Ancillary databases in polarization of extragalactic sources

M. Massardi & the Italian ARC node

Catalogues of polarized extragalactic sources

Job begun for AT20G and Planck polarization activities

References	Frequency (GHz)	# sources	Notes
Eichendorf & Reinhardt (1979)	[0.4, 15]	510	multi–frequency data
Tabara & Inoue (1980)	[0.4, 10.7]	1510	multi–frequency data
Simard-Normandin, Kronberg & Button (1981)	[1.6, 10.5]	555	multi–frequency data
Perley (1982)	1.5, 4.9	404	
Rudnick et al. (1985)	[1.4, 90]	20	flat; multi–frequency data
Aller et al. (1992)	4.8, 14.5	62	35 flat, 27 steep; complete sample ($S_{5\,GHz} > 1.3$ Jy)
Okudaira et al. (1993)	10	99	flat; complete sample ($S_{5\,GHz} > 0.8$ Jy)
Nartallo et al. (1998)	273	26	flat
Condon et al. (1998) - NVSS	1.4	$\sim 2 \times 10^6$	complete sample ($S_{1.4\,GHz} > 2.5$ mJy)
Aller et al. (1999)	4.8, 14.5	41	BL LAC
Zukoski et al. (1999)	4.75	154	28 flat, 122 steep
Lister (2001)	43	30	flat; 90% complete sample ($S_{5\,GHz} > 1.3$ Jy)
Klein et al (2003)	1.4, 2.7, 4.8, 10.5	192	B3-VLA sources with detected polarisation at 10.5 GHz
Ricci et al. (2004)	18.5	250	$S_5 > 1Jy$ Southern Kuhr sample sources
Jackson et al. (2007)	8.4	~5000	JVAS-CLASS flat spectrum sources
Massardi et al. (2008) AT20G-BSS	4.8, 8.6, 20	320	AT20G bright sample
Agudo et al. (2009)	86	146	flat-radio-spectrum AGNs $S_{86\,GHz} > 1$ Jy)
Lopez-Caniego et al. (2009)	23,33,41	22	polarisation detection in WMAP map
Jackson et al. (2010) Battye et al. (2011)	8.4, 22, 43	230	WMAP sources
Sajina et al. (2010)	4.8, 8.4, 22, 43	159	equatorial AT20G sources
Murphy et al. (2010) Massardi et al. (2011) AT20G	4.8, 8.6, 20	5890	complete sample above 100 mJy
current paper, Burke-Spolaor et al. (2009)	4.8, 8.6, 18	193	complete sample above 500 mJy

+VLA Polarization calibration project 5-43 78

+ATCA Calibrator manuals (C007) 1.4-95 ...

Catalogues of polarized extragalactic sources

>80 GHz observations

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Ricci et al. (2004)	18.5		
Jackson et al. (2007)	8.4		
Massardi et al. (2008) AT20G-BSS	4.8, 8.6, 2		
Agudo et al. (2009)	86	146	flat-radio-spectrum AGNs $S_{86\,GHz} > 1\,$Jy)
Lopez-Caniego et al. (2009)	23,33,41	22	polarisation detection in WMAP map
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Nartallo+ (1998): VLBI obs @ 1.1-0.8 mm btw 1991-1996.
Selection favours BLLacs and FSRQ.
Resolution looking into the nuclear jet-bases.
Found variability, various geometries,
various relation with total intensity.
Limited by small sample.
Need more insight on comparing subpc vs pc scales.
Frac pol mostly btw 4-7% unrelated with flux density.

Agudo+ (2010): IRAM obs @ 3.5 mm.
Selection S_{86GHz}>1Jy dec>-30deg radioloud
Selection favours BLLacs and FSRQ. Det rate 76%.
Found lin frac pol 3-4%

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WMAP follow-up & Planck perspectives

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WMAP btw 23-41 GHz (good for pol)
S_{23}>1.1Jy. Issues with noise.
Expected about 50 src detected in Planck up to 100 GHz
(or more?) Follow-up mostly with VLA >-30deg
Frac lin pol 2-2.5% no clear dep with freq and flux density

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Catalogues of polarized extragalactic sources

Not only as calibrators...

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+VLA Polarization calibration project 5-43 78

+ATCA Calibrator manuals (C007) up to 95 ...

VLA (Myers): we found five stable polarization angle calibrators (up to Q-band) other than 0137+331 (3C48) , 0521+166 (3C138) and 1331+305 (3C286) : 0423-013 , 0854+201 , 1310+323 , 1751+096 , and 2136+006 . Some of these are relatively flux-stable also. In addition, the source 2355+498 , although essentially unpolarized, has proved to have a stable flux density and thus could serve as a secondary flux calibrator. Surprisingly, the very bright sources 3C273 (1229+020) and 3C279 (1256-057) seem to have relatively stable PA at high frequency despite being highly variable in flux density!

Catalogues of polarized extragalactic sources

...also to investigate source properties...let's focus on the Southern Hemisphere

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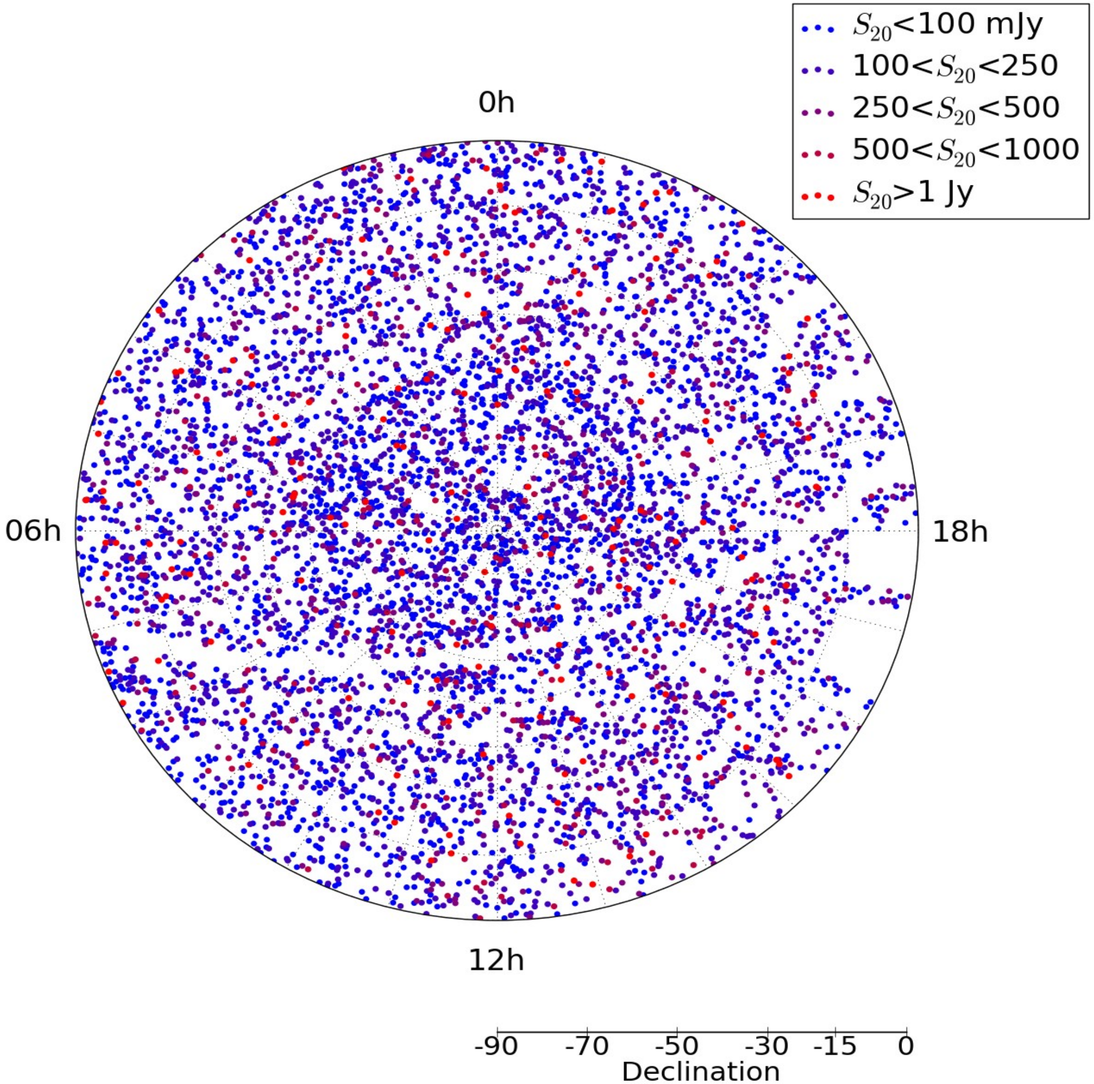
The AT20G Survey in polarization

The AT20G Survey is a blind 20 GHz survey of the entire southern sky with |b|>1.5deg. Observations were carried out using the Australia Telescope Compact Array (ATCA) from 2004-2008. The final AT20G catalogue consists of 5890 sources above a 20 GHz flux density limit of 40 mJy and includes near-simultaneous observations at 4.8 and 8.6 GHz for most sources south of -15deg.

ATCA: 6 antennas H75-214 configs
2x128 MHz bands
4.8-8.6-0 GHz follow-ups included
polarization down to sigmaP>6mJy



A Run dedicated to polarization

1st October 2006: high-sensitivity polarization run (same as for extended objects)

ATCA: 6 antennas H75 configs
31m-75m spacings
2x128 MHz bands
16.7-19.4 GHz
FOV = 2.6 arcmin
+ follow-up for high sensitivity also at 4.8 and 8.6 GHz within 1 month

Shadowing for dec<-76deg -> 11 sources reobserved with H214

1921-293 and 1934-638 once

A secondary calibrator before and after each group of 4-6 sources in the same area
Secondary used to solve for gains, xy-phase difference and leakages

2x70s cuts for each target sources separated by 4h at 18 GHz
2x30s cuts for each source at lower frequencies

The telescope on-axis receivers introduce relatively low amounts of instrumental polarisation, while all antennas are fitted with a noise diode that injects a signal to continually track the phase difference (xy-phase) over time between the two orthogonal feeds. Additionally, the linear feed system holds the benefit of very little contamination of circular polarisation signal by the full intensity signal.

The data reduction

Data reduction in Miriad
16.7 and 19.4GHz were calibrated independently and then combined for 18GHz imaging and flux density assessment. Opacity correction and a correction for the time-dependent instrumental xy-phase difference was applied upon loading.

For polarimetric calibration with calibrators of unknown polarisation and sparse data (such as in our short snapshot observations), **the standard Miriad procedure suggests calculation of the largely stable instrumental leakage terms using an unpolarised primary calibrator**. The remaining polarisation and gain terms are then calculated for each secondary phase calibrator.

Roughly 75% of the sources in our sample are registered in the ATCA calibrator database; all are sufficiently bright to determine adequate calibration solutions. However, though it is suggested that accurate Q and U levels could be calculated from a relatively small amount of data, it was apparent that this was not the case for our ∼3 minute observations.

Many solutions failed, while others produced impossible values for Q and U levels.
All polarisation and gain solutions for the main sample were determined using the secondary calibrators that were interlaced in our observations, originally intended for use for extended source only. **Merged solutions from the eight available calibrators afforded an observation every 1-2 hours in various regions of the sky spanning approximately 6 hours.**

They had **sufficient parallactic angle coverage to disentangle instrumental polarisation from the calibrator Stokes Q and U levels.**
Incidentally, tests run to check levels of residual phase instability,usually due to imperfect phase calibration, in the calibrated target sources (as given in percentage by dividing the source's vector amplitude by its scalar amplitude) showed that **using thinly spaced calibrators can give a better phase calibration than very closely tracked calibrators** (as shown by 0-20% residual decorrelation in our sample versus the 0-50% that was found in AT20G data over similar time scales and weather conditions).

Hence, **in polarimetry experiments covering large areas of the sky, it appears more pertinent to have many observations of one calibrator throughout an observation and therefore have sufficient data to determine accurate polarisation solutions, despite possible non-proximity to target sources.**

The data reduction

Stokes-I intensities were determined from the visibilities using a scalar average flux density to avoid the inclusion of phase instabilities inherent in image-based measurements. This technique takes the average of the visibility amplitudes and is robust for bright (>200mJy), point-like sources only.
To acquire Stokes Q, U and V flux densities, images were created and deconvolved using the Miriad task CLEAN. To correct the Stokes Q, U and V images for decorrelation, we took advantage of the fact that Stokes parameters, simultaneously measured, are affected by decorrelation originating in atmospheric phase instabilities (as might be left after imperfect calibration). We can thus use the fractional level of residual decorrelation in Stokes I, calculated and applied to Q, U, and V flux densities as

$$\chi = \frac{I_{\rm sca}}{I_{\rm map}}$$

$$Z = \chi \cdot Z_{\rm map}$$

where Z represents Stokes Q, U or V , Isca is the scalar averaged Stokes I flux density, and Imap, Zmap represent the values at the position of the peak Stokes I emission in the relevant image.
The image peak for all sources was sufficient to determine the decorrelated flux density measurements; the pixel size was typically 10 arcsec, and all sources in this subsample were not extended significantly beyond this.
The polarised intensity and the position angles were then calculated using standard first-order debiasing

$$P = \sqrt{Q^2 + U^2 - \sigma_{\rm V}^2}$$

Fractional polarization is estimated as

$$\Pi = 100 \cdot P/I.$$

The WMAP source extraction

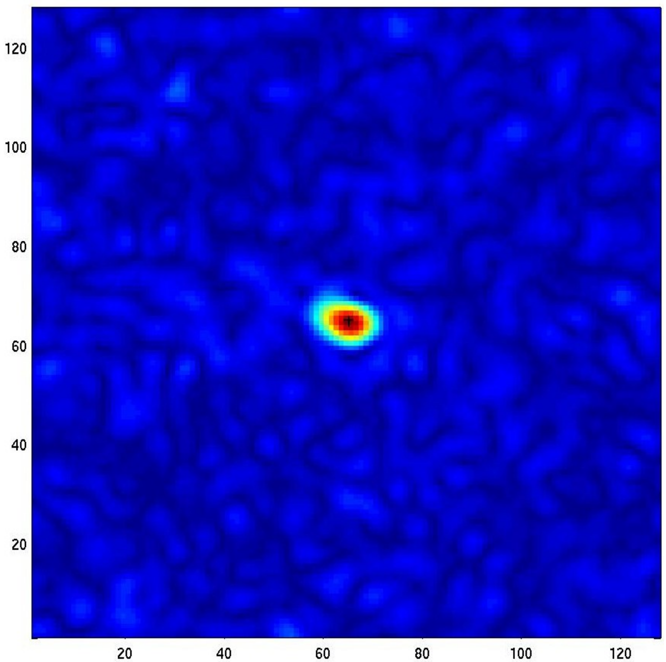
Name	$P_{23\mathrm{GHz}}$	$P_{33\mathrm{GHz}}$	$P_{41\mathrm{GHz}}$	$P_{64\mathrm{GHz}}$	$S_{23\mathrm{GHz}}$	$S_{33\mathrm{GHz}}$	$S_{41\mathrm{GHz}}$	$S_{64\mathrm{GHz}}$
Fornax A	1074_{31}	867_{44}	589_{64}	<354	9321_{134}	5350_{184}	3275_{173}	905_{255}
PicA - AT20GJ051949-454643	457_{35}	372_{50}	280_{82}	484_{137}	6464_{207}	5661_{235}	4656_{210}	3139_{270}
CenA - AT20GJ132527-430104	3322_{70}	2699_{81}	2323_{120}	2075_{173}	51006_{260}	41909_{248}	35731_{245}	26767_{335}

Of the 9 very extended sources 4 have ATCA flux densities only for subregions AT20GJ013357-362935, AT20GJ132527-430104, AT20GJ133639-335756, and FornaxA remain undetected H75
5 more objects in our initial sample were found to be extended with respect to our synthesized beam

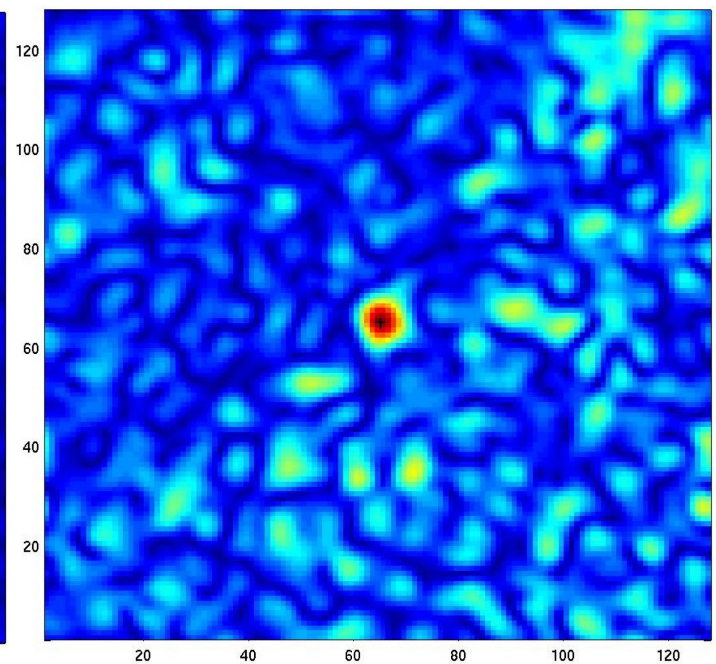
We applied the **IFCAPol software package to WMAP 9 year coadded map,** with the 0.88 degree beam at 23 GHz. This software implements the Filtered Fusion approach, where a maximum likelihood estimator is obtained for the Q and U maps of each source. As a result, denoised Q and U maps are obtained and the polarised flux density at the position of the source is obtained from the map of P

Confidence levels analysis discarded the undetections. **2 detected (+PicA), 5 upper limits, 2 missed also in I**

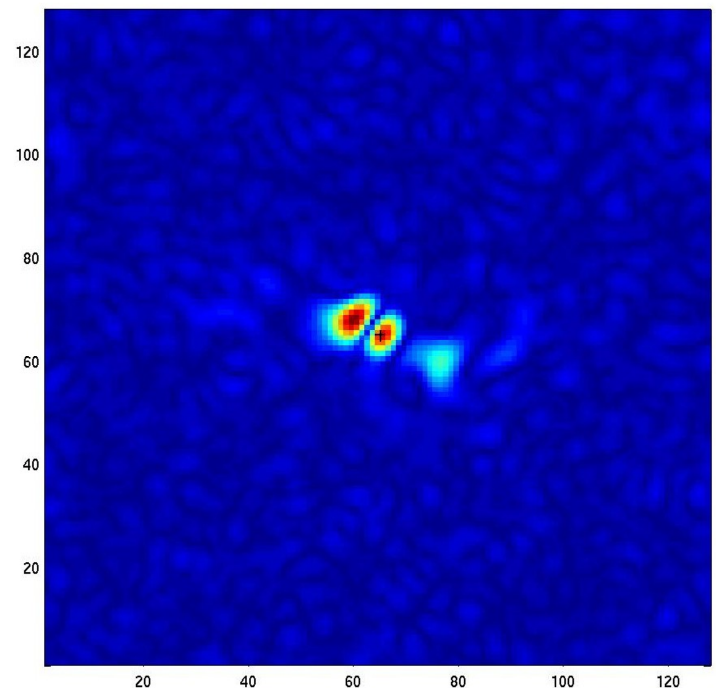
Fornax A



Pictor A



Centaurus A



The sample

All objects with flux density S20GHz > 500mJy in previous AT20G observations and declination < −30◦, excluding the Galactic plane region (|b| 6 1.5◦) and the LMC
This resulted in a complete sample of 189 sources.

180 got good ATCA data (including 5 extended sources)
169 of them with a detection at 20 GHz (**94% detection rate**)

173 and 172 sources have good quality flux densities respectively at 4.8 and 8.6 GHz.
172 sources have good quality flux densities at all the frequencies

143 sources have a polarisation detection at all the frequencies (79% of the main sample).

9 extended sources were investigated in WMAP maps, 2 detected, 5 upper limits, 2 missed

Hence, the full sample that will be used in the next section include 187 sources,
It is 99% complete with S20GHz > 500mJy at the 2006 survey selection epoch.
The polarised emission detection rate is 91.4 per cent.

Spectral properties

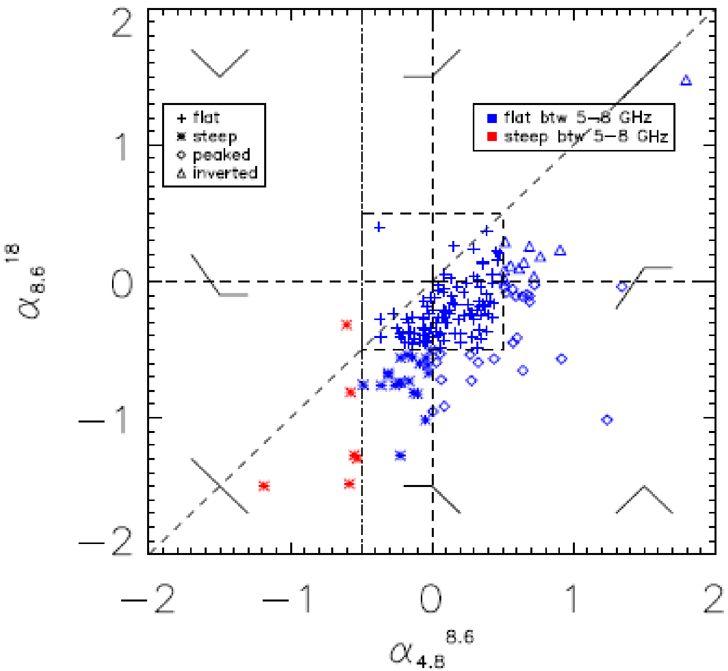
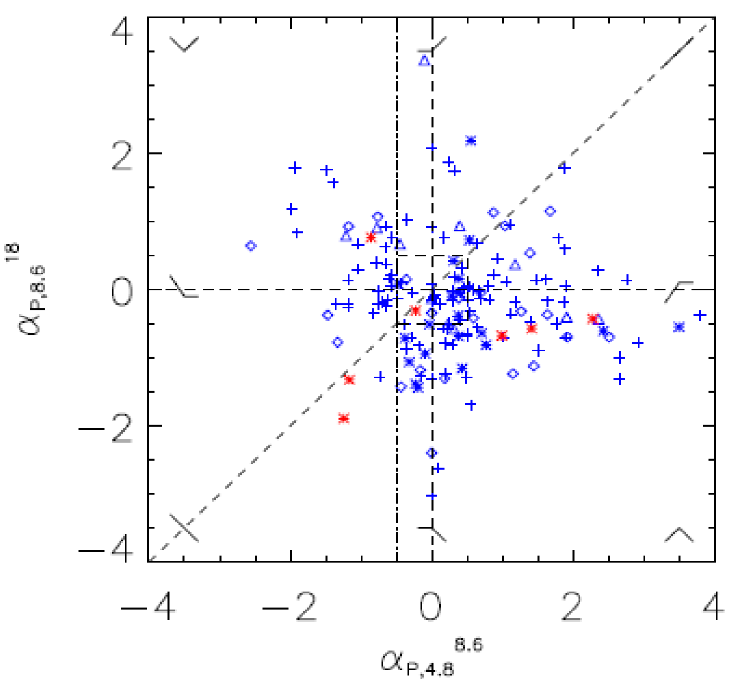


Table 6. Median values of spectral indices in different frequency ranges in total intensity and polarisation. Spectral classes are selected according to their behaviour between 4.8 and 8.6 GHz.

		4.8-8.6 GHz	8.6-18 GHz	4.8-18 GHz
$\alpha_{\nu 1}^{\nu 2}$	All	0.09	-0.28	-0.11
	Flat	0.12	-0.27	-0.08
	Steep	-0.60	-1.27	-0.95
$\alpha_{P,\nu 1}^{\nu 2}$	All	0.20	-0.16	-0.006
	Flat	0.23	-0.15	-0.006
	Steep	-0.23	-0.43	0.04



There is an overall steepening both in P and I

The spectral properties over the 5 to 18 GHz frequency range may be different in total intensity and in polarisation.

This effect could be addressed to a combination of Faraday depolarisation, operating at the lower frequencies, superposition of multiple components with different polarised spectra, different magnetic field properties for the components that dominate the emission at the different frequencies.

-> maybe we'd better go higher in freqs and resolution (mantaining high sensitivity)

Spectral properties and fractional polarization

Table 4. Matrix of the number of sources classified according to both the total intensity and polarisation spectral behaviour. The rows are the spectral shape in polarisation, the columns the spectral shape in total intensity. The spectral types are defined in the text.

S → Pol. ↓	(I)	(P)	(F)	(S)	(U)
Inverted (I)	2	4	21	2	0
Peaked (P)	5	10	33	10	0
Flat (F)	1	3	17	7	1
Steep (S)	0	4	15	9	0
Upturning (U)	4	3	17	1	0

Table 5. Median fractional polarisation for each spectral class at 4.8, 8.6, and 18 GHz. The spectral types are defined in the text.

Spectral class	4.8 GHz	8.6 GHz	18 GHz
Upturning (U)	1.32	1.23	1.37
Flat (F)	1.88	2.06	2.07
Peaked (P)	2.49	1.92	2.38
Steep (S)	1.33	1.72	2.74

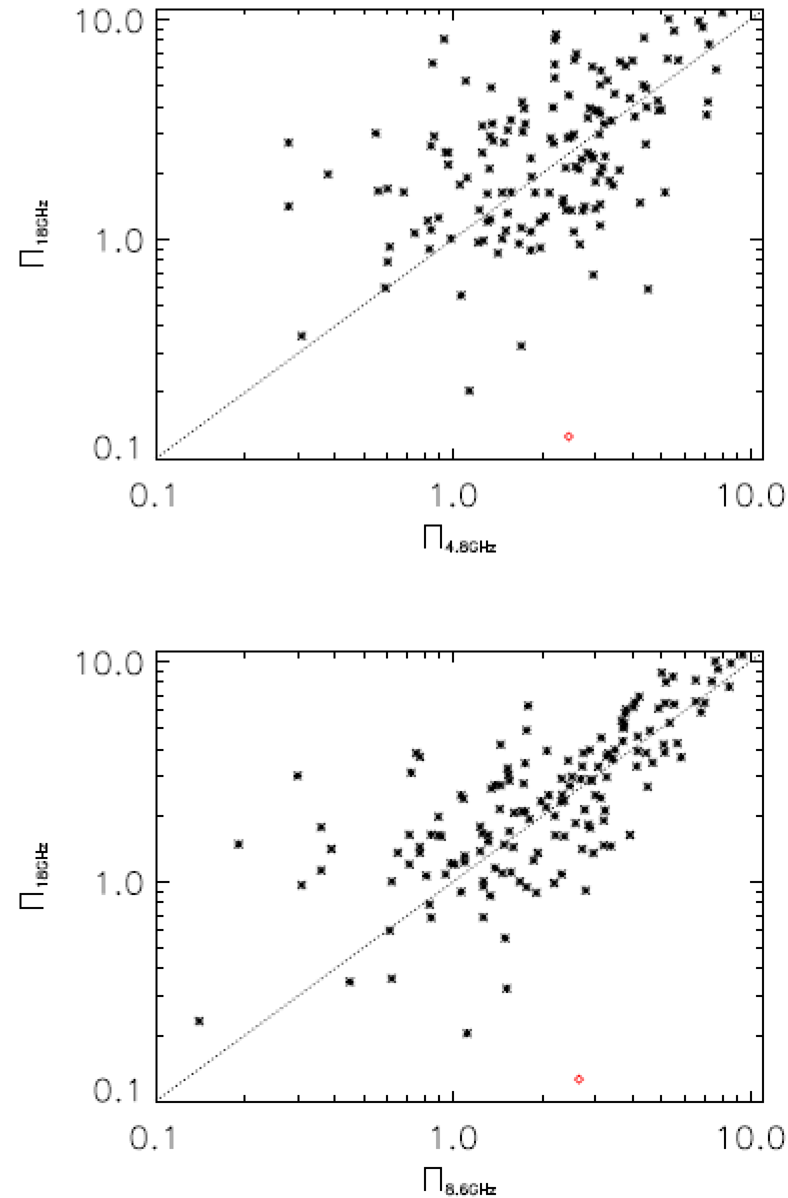


Figure 4. Fractional polarisation at 18 GHz as a function of 4.8 and 8.6 GHz for the full sample (red diamonds indicates upper limits at one or both the frequencies).

Fractional polarization distributions

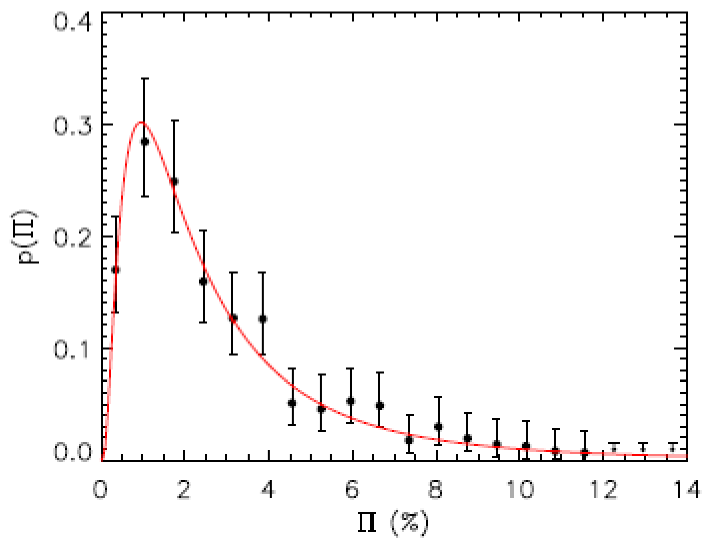


Figure 3. Distributions of the polarisation degree at 18 GHz. Errors and upper limits corresponds to a 68% c.l.. The dotted line shows the log-normal distribution with median fractional polarisation 2.12 and $\sigma^2 = 0.90$ (see the text for details).

Table 8. Parameters describing the distributions of fractional polarisation for the full sample and for the flat- ($\alpha_{\nu 1}^{\nu 2} > -0.5$) and steep- ($\alpha_{\nu 1}^{\nu 2} < -0.5$) spectrum objects selected in the frequency ranges $\nu 1 = 8, \nu 2 = 18$ GHz and $\nu 1 = 5, \nu 2 = 8$ GHz. For each frequency and spectral class we quote the number of detections, the mean fractional polarisation and its error, the first, second and third quartiles of the distribution, and the probability that flat- and steep-spectrum objects are drawn from the same parent distribution, according to the two-sample Wilcoxon test.

	Full sample	Flat	Steep
		selected between 5 and 8 GHz	
18 GHz			
N_{TOT}	187	163	9
Detections	171	157	5
$\langle\Pi\rangle\pm\sigma_{\langle\Pi\rangle}$	2.79 ± 0.17	2.76 ± 0.17	2.32 ± 0.99
$_1$ 2 $_3$ quartiles	$_{1.09}$ 2.04 $_{3.84}$	$_{1.20}$ 2.08 $_{3.82}$	$_{0.01}$ 0.55 $_{2.54}$
Prob(flat-steep)		7.8%	
8.6 GHz			
N_{TOT}	172	163	9
Detections	158	151	7
$\langle\Pi\rangle\pm\sigma_{\langle\Pi\rangle}$	2.38 ± 0.15	2.42 ± 0.15	1.80 ± 0.77
$_1$ 2 $_3$ quartiles	$_{0.94}$ 1.80 $_{3.27}$	$_{1.03}$ 1.91 $_{3.28}$	$_{0.04}$ 0.55 $_{1.46}$
Prob(flat-steep)		5.3%	
4.8 GHz			
N_{TOT}	173	164	9
Detections	149	143	6
$\langle\Pi\rangle\pm\sigma_{\langle\Pi\rangle}$	2.16 ± 0.13	2.21 ± 0.13	1.08 ± 0.54
$_1$ 2 $_3$ quartiles	$_{0.87}$ 1.82 $_{3.05}$	$_{0.94}$ 1.91 $_{3.07}$	$_{0.00}$ 0.26 $_{1.22}$
Prob(flat-steep)		0.1%	

There is a general trend towards an increase of the mean fractional polarisation as the frequency increase for the whole sample and for each spectral class (even if we have a poor statistics for the steep-spectrum sources). **This trend is not so noticeable if we consider the median values,**

There is no statistically significant evidence of an increase of the median polarisation degree with frequency above 4.8 GHz. This implies on one side that already at 4.8 GHz the Faraday depolarisation is not very important and, on the other side, that the magnetic field is not substantially more ordered in the regions dominating the emission at higher frequencies.

Fractional polarization vs flux density

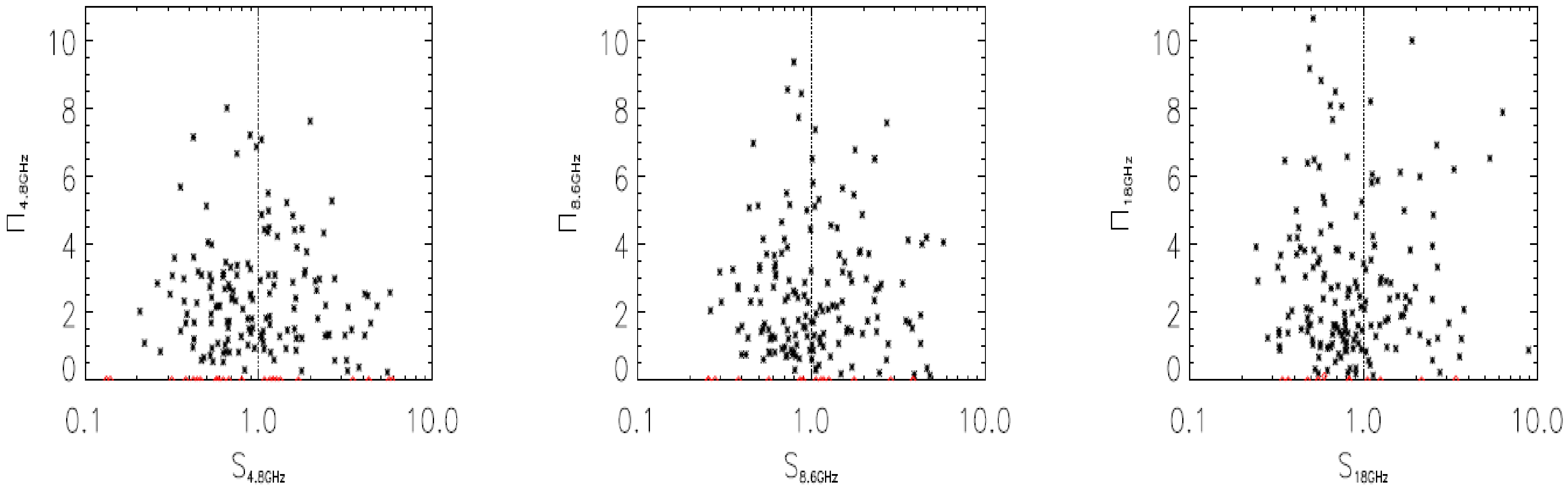


Figure 5. Polarization degree versus total flux density at 4.8, 8.6 and 18 GHz for the whole sample. The dotted line for flux densities equal to 1 Jy distinguish bright and faint subsamples.

Our data, with a high detection rate, **do not show any significant trend of with flux density** at any of the frequencies (4.8, 8.6 and 18 GHz) for S18GHz > 500mJy, with only 45% probability that the null-hypothesis that sources with flux density above and below 1 Jy at 18 GHz come from the same parent distribution.

Peculiar cases

Four point-like sources in our sample are **more than 9% polarised at 18 GHz**:
AT20GJ164737-643759(10.7% polarised with peaked spectrum in total intensity);
AT20GJ210933-411020(10.0% with peaked spectrum and S18GHz = 1.9Jy);
AT20GJ164842-330147 (9.8% polarised with steep spectrum);
AT20GJ1214712-753613 (9.1% polarised with steep spectrum).

AT20GJ181934-634548 is the source with the smaller detected fractional polarisation (0.0012%)
It is a point-like steep spectrum source with S18GHz = 2.155Jy.

The sources with the lowest limits of undetected polarised emission at 18 GHz are
AT20GJ194524-552049 <0.002% polarisation fraction, steep spectrum with S18GHz = 0.82Jy
AT20G174425-514445, <0.002% polarisation fraction, steep spectrum with S18GHz = 1.25Jy

As steep spectrum sources they are also expected to show a lower level of variability in total intensity. Hints on the structure are necessary to understand if the same holds also in polarization. If so, these sources are suitable leakages calibrators.

AT20G193424-634245 appears with < 0.0020% fractional polarisation at 18 GHz
it is the AT20G flux density calibrator, a bright compact double radio source, PKS 1934−638 with steep spectrum

Polarization source counts

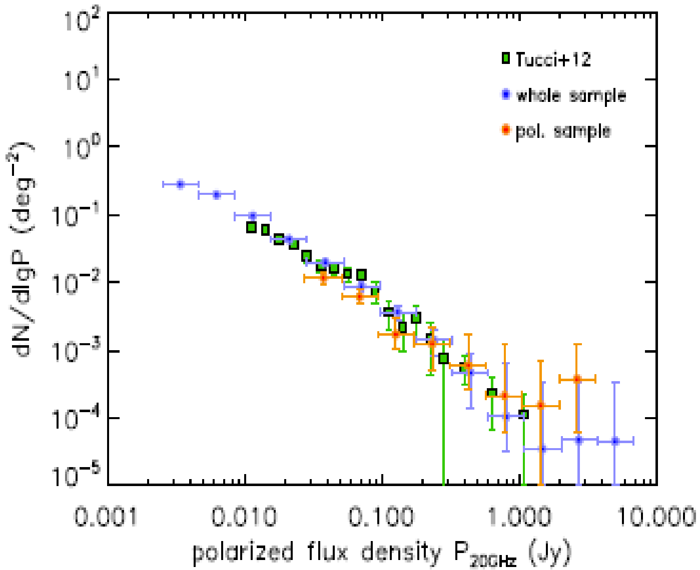


Figure 5. 18 GHz differential source counts in polarisation calculated with the two methods described in the text compared with the findings by Tucci et al. (2012).

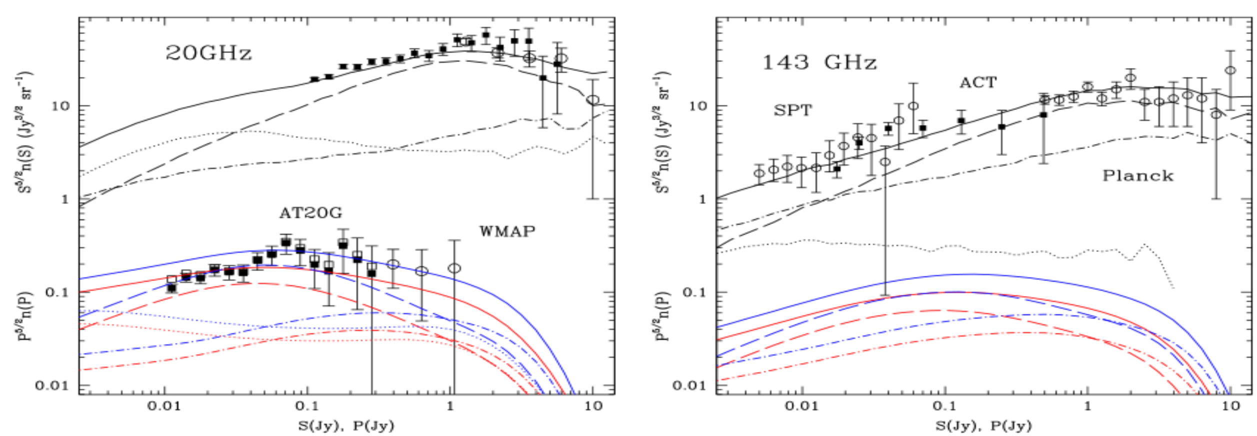


Fig. 6. Normalized number counts at 20 (*left panel*) and at 143 GHz (*right panel*) in total intensity (upper curves and data points) and in polarized intensity (lower curves and data points; blue curves are for the more "conservative" case and red curves for the more "optimistic" case). Number counts are for the different source populations discussed in the text: solid lines represent total number counts; dotted lines are for steep–spectrum sources; long–dashed lines are for FSRQs; finally, dot–dashed lines are for BL Lacs. In the *left panel*, filled squares represents our current estimates from the AT20G sub-sample (empty squares include the contribution from sources without polarization detection; see Sect. IV-C) and empty circles are from WMAP 5–years data [55]. Data points in the *right panel* are from published data [71], [72], [68].

Estimating CMB power spectrum

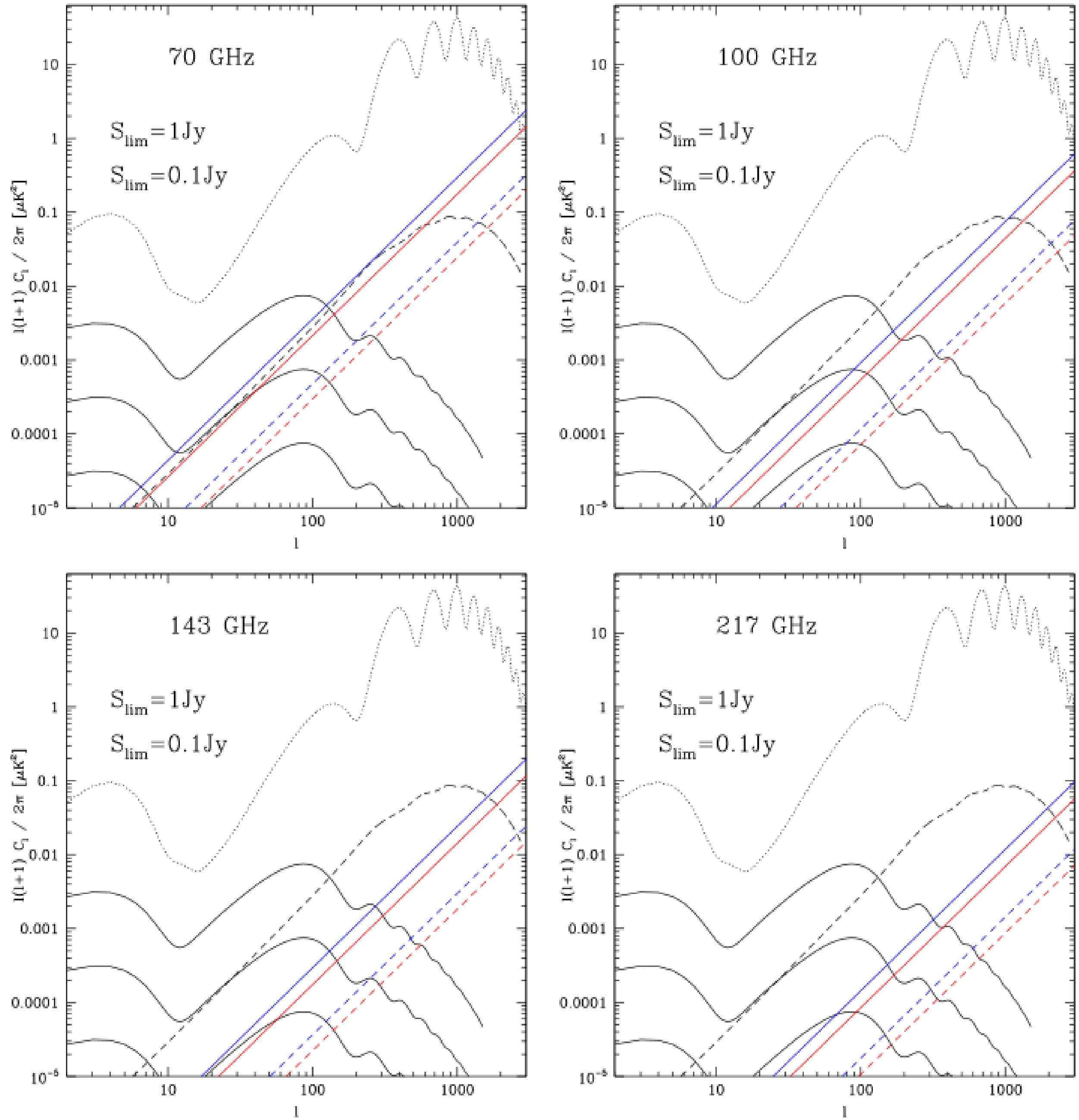


Fig. 7. Polarization power spectra at six *Planck* frequencies for the CMB radiation (black lines: dotted lines for the E–mode; solid lines for the gravitational wave B–mode with $r = 0.1$, 0.01 and 0.001; dashed lines for the lensing–induced B–mode) and for ERS (solid lines is for $S_c = 1\,\mathrm{Jy}$ and dashed lines for $S_c = 0.1\,\mathrm{Jy}$; blue lines correspond to the more "conservative" case and red lines to the more "optimistic" case).

Conclusions

The spectral behaviours in total intenisty and in polarisation are different for any population of sources. It is extremely difficult to make estimation of polarised flux densities from total intensity measurements.

There is no statistically significant evidence of increasing fractional polarisation with frequency. This implies that Faraday depolarisation is not strong enough to modify the spectral behaviour above 4.8 GHz.

Thanks to our high detection rate we could state that **there no evidence of an anticorrelation of mean polarisation degree with total intensity flux density as was previously noted by several surveys, probably biased by a selection effect**: only highly polarised sources could be detected for faint sources, while low fractional polarisation percentages could be detected in bright objects, together with the fact that faint objects in complete samples are typically more numerous than bright ones.

Thanks to the high sensitivity of our observations we were able to **extend the polarisation source counts at 18 GHz of an order of magnitude** with respect to what obtained by Tucci & Toffolatti (2012), of use also for CMB experiments.

Spectral behaviour in polarisation are, in fact, the result of the combined effects of beam depolarisation due to multiple components, chaotic magnetic fields and Faraday depolarisation.

Conclusions for ALMA

ALMA will allow to go higher in frequency and resolution
i.e. disentangle Faraday rotation from resolution effects

With high resolution and sensitivity in polarization it will be possible to investigate variability for polarized emission and identify the origin of the signals, disentangling the single components.

The AT20G list is an ancillary catalogue of use for positions and overview of the behaviour. We need something closer in time and freq.

Assuming the findings at 18 GHz for spectral indices and fractional polarization (i.e. median frac pol 2.7 and sp ind -0.16) we expect we can repeat the observing run

- **with ATCA reaching >1mJy in polarization rms in 10min on source at 93 GHz i.e. about 30hr on-source + 10hr overhead to address the polarization calibration of the full sample.**

[-with ALMA reaching about 1mJy in polarization rms in >2s on source at 93 GHz i.e. about 30min on-source + 10hr overhead...maybe better a subsample]

Maybe repeat it >twice over a year to investigate variability