The principles of 30m polarization calibration

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EMIR / XPOL – Stokes parameters

Description used by XPOL

measured:

$$
\begin{aligned}
\mathrm{I} &= \langle E_x^2\rangle + \langle E_y^2\rangle &&= \langle E_r^2\rangle + \langle E_l^2\rangle &&= \mathrm{S}(0°,0) + \mathrm{S}(90°,0)\\
\mathrm{Q} &= \langle E_x^2\rangle - \langle E_y^2\rangle &&= 2\,\langle E_r E_l \cos\delta\rangle &&= \mathrm{S}(0°,0) - \mathrm{S}(90°,0)\\
\mathrm{U} &= 2\,\langle E_x E_y \cos\delta\rangle &&= 2\,\langle E_r E_l \sin\delta\rangle &&= \mathrm{S}(45°,0) - \mathrm{S}(135°,0)\\
\mathrm{V} &= 2\,\langle E_x E_y \sin\delta\rangle &&= \langle E_r^2\rangle - \langle E_l^2\rangle &&= \mathrm{S}(45°,\tfrac{\pi}{2}) - \mathrm{S}(135°,\tfrac{\pi}{2})
\end{aligned}
$$

derived:

degree of linear polarization $\quad \mathrm{p_L} = \frac{\sqrt{\mathrm{Q}^2+\mathrm{U}^2}}{\mathrm{I}}$

degree of circular polarization $\quad \mathrm{p_C} = \frac{\mathrm{V}}{\mathrm{I}}$

polarization angle $\quad \tan 2\chi = \frac{\mathrm{U}}{\mathrm{Q}}$

Remarks:

- autocorrelations and complex cross-correlation required
- The phase δ , instrumental and astronomical, must be measured
- a coordinate system must be defined: Nasmyth cabin
- Stokes parameters Q and U are then rotated into the equatorial system
- In a well calibrated instrument, $\delta \neq 0$ only if there is circular poarization

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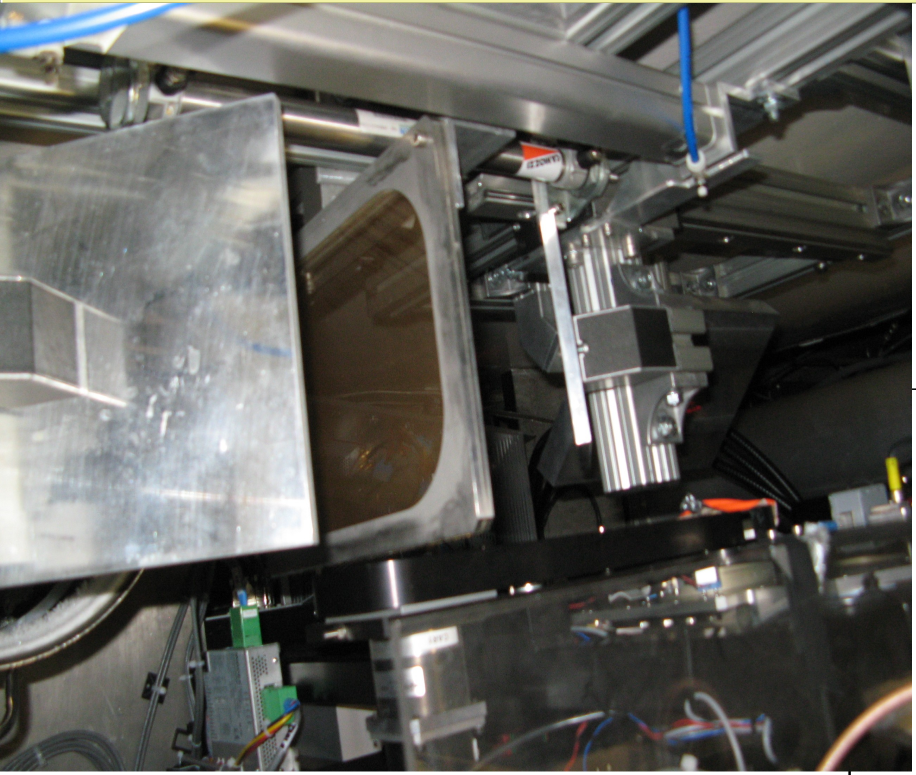
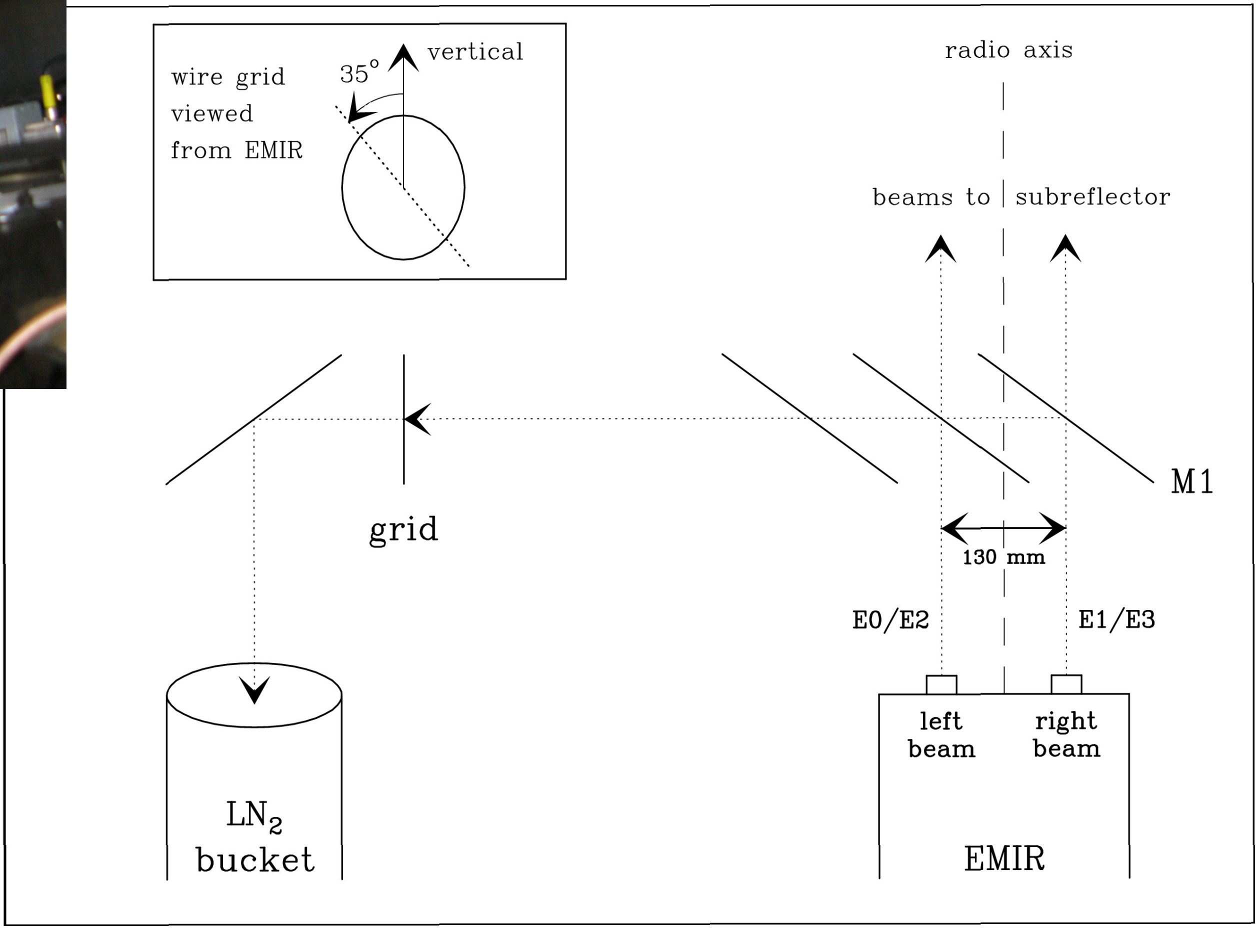


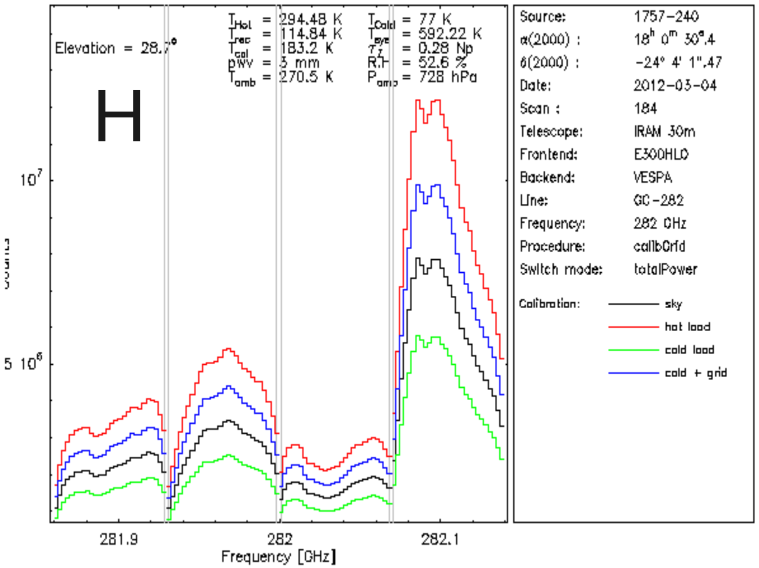
- Beams not on radio axis
- grid angle is set different from 45°
- path between M1 and subreflector is not calibrated
- Big strength of method:
  high S/N at all frequency channels
  independent of spectral resolution

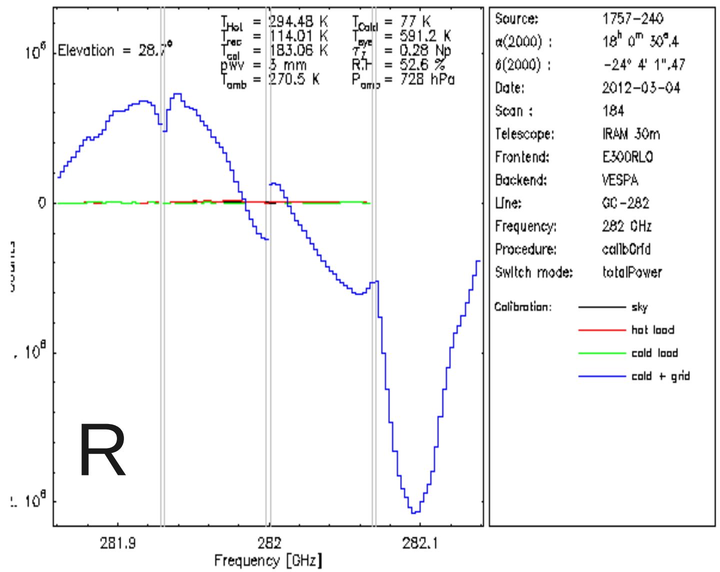


Calibration of Phase

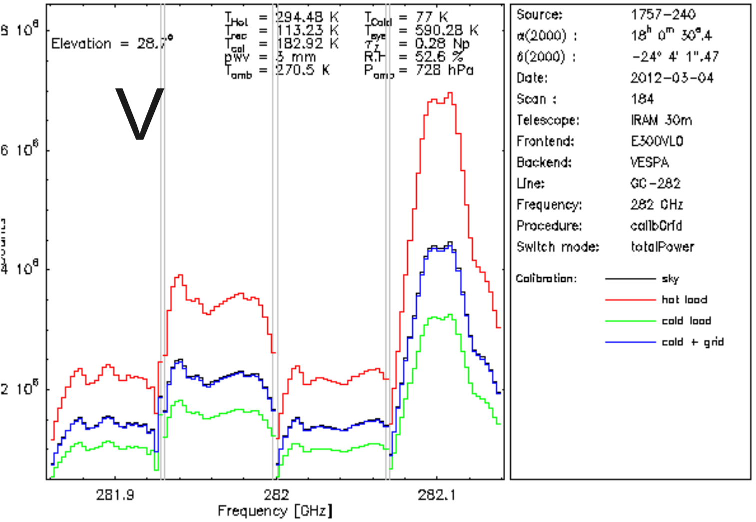
- grid generates correlated power
- H-C observed with grid (subscan 4)
- the derived δ is the instrumental phase

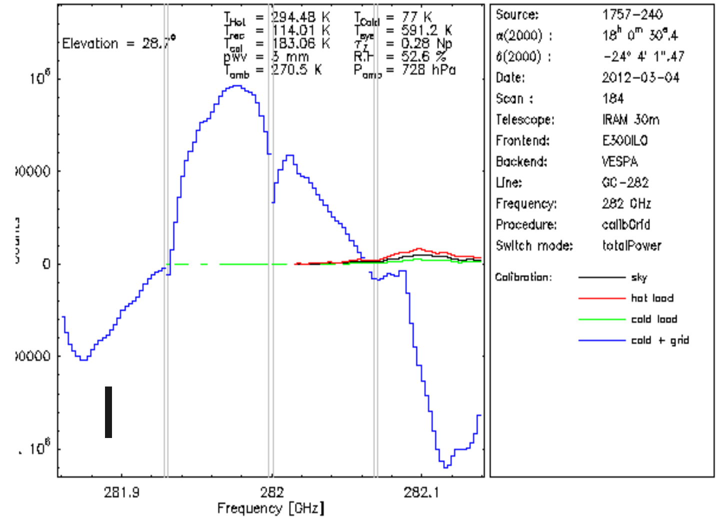
EMIR / XPOL calibration-1: observation





MIRA
Online
display



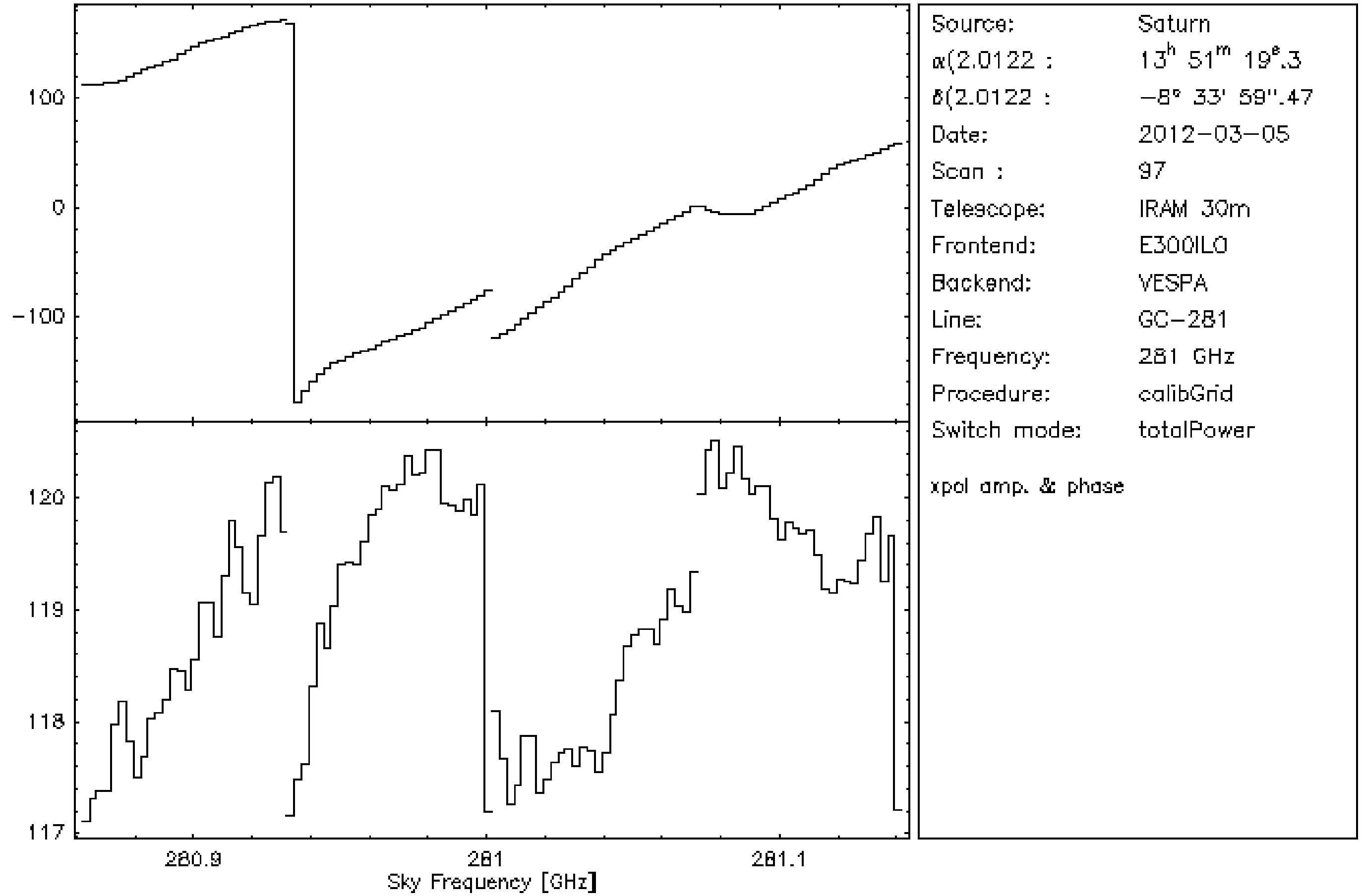


- one VESPA section shown, there can be two
- essential assumption: incident radiation is not circularly polarized: all power in I is purely instrumental
- Non-polarimetric backends may also be connected

EMIR / XPOL calibration-2: analysis

Phase, deg.

Amplitude, K



- Subscan 4 is reduced like any observation of the sky;
  NOTE: Tcal = sqrt(Tcal_H * Tcal_V) for the two crosscorrelations
- Mira transforms the R, I parts of the complex cross correlation function to amplitude and phase
- This is the instrumental phase δ, since the the H-C signal passing through the grid has no circular polarization
- When looking at a celestial source, the observed phase can be different from δ indicating that the source is circularly polarized and/or that there is a spurious conversion of I → U, V or U → V

EMIR / XPOL calibration-3: MIRA code

MIRA code:

```
phase= atan2(imaginaryPart(CC),realPart(CC))
UN     = realPart(cc)*cos(phase) + imaginaryPart(CC)*sin(phase)
V      = realPart(CC)*sin(phase) - imaginaryPart(CC)*cos(phase)
```

(Obtained from basic equations after a few intermediate manipulations)

XPOL – the instrument: VESPA in polarimetry mode

Polarimetry modes

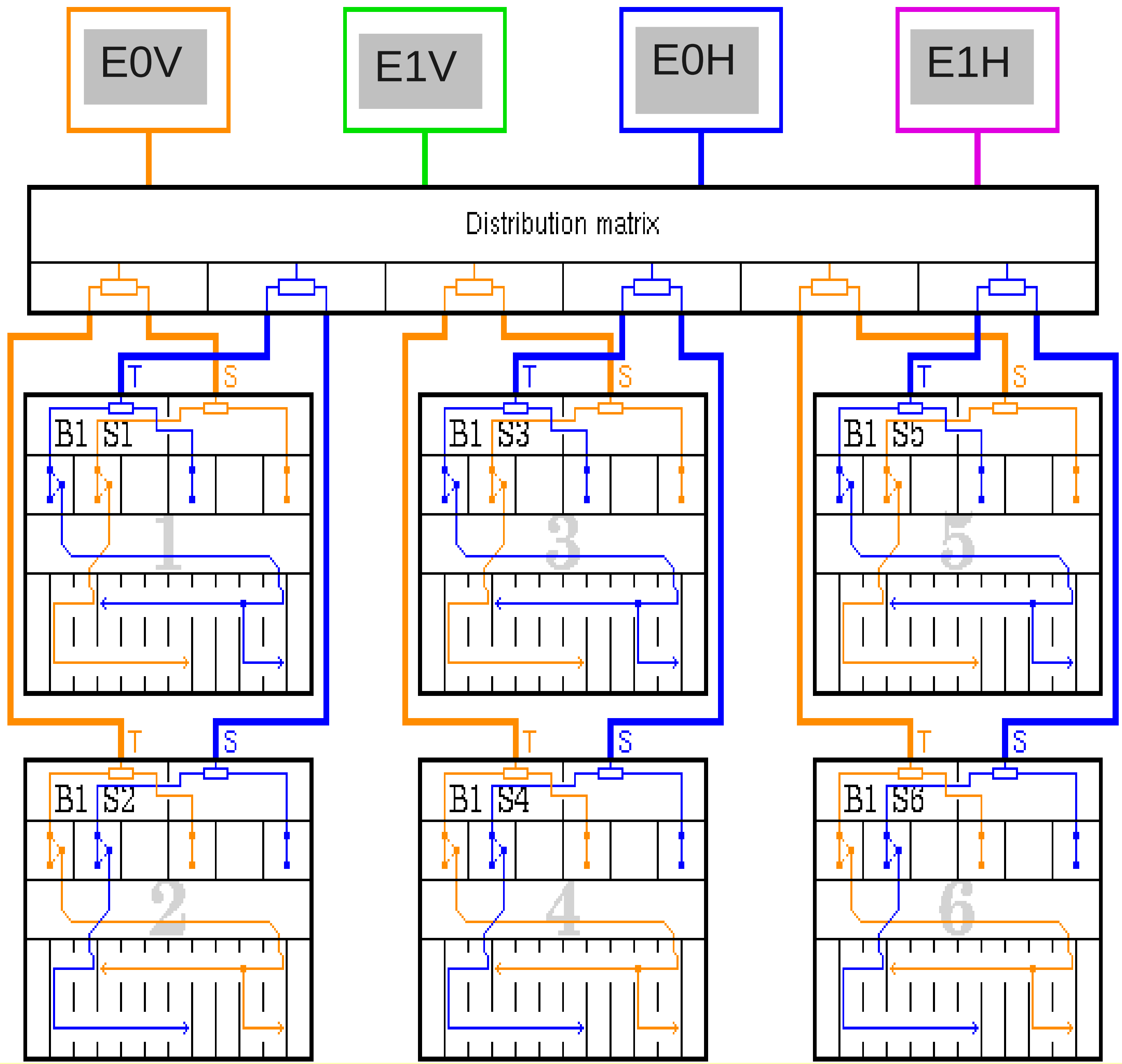
(extreme examples):

- 40 kHz / 120 MHz
- 1.25 MHz /480 MHz

Highest spectral resolution polarimetry mode shown here:

- 6 units of 20 MHz bandwidth
- each board has 256 delay channels
- spectral resolution: 40 kHz
- twice the number of channels for cross correlation

Note that auto and cross correlations share the same analog path



rotation of polarization angle - 1

Transformation from Rx Cabin to sky involves:

* two rotations (parallactic, Nasmyth)
* an odd number of reflections
* one change of handedness

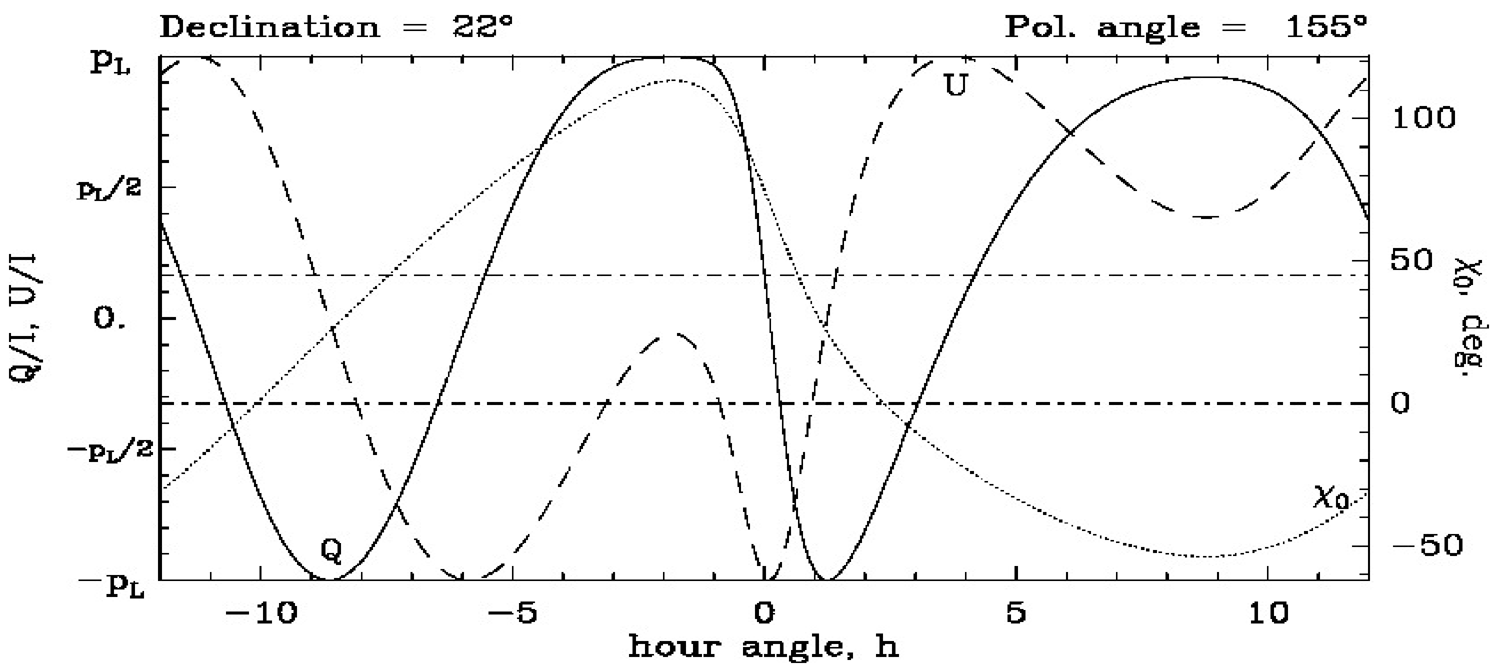
$$\tau = 90° + \chi + \varepsilon - \eta$$

χ = polarization angle, sky

τ = pol. Angle, Nasmyth cabin

ε = elevation

η= parallactic angle



rotation of polarization angle - 2

MIRA code:

Conversion between Stokes Q and U equatorial <-->Nasmyth:

```
chi = elevation-parallactic angle
I     = (H+V)/2.
QN  = (H-V)/2.
UN  = realPart(crossCorrelation)
V     = imaginaryPart(crossCorrelation)
Qeq = -QN*cos(2*chi) - UN*sin(2*chi)
Ueq =   QN*sin(2*chi) - UN*sin(2*chi)
```

XPOL: a continuum observation

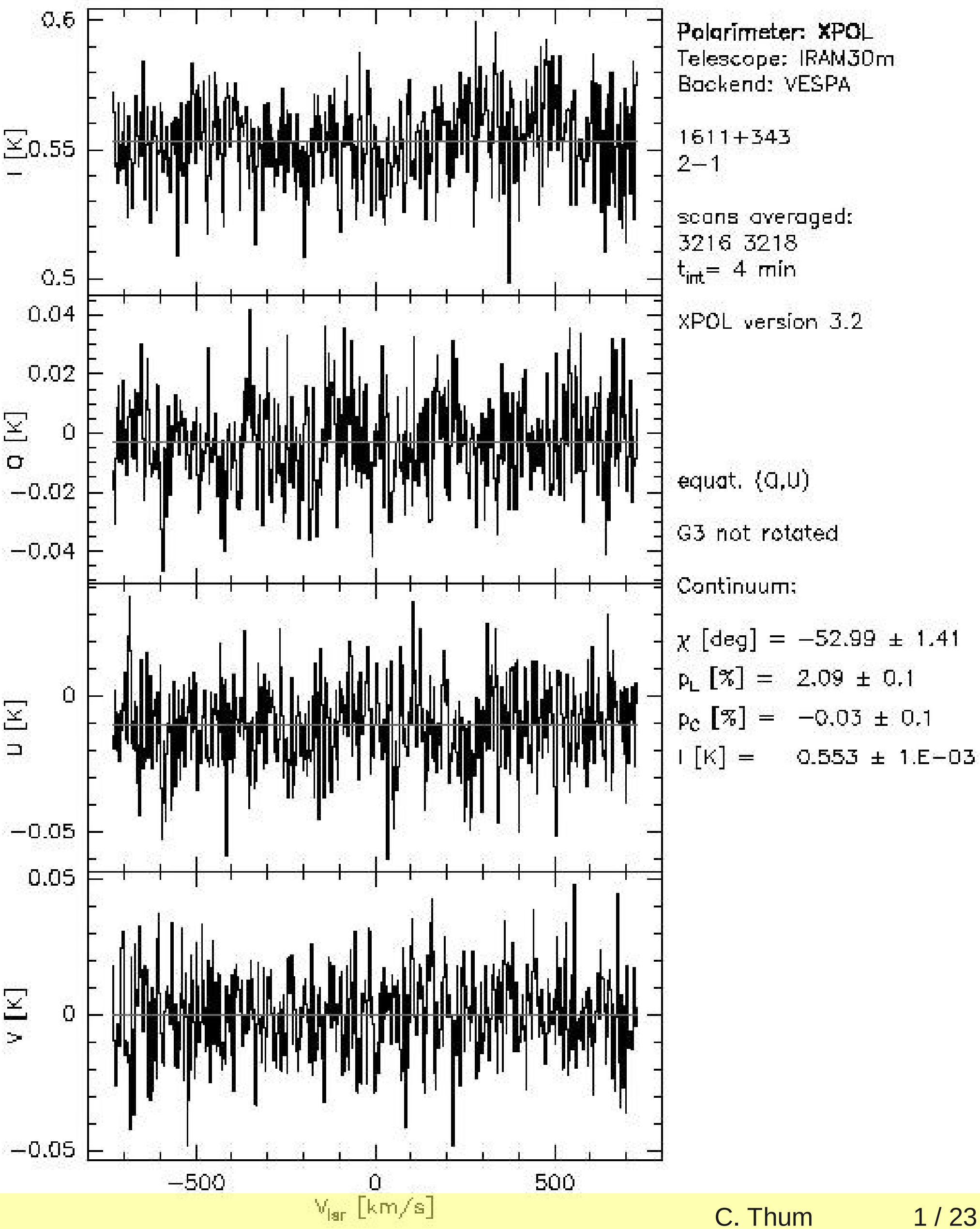
- medium strong AGN can be measured to $< 1\%$ precision in few minutes
- polarization parameters are band-averages
- noise has same ampl. in all Stokes spectra

  S/N = 1 in p_L or p_C requires S/N = 100

  in Stokes I if p_L, p_C = 1%

current limitation:

VESPA maximum bandwidth: 960 MHz



a spectral line observation

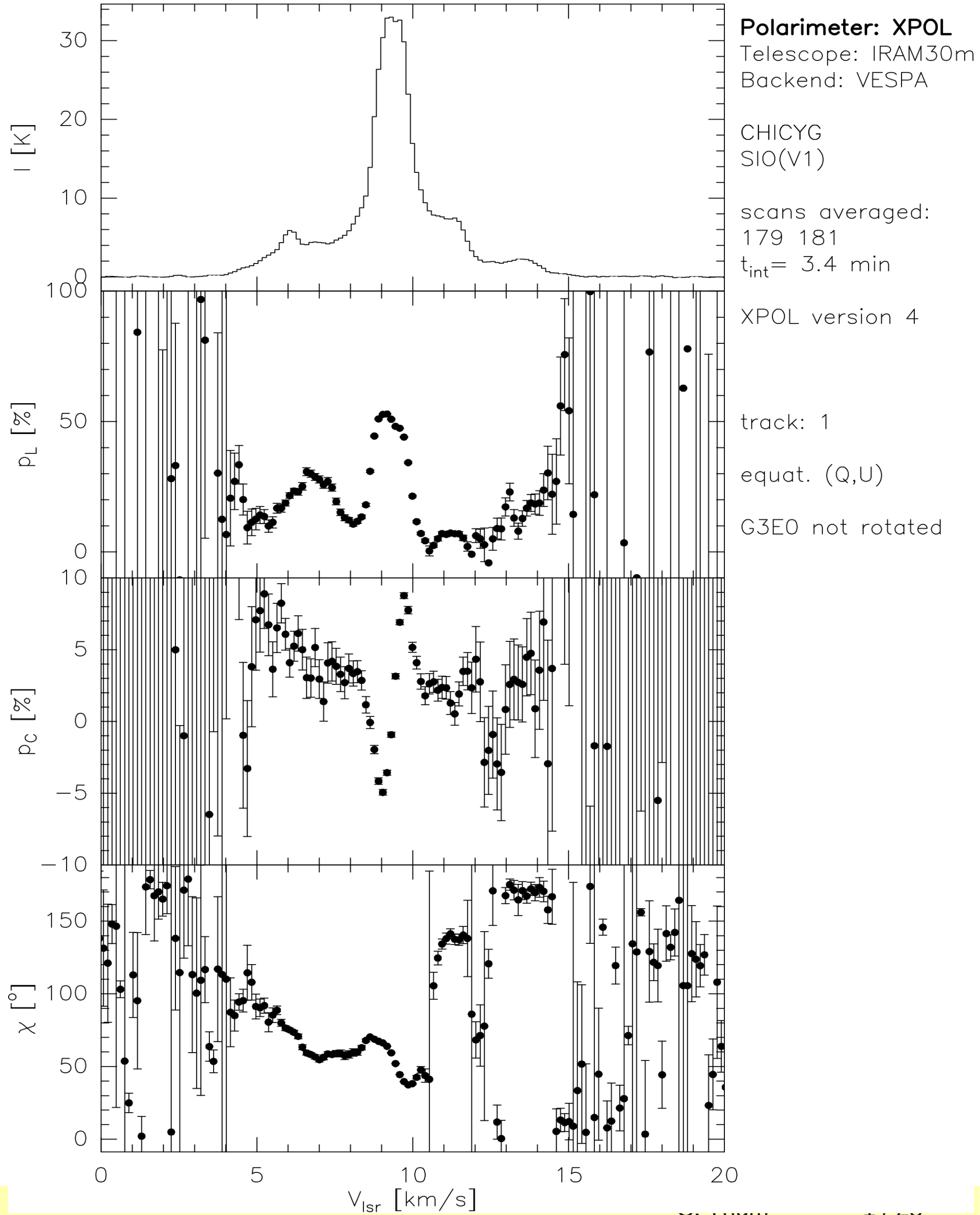
- Dark clouds, 10 K

  1% precision in 40 kHz channels at 3σ

  1 hour of integration time

limitation:

Best spectral resolution 40 kHz



EMIR / XPOL : the factor 2 conundrum

Rayleigh-Jeans: $S_\nu = \frac{2kT\Omega}{\lambda^2}$ (factor 2 since there are 2 polarizations)

Non-polarimetric calibrations `assume` that the source is unpolarized

In principle: T_A^* (H) and T_A^* (V) should be half of their standard values

Convention used in MIRA

- H,V used as derived in non-polarimetric calibrations
- Stokes I and Stokes Q: make averages, not sums
- Stokes U and Stokes V: suppress factor 2 when derived from phase-calibrated crosscorrelations

EMIR / XPOL: the CLASS @xpol package

- provides plots of 4 Stokes parameters, including smoothing, averaging, baselines
- treats line and continuum
- Input: calibrated 30m spectra of H, V, R , I
- output: spectra of 4 Stokes parameters in EQ system, plus Q and U in Nasmyth system
- In need of cleaning up

EMIR / XPOL - references

- IF polarimeter
  (includes measurements of the polarization of the moon's limb)
  http://www.iram.fr/~thum/spie.ps.gz
- XPOL – a cross-correlation polarimeter at the IRAM 30m telescope
  PASP 120, 777 (2008)
  http://www.iram.fr/~thum/XPOLwithEMIR-V4.pdf
- Polarimetry with EMIR/XPOL
  working report (bands 1 and 3) 2010-3
  Wiesemeyer & Thum
- XPOL with EMIR (2)
  working report (bands 1 and 3)
  in preparation
- Mapping the Crab Nebula
  Aumont et al. 2010, A&A 514, 70
- Calibration of the sign of Stokes V
  C. Thum & H. Wiesemeyer
  http://www.iram.fr/~thum/stokesV/wpage/index.html
- IAU definition of Stokes parameters
  Transactions of the IAU, vol. 15B, p. 166 (1974)