Estimates of Brightness Temperatures for Maser Sources of the Galaxy Observed by Space Interferometer "RadioAstron"

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The ultra-high angular and high spectral resolutions of RadioAstron provide tight limits on the sizes of the most compact maser spots and the estimates of their brightness temperatures. We present the results of the maser survey obtained by RadioAstron during the first four years of operation. Very compact features with angular sizes not exceeding about 20–60 micro-arcseconds have been detected in star-forming regions. Corresponding linear sizes are about 5–10 millions of kilometers. Brightness temperatures for a number of maser sources are estimated. Estimates of the brightness temperatures provide the values from $\sim 10^{14}$ to $\sim 10^{16}$ K.

1 Observations of masers with RadioAstron

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). Due to 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, in some cases reaching a few tens of micro-arcseconds. 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.

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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/s and coherent accumulation time of 100 s and 600 s 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 source has wide line, RA proved ability to detect 3–4 Jy water maser source.

2 Statistics of maser observations for the first 4 years of operation

2.1 Maser observation program

The goal of the scientific program for the study of cosmic masers using space interferometer RadioAstron was observations of maser emission in quantum transitions of water at frequency 22 GHz and hydroxyl at frequencies 1.665 and 1.667 GHz. 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 [1]. 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 [1]. 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

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

Source	Observed line(s)	Projected baseline length, ED
W3 IRS5	22 GHz (H_2O)	2.5–2.8; 3.5; 3.9; 5.4; 6.0
W51_E8	22 GHz (H_2O)	0.4–2.3; 1.3; 1.4–1.8
Cepheus A	22 GHz (H_2O)	0.9–1.7; 1.1; 3.1–3.5
W49N	22 GHz (H_2O)	2.2–3.0; 9.4
Orion KL	22 GHz (H_2O)	1.9; 3.4
W75N	1.665 & 1.667 GHz (OH)	0.1–0.3; 0.1–0.8
Onsala 1	1.665 GHz (OH)	0.2–0.7; 1.0–1.9
W3(OH)	22 GHz (H_2O)	3.9
NGC4258	22 GHz (H_2O)	1.3

call for proposals are published at the RadioAstron project website [2]. 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, such as NGC3079 and NGC4258. As a result, along with star-forming regions the signal from extragalactic maser NGC4258 was detected. This maser is associated with the accretion disk around super-massive black hole at the center of this galaxy. The projected baseline in this observing session was up to 2 ED, which corresponds to an angular resolution of 110 μas.

2.2 General statistics of maser source detections

This section provides statistics from the beginning of RA maser observations (November 2011) up to the present time (July 2015). During four years of operation a large amount of data was accumulated, and this allows us to sum up the first results of this work. 135 maser observation sessions were conducted, and 31 sources were observed. The majority of masers observed in RA program are related to star-forming regions – 19 sources in total. Eight masers 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.

Due to technical reasons the scientific data have been corrupted or lost in 10 sessions out of total 135. 103 observations of the remaining 125 sessions at the moment (August 2015) are processed, positive detections are obtained in 21 sessions. Thus, the current detection rate of fringes at space-ground baselines is about 20.4 %. Some scientific data is still under consideration at ASC LPI data processing center [3]. The final detection rate is likely to be higher.

All successful fringe detections for galactic masers at space-ground baselines were obtained for the sources associated with star-forming regions, – 20 positive detections. One detection was obtained for extragalactic maser. No fringes for the stellar masers were obtained at space-ground baselines yet. Probably, the spots of the brightest masers in the stellar envelopes are fully resolved at the space-ground baselines.

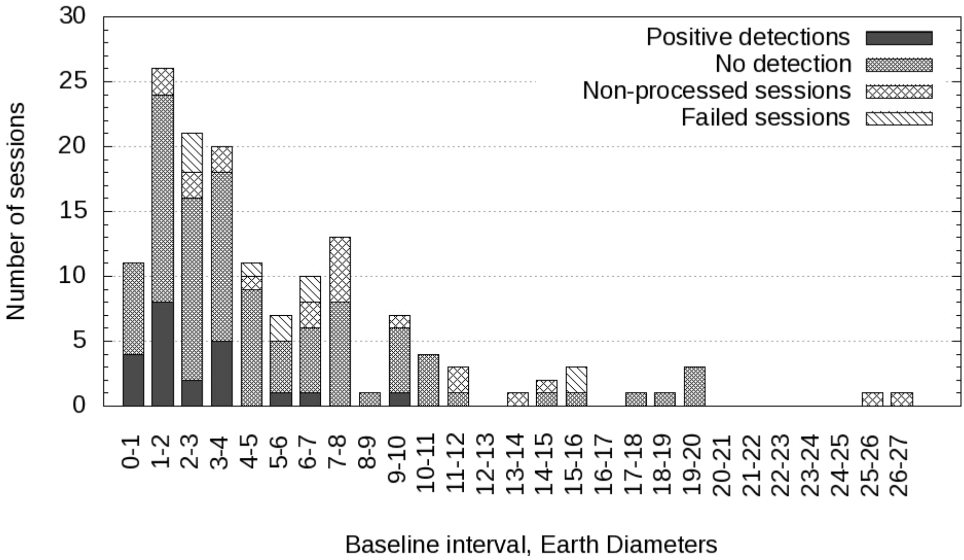

Figure 1: Statistics of maser observation results over projected baseline length of the space interferometer RadioAstron.

Table 1 provides information on the observational sessions which provided positive fringe detection with the space interferometer. The columns show source names, observed lines and projected lengths of the space-ground baselines at which the interferometric detection was obtained. Each baseline (or baseline interval) corresponds to one observational session with positive detection of the fringes.

It is instructive to show the distribution of the number of detections depending on the length of the baseline projection. 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 range from 1 to 4 ED.

3 Estimates of the minimal brightness temperatures for the maser sources of the Galaxy

Brightness temperature is one of the observational parameters of the maser emission which provides a basic and strong constraint on the theoretical models of maser pumping. Usually the brightness temperature is estimated from the source imaging using adequate range of baseline projections. This way requires involvement of many telescopes and a rather long duration of observations in order to obtain good sampling of the uv-plane. But at present the majority of RadioAstron maser data consists of the short observations with duration of about 1 hour with a few baseline sets, about 3 to 6. These are detection experiments which do not allow producing map of the source. Nevertheless, using some assumptions it is possible to estimate brightness temperature and size of the source even for such short sessions.

Table 2: Brightness temperature estimates for some H_2O masers observed by RadioAstron

Source	Baseline, ED	Resolution, μas	Minimal T_b, K	T_b, K
W3 IRS5	3.5	62	9.0×10^{14}	1.5×10^{15}
W3 IRS5	5.4	40	1.5×10^{15}	8×10^{15}
W3 OH	3.8	58	2.1×10^{14}	7×10^{14}
Cepheus A	3.4	64	1.2×10^{14}	3×10^{14}
Orion	3.3	66	1.2×10^{15}	6×10^{15}
W49N	9.6	23	4.5×10^{14}	2.6×10^{15}

For example, we can assume that the shape of the brightness distribution is a circular Gaussian. This proved to be a good approximation in many observed cases. Under this assumption we can estimate brightness temperature of the source using the formula proposed in [5]

$$T_\mathrm{b} = \frac{\pi}{2k} \frac{B^2 V_0}{\ln\left(V_0/V_q\right)}. \tag{1}$$

Here B is a baseline, V_q is an amplitude of visibility function at a single spatial frequency $q = B/l$, and V_0 is a space-zero visibility. It was shown [5] that T_b has its lowest value when $V_0/V_q = e$. This provides the minimal brightness temperature estimate $T_\mathrm{b,min}$ when the values of baseline and correlated flux are obtained from observations

$$T_\mathrm{b,min} \approx 3.09 \left(\frac{B}{\mathrm{km}}\right)^2 \left(\frac{V_q}{\mathrm{mJy}}\right) [K]. \tag{2}$$

Principles of the maser data processing have basic similarities to continuum data processing. However, maser observations greatly depend on the proper selection of the frequency band and need a large number of frequency channels for correlation. This imposes additional requirements on the correlator software. We carried out post-correlation data processing using the VLBI processing software package PIMA [4]. Source fluxes were calibrated using system temperature measurements provided by the telescopes participating in observations with RA.

4 Results and conclusions

Here we discuss some estimates of T_b and $T_\mathrm{b,min}$ obtained from the measured source flux S under the assumption that the brightness distribution is a circular Gaussian. Some results for compact features detected in star-forming regions W3 IRS5, Orion KL, W3 and Cepheus A are presented in Table 2. Each line corresponds to one observational session. In the second column the baselines in units of ED's are given. In the third column resolution in micro-arcseconds is given. The last two columns show estimates of the brightness temperatures T_b and $T_\mathrm{b,min}$ in Kelvin. The highest temperature is obtained for W3 IRS5 source (8×10^{15} K). Angular resolution is very high, so we observe very compact features of about 20 to 60 micro-arcseconds. Such angular sizes correspond to linear sizes of about 5–10 million km or several solar diameters.

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 baseline projections which considerably exceed Earth diameter. Record resolution for the maser observations at present are obtained for W49N water maser – 23 micro-arcsec at projected baseline 9.6 ED.
2. Very compact water maser features with the angular sizes of about 20–60 micro-arcseconds are registered in galactic star-forming regions. These correspond to linear sizes of about 5–10 million km (several solar diameters).
3. Estimates of the brightness temperatures for the ultracompact interstellar water maser features range from $\sim 10^{14}$ to $\sim 10^{16}$ K.

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