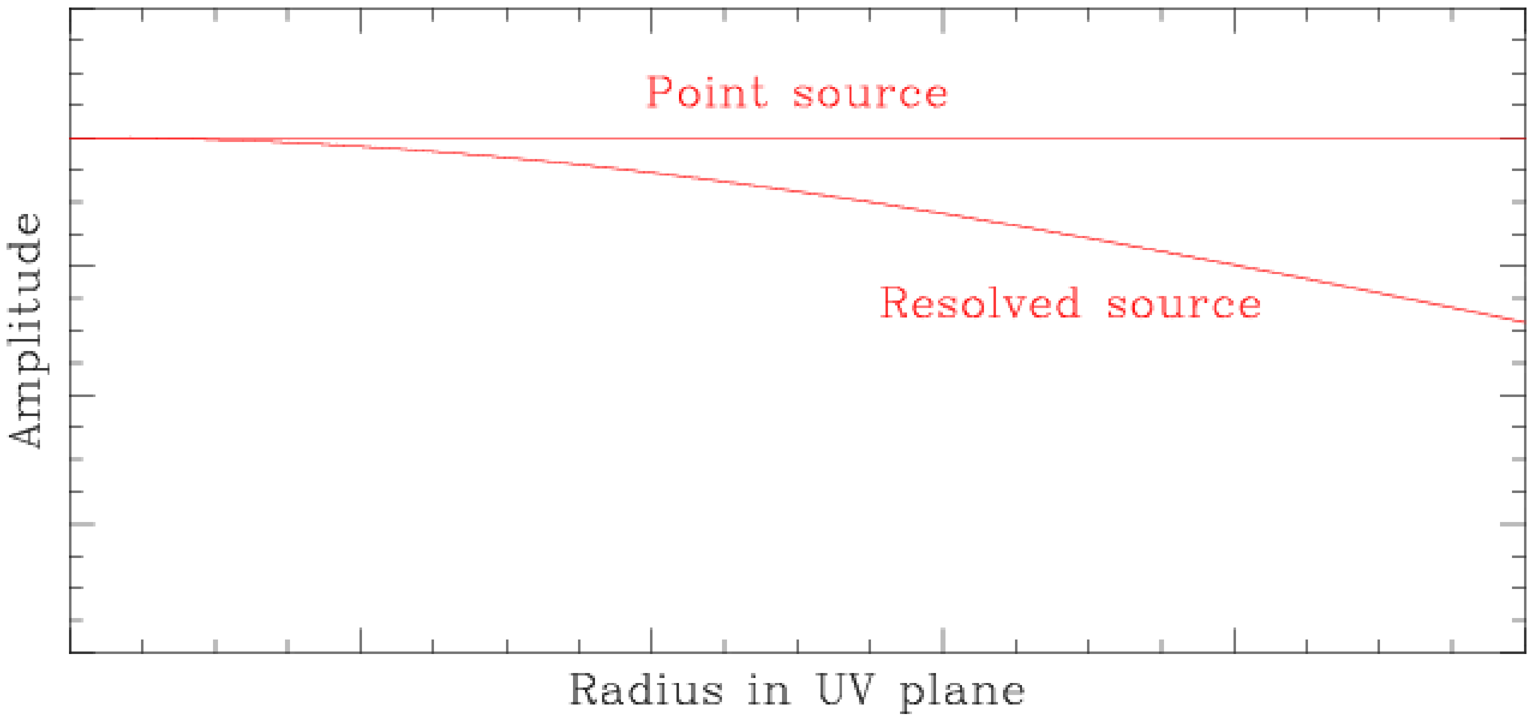
Dedicated talk by A.Castro-Carrizo

Flux calibration
Not a simple x factor



Flux calibration
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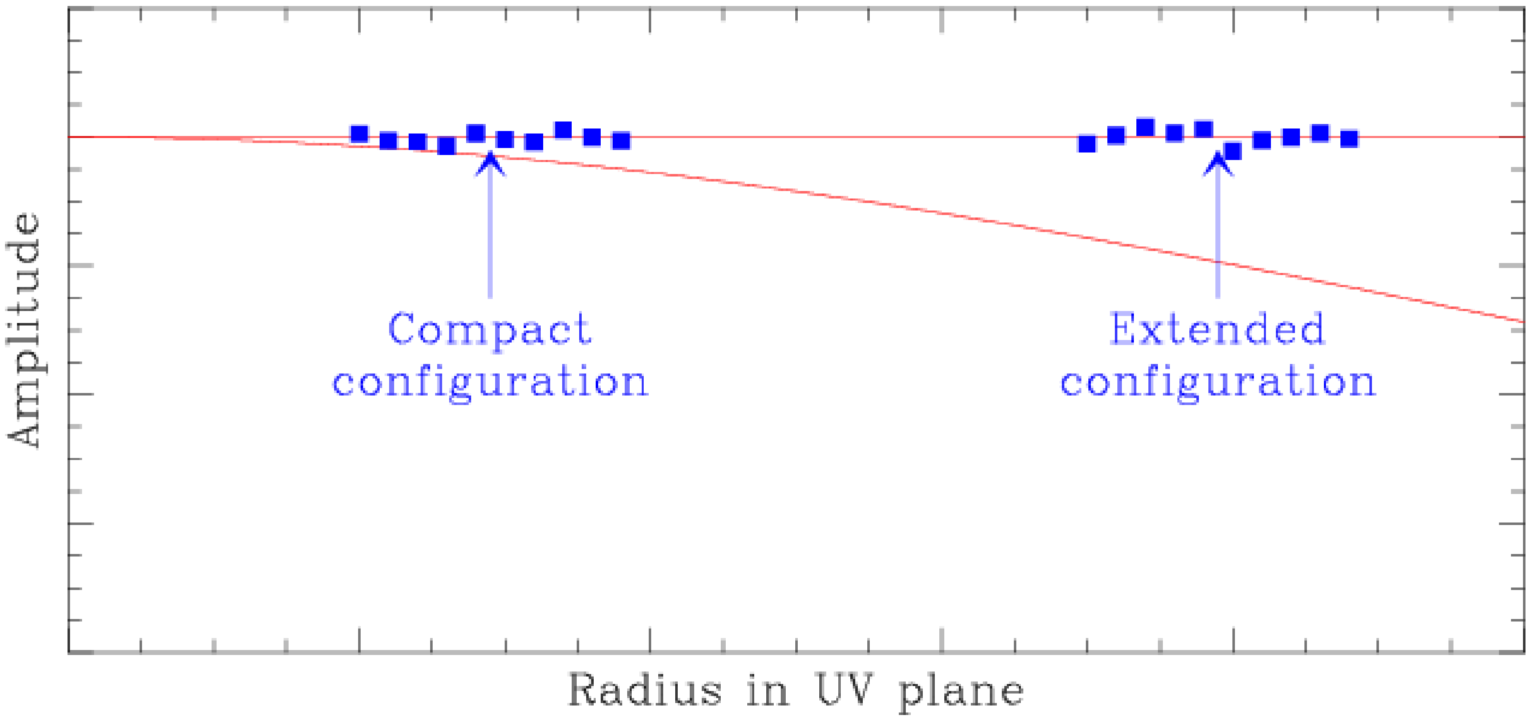

Flux calibration
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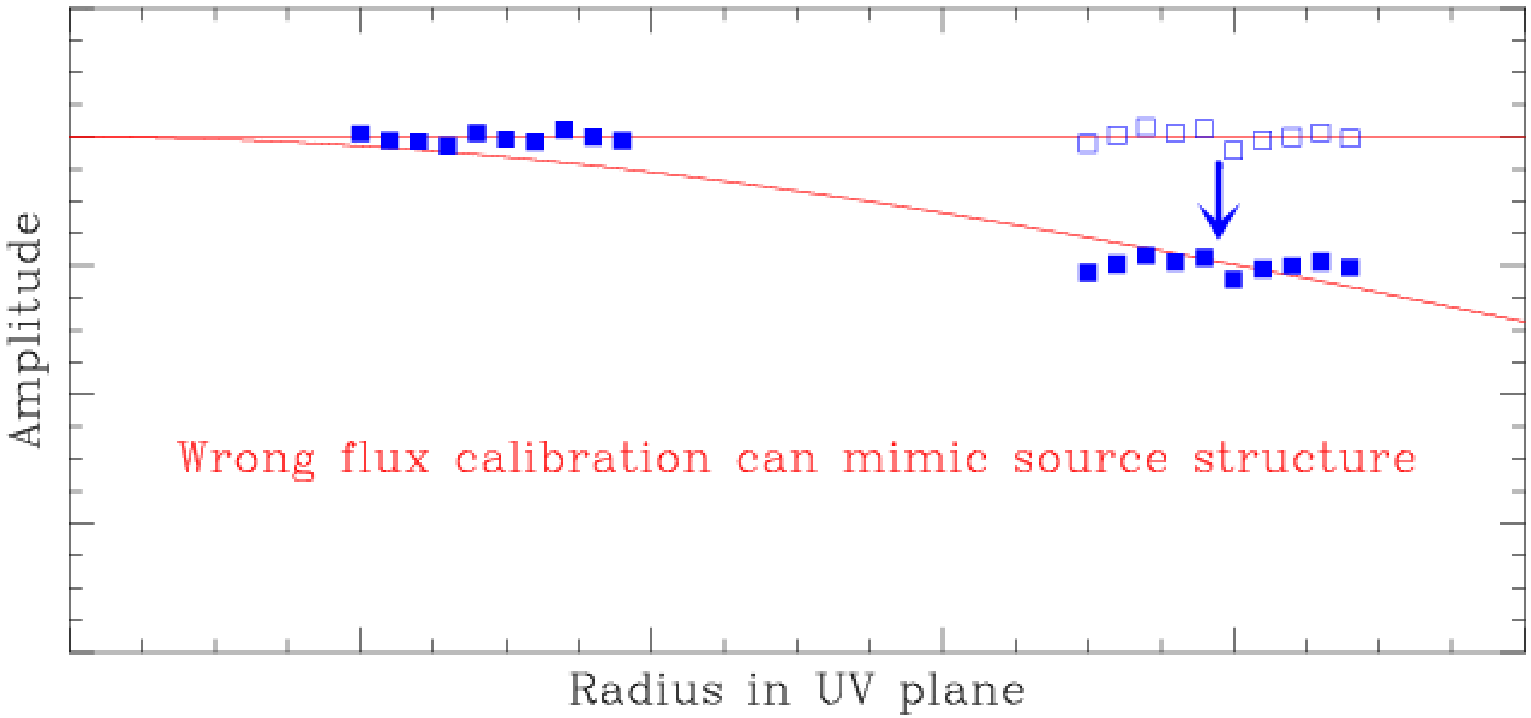

Data calibration
Conclusions

- All calibrations rely on astronomical observations of quasars = point source, continuum
- **Phase** calibration is the most critical for image quality
- **Flux** calibration is the most difficult in practice