PROCEEDINGS OF SCIENCE

Radioastron pulsar early science program: Current status and results

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The Radioastron Early Science Program (ESP) is a plan of operations to achieve first scientific results of the RadioAstron (RA) Ground-Space VLBI mission. The preliminary goal of the ESP is to obtain high profile scientific results and to provide a connection between the start of the early Radioastron operations/observations/data processing and the future standard observations by international VLBI community users.

Pulsars offer a variety of effects caused by interstellar plasma. Dispersion by interstellar plasma allows the measurement of the electron column density along the line of sight and this provides an indication of the distance to the pulsar. Scattering effects include scintillations (variations of intensity with time), frequency distortion (decorrelation bandwidth) and angular broadening. These observable issues provide us an ability to study the scattering material as a large, defective lens, producing an image of the pulsar, convolved with the response to a point source at the observer plane.

The RA mission makes possible the detection of angular broadening for many pulsars. With RA it is possible to observe the nearby pulsars with the longest VLBI baselines, up to 300 000 km. We report some results of data processing for RA pulsar experiments. We present the first direct assessments of pulsar broadening, make some constraints on the size of the emitting region and evaluate the distribution of the scattering medium by studying the dynamic cross-spectra and fringes of the Earth-Space baselines. The pulsar mode of the ASL Correlator and its particular features are also discussed.

11th European VLBI Network Symposium & Users Meeting
October 9-12, 2012
Bordeaux, France

[1] Speaker
on behalf of the RadioAstron ESP Working Group

PoS(11th EVN Symposium)050

1.Introduction

This presentation was prepared by the pulsar ESP working team which insludes M. Popov, C. Gwinn, A. Andrianov, N. Bartel, M. Johnson, E.C. Joshi, M. Kramer, V. Shishov, T. Smirnova, V. Soglasnov, V. Zhuravlev, and collaborators…

The RadioAstron project is an international collaborative mission which uses a free-flying satellite, Spektr-R, carrying a 10-m space radio telescope (SRT) on an elliptical orbit around the Earth. The aim of the mission is to use the space telescope for radio astronomical observations using VLBI (Very Long Baseline Interferometry) techniques in conjunction with ground-based VLBI networks. The orbit of the RadioAstron satellite evolves with time and has an apogee between 280,000 and 350,000 km, a perigee between 7,000 and 80,000 km, a period of 8 to 9 days, and an initial inclination of 51°. RadioAstron operates at the standard radio astronomical wavelengths of 1.19–1.63 cm (K-band), 6.2 cm (C-band), 18 cm (L-band), and 92 cm (P-band).

1.1 Pulsars are among prospective objects for space VLBI

Pulsars are very compact objects with angular sizes less then 1 μas, and they may be very conveniently studied with Space VLBI. It allows to investigate interstellar scattering and pulsar emission mechanisms, as described in 4 categories below.

1. Local scattering material

Local scattering material scatters both nearby pulsars and extragalactic intra-day variable sources. The angular broadening is too small to be detected with Earth-based baselines, but should be easily resolved with baselines to Radioastron. The local material appears to scatter in a fundamentally different way from more distant material, through refractive rather than difractive scattering [1]. The material that scatters IDV (intra-day variable) sources appears to be highly elongated (10 : 1) and extremely close ($d < 12$ pc) [2]. Observations of nearby pulsars on a variety of baselines will test this picture. From the measured angular broadening and the characteristic bandwidth of scintillation, we can estimate the distance of the scattering material.

2. Substructures within the scattering disk

The source with large disperse measure values (DM values) is expected to be visible in the speckle limit, but with non-persistent fringes with completely random phase and amplitude variations over the scintillation bandwidth, on this long baseline. Narayan & Goodman [4] proposed that the visibility might arise on long baselines, because of “fractal” substructures within the scattering disk. They suggest that such substructures would carry information about the fluctuations responsible for scattering, and might even allow interferometric imaging in spite of scattering.

3. Resolving pulsar emitting regions

Spatially resolving the source of pulsar emission requires nanoarcsecond resolution, and a lens with a diameter of an AU. Interstellar scattering provides such a lens, although it is highly corrupt. Nevertheless the statistics of the visibility provide information on the size, elongation, and position shift, and their variation over the pulse [3, 5, 6]

The figures of suitability for such observations include the size of the light cylinder (presumably related to the size of the emitting region) measured in units of the resolution of interstellar scattering viewed as a lens, observation of many scintillation elements within one recording bandwidth, and sufficient signal-to-noise ratio within one scintillation element so we can characterize the distribution.

4. Giant pulses

Pulses from all pulsars vary in intensity, but the flux density of the Crab is dominated by the strongest pulses. Strong pulses have durations of microseconds and vary on the Nyquist rate [7]. A single such giant pulse can have a flux density in excess of 10^6 Jy [8]. The short duration of such pulses indicates that they find their origin in an extremely compact region. The complicated structures hint that the propagation physics, such as multipath propagation, may be important. Scattering of the Crab pulsar is dominated by the surrounding Crab Nebula, as indicated by comparison of the angular and temporal broadening [9].

Radioastron observed giant pulses from the Crab as part of the Early Science Program. The best-observed giant pulse is clearly observable at Radioastron and at large telescopes on Earth. Interestingly, the shape of the pulse varies with station position. This suggests that the propagation in the Crab Nebula determines the shape of the giant pulse, since this spatial scale is farther than a beamed source within the light cylinder could produce, given the optics of wave difraction. The distribution function of the intensity does not match that of a scattered point source, but does match that of a resolved source, suggesting that the scattering in the Crab Nebula acts as a lens to spatially resolve the source.

2. Observations

Radioastron pulsar ESP group submitted several applications for obtaining observing time at ground-based telescopes: “Radioastron-HAS Observations of Nearby Pulsars” (Proposal ID: VLBA/12B-247), “Radioastron-LBA Observations of the Vela Pulsar” (Proposal ID:2012APRS/V479), ”Radioastron-EVN Observations of Giant Pulses from the Crab Pulsar” (Proposal ID:E11C019), ”Observations of Giant Pulses from the Crab and Milisecond Pulsars” (Proposal ID:E12B016). All of these applications have been approved and observed time was allocated in a full volume. Table 1. below shows the status of all observing sessions.

3. Data Correlation

Pulsar experiments were processed on ASC correlator. ASC Correlator has several modes for pulsar processing:

- Simple Gate Mode (allows to increase S/N ratio up to 3-5 times)
- Compound Gate Mode: the gate is weighted by the average profile (allows to increase S/N ratio up to 6-20% relative to the Simple Gate mode)
- Bins Mode: many gates (Bins) are used when the on-pulse phase is unknown. The mean profile can be obtained with this mode.

Table 1. Status of observing sessions

#	RA_code	Other_code	Pulsar	Date	Time (h)	Range	Telescopes	Status
1	Rafs01		B0531+21 Crab	15.11.11	1	L	Bd,Ev,Sv,Zk	Processing
2	Rafs12		B0950+08	25.01.12	1	P	Ar,Ef,Wb	Processed
3	Raes04a	Eg060	B0531+21 Crab GP	02.03.12	4	L	Bd,Ef,Ev,Hh,Jb, On,Sv,Ur,Wb	Processing
4	Raes04b	Eg060	B0531+21 Crab GP	06.03.12	3	L	Bd,Ef,Ev,Hh,Jb, On,Sv,Ur,Wb	Processing
5	Raes06a	V2692	B0823+26	18.04.12	2	P	Ar,Ev	Observed
6	Raes06b	V2692	B0950+08	19.04.12	0.5	P	Ar	Observed
7	Raes06c	V2692	B0834+06	26.04.12	2	P	Ar,Ef	Procesing
8	Raes07a		B0833-45 Vela	10.05.12	4	L	Hh,Mp,Pa,Ti	Processing
9	Raes07b		Vela	18.05.12	1.5	L	Hh,Mp,Pa,Ti	Processing
10	Raes09		B1508+55	07.06.12	1.5	P	Ev,ORT	Observed
11	Raes06d	V2692	B1919+21	04.07.12	2.3	P	Ar,Gb,Wb	Processed
12	Raes06e	V2692	B1929+10	07.08.12	1.0	P		No ground
13	Raes06e	V2692	B2016+28	08.08.12	1.1	P		No ground
14	Raes06e	V2692	B1929+10	01.09.12	1.5	P	Ar,Wb	No space
15	Raes06f	V2692	B0525+21	05.10.12	2.0	P	Ar,VLBA	scheduled
16	Raes04c	EP067A	B1937+21	22.10.12	3.0	L	Ar,EVN	scheduled
17	Raes04d	EP067B	Crab	23.10.12	2.0	L	Ar,EVN	scheduled
18	Raes06g	HSA12B-247	B0329+54	26-29.11.12	1.0x4	P	Gb,Ef	planned
19	Raes06h	HSA12B-247	B0809+74	17.12.12	2.0	P	Gb,Ef	planned
20	Raes06k	HSA12B-247	B1133+16	16.01.13	2.0	P	Gb,Ef	planned

Here are some estimates for the signal / noise ratio for these modes:
The full pulsar period is divided into M equal bins. Z is the Noise in a separate Bin. S(m) is the Signal in a separate Bin.
If we sum up all bins (no gate defined) we have:

$$\frac{S}{N}=\frac{\sum_{m=1}^{M}S(m)}{\sqrt{\sum_{m=1}^{M}Z^2}}$$

If we sum Bins with signal with either 0 or 1 weight for each bin (Simple Gate state), we obtain:

$$\frac{S}{N}=\frac{\sum_{m=m1}^{m2}S(m)}{\sqrt{\sum_{m=m1}^{m2}Z^2}}=\frac{\sum_{m=1}^{M}S(m)}{\sqrt{\sum_{m=m1}^{m2}Z^2}}$$

If each bin is weighted by the signal level in the current bin (for this mode we have to know the pulsar mean profile), we finally get:

$$\frac{S}{N}=\frac{\sum_{m=m1}^{m2}S^2(m)}{\sqrt{\sum_{m=m1}^{m2}(S(m)Z)^2}}=\frac{\sum_{m=1}^{M}S^2(m)}{\sqrt{\sum_{m=m1}^{m2}(S(m)Z)^2}}$$

The ASL Correlator can dedisperse data using the incoherent dedispersion algorithm. In this method for each frequency channel we have a corresponding (depending) time delay. The quality of dedispersion by this method depends on the number of frequency channels.

4. Results

Rafs01 experiment (Crab pulsar): correlations (visibilities) were found for selected strong giant pulses at both ground-ground and space-ground baselines. Observed GPs rate was 80 events per hour with SNR > 25 (S > 30000 Jy) with Evpatoria RT. The strongest GP was at a level $5*10^5$ Jy. RA-Earth distance was about 42 000 km, and the projected baseline was about 32 000 km.

Rafs12 experiment (B0950+08 25.01.12): The correlation in a simple gating mode with the ASC correlator is completed. Notable visibilities were found on all baselines including space-ground ones. RA-Earth distance was about 290 000 km, and the baseline projection was about 175 000 km. A preliminary analysis of the shape of crosscorrelation functions indicates the presence of two scattering screens: one at a distance of about 40 pc and the second one at a very close distance of 2 pc. The results of correlation on pulsar B0950+08 are presented in Fig.1 as time-delay diagram. The correlation was performed with 512 channels and a 1 sec integration time (about 4 periods); the gate window value was set to 15 ms. We use a DM value equal to 2.969 pc/cm^3.

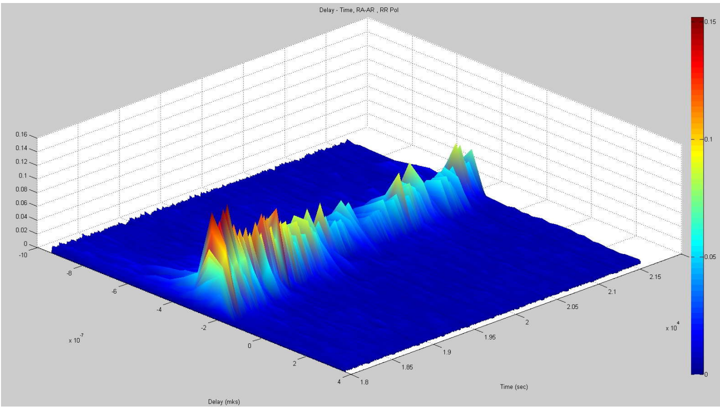

Figure 1.
Amplitude of visibility in time-delay coordinates for pulsar B0950+08 on baseline Radioastron-Arecibo

Rafs04 (a-b) experiment (Crab 02/05.03.12): Correlations (visibilities) were found in a 2x30 –minutes intervals on strong giant pulses but only on ground-ground baselines; processing is being continued. RA-Earth distance was about 280 000 km on March 2, and about 140 000km on March 6 (the baseline projections were about 145 000 km and 120 000 km respectively). In contrast to the Rafs01 case, we were unlucky with the strong GP rate: no events were observed with an SNR > 130 (150000 Jy) during the 8-hour observing period. Only 1-3 events are suitable to look for visibilities on space-ground baselines.

Raes07(a-b) experiment (Vela 10/18.05.12): ASC correlator made correlation with 1 second (10p) integration in a simple gating mode. Visibilities were found for both ground-ground and space-ground baselines. The scattering disk seems to be severely resolved. Namely, we detected fringes on the 100,000 km Radioastron-Tidbinbilla and Radioastron-Parkes baselines. The average normalized visibility was surprisingly $\langle V \rangle = 1.1\%$, whereas a Gaussian model would predict a vanishingly small $\langle V \rangle \sim 10^{-150}$ [3].

Raes06d experiment (PSR1919+21 4.07.12): The correlation in a simple gating mode with the ASC correlator was completed. Notable visibilities were found on all baselines including space-ground ones. RA-Earth distance was about 90 000 km, and the projected baseline was about 70 000 km. Preliminary analysis of the fringe-rate versus radio frequency indicates the presence of two main scattered rays.

References

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