



# Primary data processing in Space-VLBI missions ASC Correlator

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On behalf of Astro Space Center (ASC LPI), Data Processing Department

## Correlator Overview

ASC FX Correlator comprises well recognized and useful functions needed for everyday correlation:

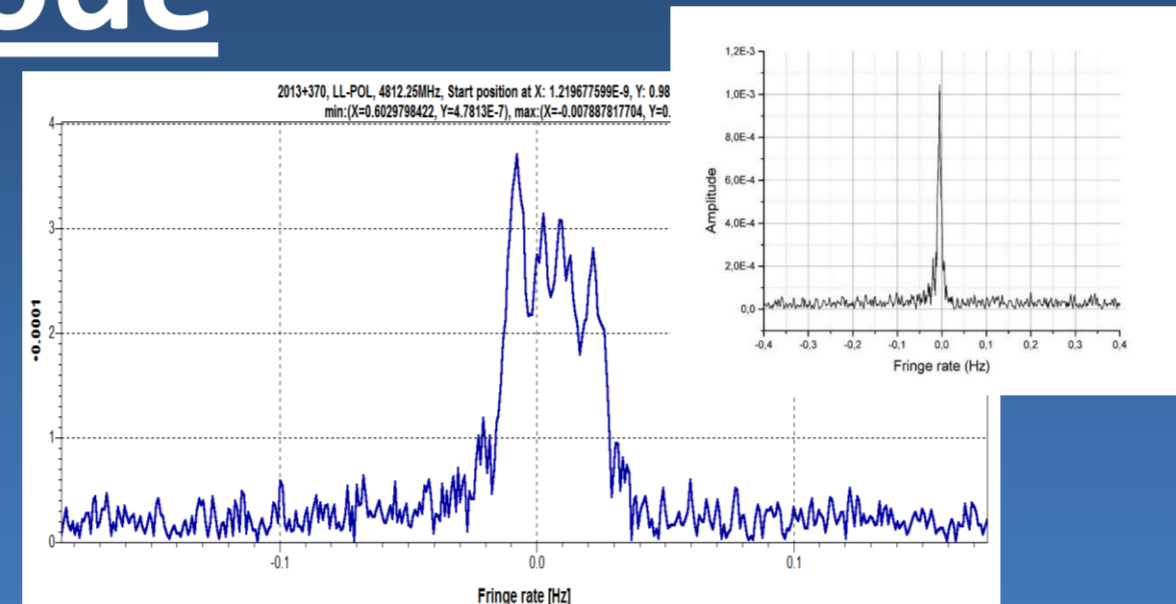
- Supported data formats: RDF (ASC design), Mark4, Mark5, K5, VDF, LBA and others.
- More than 1 Tflops/sec cluster efficiency (about 100 processor cores);
- 200 TB disk storage supported;
- 256 Mb/sec/station data flow, 10 stations (45 base lines) tested;
- More than 65536 delay channels (tested);
- Times 2 efficiency of real time processing (4-stations, 6 BL's)
- Up to 6 parallel correlation tasks
- Continuum, Maser Line and Pulsar operational modes;
- User friendly execution management and smart GUI.

## Coherent mode

Implemented and successfully tested "Coherent" mode of delay restoration.

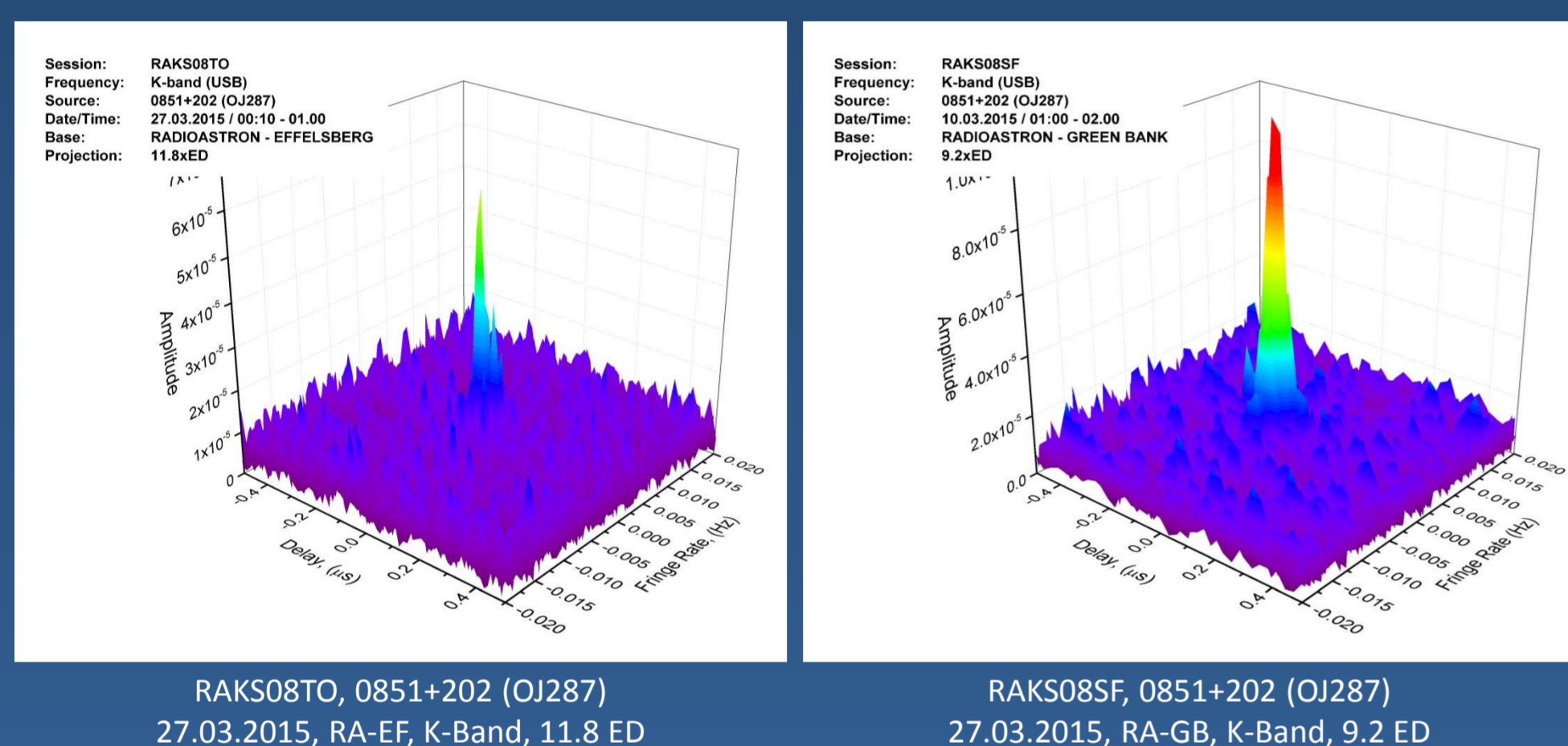
Measurements of the return Doppler on Tracking Station-Radioastron-Tracking Station route to compensate delay variation during integration interval.

It is a useful tool to synchronize RA equipment from the ground H-maser in case of spacecraft timing/frequency onboard fault.



«Coherent» mode, C-Band.  
Original response (left), Restored response (right) - clear spike with high coherence.

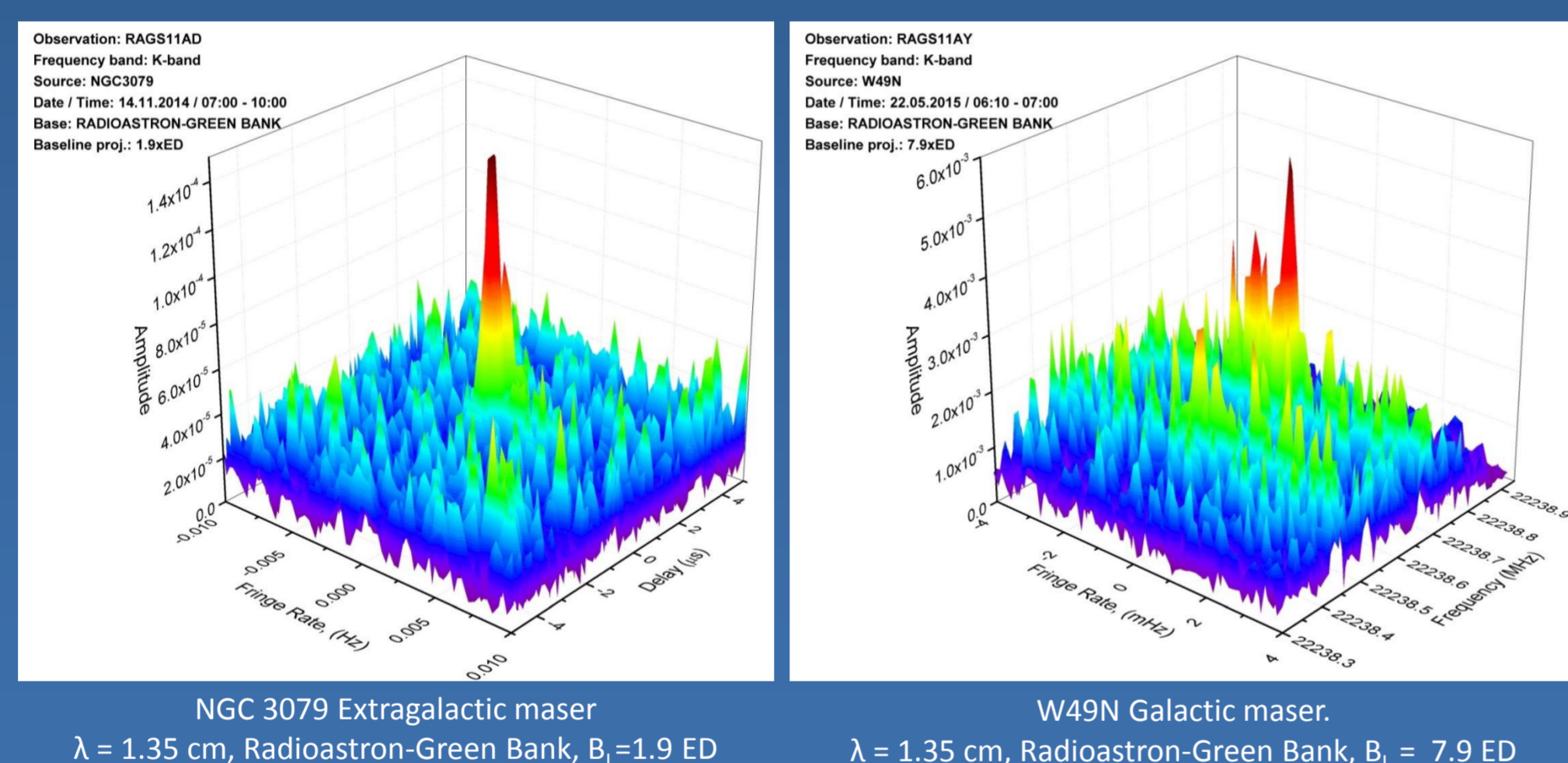
## Extremely high resolution with S-VLBI



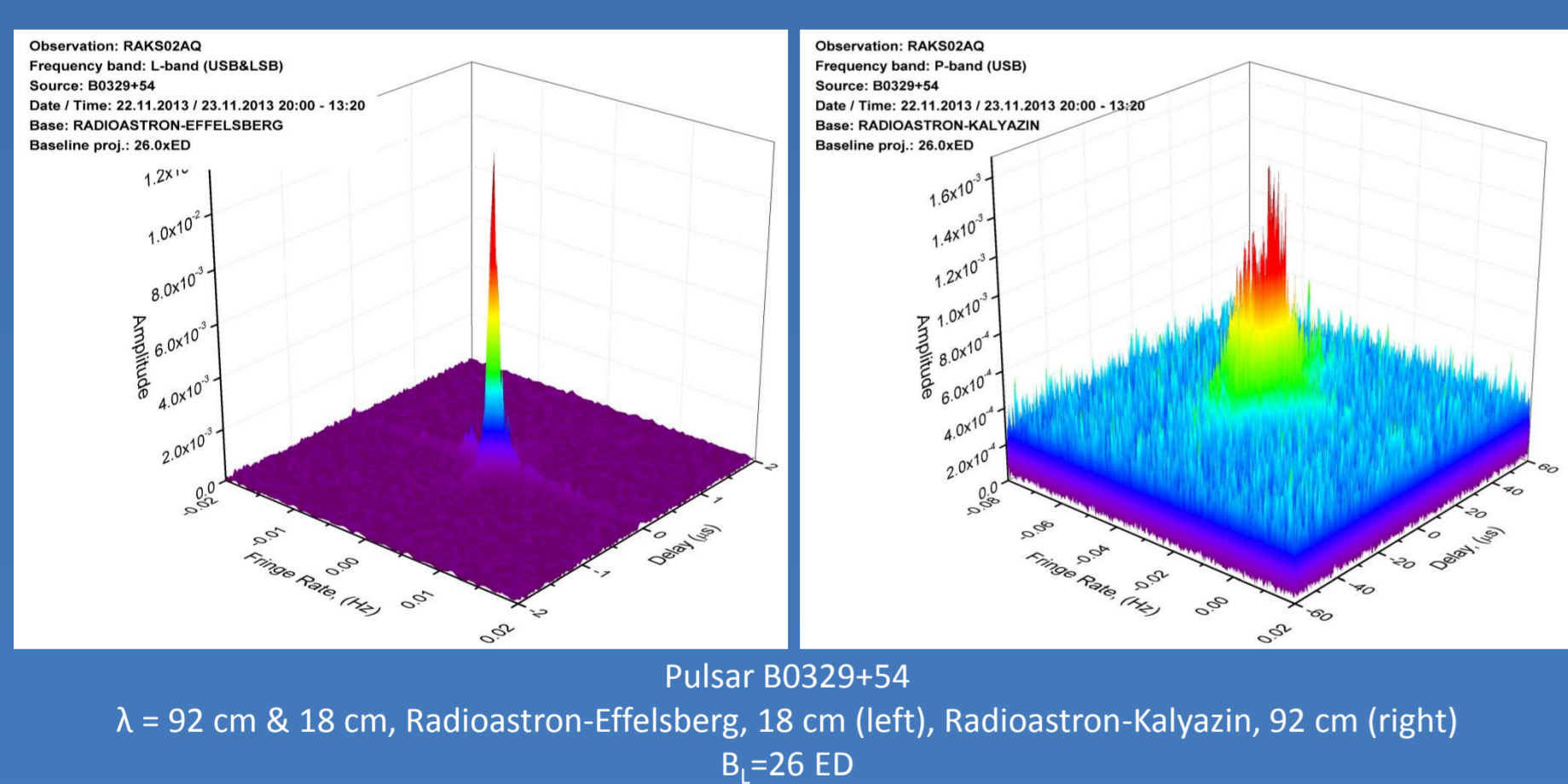
## AGN+QSO

Highest angular resolution was obtained for 0851+202 (OJ287) at maximum baseline projection of 15.5 Earth diameters at K-band (observation done 17.04.2014).  
Next observations at 11.8 and 9.2 Earth diameters showed also good fringes at K-band (figures at left).

## Masers



Highest angular resolution was obtained for W49N galactic maser (14.11.2014, 7.9 Earth diameters) and NGC 3079 (22.05.2015, 1.9 Earth diameters) extragalactic maser. Both observations done at K-band.



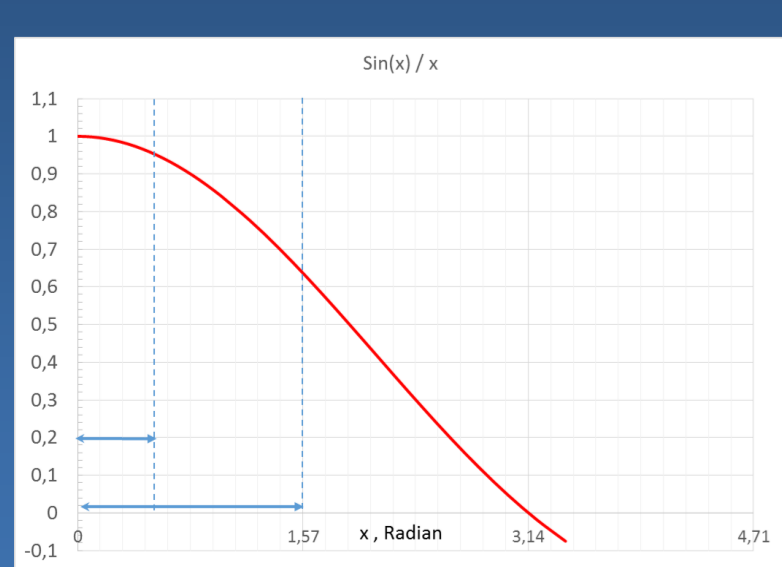
## Pulsars

Highest angular resolution was obtained for B0329+54 pulsar with detected fringes at L-band and P-band at 26 Earth diameters. Observations was done 22.11.2013.

Using ASC Correlator within the "Radioastron" project the following interferometer fringes were detected at extreme baseline projections:

- 330 000 km (26.0 ED) at P-band
- 345 000 km (27.1 ED) at L-band
- 295 000 km (23.3 ED) at C-band
- 197 000 km (15.5 ED) at K-band

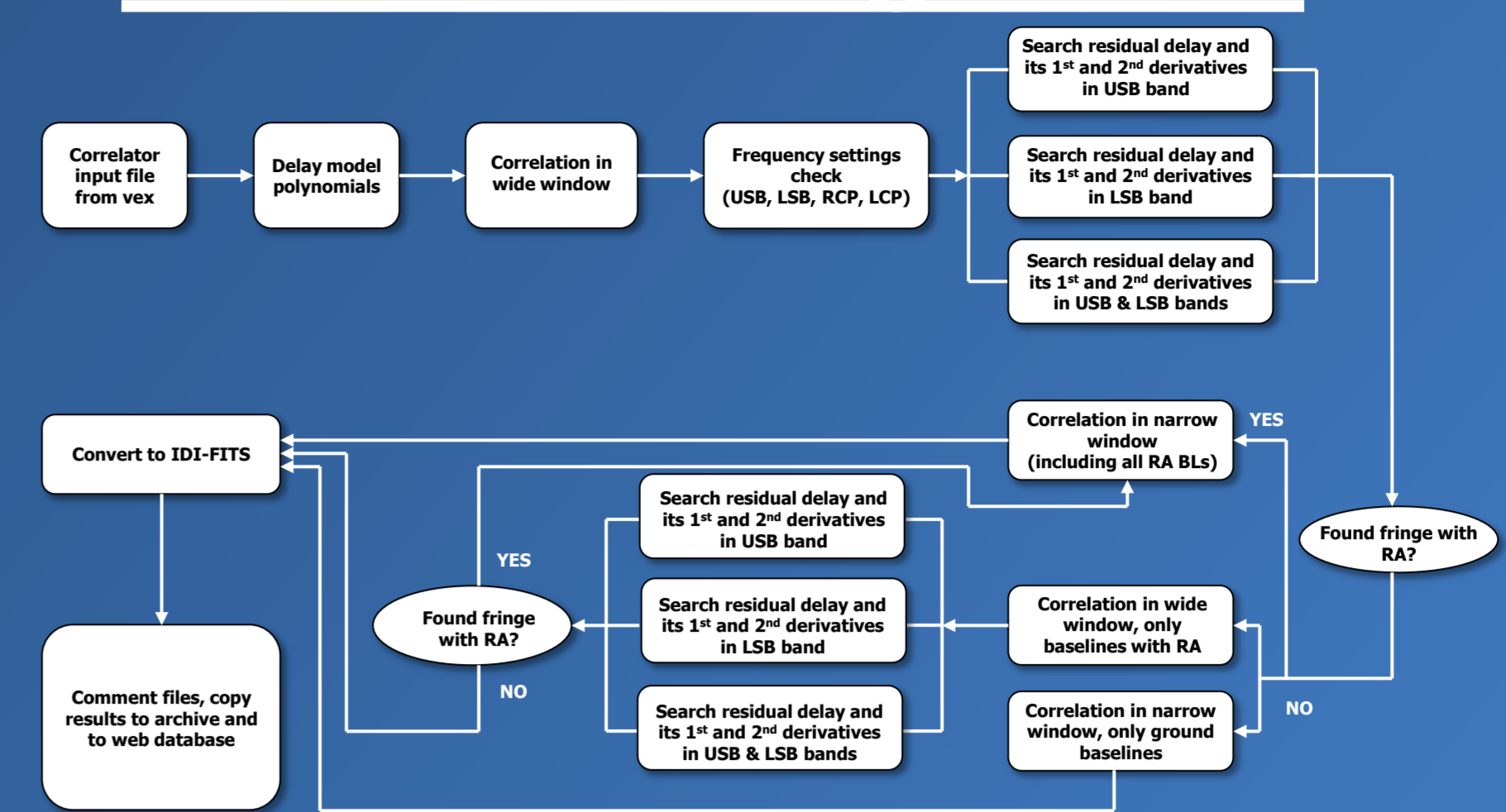
## Comments on Space-VLBI



Losses are proportional  $\sin(x)/x$

- Correlation results are certainly depend on the approximated delay model of the interferometer
- Uncertainties of "RA" reconstructed orbit put evident and strict bounds to the Fringe search procedure
- Chancy combination of integration parameters including actual delay and its 1<sup>st</sup> and 2<sup>nd</sup> derivatives should be accurately adjusted to identify correlation response with the adequate sensitivity
- The fringe search window is determined by the RA state vector, velocity and acceleration uncertainties
- These values are critical for correct choice of a number of the spectral channels and partial / total integration time intervals
- Selected number of spectral channels and solution interval covers given orbit uncertainty (i.e. 200 m coordinate accuracy and 2 cm/s velocity accuracy gives losses in amplitude and SNR less or about 4% with 2048 channels and 0.125 s solution interval)
- In this case the requirements for further orbit improvement is not critical

## Correlation algorithm



For simultaneous observations at two frequency bands (C&K, L&C, L&K): at first lower frequency is being correlated (L or C), then residual delays and its 1-st and 2-nd derivatives are used to correlate higher (K) frequency.

Due to the orbit uncertainties a preliminary correlation for space-ground baselines is required («wide fringe search window», left table), in case fringes were found for ground and space-ground baselines, the correlation will be repeated in «Narrow window» with the following parameters:

Band	FFT channels	Delay window (μs)	Integration time (sec)	F <sub>r</sub> Rate window (Hz)	Data vol. (1 h observation), Gb
K	64	2	1/8	4	1.7
C	64	2	1/2	1	0.42
L	64	2	1	0.5	0.21
P	64	2	1	0.5	0.21

Band	FFT channels	Delay window (μs)	Integration time (sec)	F <sub>r</sub> Rate window (Hz)	Data volume (1 h observation), Gb
K	2048	64	1/64 (1/8 for dual-band)	32	420
C	2048	64	1/8	4	52
L	2048	64	1/4	2	26
P	2048	64	1	0.5	6.6

For typical experiment (one frequency band):

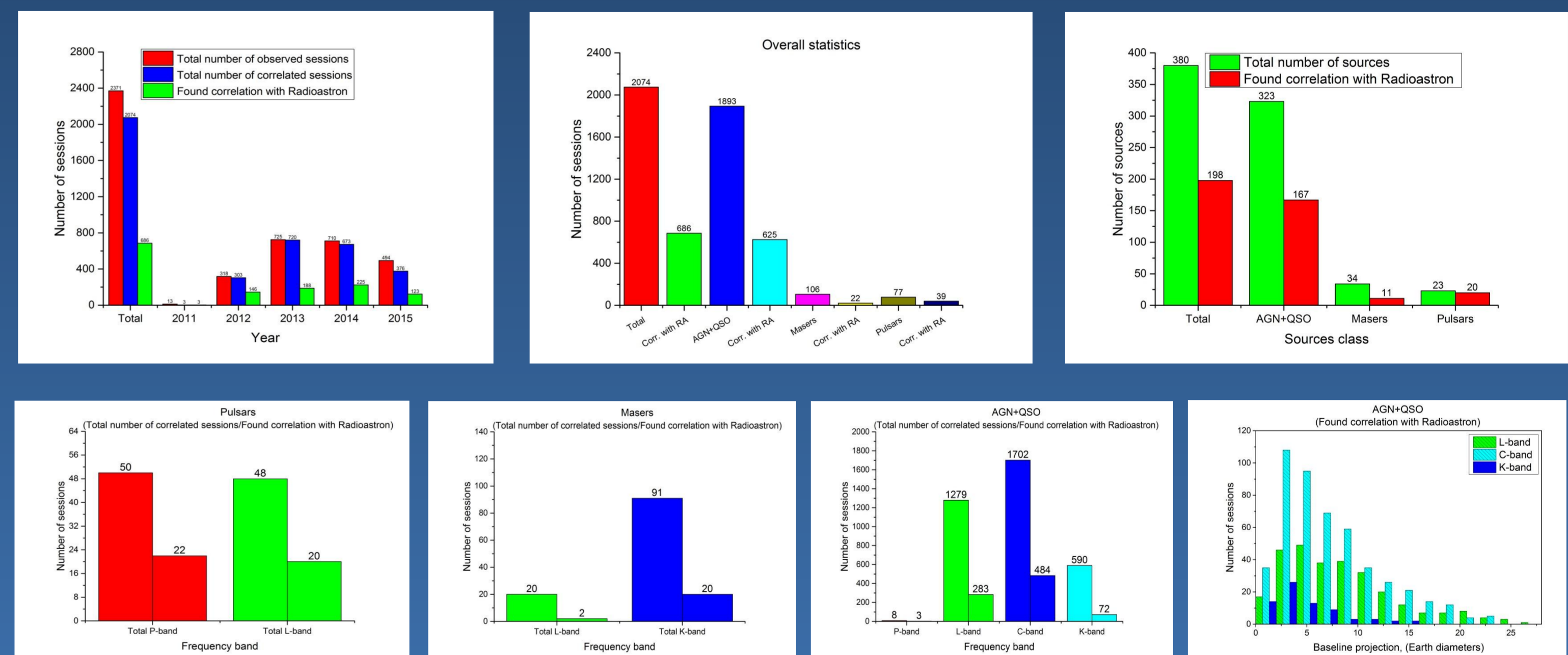
- Input data rate (4 telescopes, 6 parallel correlator task) = 6.1 Gbit/sec
- Output data flow (4 telescopes, 2048 FFT channels, 1/8 sec correlator integration time, 6 parallel tasks) = 720 Mbit/sec
- Double data rate between computing nodes results in the total data flow ≈ 13.1 Gbit/sec, while cluster network bandwidth is only 10 Gbit/sec.
- All correlated data are available at the network local storage of ASC.
- Operator comment files are available on the online database and on ASC ftp.

The correlator processing rate is largely depends on the network bandwidth and data delivery than by FFT computation rate on computing nodes!

## Correlator new features

- Modified fringe search procedure has adjustable scan length and auto selection of the best station in a given scan.
- LBA format support (Australian telescope).
- «multi-thread» VDF support along with «single-thread» (Mark 5C recorder).
- Robledo/ Tidbinbilla VDF to RDF (ASC) convertor for Robledo/ Tidbinbilla stations. Used for data volume shortage at the Australia IT input.
- Inverted video bands correlation mode for non-standard station video converters.
- No delay in correlator output after the raw data becomes available.
- Fully automated process from job script to FITS / UVX output files.
- No ways for operator faults.
- Non-stop productivity: 24 hours / 7 days per week.

## Statistics



## Processing summary

(01.11.2011-17.11.2015)

Quasars and AGN:

Total: 2074 sessions (686 correlations with RA)

Pulsars:

Total: 77 sessions (39 correlations with RA)

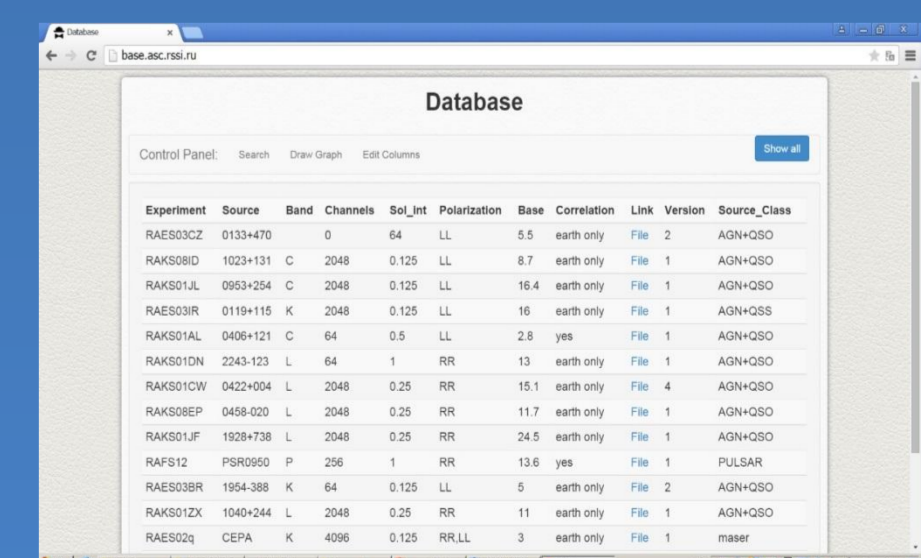
Masers:

Total: 106 sessions (22 correlations with RA)

## Correlated Data Archiving

Auto and Cross spectrum, comment files along with corresponding picture "primitives" automatically downloaded into the "online" depository to work on of scientific groups. Outside access is simply ordered through system administrator.

Search and Report generation from scans, sources, calendar intervals, correlation results etc.



## Summary

- ASC correlator is close to be fully automated machine
- Up to June 1, 2015 the Data from 1784 sessions have been successfully correlated. Fringes on Space-Ground baselines were found in 572 observations.
- Space VLBI data correlation - as opposed to ground - strongly depends on the networking and data delivery rate, rather than on the performance of the CLUSTER, expressed in "teraflops". Future - SVLBI projects need to be focused on the networking and data delivery.
- Currently, ASC correlator data processing rate within the "Radioastron" mission is about 250 sessions per month, observation rate is 80-120 experiments per month. ASC correlator performance is more than enough to correlate all the data for the "Radioastron" project, but still it strongly depends on the data upload rate.
- Generally, for space-ground VLBI missions, having good computational resources, the requirements for the orbit accuracy and improvement can have practical limit and can be covered with the optimal correlation parameters selection. So that this limit has no sense to be over reached.