Dhar *et al. Earth, Planets and Space* (2023) 75:47
https://doi.org/10.1186/s40623-023-01794-8

Earth, Planets and Space

FULL PAPER

Open Access

Favorable locations for new VGOS antennas in India depending on the assessment of geodetic parameters and environmental factors

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Abstract

VLBI simulation studies are carried out to investigate the impact of any proposed station or strategy on the geodetic parameters, such as Earth Orientation Parameters (EOP) and Terrestrial Reference Frame (TRF). In general, such studies are performed for making decisions on any new development in the existing VLBI network. Thus, for selecting the favorable locations for establishment of a VLBI antenna in India, simulation studies are performed on 42 potential locations to cover the whole Indian subcontinent. Furthermore, the simulation setup is divided into four scenarios that consider the current and future situations of the global VLBI network. Extensive simulation strategy is applied with optimized scheduling for each network geometry, Monte-Carlo simulations and analysis in the VieSched++ software. Since only the simulation results are thought to be insufficient for a thorough evaluation of the realistic performance of locations, environmental factors are also investigated in the current study. The environmental factors affecting the operation and vulnerability of the VLBI technique at the potential locations are also incorporated in the present study. For this, a weighted scoring model is developed with the scores and weights based on the probable impact and occurrence frequency of disrupting environmental events, respectively. This approach will avoid the possibility of new VLBI station ending up in an unfavorable location in India and, underperforming substantially in terms of the achieved improvement of geodetic parameters as determined from the simulation study. The VLBI Global Observing System (VGOS) network is being established at a global level to create a uniformly distributed network of the next generation VLBI system to meet the goals of the Global Geodetic Observing Systems (GGOS). India is planning to establish its first VGOS antenna, and therefore, this study helps to mark the high-performance favorable locations for VGOS. The improvements in geodetic parameters of favorable locations identified in the simulation study are 6.7–11.2% in the first scenario, 12.8–46.8% in second scenario, 9–20.5% in third scenario and 2.9–6.1% in fourth scenario. The favorable locations outperform other Indian locations by a factor of 1.1–5.8. In addition to that, the Indian locations having environmental factors that might affect the VGOS adversely are not portrayed as the favorable choice.

Keywords VLBI, Scheduling, Simulation, Environmental factors, Weighted scoring method, VGOS

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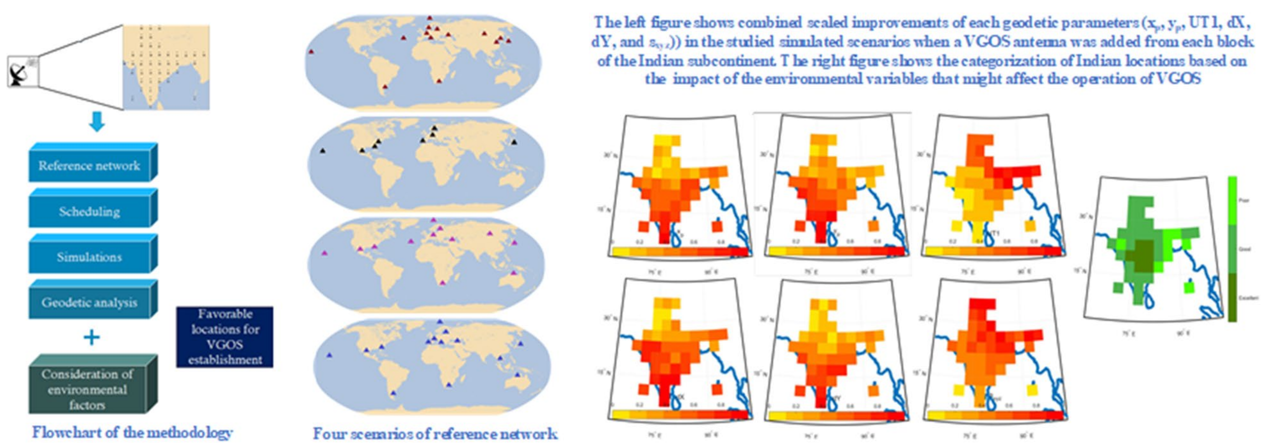
Graphical Abstract



Introduction

The observation and monitoring of various processes on Earth like sea level rise, tectonic plate motion, land subsidence, etc. or in spacelike positioning of extragalactic objects, satellites, etc. are only possible with an accurate realization of reference systems incorporating all the spatial and temporal changes (Plag et al. 2009). The International Terrestrial Reference Frame (ITRF) (Altamimi et al. 2016) and the International Celestial Reference Frame (ICRF) (Arias et al. 1995; Fey et al. 2015; Charlot et al. 2020) are the realizations of the reference systems on Earth and in space, respectively. These two frames are connected by rotations depending on five parameters, known as the Earth Orientation Parameters (EOP) (Aoki 1988; Bretagnon and Brumberg 2003). Four space geodetic techniques—Very Long Baseline Interferometry (VLBI), Satellite Laser Ranging (SLR), Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS) and Global Navigation Satellite System (GNSS), with globally distributed observing sites are used to determine the ITRF. Furthermore, VLBI along with SLR was used to realize the scale of ITRF2014 and, is the only technique to determine all five EOP consistently (Gambis 2004). Unlike ITRF, the ICRF is realized by the equatorial coordinates of radio sources provided by VLBI observations only (Ma et al. 1998).

Thus, VLBI (Robertson 1991; Sovers et al. 1998) is a significant technique that performs various applications of geodesy and astrometry (Schuh and Behrend 2012). Furthermore, VLBI plays an integral part in realizing the objectives of the Global Geodetic Observing System (GGOS) (Plag and Pearlman 2009), which is a collaborative approach for observing and monitoring the Earth system. Thus, the International VLBI Service for Geodesy and Astrometry (IVS) developed the concept of a next-generation VLBI systems that are needed to meet the GGOS goals (Petrachenko et al. 2009, 2012). This next-generation system is known as VLBI Global Observing System (VGOS) and its aim is to achieve 1-mm positional accuracy and 0.1 mm yr^{-1} stability on a global scale and to carry out observations continuously, with initial geodetic results available within 24 h after the observations. Thus, VGOS relies on fast-slewing antennas to take in more observations, on broadband signal reception to reduce the coherent integration time and on other changes for achieving GGOS goals. To modernize and improve the global network, VGOS antennas are established around the globe by either replacing the legacy ones or setting up at new locations (Hase et al. 2012). Still until today, the VGOS ground segment could not achieve a sufficiently uniform global network coverage. Main reasons for this are the relatively high establishment costs, and the requirement of highly skilled and multifaceted workforce for its operation and scientific exploitation. However, considering its indispensable role for significant contributions to monitor the Earth system, more countries are joining in this effort by establishing their own VGOS stations. This shared geodetic infrastructure will not only strengthen the National reference frame of the host country, but will also benefit the international community.

To support the proposition of establishing an additional station, simulation studies are performed to assess the improvement in the precision of determined geodetic parameters from the addition of the new station. This approach was followed by several investigations. Glaser et al. (2017) added artificial stations to the global VLBI network and then, assessed the improvement in station positions and Earth rotation parameters. A publication by Schartner et al. (2020) investigated optimal regions globally for generating high precise EOP. Huda et al. (2021) and Schonberger (2014) used similar approach for assessing the impact of planned VLBI stations. Kehm et al. (2019) investigated the locations of additional SLR stations using the same approach. In all these publications, the performance of the station locations was assessed based on its impact on derived geodetic parameters, such as station positions and EOP. The impact of the external factors on which these techniques and their observations rely on were not considered in any of them. In another publication by Glaser et al. (2019), the performance of future SLR stations was assessed not only based on the precision of geodetic parameters, but also on the visibility conditions that are limited by cloud coverage. In agreement with this work, we think that incorporating such environmental factors provides more practicality in determining the performance of future stations.

In the current study, we limit the study locations to the Indian territory. However, of course, our approach can be applied to other regions or the entire Earth surface.

VLBI uses microwave-based observations which are not directly weather dependent. However, the quantity and quality of VLBI observations are affected from certain environmental factors as perceived from the IVS analysis reports of the observed sessions (Appendix: Table 6) and personnel knowledge of operators and analysts. With VLBI observations being sparse, the number of good VLBI observations is impertinent for better estimation of geodetic products. For instance, an additional antenna on any location shows impressive improvement achieved in the precision of derived geodetic parameters compared to its counterparts in the simulation study. However, if the same location is frequently affected from problematic meteorological events, such as strong winds, thunderstorms, dust/sand storms, or heavy rainfall, that causes temporal interruption of VLBI operation. Then, this directly affects the VLBI observations and in reality, a VLBI antenna on that location might not produce such impressive geodetic results as achieved in simulations. In addition, it would not help if that same location is highly susceptible to extreme natural calamities that might partially or completely destruct the VLBI station. The reason for this is that the VLBI antennas typically observe for at least three decades and a major strength of VLBI is to provide stability to frames and EOP. Thus, assessing the performance of potential locations with just results of the simulation study might not be enough for determining favorable locations for VGOS establishment in India or elsewhere.

In general, making decision on favorable location for establishment of VLBI is a complex problem. Any one location or single station coordinates in India cannot be labelled as the best candidate. For instance, if we consider Radio Frequency Interference (RFI) free remote locations for establishment of VLBI. Then, the antenna may suffer from higher impact of environmental disturbances, such as strong winds, on these locations due to negligible obstruction in such regions. In addition, the operation and maintenance of VLBI equipment at remote regions would suffer from unavailability of skilled personals, difficulty in monitoring, power outages, broadband issues, etc. Though, there are just very few examples of VLBI stations in the world that operate in very remote areas with extreme weather conditions for most of the days in a year. In those extreme locations, the VLBI equipment is specially designed to survive the extreme weather conditions for most of the year, e.g., O'Higgins antenna at the Antarctic continent. However, these specific measures increase the establishment expenses exorbitantly and may also not meet the required design standards for efficient VGOS operations. Establishing VLBI in such extreme regions is only a matter of network geometry, rather than any other criterion. However, the situation in this study is completely different as we are comparing the performance of study locations regionally for finding the best optimal site for VGOS establishment. Thus, to provide equal opportunity to all the study locations, the performance of the locations was considered for a standard VGOS antenna with no special design considerations or radome, for any of them. Many would argue that a radome over the VLBI antenna is a way of dealing with some of the environmental factors. However, the cost of a radome is similar to that of the VLBI antenna itself and hence, it should be avoided unless it is an absolute necessity. Besides, absorption by the radome might reduce the radio signal and lower the signal-to-noise ratio to make the delays less precise (Niell 2018). More has to be researched about the latter statement.

The geodetic products of VGOS are significant for a multitude of applications in India, ranging from providing Earth rotation information for determining precise orbits of artificial satellites to monitoring Indian tectonic plate motion. Thus, a comprehensive study was designed to accomplish the objective of this paper by assessing almost every possible outcome in geodetic parameters from different locations covering the whole Indian subcontinent. Moreover, India is a distinctive country in the world with large geographical and climatic diversity. It has Himalayas in the northern boundaries, then Indo-Gangetic plains formed from the Himalayan rivers in the north and north-eastern regions. Then, comes the peninsular plateau which spreads through the central and southern parts of India. The extreme north-western regions are arid deserts. There are coastal plains, and Eastern and Western Ghats with stepped hills running parallel to the peninsular coast. Then, finally two group of islands are present in the south of India, Andaman and Nicobar Islands in Bay of Bengal sea and Lakshadweep Islands in Arabian Sea. These dynamic relief features cause varied weather pattern throughout the Indian sub-continent. Thus, India experiences variety of extreme weather conditions (De et al. 2005), and is exposed to major natural calamities (Dilley et al. 2005). This supports our plan of considering the local environmental factors at the study locations as a useful additive to simulated performance. Weighted scoring method used for the assessment of environmental factors created a value-weighted numerical score for the decision-making process and the values of scores and weights of different criteria in the model were selected to suit our requirement. In addition, normal distribution was used to determine the scores and categorize the study locations representing the choice for VGOS establishment.

With India proposing to establish its first VGOS antenna, this study would also be useful for the decision makers to get a comprehensive idea of the performance of different locations in India. In the next section, methodology, we lay out detailed methods followed in this study with reasoning. Then, in the results section, we highlight the outcome of the study with explanatory figures. Finally, the paper ends with a conclusion section, where we discuss the performance of VGOS antenna in different locations of India, so that the new station ends up in a favorable location generating maximum benefit.

Methodology

This section describes the simulation setup, scheduling, simulation, analysis of geodetic parameters, and impact of local environmental factors. Figure 1 illustrates the flowchart for the whole approach followed in this study.

Simulation setup

To fulfil the objective of this study, 42 potential locations in India were selected to cover the whole subcontinent, as shown in Fig. 2. These potential locations were selected based on an equal distribution of latitude and longitude of India, as well as including the island territories on either side of the Indian peninsula. These selected Indian locations are known as the study locations, and are represented by C'i', with 'i' as the number depicted in Fig. 2. Single VGOS antennas were added one-by-one to the reference networks shown in Fig. 3. The reference networks consist of VLBI stations which are part of the actual or proposed IVS network. The precision of geodetic parameters estimated from the reference networks was compared with that from the reference networks plus the study location. This determines whether the added study location will improve or deteriorate the geodetic solution.

Figure 3 depicts four different reference networks representing four scenarios of the present study. The results from the new addition in a simulation study depends largely on the considered reference network to which the new antenna was added. Thus, four different scenarios depicting the present and future IVS stations were investigated. The first scenario considers a current IVS R4 session, R41023, which observes in S/X mode. As depicted in Fig. 3, the reference network of first scenario comprises of 10 VLBI stations, KOKEE (Kk), MATERA (Ma), NYALES20 (Ny), WETTZELL (Wz), HART15M (Ht), ISHIOKA (Is), NYALE13S (Ns), RAEGSMAR (Sa), WARK12M (Ww), and YARRA12M (Yg). This is the only scenario which considers both legacy and VGOS antennas in S/X observing mode, as we want to examine the impact of the VGOS antennas from India to the currently operational IVS sessions. Rest of all the scenarios considers only VGOS antennas with VGOS observing mode. The second scenario considers a current VGOS session, VO1021, with the eight VGOS stations—GGAO12M (Gs), ISHIOKA (Is), KOKEE12M (K2), MACGO12M (Mg), ONSA13NE (Oe), RAEGYEB (Yj), WESTFORD (Wf), and WETTZ13S (Ws). The sessions selected for the first and second scenario are common IVS sessions and hence, they were considered in this study. The third and fourth scenarios consider the likely future situation of IVS sessions in next 3 and 10 years, respectively. For this, the portrayed VGOS status in Behrend (2021) was used. The third scenario considers the built VGOS antennas at HOBART12 (Hb), Seshan (Sn), Zelenchukskaya (Zn) along with operational ones—Gs, K2, Ns, Oe, Sa, Wf, Yg, and Ws. The reference network of the fourth scenario considers Gs, Ht, Is, K2, Mg, Ns, Yj, WETTZ13N (Wn), Ws, Zn, KATH12M (Ke), Svetloe (Ss) along with the planned VGOS antennas for the future sites at Chiang Mi (Cm), Matera (Mt), and Argentina (Ao). Higher number of VGOS antennas were considered in the fourth scenarios to keep it in coherence with the future VGOS plan of including more antennas in a session.

The above four scenarios were used for the simulation of the 24-h VLBI sessions and the estimated geodetic parameters are polar motion components (x_p, y_p), Earth

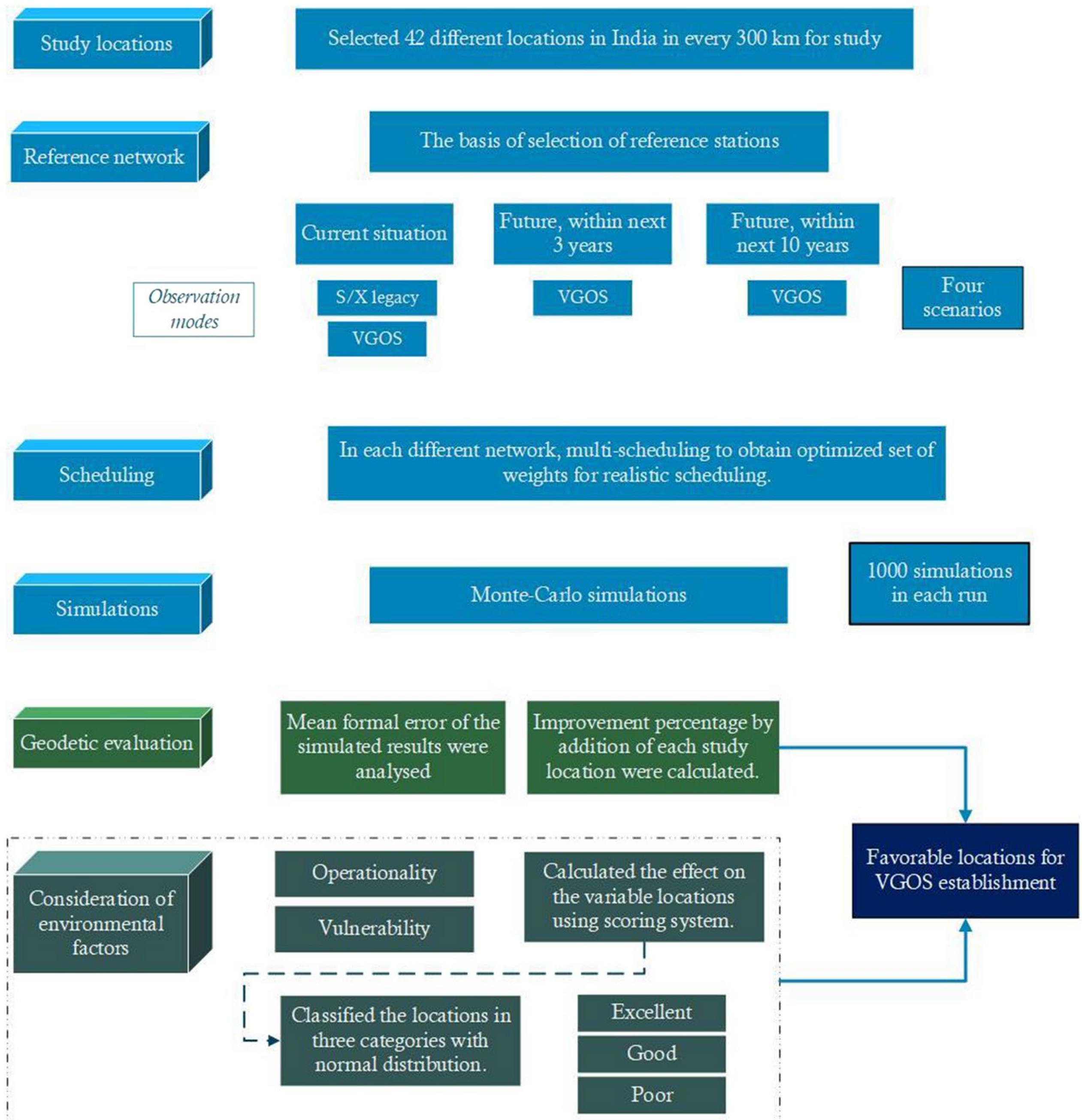


Fig. 1 Flowchart of the methodology followed in this study to determine favorable locations for VGOS establishment in India

rotation phase (dUT1), celestial pole offsets (dX, dY; or CPO), and the station coordinates.

1-h daily intensive sessions are important part of IVS sessions to estimate the highly variable dUT1 (Nothnagel et al. 2017). Thus, intensives were investigated for pairs of Indian antennas and other VGOS antennas—Gs, Sa, Yj, K2, Ss, Wn, and Is. Only five Indian antennas, C1, C15, C27, C33, and C41, were selected from five different regions in India for the simulation of intensive sessions in VGOS observing mode. This helped to assess the influence of five different potential baselines from India for the estimated dUT1.

This holistic approach in scenarios would provide detailed analysis for our objective. In general, a longer east–west baseline yields better dUT1 and long north–south baseline provide better sensitivity to the polar motion coordinates (Schuh and Schmitz-Hübsch 2000).

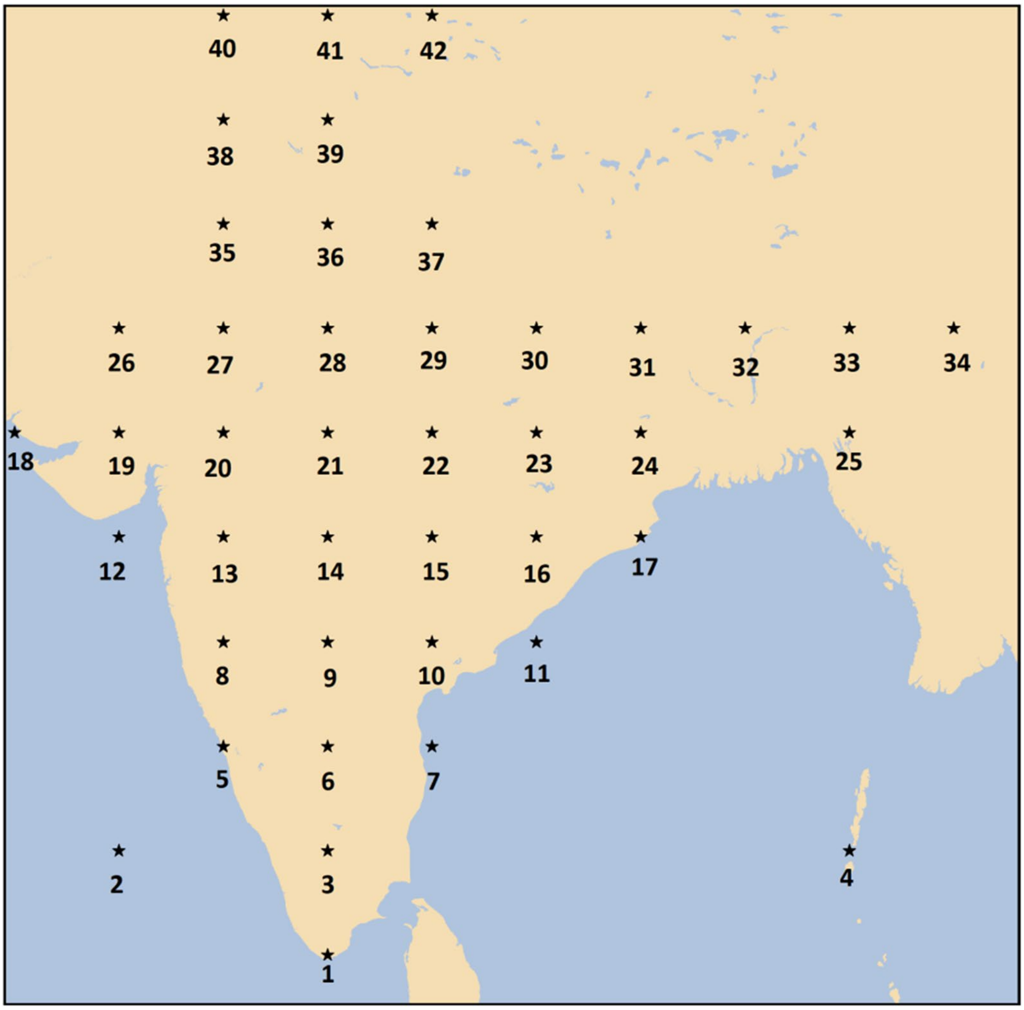


Fig. 2 Schematic figure of the study locations (black stars) with their corresponding numbers, i. Each study location is named as C 'i' for the study

VLBI scheduling

The specifications of the artificial antennas from each study locations in Fig. 2 were taken as VGOS standards with 13.2 m diameter, Az-EL axis type, slewing rates of 12°sec along azimuth and 6°sec along elevation, whereas actual values were assumed for the antenna specifications of reference stations in Fig. 3.

VieSched++ (Schartner and Böhm 2019) was used for scheduling and simulation of the sessions in this study. Station-based strategy with fill in mode was adopted for scheduling. Both the observing mode in this study uses signal to noise ratio (SNR)-based scheduling. In this, minimum SNR was set per observing band.

The multi-scheduling (Schartner and Bohm 2020) feature of VieSched++ was used to generate proper weight factors for the four most important scheduling parameters, i.e., sky coverage, number of observations, duration, and idle time. This is required for optimized scheduling. However, for different network geometries the same scheduling weight factors are not adequate and the impact of such non-optimized schedules is of the same order of magnitude as the impact of the reference network geometry on the simulations (Schartner et al. 2020). Thus, we performed multi-scheduling individually for the four scenarios, as each have different network geometry. For each scenario, 79 schedules were formed from brute–force method with different weight factor combination of the four important scheduling parameters. Then, these 79 schedules were simulated and the estimated geodetic parameters were analyzed. The schedule with best precision of geodetic parameters was selected and its weight factors were considered as optimized for generating schedules for that scenario, as listed in Table 1. This generated optimized and realistic schedules for each scenario in the study. In addition, every schedule used iterative source

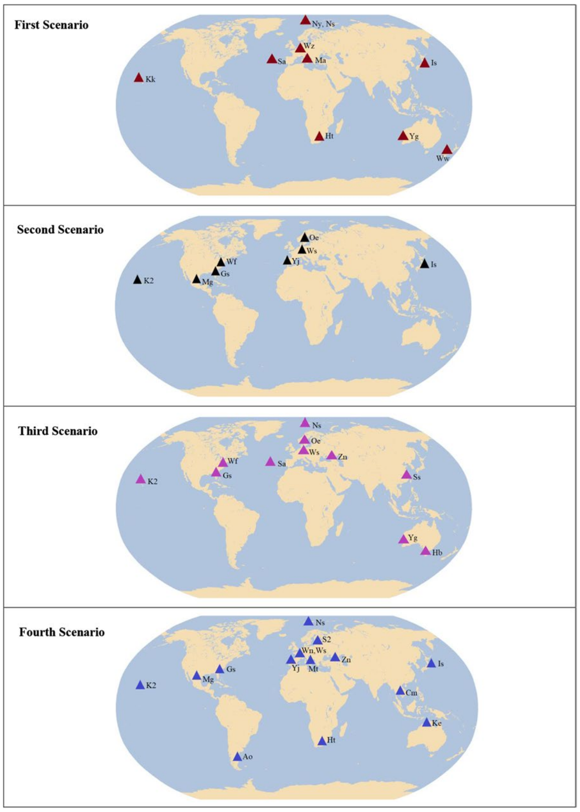


Fig. 3 Reference network of four scenarios showing reference stations marked in triangles with two-letter station name that is described in the methodology

Table 1 Weight factors used for different reference networks: "scenarios" as of Fig. 3

Parameters	Scenario 1	Scenario 2	Scenario 3	Scenario 4
Sky coverage	0.67	0.33	0.67	0.33
No. of observations	0.33	0.33	1	0.33
Duration	1	0.67	1	0.67
Idle Time	1	0.67	0.33	0.33

selection for at least three scans to avoid scheduling many radio sources with less scans.

Similar scheduling strategy was followed for intensive sessions. In this case, highest priority was given to scans that are close to the edges of the common visible sky, since those scans have the highest impact on the results (Uunila et al. 2012; Schartner et al. 2021).

VLBI simulation

For this study, we used the Monte-Carlo simulation strategy similar to Pany et al. (2011). The primary random error sources impacting the VLBI observations are measurement noise, clocks, and atmospheric delay (MacMillan and Sharma 2008; Wresnik et al. 2008). Thus, specific values were given to these random error sources for the simulations. However, radio source structure effects are also significant and larger than the primary error sources (Tornatore and Charlot 2007; Anderson and Xu 2018). However, their impact was not investigated in the present study.

In this study, two different types of observation modes, S/X and VGOS, were examined. The input parameters used to perform simulation for the S/X mode in the first scenario were 30 ps white noise per baseline, and 1×10^{-14} s @ 50 min of Allen Standard Deviation (ASD) for modelling clock drifts (Herring et al. 1990). The tropospheric delays were modelled with a structure constant (Cn) (Treuhaft and Lanyi 1987) value of $1.80 \times 10^{-7}\ \mathrm{m}^{-1/3}$ with 2 km effective wet height (Nilsson and Haas 2010) and wind velocity of 8 m/s towards east. The second, third, and fourth scenarios were observed in VGOS mode (Petrachenko et al. 2009) and their input parameters for the error sources were 4 ps white noise per baseline observation, while the clock ASD and tropospheric delay parameters were kept same as in S/X mode. These random error values were kept constant for all the stations in a simulated session depending on its observation mode.

VLBI analysis

Least squares approach following Schuh and Böhm (2013) was used to perform analysis of every simulated session in this study. The estimated parameters were station positions, station clock, tropospheric parameters (zenith wet delay (ZWD), gradients) and EOP. The station clock was estimated as linear, quadratic, and piecewise linear (PWL) function with 60 min interval and 1.3 cm constraint. PWL offset was used to estimate ZWD with 30 min interval and 1.5 cm constraint. Similarly, the tropospheric north gradients and tropospheric east gradients were estimated with 180 min interval and 0.05 cm constraint. The EOP was estimated using PWL offsets over the session length with 0.0001 mas/ms constraint. Each simulation was run 1000 times and then, every run was analyzed individually to determine the formal error of the estimated geodetic parameters. This yielded a mean formal error which was used for the assessment of the improvement by addition of VGOS antenna from Indian locations. The formal error provides the precision of the estimated values from the design matrix of least-square adjustment and was used as the primary metric of assessment in this study.

In general, the number of observations is increased with the addition of another antenna to the existing network of a session. This increase is partly the reason for the improvement detected in the derived geodetic parameters. Thus, we use following equation to determine the expected improvement percentage due to additional observations, given by %obs:

$$\%obs = -\left(\sqrt{\frac{DOF_r}{DOF_s}} - 1\right) \times 100 \quad (1)$$

where DOF_r = DOF of the reference network solutions. DOF_s = DOF of the study network solutions. DOF refers to the degree of freedom and is expressed by the number of total observations minus the number of estimates in the adjustment.

The percentage obtained from Eq. (1), %obs, was compared with the achieved improvement percentage of the derived geodetic parameters. Here, achieved improvement depicts the improvement achieved from the simulation study. There are two possible outcomes of comparison. The %obs is greater than the achieved improvement or vice versa. The first outcome implies that the achieved improvement of the derived geodetic parameter does not solely come from the increase in the number of observations, but also from the impact on the increased sensitivity of the estimated geodetic parameter due to the addition of new antenna to the reference network. In the second outcome, the achieved improvement shown by the precision of geodetic parameter comes solely from the increase in the number of observations, but it might still be advantageous as it can provide redundancy when other stations of that region are unable to participate. Therefore, %obs would help to put more insight into the determined performance of the study locations from simulation study.

Impact of local environmental factors

The impact of local environmental factors was divided into two criteria—operationality and vulnerability. Operationality deals with the problematic meteorological events listed in Table 2, which either results in noisy observations or obstructs the operation of the VLBI antenna by stowing or repairs. While vulnerability considers the extreme calamities, such as earthquakes, cyclones, floods and landslides, which has the capability to damage the VLBI station completely and are frequent to the Indian subcontinent.

A weighted scoring model, similiar to Griffith and Headley (1997) and Wang et al. (2018), was used to categorize the study locations based on the impact from the local environmental factors. This model enables multiple criteria to be considered for decision making by assigning a weighting to each criterion depending on its relative importance. The scores are assigned as a means of judging the extent to which the environmental factors will have an impact on the VLBI station. Table 3 depicts the scores used for this study and their interpretation. The final scores, $score_f$, of the study locations were calculated by the following equation:

$$score_f = (w_{opr} \times score_{opr}) + (w_{vul} \times score_{vul}) \quad (2)$$

wherew_{opr} and w_{vul} are the weights of the operationality and vulnerability, respectively. While,$score_{opr}$ and $score_{vul}$ are the scores calculated for the operationality and vulnerability, respectively. In general, '*w*' is for weights and '*score*' is for scores. The w_{opr} and w_{vul} are kept as 0.4 and 0.6. The reason for this is the seriousness of damage posed by the impact of two considered criteria.

Table 2 Following table discusses the environmental factors and their effect on the operation pf VLBI

S. No	Environmental factors	Reason for stowing the VLBI radio telescope
1	Strong Winds/Squalls	Damage the structural properties of VLBI radio telescope. High wind gusts can cause pointing error
2	Precipitation (Rain, Snow, etc.)	It reduces the reflectivity of the antenna and is attenuating to radio signals. Heavy snow accumulated over antenna may cause damage
3	Thunderstorms	Damage the receiver and other electrical parts of the system
4	Hail Storms	Damage the structural properties of VLBI Radio Telescope
5	Dust/Sand Storms	Can cause attenuation. Dust can get inside the equipments to interrupt the process and damage the system

Table 3 Scores and their interpretation for operationality and vulnerability

Scores	Interpretation of Scores	
	Operationality	Vulnerability
3	Susceptible to frequent periods of in-operation and more chances of getting noisy data	High risk of complete destruction
2	Lesser halts in operation and some chances of getting noisy data	Moderate risk of destruction
1	Very-low or no halts and no chance of getting noisy data	Low chances or no risk of destruction

Operationality factors cause relatively lesser damage and certain measures might be possible to mitigate it to some level. However, vulnerability factors pose a serious threat of irreversible destruction of the VLBI station. Thus, weighting of the latter is kept bit more than the operationality criteria. The scores in Eq. (2) are determined from the following.

$$score_{opr} = (w_p \times score_p) + (w_w \times score_w) \tag{3}$$

$$score_{vul} = \sum (w_e \times score_e) \tag{4}$$

The environmental factors affecting the operationality of the VLBI were divided into two parts for calculation in Eq. (3). It is the summation of weighted score of problematic weather events ($w_p, score_p$) and that of high-speed winds ($w_w, score_w$). The reason for separating these two scores of operationality are limitation in the data availability.

For calculating the $score_p$, the daily surface meteorological data of Indian Meteorological Department (IMD) stations located in close proximity to each of the 42 study locations were taken. The data were used to determine the number of days in a year, that were affected from the problematic weather events in each study location. The weather events that were examined for the Indian study locations are thunderstorms, dust/sand storms, snowfall, sudden squalls, hail storms and rainfall (> 15 mm/day) on the study locations. Rainfall intensity in mm per hour would have been helpful for determining operationality, but it was not present in the data set we utilized. The $score_p$ is determined based on the normal distribution or bell-shaped curve of the data (Brereton 2014). Here, data refer to the annual occurrence of weather events on study locations. Mean (μ) and standard deviation (σ) of the data was calculated to generate the normal distribution curve. The area under the curve represents the probability of operationality. The data of study locations lying in between $\mu + \sigma$ and $\mu - \sigma$ were considered to have medium chances of halts on operation and hence, were given the $score_p$ as 2. While the data falling in the area of more than $\mu + \sigma$ were assigned the score 3 and those in the area of less than $\mu - \sigma$ were assigned the score 1, as interpreted from Table 3.

Strong winds are a common cause for stowing of VLBI antennas and they are frequent to many regions, such as orographic, coastal as well as others due to changing pressure systems in the Indian peninsula. The $score_w$ was determined from the wind hazard map of the IMD (BMTPC 2019). Based on this map, the regions in 'very high damage risk zone' were assigned highest score, i.e., 3, and those in 'low damage risk zone' were assigned score as 1. All other regions in moderate to high damage risk zones were assigned with 2 as $score_w$. The w_p and w_w are kept as 0.5, since we assume that both are equally responsible for degrading the VLBI observations. The only reason for separating the $score_w$ and $score_p$ is the different data availability for the present case as the daily surface metrological data did not contain daily wind speed information. If the daily wind speed data are available then it is better to calculate the number of days in a year the location experiences high wind speeds that crosses the operational limit of VGOS antenna.

Equation (4) considers the summation of weighted scores combining the frequency and severity of four extreme natural calamities of India for determining the $score_{vul}$. According to Ministry of Corporate Affairs (2017), a large portion of India's landmass is prone to destructible calamities. The w_e and $score_e$ are the individual weights and scores assigned to the considered calamities—earthquakes, floods, cyclones and landslides. Thus, to incorporate it in our study, the w_e of considered hazards are kept as in Table 4. The weight values are based on the report by the World Bank (2016), which states the occurrence probability of natural hazards in India are 52% chances of floods, 31% of cyclones, 10% of landslides and 5% of earthquakes. Figure 4 represents the marked regions affected from

Table 4 Individual weights and the score assigning criteria for the environmental factors that affect the vulnerability of a VLBI station. For understanding the assigning criteria mentioned here, refer to Fig. 4

Scores	Basis for assigning the scores to the study locations			
	Earthquakes	**Landslides**	**Cyclones**	**Floods**
w_e	0.05	0.11	0.32	0.52
3	Regions in Zone V	Regions prone to landslides	Very high and high susceptible regions	Regions with highest flood frequency (Gupta et al. 2021)
2	Regions in Zone IV	Regions in close proximity to landslides	Moderate susceptible regions	Flood vulnerable areas
1	Remaining	Remaining	Remaining	Remaining

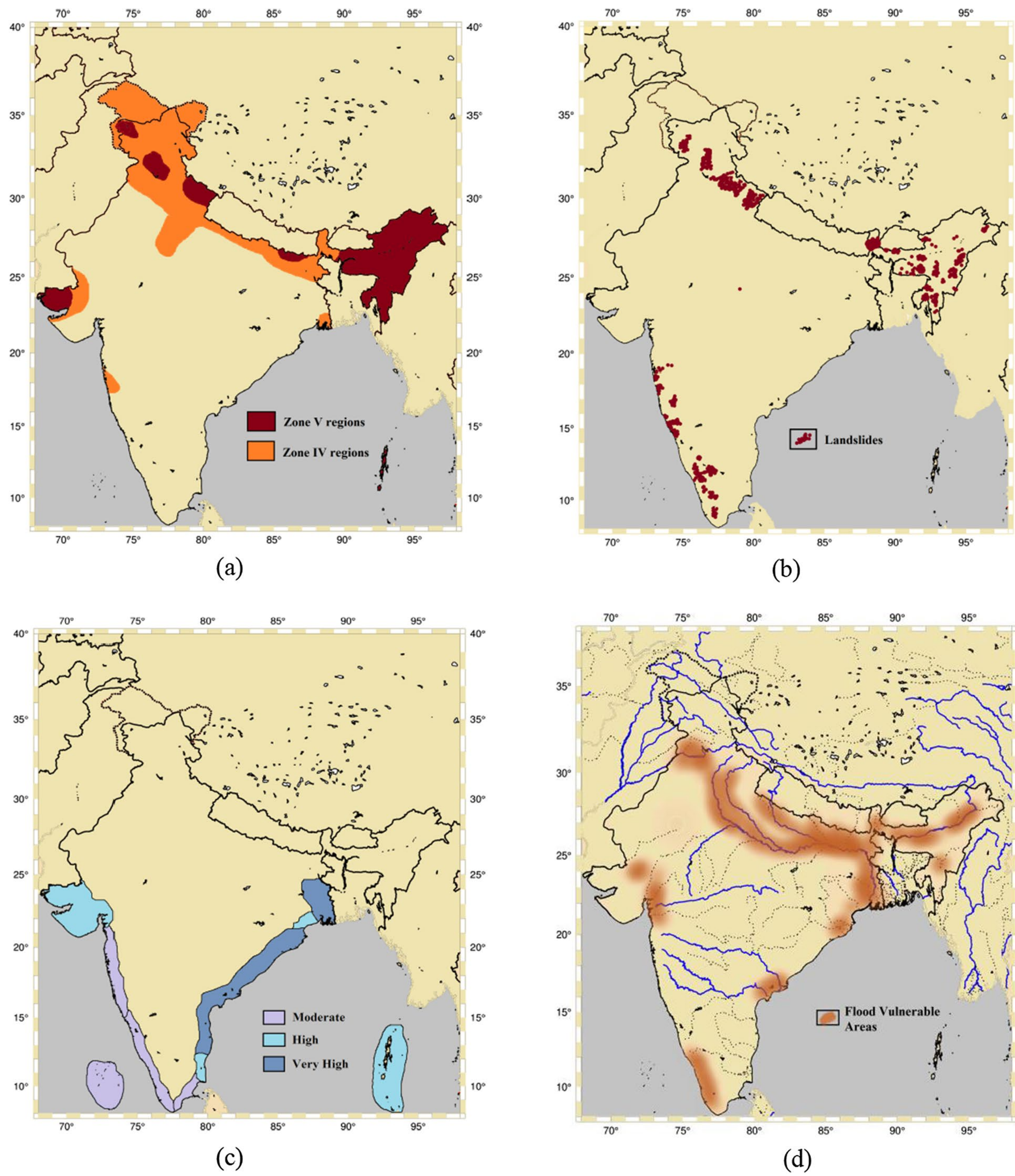


Fig. 4 Color blocks in the images represent only those zones in India which are highly susceptible to major destruction in the event of certain natural calamity (BMTPC 2019). **a** High-intensity seismic zones. **b** Regions susceptible to landslides. **c** Three vulnerable degrees of the cyclones—moderate (63–117 km/hr*), high (118–167 km/hr*), very high (above 168 km/hr*). **d** Regions vulnerable to floods with deep blue lines showing large rivers. * maximum sustained wind speeds in km/hr

the natural calamities. Figure 4a depicting earthquake prone regions, only shows zone V and zone IV as they experience frequent quakes with intensity above MSK VIII and MSK IX, respectively. Remaining regions or those which are not marked are regarded as having low or negligible possibility of experiencing a destructible earthquake and hence, assigned lowest score. Table 4 clearly depicts the basis for assigning the scores for the vulnerability calamities in this study. Concerning floods, the regions with very high flood frequency in India (Gupta et al. 2021) were assigned score '3' and the regions marked in Fig. 4d were assigned with score '2'. This completes the description for all the inputs required to calculate $score_f$ (Appendix: Tables 7 and 8).

Once the $score_f$ is determined for all the study locations, categorization was done based on the normal distribution of the $score_f$.μ and σ of the $score_f$ were calculated to form the thresholds for classification. The study locations were categorized into either one of the three choices, i.e., Excellent, Good, and Poor, for VGOS establishment in India. The $score_f$ of study locations lying in between $\mu + \sigma$ and $\mu - \sigma$ were categorized into "Good" choice. The values of $score_f$ which were more than $\mu + \sigma$ were categorized as "Poor" and those which were less than $\mu - \sigma$ were categorized as "Excellent" choice.

Results

All the study locations in Fig. 2 were individually evaluated to quantify the geodetic performance, and the effect of environmental factors. This made 42 results pertaining to 42 study locations in every studied scenario which are depicted in Figs. 5, 6, 7, 8 and 9. The figures portray 42 blocks with specific color that signifies the result obtained by each study location. These blocks are arranged as per their geographical location coordinates which makes them easier to comprehend in the figures. The color scheme for different values in each block are represented by the color bars of the plots.

Figures 5, 6, 7, and 8 show the improvement percentage in the precision of the determined geodetic parameters obtained from the addition of individual study locations to the four reference networks of Fig. 3, respectively. The improvement percentage describes the improvement or degradation in the mean formal

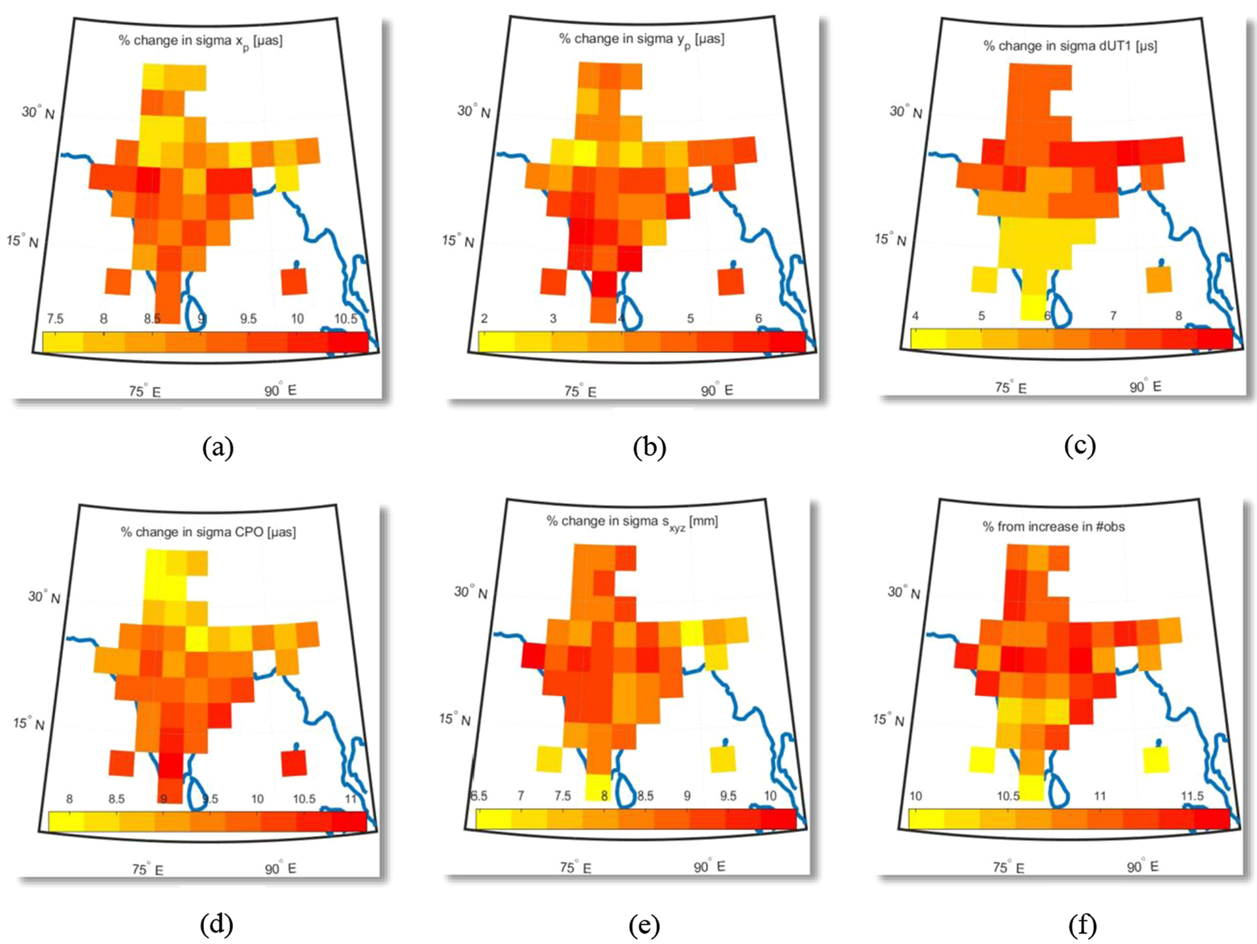


Fig. 5 **a**–**e** Percentage improvement in the mean formal error (sigma) of geodetic parameters in the first scenario; **f** expected improvement percentage from the increase in observations

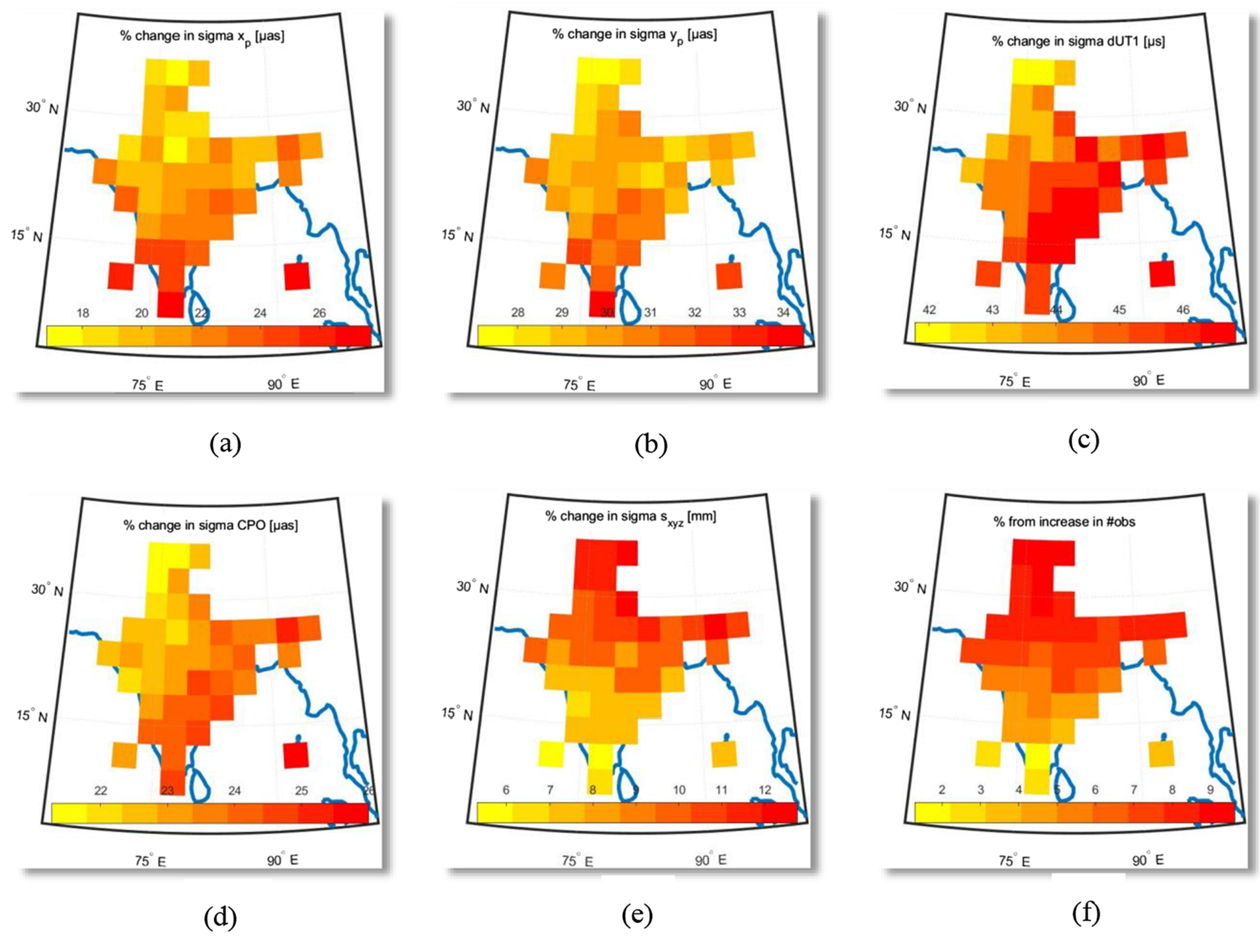


Fig.6 **a**–**e** Percentage improvement in the mean formal error (sigma) of geodetic parameters in the second scenario; **f** expected improvement percentage from the increase in observations

error when an additional VGOS antenna is added to the reference network. The geodetic parameters shown in the results are x_p, y_p, dUT1, mean of dX and dY coordinates of celestial pole offsets (CPO), and the average of the station coordinates (s_{xyz}). The mean formal errors of the x, y, and z station coordinates in the study were similar and hence they were averaged to get s_{xyz}. The reason for averaging the CPO coordinates were same as the latter. From Eq. (1), the expected improvement percentage from the increase in the number of observations is also displayed for each scenario in Figs. 5, 6, 7, and 8. As the maximal and minimal values of mean formal errors are less than that of the reference network in almost all cases of Table 5, it is evident that the precision of the geodetic parameters improves by the additional antenna.

Figure 9 shows the $score_{opr}$, $score_{vul}$ and categorization of the study locations based on the $score_f$ that assess the impact of the local environmental factors.

The results are discussed for the combined group of study locations diversified by their regions, such as south, central, east, west, north, etc., as the study locations belonging to same region portrays similar geodetic results in most of the cases. From Figs. 5, 6, 7, and 8, it can be seen that a trend in improvement can be distinguished regionally among study locations. This is discussed in the results by means of factor, which depicts the ratio of maximum and minimum improvement percentage among the study locations. Although, in some cases, a clear transition among the study locations from maximum to minimum improvement cannot be seen from the figures, this may be due to the position of the reference stations in that particular case. Nevertheless, the results obtained in this study will help to infer the performance of VGOS in different regions of India.

Scenario 1

Figure 5 portrays the results of the first scenario with the S/X observation. A maximum improvement of

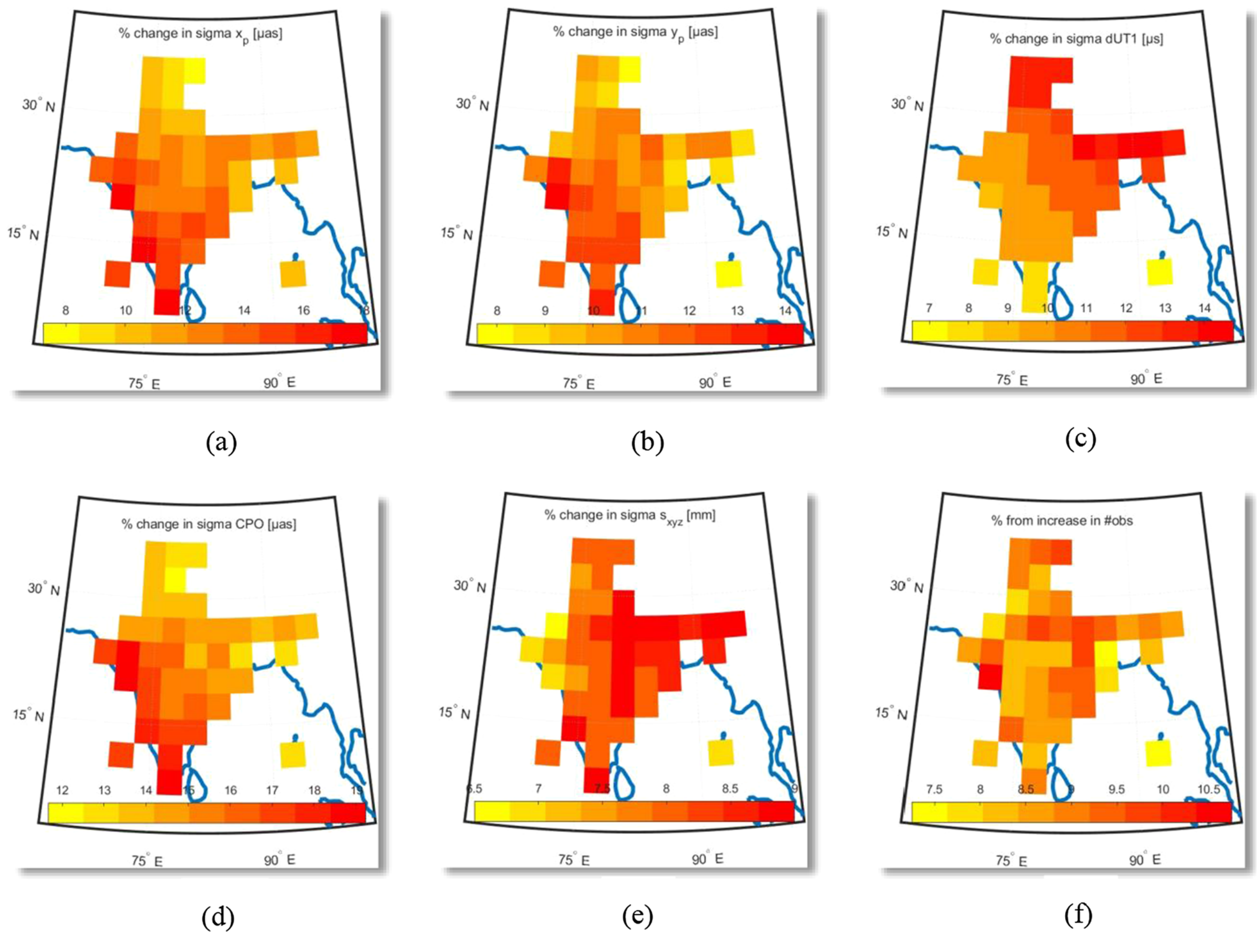


Fig. 7 **a**–**e** Percentage improvement in the mean formal error (sigma) of geodetic parameters in the third scenario; **f** expected improvement percentage from the increase in observations

10.7% in the precision of x_p is shown from the addition of antennas in central regions of India. Antennas added from the southern regions also show high improvements. These improvements are more by a factor of 1.5 than that produced by adding of antennas in north-eastern and northern regions. The best performance of 6.7% for the estimation of y_p coordinate is observed by adding antennas from the southern and then central study locations. These are a factor of 3.5 higher than those obtained from adding antennas in the northern regions. This gain in the polar motion coordinates might be from the longer north–south baselines that can be formed by putting the antenna in the southern regions of India as most of the VLBI stations in general and in the reference network of this scenario are available in the northern hemisphere of the globe above 40°N. Unlike the results for x_p, the eastern regions show more improvement in y_p than the western regions. The reason for this has to be investigated further.

The results of dUT1 contradicts that of polar motion by showing best improvement of 8.8% in precision by addition of antennas in the northern locations of India, and especially north-eastern regions. This outperforms the southern regions by a factor of 2.3. This might be due to the longer east–west baseline that can be formed from the north-eastern antennas of India with the reference stations at Kokke, Santa Maria, and others in the northern hemisphere of this scenario.

The adding of antennas at the southern regions of India produce maximum improvement in CPO precision of 11.2%, a factor of 1.4 more compared to the northern region. The study locations showing best and worst improvements in this case are similar to the results of polar motion.

The formal error of station coordinates gets improved from the addition of Indian antennas by a maximum of 10.3% in the western regions. In this scenario, study locations in the western and northern regions are

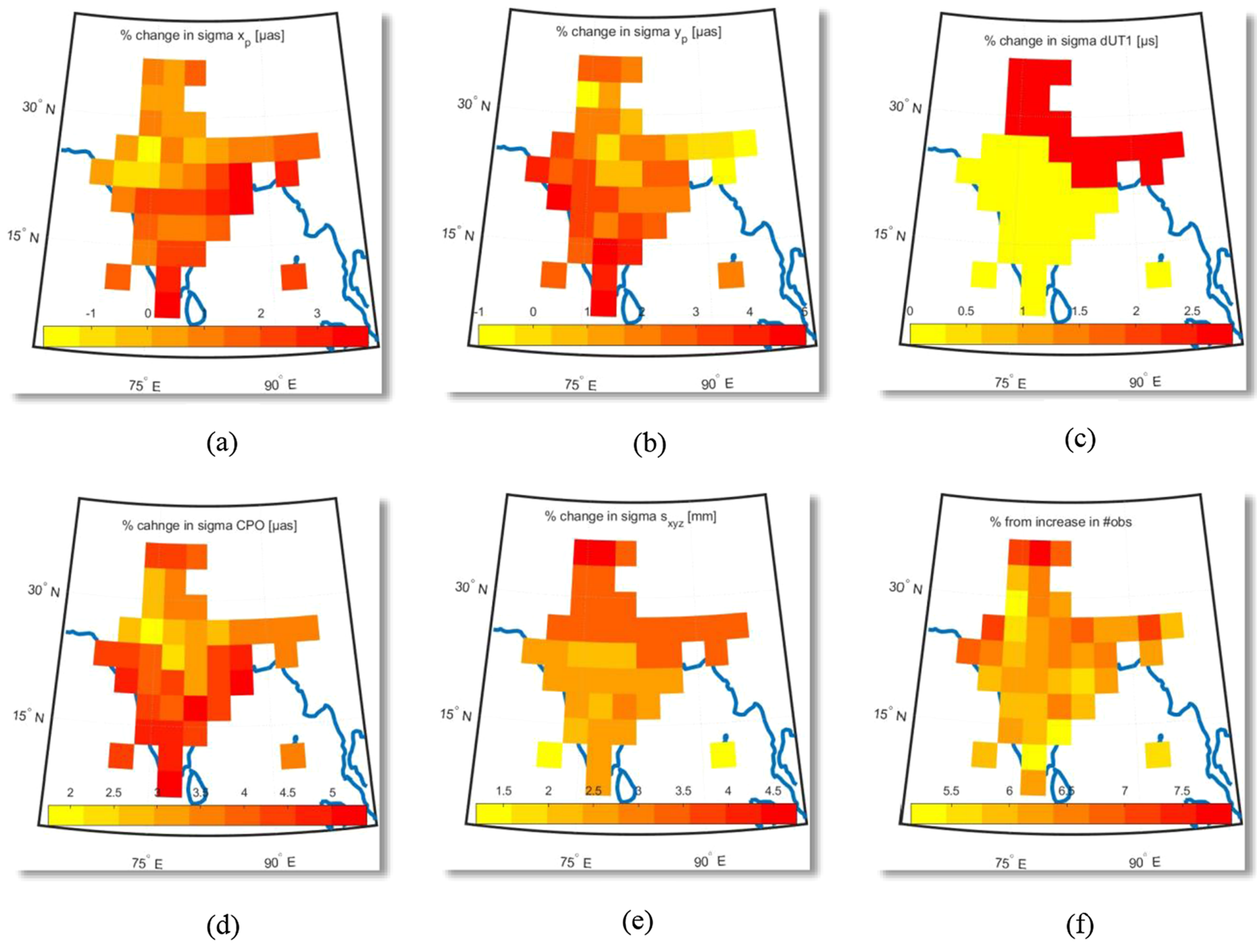


Fig. 8 **a**–**e** Percentage improvement in the mean formal error (sigma) of geodetic parameters in the fourth scenario; **f** expected improvement percentage from the increase in observations

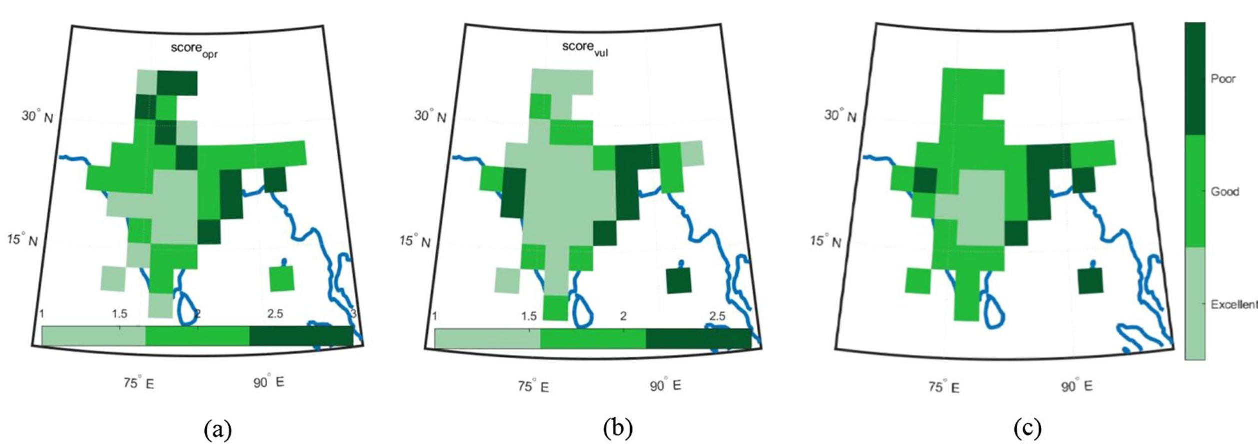


Fig. 9 **a** Scores for operationality; **b** scores for vulnerability; **c** categorization of study locations based on final scores for assessing the impact of environmental factors

Table 5 Maximum and minimum values of mean formal errors among all study locations and that of the reference network in each scenario

	Max	Min	Reference network
Scenario 1			
x_p [μas]	13.61	12.96	14.52
y_p [μas]	19.50	18.55	19.88
dUT1 [μs]	0.99	0.93	1.02
dX [μas]	9.95	9.55	10.68
dY [μas]	9.87	9.48	10.79
s_{xyz} [mm]	1.45	1.39	1.55
Scenario 2			
x_p [μas]	26.01	22.59	31.27
y_p [μas]	23.84	21.43	32.7
dUT1 [μs]	0.46	0.42	0.79
dX [μas]	13.62	12.45	17.28
dY [μas]	13.22	12.24	16.34
s_{xyz} [mm]	0.89	0.82	0.94
Scenario 3			
x_p [μas]	14.1	12.44	15.2
y_p [μas]	12.91	11.96	13.97
dUT1 [μs]	0.57	0.52	0.61
dX [μas]	9.23	8.42	10.26
dY [μas]	8.90	8.13	10.23
s_{xyz} [mm]	0.94	0.91	1
Scenario 4			
x_p [μas]	9.38	8.85	9.20
y_p [μas]	9.02	8.48	8.93
dUT1 [μs]	0.35	0.34	0.35
dX [μas]	5.89	5.66	5.98
dY [μas]	5.96	5.68	6.05
s_{xyz} [mm]	0.83	0.80	0.84

indicating better performance than others by a factor of 1.6 in s_{xyz}.

Figure 5f shows the expected improvement percentage from the increase in the number of observations. Comparing the latter to the achieved improvement in the precision of derived geodetic parameters shown in Fig. 5a–e, reveals that the improvement in the precision of CPO for southern regions are higher than that in Fig. 5f. While for other cases, the increase in the number of observations contributes solely to the achieved improvement in the precision of geodetic parameters.

Scenario 2

Scenario 2 shows the results when the study locations are added to the current VGOS sessions (Fig. 6). The antennas in southern regions of India displays largest improvement of 27.8% in x_p and 34.5% in y_p. The regional variability in the polar motion coordinates are similar and the southern study locations improve x_p and y_p by a factor of 1.7 and 1.3, respectively, more than the northern regions. The reason for far south Indian regions showing clear maxima might be that all the VGOS reference stations in this scenario are located north of India in between 22°N and 57°N latitudes.

The dUT1 estimates show the best precision of 46.8% improvement over study locations in the eastern regions of India, by a factor of 1.2 more compared to the western and far northern regions. This may be due to the positions of reference stations in this scenario, as most of them are located to the west of India and can form long east–west baselines with antennas in the eastern regions of India.

The maximum improvement of 26% in the precision of CPO is shown by antennas located at the far-east of India, by a factor of 1.3 more than the study location portraying minimum improvement. In this scenario, clear minima are shown by the far northern study locations.

The s_{xyz} can be estimated best by adding antennas at the northern study locations as they show maximum improvement of 12.8%, a factor of 2.4 more compared to the southern regions.

The achieved improvement in the precision of geodetic parameters in this scenario is more than the expected improvement caused by the increase in number of observations displayed in Fig. 6f. This clears that mainly all additional antennas in this scenario improves the network geometry and do not just add observations.

Scenario 3

This scenario considered a possible future VGOS session in next 3 years. Therefore, it has 11 reference stations with a better network density than the previous VGOS scenario. However, still there is a shortage of southern hemisphere VGOS antennas in this session. This may be the primary reason for the antennas added from the southern regions of India, still performing better than its counterparts by showing maximum improvement in the estimation of x_p by 18.2% and y_p by 14.4%. These regions of best improvement outperform the northern regions by a factor of 2.5 in x_p and 1.9 in y_p.

The precision of dUT1 estimates show maximum improvement of 14.8% from the addition of antennas in northern and north-eastern study locations in India. The improvement of these regions is more by a factor of 2.3, compared to the southern regions which shows minimum improvement. A clear transition from maximum to minimum improvement is portrayed in Fig. 7c.

The CPO can be estimated best by 19.2% improvement when antennas are added from the southern regions of India. They perform better by a factor of 1.6 than the northern and north-eastern regions. The regional variability of improvements for CPO and polar motion coordinates are similar.

Adding a VGOS antenna at any Indian location will improve the precision of s_{xyz} by 6.5–9%. From Fig. 7e, it can be inferred that only some of the study locations in the extreme western parts produce minimum improvement that are less by a factor of 1.4 compared to study locations in the eastern and northern regions.

The values of expected improvement due to the increase in the number of observations (Fig. 7f) demonstrates that adding a VGOS antenna from any Indian location to the reference network of this scenario will improve the sensitivity of derived geodetic parameters in almost all cases. Even though the achieved improvement for the precision of s_{xyz} in this scenario is lower than the expected improvement, the difference between them is not substantial.

Scenario 4

This scenario anticipates a 10 years future situation of the VGOS network. In spite of larger VGOS stations planned in the future, there is still a difference between the number of VGOS stations above 22°N and below it. Thus, the southern study locations of India show maximum improvement of 3.9% and 5% for x_p and y_p, respectively. The minimum improvement in polar motion coordinates are negative values which are shown by antennas added in some north-western study locations for x_p and in north eastern study locations for y_p. The reason for this may be that the addition of antenna at those study locations impacts the scheduling negatively for this session. However, they may still reap in useful benefits by adding redundancy to the network.

It is peculiar to see only two values of improvement percentages in dUT1 precision. This may be due to the assumption of considering mean formal error values significant up to two decimal places in this study. Therefore, there might be improvement in this case also, but they were so negligible that they appeared as 0% improvement in the results. In addition, the same reason applies for 2.7% improvement in northern and north-eastern regions. In these regions, the difference in obtained precision values are beyond the second decimal and hence, any change is not seen in the achieved improvement.

The precision of CPO estimates shows 1.7–5.4% improvements from the addition of an Indian antenna. The study locations from southern regions of India show maximum improvement by a factor of 3.1 more compared to the north-western and northern regions. In spite of that, some far northern regions do not show less improvements.

For the precision of s_{xyz}, adding of antennas from the far northern Indian regions produces a maximum improvement of 4.8%, a factor of 4 more compared to southern regions.

Figure 8f shows that the expected improvement due to the increase in the number of observations is higher than that achieved for the geodetic parameter estimates for all study locations. This shows that adding Indian antennas in this scenario only benefits by increasing the number of observations for determination of geodetic parameters.

Comparison of the scenarios

On comparing all the studied scenarios, the higher percentages of achieved improvement in the precision of estimated geodetic parameters obtained in the second scenario can be explained by the fact that only few VGOS antennas are currently operational, and almost 90% of them are located in Europe and North America. The achieved improvement in the third scenario is smaller than the second as they project the VGOS network situation in 3 year future and thus, has more reference stations. Surprisingly, the results of the third scenario show twice the improvement than that of the first scenario, when the latter had just one station less in the total count of reference network. Though, the number of reference stations are comparable in both scenarios, the only difference in the network geometry of first scenario is that it includes a VLBI antenna from the South African station. This may be the reason for the increased impact shown by additional Indian antennas to the third network. Partly, the reason might be the increased observations in third scenario due to the difference in observing modes of these two scenarios. The achieved improvement percentages in the fourth scenario are less than that observed in any of the previous scenarios. This is due to the higher number of reference stations which are better distributed, and the new VGOS antenna at Thailand that was considered in this scenario. However, a suitable Indian antenna in this scenario can still improve the geodetic result by 5.4%.

Intensives

In this section, the impact of Indian antennas on intensives are reported. Results shown in Fig. 10 depicts that an Indian antenna from any region of India gives best precision of dUT1 when paired with GGAO (USA). The primary reason for this might be the long east–west

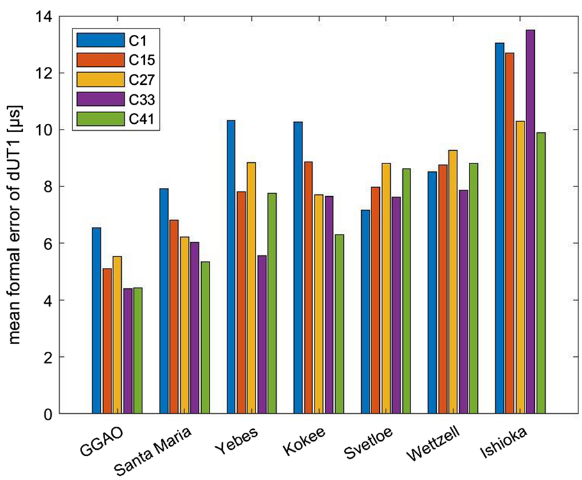


Fig. 10 Mean formal error of the intensives of five study locations paired with different VGOS stations shown in the *x* axis of the plot

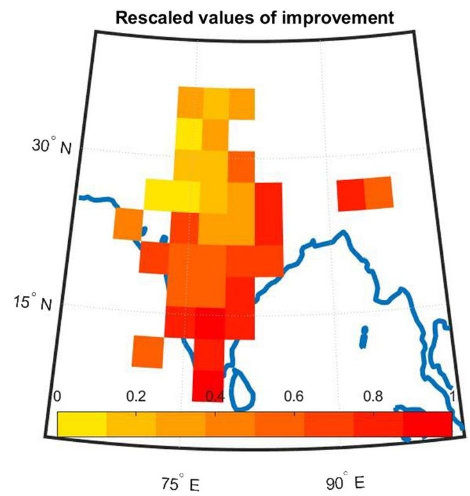


Fig. 11 Cumulative rescaled values of improvement percentage between 0 and 1 with masking of study locations falling in the 'poor' choice category with respect to environmental factors

extension of the baseline formed by the Indian antennas at one end and GGAO at the other. This is in accordance with the knowledge that the longer the east–west extension of the baseline, the better the precision of dUT1. However, there should be enough common sources available between the VLBI stations of the considered long baseline to achieve better precision in reality. The Santa Maria (Spain) VGOS antenna also provides improved dUT1 precision when paired with Indian antennas for intensives. The five precision values of five Indian antennas for each pairing set shows variations among them. This is because the five Indian antennas are located in different regions of India. Like from the results of GGAO in Fig. 10, C33 performs better than C1. As C33 forms a longer and better east–west orientation with GGAO, than C1. VGOS antenna, Is (Japan) is nearest from India among all the antennas selected for this intensive study. Thus, it is clear that the baselines of Is observing with Indian antennas will not achieve higher sensitivity and hence, it shows poor precision for estimated dUT1 than other cases.

Environmental variables

Figure 9a, b demonstrates the scores of operationality and vulnerability, respectively. These were as calculated from the procedure explained in the methodology section. Figure 9c shows the categories assigned to the study locations based on final scores,$score_f$. This is solely based on the impact of local environmental factors on VGOS. Most of the study locations lie in the middle category, i.e., 'good' choice for the VGOS establishment. The main reason for this is the normal distribution curve used for classification in this case. This curve tends to classify maximal number of points near the mean value of the distribution. Some of the far-eastern study locations are in the 'poor' category. This is because the study locations, C24, C17, C11 and C4, are commonly affected by severe cyclones and floods, risking the vulnerability of VLBI antennas and sub-systems. They also show higher scores for low operationality conditions, such as strong winds. In addition, C4 are at higher risks of high magnitude earthquakes or tsunamis in general. The study location C25 is located in the seismic north-eastern hilly regions which are affected from heavy rainfall throughout the year, making most of the accessible regions prone to landslides and floods. This region is also affected by strong winds, and relatively high thunderstorms that lowers the operationality of VLBI in this region. C31 and C32 are located in the high seismic regions of the Indian plains at the foothills of Himalayas and are commonly affected from floods. These study locations also lie at the high damage risk locations for winds, and suffer from thunderstorms and rainfall to make it a 'poor' choice for VGOS. C19 is the only 'poor' choice that is located in the western region of India which is frequented by severe cyclones and flooding. In addition, they fall in seismic prone regions with high probability of extreme weather events like squally winds that will affect the VGOS operation. The study locations falling in the 'good' category have relatively better conditions than those in the 'poor' category. The study locations presenting the 'excellent' choice for the VGOS establishment lie in the central plateau regions of India. This implies that the VLBI antennas in those regions will get much less affected from the extreme environmental factors than other Indian regions.

Scaling for combined assessment

The improvement percentages determined for each scenario were scaled from 0 to 1 for each geodetic parameter. The minimum improvement was kept as 0 and the maximum improvement as 1, while all other improvements were arranged with values in between 0 and 1. These scaled values of each study location were summed among the four scenarios for cumulative assessment (Appendix: Table 9). Here, each of the six geodetic parameters, i.e., x_p, y_p, dUT1, dX and dY coordinates of celestial pole offsets (CPO), and the average of the station coordinates (s_{xyz}), were given equal weightage. Then, the outcome was combined with the impact of local environmental factors by masking (excluding) the 'poor' choice of study locations, as shown in Fig. 11. It is evident that southern and central regions, and some northern regions specially towards east will beneficial for establishment of VGOS. This cumulative assessment does not consider relative improvements among the six geodetic parameters. In addition, it does not give priority to any one estimated geodetic parameter for the assessment.

Summary and conclusion

The main objective of this study was to choose favorable locations for establishment of a VGOS station in India. Hence, we assessed 42 study locations covering the whole Indian subcontinent. A VGOS antenna was simulated at each study location one-by-one in addition to the reference network to determine the impact on the precision of the geodetic parameters, i.e., EOP and station coordinates. Different scenarios were considered for a comprehensive investigation. Multi-scheduling was performed on network geometry of each scenario to provide optimized weighing parameters for realistic schedules. Then, these schedules were simulated and analyzed to obtain the improvement in geodetic parameters. However, we believed that this alone probably was not sufficient for a thorough analysis to identify the favorable locations in India. As the simulation study assumes that all the scheduled observations in a session were observed and each of them generated good quality data for analysis. However, in reality, the VLBI operation is affected from external environmental factors, and this affects the quantity and quality of observations, which reduces the performance of an antenna as speculated from simulation. In addition, the vulnerability of study locations being hit by destructible natural calamities were considered in the decision. The stability of reference frames depends on maintaining the extensive history of data provided by these sites; therefore, the latter is applicable to VLBI as well as other space geodetic techniques. Adding to it, the re-establishment or repair of sophisticated systems like VLBI would incur unnecessary exorbitant expenses. To assess the environmental impact, the local environmental factors of the study locations were considered with a weighted scoring model and normal distribution to categorize the different locations in India.

We completely understand that the decision of suitable locations might not solely depend on the environmental factors considered in this study. They also depend on other factors, such as staff availability, vicinity to supporting supplies, RFI, power availability, broadband internet access, funding and other requirements. However, these other factors are highly variable and complex to quantify and hence, they were beyond the scope for this study.

The results show that the addition of VGOS antenna from any Indian location improves the precision of determined geodetic parameters in almost all the cases. In addition, the comparison between the expected improvement to the achieved improvement, depicted that in most of the cases, the additional antennas improve the network geometry and do not just increase the number of observations. The remaining cases, in which additional antennas simply increase observations, are also important because they will be useful in other geodetic sessions, during maintenance, or as replacements for any fall-out antennas.

In the present study, adding a VGOS antenna to southern locations of India showed better performance for polar motion coordinates by 11–3%, and CPO by 8–3%, depending on the studied scenario. These percentages are the difference between the maximum and minimum improvement in each scenario. Whereas, for dUT1 estimates, the antennas at north-eastern and northern regions shows larger improvements by 8–3%. The latter locations also perform optimally for intensives. For s_{xyz}, the antenna added at northern India performed well in all cases by 7–2%. Furthermore, the regions of India categorized as 'good' and 'excellent' in terms of the impact of environmental factors offer suitable environmental conditions for VLBI.

Finally, the selection of favorable locations for VGOS establishment in India will depend on the geodetic parameter of interest and the environmental conditions in that region. However, the most noteworthy or unique characteristic of VLBI is that, it determines dUT1. Therefore, the study locations in India that showed improved dUT1 determination should outweigh in the decision for establishment of VGOS. Although, if there is no specific requirement for any specific geodetic parameter, then VGOS antenna at southern and central regions, or some northern regions specially towards east would be fine as depicted from the scaling for combined assessment of the improvements. An important thing to note is that any shortcoming in the data recorded or provided by the meteorological facility at the study locations will crypt in the assessment of local environmental conditions.

In conclusion, the addition of an Indian VGOS antenna will be beneficial in realizing the GGOS goals and ultimately benefit the quantification of societal impacts of India and, the world. VGOS will be a shared national asset that will serve the national geodetic community well by creating opportunities for leadership in significant scientific aspects at a global level. The holistic approach of this study will give a realistic idea of VGOS station performance in different locations of India. The favorable locations selected in this study were with respect to adding a single VLBI antenna at different locations of India and no local ties were considered in this study. Co-location site are essential for the TRF, hence further simulation studies can be conducted with the newly arising space geodetic techniques in India and their co-location. Furthermore, investigation of different antenna locations based on u–v coverage are planned to be conducted in another study. It might also be interesting to use different scheduling strategy, like source-based, to check the full potential of additional antennas and to study the improvements. Many countries are joining the VGOS network to get benefits from the sub-millimeter accuracy provided by VLBI. The present study focuses on India; however, it can be carried out for any other country planning to establish a VGOS station, in case the environmental data is available at a comparable level.

Appendix

See Tables 6, 7, 8 and 9

Table 6 Detailed snippets of few examples from the IVS analysis report

S. No.	Session	Problem	% Scheduled observations used
1	2014-05-17-XA	HOBART12 and HOBART26 missed the first ~ 7 h due to high winds TSUKUB32 also missed ~ 2 h due to high winds	HOBART12–61.3% HOBART26–62.6% TSUKUB32–80.2%
2	2020-04-14-XA	Strong winds at NyAlesund. NYALE13S did not observe and NYALES20 observed only the last 10.5 h ZELENCHK missed ~ 2 h, wind stowed	NYALE13S–0% NYALES20–41.7% ZELENCHK–80.1%
3	2021-06-28-XA	WETTZELL: thunder strike hit the area of the observatory (00:16–02:20 UTC)	WETTZELL–55.8%
4	2021-02-01-VG	GGAO12M did not observe due to winter storm	GGAO12M–0%
5	2021-08-10-XA	ZELENCHK: thunderstorm (21:09–01:15)	ZELENCHK–54.6%
6	2021-12-05-XK	Due to blizzard, MK-VLBA did not observe	MK-VLBA–0%
7	2021-10-18-XA	MATERA: RFI in S-band particularly RAEGSMAR: RFI in S-band particularly YARRA12M: wind stowed (04:40–05:16)	MATERA–65.6% RAEGSMAR–66.6% YARRA12M–55.3%
8	2021-11-08-XA	SEJONG is very noisy NYALE13S snow storm 15:25–17:00	SEJONG–47.2% NYALE13S–70.0%
9	2021-11-04-XE	HART15M: wind stowed a few times	HART15M–66.7%
10	2021-07-26-XA	ISHIOKA: stopped the antenna from start to 208-0049a, because typhon was approaching. Few missed scans due to antenna safety and motor troubles	ISHIOKA–35.7%
11	2021-11-17-XN	HARTRAO: no data 18:26–07:22. The log says "Just over 13 h of data was lost due to a storm induced power supply failure on the antenna that could only be repaired once a technician got to site in the morning."	HARTRAO–32.7%

Table 7 Scores ($score_{vul}$) of the study locations for their vulnerability in the mentioned natural hazards. The vulnerability score ($score_{vul}$) calculated from Eq. 4 with weights (w_e)

Study locations	$score_e$				$score_{vul}$
	Earthquakes	Landslides	Cyclones	Floods	
w_e	0.05	0.11	0.32	0.52	
C1	1	2	2	2	2.0
C2	1	1	2	1	1.3
C3	1	1	1	1	1.0
C4	3	1	3	2	2.3
C5	1	2	2	2	2.0
C6	1	1	1	1	1.0
C7	1	1	3	1	1.6
C8	2	2	2	1	1.5
C9	1	1	1	1	1.0
C10	1	1	1	1	1.0
C11	1	1	3	2	2.2
C12	1	1	3	2	2.2
C13	1	1	1	1	1.0
C14	1	1	1	1	1.0
C15	1	1	1	1	1.0
C16	1	1	2	1	1.3
C17	1	1	3	2	2.2
C18	3	1	3	1	1.7
C19	2	1	3	2	2.2
C20	1	1	1	1	1.0
C21	1	1	1	1	1.0
C22	1	1	1	1	1.0
C23	1	1	1	1	1.0
C24	1	1	3	3	2.7
C25	3	3	1	2	1.8
C26	1	1	1	1	1.0
C27	1	1	1	1	1.0
C28	1	1	1	1	1.0
C29	1	1	1	2	1.5
C30	2	1	1	2	1.6
C31	3	1	1	3	2.1
C32	3	1	1	3	2.1
C33	3	3	1	2	1.8
C34	3	3	1	1	1.3
C35	1	1	1	1	1.0
C36	2	1	1	2	1.6
C37	3	3	1	2	1.8
C38	2	1	1	2	1.6
C39	3	3	1	1	1.3
C40	3	3	1	1	1.3
C41	2	1	1	1	1.1
C 42	2	1	1	1	1.1

Table 8 Scores from effect of extreme weather events and strong winds for Eq. (3) and the determination of final scores of the study location. The weights used for the calculation of these scores are also shown

Study locations	Number of affected days in a year	$score_p$	$score_w$	$score_{opr}$	$score_{vul}$	$score_f$
weights		0.5	0.5	0.4	0.6	
C1	100	2	1	1.5	2.0	1.8
C2	145	2	1	1.5	1.3	1.4
C3	100	2	2	2.0	1.0	1.4
C4	112	2	2	2.0	2.3	2.2
C5	101	2	1	1.5	2.0	1.8
C6	160	3	1	2.0	1.0	1.4
C7	59	1	3	2.0	1.6	1.8
C8	129	2	2	2.0	1.5	1.7
C9	58	1	2	1.5	1.0	1.2
C10	58	1	2	1.5	1.0	1.2
C11	98	2	3	2.5	2.2	2.3
C12	45	1	2	1.5	2.2	1.9
C13	129	2	1	1.5	1.0	1.2
C14	47	1	2	1.5	1.0	1.2
C15	138	2	1	1.5	1.0	1.2
C16	138	2	2	2.0	1.3	1.6
C17	90	2	3	2.5	2.2	2.3
C18	62	1	3	2.0	1.7	1.8
C19	120	2	2	2.0	2.2	2.1
C20	120	2	2	2.0	1.0	1.4
C21	97	2	1	1.5	1.0	1.2
C22	97	2	1	1.5	1.0	1.2
C23	193	3	1	2.0	1.0	1.4
C24	193	3	3	3.0	2.7	2.8
C25	235	3	3	3.0	1.8	2.3
C26	79	2	2	2.0	1.0	1.4
C27	79	2	2	2.0	1.0	1.4
C28	90	2	2	2.0	1.0	1.4
C29	75	2	3	2.5	1.5	1.9
C30	71	2	2	2.0	1.6	1.7
C31	71	2	2	2.0	2.1	2.1
C32	77	2	2	2.0	2.1	2.1
C33	97	2	2	2.0	1.8	1.9
C34	87	2	2	2.0	1.3	1.6
C35	115	2	2	2.0	1.0	1.4
C36	112	2	3	2.5	1.6	1.9
C37	53	1	1	1.0	1.8	1.5
C38	67	2	3	2.5	1.6	1.9
C39	191	3	1	2.0	1.3	1.6
C40	132	2	1	1.5	1.3	1.4
C41	136	3	3	3.0	1.1	1.8
C42	136	3	3	3	1.1	1.8

Table 9 Cumulative rescaled values of improvement percentage of each geodetic parameter in this study

Study locations	Latitude (°N)	Longitude (°E)	x_p	y_p	dUT1	dX	dY	S_{xyz}
C1	8.197144	77.49865	1.00	1.00	0.00	0.97	1.00	0.32
C2	11.197144	71.49865	0.74	0.69	0.07	0.68	0.73	0.04
C3	11.197144	77.49865	0.79	0.88	0.07	1.00	0.76	0.30
C4	11.197144	92.49865	0.72	0.42	0.16	0.72	0.48	0.00
C5	14.197144	74.49865	0.67	0.80	0.14	0.82	0.72	0.48
C6	14.197144	77.49865	0.85	0.77	0.22	0.91	0.75	0.44
C7	14.197144	80.49865	0.67	0.89	0.22	0.91	0.62	0.44
C8	17.197144	74.49865	0.60	0.69	0.05	0.67	0.56	0.42
C9	17.197144	77.49865	0.53	0.69	0.23	0.60	0.65	0.46
C10	17.197144	80.49865	0.66	0.70	0.23	0.83	0.76	0.59
C11	17.197144	83.49865	0.54	0.38	0.30	0.73	0.78	0.41
C12	20.197144	71.49865	0.66	0.86	0.09	0.78	0.69	0.38
C13	20.197144	74.49865	0.57	0.72	0.12	0.74	0.43	0.40
C14	20.197144	77.49865	0.56	0.61	0.21	0.66	0.47	0.48
C15	20.197144	80.49865	0.59	0.54	0.44	0.46	0.58	0.62
C16	20.197144	83.49865	0.74	0.46	0.44	0.73	0.52	0.53
C17	20.197144	86.49865	0.61	0.44	0.37	0.62	0.51	0.55
C18	23.197144	68.49865	0.52	0.55	0.10	0.58	0.48	0.56
C19	23.197144	71.49865	0.45	0.54	0.18	0.79	0.47	0.42
C20	23.197144	74.49865	0.53	0.63	0.26	0.77	0.46	0.63
C21	23.197144	77.49865	0.46	0.42	0.28	0.52	0.19	0.57
C22	23.197144	80.49865	0.29	0.34	0.28	0.51	0.23	0.64
C23	23.197144	83.49865	0.65	0.51	0.70	0.61	0.49	0.86
C24	23.197144	86.49865	0.64	0.29	0.92	0.61	0.43	0.78
C25	23.197144	92.49865	0.34	0.15	0.74	0.34	0.35	0.59
C26	26.197144	71.49865	0.33	0.28	0.17	0.34	0.18	0.43
C27	26.197144	74.49865	0.06	0.18	0.19	0.20	0.28	0.58
C28	26.197144	77.49865	0.19	0.26	0.18	0.29	0.29	0.82
C29	26.197144	80.49865	0.23	0.31	0.68	0.29	0.04	0.74
C30	26.197144	83.49865	0.34	0.47	1.00	0.34	0.37	0.99
C31	26.197144	86.49865	0.21	0.14	0.77	0.46	0.21	0.75
C32	26.197144	89.49865	0.38	0.26	0.98	0.46	0.32	0.59
C33	26.197144	92.49865	0.50	0.33	1.00	0.53	0.41	0.91
C34	26.197144	95.49865	0.41	0.17	0.84	0.50	0.30	0.76
C35	29.197144	74.49865	0.20	0.33	0.52	0.08	0.09	0.62
C36	29.197144	77.49865	0.12	0.39	0.53	0.21	0.20	0.68
C37	29.197144	80.49865	0.19	0.37	0.74	0.45	0.21	1.00
C38	32.197144	74.49865	0.32	0.00	0.60	0.00	0.00	0.68
C39	32.197144	77.49865	0.22	0.23	0.68	0.00	0.17	0.83
C40	35.197144	74.49865	0.11	0.30	0.51	0.14	0.25	0.90
C41	35.197144	77.49865	0.00	0.32	0.51	0.28	0.00	0.90
C 42	35.197144	80.49865	0.17	0.21	0.59	0.17	0.26	0.89

Acknowledgements
We are grateful to Dr. Hayo Hase, Bundesamt für Kartographie und Geodäsie (BKG), Argentinean-German Geodetic Observatory (AGGO) for providing significant information about the operation and working of VLBI on site. We sincerely acknowledge the Indian Meteorological Department (IMD), Pune, India for providing us with the surface meteorological data of the stations. We would like to thank the editor and the reviewers, Dr. Matthias Schartner and the other reviewer, for taking the necessary time and effort to review the manuscript. We sincerely appreciate their insightful comments and suggestions, which allowed us to improve the quality of our manuscript.

Author contributions
SD visualized the research. SD and SG designed the research methodology. SD performed the research and wrote the manuscript. SG and RH made

significant contribution for improving the manuscript. SG, RH, HS, NB, and ON read and reviewed the manuscript. All authors have read and approved the final manuscript.

Funding
Open Access funding enabled and organized by Projekt DEAL. We are grateful to DAAD Research Grants—Bi-nationally Supervised Doctoral Degrees, 2020/21 for funding the research stay of lead author in GFZ Potsdam. The meteorological data were purchased from the contingency grant of the Prime Minister Research Fellowship (PMRF) of the lead author.

Availability of data and materials
The data set used and/or analyzed during the current study are available from the corresponding author on request.

Declarations

Competing interests
The authors declare that they have no competing interests.

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Received: 12 October 2022 Accepted: 28 February 2023
Published online: 30 March 2023

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