Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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Sub-mm spectral astrometric VLBI with the ngEHT

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Abstract.
We present the prospects from astrometric spectral line VLBI in the era of ngEHT. We review the potential targets, that span many interesting science cases. We summarise the approaches that have been demonstrated to work at lower frequencies and touch on the simulations that give us great confidence that these same approaches will continue to work at sub-mm wavelengths. We conclude that this is a worthwhile pursuit with a high probability of success.

Keywords. Astrophysics - astrometry; Astrophysics - masers; Astrophysics - Instrumentation and Methods for Astrophysics

1. Introduction

We present our conclusions on the opportunities provided by the Next Generation Event Horizon Telescope (ngEHT), which include the ability to perform astrometric VLBI observation at millimeter and sub-millimeter wavelengths.

The challenges for Astrometry at high frequencies is all about the atmosphere; as the frequency get higher the coherence time also gets shorter as the same extra atmospheric pathlength represents an increasing fraction of the wavelength. But additionally the system temperatures of the radio telescopes gets worse, as the engineering challenges become more difficult. The trigger for this paper was the work towards a new sub-mm VLBI array, the next-generation Event Horizon Telescope, led by the Black Hole Institute out of CfA in Harvard (Johnson *et al.* (2023)). The ngEHT will eventually be 10 antenna sites, all capable of performing simultaneous observations at 86, 230 and 340GHz bands, with new small high performance parabolic dishes. It is envisaged to operate both in conjunction with the Event Horizon Telescope (EHT) and in isolation. To ensure sensitivity when observing without the massive collecting area of ALMA it is possible that there will be a small number of high sensitivity sites with multiple antennas that will be phased up together.

2. Maser targets for ngEHT

There has been a recent study on the range of spectral line VLBI that would be possible with the ngEHT (Kim & Fish (2023)), as summarised by their figure reproduced in Figure 1. They point to the myriad of detections of unexpected mazing species made by the ALMA connected array, at lower resolutions. This provides confidence that there are maser targets for ngEHT.

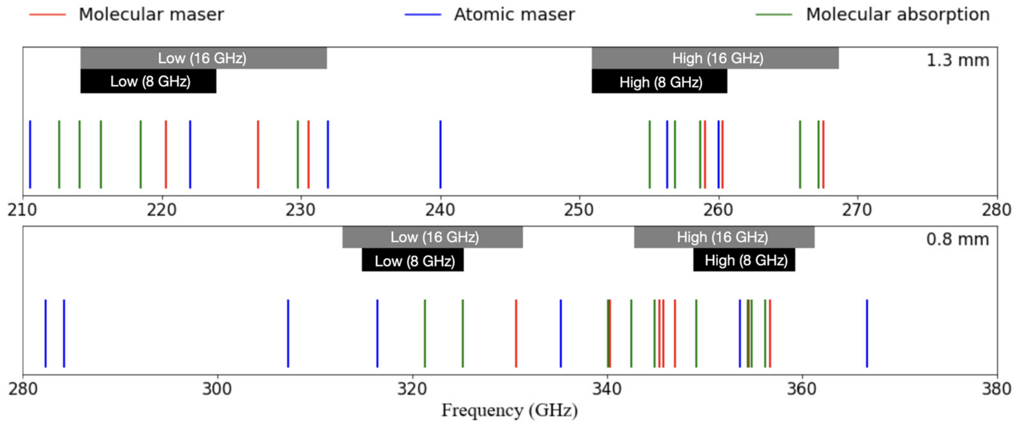

Figure 1. Distribution of spectral lines over the frequency range of 1.3 mm and 0.8 mm. Each color indicates the type of spectral lines. Frequency coverage of 8 GHz and 16 GHz observations is marked with two different frequency tunings (low and high).

These can be summarised as:

• Molecular lines

These trace distinct excitation conditions in the circumstellar envelopes of AGB stars and star forming regions. Asymptotic Giant Branch (AGB) are the final stage of the majority of the stars on the main branch and their pulsations seed the ISM with molecular species generated in the stellar body. Thus these are of vital importance for our understanding of galactic evolution. They act as delicate probes of the astro-chemistry (i.e. temperature, the elements present, and pressure). Some of the most common maser species are SiO, which forms in the outer atmospheres of the star, and 22GHz H_2O, which form via shock interactions in the accelerated outflows. The sub-mm H_2O (e.g. 345GHz) will also form closer to the stellar surface in inner regions and connect the two most common species, allowing the seamless connection of the matter transfer. The sub-mm H_2O is expected to form and this would be about 2-5$R_\odot$ (which is half of the radius at which 22GHz emission is to be found).

On the other hand carbon rich, and thus oxygen poor, AGBs lack water and SiO. Thus the masing species of HCN and SiS, which both have sub-mm transitions, will fill similar roles as H_2O and SiO in those AGB stars.

Massive Star Forming Regions (SFR) host OH, H_2O and CH_3OH masers, which have been widely used to measure the proper motion, parallax and outflows of these regions (e.g. Reid *et al.* (2019)). The distances to these relatively rare objects has been vital to, for example, measuring their individual physical conditions (e.g. absolute brightness) as well as global parameters such as the Galactic Rotation curve. Lower mass SFRs host sub-mm masers of similar character, as has been observed by ALMA. High sub-mas resolution and precision is required to resolve the proper motion, parallax and outflows of these objects.

• Atomic lines:

Hydrogen Radio Recombination Lines (RRL) can maser in sub-mm range; first observation were reported in Cox *et al.* (1995). For example the H_α-30 line has been used to probe post-AGB and Planetary Nebulae for bipolar outflows using VLBI. Of particular interest are ultra-compact H-II regions, where the low resolution observations suggest bipolar outflows, but VLBI is required to confirm this and to image the details.

• Molecular Absorption Lines:

It is important in the study of Gravitational Lens to identify the distance to the lensing

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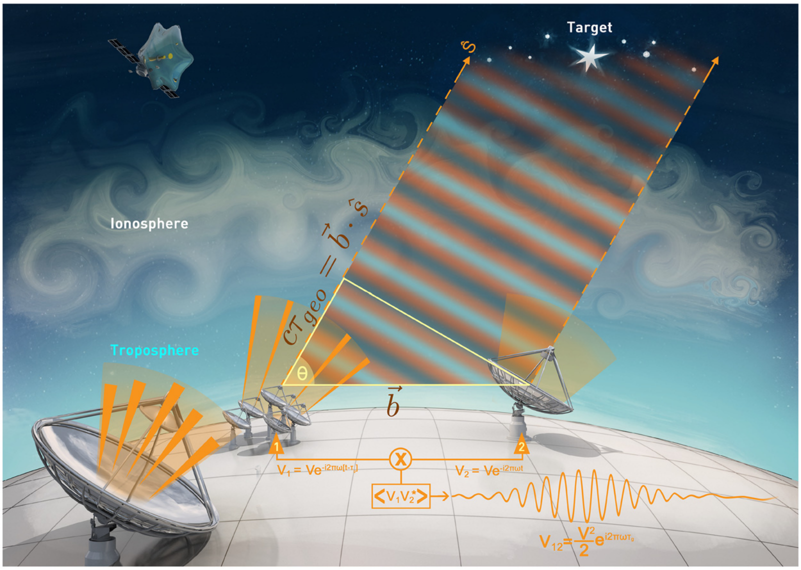

Figure 2. Schematic from Rioja & Dodson (2020) that shows all the possible approaches for sub-mm astrometric VLBI. Next generation methods include: Source/Frequency Phase referencing using different frequencies to solve for non-dispersive terms, and MultiView which use multiple sources to solve for spatially varying terms. Next generation technology options for SFPR include rapid frequency switching (order of seconds) and simultaneous multi-band receivers. Next generation technology options for MultiView include moderate sized single dishes combined with: large single dishes with multiple beam technologies, arrays of smaller dishes with multiple Tied Array Beams and paired antennas of smaller dishes with multiple pointing centres.

galaxy, which can be very hard. For example for the gravitational lens 1830-211 it took a long time to identify the distance to the lensing galaxy (Winn *et al.* (2008)). Absorption is one of the tools that will give a distance to the lensing galaxy directly. Furthermore, the detection of rare molecular species is easier in absorption, as high resolution is required to resolve the clouds, improve the SNR of the detection and to get accurate mass estimates of the absorbers. Similarly absorption from the circumnuclear gas in AGN allows studies of the structure and chemical composition of these disks surrounding and feeding the central black hole.

3. Approaches for astrometry with mm-VLBI

We have completed a through and deep analysis of the paths to ultra-precise astrometry, as reported in Rioja & Dodson (2020). This was focused on the lower frequencies and SKA, but the conclusions are still applicable to the higher frequencies, and potentially ngEHT. For example we have completed a study of the expected performance of the Frequency Phase Transfer (FPT) between the 86- and 340-GHz frequency bands (Rioja *et al.* (2023)), and a survey of the major science applications (Jiang *et al.* (2023)). Figure 2, reproduced from Rioja & Dodson (2020), shows schematically the possible station combinations for sub-mm astrometric VLBI.

For sub-mm VLBI astrometry the most well established method is that of Source/Frequency Phase Referencing (Rioja & Dodson (2011)), where the calibration from lower frequency is scaled and applied to the higher frequency. This implicitly assumes that the calibration errors are non-dispersive, which include the antenna position or the source position, but are dominated by the troposphere residual path-length. Additionally we are coming to realise that MultiView (Rioja *et al.* (2017)) will also be

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applicable to sub-mm VLBI, even though it was developed for the lower frequencies. This is because MultiView uses multiple calibrators to solve for all contributions for the errors, interpolated to the line of sight of the target. Thus all (linear) systematic contributions are removed. In the sub-mm domain the one additional requirement is that observations of the sources are performed simultaneously, at least to some extent. This is discussed further in the next section.

4. Prospects

Firstly it is important to note that no one has performed sub-mm astrometric VLBI. The requirements have long been considered impossible. Nevertheless we now believe we can see a path to achieving this goal.

The Frequency Phase Transfer method is expected to work up to the sub-mm regime; similar demonstrations have been performed in band-to-band calibration with ALMA (Asaki *et al.* (2020)). Source/Frequency Phase Referencing tests between 86-GHz and 215-GHz have been performed, but are yet to be released. However the data seems good with potential simultaneous observations at Pico Valeta and the combined SMA/JCMT site, which will demonstrated a 'paired antenna' configuration. Unfortunately simultaneous observations at KVN-Yebes failed; the experiment will be repeated.

Demonstrations of the MultiView method at 86GHz are under consideration. Ideally MultiView would be performed with multiple beams from one antenna, but a dish small enough to see multiple 86GHz compact sources would be too small to be sensitive enough. Thus the only option is to have pairs of antennas, which are sufficiently physically close such that the atmospheres can be considered common. Using the typical wind speed of 10m/s would imply that the same formulae for the errors due to the 'temporal sampling' of the atmosphere could be used with the distance between the paired antennas standing in as the time step. See Walker *et al.* (2020) for discussions. Groups of paired antennas were a suggested concept for some of the stations of the ngEHT, to provide an increased collecting area for crucial hub stations that would then be the reference antennas for the other less sensitive sites.

To investigate the possibilities and requirements we have started to do some testing in this direction, using the fastest possible switching times on the VLBA. Currently we have made 43GHz observations switched at sub-minute timescales over angular scales as much as 5 degrees. These seem to be promising.

5. Conclusions

In conclusion, there are multiple interesting targets for spectral line sub-mm astrometric VLBI. These provide unique probes of different aspects of astrophysics, such as the various regions around AGB stars. There are routes to perform sub-mm astrometric VLBI; for a single source the reference of emission between transitions and molecules is a delicate and precise probe of the thermal and chemical conditions in the pumping regions of astrophysical masers. The frequency phase transfer method is well tested and can be expected to work between the 86 and 340GHz bands. The potential for relative spatial astrometry is under investigation, and has rigorous requirements, such as multiple paired antennas per site. On the other hand these seem to be achievable, if a sufficient strong science case can be made to address the additional costs.

In summary, it is worthwhile to attempt spectral line astronomical VLBI at sub-millimeter wavelengths, we are confident that it will be possible to perform trans-frequency astrometry and we are hopeful it will be possible to perform trans-source astrometry.

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