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ORIGINAL ARTICLE

Measuring the impact of Indonesian antennas on global geodetic VLBI network

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Abstract
In the near future, two radio telescopes will be installed in the Indonesian region. These telescopes are proposed to be integrated into the existing Very Long Baseline Interferometry (VLBI) network both for astronomical and geodetical purposes. Here we simulate the impact of the inclusion of the future Indonesian antennas to the estimates of Earth Orientation Parameters and the station position. The simulation was performed in two types of VLBI sessions. First, we analyse the contribution of Indonesian antennas to the existing intensive session INT3 (IN320-314), which focuses on the estimation of dUT1. We found that the addition of Indonesian antennas has reduced the estimated dUT1 repeatability value by about 25%. Next, we simulate the 24-hour session by considering two existing network configurations, which are R4 (R4934) and AOV (AOV049). Overall we found that the addition of Indonesian antennas to each network configuration decreases the repeatability value of the Earth Orientation Parameter by about 20%. Meanwhile, the repeatability value of station position is reduced up to 12%. This reduction is already achieved even when we include only one Indonesian antenna.

Keywords VLBI · Radio telescope development · Earth orientation parameter · Antenna position

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1 Introduction

Modern astronomy in Indonesia was initiated almost a century ago with the establishment of Bosscha Observatory in West Java with stellar physics as its main scientific program. To keep up with the world advancement of astronomy, Indonesian astronomers have been for decades studying and planning for new astronomical facilities. We have considered the south-eastern region in the country with astronomically dark sky and drier weather to be the possible sites for the new facilities [6].

Presently an optical observatory (dubbed Timau National Observatory) is under construction near Mount Timau in Timor island (lat = −9.60°, long = 123.78°) [12]. In addition to optical wavelength, radio regime is the next natural choice in expanding the multi-wavelength domain as detail probes are demanded from various deeper astrophysical interests. The site in Mount Timau is spacious enough to also accommodate radio telescopes. Radio Frequency Interference (RFI) measurement in the environment shows pristine radio sky, thus very suitable to host radio telescopes [7]. This pushes Indonesia to develop radio astronomy in the region by developing relevant infrastructure and including Indonesia in the already existing radio astronomy networks, such as the Very Long Baseline Interferometry (VLBI). Joining established networks, for example, VLBI Global Observing System (VGOS) [13], might prove to be essential in intensifying the learning process while immediately engaging in on-going programs.

In addition, we notice that the growth of VLBI Network has recently been increasing significantly around the globe thanks to the conversion projects of decommissioned telecommunication antennas to radio telescopes in a number of countries [see, for example, [4, 8, 19, 20]]. Accordingly, in this spirit, a decommissioned telecommunication antenna in the town of Jatiluhur (lat = −6.52°, long = 107.41°) in West Java, hereafter called “Ja” Station, is currently being prepared to be converted into a radio telescope (see Fig. 1).

Indonesia straddles the equator and is located between East Asia and Australia. So far, there are no VLBI stations in this region of South East Asia. Considering a rising of VLBI regional cooperation between Asia-Oceania countries, such as AOV [10], new stations between these two continents must be of great interest.

To develop the Indonesian VLBI campaign, and considering the two antennas that will be available in Jatiluhur and in Mount Timau site (hereafter called “Ti” Station), in this work we first undertake the study of various possible usages of the telescopes, including for astronomy, astrometry, and geodesy. The latter is, in particular, to increase the interest to a more multi-disciplinary and collaborative work. As already known, VLBI is a major space-geodetic technique. It contributes significantly to the estimation of Earth Orientation Parameters (EOP), i.e., polar motion (xpol, ypol), nutation (xnut, ynut), and UT1 - UTC (dUT1) and it is the only employable technique that is able to estimate a complete EOP. As one of the geodetic parameters, the EOP measurement is crucial in satellite navigation and the study of Earth rheological properties.

Meanwhile, VLBI measures the position of the radio antennas very precisely. Therefore, VLBI can contribute in establishing and maintaining International Terrestrial Reference Frame [1]. VLBI is also used for realizing International Celestial

Fig. 1 A decommissioned telecommunication antenna (18.3-m) in Jatiluhur, Indonesia. Its conversion to a radio telescope is considered for geodetic purposes

Reference Frame by observing the position of extragalactic source [3]. As mentioned in the United Nation General Assembly Resolution, the improvement of accuracy and stability of reference frames has become a scientifically and economically important [17]. Conducting VLBI observation in the southern hemisphere is one of the key factors for improving these reference frames. Hence, the Indonesian future antennas which are located in the south will play a crucial role.

In the following we explore the benefit of using VLBI system which includes the two antennas mentioned above on the estimation of geodetic parameters. In particular, here we investigate the role of the future Indonesian antennas in improving the estimation of EOP and the station positions. To do so, we carried out a VLBI simulation by integrating these antennas to the existing network. This approach is already used by several authors, among others: [15] for analyzing the impact of new VLBI antenna in Africa continent, [9] for identifying a good location for new SLR stations, and [16] for investigating the best site around the world to install VGOS antennas.

The rest of this article is elaborated as follows. In Section 2, we explain the data and method that we used as well as the details about scheduling and the VLBI simulation. The results are presented in Section 3. Finally, Section 4 delivers the conclusion of this study.

2 Method of Simulation

In this study, we measure the impact of new antennas by creating a simulation based on two different types of VLBI sessions. First, we analyse the contribution to the IVS official intensive session by including the baseline of Indonesian antennas to the default baseline of INT3 session. Here we used the experiment of IN320-314 which was performed on 9 November 2020, from 07h00 UT to 08h00 UT. Figure 2 shows the baseline configuration used in this intensive session. We note, however, during the realization of this session, NYALES20 could not participate in the observation due to elevation encoder problems. In spite of this, in this study we still took this station into account in our simulation.

Here we investigate the influence of both Indonesian antennas as well as the impact of each antenna. For this, first we simulate the default INT3 session by considering the default baseline configuration and then we create another simulation by including one/both Indonesian antennas in the baseline configuration. So, we set four different network configurations as follows:

- Ny - Sh - Wz - Wn
- Ny - Sh - Wz - Wn - Ti
- Ny - Sh - Wz - Wn - Ja
- Ny - Sh - Wz - Wn - Ja - Ti.

The intensive session was simulated by considering the default IVS-INT3 observing mode which uses a recording rate 1024 Mbps and two-bit sampling. We simulated the session by instructing the antennas to observe the two corners of the common visible sky. This technique is needed to improve the quality of the intensive session since the extragalactic source located in these regions contribute mostly to the estimation of dUT1 [18].

Next, we investigate the possible contribution of Indonesian telescopes to a 24-hour VLBI session. Here we test the impact on two different existing sessions, with each session having seven existing antennas. For the first session, we consider the R1/R4 session, which is dedicated by IVS for monitoring the EOP. Here we chose the official IVS session of IVS-R4934 (called R4 hereafter). In this session, the antennas

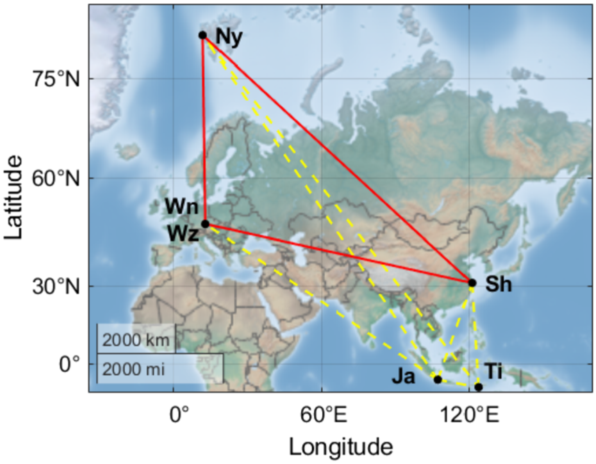
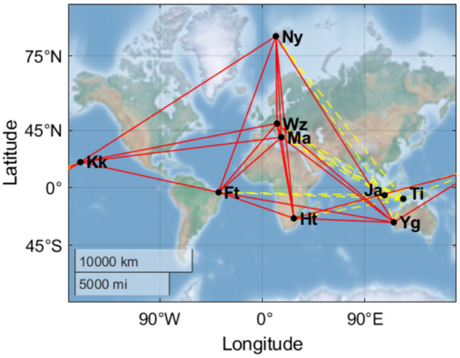


Fig. 2 The baseline configuration between Indonesian antennas and INT3 session (Ny - Sh - Wz - Wn). Here the solid red line corresponds to the original baseline configuration and the dashed yellow line means the baseline of the Indonesian antenna and INT3 antenna. Notes: NYALES20 (Ny), SESHAN25 (Sh), WETTZELL (Wz), WETTZ13N (Wn)

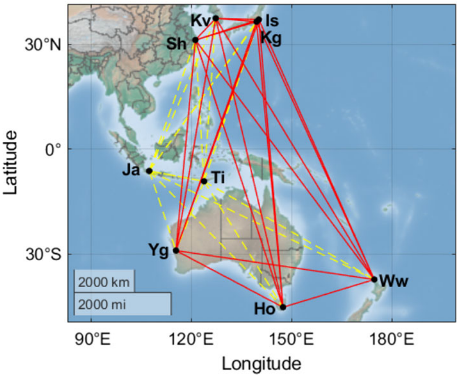
are evenly distributed around the globe, with most of the station is located on a different continent. The second session is AOV session (AOV049). Unlike R4, this session only uses the antennas located in the Asia-Oceania region and more focuses on the estimation of station positions. Figure 3 shows the baseline configuration of the chosen R4 and AOV session. In the case of AOV session, even though ISHIOKA antenna was not considered in the real experiment, we chose to include it in our simulation.

These two sessions have different observing mode. In this work, we used the default observation mode of these two sessions. The recording speed of 256 Mbps and one-bit sampling was applied for R4 session and we used 1 Gbps data rate and two-bit sampling for AOV session. We adopted 8 MHz channel bandwidth for R4 session and 16 MHz channel bandwidth for AOV session. In order to determine the impact, we compare the results from the default network configuration to the same configuration added with one/two Indonesian antennas.

To do the scheduling and modelling of VLBI observations, we used software namely VieSched++ [14] and VieVs [2]. The official IVS catalogue (https://ivscc.gsfc.nasa.gov) was adopted for the specification of existing antennas. Here Ja antenna is modelled with the properties assumed equal to the Italian antenna MATERA, whereas the properties of Ti antenna is adopted to mimic the Australian antenna YARRA12M. The simulation is generated by considering the observations at X- and S-band.



(a) R4



(b) AOV

Fig. 3 The baseline configuration between Indonesian antennas and R4 session (**a**) and AOV session (**b**). Here the solid red line corresponds to the original baseline configuration and the dashed yellow line means the baseline of the Indonesian antennas and the antennas of the original session. Notes: FORTLEZA (Ft), HART15M (Ht), KOKEE (Kk), MATERA (Ma), NYALES20 (Ny), WETTZELL (Wz), YARRA12M (Yg), HOBART26 (Ho), ISHIOKA (Is), KOGANEI (Kg), SEJONG (Kv), SESHAN25 (Sh), and WARK12M (Ww)

In the intensive session, we focus to compute the target parameter of dUT1. Likewise, following the standard procedure of intensive session analysis, we estimated the station clock, with excluding the reference clock. The tropospheric zenith wet delay per station was also estimated by using Piece-Wise Linear Offsets every 30 minutes. The minimum and maximum scan time are set to 30 and 120 seconds respectively. Meanwhile, for 24 hours session, we estimate the complete EOP as well as the station position. Other parameters such as source coordinate, station clock, and tropospheric zenith wet delay were estimated as well. Here the minimum and maximum scan time are fixed at 30 and 600 seconds for R4 session and 20 and 180 s for AOV session.

In order to produce a high quality VLBI schedule, we need to consider several criteria. These criteria can be shortened to the four most dominant criteria as follows. First, good sky coverage is needed in VLBI observations for improving time delay estimation. Second, the number of observations per scan should be large. Third, the duration per scan has to be short enough to produce more scans during a VLBI session. Fourth, the idle time of each station has to be short for making the scan period more effective. Since it is impossible to maximize all of these criteria, we need to apply a weight factor (ω) to the considered criteria in order to produce better VLBI scheduling. Following [16], we take all these elements for the 24-hour observation: sky coverage (ω_{sky}), number of observation (ω_{nobs}), duration (ω_{dur}), and idle time (ω_{idl}). Meanwhile, for this work, we restrict only ω_{sky} and ω_{dur} for the intensive session. In order to get the best optimization criteria, we simply try out the different experiment with various configurations of weight factor for each element with some possible values. Accordingly, four possible values, i.e., 0.0, 0.33, 0.67, and 1.0, are considered for the 24-hour session, while the intensive session takes into account 11 different values ranging from 0.0 to 1.0. A higher weight means that this criteria is more important than another. Besides the weight factor combination, the time interval for switching the observation corner (t_{cor}) becomes one of the important parameters in the intensive session. Thus we searched the optimum value of this parameter by trying some possible values ranging from 600 to 1050 seconds. Here we used multi-scheduling feature in VieSched++ to generate all of the schedules from each network configuration.

Each schedule is simulated 1000 times. In this simulation, we include the modelling of tropospheric delays, clock drifts, and white noise. The tropospheric delay was simulated by adopting the constant C_n of $1.8 \times 10^{-7}\ \mathrm{m}^{-1/3}$ with a scale height of 2000 m for every station. The wind velocity is 8 $\mathrm{m\ s}^{-1}$ toward the East. Meanwhile, the clock drifts are simulated through the sum of random walk and integrated random walk [5] with an Allan Standard Deviation of 1×10^{-14} s after 50 min. The white noise contribution is set to 20 picoseconds.

Furthermore, the quality of VLBI scheduling can be determined through their repeatability (or standard deviation; σ) from Monte Carlo simulation. If N is the total number of simulation and p_j is the estimated parameter of i-simulation, then the suitable parameter of standard deviation σ_p is

$$\sigma_p = \sqrt{\frac{1}{N-1}\sum_{j=1}^{N}\left(p_j - \bar{p}\right)^2}, \tag{1}$$

where $\bar{p}$ is the mean value of p. Consequently, the best weight factor combination has the smallest σ. In the intensive session, the smallest repeatability of dUT1 is chosen to be the best one. Meanwhile, the best for R4 and AOV sessions are chosen by considering the smallest repeatability value of the EOP and station position, respectively. Large observation number was considered as well for determining the best configuration.

3 Results

3.1 Intensive session

We create the simulation for one-hour observation and concentrate to estimate dUT1. We found that the inclusion of Indonesian antennas on the INT3 network did not change the optimized weight factor combination very much. For the four configuration network, the optimized weight factor combination has ω_{sky} between 0.1 and 0.3 and ω_{dur} has the value 0.8 or 0.9. Meanwhile, the optimized simulation strategy has t_{cor} between 750 and 900 s.

Table 1 displays the estimated σ of dUT1 from the optimized simulation strategy. The addition of Timau antenna has a small influence on the reduction of σ dUT1, but the number of observations increased significantly. The result is even better if we include solely Jatiluhur antenna, where the σ of dUT1 becomes 10 μs and the number of observations is 330. Moreover, the addition of both Indonesian antennas has increased the number of observation by a factor of 1.7 and reduced the σ of dUT1 by 3 μs (or decreased by about $\sim$ 25%).

3.2 24 hour session

As shown in Fig. 4, the inclusion of Indonesian antennas has improved the estimation of EOP in both considered network configuration. By adding the new antennas, σ of dUT1 has reduced about 5 μs for AOV session and 0.2 μs for R4 session. Meanwhile, the addition of Indonesian antennas has decreased σ xpol around 30 μas and σ ypol about 15 μas both for R4 and AOV session. This improvement, notably for R4 session, is in line with the IVS goal for achieving an accuracy of polar motion estimation at the level of $\sim$ 40 μas. The inclusion of new antennas has decreased the σ nutation for more than 6 μas in R4 session both for ynut and xnut. In AOV session, σ of xnut and ynut has decreased by about 4 μas. In general, the σ of EOP has reduced

Table 1 The repeatability value of dUT1 driven from VLBI intensive session. INT3def means the default network configuration of INT3 (Ny - Sh - Wn - Wz)

Network conf.	num. obs.	dUT1 (μs)
INT3def	234	12.46
INT3def + Ti	300	11.80
INT3def + Ja	330	9.97
INT3def + (Ja + Ti)	408	9.58

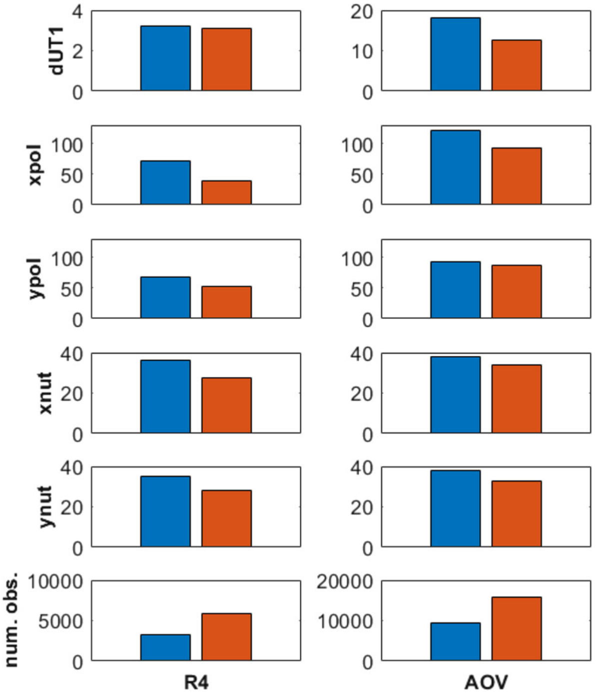


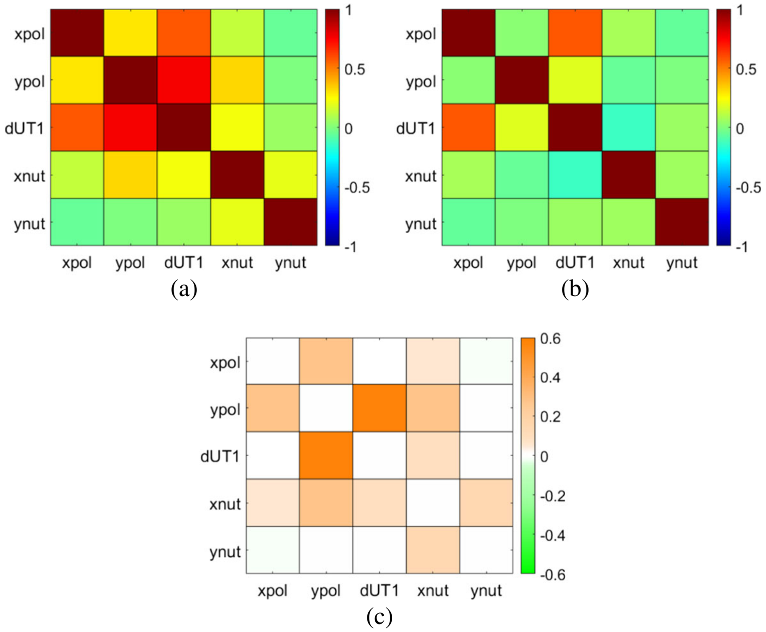
Fig. 4 Repeatability for EOP parameter in R4 and AOV sessions as well as their number of observations. Here 🟦 represents the results from the default baseline configuration while 🟧 means the results from the default baseline configuration + (Ja + Ti). The unit of nutation and polar motion are given in μas while dUT1 is in μs

by about 20% both for AOV and R4. Besides the EOP repeatability value, the inclusion of Indonesian antennas has increased the number of observations for R4 and AOV sessions by more than 60%, where the number of observations increases from around 3,000 to nearly 6,000 in R4 session and from about 9,000 to nearly 16,000 in AOV session.

As mentioned in the previous section, AOV session is dedicated to estimate the station position. So, we chose the best weight factor combination for station position estimation instead of EOP estimation. However, if we use the best weight factor combination for EOP estimation, the result of σ EOP is not so much different. The poor result of AOV session, especially for dUT1, is caused by its antenna distribution. As shown by previous authors, the best estimates of dUT1 are produced by the network which has long baseline in East-West direction while the best of polar motion and nutation are produced by a network with long North-South baseline. Meanwhile, as stated by [11], there is a strong negative correlation between EOP repeatability and the size of the observing network, or more specifically the volume of a polyhedron formed by the network antennas. We calculated the volume of corresponding R4 and AOV sessions for default network configuration and found that the volume of R4 is 211 Mm^3 (cubic megametre), which is far greater than AOV (3 Mm^3). The volume of both VLBI session increase when we add Indonesian antennas, with R4 and AOV volume become 268 and 12 Mm^3 respectively.

The addition of Indonesian antennas has reduced the post-fit WRMS delay from 41.2 ps to 37.4 ps for R4 session and from 39.8 ps to 38.8 ps for AOV session. Figure 5 shows the correlations between the estimated EOP for R4 session. The inclusion of all Indonesian antennas permits to lower the correlation of certain parameters significantly, with the biggest one is between dUT1 and ypol (reduced almost 0.6). On average, the inclusion of Indonesian antennas permits to lower the correlation by 12%. This conclusion is the same for AOV session (not shown here) even though the difference in the correlation is much less contrast. Meanwhile, Fig. 6 shows the UV coverage of an example source in AOV session. The Indonesian antennas greatly improve the UV coverage, which is important for imaging and hence correcting source structure effect. This improvement also happens for R4 session.

We test the influence of each station on the estimated repeatability by excluding one of the stations in the simulation, so here we have eight stations in each simulation. As shown in Table 2, σ of dUT1 increases mostly when we exclude KOKEE in R4 and WARK12M in AOV, which is understandable since these two stations located in the easternmost or westernmost sides in their respective network. For the polar motion and nutation, the removal of KOKEE and HART15M vastly increases σ in R4 while the σ in AOV greatly increases when we remove KOGANEI and WARK12M

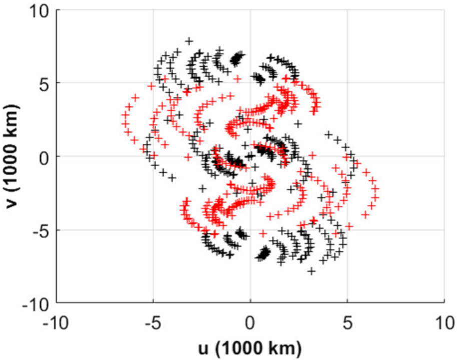


(a) (b)

(c)

Fig. 5 Correlation of R4 session (**a**) without Indonesian antennas and (**b**) with Indonesian antennas. (**c**) The absolute correlation coefficients without Indonesian antennas minus the absolute correlation coefficients with Indonesian antennas. A positive value in (c) means that the correlation is diminished when considering Indonesian antennas

Fig. 6 VLBI UV diagram for source 0402-362 (declination $= -36°$) in AOV session. Here + is associated with the original baseline configuration while + represents the improvement of UV coverage by adding the Indonesian antennas



in the simulation. We note that the exclusion of either Jatiluhur or Timau mostly increases the value of σ. However, this change is still smaller than that of the default configuration (see the blue bar of Fig. 4). In other words, the improvement of EOP estimation is already achieved even when we include only one Indonesian antenna in the corresponding network. Here we found that the inclusion of solely Jatiluhur antenna has generally improved the estimation better than Timau.

Figure 7 shows the σ value for the estimated station position. Here AOV session has a lower repeatability compared to R4 for all of its stations. The inclusion of two Indonesian antennas has reduced the repeatability for all antennas in R4 session except for Ft. Moreover, this has reduced the σ for all station in AOV session except for Is and Kg. This tendency is also valid for the case of one Indonesian antenna only,

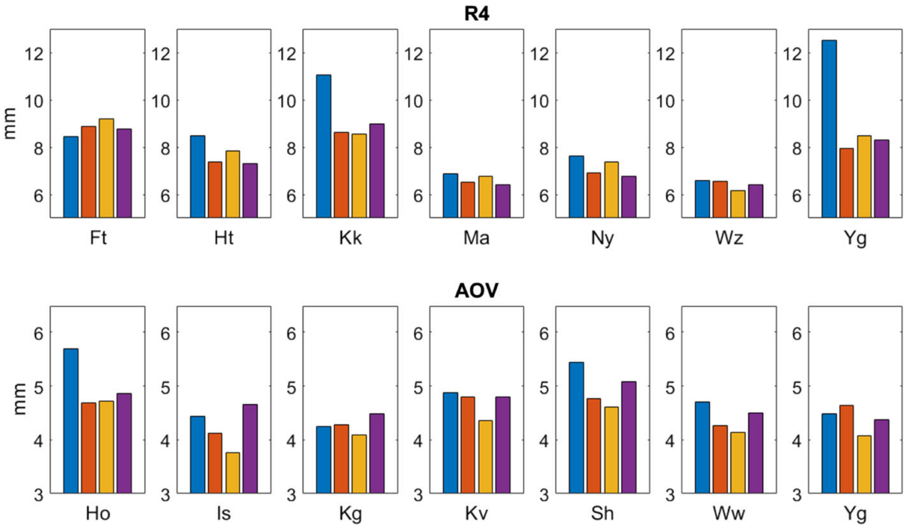


Fig. 7 Comparison of repeatability of mean station position $(\sqrt{x^2 + y^2 + z^2})$. Here 🟦 represents the results from the default baseline configuration, 🟧 means the default baseline configuration + Ja, 🟨 signifies the default baseline configuration + Ti, and 🟪 means the default baseline configuration + (Ja + Ti). The abbreviation of each station name can be found in Fig. 3

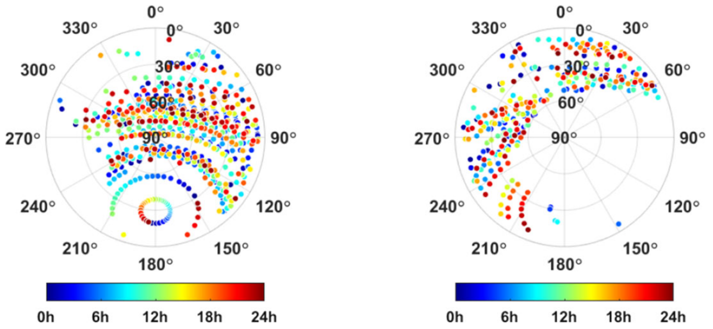
Table 2 The repeatability value estimated from 24-hour session by excluding one of the antennas

Ignored station	dUT1 (μs)	xpol (μas)	ypol (μas)	xnut (μas)	ynut (μas)
R4					
None	3.08	39.12	52.33	27.44	28.26
FORTLEZA	3.88	44.48	70.00	29.00	26.95
HART15M	3.51	62.04	**71.28**	**43.06**	**49.54**
KOKEE	**6.63**	**63.05**	71.27	35.48	36.83
MATERA	3.06	42.55	48.83	28.38	28.25
NYALES20	3.67	47.52	53.14	33.13	32.55
WETTZELL	3.29	44.48	51.97	28.98	28.57
YARRA12M	3.10	46.90	53.48	28.46	32.28
JATILUHUR	3.09	43.09	49.53	28.68	30.35
TIMAU	2.83	39.56	52.36	29.87	28.98
AOV					
None	12.58	93.40	86.13	33.71	32.49
HOBART26	14.54	99.70	99.02	35.45	36.19
ISHIOKA	12.91	101.75	93.60	35.50	37.91
KOGANEI	11.83	**106.06**	99.37	34.42	35.32
SEJONG	12.07	99.73	86.40	33.81	35.19
SESHAN25	12.32	97.33	85.20	35.19	37.76
WARK12M	**16.03**	91.80	**110.99**	**40.07**	**43.37**
YARRA12M	13.58	103.60	87.99	37.18	40.87
JATILUHUR	14.10	104.54	89.13	36.36	32.88
TIMAU	12.47	94.17	85.19	31.19	34.76

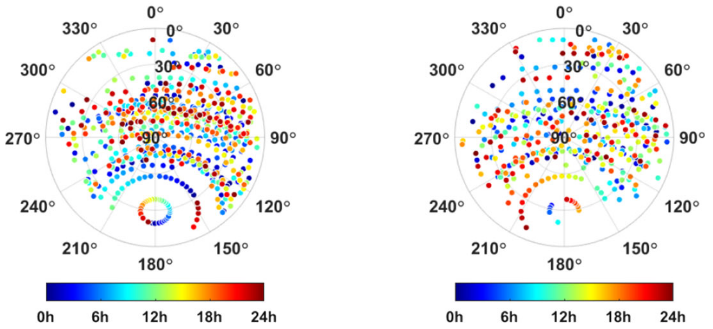
The largest repetability in the corresponding parameter is highlighted in bold

except for three stations in AOV session. Is, Kg and Yg have smaller σ if we consider Timau antenna only. On average, the inclusion of all Indonesian antennas has reduced the repeatability of station position by about 1.23 mm, or decreased around 12%, for R4 session and diminished the repeatability in AOV session by about 0.2 mm (or reduced by about 3%).

The inclusion of Indonesian antennas has generally improved the sky coverage of the observation. Figure 8 shows the example of skyplot in the case of Yg station. The addition of Indonesian antennas has significantly improved the sky coverage, notably for R4 session. This improvement has an impact on the estimation of Yg station coordinate as shown in Fig. 7, where the repeatability in R4 session is drastically decreased for up to 4 mm. Indeed, the number of scans of Yg increases significantly after we add Indonesian antennas. In R4 session, the number of scan increases from 286 to 387. The increment is already achieved even when we add only one antenna, where the number of scans becomes 361 for Timau and 388 for Jatiluhur. This trend is also visible in AOV session even though it is not as significant as R4.



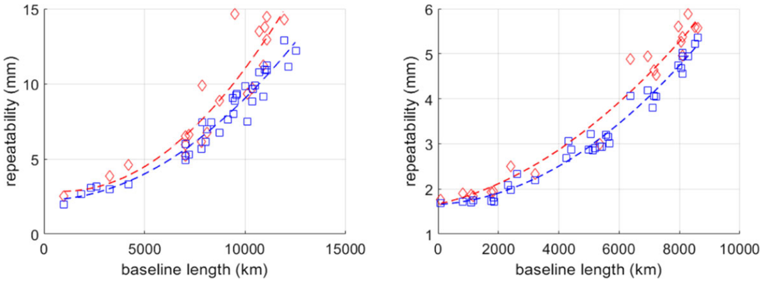
(a) AOV (no Indonesian antennas) (b) R4 (no Indonesian antennas)



(c) AOV (with Indonesian antennas) (d) R4 (with Indonesian antennas)

Fig. 8 The comparison of YARRA12M skyplot (azimuth, elevation) for AOV and R4 session. The color shows the passed time after the session is started. The top figures show the skyplot without Indonesian antennas while the bottom figures display the skyplot after the inclusion of all Indonesian antennas

Besides station positions, baseline length repeatability can be used to determine the influence of Indonesian antennas, with smaller baseline length repeatability means a better result. As shown in Fig. 9, the value of repeatability decreases when



(a) R4 (b) AOV

Fig. 9 Baseline length repeatability of session R4 (**a**) and AOV (**b**), with (blue square) and without (red diamond) Indonesian antennas. Dashed line represents the fitting of the points with quadratic function we include the Indonesian antennas in the estimation. In general, the repeatability reduces more significant for a longer baseline both for R4 and AOV session.

4 Conclusions

In this work, we have simulated the impact of including future Indonesian antennas in the existing VLBI system. The simulation was performed in two types of VLBI sessions: intensive and 24-hour.

In the intensive session, we focus to estimate dUT1 as a target parameter. The simulation was conducted by including Indonesian antennas in INT3 (IN320-314) session. We found that the inclusion of all Indonesian antennas in this session has decreased the repeatability of dUT1 for about 3 μs (or decreased by about $\sim$ 25%) and increase the number of observation by a factor of 1.7.

Meanwhile, we consider two network configurations for 24-hour session, i.e. R4 (R4934) and AOV (AOV049) sessions. The addition of Indonesian antennas generally improves the estimation of EOP and station position. To sum up, the σ of EOP has decreased in general by about 20%. The repeatability of station position has reduced around 12% in R4 session and by about 3% in AOV session. The number of observation has increased by more than 60%. We found that the improvement of EOP and station position estimation is already achieved even when we include only one Indonesian antenna.

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