

Radioastron Primary Data Processing. Technology and Results.

A.S. Andrianov, S.F. Likhachev, V.I. Kostenko, I.A. Guirin,
V.E. Zharov, A.G. Rudnitsky, M.V. Shatskaya

Overview

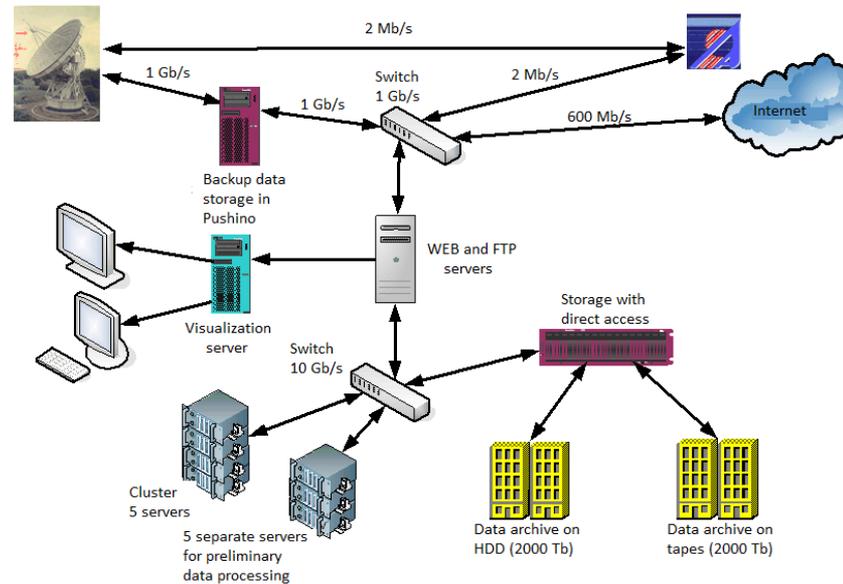
The 10-m radio telescope is fully operational onboard of 'Spektr-R' observatory for more than 3 years since 15 November, 2011.

It is successfully used as Space element of Ground-to-Space Interferometer in the orbit with the apogee up to 350 000 km.

- Described main features and operational procedures.
- Considered evaluation methods in terms of efficiency and parameterization of the correlator.
- Presented processing statistics to the current date.



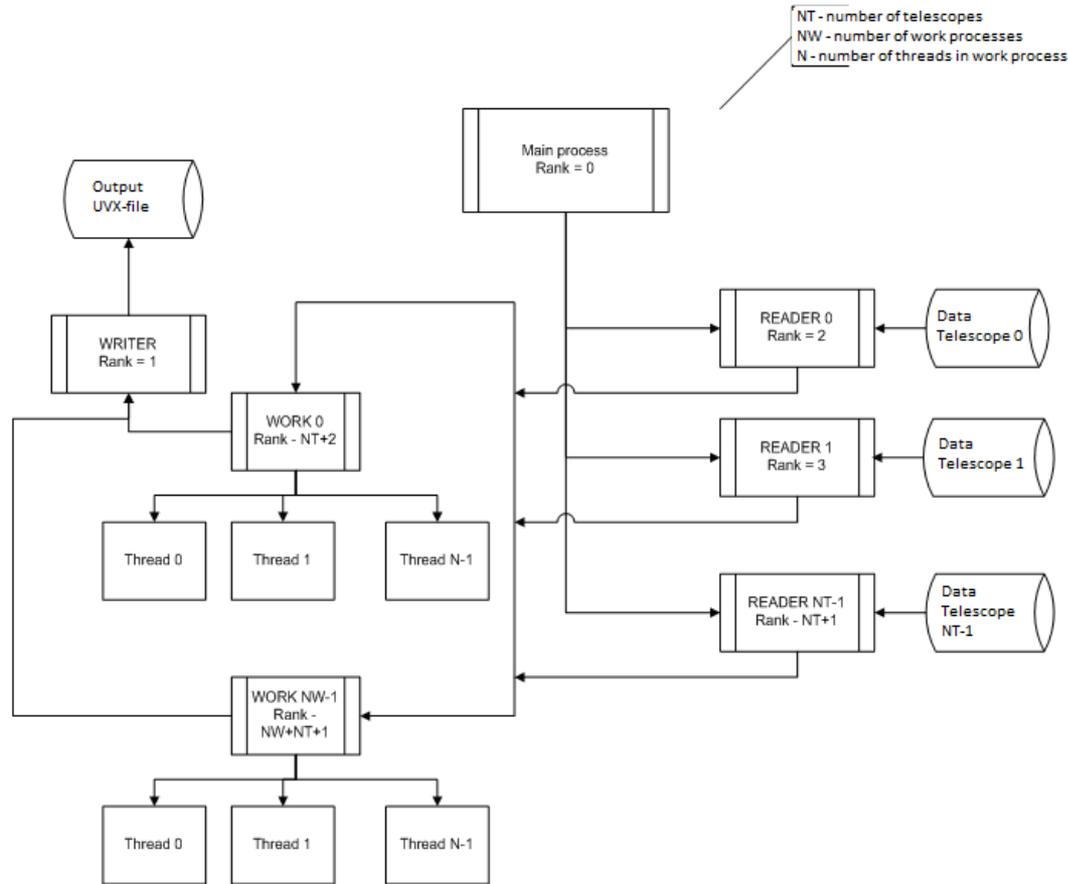
ASC Correlator Round-up



- Main external data channels (Tracking stations, Ground stations)
- Communication channels (commHost, Internet cloud etc.)
- Internal exchange functional channels
- Computing resources



ASC Correlator Operational Scheme



- The ASC FX software correlator serves as aggregate quality measure of whole Radioastron mission and mainly determines the success of the intended scientific goals.
- MPI application
- FX architecture



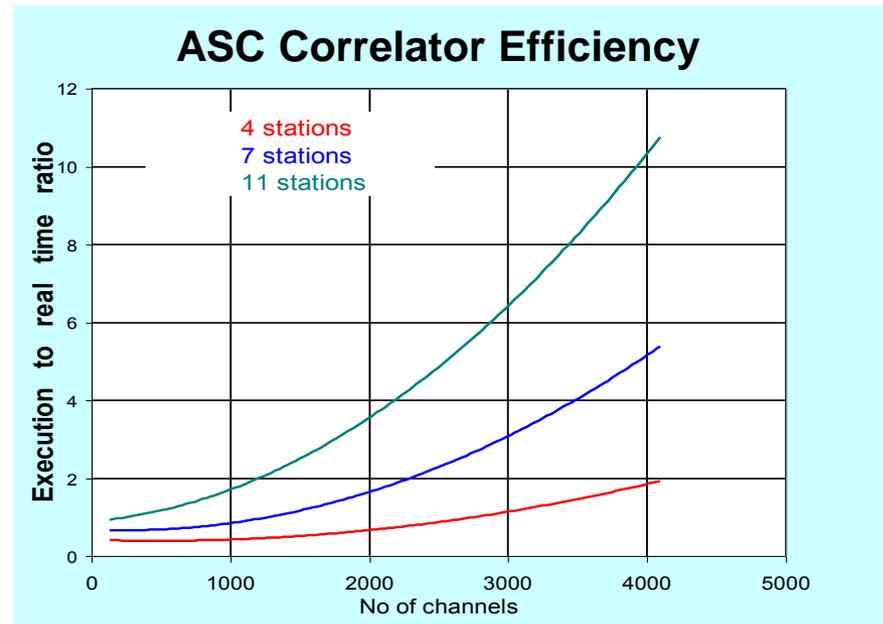
ASC Correlator Functionality

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

- RDF (ASC design), Mark5(*), K5, VDIF and others in use data input formats.
- “Arriadna” delay model (V.E. Zharov)
- 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.



Important Comments for Space VLBI

- 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 trial procedure.
- Chancy combination of integration parameters including actual delay and its **1-st and 2-nd derivatives** should be accurately adjusted to identify correlation response with the adequate sensitivity.
- The fringe search window is determined by **RA state vector, velocity and acceleration uncertainties**.
- These values are critical **for correct choice of number of the spectral channels and partial/ total integration time intervals**.



Delay and Fringe Rate Windows

- Due to the orbit errors in the distance and velocity we need to make preliminary correlation of Space-Ground baseline in «Wide search window» :

Frequency band	FFT Channels	Delay window (mks)	Integration time (sec)	Fr. rate window (Hz)	Data volume (1 hour observation)
K-band	2048	64	1/64 (1/8 if C-band exists)	32	420 Гб
C-band	2048	64	1/8	4	52 Гб
L-band	2048	64	1/4	2	26 Гб
P-band	2048	64	1	0.5	6.6 Гб

- For positive results for Ground to Ground baselines and Space to Ground correlation (fringe was found) the correlation is done in «Narrow window» with the following parameters:

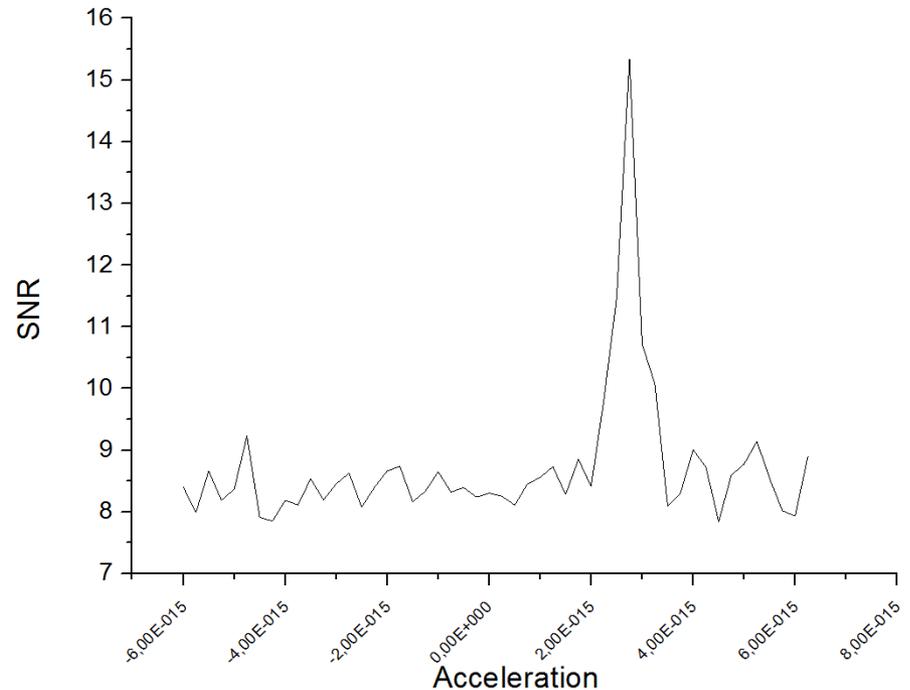
Frequency band	FFT Channels	Delay window (mks)	Integration time (sec)	Fr. rate window (Hz)	Data volume (1 hour observation)
K-band	64	2	1/8	4	1.7 Гб
C-band	64	2	1/2	1	420 Мб
L-band	64	2	1	0.5	210 Мб
P-band	64	2	1	0.5	210 Мб



Correction of 2-nd Derivative of Delay (Acceleration)

Not only delay and its first derivative affect the coherence time and SNR.

- 1) Errors in acceleration of space radio telescope have strong effect on the maximum coherent integration time and maximum SNR.
- 2) It is required to apply some additional routines to find residual acceleration and compensate it.



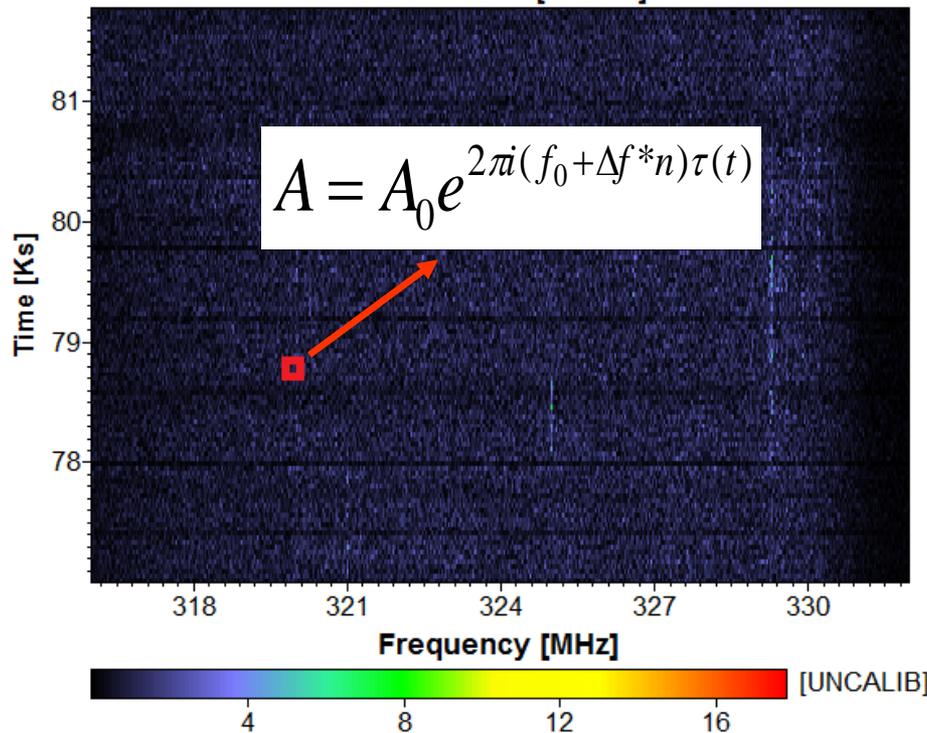
Raes08 session.

Plot: Dependency of SNR from Acceleration



Correction of 2-nd Derivative of Delay (Acceleration)

- Correct a priory delay model by applying additional phase to every pixel on the time-frequency diagram (fr-del before FFT).
- Search a_2 for max SNR
- Use a_2 value for next correlation pass



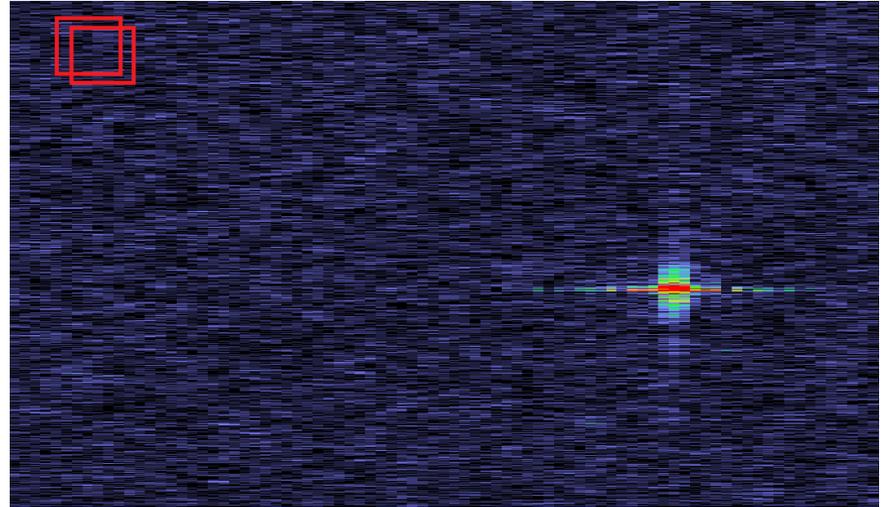
$$\tau(t) = a_0 + a_1(t - t_0) + a_2(t - t_0)^2 \quad \tau(t) = 0 + 0 + a_2(t - t_0)^2$$



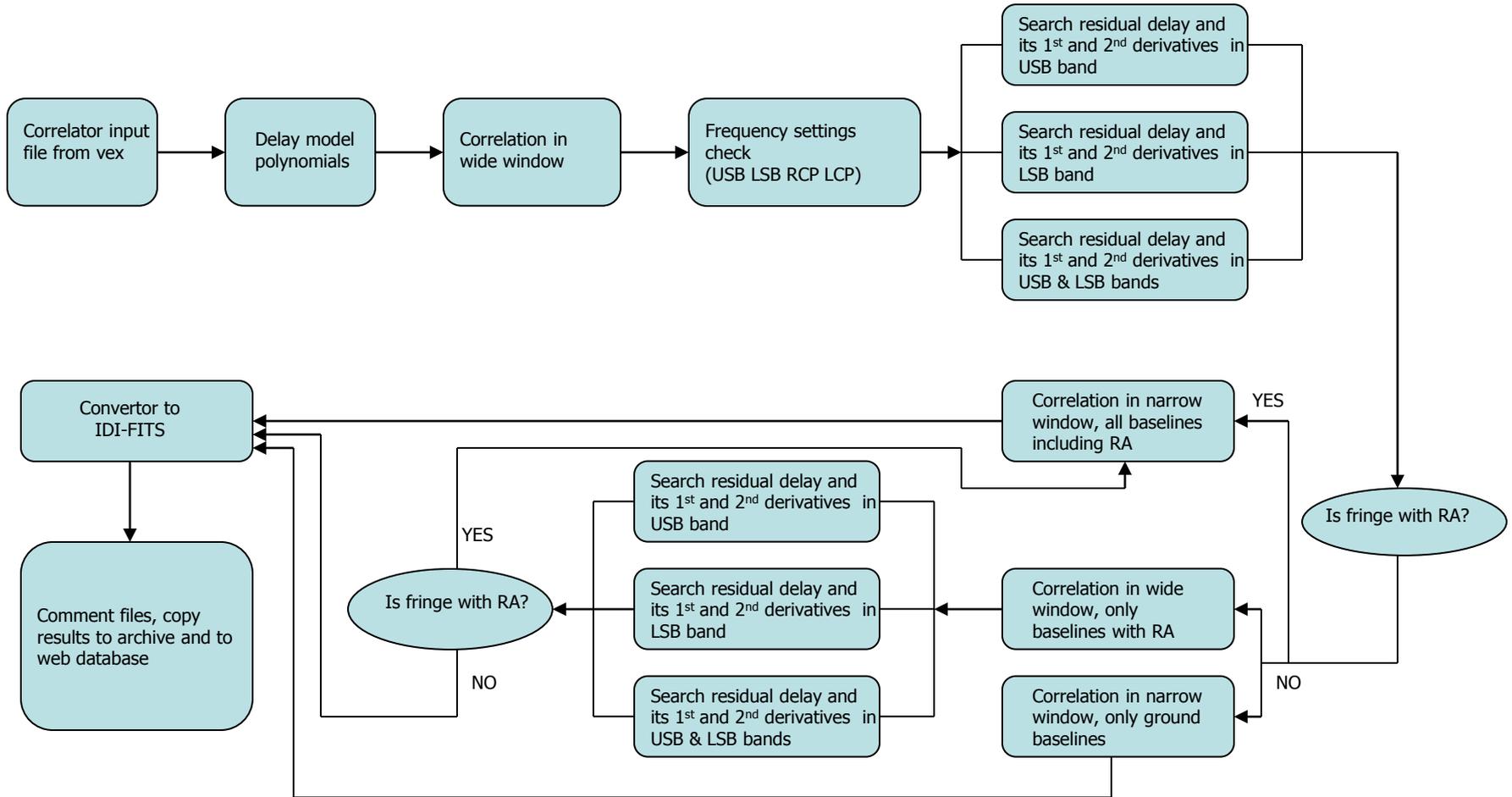
Search Fringe Subroutine

For every scan (typically 570 sec duration) ASL subroutine search rectangle with maximum total flux on fr-del diagram. Detected fringe must satisfy to one of the following conditions:

- Residual delay and fringe rate of correlation peak for the RA-Best Ground Telescope baseline must have close values in different scans (at least two)
- If fringe appears only in one scan, the residual delay and fringe rate in USB and LSB channels should have close values



Typical Correlation Algorithm : Quasars/AGN Sessions



- For simultaneous observations at two frequency bands (C&K or L&C): first correlate lower frequencies L&C, then use residual delay and its 1-st and 2-nd derivative to correlate at higher (K) frequency.



Correlator Data Flow

For typical experiment (one frequency band)

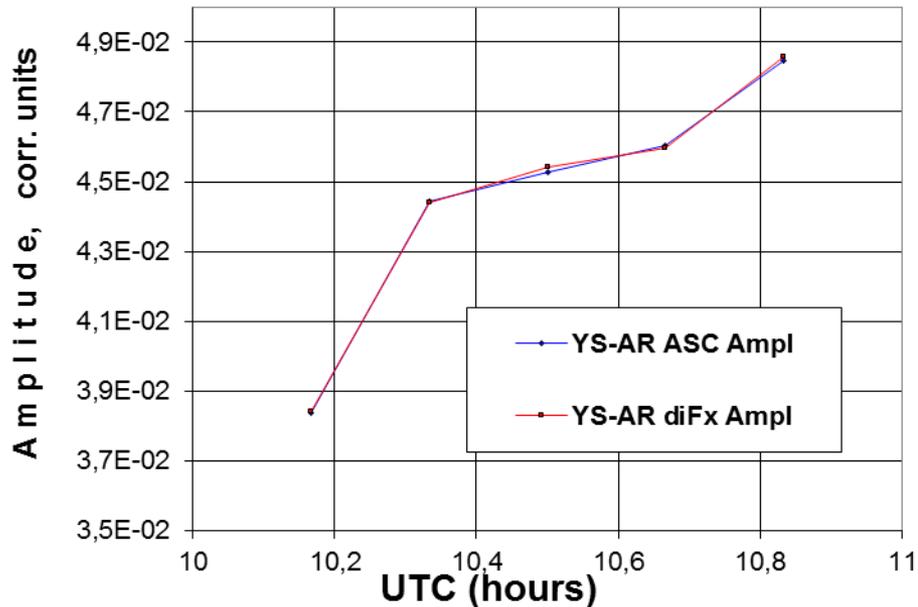
- Input data volume:
4 telescopes, 6 parallel correlator tasks = 6.1 Gbit/sec
- Output data volume:
4 telescopes, 2048 FFT channels, 1/8 sec correlator integration time, 6 parallel tasks = 720 Mbit/sec
- Double data volume between computing nodes results in the total data volume \approx 13.1 Gbit/sec, while we have only 10 Gbit/sec bandwidth in cluster network.

Speed of correlation data processing is largely determined by the network bandwidth and data delivery than by FFT computation rate on computing nodes!



Comparison with DiFX Correlator

0748+126, YS-AR, BAND: C , Amplitude

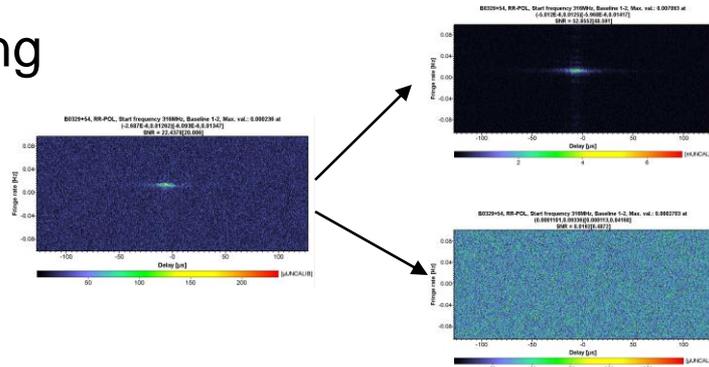


- ASC and DiFX correlator have been tested and gave the similar results on similar data.
- 3 years of Radioastron operations do not show any experiment with significant difference between correlation outputs of ASC and DiFX correlators.



Pulsar and Spectral Line Processing in ASC Correlator

Gating

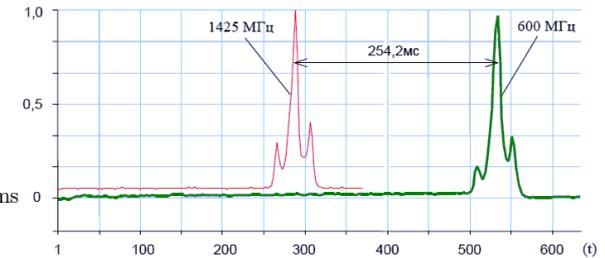


Incoherent dedispersion

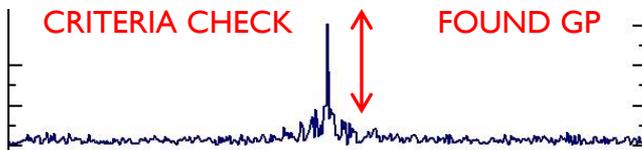
$$\Delta t = k_{DM} \times DM \times \left(\frac{1}{\nu_{lo}^2} - \frac{1}{\nu_{hi}^2} \right)$$

$$DM = \int_0^d n_e dl$$

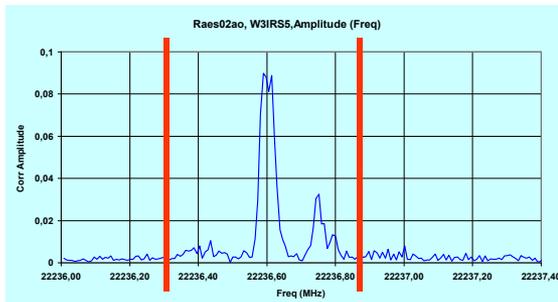
$$k_{DM} = \frac{e^2}{2\pi m_e c} \approx 4.149 \text{ GHz}^2 \text{ pc}^{-1} \text{ cm}^3 \text{ ms}$$



Giant pulses mode



Spectral lines

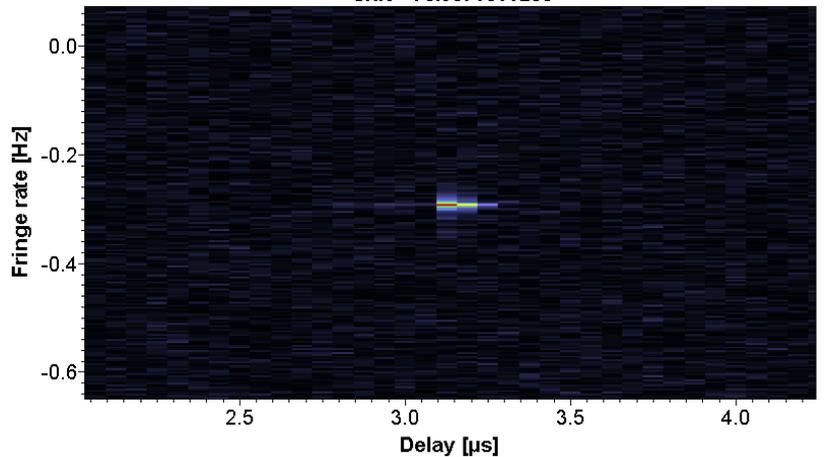


Cuting spectral range to minimize correlator output data flow

ASL Software – Continuum Source (Fringe Rate – Delay Diagram)

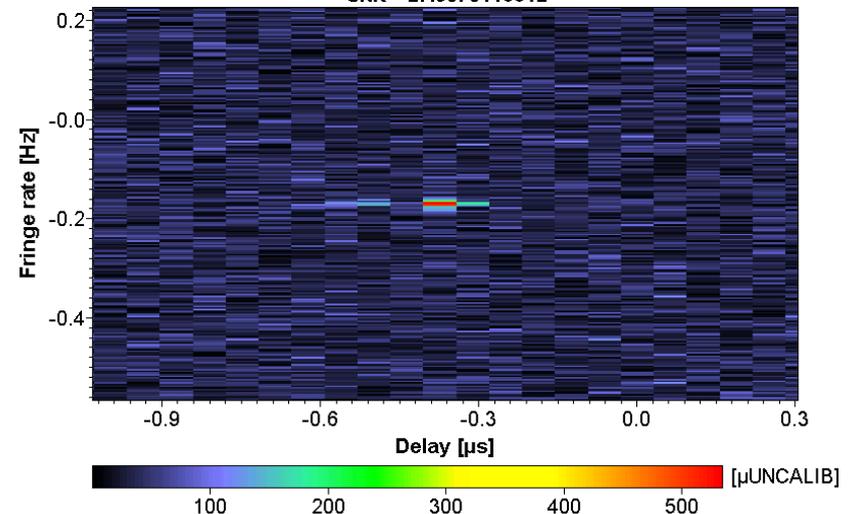
Correlator output can be easily analysed and visualized by ASL user applications library with a variety of important modes of operation:

TEMP, LL-POL, Start frequency 4828MHz, Baseline 1-4, Max. val.: 0.001513 at
(3.125E-6,-0.2933)
SNR = 75.9870360238



1823+568
Stations RA- EF,
BL= 4.99 ED
C-Band, S/N = 76
A = 0.001513
 $\tau = 300$ sec
 $\Delta\tau = 0.1$ sec

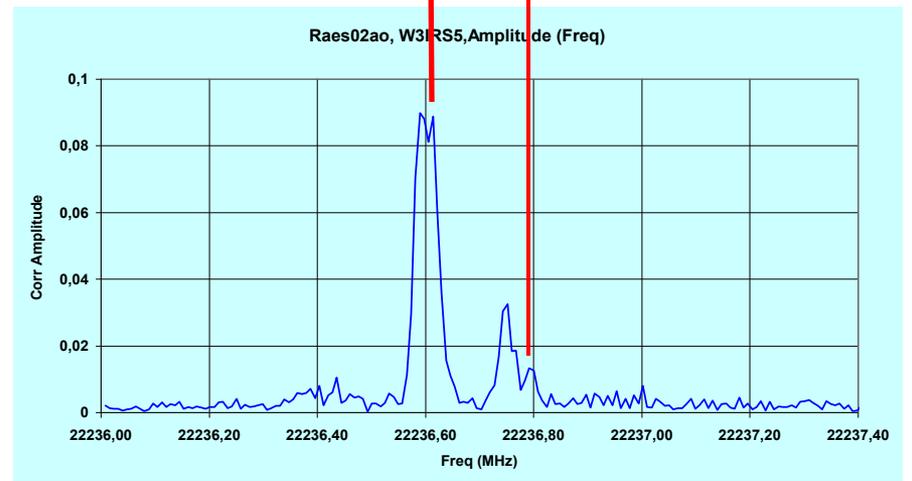
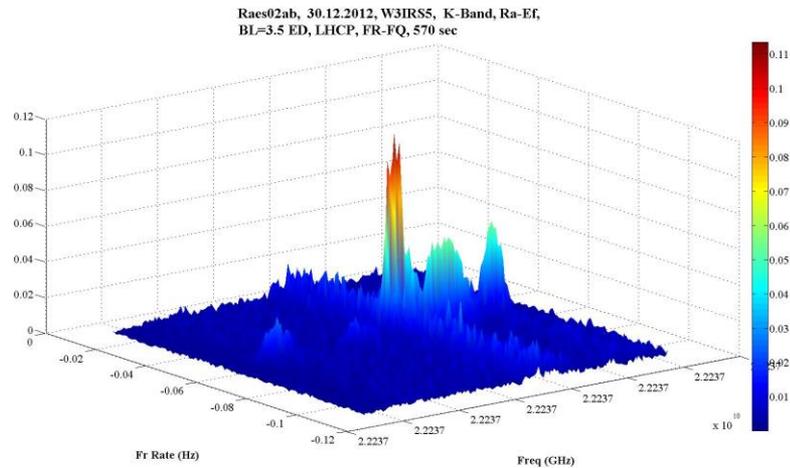
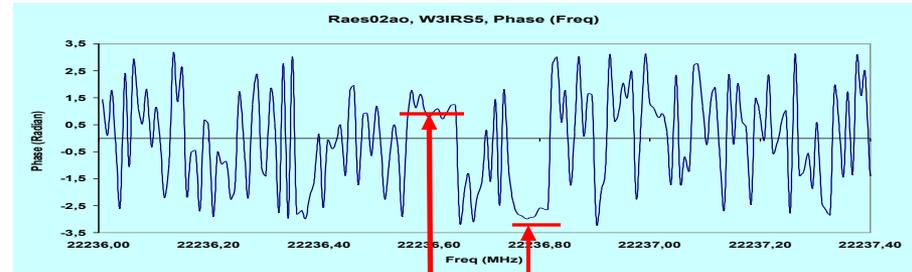
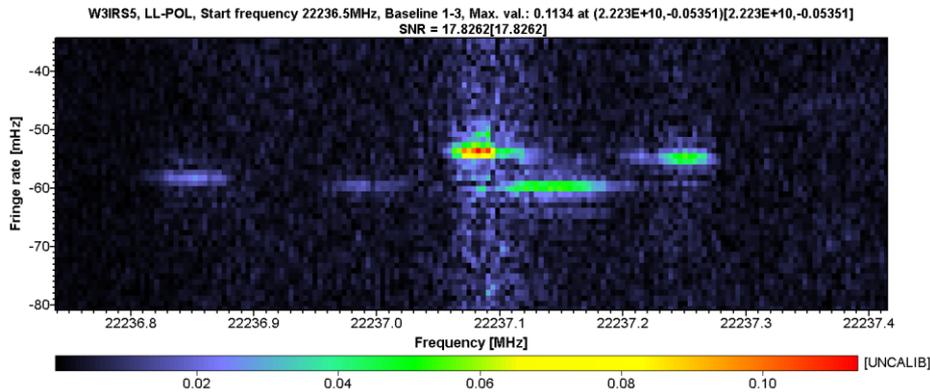
TEMP, LL-POL, Start frequency 4828MHz, Baseline 1-2, Max. val.:
0.0005347 at (-3.75E-7,-0.1684)
SNR = 27.9878440642



1823+568
Stations RA-YS,
BL= 4.91 ED
C-Band, S/N = 28
A = 0.0005347
 $\tau = 300$ sec
 $\Delta\tau = 0.1$ sec



ASL Software – Example of Spectral Line Source (Fringe Rate – Frequency Diagram)

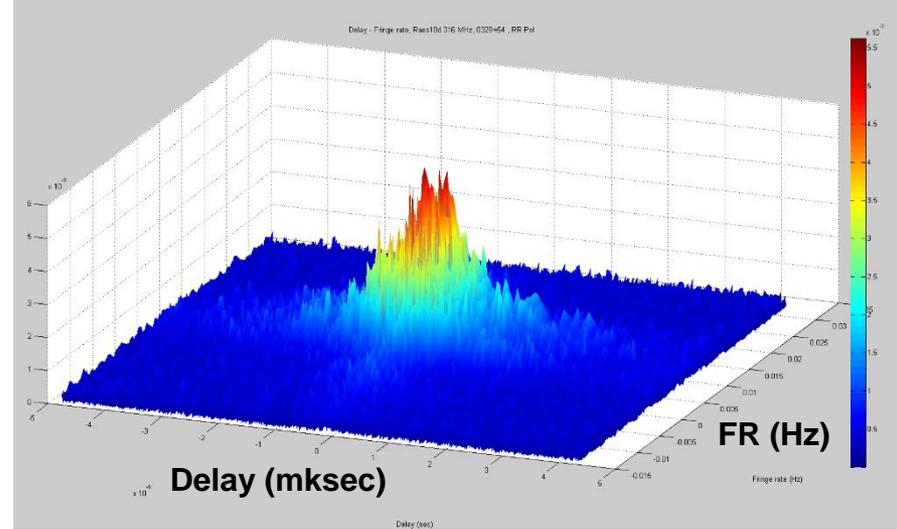
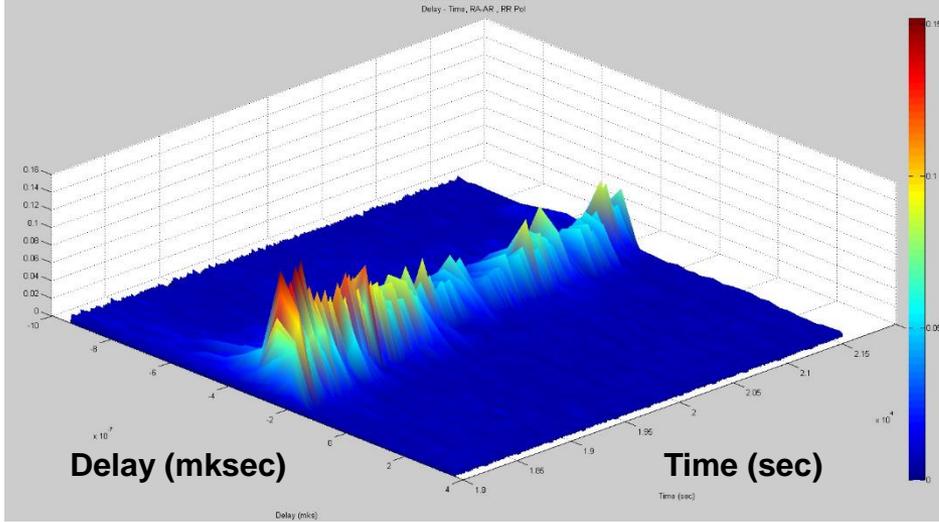


W3IRS5, K-band, LHCP, Ra-Ef, BL 3.5 ED

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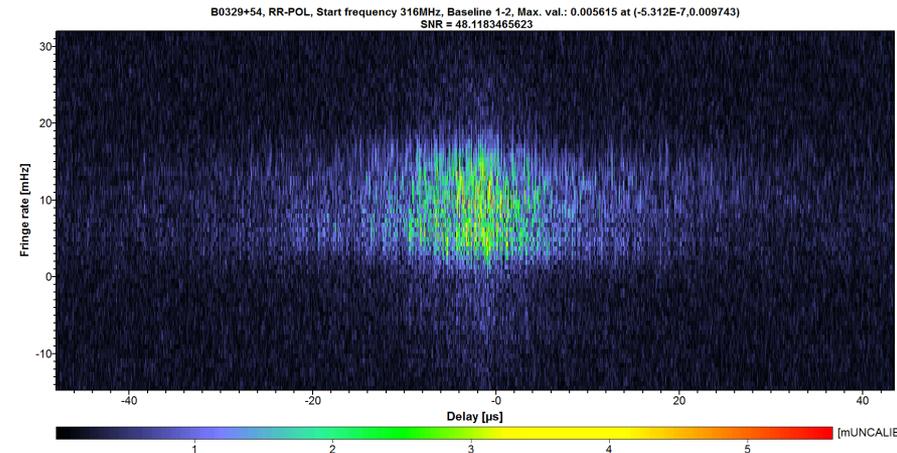


ASL Software – Example of Pulsar Source (Fringe Rate – Delay Diagram)



Pulse crosscorrelation at Ra-Ar BL.
Del & Ampl time scintillations due to propagation effects in ISM.

PSR 0329+54, Ra-Ar.
Freq = 316 MHz.
Crosscorrelation at Ra-Ar
BL. FR-Del spectrum
smearing

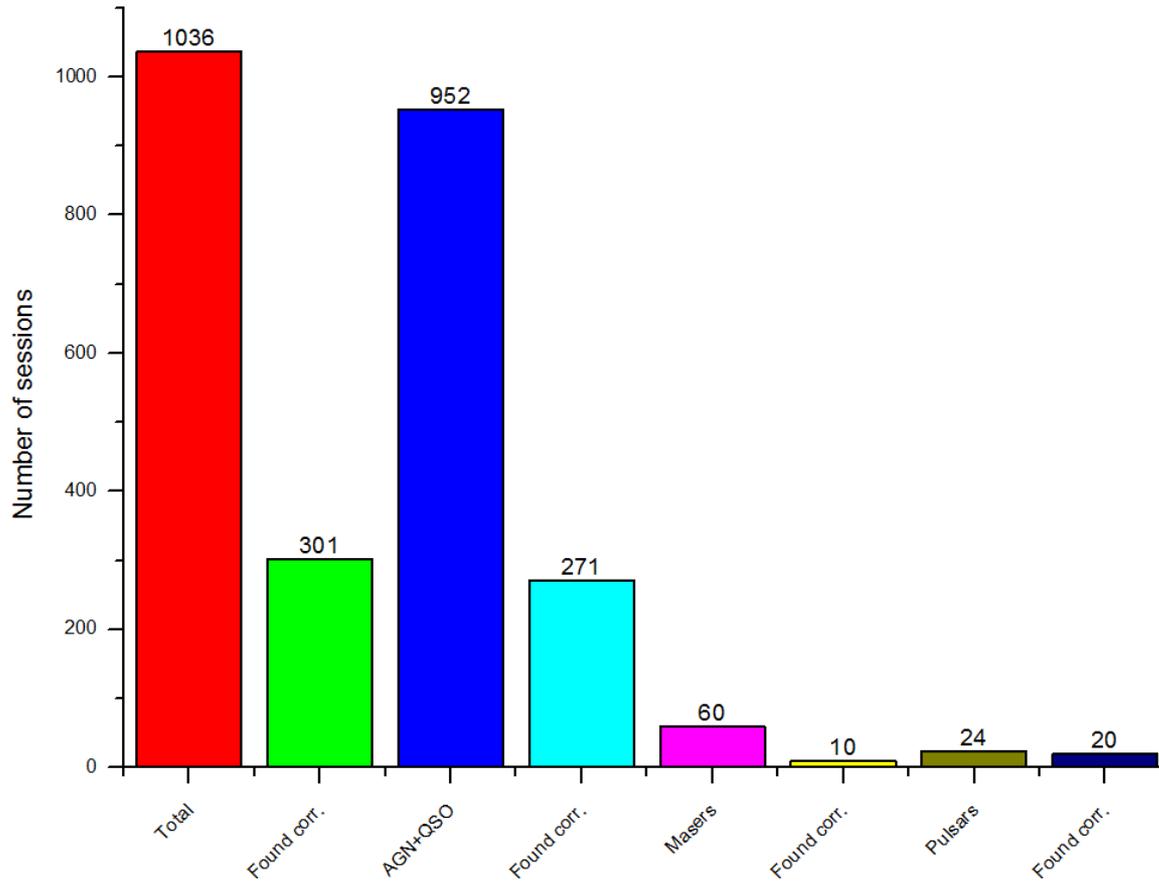


Radioastron Scientific Program

- Radioastron Fringe Search experiments (RAFS):
 - **27** observations
- Radioastron Early Science program (RAES):
 - **Total 639 sessions:**
 - 555 – quasars and AGN (observation code RAES--)
 - 29 – pulsars (9 unsuccessful due to technical faults)
 - 55 – masers
- Radioastron Key Science Program (RAKS):
 - **931** sessions (at 28.10.2014)

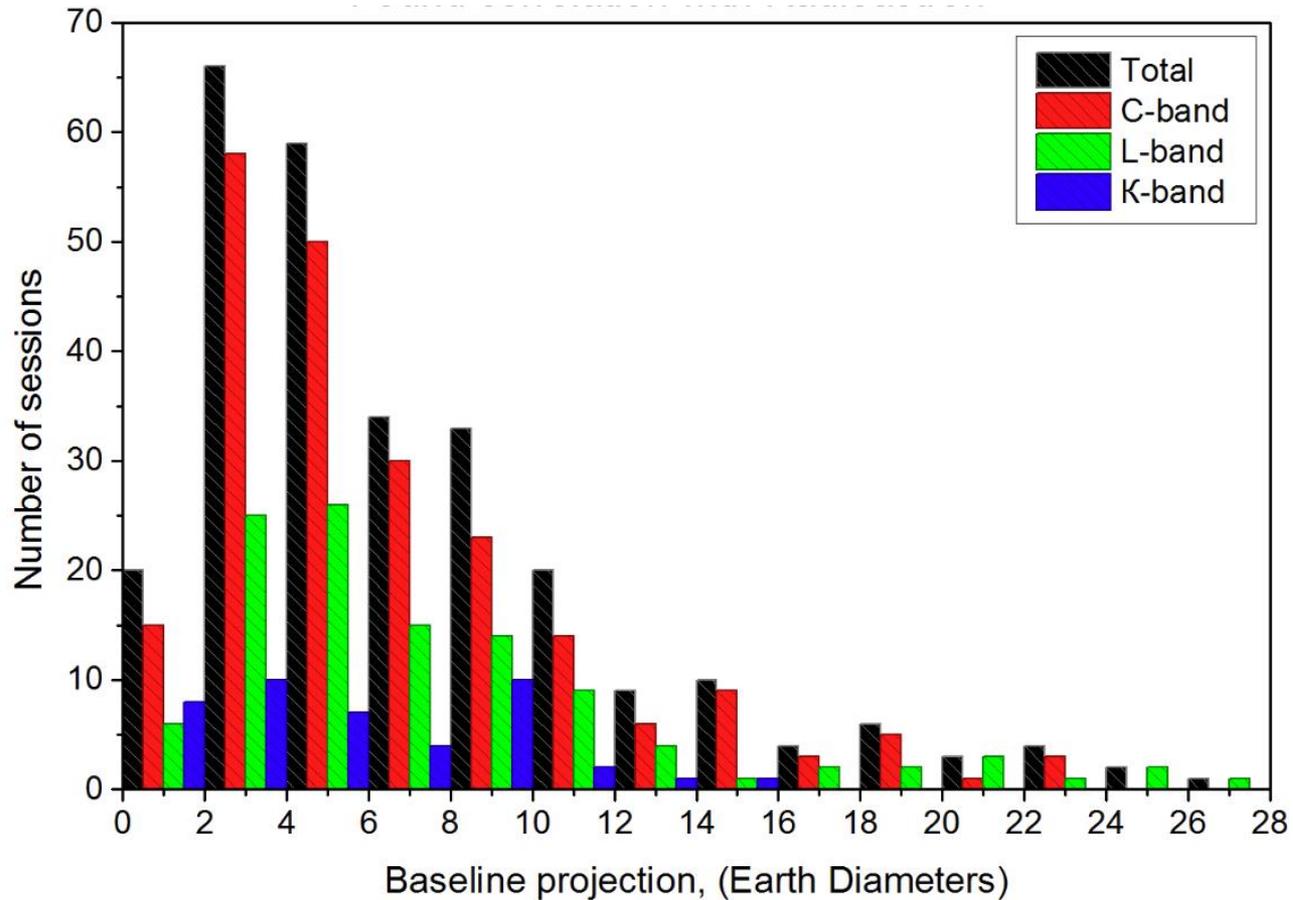


Overall Statistics



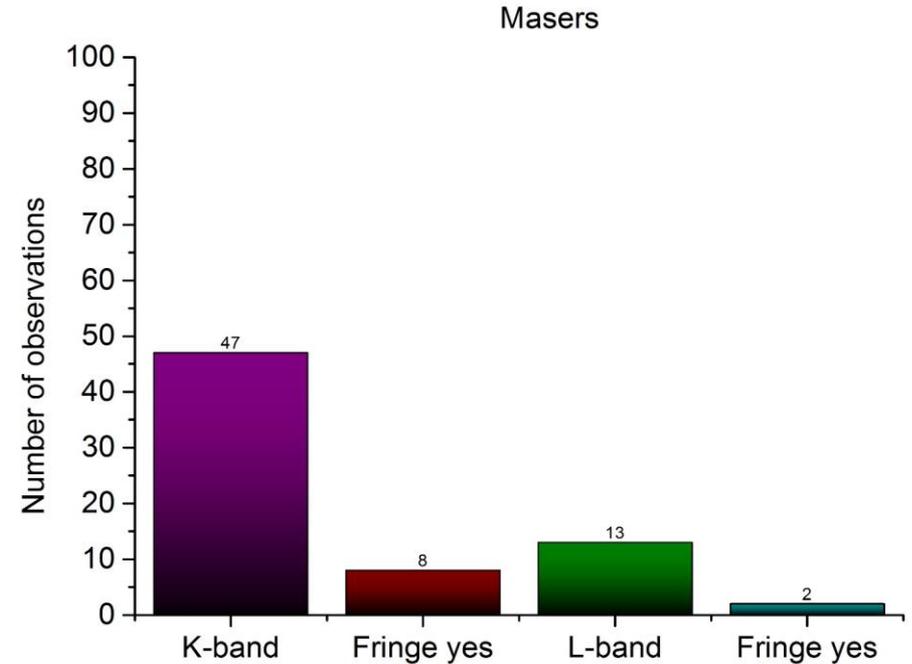
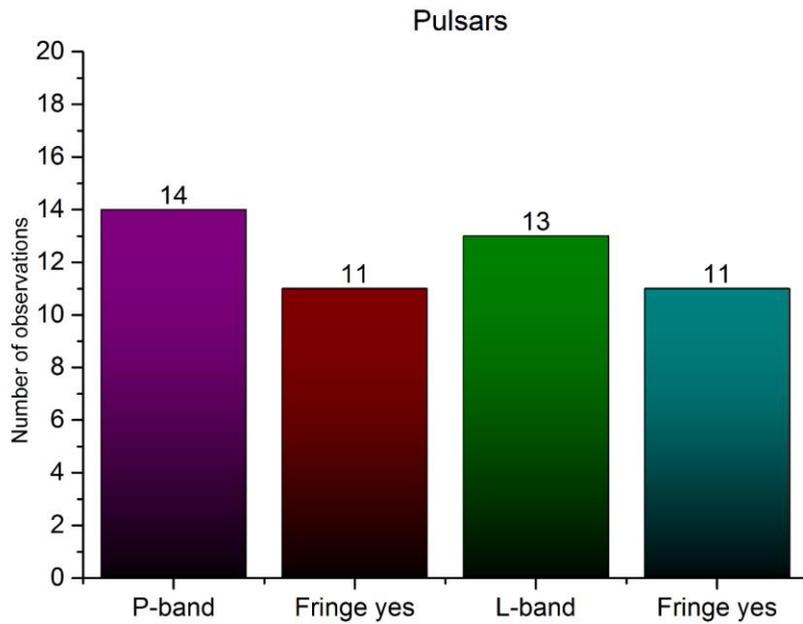
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Correlation Statistics (AGN+QSS). 2012 –2014 (correlation with RA was found)



Correlation Statistics (Pulsars and Masers)

2012 –2014



Summary

Quasars and AGN:

Total: 952 observations (271 correlation with RA)
21 observation failed due to lack of ground support

Pulsars:

Total: 24 observations (20 correlation with RA)

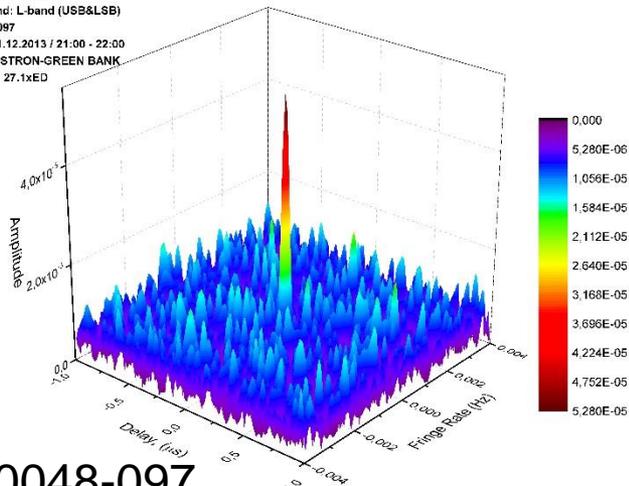
Masers:

Total: 60 observations (10 correlation with RA)



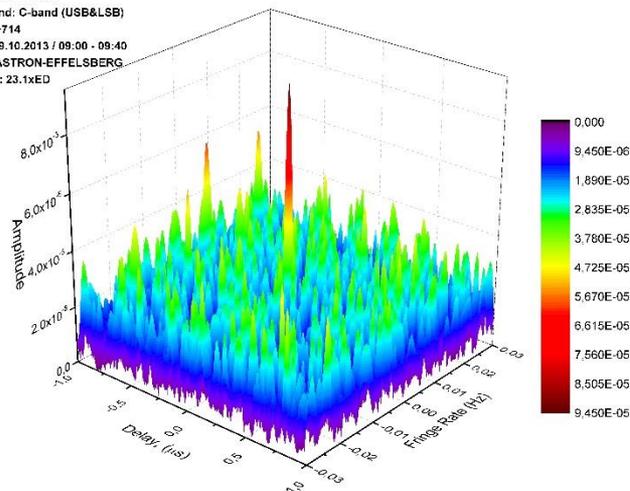
Radioastron Fringe Detection Records

Observation: RAKS01KT
 Frequency band: L-band (USB&LSB)
 Source: 0048-097
 Date / Time: 01.12.2013 / 21:00 - 22:50
 Base: RADIOASTRON-GREEN BANK
 Baseline proj.: 27.1xED



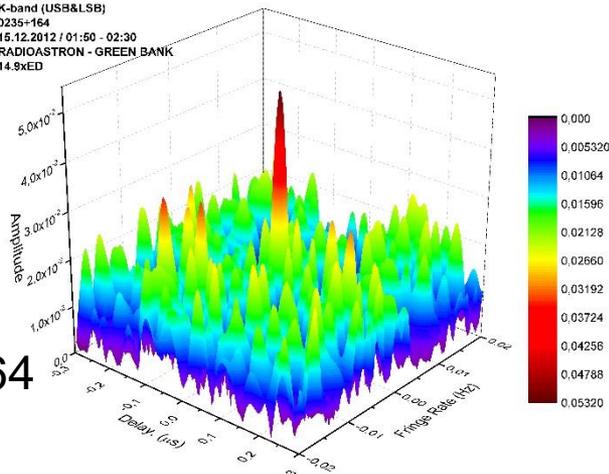
0048-097
 L-band
 27.1 ED

Observation: RAKS01GC
 Frequency band: C-band (USB&LSB)
 Source: 0716+714
 Date / Time: 19.10.2013 / 09:00 - 09:40
 Base: RADIOASTRON-EFFELSBERG
 Baseline proj.: 23.1xED



0716+714
 C-band
 23.1 ED

Session: RAES03HU
 Frequency: K-band (USB&LSB)
 Source: 0235+164
 Date/Time: 15.12.2012 / 01:50 - 02:30
 Base: RADIOASTRON - GREEN BANK
 Baseline proj.: 14.9xED

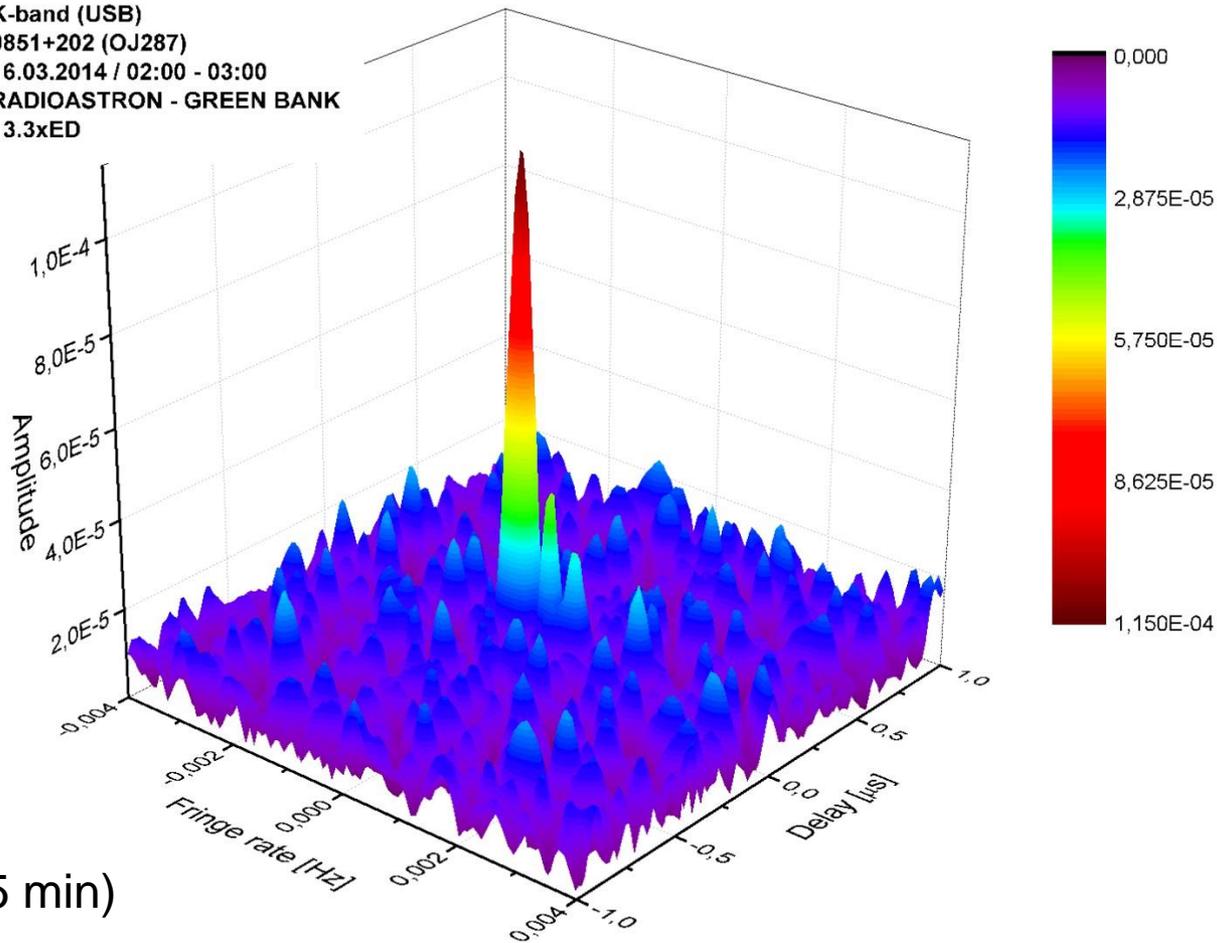


0235+164
 K-band
 14.9 ED



RAKS01VT, 0851+202 (OJ287)

Session: RAKS01VT
Frequency: K-band (USB)
Source: 0851+202 (OJ287)
Date/Time: 16.03.2014 / 02:00 - 03:00
Base: RADIOASTRON - GREEN BANK
Baseline proj.: 13.3xED



Scan: 900s (15 min)

Estimated angular resolution: 18 [μ as]

Estimated flux: 90 mJy

Conclusions

- Data from 1036 sessions have been successfully correlated. Fringes on Space-Ground baselines were found in 301 observations.
- Space VLBI data correlation - as opposed to ground - largely depends on networking and data delivery, rather than on the performance of the cluster, expressed in "teraflops". Future projects need to be focused on networking and data delivery.
- For today, data processing rate in "Radioastron" mission is about 160 sessions per month, observation rate is 80-120 experiments per month. Thus, ASC correlator performance is enough to correlate all the data in "Radioastron" project, but still it depends from data upload rate.

**With ASC Correlator in "Radioastron" project the interferometer fringes
Were obtained at the extreme baseline projections:**

**345 000 km (27.1 ED) in L-band,
295 000 km (23.1 ED) in C-band and
190 000 km (14.9 ED) in K-band.**





Thank You for your attention!

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