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# I-VLBI of molecular masers

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**Abstract.** Intense maser emissions of several molecular species (OH, $CH_3OH$, $H_2O$, SiO) are widely observed toward both star-formation regions and late-type stars. VLBI observations of molecular masers offer an unique opportunity to study the kinematics of the circumstellar gas in both the earliest and latest evolution phases of a star. The forthcoming Sardinia Radio Telescope (SRT) together with the other two Italian antennae of Medicina and Noto, will in the near future constitute a three-element VLBI array of sufficiently high sensitivity and angular resolution to allow one to map the strongest maser lines of $CH_3OH$ (at 6.7 GHz), $H_2O$ (at 22.2 GHz) and SiO (at 43 GHz). The Italian VLBI network (I-VLBI) can be competitive in the observation of molecular masers provided that time flexibility and frequency agility will be granted.

## 1. Introduction

Several molecular species (OH, $H_2O$, $CH_3OH$, SiO) are observed to emit intense maser emission in different rotational transitions at cm wavelengths. The spatial structure of molecular masers consists of several compact (size $\sim$ 1 AU) emission centers (named "maser spots"), distributed across a region of typical diameter of hundreds to thousands of AU. Typical flux densities of maser spots range from $\leq$1 Jy up to 1000 Jy. The compact nature and the high intensity of maser spots makes it feasible to observe them using the Very Long Baseline Interferometry (VLBI) technique, achieving very high angular resolutions $\leq$1 mas. For maser sources at distances of $\approx$1 kpc, such a high angular resolution permits to measure proper motions of maser spots of a few km s$^{-1}$ performing multi-epoch observations over time baselines of a few months. Putting together the transverse and line-of-sight velocities (the latter are derived via the Doppler effect), the full 3-dimensional velocity pattern traced by the masing gas can be measured.

The maser lines of $CH_3OH$ at 6.7 GHz and $H_2O$ at 22.2 GHz are particularly strong toward massive star-forming regions. Single-dish surveys and interferometric observations have indicated that these two masers trace the earliest stages of the high-mass star-forming process (Walsh et al. 1998; Beuther et al. 2002; De Buizer 2003). In particular, VLBI observations have shown that in several sources the $H_2O$ 22.2-GHz masers trace the base of (proto)stellar jets (Torrelles et al. 2003; Moscadelli et al. 2005). Intense $CH_3OH$ 6.7-GHz masers have been observed with VLBI to exhibit a linear or arc-like distribution of maser spots, with also a regular variation of line-of-sight velocity with the spot position (Minier et al. 2000). The nature of these ordered structures traced by 6.7-GHz masers has still to be clarified. Young Stellar Objects (YSO) where both (6.7-GHz and 22.2-GHz) masers are observed, are of particular interest, as comparing VLBI positions and velocities of

**A)** ANGULAR RESOLUTION ( MILLIARCSECOND )

| | 1.7 GHz | 6.7 GHz | 22.2 GHz | 43.0 GHz |
|---|---|---|---|---|
| VLBA | 4.3 | | 0.3 | 0.17 |
| EVN | 5 | 5 | 0.3 | 0.6 |
| I-VLBI | 42 | 10 | 3 | 1.6 |

**B)** 0.2 km s$^{-1}$ AVERAGE BASELINE SENSITIVITY (Jy)

| | 1.7 GHz | 6.7 GHz | 22.2 GHz | 43.0 GHz |
|---|---|---|---|---|
| VLBA | 0.35 | | 0.8 | 1.4 |
| EVN | 0.09 | 0.11 | 0.28 | 0.77 |
| I-VLBI | 0.2 | 0.17 | 0.29 | 0.73 |

**C)** 0.2 km s$^{-1}$ IMAGE RMS SENSITIVITY (mJy beam$^{-1}$)

| | 1.7 GHz | 6.7 GHz | 22.2 GHz | 43.0 GHz |
|---|---|---|---|---|
| VLBA | 10 | | 8 | 9 |
| EVN | 2 | 6 | 3 | 9 |
| I-VLBI | 28 | 26 | 21 | 20 |

**Fig. 1.** Each of the three (A, B, C) tables compares the I-VLBI performance (last row) with that of the VLBA (first row) and the EVN (second row) arrays, when operating at four characteristic maser frequencies. Table A gives the array angular resolution in milliarcsec. Table B the baseline sensitivity in Jy, adopting a velocity resolution of 0.2 km s$^{-1}$ comparable with the maser line-width. Table C the rms sensitivity on the channel (0.2 km s$^{-1}$), synthesized map. For each VLBI array and frequency, the reported baseline sensitivity is calculated taking an average over the baselines to the most sensitive antenna (Effelsberg for EVN, SRT for I-VLBI). The image rms sensitivity of the EVN has been calculated making use of the 'EVN Calculator" (http://www.evlbi.org/cgi-bin/EVNcalc), which takes into account the quite large spread in sensitivities of the EVN antennae.

the two maser species offers the best opportunity to unveil the gas kinematics in the proximity of the forming star.

The atmosphere of Mira variable stars can be accurately studied using molecular masers. SiO 43-GHz masers emerge very close to the photosphere of the star at distances of only a few stellar radii (∼1 AU). $H_2O$ 22.2-GHz masers trace the inner, more turbulent portion of the stellar wind, whereas OH 1.7-GHz masers are found more externally, arising from gas of the stellar wind which has already reached the terminal velocity. Therefore, multi-frequency VLBI observations of these molecular masers permit one to obtain a detailed description of the gas kinematics around Mira variable (and other late-type) stars.

## 2. I-VLBI compared to other VLBI arrays

The forthcoming 64-m Sardinia Radio Telescope (SRT) together with the other two Italian 32-m antennae of Medicina and Noto, will in the near future constitute a three-element VLBI array (I-VLBI) suitable for the observation of various maser lines. Figure 1 is a collage of three tables comparing the performance (in terms of angular resolution, baseline and image sensitivity) of the I-VLBI array with that of the two VLBI arrays, EVN (European VLBI Network) and VLBA (Very Long Baseline Array), presently in use. The comparison is done at four operation frequencies corresponding to the emissions of the OH (1.7 GHz), $CH_3OH$ (6.7 GHz), $H_2O$ (22.2 GHz) and SiO (43.0 GHz) masers. Table A shows that the angular resolution achievable with I-VLBI, $\leq$10 mas for frequencies higher than $\approx$7 GHz, will be sufficient to separate the contribution of different spot clusters, typically separated by tens of milliarcsec. In particular, at 6.7 GHz, not operated by the VLBA, the I-VLBI will have an angular resolution "only" twice worse than that of the EVN (Chinese antennae are not working at this frequency). Table B shows that the I-VLBI baseline sensitivity will be significantly better than for the VLBA and comparable with that of the EVN. Adopting a $5\sigma$ detection threshold, the I-VLBI will be able to fringe-fit and correct for atmospheric phase errors, 6.7 and 22.2-GHz masers with peak flux density $\geq$1 Jy. Finally Table C indicates that, coherently integrating the visibility phases, spots as weak as $\sim$100 mJy will be detectable (using a threshold of $5\sigma$).

Since, typically, molecular masers have a peak flux density of (at least) a few Jy, the I-VLBI array will have the potentiality to map most of the known maser sources. One of its major contributions might be the observation of 6.7-GHz and 22.2-GHz maser associations. These latter cannot be easily observed, either by EVN (which is not agile in frequency) or by VLBA (not working at 6.7 GHz). After recent upgrades, the Noto antenna is now able to switch among different observing frequencies in a few minutes. The SRT is also planned to be agile in frequency. Should Medicina be upgraded for fast receiver change, similar to Noto, I-VLBI might observe the two maser species in two consecutive runs, providing a simultaneous picture of the kinematics of these masers.

In order to measure proper motions of the maser spots, it is essential to optimize the epochs' time separation, which is required to be as short as a few weeks for fast variable, close-by $H_2O$ masers and as long as many months – 1 yr for slow and distant $CH_3OH$ masers. Therefore it is clear that I-VLBI needs to be a time-flexible VLBI facility, which in turn implies that each of the three antennae should move rapidly from single-dish to VLBI operation.

## 3. 6.7-GHz Medicina–Noto VLBI

Since a few years we have been carrying on observations of a sample of 6.7-GHz methanol masers using (single-baseline) Medicina–Noto VLBI. Our immediate aim was to establish sub-arcsecond absolute positions of the 6.7-GHz masers. Their single-dish coordinates are in general accurate to within 1 arcmin or less, and that prevents them from being observed with VLBI (EVN), which requires coordinates accurate to within (at least) a few arcsec. The determination of precise absolute positions is therefore mandatory for VLBI follow-up observations of these masers. In addition to that, we were interested in evaluating the potentiality of Medicina–Noto VLBI for the purpose of determining the 6.7-GHz maser structure, in view of future observations of these masers using the I-VLBI.

Since only one 6.7-GHz receiver was available to the Italian community, in order to perform Medicina–Noto VLBI, the first step was to build a new 6.7-GHz receiver. A copy of the already existing 6.7-GHz receiver was produced by a collaboration of the Osservatorio Astronomico di Cagliari and the Istituto di Radioastronomia, Bologna. Up to now, two sessions of VLBI observations have been conducted, in May 2003 and March 2004. The data have been correlated at the MPIfR (Max-Planck-Institute-für-Radioastronomie) correlator, using an integration time (0.5 s) sufficiently small to provide a field-of-view of several arc-minutes, larger than the single-dish uncertainties in the maser target positions. The observations have been performed in phase-referencing mode, alternating scans (2–3 min long) between the maser target and a close-by (separated by $\leq 5^o$) phase-reference continuum

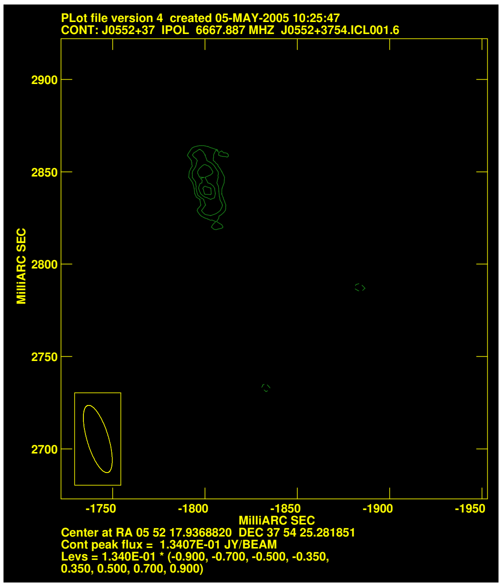


**Fig. 2.** Image of the quasar J0552+3754 obtained using single-baseline Medicina–Noto VLBI. Before mapping, the visibility phases of the quasar have been corrected with the fringe-fit solutions obtained from the nearby maser source S231. The contour levels of the map are indicated at the bottom of the panel.

source, whose position is known with an accuracy of ~1 mas or better.

We determined sub-arcsec positions for 15 of the 19 observed 6.7-GHz masers. With only two antennae, the phase-referencing technique worked well with phase-reference sources of intensity higher than ≈ 0.1 Jy and separated from the maser target by less than $5^o$. The few failures regarded sources very close ($\pm 5^o$) to the celestial equator, for which the $u - v$ coverage was too poor and the corresponding synthesized beam too extended along the North-South direction. The measured maser positions have uncertainties ranging from ≈30 mas to 1 arcsec, depending on the maser source intensity and declination, and on the phase-reference intensity and separation.

The limited $u{-}v$ coverage achievable working with only two antennae, results in large synthesized beams (the typical FWHM size along the major axis was 30–40 mas) and very high side-lobes (75–95% of the main lobe). Besides, with only two antennae it is not possible to perform self-calibration of the visibility phases (which requires one to relate the phases of at least three antennae) and to correct for rapid atmospheric phase fluctuations. Then, unavoidably, residual phase errors in the produced maps scatter the source signal and degrade the signal-to-noise of the image. Our conclusion is that Medicina–Noto VLBI results inadequate to determine the structure of most (but the most extended) 6.7-GHz masers, as the accuracy with which relative spot positions can be determined is only of the order of tens of mas. Figure 2 shows the Medicina–Noto image of the quasar J0552+3754, used as phase-reference calibrator for the maser source S231. Before mapping, the phase corrections obtained fringe-fitting the maser data were applied to the phase-reference calibrator. One can note that the quasar image has an irregular elongated shape, ≈40 mas in size, and that negative peaks (in absolute value ≥ 35% of the positive maximum) are visible at distances up to 100 mas from the map peak.

In order to evaluate the improvement of the image quality when the SRT (together with Medicina and Noto) will be used, we produced a map of the 6.7-GHz maser source 19217+1651, recently observed by us with EVN, selecting only data of three antennae: Effelsberg, Jodrell and Onsala. Before mapping, the maser data were corrected with the phase solutions obtained working with the nearby phase-reference source 1924+1540. In this case, having three antennae allowed us to self-calibrate the data and to remove most of the residual atmospheric phase errors. The image of the strongest 6.7-GHz maser component in 19217+1651, shown in Fig. 3, is of better quality than the image of the quasar J0552+3754 of Fig. 2. The synthesized beam is smaller (the FWHM size along the major axis is 11 mas) and the first side-lobe is (in absolute value) 60% of the main lobe. The strongest spot appears to have a compact emission, its intensity distribution being close to that of the (Gaussian) clean beam. Fitting an elliptical Gaussian, it is possible to determine the absolute position of the map peak with an accuracy of a few mas. Relative positions of less

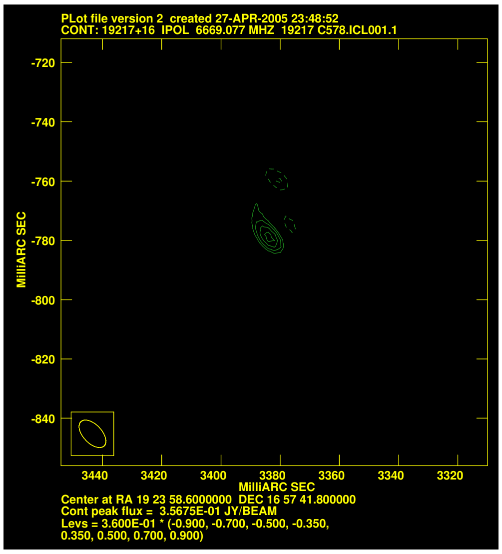


**Fig. 3.** Image of the strongest 6.7-GHz maser spot in 19217+1651 obtained using the subset of EVN data relative to antennae of Effelsberg, Jodrell and Onsala. Before mapping, the visibilities of the maser have been corrected with the phase solutions obtained by fringe-fitting and self-calibrating the visibilities of the nearby phase-reference source 1924+1540. The contour levels of the map are indicated at the bottom of the panel.

intense spots in other channels can be derived with similar precision. This result allows us to be confident that the future three-antennae (SRT, Medicina and Noto) Italian VLBI array will potentially have the capability of studying also the spatial structure of the 6.7-GHz masers.

## References

Beuther, H., Walsh, A., Schilke, P., et al. 2002, A&A, 390, 289

De Buizer, J.M. 2003, MNRAS, 341, 277

Moscadelli, L., Cesaroni, R., & Rioja, M.J. 2005, A&A, 438, 889

Minier, V., Booth, R.S., & Conway, J.E. 2000, A&A, 362, 1093

Torrelles, J. M., Patel, N. A., Anglada, G., et al. 2003, ApJL, 598, L115

Walsh, A.J., Burton, M.G., Hyland, A.R., & Robinson, G. 1998, MNRAS, 301, 640