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Effective expansion of satellite laser ranging network to improve global geodetic parameters

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Abstract

The aim of this study is to find an effective way to expand the ground tracking network of satellite laser ranging on the assumption that a new station is added to the existing network. Realistic numbers of observations for a new station are numerically simulated, based on the actual data acquisition statistics of the existing stations. The estimated errors are compared between the cases with and without a new station after the covariance matrices are created from a simulation run that contains six-satellite-combined orbit determination. While a station placed in the southern hemisphere is found to be useful in general, it is revealed that the most effective place differs according to the geodetic parameter. The X and Y components of the geocenter and the sectoral terms of the Earth's gravity field are largely improved by a station in the polar regions. A middle latitude station best contributes to the tesseral gravity terms, and, to a lesser extent, a low latitude station best performs for the Z component of the geocenter and the zonal gravity terms.

Keywords: Space geodesy, Satellite laser ranging, Geodetic satellites, Terrestrial reference frame, Earth gravity field, Global geodetic observing system

Introduction

Satellite laser ranging (SLR) is a high-precision measurement technique for the two-way distance between a ground station and an artificial satellite, and it has been regarded as one of the key elements of global-scale geodesy (Pearlman et al. 2002). SLR data have been used to determine satellite orbits and retrieve global-scale geodetic products. In particular, it has provided the origin (three components) and the scale (one component) of the latest International Terrestrial Reference Frames (e.g., Altamimi et al. 2011; IGN 2016) and also gravity coefficients of the Earth (e.g., Reigber 1989).

The origin of terrestrial reference frames has been defined as a long-term average of the geocenter, that is, the gravity center of the Earth, but annual and interannual variations of the geocenter have also been observed from SLR data (e.g., Chen et al. 1999; König et al. 2015). The gravity field also varies in time, and SLR has played an important role in long-term monitoring of low-degree terms (e.g., Cox and Chao 2002; Sośnica et al. 2015). These global-scale geodetic products have helped to understand global-scale mass transfers such as ice mass depletion in the polar regions (Nerem and Wahr 2011; Matsuo et al. 2013).

SLR is composed of its satellite segment and its ground segment. In space, dozens of artificial satellites equipped with retroreflectors have been launched into various types of orbits. Among them spherical-shaped geodetic satellites are often used for the determination of terrestrial reference frames and Earth gravity fields. As for the ground segment, about 40 laser-tracking stations all over the world are routinely operational (ILRS 2016a) where the majority of them has now attained sub-centimeter precision (Otsubo et al. 2015).

Realizing the importance of uniform global station coverage, the SLR community has been extending the

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network during the last decade by building stations, especially in the southern hemisphere and recently in Russian territory, but there are still some gaps remaining on the globe. Pavlis and Kuzmicz-Cieslak (2008) showed that geodetic products such as the origin and the scale of a terrestrial reference frame can be improved by 50 % or more when the number of laser ranging stations increases from 8 to 32, assuming reasonably uniform station distributions and perfect collocation with four techniques, i.e., SLR, VLBI (Very Long Baseline Interferometry), GNSS (Global Navigation Satellite Systems) and DORIS (Doppler Orbitography and Radiopositioning Integrated by Satellite).

In this paper, we focus on the SLR ground segment and, through a numerical simulation study, discuss what the best way is to reinforce the existing SLR ground network. We look at several geodetic parameters in this study, and the best position for a new SLR station may depend on a geodetic parameter. The simulation analysis in this study is composed of two parts. First, a set of virtual SLR data is generated for any position on the Earth. Then, the data set, combined with the actual SLR data, is processed by our orbit determination software so that we can compare the estimated formal errors.

Data acquisition simulation

In this section, the planning of the simulated observations is outlined. The inclination angle of a satellite orbit, combined with the altitude, significantly affects its observability, which depends on the latitude of a ground station. This is shown in Fig. 1 where the number of all fly-over normal points during a 1-year span is plotted for

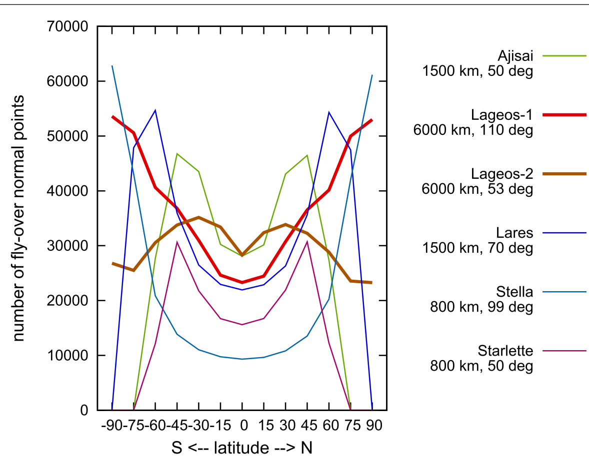

Fig. 1 Number of fly-over normal points with respect to the latitude (in degrees) of a ground station, for six geodetic satellites during a 1-year period from July 2014 to June 2015. The distance (km) and the angle (degrees) in the legend are the altitude and the inclination of satellite orbits

the six geodetic satellites, LAser GEOdynamics Satellite (LAGEOS)-1, LAGEOS-2, Ajisai, LAser RElativity Satellite (LARES), Starlette and Stella, with the sky coverage being defined above 20 degrees of elevation. Visibility of low-orbit satellites is heavily dependent on their inclination angles. For instance, Ajisai and Starlette cannot be seen from the polar regions at all due to their inclination angles of 50 degrees. Even the LARES satellite whose inclination is about 70 degrees is not observable from the poles, whereas Stella, with its highly inclined orbit, can be seen more often from the polar regions. On the other hand, despite the similar inclination angles, the two LAGEOS satellites can be seen from any point on the Earth due to their higher altitudes around 6000 km. What is notable is that a station in a higher latitude has more chances to observe the highly inclined LAGEOS-1 satellite because the satellite flies over the polar regions every revolution.

A normal point is a compressed form of a ranging observation made from a number of actual shot-by-shot measurements per a certain duration, 2 min for the LAGEOS satellites and 30 s for Ajisai, LARES, Starlette and Stella (ILRS 2016b). The six-satellite-combined number of fly-over normal points is maximized at around 45 degrees of latitude, and it does not vary much (10 % or less) in regions from 30 to 75 degrees. However, it drops by 18 % at the poles and 30 % around the equator. Due to the difference in the normal-point bin size, 2 min and 30 s, the total duration of the observable time for the two LAGEOS satellites is much longer than the other low-orbit satellites.

Unlike other space geodetic techniques based on microwave bands and automatic data acquisition, the operation of SLR is dependent on weather conditions and often relies on human resources at a ground station. In addition, even if conditions are met, only one satellite can be tracked at one time whereas a large number of SLR satellites orbit above a station these days. Hence, it is too optimistic to expect horizon-to-horizon coverage of all possible passes.

We collect all SLR observations made during a 1-year period from July 2014 to June 2015 to see the ratio of successful ranging observations with respect to all possible observations. Figure 2 illustrates the success rates of the most productive 15 stations in two ways: a pass-based ratio (solid) and a normal-point ratio (gray). The former is the number of observed passes divided by that of fly-over passes. The latter is the number of normal-point observations divided by that of all fly-over normal-point chances, setting the lowest limit of the elevation angle at 20 degrees. We see from Fig. 2 that full coverage cannot be expected as only the top three stations, Yarragadee (station code 7090), Changchun (7237) and Mt Stromlo

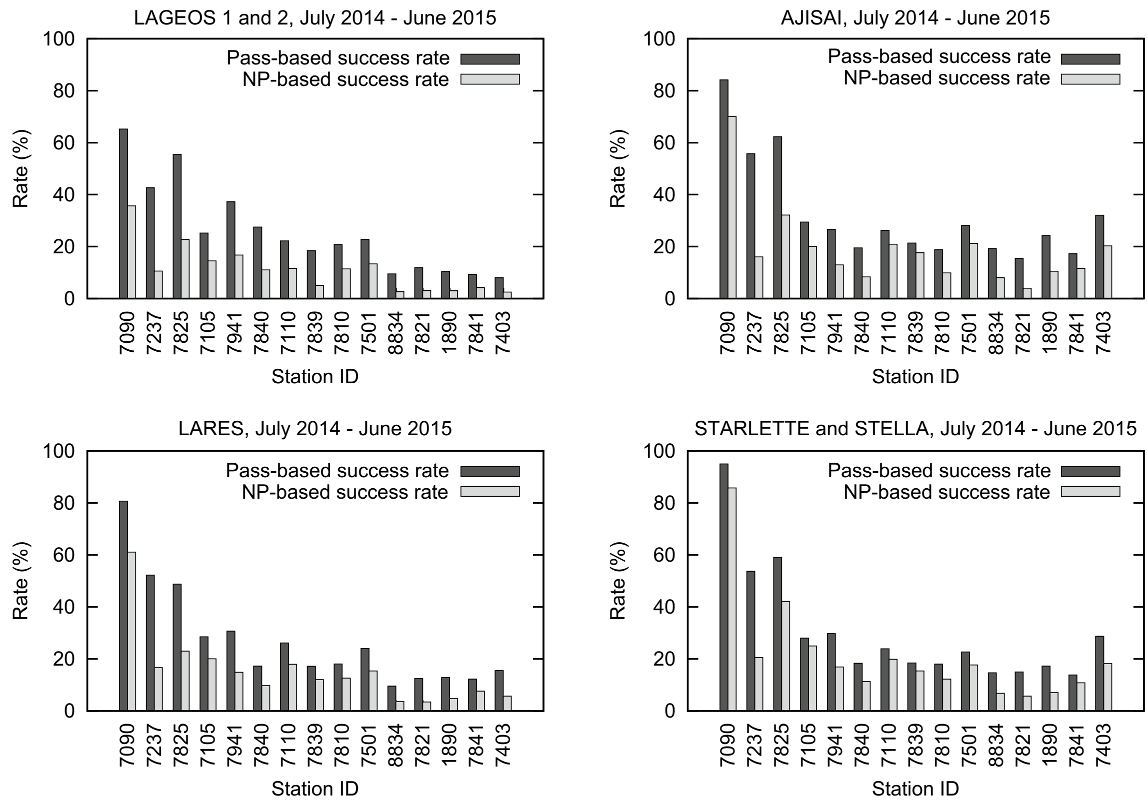

Fig. 2 Pass-based success rates and normal-point-based success rates for four types of satellites during a 1-year period from July 2014 to June 2015. Fifteen highly productive stations are shown where the four-digit station IDs are the NASA CDDIS Codes

(7825), exceed or come close to 50 %. In order to generate simulation data, we assume, for all types of satellites, 25 % for a pass-based rate and 15 % for a normal-point-based rate so that the data productivity correspond to a station between the 5th and the 10th in the rankings, assuming that this new station will be among the top-ranked. This means 60 % (=15 %/25 %) of possible normal points are observed among the observed 25 % passes. Practically, in the simulation data generating procedure, after calculating all fly-over passes and normal points for a certain virtual station, we randomly take 25 % of possible passes and then, for each pass, take a segment that covers 20–100 % (average 60 %) of possible normal points. The lowest elevation angle is set to 20 degrees. A segment is chosen so that it starts at the beginning of a pass, it ends at the end of a pass, or its center is aligned to the center of a pass, randomly at a rate of one-third each. This procedure for generating simulation data is repeated for the six satellites (LAGEOS-1, LAGEOS-2, Ajisai, LARES, Starlette and Stella) and for 134 virtual station points placed at intervals of 15 degrees in latitude and 30 degrees in longitude.

Orbit determination simulation

In this study, software "c5++," cooperatively developed and maintained by institutes in Japan and Sweden (Hobiger et al. 2014), is operated in a simulation mode in which a covariance matrix is created and actual observation values are not used. We look at estimated errors that are the square root of the diagonal elements of the covariance matrix. We focus on not the absolute values of estimated errors, but the relative change of them. The covariance matrix is first generated without including a new station (to be referred to as the baseline case and as C^0), and the result is then compared with that generated by adding one of the virtual stations to the existing ground network (to be referred as C^i for the i-th virtual station).

Assuming that a parameter in the n-th row/column in the case of the i-th virtual station is to be investigated in comparison with the baseline case, we define the improvement rate of the estimated error as:

$$\text{Improvement rate (\%)} = \left(1 - \sqrt{\frac{C^i_{nn}}{C^0_{nn}}}\right) \times 100.$$

The number of observations of a virtual station corresponds to 4–6 % of that of the entire existing network. If the existing stations uniformly increased their observations by 4–6 %, the estimation error of every parameter would be reduced from the baseline case by its square root, 2–3 %. If the improvement rate is significantly better than that, we can conclude that the virtual station will effectively work together with the existing network.

The actual SLR data in March and April 2015 are merged with the simulation data set that is generated for each virtual station placed at a grid point. Software c5++ is used to simulate the orbit determination and the parameter estimation.

The analysis procedure for examining the effect of a new station is as follows. The whole span is 60 days, and the orbits are chopped into 5-day arcs for the LAGEOS satellites and 3-day arcs for the other four satellites. Based on a fact that the post-fit residual scatter of LAGEOS data is about half of that of the low-orbit satellites, the LAGEOS normal-point data are assigned a weight double that of the other satellites' data. On the other hand, all stations' data are treated equally. In addition to the six orbital elements, five empirical parameters, i.e., one along-track offset coefficient, two along-track once-per-revolution coefficients and two cross-track once-per-revolution coefficients, are estimated per arc. The Earth gravity field coefficients up to degree and order of 4 are estimated as common parameters. A range bias as a constant for the 60-day span is estimated for each station and for each type of satellite, i.e., LAGEOS-1 and 2 combined, Ajisai only, LARES only, and Starlette and Stella combined, so that they can absorb station-dependent, satellite-dependent biases primarily caused by target signature effects (Otsubo and Appleby 2003; Otsubo et al. 2015; Kucharski et al. 2015). Earth orientation parameters are also solved for per day. While the positions of all stations are fixed to an a priori set of coordinates, three transformation parameters and a scale parameter of the whole network with respect to the a priori set are solved for in the same batch estimation as other parameters.

Results and discussion

The improvement rates for geodetic parameters are presented in this section. We begin with the translation and scale parameters of a terrestrial reference frame. In Fig. 3, the triangles are the positions of existing laser

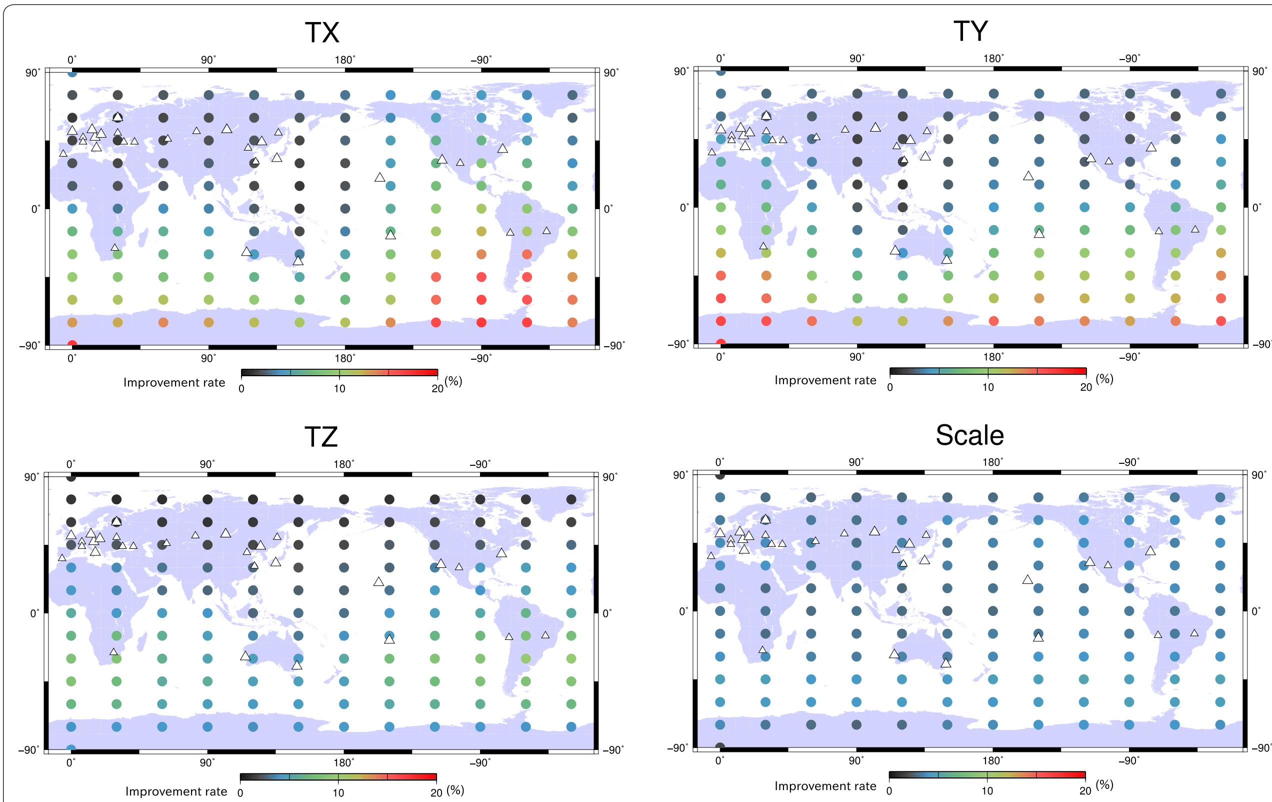

Fig. 3 Simulated improvement rate of three translation parameters and a scale parameter of a terrestrial reference frame when one laser-tracking station (one of the *colored circles*) is added to the existing laser-tracking network (*white triangles*; large ones are high productive stations with >2000 normal points during the March–April 2015 period)

ranging stations where large ones represent stations with high productivity that yielded more than 2000 normal points to the six satellites during the 2-month period. For the case when a virtual station at one of the circles aligned on the grid is added to the station network, the improvement rate with respect to the baseline setup is illustrated in color for each parameter. We can read from the graphs that the X and Y components can be significantly improved by adding a station in the southern hemisphere, especially in the high-latitude region. The best position was the South Pole, which drastically improves the two components by about 17 %. The Z component, on the other hand, is not benefitted so much by a high-latitude station but is most effectively determined by adding a station in a lower latitude, 15S–30S. Different outcomes are observed in the scale parameter case where the improvement rate is not so high at 2–5 %, no matter where a new station is placed.

Turning now to low-degree gravity coefficients, among all the coefficients up to degree and order 4 treated as solved-for parameters, the five cases of the degree-2 coefficients are plotted in Fig. 4 in the same way as in

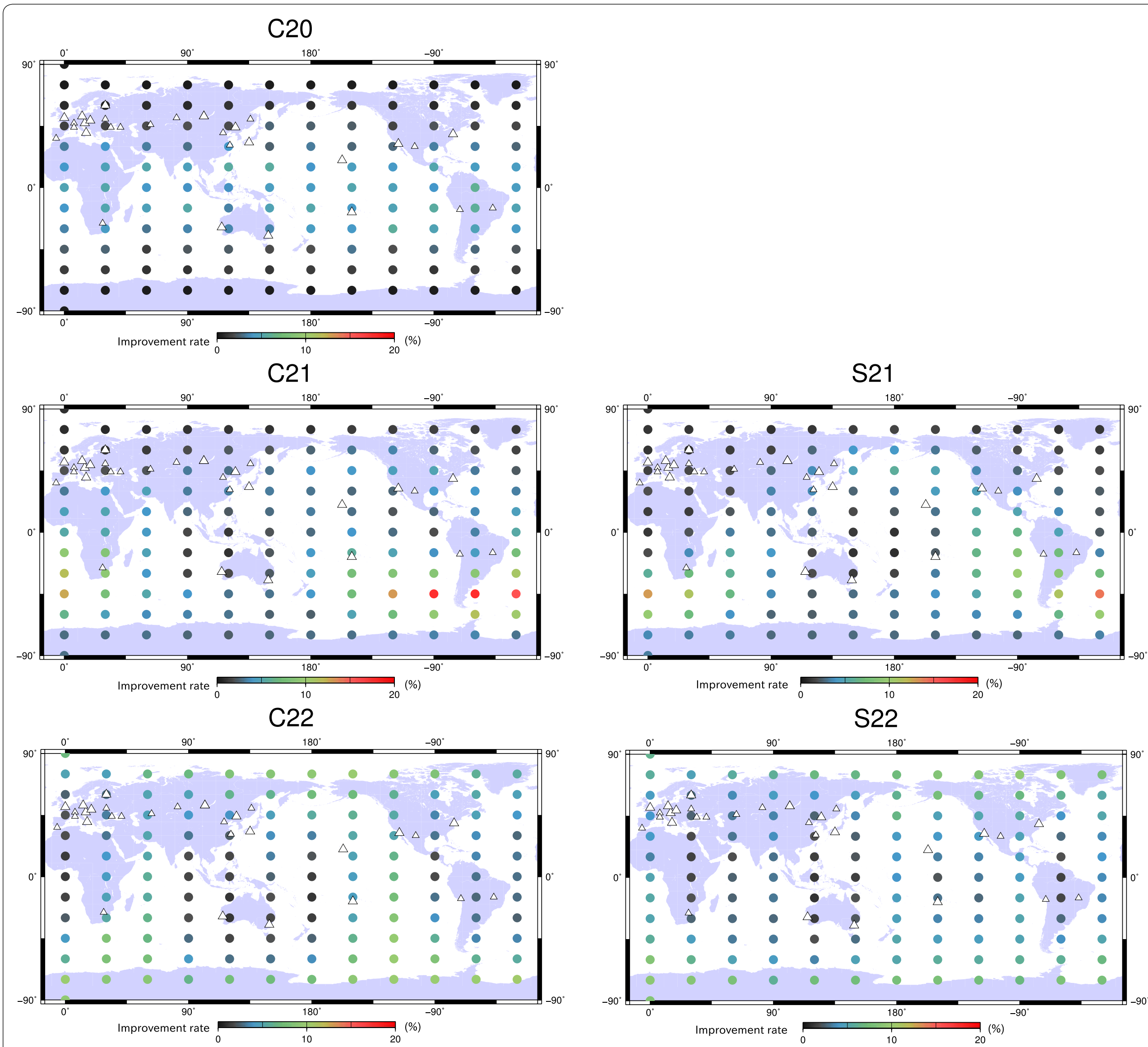

Fig. 4 Simulated improvement rate of degree-2 Earth gravity parameters when one laser-tracking station (one of the *colored circles*) is added to the existing laser-tracking network (*white triangles*; large ones are high productive stations with >2000 normal points during the March–April 2015 period)

Fig. 3. It is clearly seen that the station's latitude plays an important role again. For the zonal term C_{20}, a station at a low latitude has the largest impact while the improvement rate is not so high, up to 6 %, as other coefficients below. A new station placed in a middle latitude or a high latitude has a larger effect on the order 1 terms C_{21} and S_{21} by 18 % at maximum, and the order 2 terms C_{22} and S_{22} by 10 % at maximum, respectively. Similar patterns have been observed for the degree 3 and 4 coefficients although these are not shown graphically: A station near the equator is the most effective for the zonal terms, whereas a station near the poles best performs for the sectoral terms and a station in a middle latitude best performs for the tesseral terms.

In the end, it should be noted that the productivity of a new station has been modeled in a simplified way, and the actual improvement rate depends on the quantity and also the quality of the station's SLR data.

Conclusions

Under a realistic assumption that a laser ranging station can be added to the existing network, our set goal is to find the best position on Earth for a new station, but it is concluded that the best position depends on a geodetic parameter.

Filling the network gaps, especially in the southern hemisphere, has the expected efficacy on the whole, but our study also revealed that the effect largely depends on station latitude and target parameters. The most remarkable impact is expected for the X and Y components of the geocenter and the sectoral gravity terms such as C_{22} and S_{22} by adding a station near the South Pole. A station in a middle latitude also significantly improves the tesseral gravity terms such as C_{21} and S_{21}. A station in a low latitude is shown to be effective for the geocenter's Z component and the zonal gravity terms where the improvement rates do not match the above cases.

This study focused on the best-performing cases and areas, but considering the fact that the derived improvement rates, in most cases, exceed those predicted by the square root of the number of observations, adding more stations to the SLR network should be strongly encouraged.

This simulation study has assumed a very simple error model and compared relative changes of formal errors, but that various error sources and the measurement correlations should be taken into account when we handle an actual observation data set.

We hope this study will be used to seek a strategic expansion of the geodetic network, which the global geodetic observing system component (Plag and Pearlman 2009) under the International Association of Geodesy has been formed to discuss. Further, comparison and combination with different geodetic techniques should be targeted as proposed by Schuh et al. (2016).

Abbreviations

CDDIS: crustal dynamics data information system; LAGEOS: LAser GEOdynamics Satellite; LARES: LAser Relativity Satellite; NASA: National Aeronautics and Space Administration; SLR: Satellite laser ranging.

Authors' contributions

TO led the whole study and drafted the manuscript. KM was involved with the SLR data analysis, and YA and KY interpreted the outcome of the simulation analysis. TH, TK and SM developed key components of the c5++ software. All authors read and approved the final manuscript.

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Competing interests

The authors declare that they have no competing interests.

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