VLBI Calibrator Surveys — the foundation of VLBA astrometry

Leonid Petrov *ADNET SYSTEMS Inc./NASA GSFC, USA*
Yury Y. Kovalev *Astro Space Center, Russia*
Ed Fomalont *NRAO, USA*

1 nrad $\approx$ 0.2 mas $\approx$ 14 μsec

The pyramid of VLBA astrometry

IV. Science: distances, kinematics, planet search, cosmology, etc.

III. Applications: differential astrometry; phase referencing.

II. Absolute astrometry: catalogue of calibrators.

I. Instrument monitoring: geodesy, EOP.

Differential astrometry: determines differences in positions.

Absolute astrometry: determines source coordinates, subject of 3 arbitrary constants, **and** instrument orientation.

Accuracy of **differential astrometry** is determined by:

- availability of the absolute position **catalogue**;
- proximity to the **calibrator**;
- accuracy of **calibrator** positions.

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Problem: to **improve** a catalogue of source positions.

Two possible strategies of a solution:

1. **Extensive way:** to observe a small subset of sources more often;

   Rationales:

   - the more observations, the more precise coordinates we get;
   - we can get time series analysis and get better characteristics of source positions

   Implementation: observing a list of 14–114 geodetic sources for 20 years, 10–100 times a year.

2. **Expansive way**: to observe more sources.

   Rationales:

   - many applications do not need a record-breaking accuracy, but need more sources;
   - big samples produce meaningful statistics, especially if a sample is complete.

   Implementation: observing a list of $\sim$5000 sources, many of them only once, in **VLBI astrometric surveys**.

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Major VLBI survey programs

Program	Epochs	# Exp	# sources
CDP, JPL, CRF	1979–1994	4500	965
RDV	1994–present	112	871
VCS, NPCS	1994–2007	27	3575
LCS	2008–present	3	317
GaPS	2006–present	3	327

Dense astrometric VLBI catalogue is needed for

- phase-referencing for differential astrometry (parallaxes, proper motion, positions of pulsars);
- phase-referencing for VLBI imaging of weak objects;
- identification of γ-ray objects;
- connection of positions at other wavelengths, f.e. GAIA;
- as targets for geodesy observations.

Technology of VLBI surveys: source selection

Source selection

- Selection of a (wide) pool of candidates;
- Computing the probability of detection of each source;
- Maximization of the target function.

The most difficult part is prediction of the correlated flux density.

We need to guess, whether a given source is

- extragalactic
- compact

Remember: an interferometer is a filter of spatial frequencies

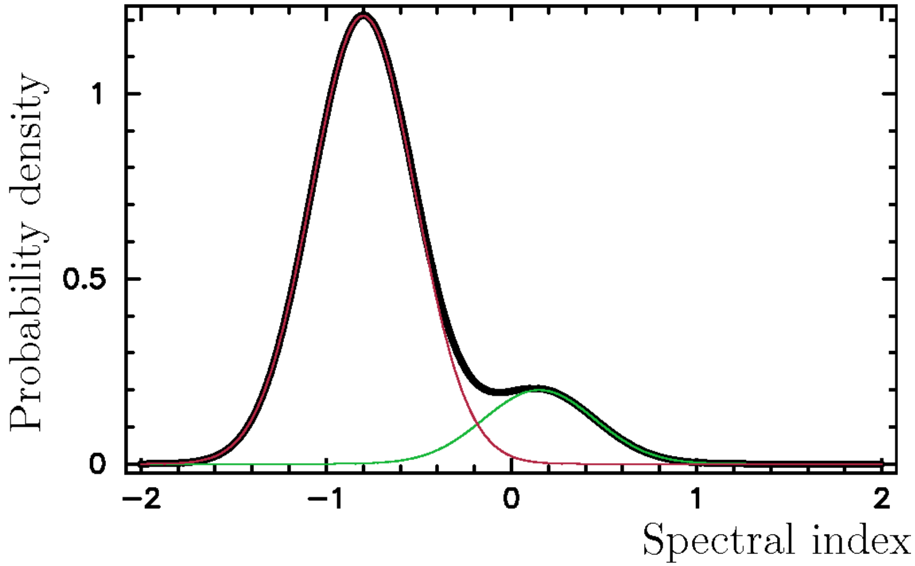
We need to predict F_{comp}/F_{tot} where F_{comp} is the correlated flux density in the range of spatial frequencies, the interferometer can see (5–500 Mλ).

How to do it?

Consider two source populations:

extended sources	$F_{comp}/F_{tot} < 0.01$
highly compact sources	$F_{comp}/F_{tot} \approx 0.1–0.9$

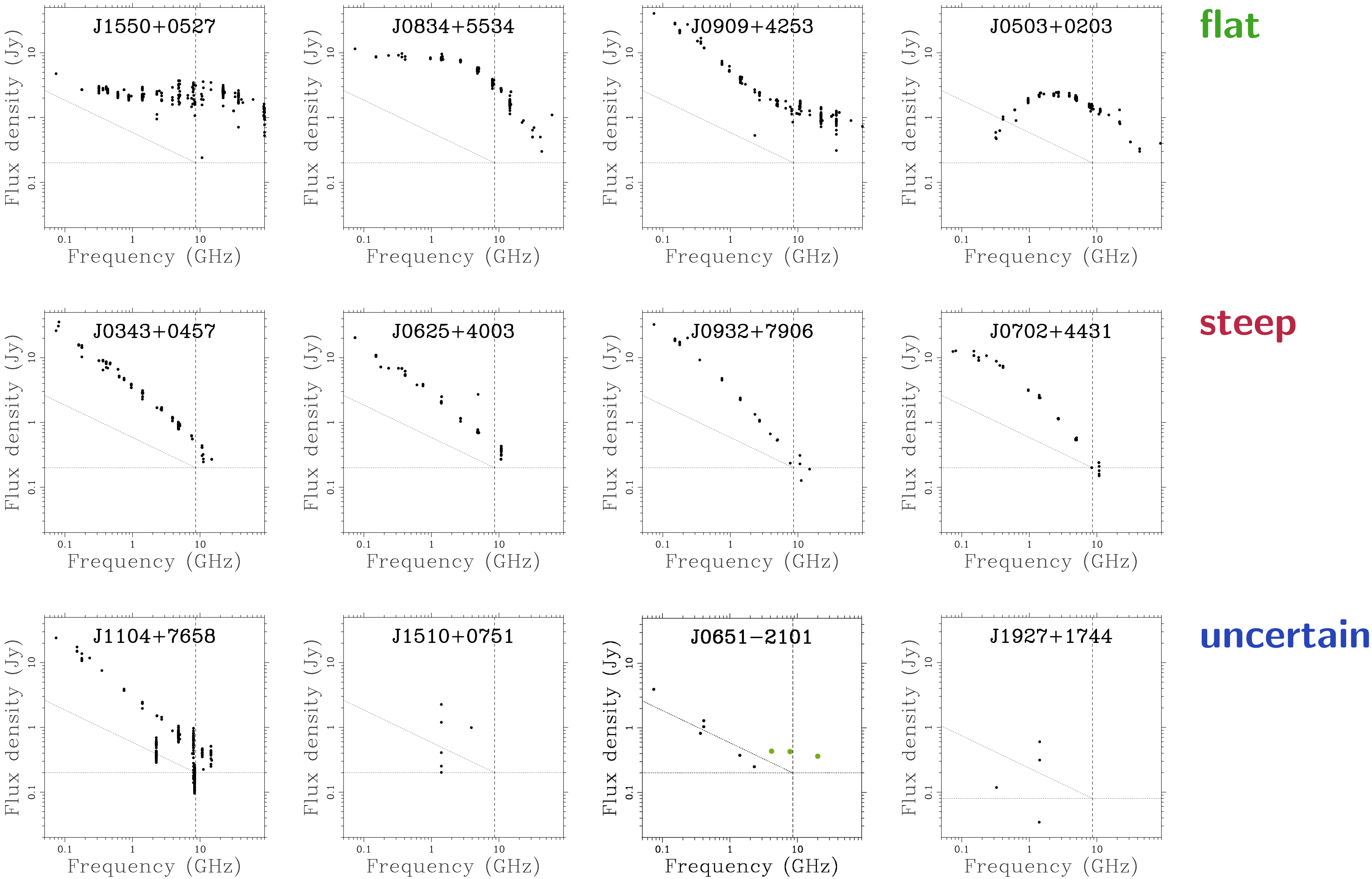
These populations *mostly* have a distinctive spectrum index α $(F \propto \nu^{+\alpha})$



The distribution over spectral index has two peaks:

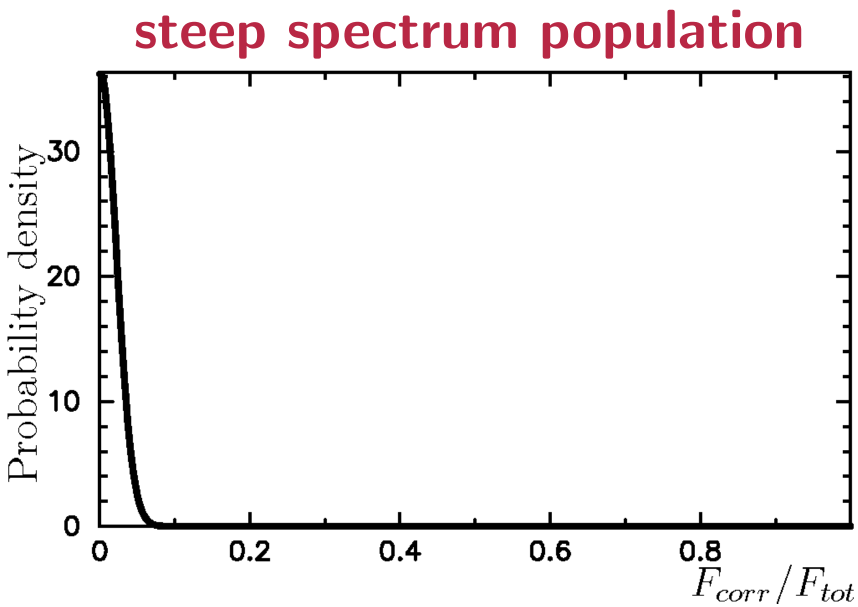
near $\alpha = -1$	**steep spectrum**
near $\alpha = \ \ 0$	**flat spectrum**

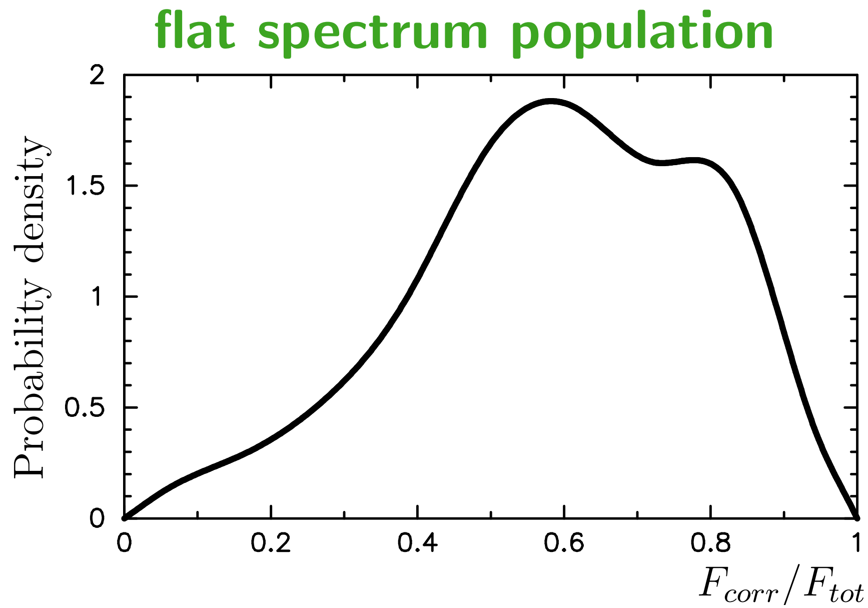
Typical source spectra from **CATS** (**http://cats.sao.ru**)



1 nrad ≈ 0.2 mas ≈ 14 μsec

The probability density distribution of F_{comp}/F_{tot} at $|b| = R_\oplus, F = 8$ GHz among the two source populations:





Problems:

- Spectrum is not always certain (errors, confusion, sources variability)
- Spectral information is incomplete for sources with $F_{8GHz} < 200$mJy and rare for sources with $F_{8GHz} < 100$mJy.

Alternative approach:

- select sources with known high frequency (20–100 GHz) flux densities.

Source selection strategy

Algorithm for predicting correlated flux density:

1. gather the spectrum (f.e. using super-catalogue CATS);
2. compute the spectral index and extrapolated flux density;
3. classify a source: **steep** or **flat**;
4. compute the cumulative probability density of F_{corr};
5. compute the cumulative probability density of the SNR;
6. compute the probability of detection.

Survey optimization:

1. formulate the target function, for example:
   - to maximize the total number of detected sources
   - to fill areas with low source density;
   - to reach completeness on correlated flux density
2. To find such a subset of candidate sources that maximize the target function.

Output: a source list and associated integration times.

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Scheduling survey observations

- find a sequence of scans that minimizes slewing time and satisfy antenna constraints
- Insert every 1–1.5 hours calibrator sources. The purpose of calibrators:
  - to be able to solve for atmosphere path delay in zenith
  - to tie the positions with the core of frequently observed sources (absolutization).

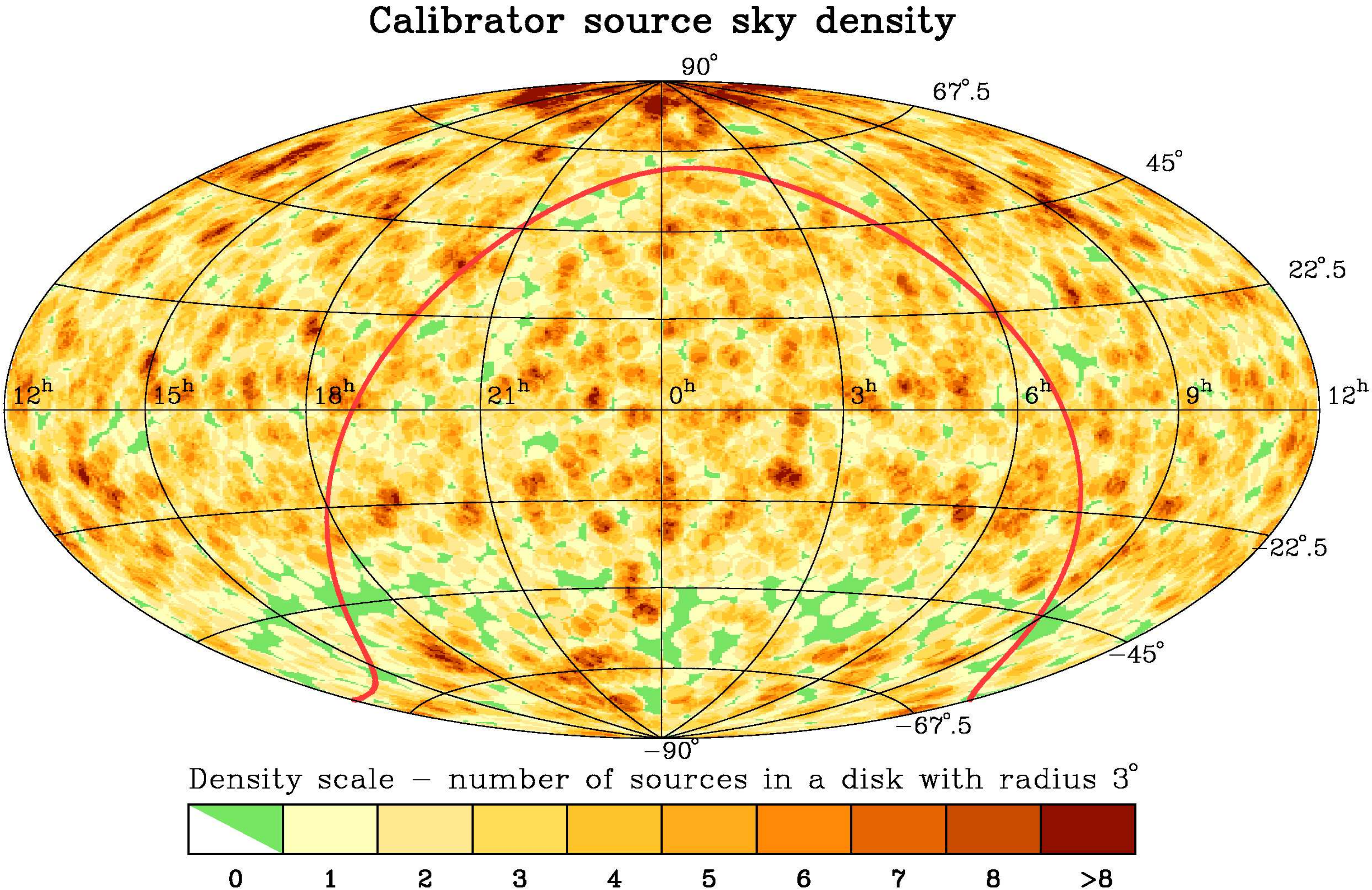
  NB: The source list always **must** have an overlap.

Analysis of observations

- Fringe fitting;
- Group delay ambiguitiy resolution;
- Outlier elimination;
- Global LSQ solution using **all** available observations, including the new one, for estimating sources, positions, station positions, EOP, and more than 1 million nuisance parameters.

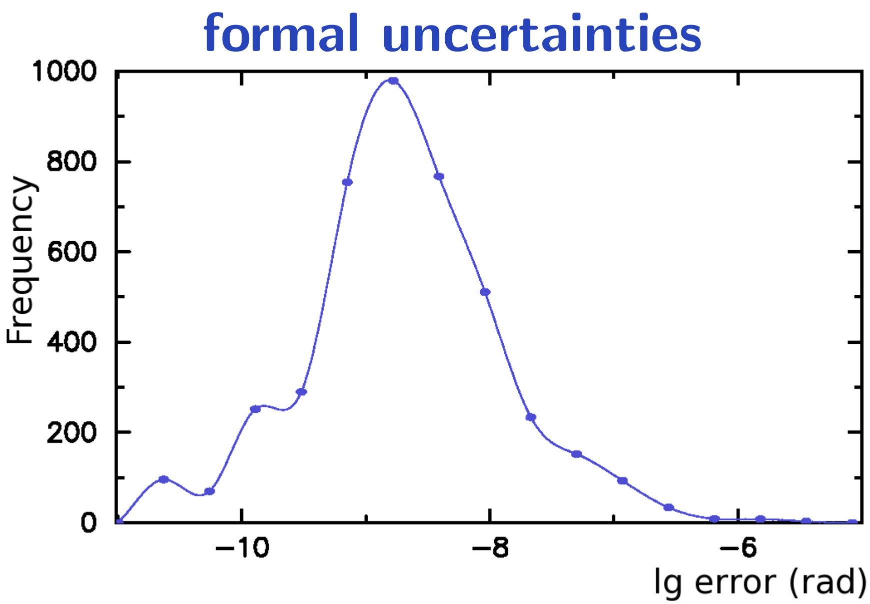
NB: VLBI source catalogues are made **incrementally**.

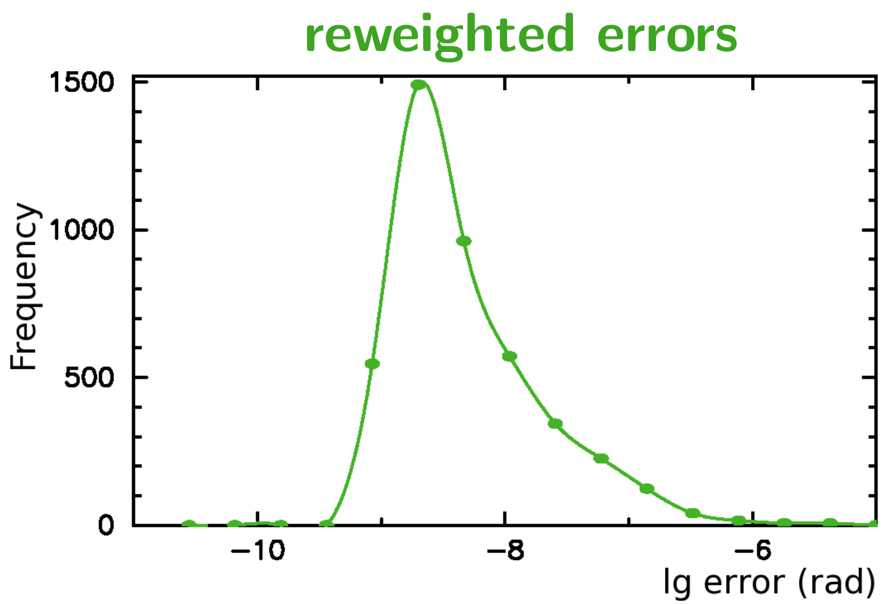
Results: 2009b_astro (http://astrogeo.org/rfc)



4337 objects

Position error distribution





Reweighting:

$$\sigma(\alpha)_{new} = \sqrt{(r\sigma(\alpha))^2 + F_\alpha(\delta)^2}$$

$$\sigma(\delta)_{new} = \sqrt{(r\sigma(\delta))^2 + F_\delta(\delta)^2}$$

Reweighted error is < 5 nrad for 83% objects, < 25 nrad for 90% objects.

Error floor is around 1 nrad.

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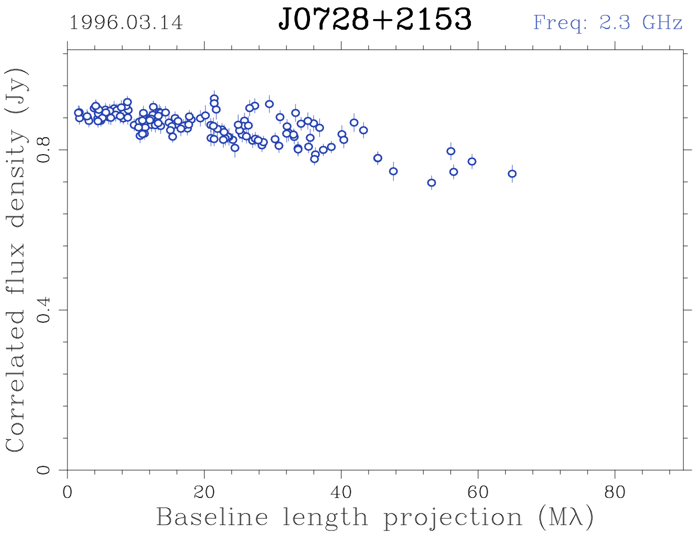
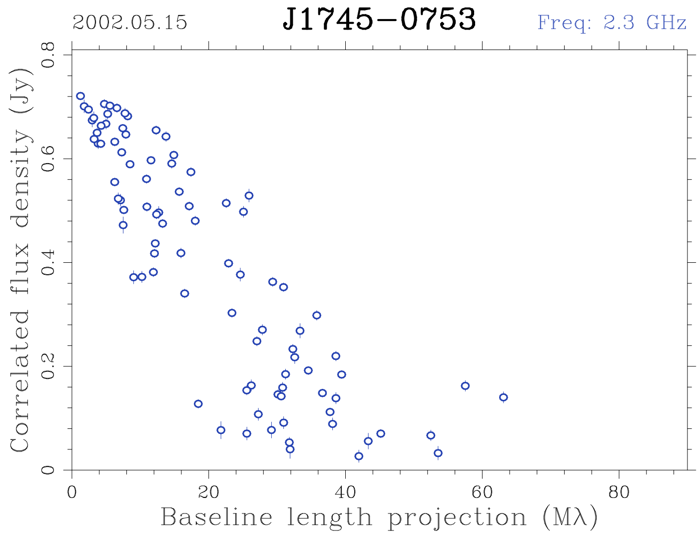
Factors that affect errors

- whether observations at long baseline have been scheduled;
- whether observations at long baseline yield detections;
- whether a source has been observed and/or detected at one or two bands;
- whether a source is observed predominantly at low elevations;
- how many detections have been gathered:
  - 1 — useless;
  - 2–8 — unreliable positions due to group delay ambiguities;
  - 9–50 — moderate. Error $\sim 1/\sqrt{n}$;
  - 51–500 — good. Error law deviates from $\sim 1/\sqrt{n}$;
  - > 500 — error floor is reached.





Major surveys

- **CDP, JPL, IVS, Navnet**. 1979–present. ~ 4500 experiments. S/X. Instrument: global VLBI geodesy network. Main goal: geodesy. Geodesy list: 14–114 sources, astrometric list 100–300 sources, occasional objects: 300–500 sources. Images are not available.

- **RDV**. 1994–present. 114(112) experiments. Instrument: VLBA. S/X. Main goals: monitoring of VLBA network, monitoring of 300–400 sources. In addition, 50–90 sources per year are added on an ad hock basis. Images are available for 85% sources.

- **VCS**. 1994–2007. 24(24) experiments. Instrument: VLBA. S/X. Main goals: astrometric catalogue at 1–10 nrad accuracy level of 3000–4000 sources. All three strategies were used: first phase "take them all", second phase "fill holes", third phase: "reach completeness" on a 3/4 of the celestial sphere. Images are available for all the sources.

- **NPCS**. 2006, 3(0) experiments. Instrument: VLBA. S/X. Goal: study the steep spectrum source population. All sources, 502 objects, at 0.2 srad region with $F_{1.4GHz} > 200$mJy were observed. Images will be available for all the sources. 219 out of 502 objects were detected.

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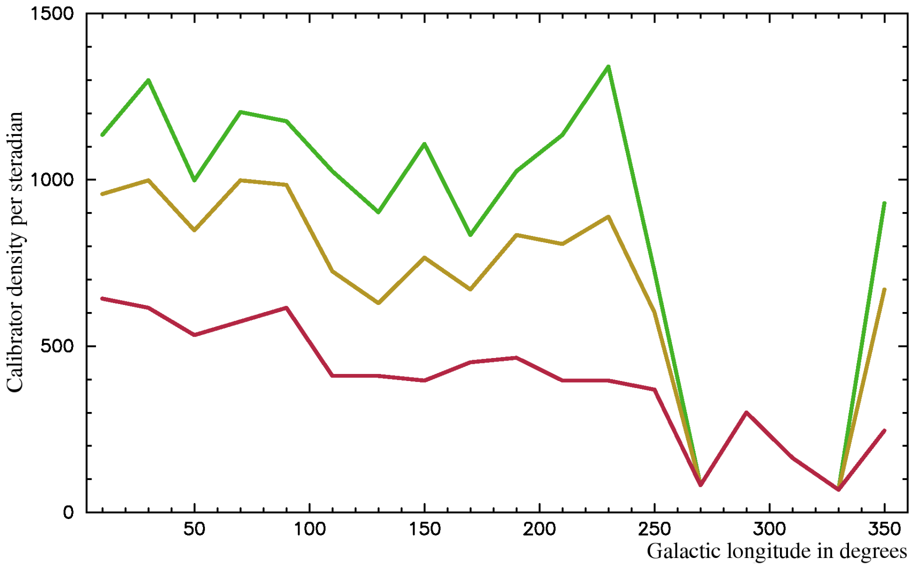
- **KQ**. 2002–present. 15(15) experiments. Instrument: VLBA. K-band (22 GHz). Images are available for the majority of sources.

- **GaPS**. 2006, 3(0) experiments. Instrument: VLBA. K-band (22 GHz). Goal: to increase the astrometric catalogue density at the Galactic plane. 327 out of 490 sources were detected. Images of the majority of detected sources will be available.

Ongoing projects (observing time has been approved)

- **GAIA astrometric link** 2008–? 70–200 objects. Goal: to get absolute coordinates of radio sources associated with optically bright quasars.
- **EVN-GaPS** November 2009, 2 sessions, 613 objects. Instrument: EVN, K-band. Goal: increase the density of astrometric catalogue at $|b| < 6°$.

  The plot shows the source density per steradian in various galactic longitude zones. **The lower red line** shows the current density, in April 2009, **the middle orange line** shows the predicted density under a conservative assumption of the detection rate of 60%, and **the upper green line** shows the predicted density assuming 100% detection rate.

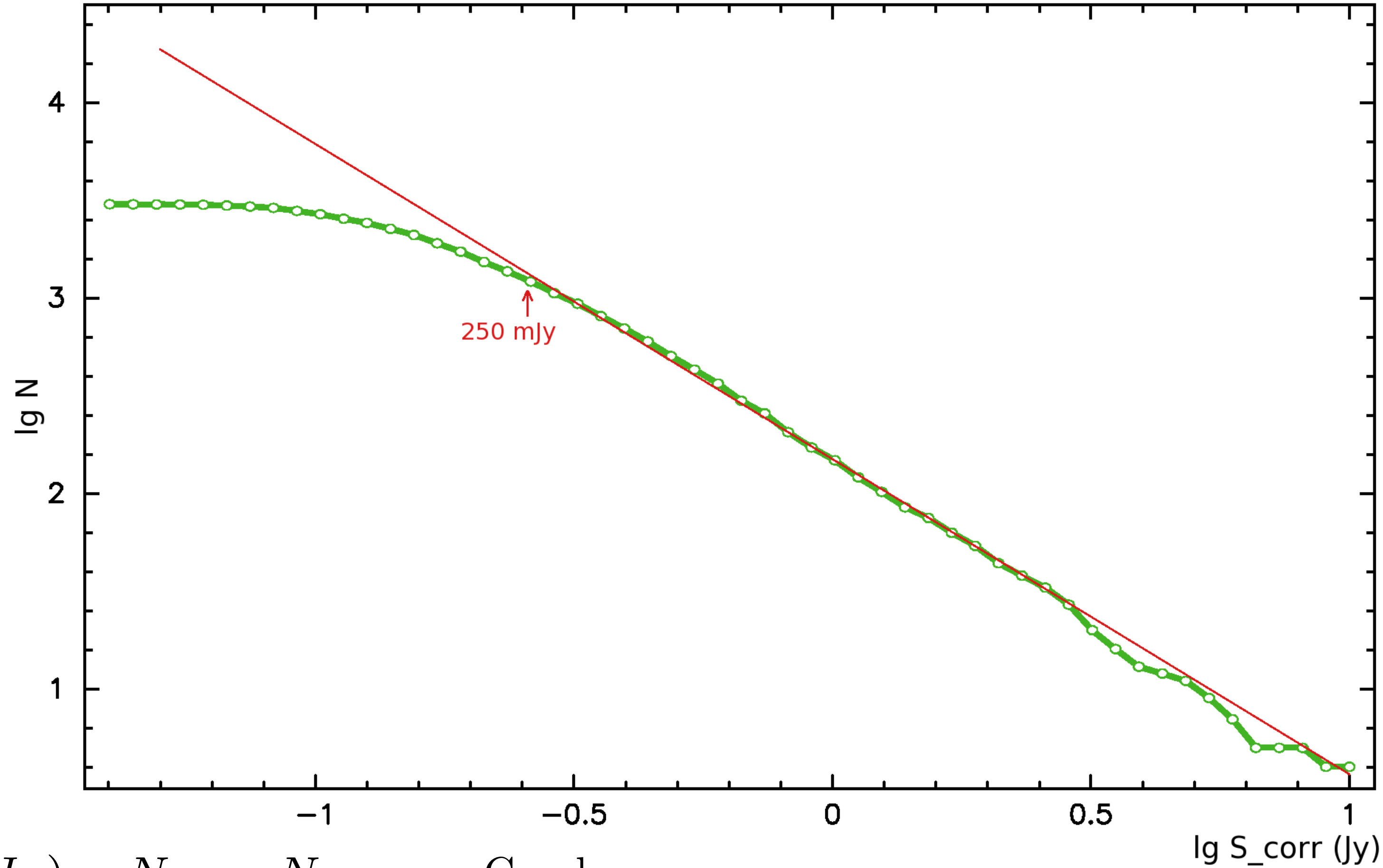


- **LCS** 2008–2010. Instrument: LBA, 8(3) sessions, 900(317) objects. X-band. Goal: to increase the astrometric catalogue density at the declination zone $[-90°, -40°]$ in order to match the northern hemisphere.

On-going analysis improvement development

- Migration from AIPS to the custom fringing software;
- Using numerical weather models for modeling troposphere path delay and atmospheric extinction;
- Using ionosphere models for processing single-band data.

VLBI Calibrator list completeness for $\delta > -30°$ at 8.6 GHz



$F_{corr}(Jy)$	N_{obs}	N_{pred}	Cmpl
0.050	3011	18700	16%
0.075	2937	9800	30%
0.100	2708	6100	44%
0.150	2154	3200	67%
0.200	1639	2000	$>$ 86%
0.250	1278	1350	$>$ 96%

Hunt for more calibrators

How much time is needed?

The number of target sources and the baseline sensitivity for a 24^h absolute astrometry experiment.

Int. time	N_{src}	256 Mbps SNR=10		4096 Mbps SNR=10	
		S/X	K	S/X	K
2^{m}	**220**	**66 mJy**	**50 mJy**	16 mJy	13 mJy
1^m	330	90 mJy	70 mJy	22 mJy	18 mJy
30^{s}	**470**	130 mJy	100 mJy	**32 mJy**	**26 mJy**

How many candidate sources remained?

The number of known flat-spectrum sources ($\alpha > -0.5$)

Flux 8.6 GHz	$S_{max} > 1.4$ GHz	$S_{max} > 3$ GHz		$S_{max} > 8$ GHz	
200 mJy	**4 070**	**3 900**	(**1 400**)	**2 980**	(**300**)
100 mJy	**9 170**	**8 500**	(**4 500**)	**5 910**	(**2 200**)
50 mJy	**18 400**	**16 300**	(**11 250**)	**9 530**	(**5 500**)
30 mJy	**29 100**	**22 500**	(**17 260**)	**10 980**	(**7 100**)

Blue: the total number
Green: the number of sources not yet observed

For comparison: the prorated number of sources in NVSS, except $|b| < 6°$.

Flux 1.4 GHz	$S_{max} > 1.4$ GHz
200 mJy	24 900
100 mJy	61 900
50 mJy	136 730
30 mJy	228 490

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Calibrator search efficiency

I. If to observe all sources. VLBA Northern Polar Cap survey:

All sources from NVSS $S_{1.4GHz} > 200$ mJy, $\delta > +75^\circ$ were observed with VLBA, 496 target objects.

	$S_{corr} > 50$mJy		$S_{corr} > 100$mJy	
Baselines $<$ 1000 km	57	11.5%	43	8.7%
Baselines $>$ 6000 km	38	7.7%	29	5.8%

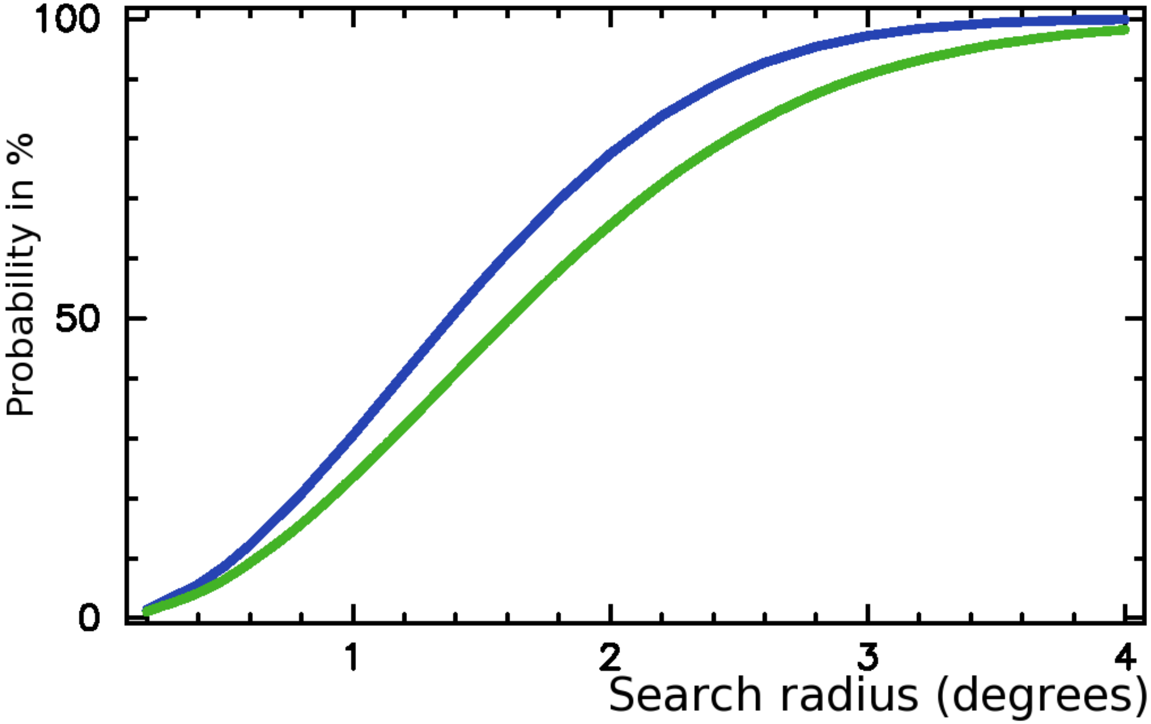
II. If to observe flat-spectrum sources.
Search efficiency ($S_{corr} > 50$ mJy)

With reliable spectrum:	80%
With unreliable spectrum:	50–80%
No spectrum $S_{1.4GHz}$	11%

Rough estimate of efficiency:

next	1000	sources	80%
next	5000	sources	70%
next	10000	sources	60%

Probability to find a calibrator for $\delta > -40^\circ$



$S_{corr} > 50$ mJy at L > 1000 km

$S_{corr} > 50$ mJy at L > 6000 km

	All sky: $\delta > -30^\circ$		**Gal. plane:** $\lvert b\rvert < 6^\circ, \delta > -40^\circ$	
			Today	Mid 2010
1°	23.0%	30.0%	28.7%	47.6%
2°	64.7%	76.9%	76.0%	90.3%
3°	90.2%	97.1%	96.8%	99.0%
4°	98.1%	99.9%	99.9%	100.0%

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How many new calibrators would improve the probability?

All sky

	1°			2°			3°		
50%	3 740	4 420	11^d	—	—		—	—	
67%	8 500	9 400	28^d	—	—		—	—	
80%	13 600	15 000	42^d	510	1 300	$1.5–4^d$	—	—	
90%	21 000	22 000	70^d	2 380	3 150	$7–9^d$	—	—	
95%	35 000	36 000	120^d	4 420	5 270	$13–16^d$	—	340	1^d

Galactic plane $(|b| < 6^\circ, \ \delta > -40^\circ)$

	1°		2°		3°
67%	500	$1^d.5$		—	—
80%	1 000	3^d		—	—
90%	1 700	6^d		—	—
95%	2 200	8^d	100	$0^d.3$	—

Ecliptic plane $(\ |\beta| < 7^\circ \ )$

	1°		2°		3°
67%	1 200	4^d		—	—
80%	2 000	6^d	80	$0^d.2$	—
90%	3 200	11^d	340	1^d	—
95%	4 300	15^d	640	2^d	—

Estimates of the number of 24^h observing sessions at 4096 Mbps.

S_{corr} > **50 mJy at L > 1000 km**

S_{corr} > **50 mJy at L > 6000 km**

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Strategies for getting more calibrators

I Full sky survey

Pro:
- Gives a complete sample for statistics studies
- Suitable for all needs

Contra:
- high cost

II Survey in a zone of special interest (f.e. Galactic plane)

Pro:
- reduces cost

Contra:
- zone of interest may be conflicting
- zone of interest may be too wide

III Observing candidate sources near potential targets

Pro:
- sources are observed only there where they are needed for phase referencing

Contra:
- how to guess **today** what will be an interesting target **tomorrow**?
- requires accumulation of large lists
- requires coordination among different groups

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Summary

- Today VLBI surveys provide positions of 4337 sources with accuracies 1–5 nrad for 83% objects and 1–25 nrad for 90% objects;
- The catalogue is approaching to completeness at a level of 200 mJy for $\delta \in [-30^\circ, +90^\circ]$.
- Images in FITS format, in total 26,486 brightness distributions of 4191 compact sources, are available.
- Further growth of the VLBI Calibrator List can go in three directions. Estimates of necessary resources are available.

Up to date the source position catalogue, search engine, images are available at
http://astrogeo.org/rfc

Tables and figures from this presentation are available at
http://astrogeo.org/calib

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