Calibrating ALMA

Marcella Massardi
Italian ALMA Regional Center
INAF-Istituto di Radioastronomia (Bologna, Italy)

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ALMA numbers

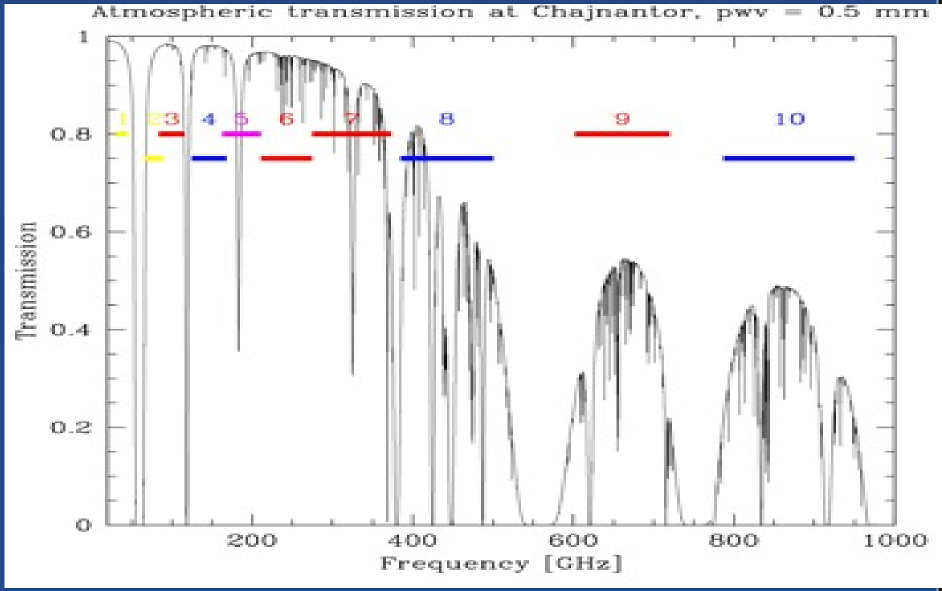
Dry site, low pwv, low Tsys, unprecedented high sensitivity also at submm frequencies

>6500sqm of effective area and 1225 baselines for the 12m array
+ Short spacings with ACA
Excellent instantaneous uv coverage & high sensitivity
<0.05mJy @100 GHz in 1 hr

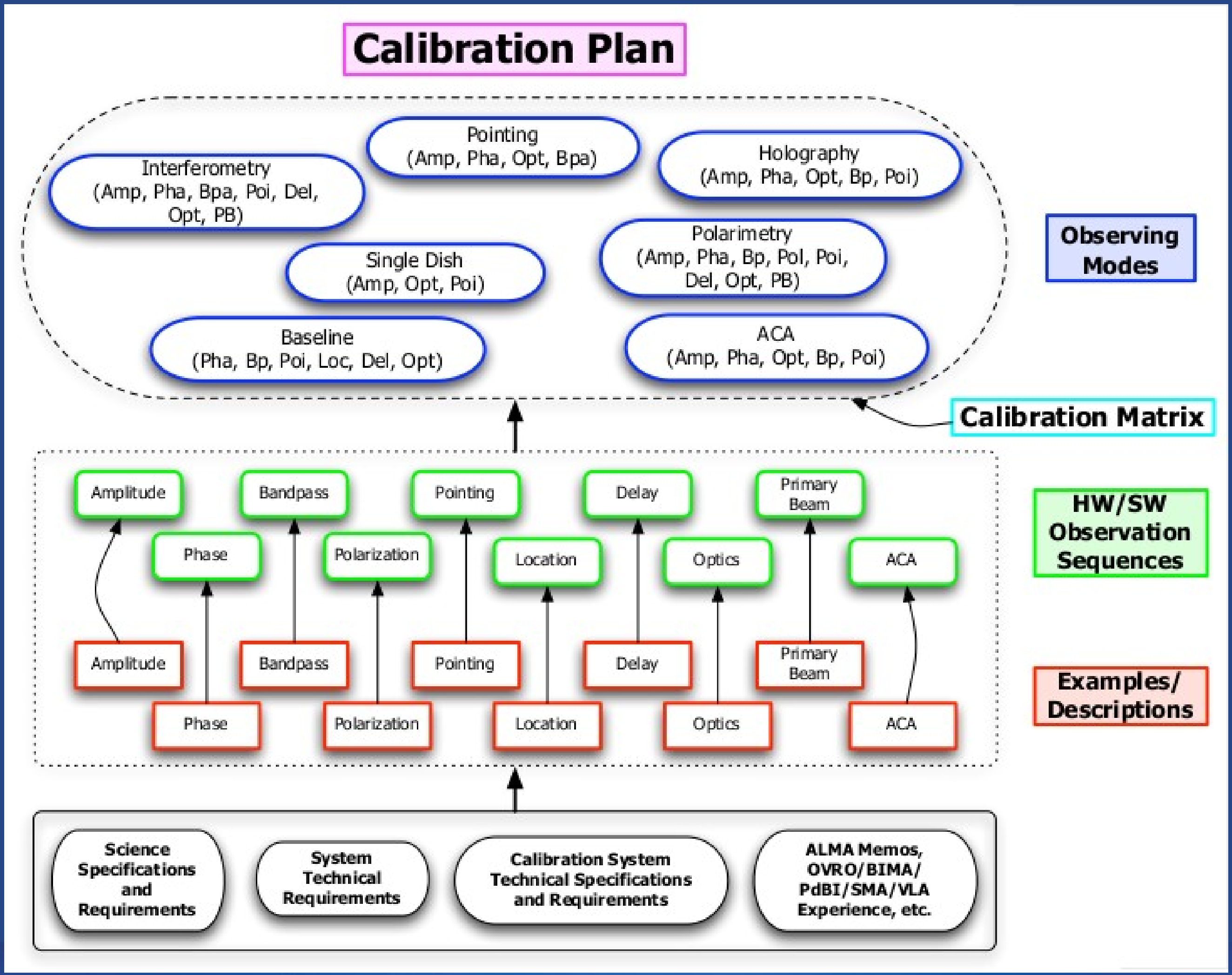
Up to 16km baselines, subarcsec resolution
40 mas @ 100 GHz,
5 mas @ 900 GHz

Flexibility in spectral and spatial studies
with broad bands and high spectral resolution

Needs accurate calibration to be exploited!!!



The plan



Requirements & experience feed the description of the various kinds of calibration which drived the HW/SW developement.
The descriptions generate the sequences of observations that constitute the various observing modes.
Reference doc in Mangum (2006)'s memo

Remember that:
- **ALMA has unprecedented sensitivity & resolution at mm-submm frequencies**
- **Projects are dynamically scheduled.**
- **PI receive the calibrated, reduced data (in FullALMA).**
- **ALMA structure is also for not expert (in FullALMA).**

Beam, Delay and Baseline location

Baseline location	To minimize the phase,bandpass and amplitude errors due to wrong measurement opf the baselines. It is necessary **every time an antenna is moved by comparing it with an unmoved close baseline.**
Delay	The goal of antenna and electronic delay calibration is to measure the delay offsets induced by the hardware in the antenna, fibers, cables, etc.. These delays have to be compensated by appropriate delays in the correlator to limit amplitude losses due to de-correlation across the observing bands. It is done **for each baseband, at least every time the correlator configuration is changed.**
Beam shape	The goal is to accurately measure the primary beam response for all antennas.It will be done **in dedicated holographic sessions.** The primary beam model derived from these measurements will need to be incorporated into any imaging software, including pipeline and offline analysis tools.

Bandpass

Goals	**Correct for the frequency fependence of the atmospheric attenuation and for the bandpass shape in amplitude and phase.** Accuracy as low as 0.1% can be reached (the narrower the band the higher the accuracy).
Main Steps	**Observe the calibrator at the observing frequencies.** Integration time depends on frequency and on the calibrator properties (from 1min to 1 hour).
Targets	Strong point like source of known spectral index (better knowledge for larger bandwidth). **Some quasars** have demonstrated to be suitable up to high frequencies.(see Planck catalogues...later discussed)

Source	α(J2000)	δ(J2000)	Flux@90	flux@230	SpI	flux@850
1226+023—3C273	12:29:06.69985	02:03:08.596	20.0	10.0	-0.7	3.8
1253-055—3C279	12:56:11.16644	-05:47:21.523	20.0	10.0	-0.7	3.8
1334-127—OP-158.3	13:37:39.78281	-12:57:24.692	6.0	3.0	-0.7	1.1
1641+399—3C345	16:42:58.81020	39:48:36.995	6.0	3.0	-0.7	1.1
1730-130—NRAO530	17:33:02.70580	-13:04:49.547	5.0	3.0	-0.5	1.5
1921-293—OV-236	19:24:51.05610	-29:14:30.120	9.0	5.0	-0.6	2.2
2145+067	21:48:05.45899	06:57:38.606	5.0	2.5	-0.7	1.0
2223-052—3C446	22:25:47.25951	-04:57:01.389	5.0	2.5	-0.7	1.0
2251+158—3C454.3	22:53:57.74830	16:08:53.563	7.0	5.0	-0.3	3.1

Pointing

Goals	establish the **antenna-based pointing offsets**
Main Steps	- **Global Pointing Model** Parameters for all ALMA antennas. This will generally be done with a linear least-squares fitting algorithm applied to a sequential series of randomly-distributed radiometric pointing measurements of ~ 100 or more radiometric point sources (**once per month**). – **Relative Receiver Band Pointing Offsets** for each antenna and receiver band. Necessary to monitor longer (**several month**) timescale variations in the relative pointing between receiver bands for each antenna. – **Reference Pointing Offsets** for each antenna and receiver band. This pointing measurement tracks shorter timescale variations in the pointing performance of each antenna. These pointing variations can be tracked with either single (Az,El) offset measurements or derivation of a **“local pointing model” in the region around a target source.**
Targets	Some **quasars** works as targets at all the frequencies. Sources must be **pointlike**. Several schemes for local pointing are being evaluated (5 or 3 points, anuli...)

Polarisation

Goals	It aims at determining the cross-talk between the two measured orthogonal source polarisations
Main Steps	The full-Stokes calibration of interferometric data is generally done in two steps: (1) calibration the total intensity data; (2) **calibrate the cross-polarization data using the total intensity callibration**. Requires **observations over several hours in order to obtain sufficient parallactic angle coverage** to separate out the cross-polarization terms and the calibrator polarization degree (eventually 0).
Targets	(a) **Unpolarized calibrator** — need only observe single scan. Can determine dX and dY up to a single complex number (equivalent to offsetting all d's or setting one to zero) that can be absorbed into gains, plus an unknown φXY . (b) **Polarized calibrator, polarization known** — also need only observe a single scan. Can determine dX and dY up to a single unknown amplitude factor that can be absorbed into gains. The phase φXY is fixed by the calibration (see below) to the extent that the source has known and measurable linear polarization. (c) **Polarized calibrator, polarization unknown** — need to observe calibrator in at least 3 scans spanning a range of at least 90◦ in parallactic angle. In general, this means the calibration source needs to be at a declination within ±20◦ of the observatory latitude. If well modelized **edges of the planets** might work as polarisation calibrators.

Phase

Goals	To **minimize the atmospheric, electronic phase fluctuations and decorrelation.** The corrected visibility phase fluctuations must be **<1 radian at 950 GHz**. Residual errors (and cycle timings) depend on obs frequency, project requirement, weather.
Main Steps	**Fast switching and/or WVR methods** available. - low SNR: FS every 10-60 sec - moderate SNR: WVR 1s cycles + FS every 10-30s - high SNR: Self-calibration for pointlike sources, initial FS for extended to set the self calibration model + self-cal. **Below 300GHz can calibrate at obs frequency.** **For higher frequency obs should calibrate phases at 90GHz**+ a coarse cross-band phase drift calibration every few minutes.
Targets	The best calibrator is **a source that minimizes the time it takes to detect the calibrator with sufficient SNR** (at the frequency of calibration) plus the time it takes to slew to and from the source. For effectiveness **a database** with thousands of objects is necessary, better if up to mm frequencies and pointlike (not to loose baselines).

Existing calibrator databases

- ATCA, SMA, VLA **calibrator pages** including planetary data

- **Herschel catalogues**

- **Planck Early Release Compact Source Catalogue** (Planck collaboration 2011)
  30, 44, 70, 100, 143, 217, 353, 545, 817 GHz allsky

- **AT20G** *(Murphy et al. 2010) 4.8, 8.6, 20 GHz Southern sky >50mJy @20GHz +pol*
- ***PACO*** *(MM et al. 2011) 4.5-40GHz Southern sky 463 sources +pol*
  BS>500mJy in AT20G
  FS>200mJy in AT20G
  + inverted & upturning +ATCA calibrators
- ***SiMPIE*** *(Procopio et al.2011, Righini et al. In prep) 5,8,20 GHz Northern sky WMAP sources*

All the ALMA observations will update the ALMA calibrator catalogue.

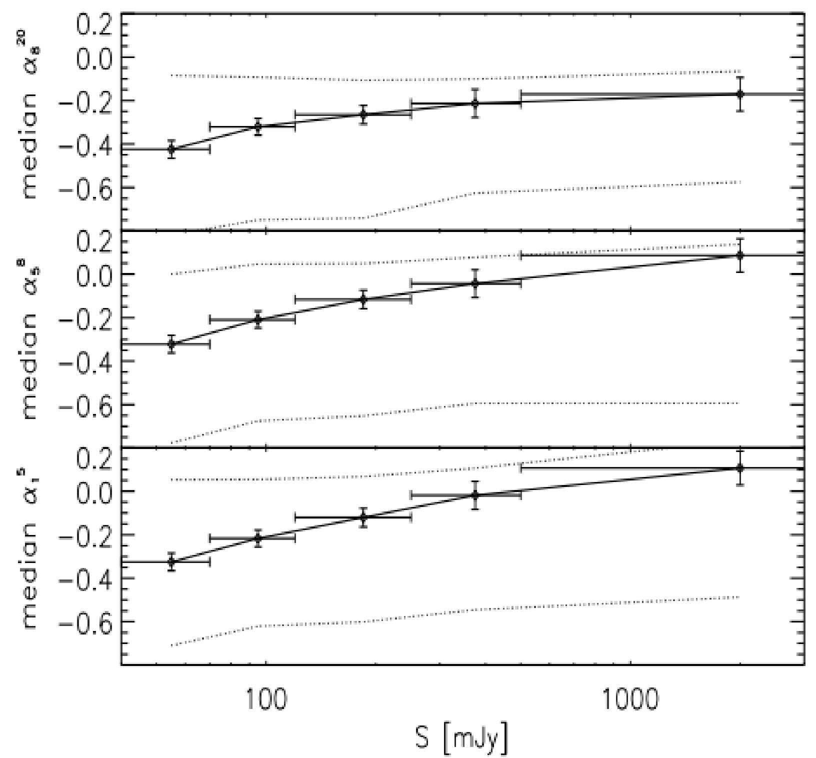
Reasons for new databases

The knowledge of the properties of extragalactic radio source populations at frequencies >10 GHz is poor because large-area high-frequency surveys are very time-consuming with high sensitivity ground-based diffraction-limited telescopes.

To date, **the Australia Telescope 20 GHz** (AT20G, Murphy et al. 2010) is the largest ground-based sample of the high radio frequency sky: it is 93% complete above 100 mJy at 20 GHz over the whole Southern sky with follow-up (within a few weeks time) at 4.8 and 8.6 GHz. No comparable samples exist for the Northern hemisphere.

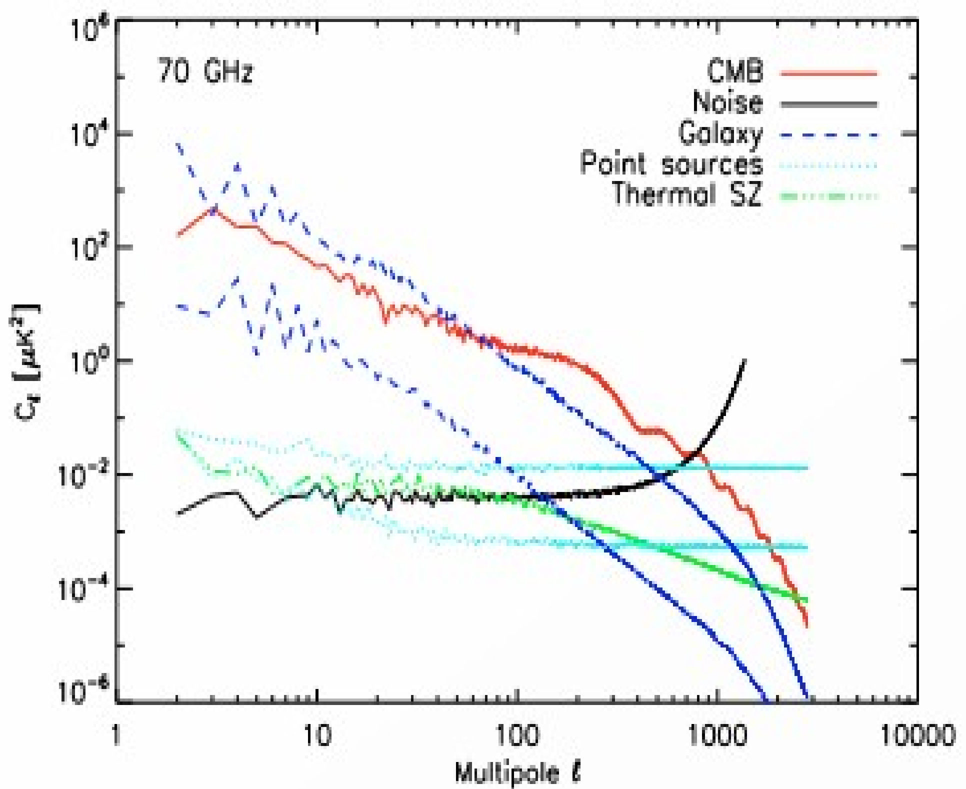
It demonstrated that (MM et al. 2010):
- **The bright samples are dominated by flat-spectrum sources**
- **Steep-spectra sources grew important at lower flux densities and higher frequencies**
- **The spectral behaviour cannot be easily described by a power law**
- **The spectral index distribution changes with flux density and frequency**
- **The median 1yr variability at 20GHz is 6.9% increasing with frequency** (Sadler et al. 2006)

Median and quartiles for spectral index distributions as function of flux density



Sources as CMB contaminants

Foregrounds power spectra (Leach et al. 2008)



Fluctuations due to radio sources are **the main contaminants of the CMB signal on scales smaller than 30 arcmin** (De Zotti et al. 1999, Toffolatti et al. 2005).

They need therefore to be carefully subtracted to avoid biasing the estimates of cosmological parameters.

Extrapolation from low frequencies are highly unreliable and modelization of source population is extremely challenging.

Planck offers a unique opportunity to carry out an unbiased investigation of the spectral properties of radio sources in a poorly explored frequency range, partially unaccessible from the ground before ALMA.

The Planck Early Release Compact Source Catalogue

The ERCSC (Planck collaboration 2011) is a list of high reliability (>90%) sources, both Galactic and extragalactic, derived from the data acquired by Planck between August 13 2009 and June 6 2010. (~1.6 full sky surveys). It consists of:

- **9 lists of sources, extracted independently from each of Planck's nine frequency channels**.
- 2 additional lists extracted using multi-channel criteria:
  - the Early Cold Cores catalogue (ECC), consists of galactic dense and cold cores, selected mainly on the basis of their temperature
  - the Early Sunyaev-Zeldovich catalogue (ESZ), consists of galaxy clusters selected by the spectral signature of the Sunyaev-Zeldovich effect.

Freq [GHz]	30	44	70	100	143	217	353	545	857
$\lambda(\mu m)$	10000	6818	4286	3000	2098	1382	850	550	350
Sky Coverage (%)	99.96	99.98	99.99	99.97	99.82	99.88	99.88	99.80	99.79
Beam FWHM (′)[a]	32.65	27.00	13.01	9.94	7.04	4.66	4.41	4.47	4.23
# of Sources	705	452	599	1381	1764	5470	6984	7223	8988
# of $\|b\| > 30°$ Sources	307	143	157	332	420	691	1123	2535	4513
$10\sigma^b$ (mJy)	1173	2286	2250	1061	750	807	1613	2074	2961
$10\sigma^c$ (mJy)	487	1023	673	500	328	280	249	471	813
Flux Density Limit[d] (mJy)	480	585	481	344	206	183	198	381	655

Notes. [a] The precise beam values are presented in Planck Collaboration (2011e) and Planck Collaboration (2011f). This table shows the values which were adopted for the ERCSC. [b] Flux density of the median $>10\sigma$ source at $|b| > 30°$ in the ERCSC where σ is the photometric uncertainty of the source. [c] Flux density of the faintest $>10\sigma$ source at $|b| > 30°$ in the ERCSC. [d] Faintest source at $|b| > 30°$ in the ERCSC.

The databases sensitivity

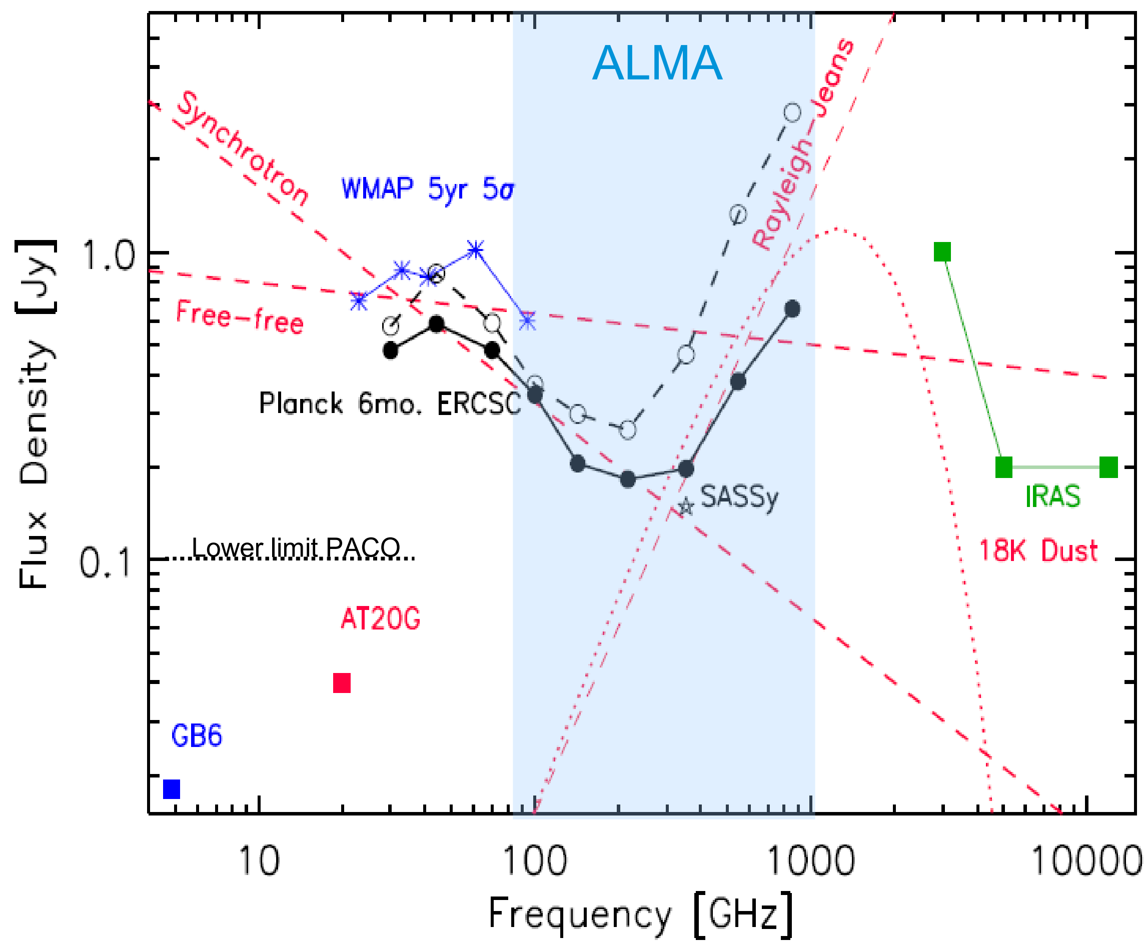
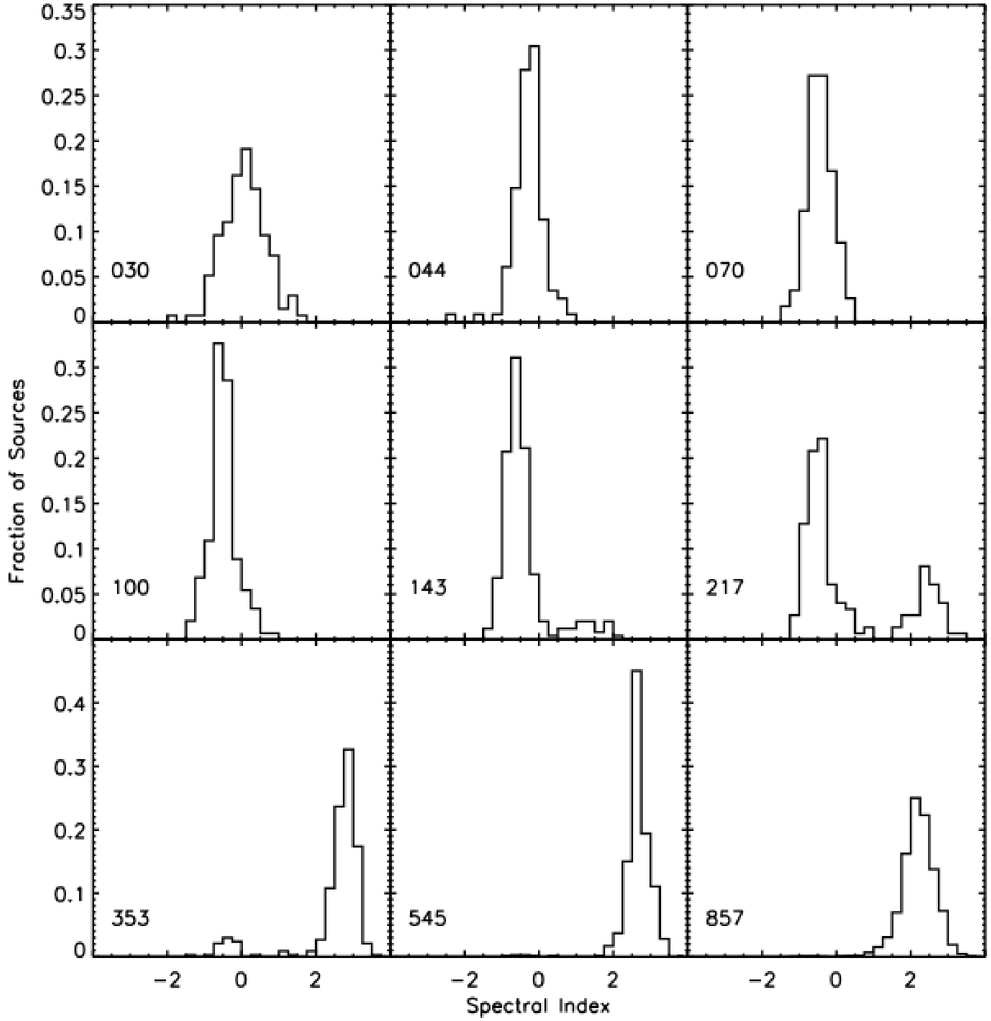
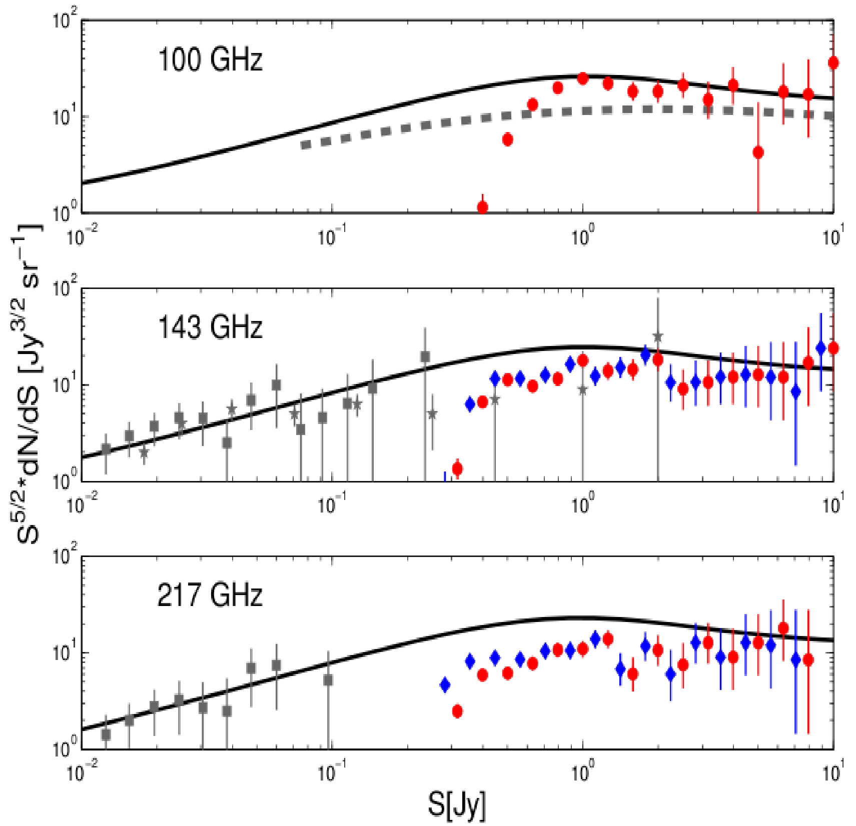


Fig. 5. The *Planck* ERCSC flux density limit both at $|b| < 10°$ (dashed black line) and at $|b| > 30°$ (solid black line) is shown relative to other wide area surveys. Also shown is the spectrum of known sources of foreground emission with red lines. The ERCSC sensitivity is worse in the Galactic Plane due to the strong contribution of ISM emission especially at submillimetre wavelengths. In the radio regime, the effect is smaller. The WMAP 5σ values are derived from the NEWPS catalogue of González-Nuevo et al. (2008).

The Planck Early Release Compact Source Catalogue



Spectral index distribution for ERCSC sources with dec>30deg and radio sources source counts up to 217GHz



A population of bright flat/inverted spectrum objects is suitable up to high frequencies.
An issue for ALMA is their size, not given by the confusion limited ERCSC.

The Planck ATCA Co-eval Observations database

The selection was done in the AT20G catalogue + long term observations data

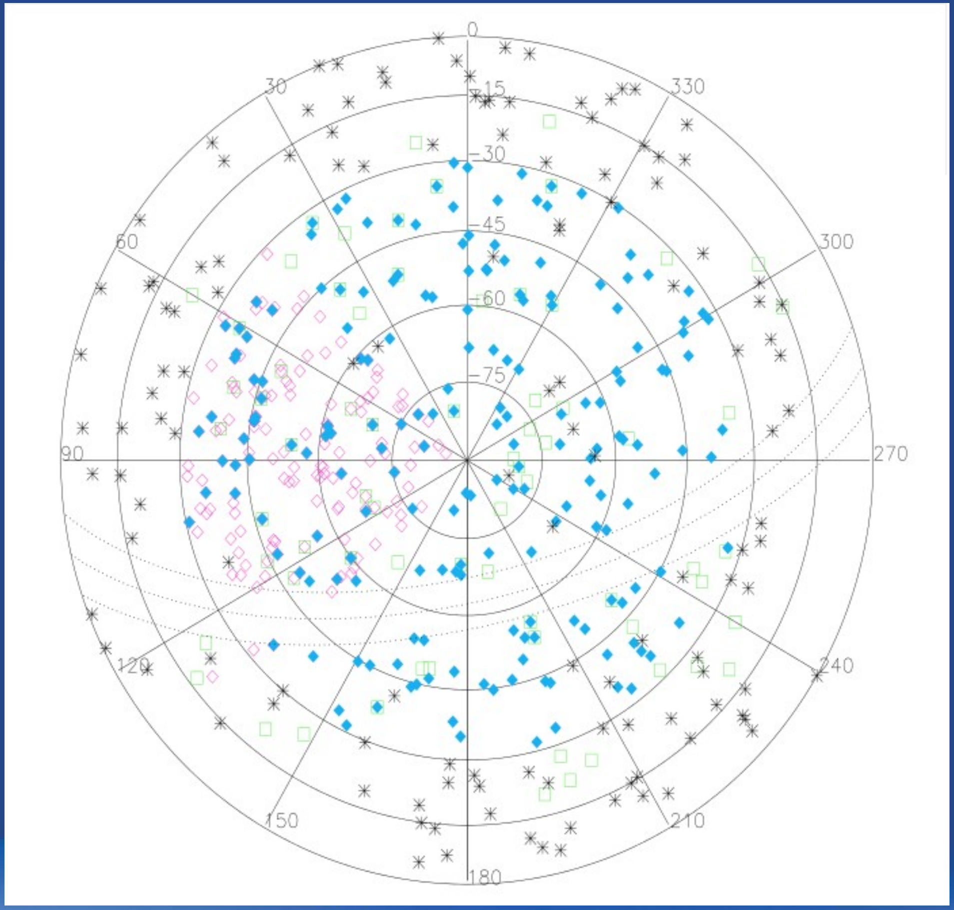
Complete sample of **inverted and upturning sources** between 5 and 20 GHz (69)

Complete sample of **flux density selected**:
162 S(@20GHz)>200 mJy (Bonavera et al. In prep)
189 S(@20GHz)>500 mJy (MM et al. 2011)

Variable sources (in ATCA observations)

63 **known Blazars** observed with APEX

Total number of sources: 483



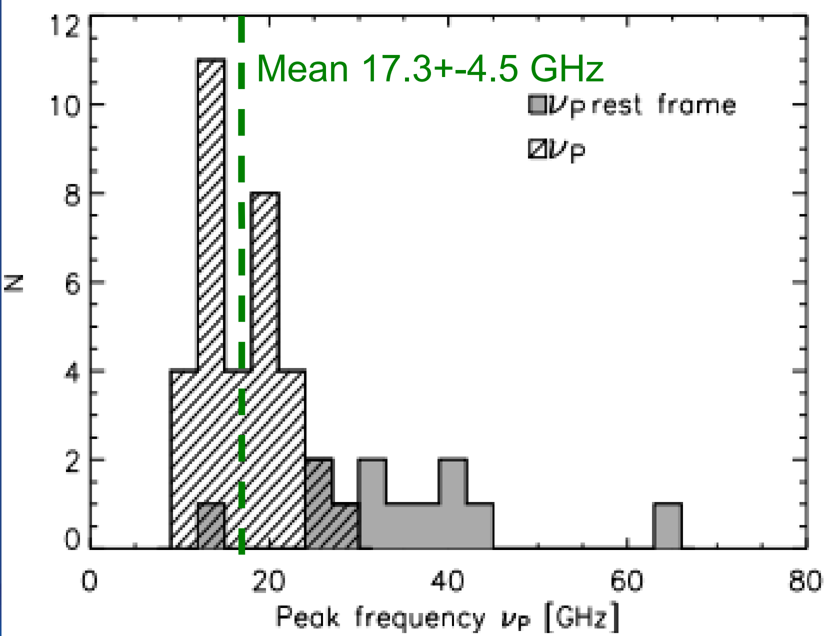
The Planck ATCA Co-eval Observations database

174 bright sample compact sources

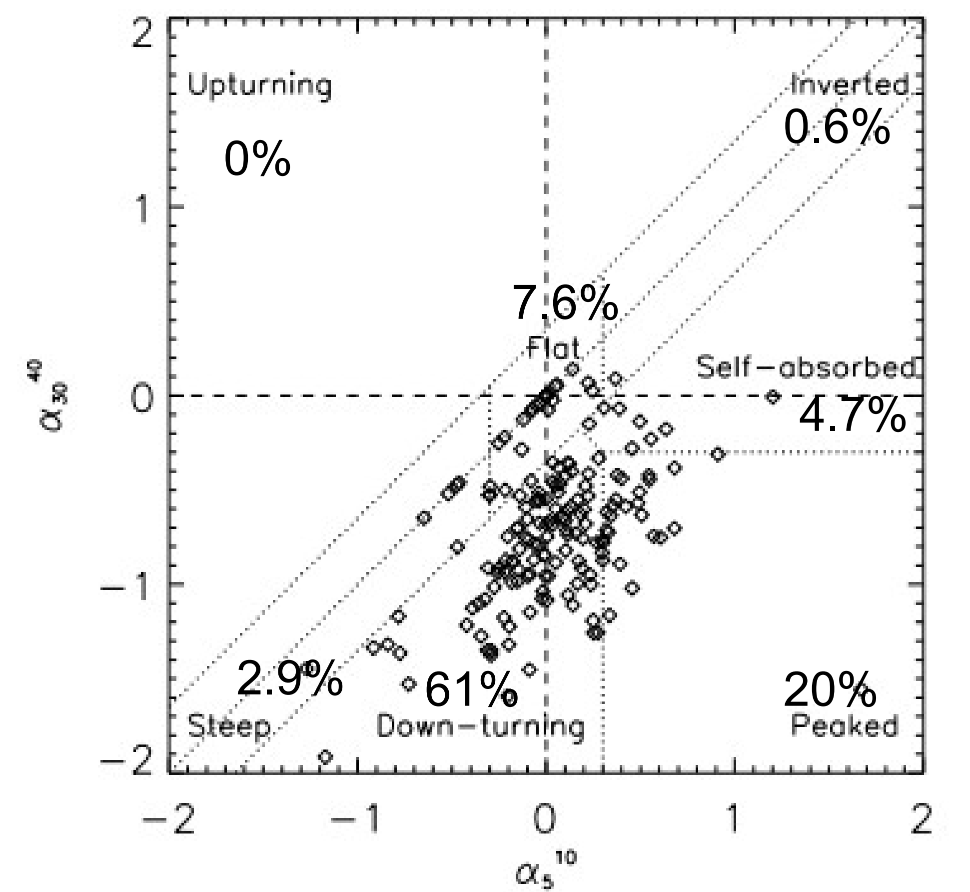
Fit with a double power law

$$S(\nu) = S_0/[(\nu/\nu_0)^{-a} + (\nu/\nu_0)^{-b}]$$

- estimation of spectral indices on the fit
- source classification
- estimation of peak frequency for the peaked



Distribution of peak frequency in obs and rest frame



Radio colour-colour plot between 5-10 and 30-40 GHz:

-11% single power law – mostly flat

- few low freq rising probably self-absorbed

- 20% peaking

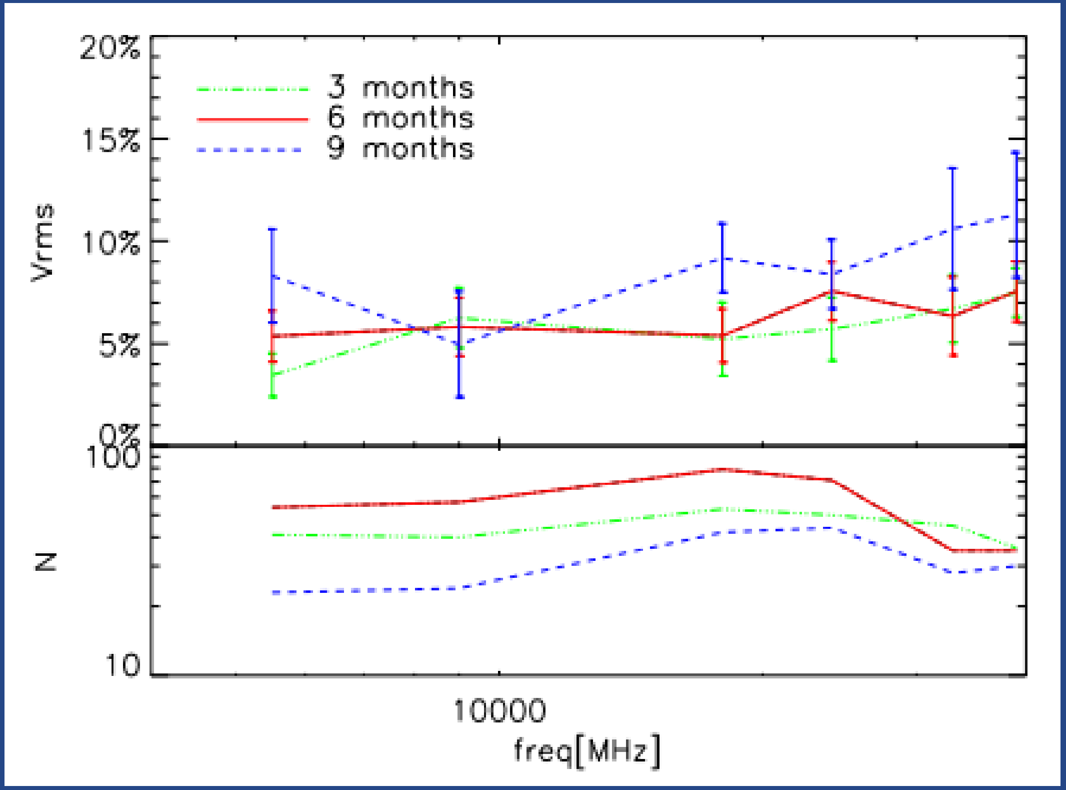
The Planck ATCA Co-eval Observations database

The variability index

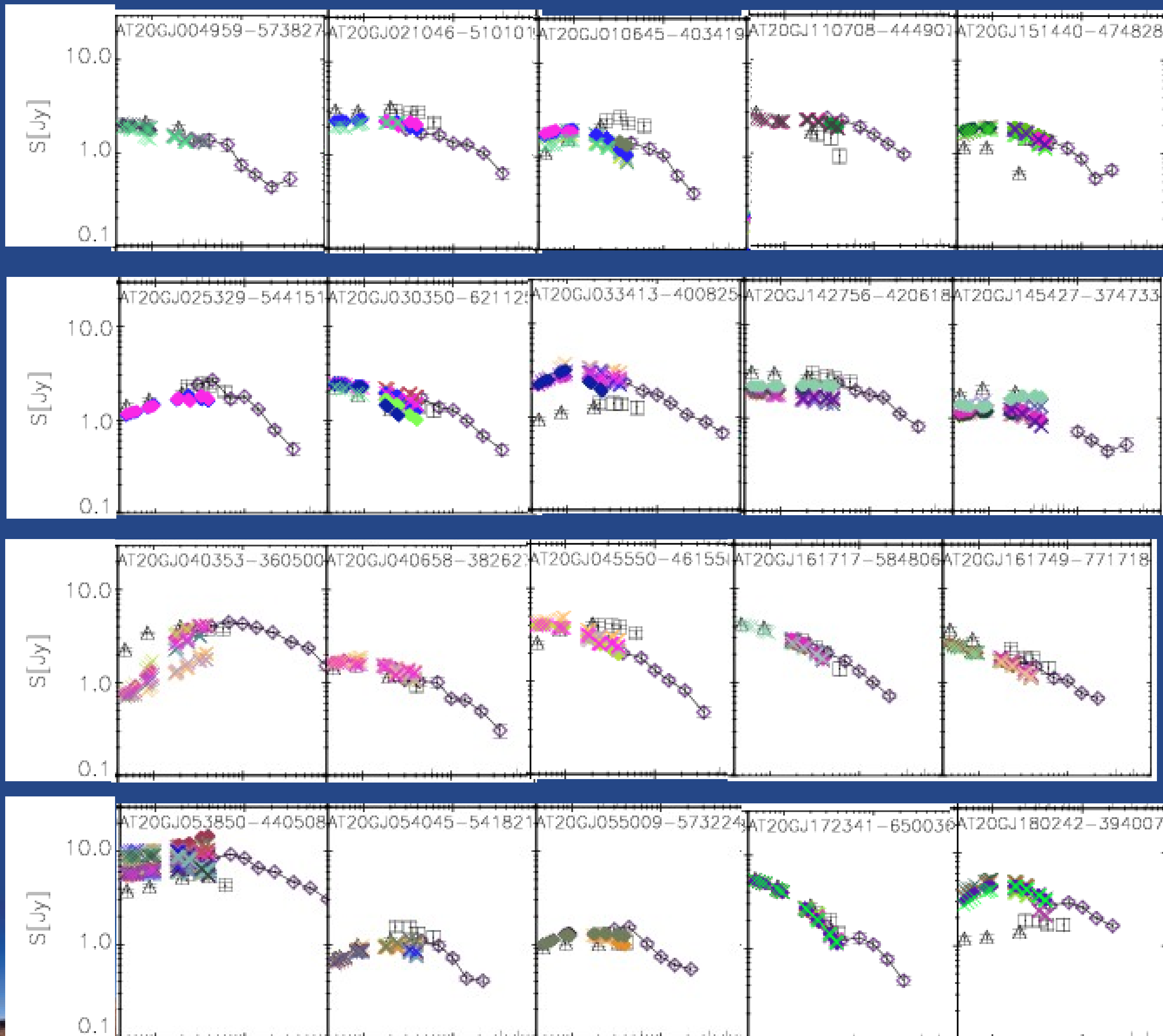
$$V_{\rm rms} = \frac{100}{\langle S \rangle} \sqrt{\frac{\sum [S_i - \langle S \rangle]^2 - \sum \sigma_i^2}{n}},$$

Has been estimated for the best couple of observations for each source.
We confirmed the trend towards an **increase of variability with frequency and a marginal indication of a larger variability on longer time scales**

The median variability at 20GHz on 9 months is about 9%



The Planck ATCA Co-eval Observations database



SEDs between 4.5 and 857 GHz

PACO, asterisks (different colours= different epochs)
ERCSC, diamonds
AT20G, triangle
NEWPS, squares

ATCA+Planck shows that these objects are pointlike and still bright enough to be suitable ALMA calibrators up tosubmm freqs.

(MM et al. 2010, Bonavera et al. 2011)

Amplitude

Goals	Convert raw data into antenna temperature scaled as above the atmosphere, relative cal), and from it to flux density (S) or surface brightness The corrected **visibility amplitude fluctuations on time scales of 1 second to 300 seconds shall not exceed 1% at frequencies less than 370 GHz, 3% at higher frequencies.**
Main Steps	**Relative calibration**: setup of attenuators and observations of known loads **Absolute calibration**: observation of astronomical objects with known or well modelized flux density. **10mJy sources are ok for freqs<250GHz, 100-250mJy are ok for freqs>350GHz**

Targets		PROS	CONS
	Planets and satellites	Fluxes known at <5% accuracy. $<S_{230GHz}>$=2.5Jy, Known variability Predictable polarisation	Size 1-45” (some baselines lost) But can bootstrap from secondary
	Asteroids	Small size <1” Good as secondary cals at high freqs 200km at 2.5AU = 0.1”, $<S_{230GHz}>$=50mJy	5% intraday flux variation due to rotation Polarized emission from the edges
	Stars (or HII)	Giants: 0.005”, $<S_{690GHz}>$=25mJy Long term variables: <0.1”, $<S_{690GHz}>$=1Jy Early type stars(MWC349) : 0.05” $<S_{230GHz}>$=50mJy, known spectral index, not variable	Stellar wind extended emission Low accuracy in spectral indices Models based on extrapolation from low frequency Too weak ones require too much time
	Quasars	Compact core <0.001” Ok as secondary	Mostly variable, varying spectral indices with frequency (and time). Extended structure in jets

Absolute Amplitude Calibration

- **ALMA absolute calibration goal is 1 %**

- Relative amplitude accuracy of 1 % is needed for high dynamic range images (up to 10^4).

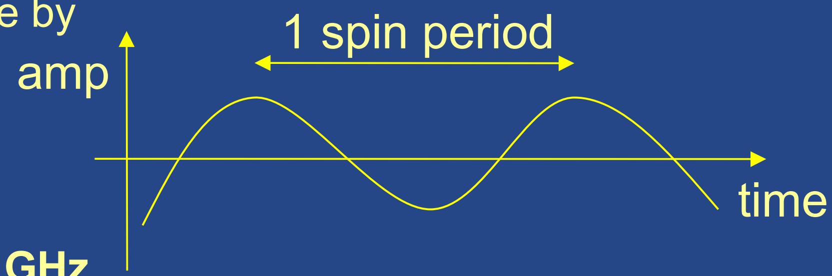
- So far, “**absolute” calibration is hardly ever performed**: most arrays (even at cm wavelengths) rely on so-called primary amplitude calibrators, which have been measured in an absolute way once (or twice) and are assumed constant since then.

- **At mm wavelengths, the primary calibrators are the solar system planets**. However, they have not yet been measured or modeled with better than 5% accuracy.

- At sub-mm wave-lengths, the situation is even worse. The IRAM interferometer currently achieves about 5 % accuracy at 3 mm, and 10 % at 1.3 mm.

Telescopes absolute & cross calibration

Absolute calibration of the Planck detectors (up to 353 GHz) is derived from the annual modulation of the CMB dipole by the Earth's orbit around the Sun.

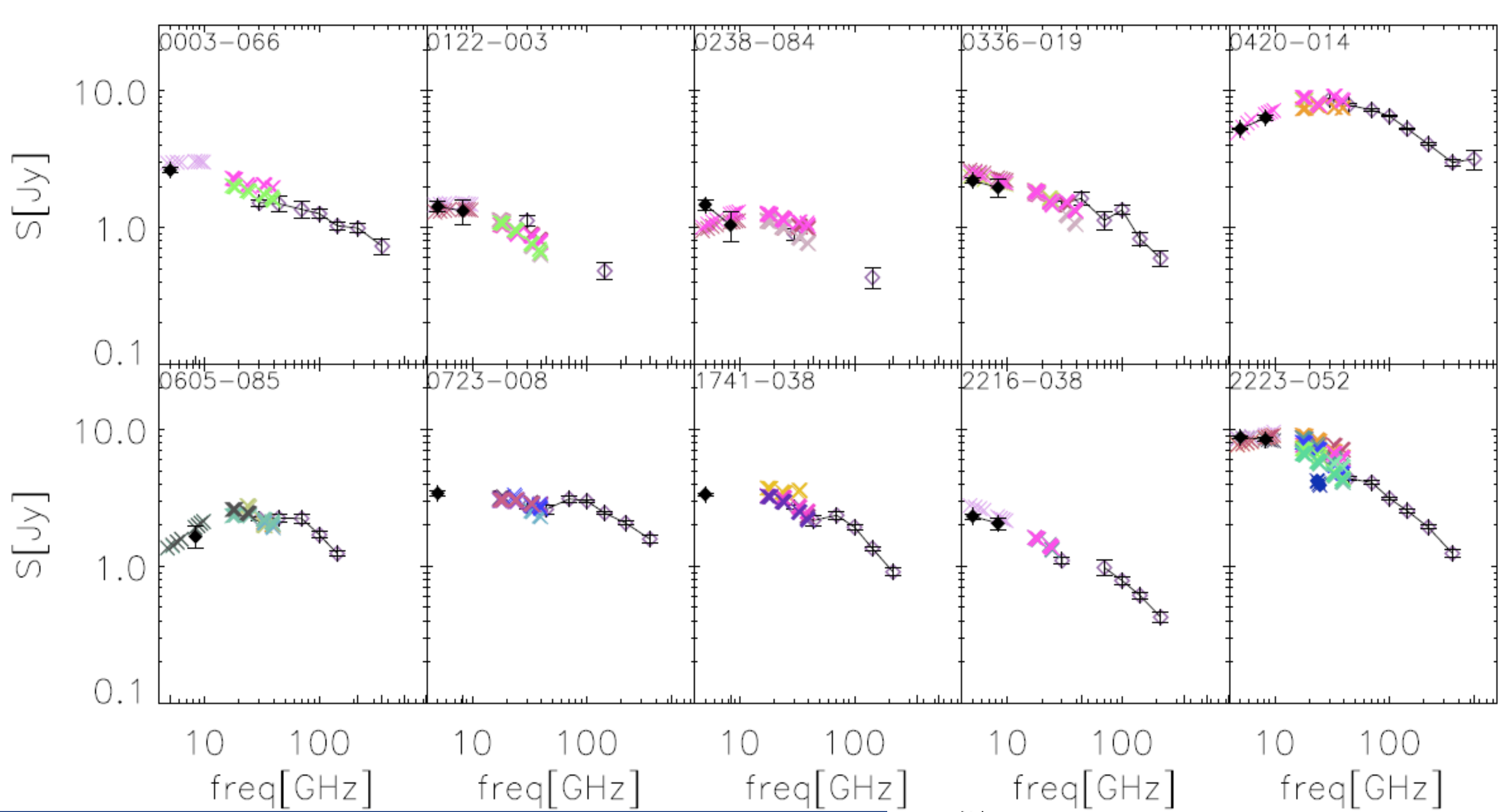


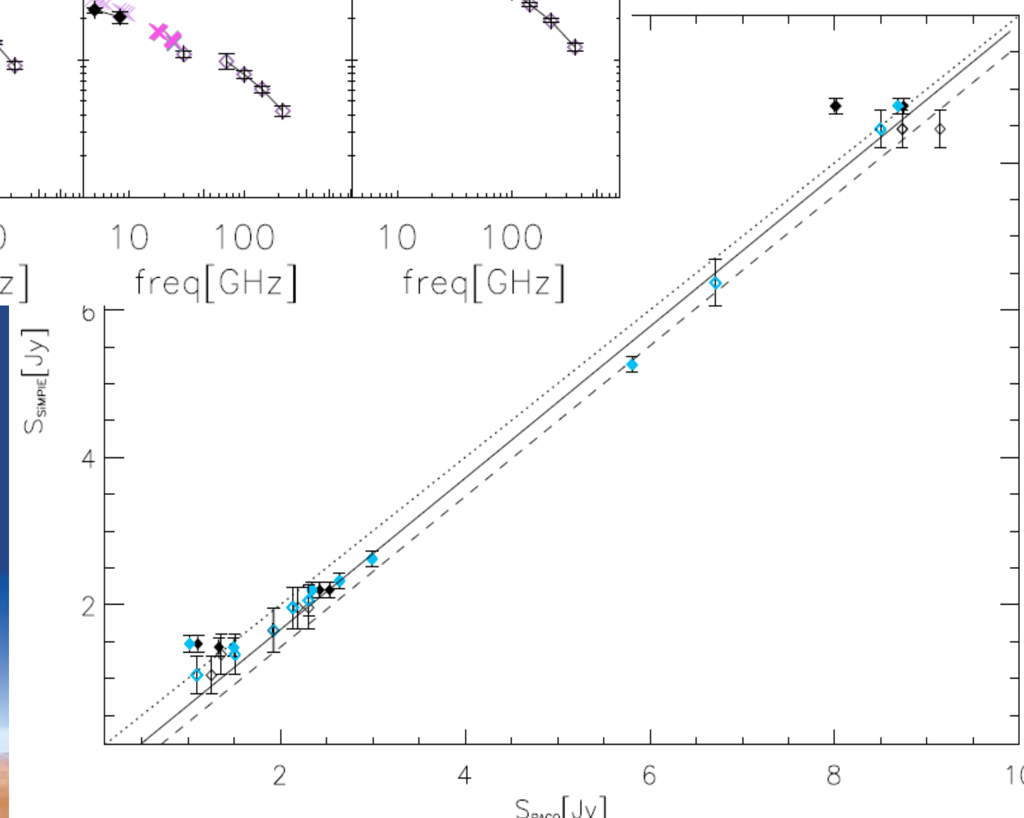
Absolute dipole measurement is obtained by differentiating along a spin period. Flux density calibration is expected as accurate as 1% up to 353 GHz

By exploiting the CMB dipole-based Planck calibration we can:
- establish the relative flux scale between Planck and ground-based tel at mm freq
- define an absolute calibration for all the telescope
The fluxes can be both transferred to the primary calibrators and used to **improve the models** for planets and calibrator sources

An observing project for cross-comparisons is observing about 20 bright sources simultaneously (i.e. within few days) with ATCA, Medicina and AMI at 3-6cm and 12mm, at 7mm between ATCA and VLA + Planck, at 3mm between ATCA, ALMA and CARMA + Planck.

SiMPIE+PACO+Planck





Cross-calibration of ATCA and the Medicina radiotelescope at 5 and 8GHz (...preiiminary results of the project)

Soon to come ALMA+ATCA at 3mm...

(Procopio et al. 2011)

ALMA calibration summary

Phase calibration

- **Bright unresolved sources (quasars from AT20G, Planck, PACO ...)**
- Fast switching on calibrators within 2° every few min
- Water vapour radiometry (emission at 183GHz atmospheric line, deduce phase fluctuations on 1s timescale)
- positional accuracy <1/10 synthesized beam-width

Flux density scale (primary)

- **Planets/moons can be used (Neptune, Titan)**
- Asteroids, Radio stars, quasars depends on quality of models, frequency, configuration...
- Initial expected accuracy <5% B3, <10% B6-7, <20% B9

Bandpass calibration

- **Bright unresolved sources (mostly quasars from Planck catalogues)**

Polarisation calibration

- **Well known polarized or unpolarized sources** (edges of planets/moons?). Models being defined.

ALMA next milestones

Science Verification

- On-going to observe known sources to validate the output of ALMA
- Data made public (in June): not for science

Early Science

- 31 March: call for proposals and ALMA Science Portal opening
- 1 June: opening of the archive for proposal submission
- 30 June: proposal submissione deadline
- 30 September 2011 - 30 June 2012:
  ES Phase 0 observations (500-700 h)

http://almascience.eso.org/call-for-proposals

	Full array	Early Science
Frequency range:	**10 bands 30-900 GHz**	**4 bands (3, 6, 7, 9)**
Antennas:	**50x12m +** ACA	**16x12m** (no ACA)
Sensitivity	**0.15 mJy in 1 min at 230 GHz**	**0.5 mJy in 1 min at 230 GHz**
Max baseline:	150**m-16km**	**2 configs: 18-125m** **36-400m**
Resolution:	**20 mas @ 230 GHz** **70 correlator modes**	**1000 mas @ 230 GHz** **20 correlator modes**
	Mosaic capability	**Limited mosaic** capabilities
	Pipeline reduction in Chile	Reduction @ ARCs

Care about resolution and sensitivity limits in ES

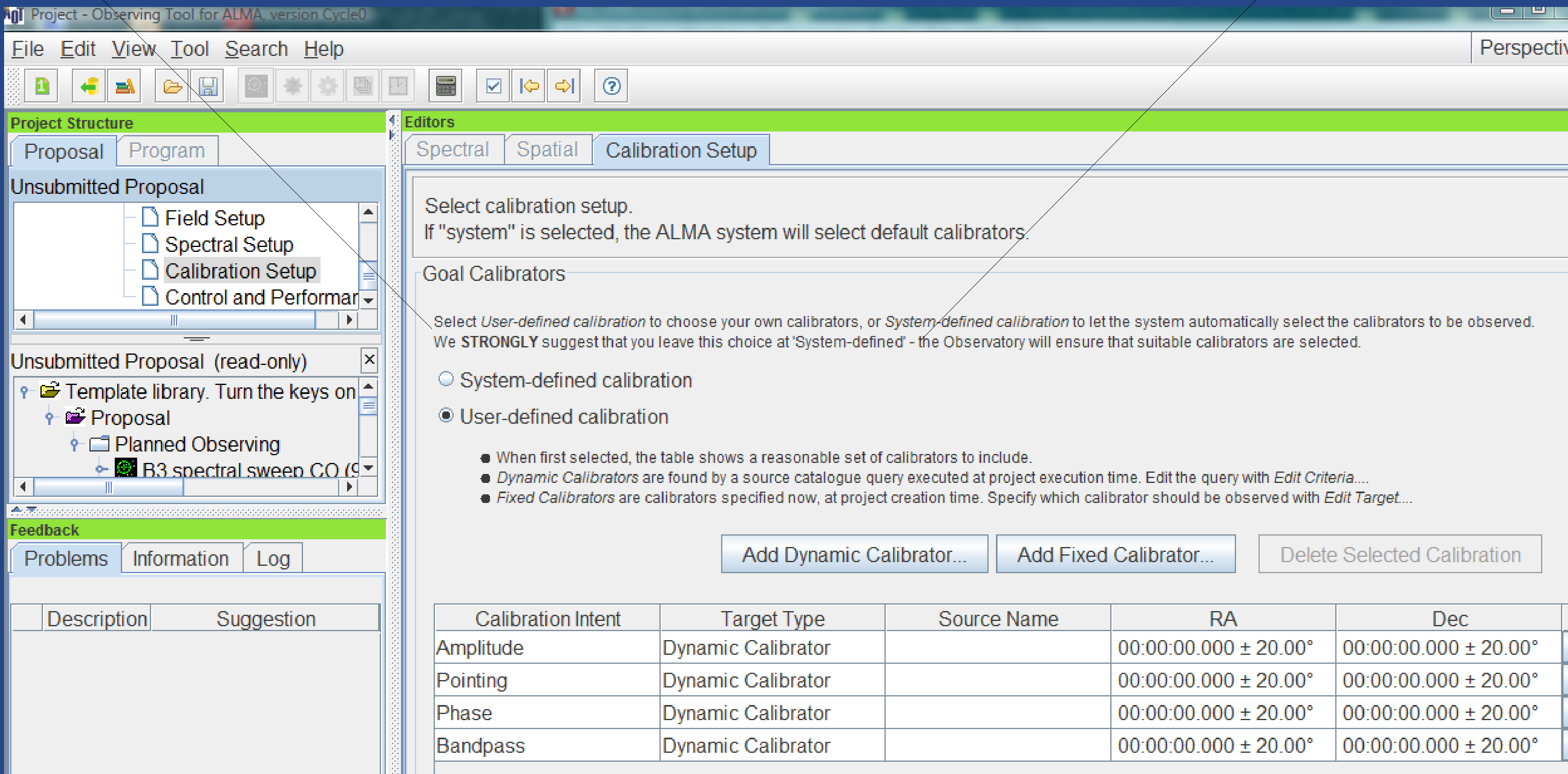
Band	Frequency [GHz]	Angular Resolution ["]	Maximum Scale ["]	T_{bc} [mK]	Flux [mJy]	T_{bl} [K]	Field of View ["]
Properties of the Compact Configuration (baselines of ~18 m to ~125 m)							
3	100	5.3	21	0.65	0.14	0.030	62
6	230	2.3	9	1.0	0.20	0.029	27
7	345	1.55	6	1.8	0.37	0.043	18
9	675	0.80	3	15	3.2	0.27	9
Properties of the Extended Configuration (baselines of ~36 m to ~400 m)							
3	100	1.56	10.5	7.6	0.14	0.35	62
6	230	0.68	4.5	11	0.20	0.34	27
7	345	0.45	3.0	20	0.37	0.50	18
9	675	0.23	1.5	175	3.2	3.1	9

Band	Lower frequency [GHz]	Upper frequency [GHz]	Type
3	84	116	2SB
6	211	275	2SB
7	275	373	2SB
9	602	720	DSB

The Calibration setup in the observing tool

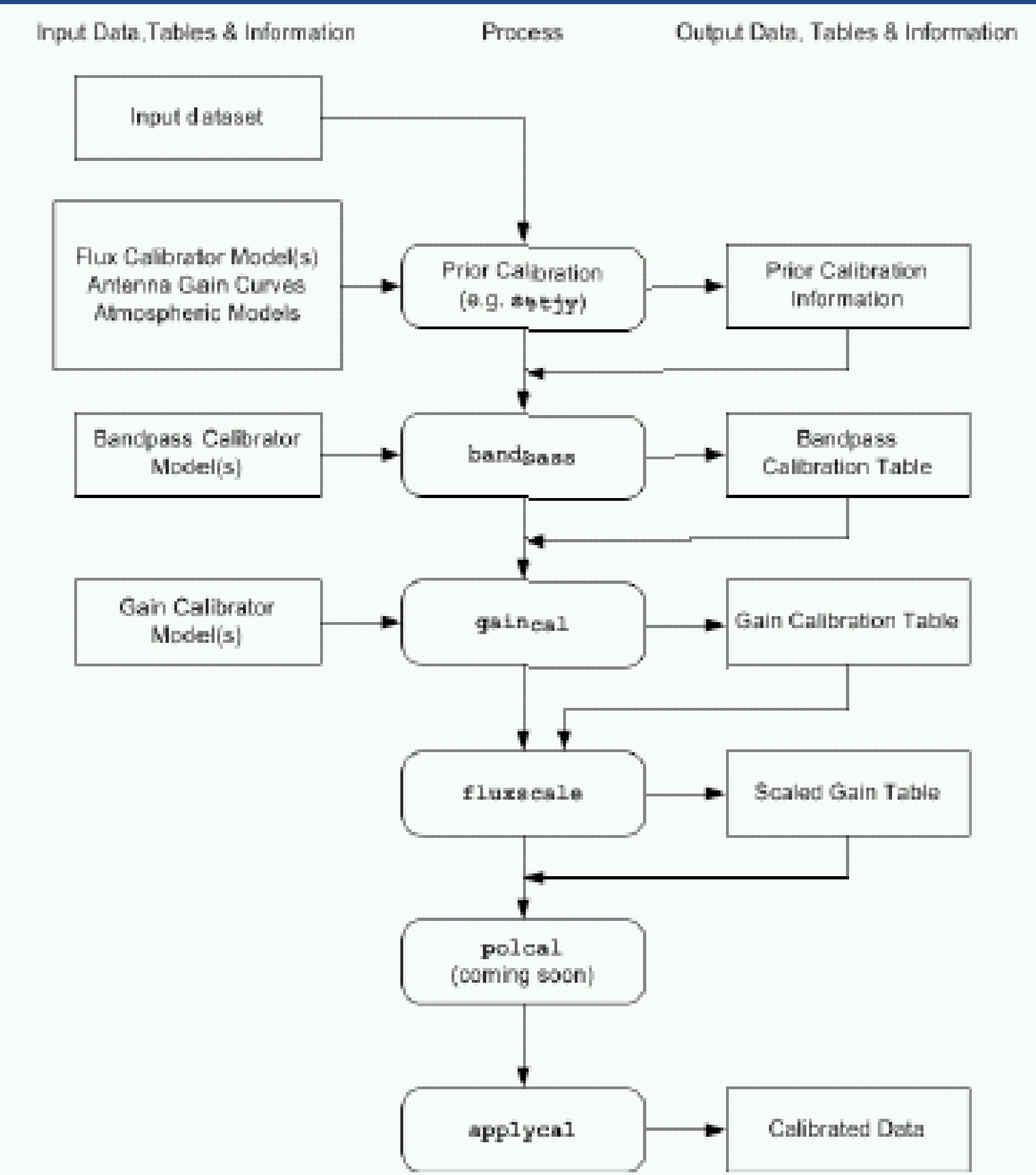
"...We STRONGLY suggest that you leave this choice at 'System-defined'..."

at least for the ES Phase 0



If user-defined calibration is necessary, care to justify it in the proposal!!!

Calibration scheme in CASA



For the ALMA full array
PIs will receive fully reduced data

For Early Science
"...ALMA staff will conduct quality assurance on ALMA data..."

Proposer experience in radio-mm interferometry is required to reduce Early Science data.

CASA scripting helps in calibration
Care for the huge amount of data!!!

Summary

ALMA calibration procedures are based on an iterative process that aims at improving the accuracy by:

- refining the databases through
    - investigating the existing datasets at mm-submm Freqs (AT20G, PACO, Planck, Herschel...)
    - feeding the databases with new targets
- cross-calibrating with other mm-submm facilities (PACO_2)
- getting absolute calibrations (Planck)

Main targets are

- bright pointlike quasars for bandpass & pointing
- pointlike quasars for phase
- planets/satellites edges or known polarization sources for polarisation
- planets/satellites (Neptune, Titan, Uranus) for flux density

Care of the limits for the ES which include also the fact that investogators should analyze their own data (ask to ARC for help).