# Astrometry of $H_2O$ maser sources in Orion KL with VERA

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## Abstract

We present the initial results of multiepoch VLBI observations of 22 GHz $H_2O$ masers in the Orion KL region with VERA (VLBI Exploration of Radio Astrometry). With the VERA dual-beam receiving system, we carried out phase-referencing VLBI astrometry, and successfully detected the annual parallax of Orion KL to be 2.29±0.10 mas, corresponding to a distance of 437±19 pc from the Sun. The distance to Orion KL was determined for the first time with the trigonometric parallax method in these observations. Although this value is consistent with that previously reported, 480±80 pc, which was estimated from a statistical parallax method using the proper motions and radial velocities of the $H_2O$ maser features, our new results provide a much more accurate value with an uncertainty of only 4%. In addition to the annual parallax, we detected an absolute proper motion of the maser feature, suggesting an outflow motion powered by the radio source I along with the systematic motion of source I itself.


## 1. What is *VERA*?

VLBI Exploration of Radio Astrometry
- Newly constructed VLBI array in Japan
- Dedicated to phase referencing VLBI
- Astrometry of $H_2O$ and SiO maser sources with 10 micro arcsec. accuracy

Scientific target
- Absolute proper motion and annual parallax measurements
- 3-dimensional map and velocity field of the Galaxy, distribution of dark matter
- Detailed study on molecular gas in star-forming regions and evolved stars
- Period-luminosity relation of Mira valuables

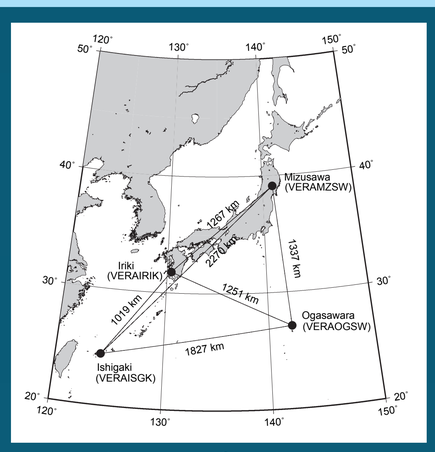


Fig. 1: VERA array configuration. Maximum baseline is 2270 km (between Mizusawa and Ishigaki-jima).

## 2. Basic Specification of VERA

Main reflector
- Diameter ; 20 m
- Aperture efficiency ; 50-55%@22 GHz
- HPBW ; 160"@22 GHz

Receiver
- Observing bands ; 22 GHz ($H_2O$ maser) 43 GHz (SiO maser)
- Receiver temperature ; 50 K @22 GHz
- System temperature ; 100-200 K @22 GHz

Fig. 2: VERA 20 m antenna at the Ishigaki station.

Backend
- Tape recording rate ; 1 Gbps (Maximum bandwidth is 16 MHzX16IFs)

Dual beam receiving system
- Phase referencing to improve sensitivity with long integration
- Simultaneous observations of maser sources and reference sources (QSOs).
- Instrumental phase error is estimated by measuring radiation from noise sources on the main reflector.
- Path error between 2 beams is better than 100 micro meter.

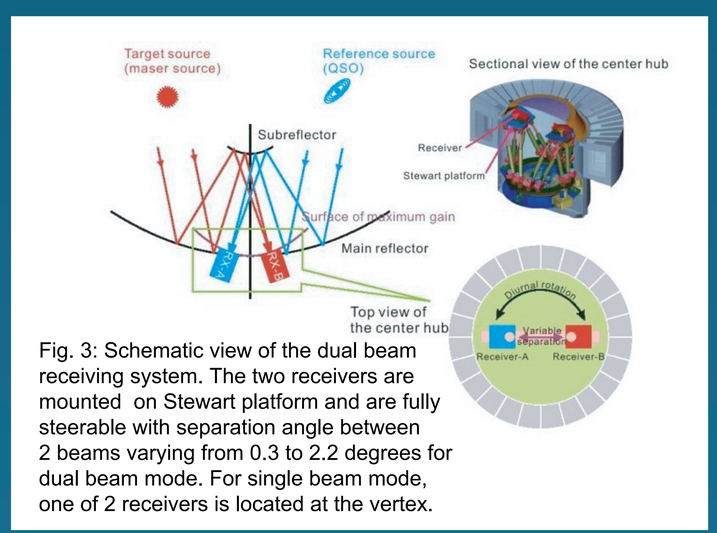


Fig. 3: Schematic view of the dual beam receiving system. The two receivers are mounted on Stewart platform and are fully steerable with separation angle between 2 beams varying from 0.3 to 2.2 degrees for dual beam mode. For single beam mode, one of 2 receivers is located at the vertex.

Fig. 4: The dual beam receiving system of VERA.

## 3. Parallax measurements with VERA

Low-mass YSOs
- IRAS 16293-2422: $5.6^{+1.5}_{-0.5}$ mas---$178^{+18}_{-37}$ pc (Imai et al. 2007)
- NGC1333 SVS13A: 4.25+/-0.32 mas---235+/-18 pc (Hirota et al. 2008)

High-mass YSOs
- S269: 0.189+/-0.008 mas---$5.28^{+0.24}_{-0.22}$ kpc (Honma et al. 2007)
- Orion KL ($H_2O$): this poster (Hirota et al. 2007b)
- Orion KL (SiO): Kim et al., poster in this symposium
- NGC281 West: Sato et al., poster in this symposium (Sato et al. 2007)

Measurements for other YSOs and late-type stars are now ongoing.

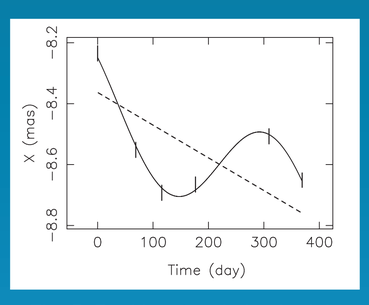


Fig. 5: Positional variation in right ascention for the $H_2O$ maser spot in S269. A solid line represents the best fit model with the parallax and absolute proper motion (Honma et al. 2007). Position of S269 is α=06h14m37.08s, δ=+13d49'36.7" (J2000).

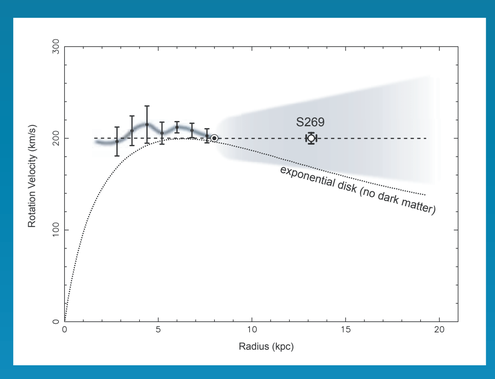


Fig. 6: Rotation curve of the Milky Way Galaxy obtained in the result from S269. Dashed line is the flat rotation curve and shadowed area shows possible range of outer rotation curves in previous studies. Points at R ≤ 8 kpc are inner rotation curves determined from the tangential velocities of Galactic HI gases. Dotted curve is the rotation curve for an exponential disk. Discrepancy between the observed point for S269 and the exponential disk demonstrates the existence of large amount of dark matter in the outer region of the Galaxy (Honma et al. 2007).

## 4. Astrometry of the $H_2O$ masers in Orion KL

Observations
- Orion KL and J0541-0541 (reference source); separation angle ~ 1.6 deg.
- Monitoring from 2004 January to 2006 July

Analyses using AIPS
1. Amplitude calibration, bandpass calibration
2. Fringe fitting with the reference source
3. Self-calibration with the reference source
4. Phase-referencing
   - 4.1. Apply above results to the maser source
   - 4.2. Dual beam phase-calibration
   - 4.3. Correction of atmospheric zenith delay (GPS)
5. Imaging the maser source

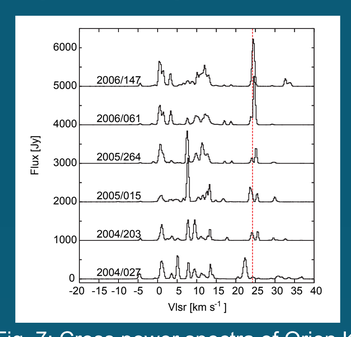


Fig. 7: Cross power spectra of Orion KL observed with the VERA Mizusawa–Iriki baseline (1267 km). The red line indicates the velocity of the maser feature adopted for the parallax measurement (25 km/s).

Results
- Only single maser feature was analysed
- Annual parallax of Orion KL
  $\pi$ = 2.29+/-0.10 mas; D = 437+/-19 pc (RA data only)
- *Absolute* proper motion of maser feature (w.r.t. reference source J0541-0541)
  $\mu_{RA}$=2.77+/-0.21 mas/yr, $\mu_{Dec}$=-8.97+/-0.21 mas/yr
  ---- Parallel to that of source I (Rodriguez al. 2005)

Comparison with other studies
- SiO masers in Orion KL (Kim et al., poster in this symposium) 401+/-11 pc
- Radio continuum (15 GHz) source GMR-A (Sandstrom et al. 2007); $389^{+24}_{-21}$ pc
- Radio continuum (8 GHz) sources in ONC (Menten et al. 2007); 414+/-7 pc

All of the results are consistent with ~410 pc, rather than 480 pc (Genzel et al. 1981)

Discussions
- Large scatter in position of maser feature
- Larger uncertainty in the annual parallax
  ---- Structure of $H_2O$ maser feature
  Atmospheric zenith delay
- Jet/outflow from source I (GMR I) and systematic motion of Orion KL system

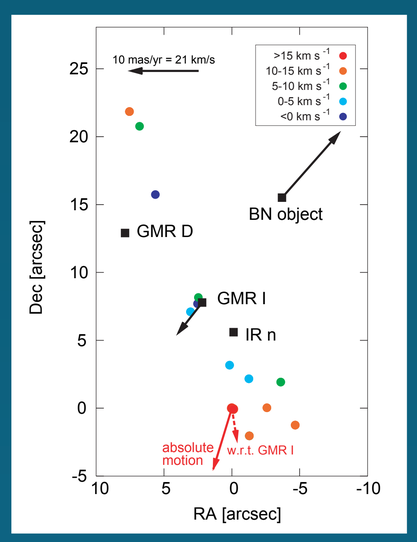


Fig. 8: Distribution of $H_2O$ maser features (filled circles) and radio continuum sources (square; Gomez et al. 2005) in Orion KL. Bold arrows indicate the absolute proper motion vectors based on our study and Rodriguez et al. (2005), while the dashed arrow shows the proper motion of the maser feature with respect to source I.

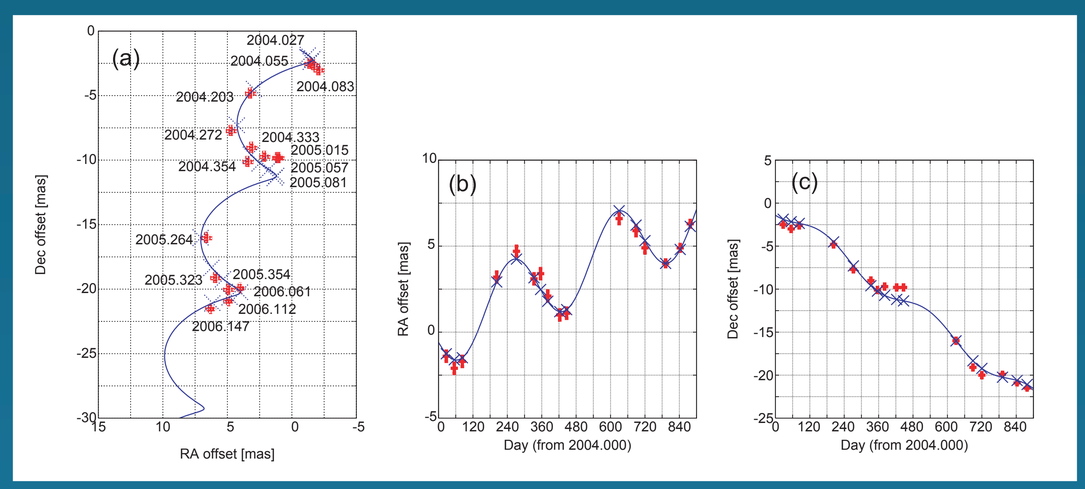


Fig. 9: Results of the position measurement of the maser feature in Orion KL. (a) Movement of the maser feature on the sky. (b) Movement of the maser feature in right ascension as a function of time. (c) Same as (a) in declination. Blue lines represent the best-fit model with the annual parallax and linearproper motion for the maser feature. Red points represent the observed positions of the maser feature with error bars indicating the standard deviations of the least-squares analysis (0.36 mas in RA and 0.74 mas in Dec). Observed epochs are indicated in panel (a).

## 5. Future work

Other maser spots in Orion KL
- Annual parallax/distance measurements, comparison with other works
- Proper motion measurements
  --- To reveal large scale structure and kinematics of jets/outflows
  To specify powering sources

Other YSOs in Orion-Monoceros Molecular Cloud Complex
- HH1 in Orion A
- OMC-2 in Orion A
- Mon R2 IRS3 in Monoceros
- Others ... (e.g. in Orion B)
  --- To reveal 3D structure and kinematics of molecular cloud complex

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