Quasar jet structures at ~300 micro-arcsecond angular resolution using Event Horizon Telescope imaging algorithms

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Very Long Baseline Interferometry (VLBI) is a technique where radio telescopes from different geographical locations simultaneously observe a source to provide the highest resolution imaging and precision astrometry (at sub-milli-arcsecond and tens of micro-arcsecond scales respectively). Geodetic and astrometric VLBI observations of extragalactic radio sources at 2.3 GHz (S-band) and 8.4 GHz (X-band) are used to define the International Celestial Reference Frame (ICRF), a quasi-inertial radio reference frame adopted by the International Astronomical Union (IAU) in 1997. In turn, geodetic VLBI observations of these reference sources are critical to many applications, for example, the realization of the International Terrestrial Reference Frame (ITRF); calculating the orientation of the Earth in space; providing calibrator sources for parallax measurements, as well as for imaging faint sources in astronomy; studying the motion of tectonic plates; measurements of the sea level rise; and spacecraft navigation, to name but a few.

Bright extragalactic radio sources that are well suited to improve the high-accuracy reference framework must be compact or core-dominated on VLBI scales. However, at the standard S/X frequencies, many ICRF sources exhibit spatially extended intrinsic structures that may vary with time, frequency and baseline projection. Such structures can introduce significant errors in the VLBI measurements thereby degrading the accuracy of the estimated source positions. On VLBI scales, sources generally appear more compact at higher frequencies (see Fig 1). It may, therefore, be possible to reduce source structure effects by transitioning to higher frequency VLBI observations. However, while spatially-resolved sources are not desirable for astrometric purposes, they could be of great interest from an astrophysical standpoint, including rare objects such as binary, offset or recoiling supermassive black holes and complex relativistic jet structures that probe the physics of these central engines. The identification and high-fidelity imaging of these resolved objects is therefore of key dual importance in this project.

A K-band (24 GHz) celestial reference frame of 919 quasar sources covering the full sky has been constructed using over 0.5 million observations from 68 observing sessions from the Very Long Baseline Array (VLBA) and two radio telescopes in the South, the HartRAO 26 m telescope in South Africa and the Hobart 26 m telescope in Tasmania. As mentioned before, observations at K-band are motivated by their access to more compact source morphology and reduced core shift relative to observations at the historically standard S/X-band (2.3/8.4 GHz). Some preliminary K-band imaging results from the VLBA are shown in Fig. 2. These have been produced with standard VLBI imaging software.
The aim of this proposed MSc project will be to produce images of sources observed in the K-band ICRF using the VLBA, to determine their suitability as reference sources, and identify sources of astrophysical interest. These higher frequency data should show more compact structure due to the lower brightness temperature sensitivity, which this project will verify. In addition, multi-epoch VLBA imaging can be used to compare the direction of radio-optical and radio-radio astrometric offsets with jet direction. We have ~40 sources that show > 5 sigma astrometric optical-radio offsets, that will be a priority for imaging.

The imaging using traditional software with be compared with the results of cutting-edge imaging algorithms developed for high-frequency VLBI by members of the Event Horizon Telescope (EHT) Consortium, of which co-supervisor Deane is a member. This software has been demonstrated to perform better than traditional methods if suitably tuned, as seen is the one-sided jet of M87 reported in Chael et al. 2016, see Figure 2.

This project will be based at the South African Radio Astronomy Observatory's HartRAO facility as well as the University of Pretoria's radio astronomy group. The student will also work in collaboration with other members of the VLBI groups at these two institutes. International travel is likely, depending on progress.

![Fig 1. Radio source structure versus frequency, showing more compact structure and higher angular resolution.](image1)

![Fig. 2. Demonstration of the superior performance of the eht-imaging algorithm (middle and right panels) on 43 GHz VLBA observations of the famous one-sided jet source, M87, when compared to the traditional method (CLEAN, left panel). These maps have all been convolved by the same beam, however, eht-imaging can achieve super-resolution factors of 2-3. Reproduced from Figure 9 of Chael et al. (2016).](image2)