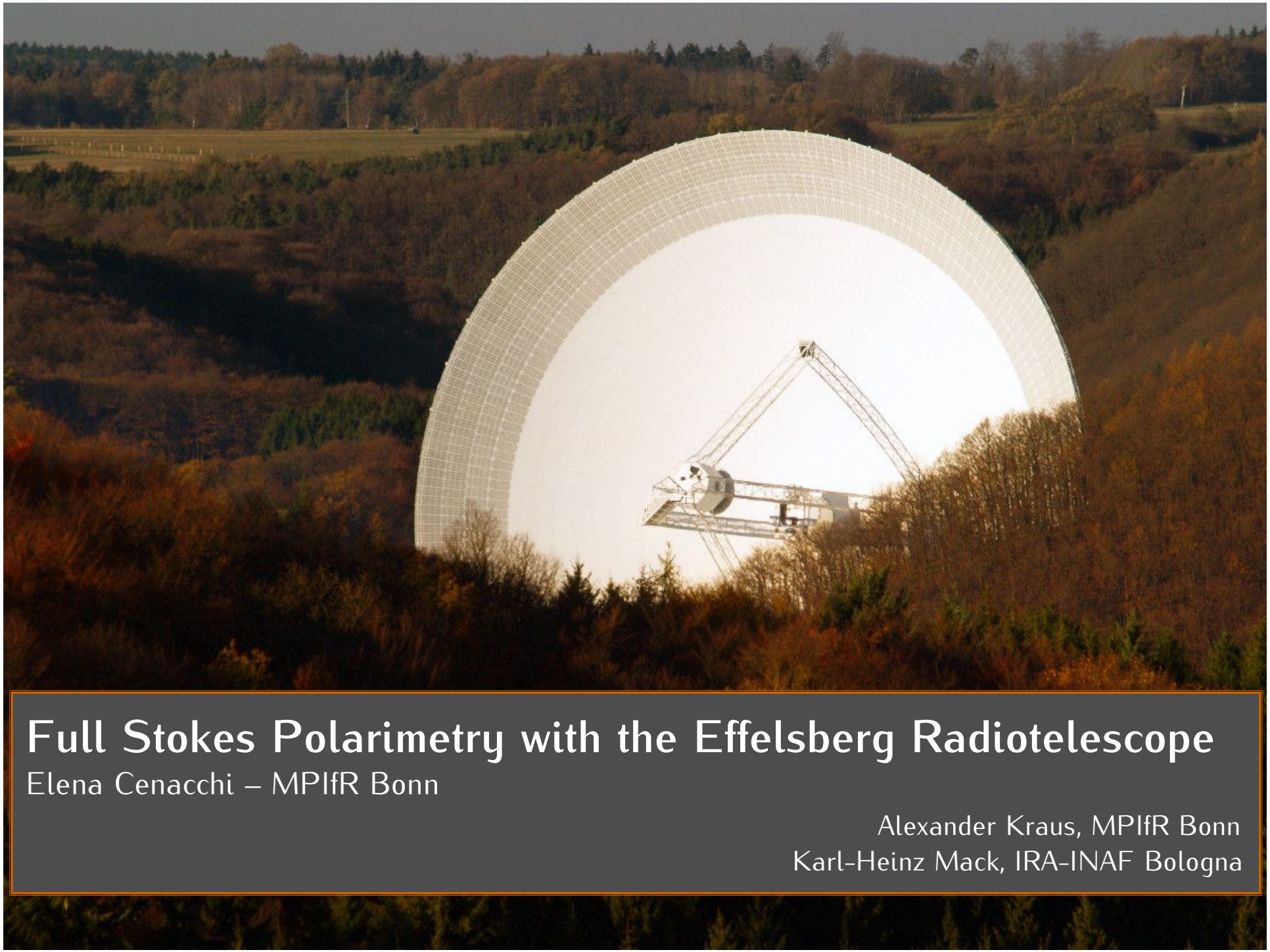

Full Stokes Polarimetry with the Effelsberg Radiotelescope

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Outline

Measuring Circular Polarization	• Full Stokes polarimetry with a single-dish radiotelescope • A new calibration procedure for the 100-m Effelsberg telescope
Observed Sample	• The selected sample of extragalactic radio sources • Monitoring of the sample at 5 GHz during 2007 • Extension of the calibration procedure in the range 2.6 ÷ 10.6 GHz
Source Model: Mode Conversion	• Mode conversion as origin of circular polarization (CP) • A theoretical model that can frame the observed data both in linear (LP) and circular polarization
New Polarimetric Survey	• August, 2008: 5 GHz full Stokes survey of the Northern Kühr Catalogue • Combined efforts of the Effelsberg and Westerbork Radiotelescopes

CP and LP with a single-dish radio-telescope

Jones formalism: used to describe the instrument adopted to measure the incoming radiation

Stokes parameters: used to describe the radio-astronomical source polarimetric properties

A perfect instrument that doesn't affect the measurements would supply a simple relation of proportionality between the incoming radiation $\tilde{E}$ and the corresponding measured voltage $\tilde{V}$

Total Power Detectors

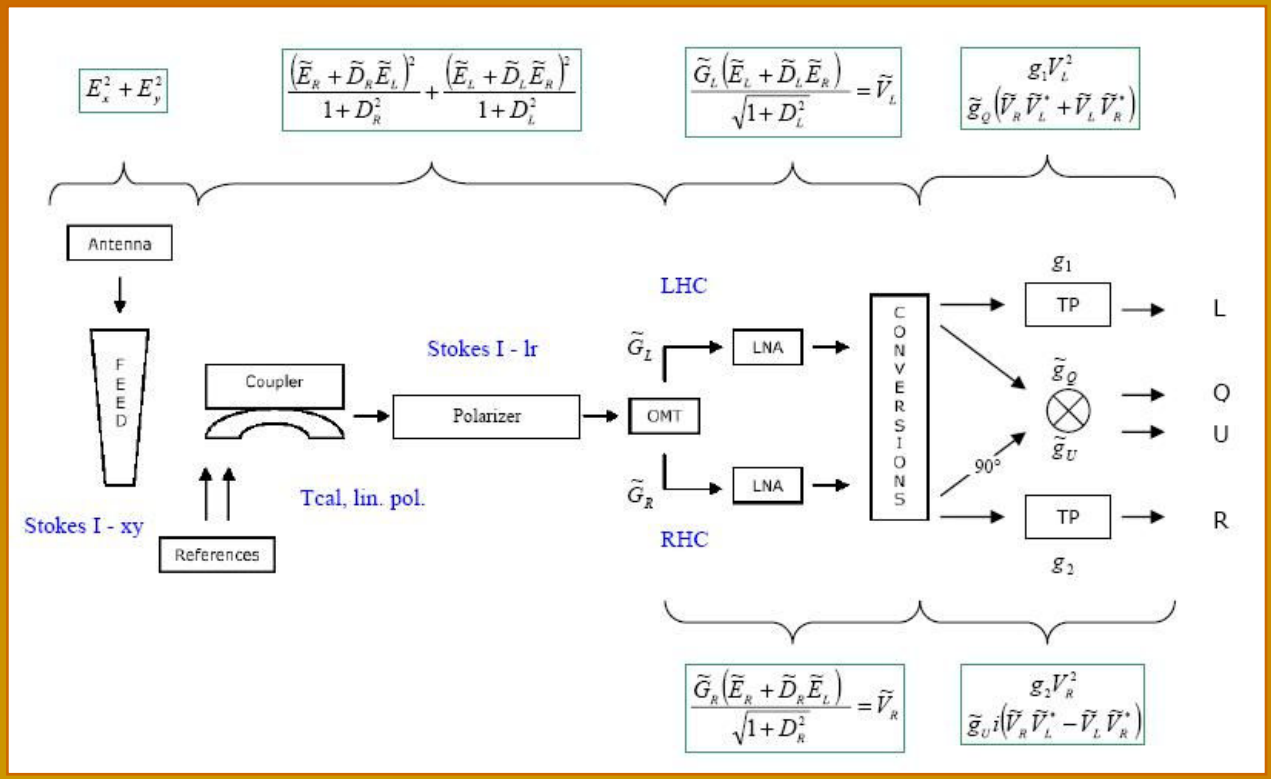
$$V_L^2 \propto E_L^2$$
$$V_R^2 \propto E_R^2$$

Multiplying Polarimeter

$$\left(\tilde{V}_L \tilde{V}_R^* + \tilde{V}_R \tilde{V}_L^*\right) \propto \left(\tilde{E}_L \tilde{E}_R^* + \tilde{E}_R \tilde{E}_L^*\right)$$
$$i\left(\tilde{V}_R \tilde{V}_L^* - \tilde{V}_L \tilde{V}_R^*\right) \propto i\left(\tilde{E}_R \tilde{E}_L^* - \tilde{E}_L \tilde{E}_R^*\right)$$

$$I_{out} = \tilde{V}_L^* \tilde{V}_L + \tilde{V}_R^* \tilde{V}_R = V_L^2 + V_R^2$$
$$Q_{out} = \tilde{V}_L \tilde{V}_R^* + \tilde{V}_R \tilde{V}_L^*$$
$$U_{out} = i\left(\tilde{V}_R \tilde{V}_L^* - \tilde{V}_L \tilde{V}_R^*\right)$$
$$V_{out} = \tilde{V}_L^* \tilde{V}_L - \tilde{V}_R^* \tilde{V}_R = V_L^2 - V_R^2$$

Receiver influence on the measurements



$$\tilde{V}_R\tilde{V}_R^* = \frac{g_2 G_R^2}{1+D_R^2}\left[E_R^2 + D_R^2 E_L^2 + \tilde{E}_R\tilde{E}_L^*\tilde{D}_R^* + \tilde{E}_L\tilde{E}_R^*\tilde{D}_R\right]$$

$$\tilde{V}_L\tilde{V}_L^* = \frac{g_1 G_L^2}{1+D_L^2}\left[E_L^2 + D_L^2 E_R^2 + \tilde{E}_L\tilde{E}_R^*\tilde{D}_L^* + \tilde{E}_R\tilde{E}_L^*\tilde{D}_L\right]$$

$$\tilde{V}_R\tilde{V}_L^* = \frac{\tilde{G}_R\tilde{G}_L^*}{\sqrt{2+D_R^2+D_L^2}}\left[\tilde{E}_R\tilde{E}_L^* + \tilde{D}_R E_L^2 + \tilde{D}_L^* E_R^2 + \tilde{D}_R\tilde{D}_L^*\tilde{E}_L\tilde{E}_R^*\right]$$

$$\tilde{V}_L\tilde{V}_R^* = \frac{\tilde{G}_L\tilde{G}_R^*}{\sqrt{2+D_R^2+D_L^2}}\left[\tilde{E}_L\tilde{E}_R^* + \tilde{D}_R^* E_L^2 + \tilde{D}_L E_R^2 + \tilde{D}_R^*\tilde{D}_L\tilde{E}_L^*\tilde{E}_R\right]$$

Calibration of the 100-m telescope

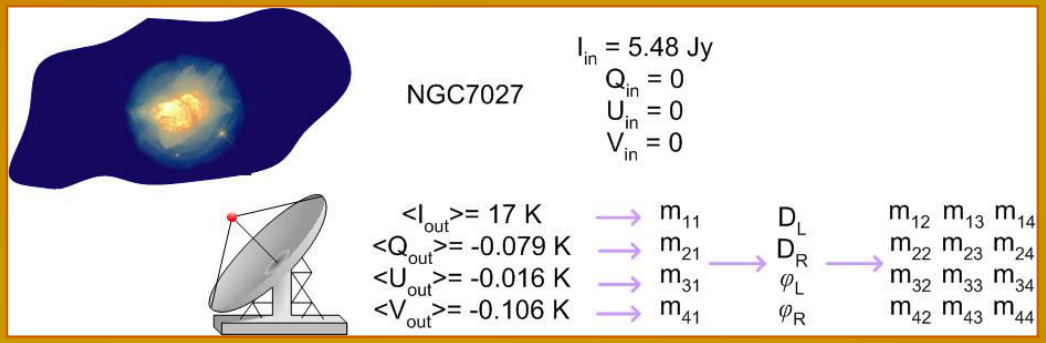
Müller matrix of the instrument

$$
\begin{aligned}
I_{out} &= m_{11} I_{in} + m_{12} Q_{in} + m_{13} U_{in} + m_{14} V_{in} \\
Q_{out} &= m_{21} I_{in} + m_{22} Q_{in} + m_{23} U_{in} + m_{24} V_{in} \\
U_{out} &= m_{31} I_{in} + m_{32} Q_{in} + m_{33} U_{in} + m_{34} V_{in} \\
V_{out} &= m_{41} I_{in} + m_{42} Q_{in} + m_{43} U_{in} + m_{44} V_{in}
\end{aligned}
$$

Mathematical definition of each element up to the 2nd order (frequency independent), e.g. m_{41} :

$$
\frac{D_R \cos(\varphi_R - \Delta_c) - D_L \cos(\varphi_L + \Delta_c)}{1 + D_R^2 + D_L^2 + 2D_R \cos(\varphi_R - \Delta_c) + 2D_L \cos(\varphi_L + \Delta_c) + 4D_R D_L \cos(\varphi_R - \Delta_c)\cos(\varphi_L + \Delta_c)}
$$

Cenacchi, E. et al., 2009, A&A Accep.



Example at 5 GHz

$$
\mathbf{M} = \begin{pmatrix}
0.9951 & -0.0049 & -0.0008 & -0.0069 \\
-0.0048 & 0.9913 & -0.0867 & 0.0068 \\
-0.0012 & 0.0867 & 0.9913 & 0.0015 \\
-0.0069 & -0.0069 & -0.0009 & 0.9951
\end{pmatrix}
$$

Regular test observations at 5 GHz from Dec. 2006 to Dec. 2007

D_L = 0.59 ± 0.04%

D_R = 0.16 ± 0.08%

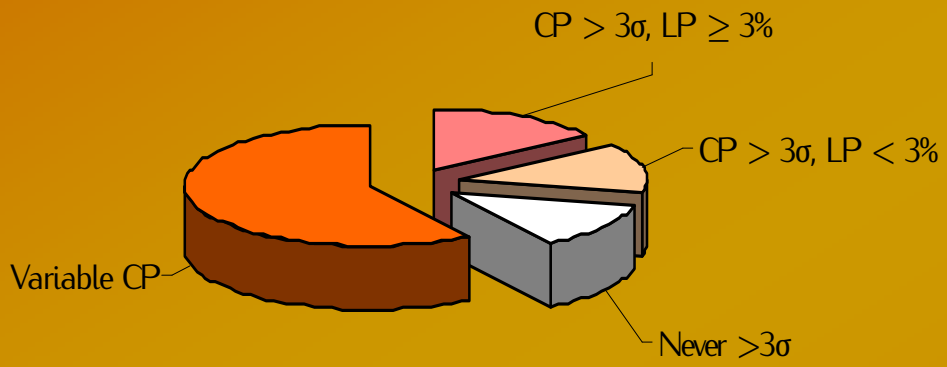
φ_L = -2.4 ± 3.8°

φ_R = -3.7 ± 8.4°

Selected sample of extra-galactic radio sources

43 sources: 39 extragalactic sources, 2 planetary nebulae, 2 planets (calibration purpose).

Nearly monthly observations at 5 GHz from December 2006 to December 2007.



Typical CP accuracy of 0.05÷0.2%

Good agreement with the few previously known CP values [%], e.g. :

Source	Michigan 26m[1]	VLBA[2]	Effelsberg[3]	Effelsberg[4]
1519-273	-0.92 ± 0.17	-	-0.77 ± 0.21	-0.76 ± 0.01, rms 0.37
0743-006	-0.51 ± 0.08	-0.46 ± 0.05	-0.50 ± 0.10	-0.51 ± 0.02, rms 0.15
3C84	-0.15 ± 0.02	-	-0.09 ± 0.05	-0.06 ± 0.01, rms 0.23

[1] *Aller, H.D., Aller, M.F., & Plotkin, R.M. 2003*

[2] *Homan, D.C., Attridge, J.M., & Wardle, J.F.C. 2001*

[3] *From November 2007 single observing session*

[4] *From the whole set of available measurements*

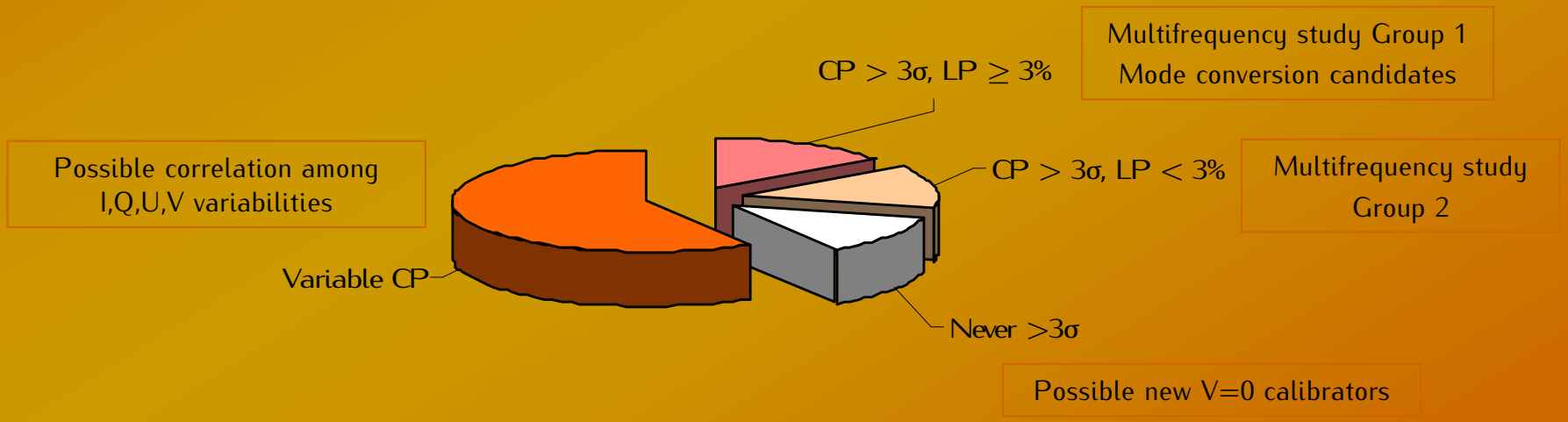
Multi-frequency polarimetric study

Advantages of the new calibration procedure

- Contemporary measurement of I,Q,U,V
- Frequency independent
- Technical description of the receiver (D-terms in amplitude and phase)

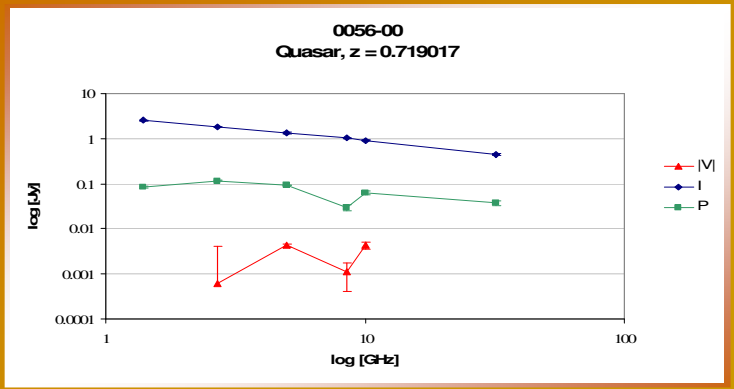
The calibration procedure is suitable to any receiver that supplies circularly polarized outputs and is equipped with 2 total power detectors and a multiplying polarimeter (nowadays the most common receiving architecture)

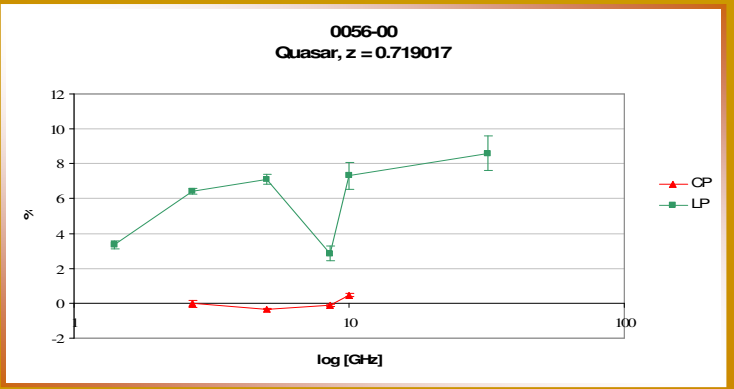
Dec. 2007 First cross-check: 3 sources observed by ATCA during a technical session → encouraging results, but not enough → we start planning a larger survey.

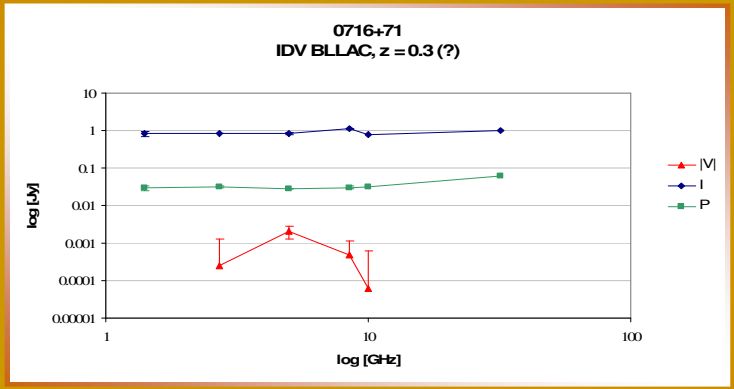


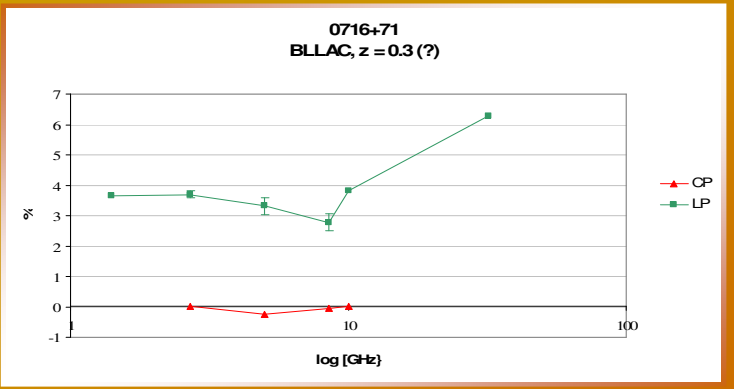
Multi-frequency polarimetric study

The sub-sample of 6 sources that exhibited a CP value systematically above 3σ and an LP level greater than 3% has been selected for the first multi-frequency full Stokes study at 2.7, 5, 8.5 and 10 GHz. Old data for I,Q,U were available in the Effelsberg archive also at 1.4 and 32 GHz.





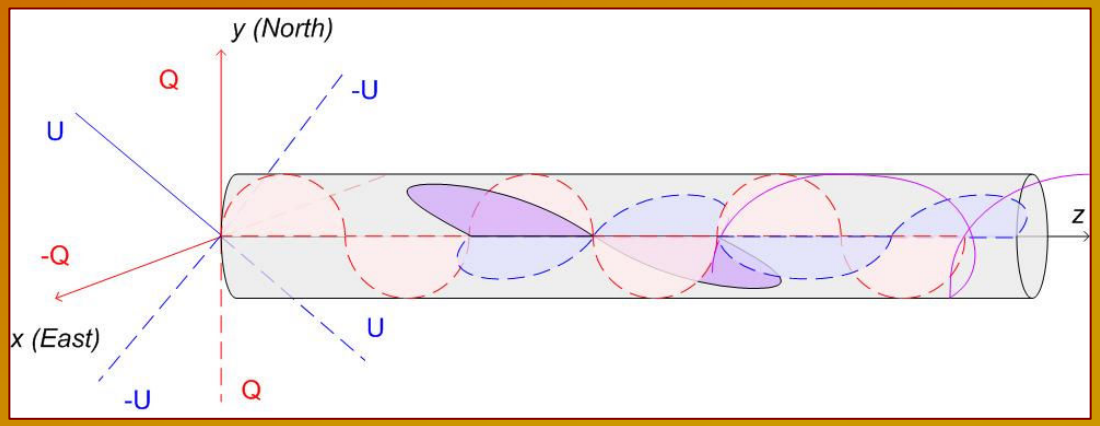




Mode conversion as origin of CP

Magnetized plasma of low-energy electrons

Isotropic particle distribution



Non-null component of B perpendicular to the line of sight (e.g. helical field)

Variation of the Stokes parameters along the line of sight, according to the radiative transfer (emissivity and absorption coefficients) in a typical frame appropriately rotated:

$$\frac{dI}{ds} = \eta_I - k_I I - k_Q Q - k_V V$$
$$\frac{dQ}{ds} = \eta_Q - k_I Q - k_Q I - k_F U$$
$$\frac{dU}{ds} = -k_I U + k_F Q - k_C V$$
$$\frac{dV}{ds} = \eta_V - k_I V - k_V I + k_C U$$

$k_{I,Q,V}$ Absorption coefficients

k_F Rotation coefficient

k_C Conversion coefficient

Beckert, T., Falcke H., 2001

Theoretical model vs. Measured values

0056-00

Extended
Unpolarized
Synchrotron
Source

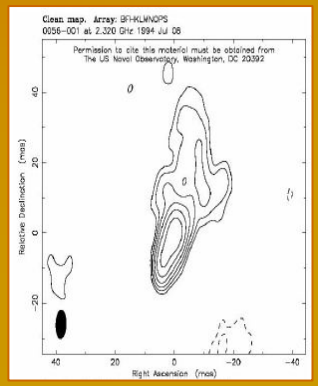
$L = 8x10^{21}$ cm

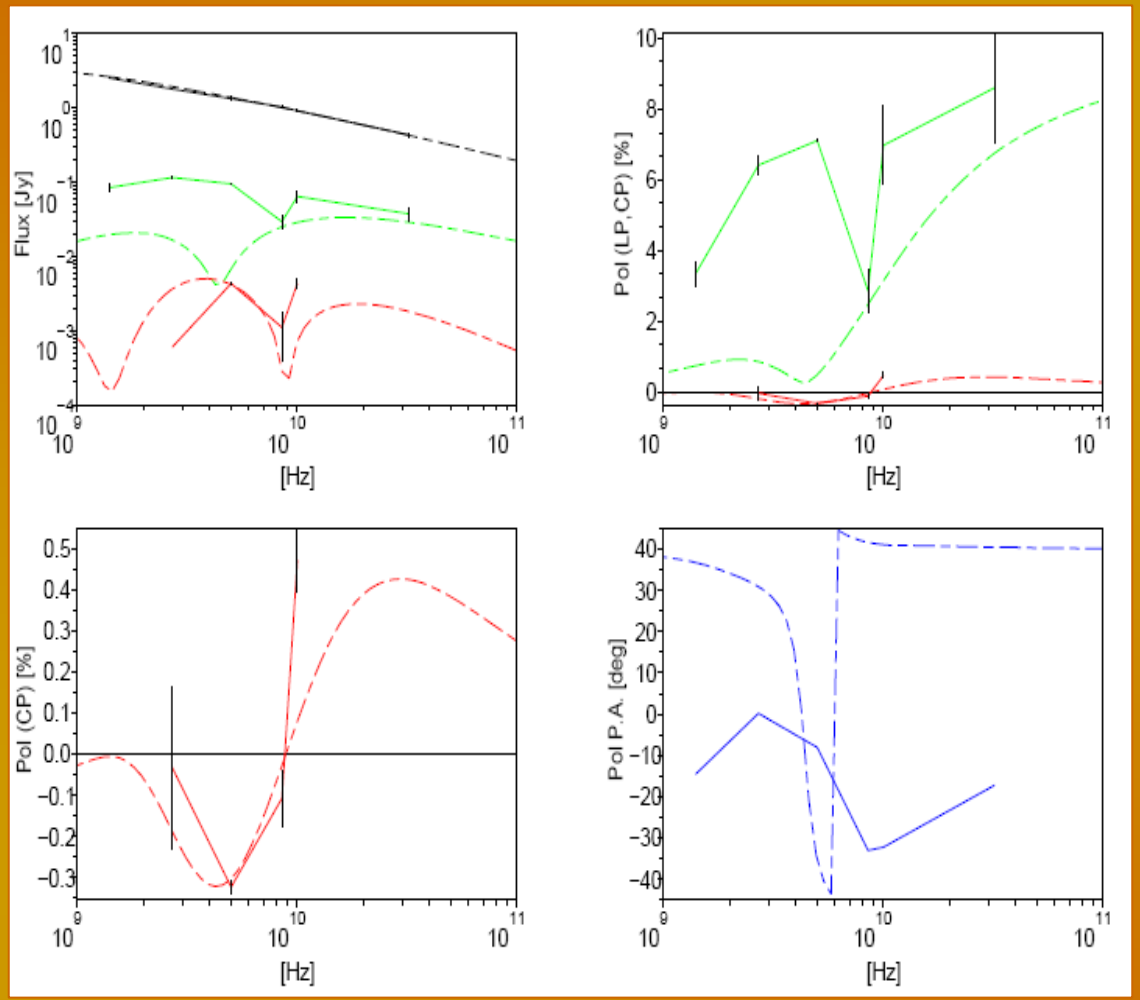
$n_e = 10^{-3}$ cm^{-3}

$p = 2.45$

$B = 4$ mG

Equipartition





Compact
Jet Component

$L = 1.5x10^{19}$ cm

$n_e = 5x10^{-1}$ cm^{-3}

$B = 90$ mG

Helical B

$\chi = 85°$

$\delta = 6$

3rd Component ?

The 5 GHz Northern Kühr full Stokes survey

Westerbork Array

- 14 x 25-m dishes interferometer
- 2.7 km linear array
- Equatorial mounting
- Native linear feeds at 5 GHz

$$V = 2\langle E_x E_y \sin\Delta \rangle = i\left(\tilde{E}_x \tilde{E}_y^* - \tilde{E}_y \tilde{E}_x^*\right)$$

→ CORRELATOR

Effelsberg Telescope

- Single dish radiotelescope
- 100-m diameter antenna
- Alt-Azimutal mounting
- Native circular feeds at 5 GHz

$$V = \langle E_L^2 \rangle - \langle E_R^2 \rangle = \tilde{E}_L^* \tilde{E}_L - \tilde{E}_R^* \tilde{E}_R$$

→ POST PROCESSING

The 5 GHz Northern Kühr full Stokes survey

Aug. 8th-11th, 2008: EB-WB contemporary observation

Northern Kühr Cataloge

283 „point like“ sources at $\delta > -10°$, flux > 1 Jy at 5 GHz

44 Sources (including calibrators) observed by both the instruments → **CP CALIBRATION**

175 Sources observed by Effelsberg only, $-10° < \delta \leq 30°$

65 Sources observed by Westerbork only, $\delta > 30°$

→ **UPDATED FULL STOKES CATALOGUE**

Effelsberg data already reduced, Westerbork reduction currently ongoing at IRA

Conclusions

So far…

- A new polarimetric calibration for the Effelsberg telescope has been developed, allowing full Stokes measurements with an overall accuracy in CP of 0.05÷0.1 %
- Nearly monthly observations of a sample of 39 extragalactic radio sources have been carried out at 5 GHz, during 2007. Nearly 30% of the CP detections are over 3σ
- Sources that systematically exhibited CP above 3σ and LP>3% were object of a first full Stokes multi-frequency study, during 2008, to investigate the mode conversion process
- Comparison with a theoretical model, to derive the physical properties of the source magnetic field and surrounding medium.
- 5 GHz Northern Kühr full Stokes survey, August 8th-11th 2008, performed by Effelsberg and Westerbork together.

…and in the next future

- Completion of the data reduction from the polarimetric survey (Westerbork part)
- Extension of the multi-frequency full Stokes observations to other sources, selected from the Kühr polarimetric survey

End of PhD planned by the end of 2009