Cosmic Masers: Proper Motion toward the Next-Generation Large Projects
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The 40-m Thai National Radio Telescope with its key sciences and a future South-East Asian VLBI Network

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Abstract. National Astronomical Research Institute of Thailand (Public Organization) initiated a national flagship project in 2017 for development of radio astronomy and geodesy in Thailand. In this project, a 40-m Thai National Radio Telescope (TNRT) and a 13-m VLBI Global Observing System (VGOS) radio telescope as its co-location are constructed in Chiang Mai. The 40-m TNRT is the largest telescope for radio astronomy in South-East Asia. Its flexible operation with a wide-coverage of observable frequencies 0.3-115 GHz will allow us to uniquely contribute to the time-domain astronomy as well as carry out unbiased surveys for a wide variety of science research fields, which were published in a white paper. Within the framework of collaboration with VLBI arrays in the world, TNRT will drastically improve the imaging quality and performances based on its unique geographical location, for both radio astronomy and geodetic VLBI studies in South-East Asia for the first time. On-going commissioning of TNRT particularly in the L-band system (1.0–1.8 GHz) is introduced as well as vision for establishment of forthcoming regional VLBI networks based on TNRT: Thai National VLBI Array and South-East Asian VLBI Network in collaboration with Indonesia, Malaysia, and Vietnam.

Keywords. Telescopes, Radio continuum, Radio lines, Interferometers

1. Introduction

Along with an essential probe of electromagnetic waves in the multi-messenger astronomy era, following the successful pathway of the 2.4-m optical telescope (Thai National Telescope) in the last decade, National Astronomical Research Institute of Thailand

Figure 1. The 40-m Thai National Radio Telescope in Chiang Mai, Thailand, with its operation room (Image credit: Left - NordNordWest in Wikipedia; Middle and Right - TNRO/NARIT).

(NARIT: Public Organization) initiated a national flagship project in 2017 for development of radio astronomy and geodesy, known as Radio Astronomy Network and Geodesy for Development. This project was strongly motivated by the importance of the development by "Ourselves" to achieve an empyreal goal of "Capacity building through radio astronomy and geodesy", via constructing national radio telescopes in Thailand. This construction has provided precious opportunities to develop engineering / technical / instrumental skills, its technology, unique sciences achieved with these telescopes, and essential experiences on the basis of collaboration with world-wide colleagues at the world-class facilities, as well as contribute to education via cultivating potential young astronomers, engineers, and geodesists.

For this, NARIT has established the Thai National Radio Observatory (TNRO) in Huai Hong Khrai Royal Development Study Centre, Doi Saket District, Chiang Mai, in the northern part of Thailand since 2018, which is 40 km away from NARIT headquarters in the North-East direction. Given a radio quiet zone and low amount of water vapor on the basis of site investigations, this location is the best suitable site to build up radio telescopes covering low to high frequencies, consisting of a 40-m Thai National Radio Telescope (TNRT, Figure 1) and a 13-m VLBI Global Observing System (VGOS) radio telescope (TNRT co-location, in collaboration with Shanghai Astronomical Observatory (SHAO)), with a visitor center to be opened to general public (Jaroenjittichai 2018; Jaroenjittichai *et al.* 2017).

2. Overview of the 40-m Thai National Radio Telescope (TNRT)

The 40-m TNRT is located at latitude 18°51′52″ N and longitude 99°13′01″ E at 450 m above mean sea level. This is the largest telescope for radio astronomy in South-East Asia. The TNRT was started to be built in 2018, based on the National Geographical Institute (IGN) 40-m Yebes telescope (e.g. López Fernández *et al.* 2006; de Vicente *et al.* 2006) with a classical Nasmyth-Cassegrain focus optics, but is upgraded with the installation of a Tetrapod Head Unit at the prime focus. This upgrade enables the selection of either a receiver at the prime focus or the sub-reflector to be used for receivers installed at the Nasmyth focus in the receiver cabin. Given the specifications at the best performance: a pointing accuracy of 2 arcsec (no wind case) and a surface accuracy of 150 μm rms, we plan to install multiple receivers for the telescope from 300 MHz up to 115 GHz, which contains P/L/C/X/Ku/K/Q/W-bands.

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The first receivers to be installed for commissioning and early sciences are the L-band (1.0–1.8 GHz, linear pol.) and K-band (18–26.5 GHz, circular pol.) receivers equipped with the Universal Software Backend (USB) system enabling multiple observation modes. These were developed in collaboration with Max Planck Institute for Radio Astronomy (MPIfR), while the Ku-band receiver (10.70–12.75 GHz) used for microwave holography was developed in collaboration with Yebes Observatory, IGN (e.g. Lopez-Perez *et al.* 2014). The Telescope Control Software (TCS) is based on the ALMA Common Software and was also developed in collaboration with Yebes Observatory, IGN. The L-/Ku-bands and K-band receivers have been installed at the prime and the Nasmyth focuses, respectively. The multiple observation modes consist of 1) pulsar with coherent dedispersion, baseband and search mode recording; 2) spectrometer / continuum; 3) polarimeter; and 4) Very Long Baseline Interferometry (VLBI) with vdif format. This will be followed-up by developing and installing forthcoming receivers step by step: C/X/Ku-bands (4.5–13.6 GHz), Q/W-bands (35–50 and 75–115 GHz) to be integrated with existing K-band into a simultaneous quasioptics triband system in collaboration with Korea Astronomy and Space Science Institute (KASI), and 0.7–2.1 GHz Phased Array Feed in the design study phase.

2.1. *The First Lights of TNRT*

The first lights of TNRT were achieved in 2022 at last, reaching a milestone, as shown in Figure 2. The intrinsic first light received was an HI emission at 1.42 GHz from our Milky Way Galaxy with the L-band receiver transiting the zenith standby position on 24 March 2022 (Figure 2 left). The first light from tracking a source was completed through receiving a pulsar signal from B0329+54 on 15 June 2022 (Figure 2 upper-right), which is the brightest pulsar in the Northern hemisphere. The latest light in L-band was detected on 25 October 2022 in the spectrometer mode for ground-state of all four OH maser lines in the high-mass star-forming region W49 North. In particular, the brightest emission at 1.665 GHz (Figure 2 lower-right) presented multiple spectral components in the LSR velocity range from 0 to +25 km s^{-1}, which is consistent with the spectrum in previous literature (e.g. Bayandina *et al.* 2021). These milestones were immediately publicized via NARIT Facebook (accessible through scanning QR codes in Figure 2) and news media with the PR divisions at NARIT. In addition, the first light at K-band was also achieved via detecting one of the brightest H_2O maser emission in the same high-mass star-forming region W49 North on 16 December 2022.

3. Key Science Cases with TNRT

To prepare for launching TNRT, a science working group was organized with world-wide collaborators to discuss key science cases achievable with TNRT for a wide-variety of research fields and the wide-coverage of observable frequencies: pulsar, fast radio burst, gravitational wave, star formation, galaxy, active galactic nucleus (AGN), evolved star, chemically peculiar star, maser, and geodesy. Based on an advantage as our own radio telescope with flexible operations and as being accessible to both the Northern and the Southern hemisphere, key sciences with TNRT as a single dish focuses on time-domain astronomy, which addresses exploration of transients / variability and achievement of high-cadence monitoring campaigns planned for known sources or as unbiased surveys for all the sky. These ideas were published as a white paper in arXiv website on 12 October 2022 (Jaroenjittichai *et al.* 2022).

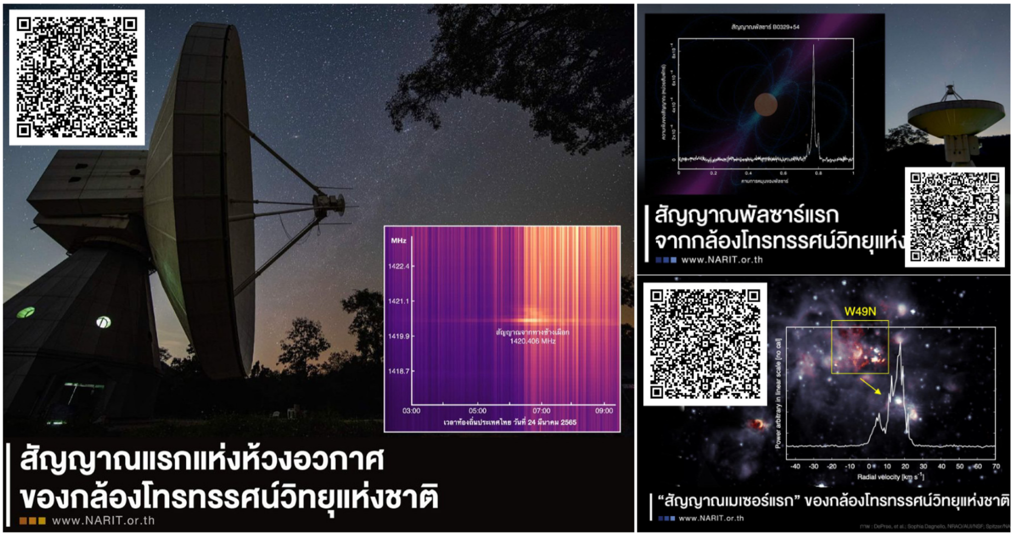

Figure 2. (Cited from NARIT Facebook, accessible through scanning QR codes in each panel) The 1st lights detected with TNRT L-band receiver in 2022. (Left) HI emission from the Milky Way Galaxy. (Upper-right) Pulsar signal from B0329+54. (Lower-right) OH maser at 1.665 GHz in the high-mass star-forming region W49 North (Image credit of background: DePree, et al.; Sophia Dagnello, NRAO/AUI/NSF; Spitzer/NASA).

3.1. *Impacts on VLBI*

Moreover, TNRT will be a powerful telescope for promoting any VLBI activities, with VLBI arrays that have sufficient common-sky with TNRT: East Asia VLBI Network (EAVN), European VLBI Network (EVN), Long Baseline Array (LBA), and Giant Metrewave Radio Telescope (GMRT). For any of those cases, due to its unique geographical location, TNRT contributes to improving the UV-coverage effectively, by adding one of the longest baselines in unique directions as well as filling gaps in the coverages, such as shown in Figure 3 for K-band. The TNRT will thus enhance spatial angular resolution and imaging quality for a wide-range of frequencies for each VLBI array. Figure 4 is an example of a simulation for VLBI towards the collimated radio jet ejected from AGN M87, using EAVN without TNRT (left panel: K. Hada & Y. Cui, in private communication), and using EAVN with TNRT (right panel) in K-band, respectively. This simulation presents the drastic improvement of the imaging quality via reduced side-lobes and also demonstrates the impressive snap-shot imaging capabilities. The TNRT participation will thus enhance VLBI large programs, accelerate the synergy with essential projects in multi-messenger astronomy era, and achieve the first trial of Geodetic VLBI in South-East Asia.

4. Commissioning

To prepare TNRT for operations, performance evaluations for the telescope are currently undertaken, particularly for the general engineering commissioning of the L-band receiver.

4.1. *RFI Bird's-eye View*

Even in the radio quiet zone at the site, an essential commissioning component is to clarify the directions and the strengths of dominant radio frequency interference (RFI). This is achievable with making an RFI distribution map. It enables us to mitigate the

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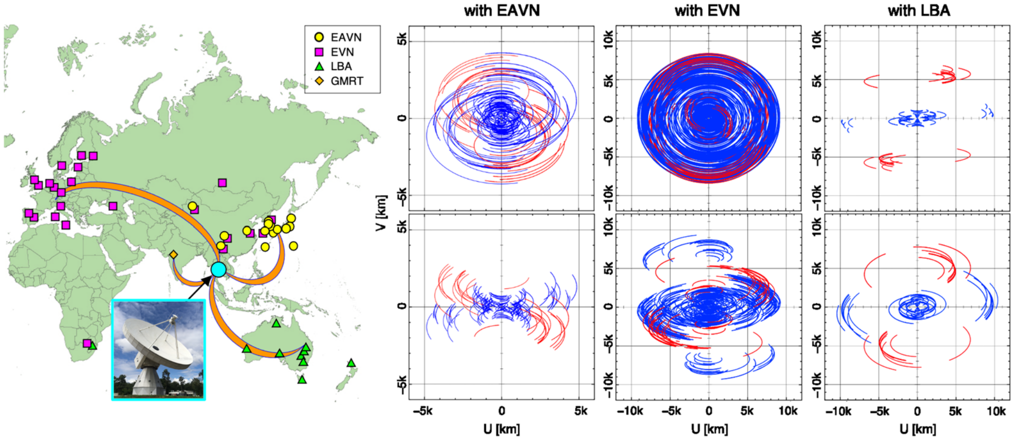

Figure 3. (Cited from the white paper, section 1 and appendix) (Left) Geographical location of TNRT and VLBI arrays that have sufficient common-sky with TNRT: EAVN (circle), EVN (square), LBA (triangle), and GMRT (diamond) (Image credit of background world-map: Illust AC). (Right) simulated results of uv-coverages in K-band for EAVN+TNRT, EVN+TNRT, and LBA+TNRT, respectively. Contributions of TNRT are shown by bold-red lines. The upper and lower panels are for source declination of +40, +60, +10, and −29, +20, −29 deg (toward the Galactic Center) from left to right, respectively.

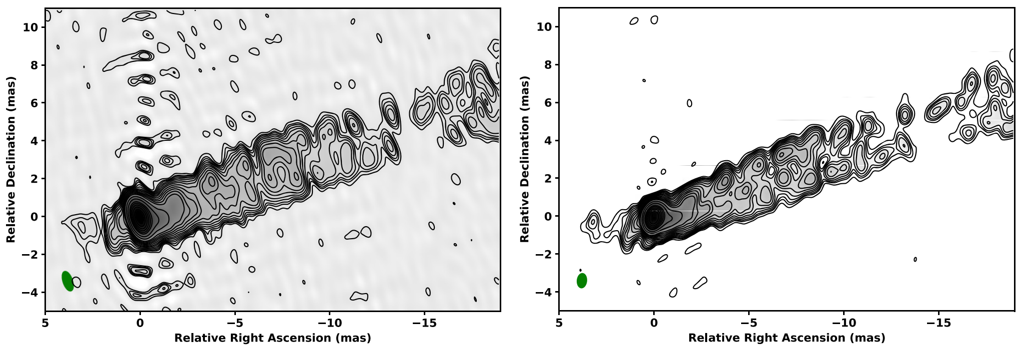

Figure 4. (Cited from the white paper, section 4) Simulated VLBI CLEAN (uniformly weighted) images of M87 at 22 GHz in K-band. (Left) image reconstructed with EAVN (KaVA+Tianma+Nanshan+Takahagi: K. Hada & Y. Cui, in private communication). (Right) image reconstructed with EAVN+TNRT. Beam size is shown as an ellipse in the bottom left corner of each panel. For both images, the contours start from −1, 1, 2, ... times 240 μJy beam^{-1} and increase by a factor of $\sqrt{2}$.

impact on TNRT in L-band and to avoid saturation of total-power in the receiver. This mapping was conducted with a 90-cm parabolic reflector antenna (Rohde & Schwarz AC008 with HL024A1: Figure 5 left) and the data were recorded with a spectrum analyzer (Keysight Fieldfox N9918B). The 90-cm antenna was installed on the top of GNSS (Global Navigation Satellite System) tower, which is 80 m away from the TNRT in roughly North-East direction and enables us to watch the same sky and the directions as for with the TNRT. The observations were designed with 3 deg steps both in AZ and EL directions with an integration time of 30 sec at each point and completed in February 2023. Integrated over 1–2 GHz for 30 sec, the first RFI bird's-eye view at the TNRO site was unveiled, as shown in Figure 5 (right). This viewing map clarified the direction and zone of the strongest RFI with an approximately 15 dB increased power level, corresponding to the South-East direction in AZ from 90 to 180 deg in EL lower

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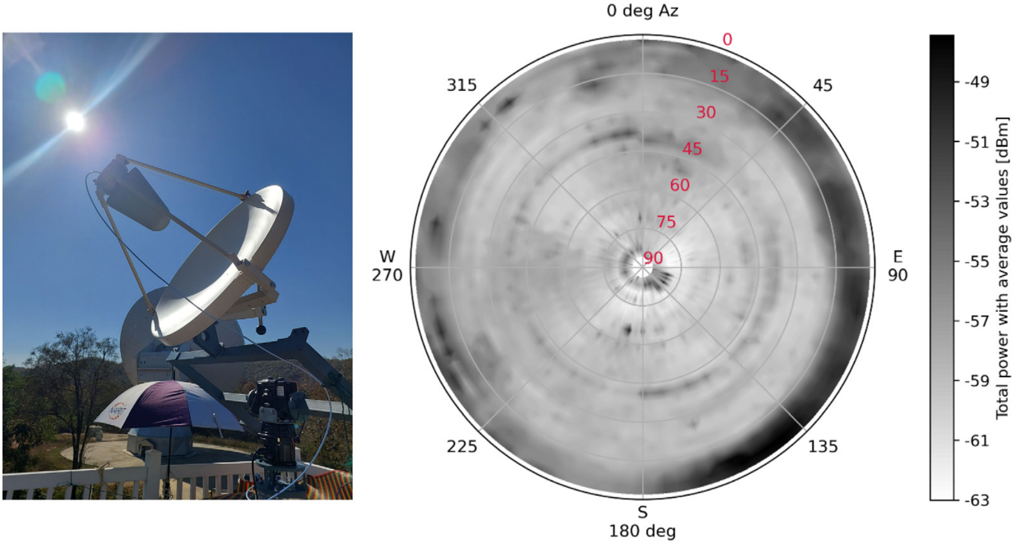

Figure 5. RFI bird's-eye view map at the TNRO site observed with a 90-cm parabolic reflector antenna. Color scale (white to black) is indicated with the right-hand side bar.

than 15 deg (shown in black). This zone should be avoided. Investigated with spectra, a major contributor of this elevated power level is found in the range of 1.805–1.845 GHz, which could be caused by transmission from a mobile phone tower/station. This on-going essential activity will be conducted continuously 24 hrs/day and 7 days/week as a regular RFI monitoring using the 90-cm dedicated antenna to be installed permanently covered by a membrane. Its continued operations will be useful for confirming the repeatability, for verifying the time variability, and for finding new RFI impacting TNRT operations immediately.

4.2. *Determining the Temperature of a Noise-source (NS)*

Another essential commissioning component is to calibrate an amplitude with its scaling into temperature. For this, the temperature of a NS ($\mathrm{T_{NS}}$) in the L-band system was determined with the R-Sky method and injecting the NS. The basic formula to determine $\mathrm{T_{NS}}$ is

$$\mathrm{T_{NS}} = (\mathrm{T_{rx}} + T_{\mathrm{amb}}) \cdot \{(P_{\mathrm{R+NS}}/P_{\mathrm{R}}) - 1\} \tag{1}$$

where $\mathrm{T_{rx}}$ and T_{amb} is the temperature of the receiver and the ambient environment, respectively, and $P_{\mathrm{R+NS}}$ and P_{R} represents the power in the case of covering the horn by an absorber with and without injecting the NS, respectively. The term $\mathrm{T_{rx}} + T_{\mathrm{amb}}$ can be estimated by the sec$Z$ method with an absorber (temporary installed on top of the L-band horn, shown in Figure 6 right). As a result, $\mathrm{T_{NS}}$ was determined to be 30.9 ±1.1 K. Verification that this $\mathrm{T_{NS}}$ works well was done by comparing the system noise temperatures T^{*}_{sys} measured by injecting the NS to the ones by R-Sky. Along the sec$Z$ axis, T^{*}_{sys} consistently ranged between 15 and 30 K using either of the methods as shown in Figure 6 (left). The best T^{*}_{sys} of around 15 K signifies that this L-band receiver has one of the best noise performances in the world.

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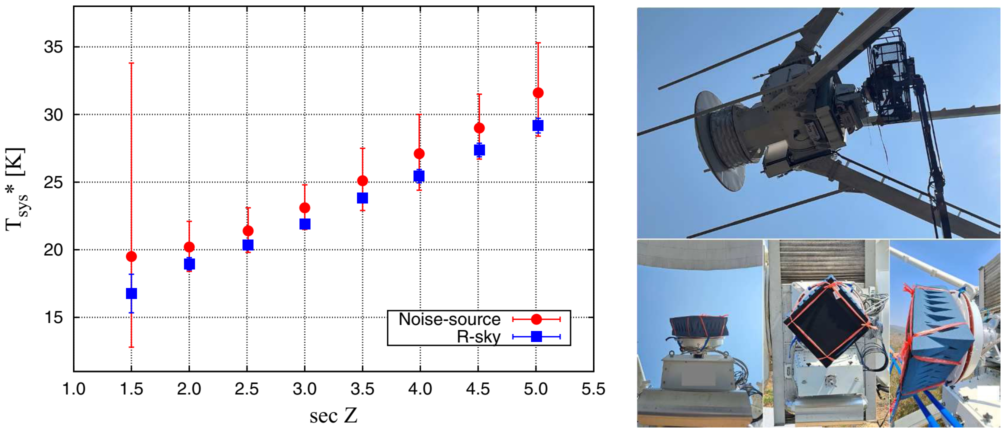

Figure 6. (Left) System noise temperature $T^*_{\rm sys}$ (included atmosphere) versus sec$Z$. $T^*_{\rm sys}$ measured with injecting the noise-source and R-sky methods are shown by circle and square symbols, respectively. (Right) scene in temporal installation of an absorber on top of the L-band horn (detached already).

4.3. *Others*

Other commissioning items are on-going for the L-band system: pointing tuning†, beam-pattern confirmation, aperture efficiency with gain-curve measurement, skyline bird's-eye view mapping, linearity investigation, and Allan variance evaluation. This will be followed by commissioning for the K-band receiver installed at the Nasmyth focus.

5. Vision for Establishment of Regional VLBI Networks

5.1. *Thai National VLBI Array (TVA)*

As introduced in section 1, NARIT is working on facilitating a 13-m VGOS station in TNRO in collaboration with SHAO, to be launched in 2024. This will be followed by building another VGOS station in Songkhla, in the southern part of Thailand, at a distance of 1,330 km from Chiang Mai, allowing extensive applications in geodesy and tectonic studies covering the two different Eurasian and Sunda plates in South-East Asia. A receiver installed at the Songkhla VGOS has been developed in collaboration with Yebes Observatory, IGN. Futhermore, there are other possible candidate antennas available for radio astronomy in Thailand: telecommunication antennas with the diameter of 32-m at the campus of CAT Telecom Public Company Limited in Chonburi and Ubon Ratchathani, in the central and eastern part of Thailand. These antennas will potentially be converted into radio telescopes with a similar technique used for the Yamaguchi 32-m, Hitachi and Takahagi 32-m, Warkworth 30-m radio telescopes, and so on (e.g. Fujisawa *et al.* 2002; Yonekura *et al.* 2016; Woodburn *et al.* 2015). Completing these plans will result in the establishment of Thai National VLBI Array (TVA: Figure 7 left), aiming to be launched since 2026 in C/X/Ku-bands and possibly in K-band.

5.2. *South-East Asian VLBI Network (SEAVN)*

The TVA will be the solid foundation for establishing a forthcoming regional VLBI network: South-East Asian VLBI Network (SEAVN). The SEAVN will be achieved in collaboration with Indonesia, Malaysia, and Vietnam. The Institut Teknologi Bandung together with the Timau National Observatory in Indonesia plan to build a new radio telescope at the Timau site, in the eastern part of Indonesia, and conduct the conversion

† Deconstructed pointing model: https://icts-yebes.oan.es/reports/doc/IT-OAN-2007-26.pdf

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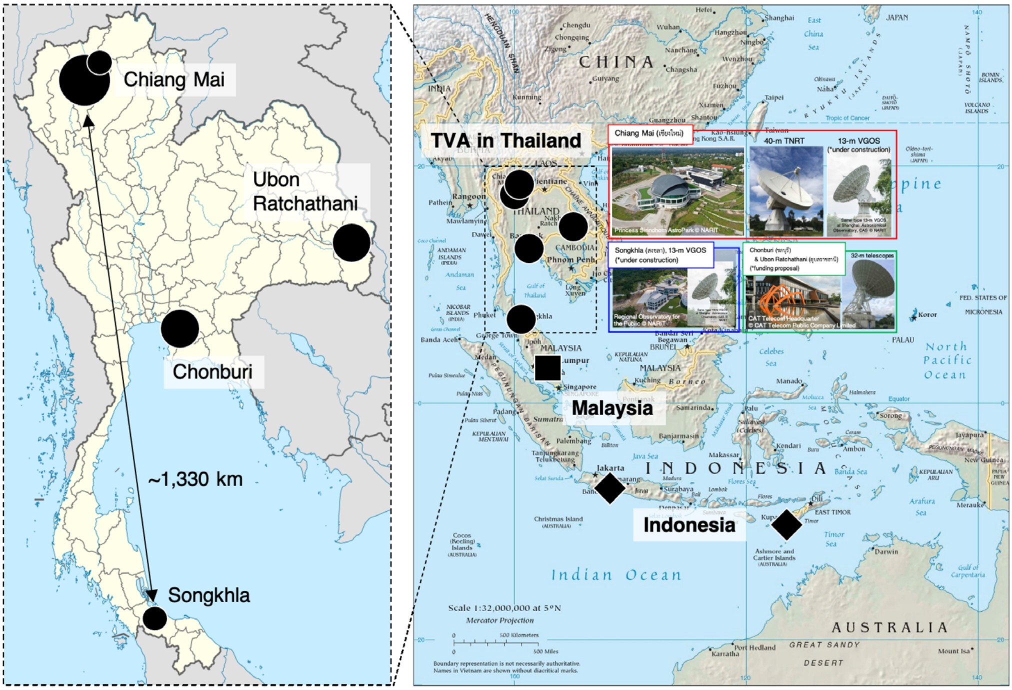

Figure 7. Forthcoming regional VLBI networks: Left - Thai National VLBI Array; Right - South-East Asian VLBI Network. In the left-panel, each radio telescope is shown by circles with the size proportional to its diameters. In the right-panel, radio telescopes (including forthcomings) are shown by circle, square, and diamond symbols with its fixed sizes for in Thailand, Malaysia, and Indonesia, respectively (Image credit of backgrounds: Left - NordNordWest in Wikipedia; Right - Monedula, CIA World Factbook, Wikimedia).

of a 32-m telecommunication antenna of Indosat Ooredoo located at Earth Station in Jatiluhur, West Java, at a distance of 1,840 km from the Timau site. Universiti Malaya (UM) in Malaysia is hosting a 13-m VGOS telescope in Jelebu in collaboration with SHAO. These stations combined with the TVA, eight stations in total, will constitute the start of SEAVN, as shown in Figure 7 (right). Key science goals of the SEAVN will be updated to reflect the fact that SEAVN will be one of the most flexible operations for VLBI accessible both in the Northern and Southern hemispheres, in collaboration with ITB, UM, and Vietnam National Space Center, Vietnam.

The development of the SEAVN will enhance VLBI networks, bringing them to the next level, through the drastic upgrade of baseline lengths, baseline / imaging sensitivities, and the UV-coverages resulting in much better synthesized-beams and improved imaging qualities. In particular, this enhancement is notable for reconstructing the Asia-Pacific Telescope, by filling in severe holes in the UV-coverage with the SEAVN telescopes located around the equator. These upgrades will result in the acceleration of an essential activity for the VLBI future led by the Global VLBI Alliance†.

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† http://gvlbi.evlbi.org/welcome

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the development of the Ku-band receivers for holographic measurement and the TCS, and advice on telescope construction with its operations; (3) Gundolf Wieching and the electronics division team in MPIfR for the development of the L- and K-band receivers, and the USB system.

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