Stars: from Collapse to Collapse
ASP Conference Series, Vol. 510
Yu. Yu. Balega, D. O. Kudryavtsev, I. I. Romanyuk, and I. A. Yakunin, eds.

RadioAstron Maser Observations: a Record in Angular Resolution

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Abstract. Extremely long baselines of the space-ground interferometer RadioAstron allow to achieve ultra-high angular resolutions. The possibility of detection of a maser emission with resolutions about tens of micro-arcseconds was arguable before successful experiments reported in this paper. We present the results of the maser survey obtained by RadioAstron during first 5 years of operation. Extremely high angular resolution of 11 microarcseconds have been achieved in observations of the megamaser galaxy NGC 4258. For the galaxy at the distance about 7 Mpc this corresponds to linear resolution around 80 AU. Very compact features with angular sizes about 20 microarcseconds have been detected in star-forming regions of our Galaxy. Corresponding linear sizes are about 5–10 millions of kilometers.

1. Observations of Masers with RadioAstron

The space-ground interferometer RadioAstron allows observations with the longest-ever baselines exceeding size of the Earth by more than an order of magnitude. Maser sources represent one of the main targets of the RadioAstron (RA) science program along with active galactic nuclei and pulsars. The RadioAstron project allows us to observe maser emission in one quantum transition of water at 22.235 GHz and two transitions of hydroxyl at 1.665 and 1.667 GHz. Water and hydroxyl masers are found in star-forming regions of our and nearby galaxies, around mass-loosing evolved stars, and in accretion discs around super-massive black holes in external galaxies.

Masers have small angular sizes (a few milli-arcsec and smaller), very high flux densities (up to hundreds of thousand Jy), and small line widths (normally about 0.5 km/s and smaller). Because of that masers proved to be precise instruments for studies of kinematics and physical parameters of the objects in our and other galaxies.

The space radio interferometer RadioAstron provides a record of high angular resolution. This provides tight limits on the sizes of the most compact maser spots and estimates of their brightness temperatures, which are necessary input for the studies of the pumping mechanisms.

Typical values of the minimal flux density detectable with RA for the water masers at 22 GHz and hydroxyl masers at 1.665/1.667 GHz are 15 Jy and 3.5 Jy, respectively. These values were calculated for a typical line width of 0.1 km/sec and coherent accumulation time of 100 sec and 600 sec for 22 GHz and 1.665/1.667 GHz, respectively.

So, the sensitivity in Jy for hydroxyl masers is better than for water masers. Anyhow, when we use the large ground-based antenna, for example 100-m GBT, and the line is broad, RA proved ability to detect 3-4 Jy water maser source.

2. Statistics of Maser Observations for the First Five Years of Operation

2.1. Maser Observation Program

During the period from November 2011 to May 2012 interferometric mode of RA operation was tested. For that purpose a number of bright quasars and the brightest and most compact sources of maser emission were selected Kardashev et al. (2015). Basic conditions for choosing these sources were the existence of details that remain compact (i.e. unresolved) on the longest baseline projections and the highest brightness temperatures measured during VLBI and VSOP surveys. The first positive detections of maser sources by space interferometer were achieved for W51 (water) and W75N (hydroxyl) in two sessions in May and July 2012. Baseline projections were 1.0–1.5 and 0.1–0.8 Earth diameters (ED), respectively. Later, more sophisticated data analysis led to even more positive results in these test sessions: compact water maser features were detected in W3 IRS5 and W3(OH) in two sessions in February 2012. Baseline projections were 3.7-3.9 ED.

After the first successful tests the early science program started. The main purpose of these observations was to obtain first astrophysical results and measurements of the main parameters of the operating interferometer. List of observed sources has been significantly expanded, objects of other types were included in addition to the star-forming regions. Stellar masers in S Per, VY CMa, NML Cyg, U Her and extragalactic masers in Circinus and N113 were observed. It was proved that RadioAstron can observe cosmic masers with very high spectral resolution. This was not obvious at the beginning, indicates presence of the ultra-fine structure in the maser images, and that interstellar scattering does not prevent observations of masers in the galactic plane Kardashev et al. (2015). Positive detections for stellar and extragalactic masers were not obtained during the early science program.

The early science program was followed by the key and general research programs which were conducted (and the general program continues at the moment) on the basis of the open call for proposals received from research teams around the world. Details of the preparation and the conditions of the call for proposals are published at the RadioAstron project site[1]. The main objectives of this phase of the maser program are studying the kinematics and dynamics of the compact sources of maser emission in star-forming regions, as well as the study of extragalactic masers. As a result, the signals from extragalactic masers NGC3079 and NGC4258 were detected along with star-forming regions. The maser of NGC4258 is associated with the accretion disk around super-massive black hole at the center of this galaxy. Projected baselines in these observing sessions were up to 2.0 ED (for NGC3079) and 19.5 ED (for NGC4258) corresponding to angular resolutions of 115 μas and 11 μas, respectively.

[1] http://www.asc.rssi.ru/radioastron

Table 1. Maser sources detected on the space–ground baselines

Source	Projected baseline length, ED	Best angular resolution, μas
OH masers, galactic	0.1-1.9	1540
Onsala 1	0.2-0.7; 1.0-1.9	1540
W75N	0.1-0.3; 0.1-0.8	3660
H_2O masers, galactic	0.4-10.0	22
W3 IRS5	2.5-2.8; 3.5; 3.9; 5.4; 6.0; 6.0-10.0	22
W49N	2.2-3.0; 4.5; 7.9; 9.4	23
W3(OH)	3.9	56
Cepheus A	0.9-1.7; 1.1; 3.1-3.5	62
Orion KL	1.9; 3.4	64
W51_E8	0.4-2.3; 1.3; 1.4-1.8; 1.7	95
OH043.8-00.13	1.2; 1.2	182
H_2O masers, extragalactic	1.3-19.5	11
NGC4258	1.3; 1.7; 6.5; 9.5; 11.8; 19.5	11
NGC3079	1.9; 1.9	115

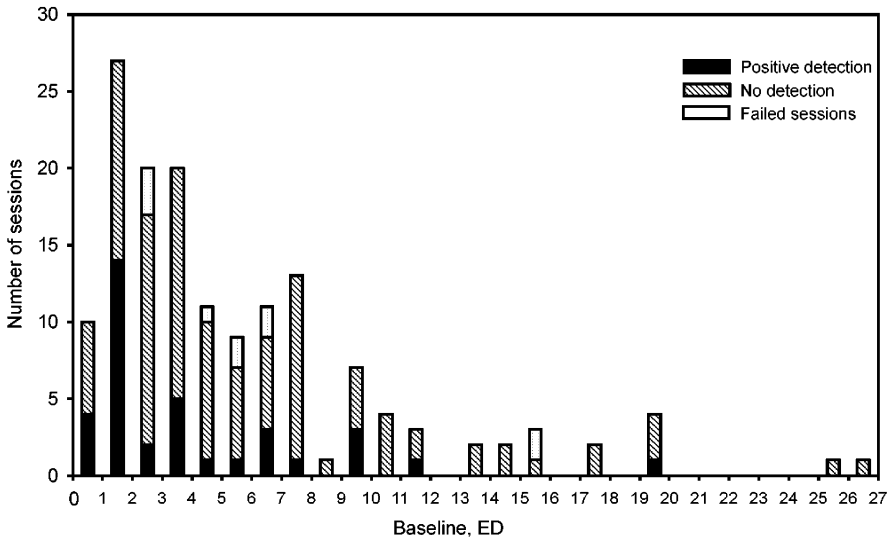

Figure 1. Statistics of maser observation results over projected baseline length of the space interferometer RadioAstron.

2.2. General Statistics of Maser Source Detections

This section provides statistics from the beginning of RA maser observations (November 2011) up to present time (November 2016). During this period a large amount of data was accumulated. 145 maser observation sessions were conducted, and 31 sources were observed. The majority of masers observed in RA program is related to star-forming regions – 19 sources in total. 8 maser sources in the envelopes of late-type stars of the Galaxy were observed, and 4 extragalactic masers in star-forming regions and circum-nuclear disks of external galaxies were observed.

The scientific data have been corrupted or lost in 10 sessions out of total 145 due to technical problems. All observations of the remaining 135 sessions at the moment (November 2016) are processed at the ASC LPI data processing center Kardashev et al. (2013), positive detections are obtained in 34 sessions. Thus, the current detection rate of fringes at space-ground baselines is about 25.2 %.

All of successful fringe detections for galactic masers at space-ground baselines were obtained for the sources associated with star-forming regions, – 26 of all 34 positive detections. 8 detections were obtained for extragalactic masers. No fringes for the stellar masers were obtained at space-ground baselines yet.

Table 1 gives information on the observational sessions which provided positive fringe detection with the space-ground interferometer. The columns show source names, projected lengths of the space-ground baselines at which the interferometric detection was obtained and the last column shows the best angular resolution achieved for each source. Each baseline (or baseline interval) corresponds to one observational session with positive detection.

It is instructive to show the distribution of the number of detections depending on the length of the baseline projection. The Figure 1 presents statistics of observational sessions for the whole set of database lengths. It is seen that most of the positive detections fall in the range from 1 to 4 ED.

3. Summary

The main conclusions of the work are the following:

1. Space-VLBI observations of the water and hydroxyl masers show that the bright details of the masers in galactic star-forming regions often remain unresolved at projected baseline which exceed Earth diameter many times.

2. Record resolution of 11 micro-arcsec for any astronomical observation is obtained for NGC4258 extragalactic water maser. Corresponding linear resolution for this galaxy is around 80 a.u. Scintillation does not prevent fringe detection.

3. Very compact water maser features with the angular sizes of about 20 – 60 micro-arcseconds are registered in galactic star-forming regions. The best linear resolution better than 4 million km (a few solar diameters) was achieved for Orion maser. The best for galactic maser angular resolution of 23 micro-arcsec was achieved for W 49 N. This source is located in galactic plane about 11 kpc away. So, detection provides important input for the theory of interstellar scattering in the Galaxy.

Acknowledgments. The RadioAstron project is led by the Astro Space Center of the Lebedev Physical Institute of the Russian Academy of Sciences and the Lavochkin Association of the Russian Federal Space Agency, and is a collaboration with partner institutions in Russia and other countries. This research is partly based on observations with the 100 m telescope of the MPIfR at Effelsberg; radio telescopes of IAA RAS (Institute of Applied Astronomy of Russian Academy of Sciences); Medicina & Noto telescopes operated by INAF; Hartebeesthoek, Torun, WSRT, Yebes, and Robledo radio observatories. The National Radio Astronomy Observatory is a facility of the National Science Foundation operated under cooperative agreement by Associated Universities, Inc. Results of optical positioning measurements of the Spektr-R spacecraft by the global MASTER Robotic Net, ISON collaboration, and Kourovka observatory were used for spacecraft orbit determination in addition to mission facilities.

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