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QUALITY ASSESSMENT OF SATELLITE LASER RANGING STATIONS OPERATING IN 2020

OCENA JAKOŚCI SATELITARNYCH STACJI LASEROWYCH DZIAŁAJĄCYCH W ROKU 2020

Abstract

The paper assesses the quality of satellite laser ranging stations that were operational in 2020. The assessment is based on the results obtained from the LAGEOS-1 and LAGEOS-2 satellites between 2011 and 2020. In 2020, 41 SLR stations conducted laser observations on both LAGEOS satellites. Out of these stations, 20 had been making observations for ten years, while some stations started their observations during this period, resulting in a shorter observation period. NASA's GEODYN-II orbital software was used to compute the satellite orbits for fifteen core stations. The accuracy of the observations from each station was evaluated by determining the stability of the designated coordinates (3DRMS) in the International Terrestrial Reference Frame 2020. The results show that 16 stations achieved accuracy ranging from 4 mm to 10 mm, 17 stations between 10 mm and 15 mm, and 8 stations above 15 mm. Similarly, the standard deviation of the determined coordinates ranged from 1.0 mm to 2.6 mm, from 3.0 mm to 4.0 mm, and above 4.0 mm, respectively. The discussion focuses on the reasons for the inadequate accuracy in determining the coordinates for most stations. These reasons include a lack of sufficient normal points for most stations, a significant random scatter of normal points in the orbit, and

Streszczenie

W pracy przedstawiono ocenę jakości stacji laserowych działających w roku 2020 na podstawie wyników uzyskanych dla satelitów LAGEOS-1 i LAGEOS-2 w latach 2011-2020. W 2020 roku obserwacje laserowe obu satelitów LAGEOS prowadziło 41 stacji SLR, z czego 20 stacji zrealizowały obserwacje w ciągu dziesięciu lat, pozostałe stacje rozpoczynały obserwacje w tym okresie, stąd krótszy okres obserwacji. Orbity satelitów zostały obliczone za pomocą programu orbitalnego GSFC NASA GEODYN-II dla wybranych piętnastu najlepszych stacji. Dokładność obserwacji poszczególnych stacji oceniono na podstawie stabilności wyznaczonych współrzędnych (3DRMS) w układzie International Terrestrial Reference Frame 2020. Wyniki pokazują, że 16 stacji uzyskało dokładność w zakresie od 4 mm do 10 mm, 17 stacji od 10 mm do 15 mm i 8 stacji powyżej 15 mm. Podobny rozkład przedstawia odchylenie standardowe wyznaczonych współrzędnych, odpowiednio od 1,0 mm do 2,6 mm, od 3,0 mm do 4,0 mm i powyżej 4,0 mm. Omówiono przyczyny niewystarczającej jakości wyznaczania współrzędnych dla większości stacji, do których należy zaliczyć zbyt małą ilość punktów normalnych, duży rozrzut przypadkowy punktów normalnych na orbicie, niewystarczającą stabilność odchyleń

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insufficient long-term stability of systematic deviations. It is important to note that the results for both LAGEOS satellites are highly consistent.

Keywords: International Terrestrial Reference Frame, satellite geodesy, satellite laser ranging, satellite orbits, station position

systematycznych. Należy podkreślić, że wyniki dla obu satelitów LAGEOS są bardzo zgodne.

Słowa kluczowe: Międzynarodowy Ziemski Układ Odniesienia (ITRF), geodezja satelitarna, satelitarne pomiary laserowe, orbity satelitów, pozycje stacji

1. INTRODUCTION

Periodic determination of the International Terrestrial Reference Frame (ITRF) is a key task for the creation of other terrestrial reference systems in the field of satellite geodesy and satellite navigation, which enable precise determination of the position and velocity of points on the Earth's surface and moving objects. Each subsequent ITRF is more accurate due to the increased number of entered observation results. The last reference frame is ITRF2020[1], covering measurement data from the period from 1983.0 to 2021.0 (for SLR). The previous reference frames are ITRF2014 and ITRF2008. The ITRF has been created for many years based on the results of four space techniques: Satellite Laser Ranging (SLR), Very Long Base Interferometry (VLBI), Global Navigation Satellite Systems (GNSS) and Doppler Orbitography and Radiopositioning Integrated by Satellite (DORIS)[2]. SLR plays a fundamental role among these techniques because it is the only technique that performs absolute measurements, ensuring the correct orientation of the geocentric reference system and its center, which is the center of mass of the Earth.

The satellite laser ranging (SLR) technique for precisely determining the distance to artificial Earth satellites has been used successfully since 1964[3]. Over such a long period of almost sixty years, many significant changes have been introduced in measurement technology, new equipment has been used, and the observation process has been automated, now enabling a level of accuracy of distance measurements to satellites of several millimeters. However, this is still insufficient quality due to the very important role of laser measurements in the creation of ITRF, altimetry measurements, and verification of satellite orbits, including Global Navigation Satellite Systems (GNSS) satellites. Therefore, a very important task is to improve the station quality to achieve the Global Geodetic Observing System (GGOS) assumptions of 1 mm for station position determination and 0.1 mm/year for station velocity.

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[1] ITRF2020- IGN. https://itrf.ign.fr/en/solutions/ITRF2020.

[2] CDDIS (2009) SLR and GPS (and Plate Tectonic and Earthquakes), NASA, http://cddis.nasa. gov/docs/2009/HTS_0910.pdf.

[3] NASA (2014) How Satellite Laser Ranging got its start 50 years ago. https://www.nasa.gov/content/goddard/laser-ranging-50-years.

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Work in the field of satellite laser observations is coordinated by the International Laser Ranging Service (ILRS)[4, 5]. About forty laser stations have been conducting systematic observations of laser satellites for many years. Quality control of the results of these stations is carried out regularly by several SLR data analysis centers, including: ILRS ASC Product and Information Server[6], ILRS Monthly/Quarterly Global Performance Report Card[7], Multi-Satellite Bias Analysis Report[8], Combined Range Bias Report[9], DGFI-TUM Analysis Center[10]. The methods used by ILRS to control the quality of SLR observations are presented in the paper "Rapid response quality control service for the laser ranging tracking network"[11]. Unfortunately, the results of these centers do not contain all the important parameters, either in numerical or graphical form, needed to evaluate each station. The aim of this work is to present a qualitative assessment of all SLR stations operating in 2020 based on their results from 2011-2020. This assessment was based on numerical values and on the analysis of the results of determining the topocentric positions of stations[12] in the form of time series of their components N (North), E (East) and U (Up).

2. METHOD OF ASSESSING THE QUALITY OF SLR OBSERVATIONS

Assessing the quality of individual SLR stations is a very important task to determine and select the best stations that can be used to create orbits. It should be based on orbital analysis of observational data. In this work, the NASA Goddard Space Flight Center (GSFC) GEODYN-II orbital software[13], used since 2000 at the Borowiec Observatory, was used. This is the most widespread orbital program for processing the results of SLR observations. This program can also be used to analyze the results of other space techniques such as Global Navigation Satellite Systems (GNSS), satellite optical observations, lunar and planetary flights. It uses the possibility of using many models of the impact of gravitational and non-gravitational effects on space objects, and many coordinate systems. It is a proven and universal program used to analyze the movement of objects in space. It is used, for example, by the Joint Center for Earth Systems Technology–NASA Goddard&UMBC (JCET) and Agenzia Spaziale Italia-

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[4] Pearlman M.R., Degnan J.J., Bosworth J.M., The International Laser Ranging Service, "Adv. Space Res." 2002, 30(2), 135–143. https://doi.org/10.1016/S0273-1177(02)00277-6.

[5] Pearlman M.R., Noll C.E., Pavlis E.C., Lemoine F.G., Combrink L., Degnan J.D., Kirchner G., Schreiber U., The ILRS: approaching 20 years and planning for the future, "J. Geodesy" 2019, 93, 2161-2180. DOI:10.1007/s00190-019-01241-1.

[6] ILRS ASC Product and Information Server. http://geodesy.jcet.umbc.edu/ILRS_AWG_MONITORING/

[7] ILRS Monthly/Quarterly Global Performance Report Card. https://ilrs.gsfc.nasa.gov/network/system_performance/global_report_cards/quarterly/.

[8] Geoscience Hitotsubashi: Multi-Satellite Bias Analysis Report. https://geo.science.hit-u.ac.jp/slr/bias/.

[9] Zimmerwald: ILRS Combined Range Bias Report. http://ftp.aiub.unibe.ch/slr/summary_report.txt.

[10] DGFI (2023) DGFI-TUM ILRS Analysis Centre. https://www.dgfi.tum.de/en/international-services/ilrs/.

[11] Otsubo T., Müller H., Pavlis, E.C., et al., Rapid response quality control service for the laser ranging tracking network, "J Geodesy" 2019, 93, 2335–2344. https://doi.org/10.1007/s00190-018-1197-0.

[12] Borkowski K.M., Accurate algorithms to transform geocentric to geographic coordinates, "Bull. Geod." 1989, 63, 50–56.

[13] Pavlis D.E., Luo S., Dahiroc P., et al., GEODYN II System Description, Hughes STX Contractor Report, Greenbelt, Maryland, USA, 1998.

na (ASI) analysis centers to create an Earth reference frame (ITRF)[14] from the results of SLR observations. In addition to the observation results, the program requires the introduction of many models and parameters that ensure high quality of computations. The models and parameters used in the computations using the GEODYN-II software are presented in Table 1.

To determine the station coordinates, the results of observations of the LAGEOS-1 and LAGEOS-2 satellites downloaded from EUROLAS DATA CENTER (EDC) for the period from 2011 to 2020 were used for all SLR stations that made observations at that time. The choice of LAGEOS satellites results from their common use for determining the coordinates of SLR stations, resulting from their large distance from the Earth of approximately 6000 km, which makes it possible to use low and more precisely determined tesseral harmonics of the Earth's gravity field (up to 20x20), lack of atmospheric drag, low impact Earth's albedo, a very well-determined constant correction to the satellite's center of mass and a large number of measurements of these satellites, which ensures high quality results[15].

Table 1. GEODYN-II – force models and program parameters

Force models	
Earth gravity field[16]	EGM2008 20 x 20
Earth Tides[17]	Convention IERS 2003
Ocean Tides[18]	GOT99.2
Third body gravity: Moon, Sun, and planets[19]	DE403
Solar radiation pressure	Coefficient CR = 1.13
Tide amplitudes – k2, k3, phase k2[20]	k2 = 0.3019, k3 = 0.093, phase k2 = 0.0
Earth albedo[21]	
Dynamic polar motion[22]	
Relativistic corrections[23]	

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[14] ITRF2020- IGN. https://itrf.ign.fr/en/solutions/ITRF2020.

[15] Pearlman M., Arnold D., Davis, M., et al., Laser geodetic satellites: a high-accuracy scientific tool, "J. Geodesy" 2019, 2181–2194. https://doi.org/10.1007/s00190-019-01228-y.

[16] Pavlis N.K., Holmes S.A., Kenyon S.C., Factor J.K., An Earth Gravitational Model to Degree 2160:EGM2008. Presented at the 2008 General Assembly of the European Geoscience Union, Vienna, Austria, 13 April 2008.

[17] McCarthy D.D., Petit G., (Eds.), IERS Conventions (2003), IERS Technical Note No. 32. International Earth Rotation and Reference Systems Service, Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany, 2004.

[18] Ray R.D., A global Ocean Tide Model from TOPEX/POSEIDON Altimetry: GOT99.2, "NASA/TMm1999-200478" 1999, 1-66. 19990089548.pdf.

[19] Standish E.M., Newhall X.X., Williams J.G., Folkner W.F., JPL Planetary and Lunar Ephemerides DE403/LE403, "JPL IOM" 1995, 31, 10-127.

[20] Petit G., Luzum B., (Eds.), IERS Conventions, IERS Technical Note No. 36. International Earth Rotation and Reference Systems Service, Bundesamt für Kartographie und Geodäsie, Frankfurt am Main, Germany, 2010.

[21] Pavlis D.E., Luo S., Dahiroc P., et al., GEODYN II System Description, Hughes STX Contractor Report, Greenbelt, Maryland, USA, 1998.

[22] Ibid.

[23] Ibid.

Constants	
Earth gravity parameter (GM)	3.986004415 x 1014 m3/s2
Light velocity	29792.458 km/s
Semimajor axis of the Earth	6378.13630 km
Inverse of the Earth’s flattening	298.25642
Reference frame	
Inertial reference frame	J2000.0
Coordinates reference system	true of date at 0h of the first day of the each month
Stations coordinates[24, 25]	ITRF2020 for epoch 2015.0
Precession and nutation	IAU 2000
Polar motion	C04 IERS
Tidal uplift[26]	Love model h2 = 0.6078, l2 = 0.0847
Pole tide[27]	
Estimated parameters	
Satellite state vector	6 parameters
Station geocentric coordinates	3 parameters
Acceleration parameters	along-track, cross-track and radial at 5 days intervals
Measurement model	
Observations	120 sec window of normal point, data from EUROLAS Data Center
Satellites	LAGEOS–1 and LAGEOS–2
Centre of Mass Correction	25.1 cm
Cross – section area	0.2827 m2
Mass	406.965 kg (LAGEOS-1), 405.380 kg (LAGOES-2)
Laser pulse wavelength	532 nm, 864 nm (7827)
Tropospheric refraction[28, 29]	Model Mendes–Pavlis
Editing criteria	
Normal points residua	5σ per arc
Cut – off	elevation 10°
Station coordinates cut - off	<50 normal points per station per arc
Numerical integration	
Integration	Cowell method
Orbit integration step size	120 sec
Arc length	1 month

Source: own results based on Schillak S., Satarowska A., Sankowski D., Michałek P., Analysis of the Results Determining the Positions and Velocities of Satellite Laser Ranging Stations during Earthquakes in 2010–2011, Remote Sens. 2023, 15, 3659. https://doi.org/ 10.3390/rs15143659.

To assess the quality of the station, the observation results for the period from January 1, 2011 to December 31, 2020 were used. Such a long period of time allows for a good assessment of all parameters taken into account when assessing the quality.

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[24] Altamimi Z., Rebischung P., Collilieux X., Métivier L., Chanard K., ITRF2020 [Data set]. IERS ITRS Center Hosted by IGN and IPGP 2022, https://doi.org/10.18715/IPGP.2023.LDVIOBNL.

[25] Altamimi Z., Rebischung P., Collilieux X., Métivier L., Chanard K., ITRF2020: an augmented reference frame refining the modeling of nonlinear station motions, „J Geod” 2023, 97(47).

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[28] Mendes V.B., Prates G., Pavlis E.C., Pavlis D.E., Langley R.B., Improved mapping functions for atmospheric refraction in SLR, “Geophys. Res. Lett.” 2002, 29, 10, 1414, 53-1–53-4. https://doi.org/10.1029/2001GL014394.

[29] Mendes V.B., Pavlis E.C., High-accuracy zenith delay prediction at optical wavelengths, “Geophys. Res. Lett.” 2004, 31, L14602. https://doi.org/10.1029/2004GL020308.

Stations that completed observations before 2020 were not taken into account, i.e. McDonald (7080), Koganei (7308), Daedeok (7359), Concepcion (7405), San Juan (7406), Kunming (7820), Riyadh (7832). Stations that started observations after 2020, i.e. Izana (7701) and Tsukuba (7306), were also not taken into account. In total, accuracy analysis was performed for 41 SLR stations.

To determine the orbits of the LAGEOS-1 and LAGEOS-2 satellites, several of the best SLR stations were used, which performed observations in all 10 years, had a large number of observations, and were characterized by high quality results. These stations coincide with the list of core stations used and recommended by ILRS[30]. The list of these stations with their results in the form of the number of accepted monthly arcs, the stability of the determined station coordinates (3DRMS) and the standard deviation of coordinate determination are presented in Table 2.

Table 2. List of the core stations used to compute orbits in the period 2011–2020

Station name	Station No	Number of monthly arcs	Coordinates stability [mm]	Coordinates standard deviation [mm]
Yarragadee Australia	7090	120	6.2	1.0
Greenbelt - Maryland	7105	118	6.0	1.5
Monument Peak - California	7110	114	9.4	1.8
Haleakala - Hawaii	7119	114	11.3	2.0
Changchun - China	7237	112	10.5	1.8
Hartbeesthoek - South Africa	7501	100	10.8	2.2
Zimmerwald - Switzerland	7810	102	4.4	1.0
Mount Stromlo - Australia	7825	115	5.9	1.5
Simosato - Japan	7838	100	14.3	2.0
Graz - Austria	7839	118	4.8	2.0
Herstmonceux - United Kingdom	7840	120	4.5	1.4
Potsdam - Germany	7841	111	7.0	2.2
Grasse - France	7845	116	6.7	1.8
Matera - Italy	7941	115	5.1	1.3
Wettzell - Germany	8834	90	6.9	2.3

Source: own results.

In order to determine station coordinates and their parameters from the core station results, independent monthly observation arcs were created for both LAGEOS satellites. The adoption of monthly instead of weekly arcs is more beneficial in determining station coordinates due to the much smaller impact of the heterogeneity of the core station distribution and too few observations for stations performing

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[30] The ILRS contribution to ITRF2020. E. Pavlis (GESTAR II/UMBC & NASA Goddard 61A), V. Luceri (e-GEOS S.p.A., ASI/CGS) https://itrf.ign.fr/docs/solutions/itrf2020/The_ILRS_contribution_to_ITRF2020_description_2022.09.23.pdf.

observations only at night and in the bad weather conditions (large number of rejected weekly arcs).

For the correct assessment of the results, the method of eliminating normal points[31] and orbital arcs that do not meet the statistical criteria for the obtained results is very important. First, normal points are removed, which for the arc of a given station exceed 5xRMS orbital deviations. This criterion ensures that the occurring systematic shifts relative to the designated orbit are taken into account. This criterion is particularly important for stations with a much larger spread of normal points. The second criterion is the standard deviation of the designated station coordinates. It concerns the rejection of monthly orbital arcs if obtained value of the 3D standard deviation for a given arc is greater than 3xsigma, where sigma is the average standard deviation of a given station. This error occurs mainly when the total number of normal points for the LAGEOS-1 and LAGEOS-2 satellites of a given arc is less than 50. Finally, the third criterion is the deviations of the N, E, or U components, which exceed 3x the average RMS for a given component. Each exceedance results in the rejection of a given arc for that station. Only such cleaned results allow for further analysis.

The main aim of the work is to assess the quality of currently operating SLR stations. Therefore, it is necessary to determine what result parameters allow for such an assessment. According to the authors, the best reflection of the quality of individual stations is the dispersion of determined station coordinates in the form of 3DRMS, supplemented with charts illustrating changes in station position over time for each component. These should be the topocentric components N, E, U, which reflect changes in the position of the station much better than the geocentric components X, Y, Z. An important parameter is the uncertainty of the determined positions in the form of standard deviation. It allows for the assessment of individual independent results of determining the station's position, as well as, in the form of an average, for assessing the quality of determining the average of all positions. This parameter also allows you to reject those monthly arcs for which the standard deviation significantly exceeds the mean deviation. A frequently used parameter to assess station quality is the long-term stability of the station range biases in the form of RMS monthly systematic deviations for each arc. The upper limit set by ILRS is 10 mm. Typically, this parameter is determined separately for the LAGEOS-1 and LAGEOS-2 satellites, allowing the difference in results for both satellites to be determined. Another parameter enabling the assessment of systematic errors is range bias, i.e. the constant difference between the measured distance to the satellite and its predicted value. This value should, of course, be close to zero. The deviation of the vertical component is very similar in nature to range biases, which is mainly the result of systematic errors for this component due to observations being made around the zenith. For this reason, the horizontal deviations (N and E) should be smaller than the vertical

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[31] Torrence M.H., Klosko S.M., Christodoulidis D.C., The construction and testing of normal point at Goddard Space Flight Center, In Proceedings of 5th International Workshop on Laser Ranging Instrumentation, Herstmonceux, UK, 10 September 1984, 506–516. https://ilrs.gsfc.nasa.gov/about/reports/workshop/lw05.html.

deviations U. The last parameter that should be taken into account when assessing the quality of SLR observations is the spread of the results of a given station in relation to the orbit determined from the results of the dozen or so best stations. For each monthly arc, separately for each LAGEOS-1 and LAGEOS-2 satellite, we can determine their RMS from the results for normal points. This allows us to assess which stations we can take into account when selecting core stations. The RMS results should be lower than the average RMS for all the assessed stations (for LAGEOS about 15 mm), and for both satellites the results should be of similar values, which allows confirming the correctness of calculating the orbits for both satellites.

The second important element for assessing the results of observations is their quantity and distribution over time. Generally, each station should conduct observations in all months of each year. However, due to technical problems, repairs, wear and tear of equipment, and personnel problems, most stations have difficulty maintaining continuity of observations. Longer breaks in observations disqualify the station from taking full advantage of the results. The quantity of accepted normal points is very important. This has a very significant impact on the value of the standard deviation of the determined station coordinates, and therefore on the uncertainty of the determined positions. The sum of normal points for both LAGEOS satellites should not be less than 50, otherwise the standard deviation reaches rapidly increasing high values that disqualify the results for these arcs.

3. RESULTS

This chapter contains the results of determining the parameters presented in the previous chapter for all 41 SLR stations performing observations in 2020. The results are presented in figures, which contain quantitative results (three figures): the period of observations for each station for the 2011-2020 in years (Fig. 1), the quantity of accepted monthly arcs (Fig. 2) and the number of normal points (Fig. 3). The remaining seven figures provide a qualitative assessment of each station in the form of averages for the entire observation period. The following parameters were selected for qualitative assessment: stability of the determined station coordinates in the form of 3DRMS (Fig. 4), standard deviation of the determined coordinates (3D) (Fig. 5), long-term stability of range biases in the form of their RMS separately for each LAGEOS satellite (Fig. 6), orbital distribution of normal points in the form of RMS separately for each LAGEOS satellite (Fig. 7), range biases for each station separately for each LAGEOS satellite (Fig. 8), average value of the vertical component U in relation to ITRF2020 (Fig. 9) and the average resultant of the horizontal N and E components with respect to ITRF2020 (Fig. 10).

From 2011 to 2020, for a full 10 years, observations were performed by 13 stations (Fig. 1), 17 stations observed for 8-9 years assuming that unaccepted arcs were not taken into account or started observations after 2011. Station Wettzell-1 (8834) in 2019 changed the wavelength of laser light from 532 nm to 1064 nm. The new wavelength was not included in this analysis due to the short observation period. The remaining group of 11 stations that started or resumed observations in the period after 2014 or had unacceptable results at the beginning or end of the tested period, were observed for one to seven years. To sum up, it can be said that more than half of the stations showed very good activity.

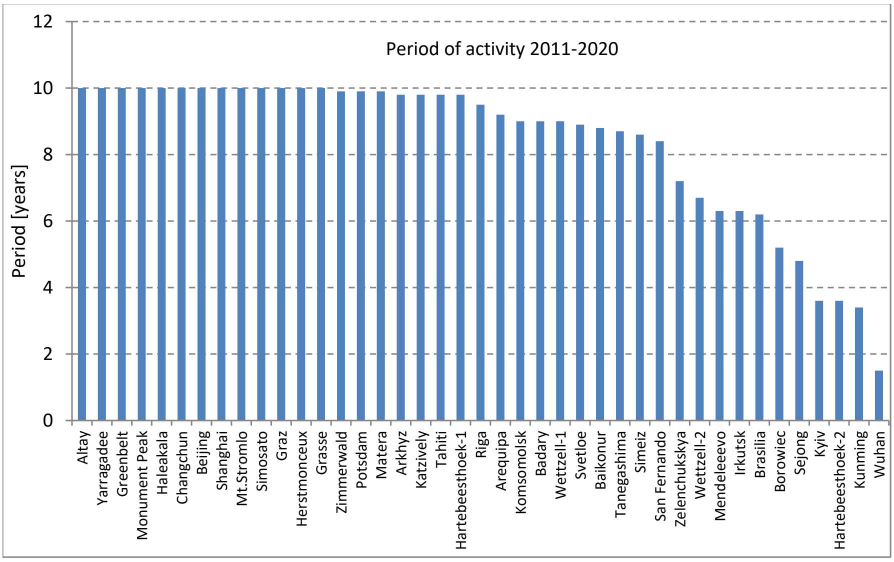

Fig. 1. Period of the SLR stations activity in 2011–2020

Source: own work.

A more important parameter assessed is the number of accepted monthly orbital arcs in the examined period 2011-2020 (Fig. 2). The maximum number of arcs is 120. Only two stations, Yarragadee and Herstmonceux, achieved this value. There were 13 more stations above 100 arcs. And only these 15 stations were considered as core stations for orbit determination, ensuring repeatability of the results in almost every orbital arc. The remaining 26 stations had fewer arcs due to technical problems or a shorter observation period.

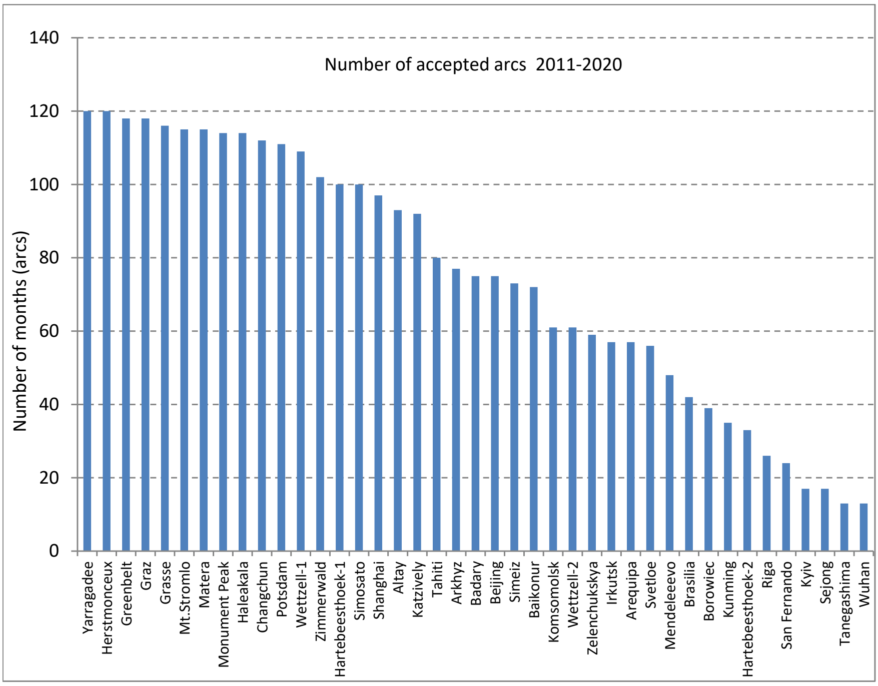

Fig. 2. Number of accepted monthly arcs in 2011–2020

Source: own work.

The most important quantitative parameter is the number of normal points of a given station (Fig. 3). It determines the uncertainty in determining the station coordinates (the number of normal points is in the denominator of determining the standard deviation). The absolute record holder (224,091 normal points in the period 2011-2020) due to the reliable NASA MOBLAS-5 station and excellent weather is the Australian Yarragadee station. The Zimmerwald station (143,214 NP) and the Matera station (114,556 NP) should also be distinguished. The remaining stations are under 90,000 PN. Figure 3 shows a clear decrease in the number of PNs from over 30,000 to 15,000. For some of these stations, the reason is a shorter observation period.

According to the authors, the most reliable parameter for assessing the quality of SLR observations is the stability of the determined station coordinates in the form of 3DRMS. This does not apply to stations where real shifts, including earthquakes, occurred. One such example is the Arequipa station (Peru), where changes in the position and velocity of the station after the strong earthquake in 2001 are still ongoing. The station coordinates stability results are shown in Figure 4. The most accurate station at the 4 mm level is the Zimmerwald SLR station. For 11 stations, the stability ranges from 4 mm to 7 mm. The remaining stations can be divided into three ranges: 13 stations in the range from 9 mm to 12 mm, 10 stations from 12 mm to 15 mm, and 7 stations above 15 mm. There are very large differences between the quality

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of individual stations. Therefore, only the most accurate stations should be used to computing orbits. The poor results of the stations in Riga and Kyiv are due to large gaps and a large dispersion of the results of the determined coordinates, especially the inconsistency of the velocity of the vertical component with ITRF2020.

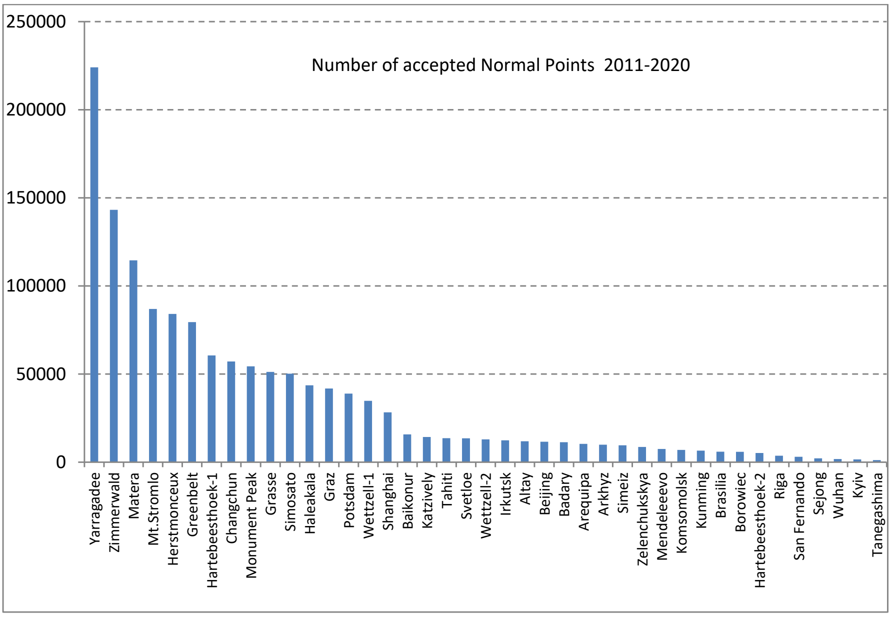

Fig. 3. Number of accepted Normal Points in 2011–2020

Source: own work.

Figure 5 shows the uncertainty in determining station coordinates in the form of standard deviation. The smallest value of ±1.0 mm have the Yarragadee and Zimmerwald stations, which is consistent with the number of normal points in Figure 3. There are 17 stations in the range from ±1.0 mm to ±2.6 mm, 16 stations from ±3.0 mm to ±4.0 mm, and 8 stations have results above ±4.0 mm. These results largely reflect the number of normal points for each station.

Another important parameter for assessing the quality of laser stations is long-term stability, which is determined as the RMS of range biases from all monthly arcs, usually separately for the LAGEOS-1 and LAGEOS-2 satellites. The results for all stations are shown in Figure 6. This value should not exceed 10 mm. This criterion is met for 26 stations. The remaining 15 stations have too large variations in range bias. It is noteworthy that for most stations there is a very good agreement between the results for the LAGEOS-1 and LAGEOS-2 satellites, which confirms the correctness of the computations of both orbits. The high values for the Arequipa SLR station are the result of the change in the station's position and velocity after the 2001 earthquake and do not reflect the actual values of this parameter.

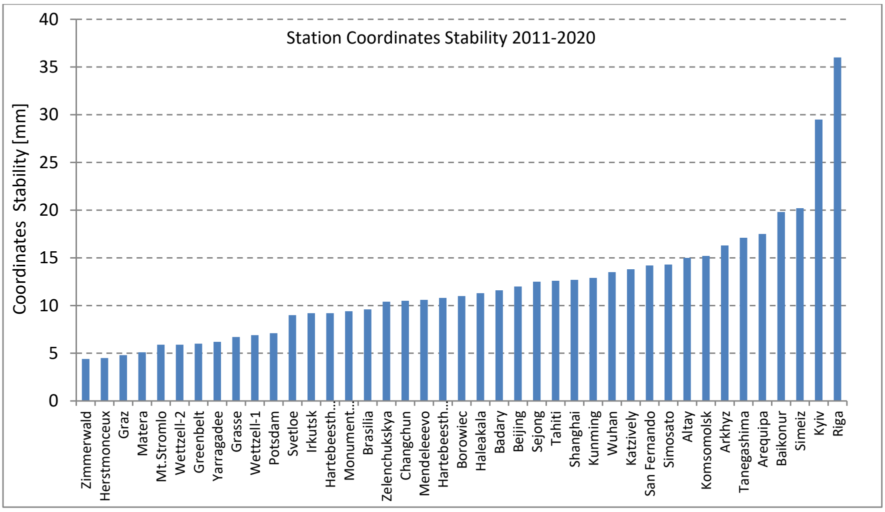

Fig. 4. SLR station coordinates stability (3DRMS) in 2011–2020

Source: own work.

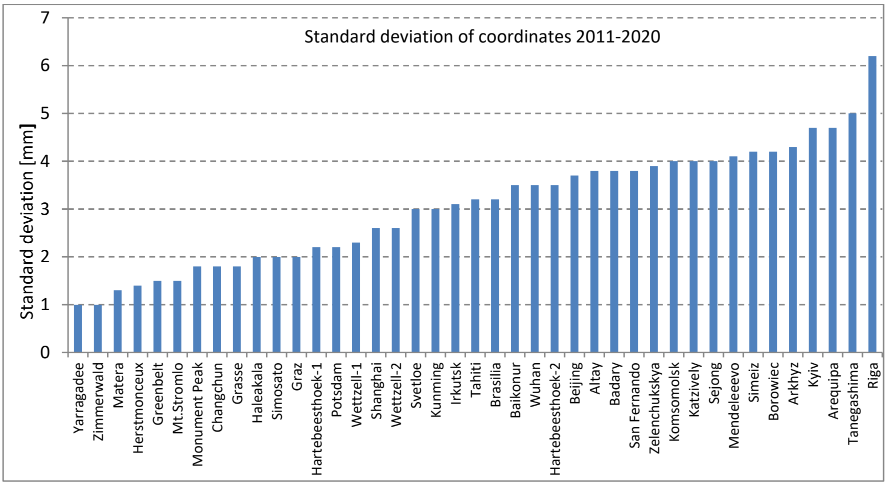

Fig. 5. Standard deviations of the SLR station coordinates determination in 2011–2020

Source: own work.

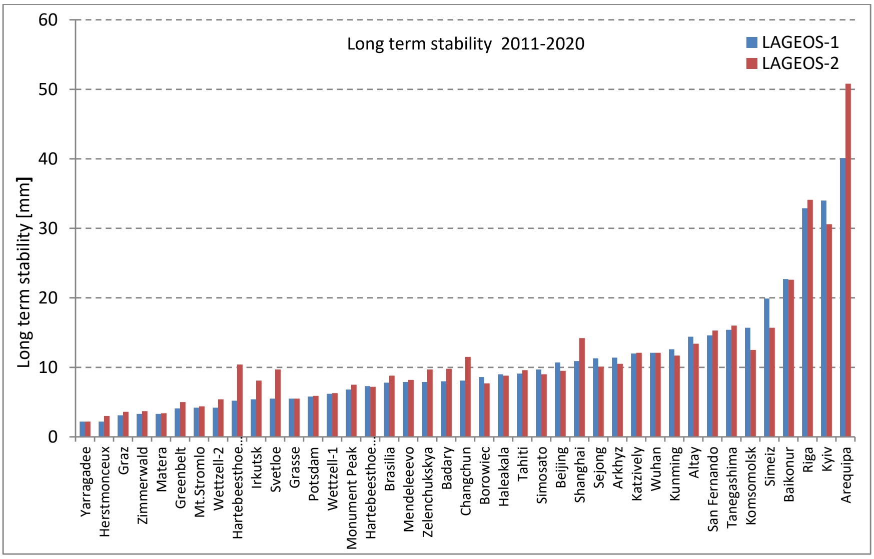

Fig. 6. Long term stability of the SLR stations for satellites LAGEOS-1 and LAGEOS-2 in 2011–2020

Source: own work.

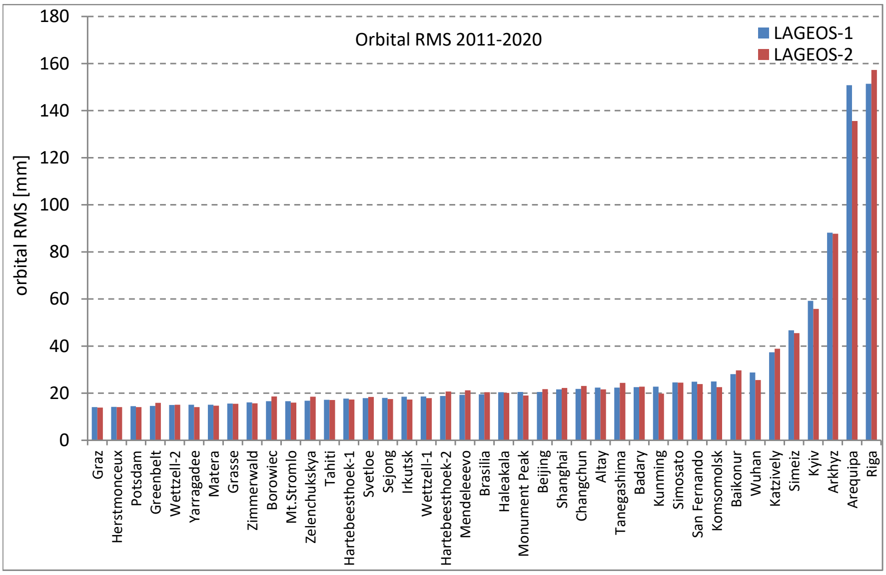

Fig. 7. Orbital RMS of the SLR stations for satellites LAGEOS-1 and LAGEOS-2 in 2011–2020

Source: own work.

The quality of the determined orbits of the LAGEOS-1 and LAGEOS-2 satellites is assessed based on the dispersion of the normal points of each station relative to the orbit (Fig. 7). The average RMS spread for the core stations for both satellites is ±17 mm. All stations with a smaller spread of normal points improve the quality of the orbit, while stations with a larger spread negatively affect its quality and cause deterioration of the quality of the determined parameters. The results for most stations are very close at around ±20 mm. Only 6 stations show higher values, the reason is large systematic deviations and a large dispersion of the results of these stations (Fig. 8).

A very important parameter is the range bias of each station. The results are shown in Fig. 8. For several stations these results are too high, due to the reasons given above. For the vast majority of stations, the range bias does not exceed 10 mm. Often, for stations that have a permanently or periodically large range bias, a permanent systematic correction is introduced to the measurement results. Range bias was not considered in this work.

Range bias has a significant impact on the value of the vertical component of the determined station coordinates shown in Fig. 9. This is clearly visible when comparing Figures 8 and 9. The value of the vertical component U is computed relative to ITRF2020.

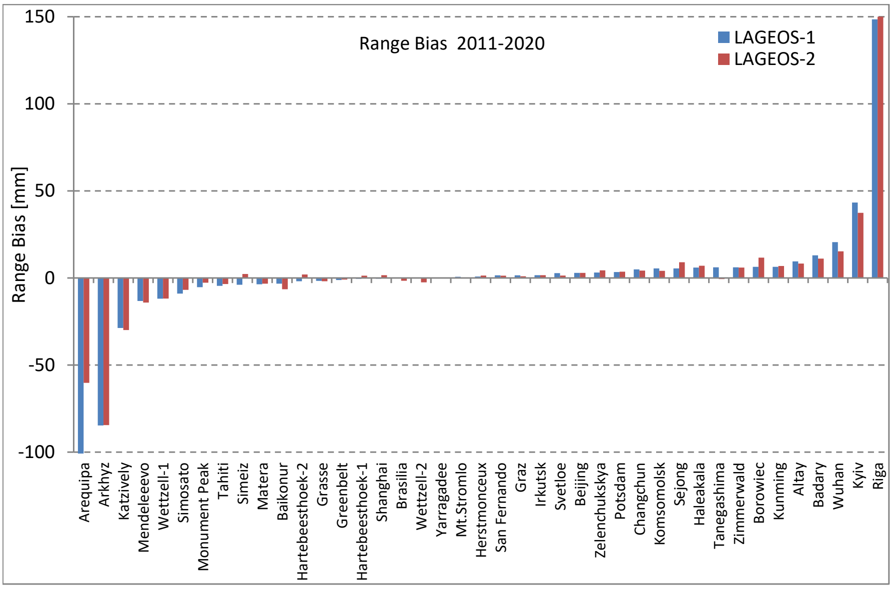

Fig. 8. Range bias of the SLR stations for satellites LAGEOS-1 and LAGEOS-2 in 2011–2020

Source: own work.

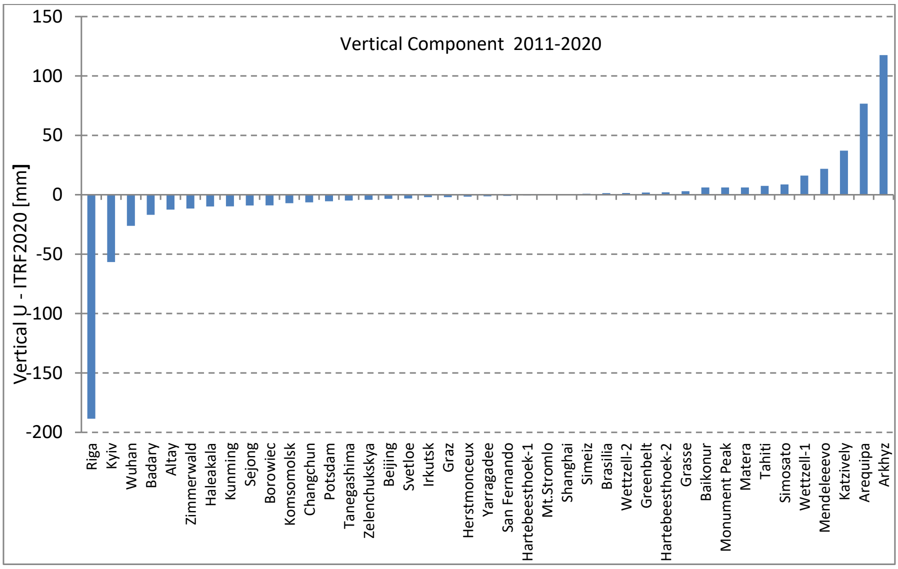

Fig. 9. Vertical component U in relation to ITRF2020 of the SLR stations in 2011–2020

Source: own work.

Figure 10 shows the average results of determining the horizontal components N and E for the epoch 2015.0. The high values of the three stations result from significant systematic shifts for the E component relative to ITRF2020.

The last, very important element of the quality assessment of SLR stations are charts illustrating changes in the designated station positions for a selected common reference epoch for the topocentric components N, E, U. They allow the detection of jumps in the components, annual waves or erroneous station velocities. Quick detection of such effects allows, in many cases, to eliminate their sources of error and ensure better quality of measurements. For the 41 laser stations evaluated in this work, unfortunately most of them contain significant shifts, which are briefly presented below. Unfortunately, the limited volume of the work does not allow to include charts for all stations.

Out of 41 stations, 13 had no significant systematic or random deviations compared to ITRF2020: Herstmonceux, Graz, Matera, Mt. Stromlo, Wettzell-2, Greenbelt, Yarragadee, Svetloe, Irkutsk, Hartebeesthoek-2, Brasilia, Zelenchukskya, Beijing. An example of good results of the U component for the Graz SLR station is shown in Figure 11.

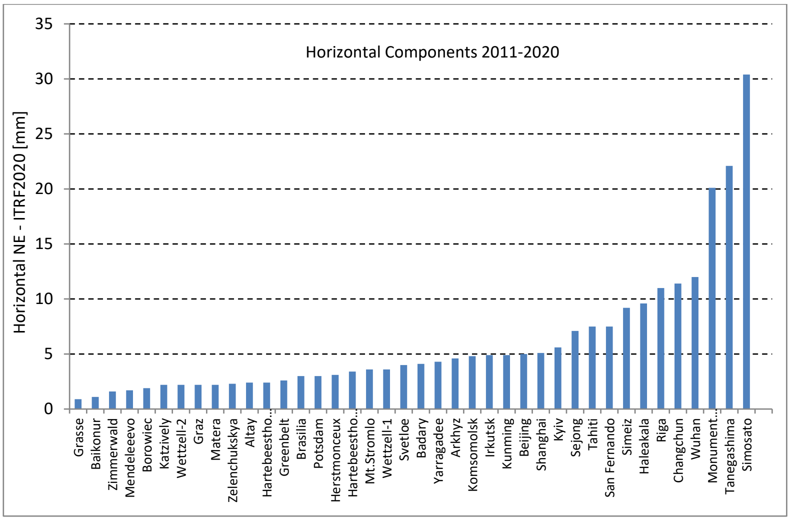

Fig. 10. Horizontal NE components in relation to ITRF2020 of the SLR stations in 2011–2020

Source: own work.

A systematic permanent shift of the component relative to ITRF2020 occurred for nine stations in U and one in E. Noteworthy is the occurrence of a constant shift in the U component of -12 mm for the Zimmerwald station, which did not occur for the previous ITRFs. This may be the result of additional corrections made to this station's results as part of the creation of ITRF2020. Monument Peak station has a similar shift of -20 mm in E.

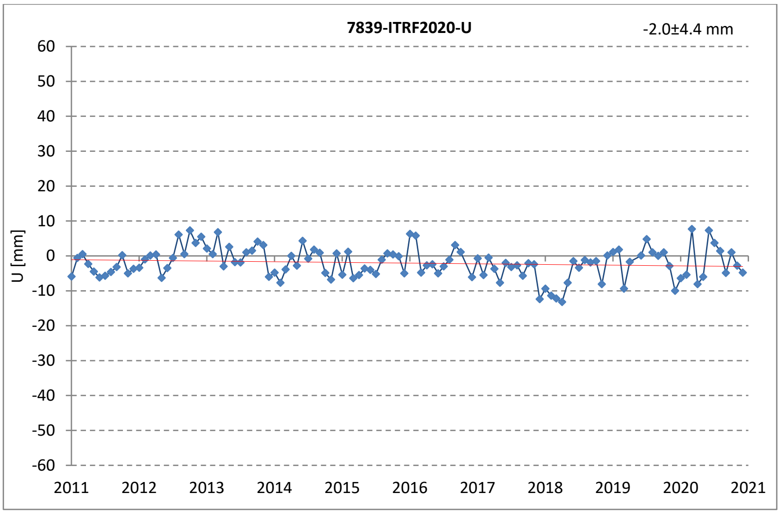

Fig. 11. Time series of the vertical component of the SLR Graz station (Austria) as an example of very good results in 2011–2020

Source: own work.

The second effect that has a very negative impact on the results are jumps in components, which were found for seven stations in the U component and for one station in the E component. Among the core stations, a jump in the U component of the Yarragadee station of -20 mm was found at the turn of 2011/2012 and in the Wettzell-1 station, which had a jump in the U component of +20 mm since 2014. These types of jumps indicate technical problems of the station.

The annual wave, which occurs mainly for the most accurate stations, has a very significant impact on the results of station position. This effect was found for eight stations for the U component, two for E and one for N. The largest wave with an amplitude exceeding 20 mm in the vertical component is recorded at the Haleakala station in Hawaii (Fig. 12). This wave does not depend on the ITRF used. It may be related to the very high altitude of the station (over 3 000 m above sea level) and strong volcanic activity. The wave effects at station positions can be taken into account in ITRF2020 by introducing annual and semi-annual periodic terms.

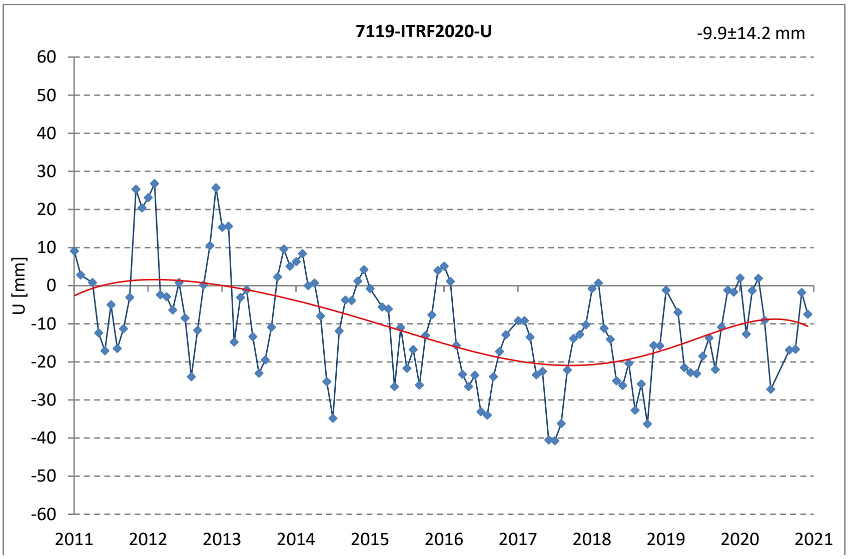

Fig. 12. Time series of the vertical component of the SLR Haleakala station (Hawaii) as an example of strong annual wave in 2011-2020

Source: own work.

Another effect affecting the results of determining station coordinates is the ITRF2020 velocity error of several mm/year found for five stations in U and one station in E. These errors significantly worsen the stability of the determined station coordinates.

The last group of errors that appear in the station position components is a random error caused by excessive dispersion of the results. In total, this concerns twelve U, four E and three N components. This is mainly related to too large random errors for the vertical component.

In total, all the presented effects cause significant deviations for the vertical component, which is easily explained by observations made around the zenith and in this direction, unlike the horizontal components, we have the most measurement errors.

4. COMPARISON OF RESULTS FOR ITRF2020 AND ITRF2014

The comparisons between results obtained from ITRF2020 and ITRF2014 show whether subsequent versions of ITRF enable improvement or deterioration of the accuracy and precision of the results obtained in determining the position of SLR stations. The comparison was performed for the same observational data for all 15 core stations used to determine orbits using the same models and parameters. The only change in the computations was the used of two SLR station coordinate frames, ITRF2020 and ITRF 2014. The results of determining 14 parameters were compared:

N – deviation from the ITRF towards the North,

RMS-N – stability of the N component,

E – deviation from the ITRF towards the East,

RMS-E – stability of the E component,

U – deviation from the ITRF in the vertical direction,

RMS-U – stability of the U component,

3DRMS – stability for three NEU components,

SIGMA – standard deviation for three components,

RB L1 – range bias for LAGEOS-1,

LONG L1 – long-term stability for LAGEOS-1,

RB L2 – range bias for LAGEOS-2,

LONG L2 – long-term stability for LAGEOS-2,

RMS L1 – orbital RMS for LAGEOS-1,

RMS L2 – orbital RMS for LAGEOS-2.

The determination results for ITRF2014 and ITRF2020 are presented in Tables 3 and 4.

Table 3. The results of comparison for ITRF2014 and ITRF2020 for core SLR stations (part I)

STATION	7090		7105		7110		7119		7237		7501		7810		7825	
ITRF	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020
N	-6.2	-3.7	3.5	-2.5	12.6	-0.7	-5.5	-8.7	-7.1	-5.2	2.4	1.5	1.4	1.2	-0.9	-3.6
RMS-N	4.3	4.2	5.7	6.0	10.0	9.8	8.1	8.4	8.5	10.1	10.4	10.0	3.1	2.9	5.0	5.1
E	-1.7	-2.1	-3.0	-0.8	-17.9	-20.1	2.0	4.0	16.2	10.1	-4.1	1.9	-2.6	-1.0	0.2	-0.5
RMS-E	5.7	5.1	5.8	5.3	8.6	8.7	10.4	10.6	8.1	7.6	8.8	8.6	4.0	3.7	5.5	5.7
U	-3.7	-1.3	2.4	1.9	-13.9	6.2	-6.1	-9.9	11.4	-6.4	-3.9	0.7	-0.7	-11.6	8.5	-0.6
RMS-U	7.9	8.4	7.6	6.7	10.9	9.6	15.9	14.2	16.3	13.0	13.9	13.3	5.2	6.1	7.2	6.7
3DRMS	6.1	6.2	6.4	6.0	9.9	9.4	11.9	11.3	11.6	10.5	11.2	10.8	4.2	4.4	6.0	5.9
SIGMA	1.1	1.0	1.6	1.5	1.9	1.8	2.1	2.0	1.8	1.8	2.0	2.2	1.1	1.0	1.6	1.5
RB L1	0.5	0.1	-0.7	-1.2	4.6	-5.3	4.3	6.0	-4.2	4.9	0.7	-0.5	1.4	6.1	-3.6	0.7

DOI: 10.55676/asi.v4i2.62

LONG L1	2.2	2.2	4.7	4.1	8.0	6.8	9.7	9.0	8.4	8.1	7.7	7.3	2.8	3.3	4.1	4.2
RB L2	0.7	0.1	1.2	-0.9	8.2	-2.7	4.2	7.0	-6.7	4.2	2.7	1.3	0.6	6.0	-4.6	-0.2
LONG L2	2.2	2.2	5.6	5.0	8.9	7.5	9.5	8.8	13.6	11.5	7.3	7.2	3.3	3.7	4.7	4.4
RMS L1	15.5	15.1	15.4	14.6	22.1	20.5	20.3	20.4	23.0	21.8	18.1	17.7	15.1	16.1	16.9	16.6
RMS L2	14.1	14.1	15.6	15.9	20.6	19.0	19.4	20.1	25.4	23.1	17.6	17.3	14.7	15.7	17.0	16.0
		57%		79%		79%		36%		79%		93%		36%		64%

Source: own results.

Table 4. The results of comparison for ITRF2014 and ITRF2020 for core SLR stations (part II)

STATION	7838		7839		7840		7841		7845		7941		8834	
ITRF	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020	2014	2020
N	-2.9	15.4	2.6	2.0	2.6	2.6	3.6	2.8	-0.5	-0.1	2.9	1.4	2.7	2.9
RMS-N	11.8	11.7	5.6	5.4	5.1	4.8	7.1	7.0	5.9	5.7	5.4	4.8	6.7	6.6
E	38.0	26.2	-2.0	-0.9	-1.5	-1.7	-2.4	-1.0	-4.4	-0.9	-3.7	-1.7	-3.2	-2.2
RMS-E	22.4	18.4	5.0	4.5	5.0	4.6	5.4	5.3	6.7	6.0	4.6	4.0	6.7	6.2
U	-28.8	8.7	1.5	-2.0	-5.7	-1.6	7.3	-5.5	9.6	3.0	8.6	6.2	15.6	16.1
RMS-U	14.5	11.9	5.1	4.4	3.9	3.9	9.8	8.5	8.5	8.2	6.4	6.2	7.4	7.8
3DRMS	16.8	14.3	5.2	4.8	4.7	4.5	7.7	7.1	7.1	6.7	5.5	5.1	6.9	6.9
SIGMA	2.0	2.0	2.1	2.0	1.4	1.4	2.3	2.2	1.9	1.8	1.3	1.3	2.4	2.3
RB L1	15.6	-9.0	-0.3	1.5	3.4	0.8	-4.6	3.4	-5.0	-1.7	-4.6	-3.6	-11.3	-11.9
LONG L1	10.6	9.7	3.4	3.1	2.4	2.2	6.6	5.8	5.7	5.5	3.6	3.3	6.0	6.2
RB L2	16.8	-6.8	-1.1	1.0	3.7	1.4	-4.5	3.6	-5.8	-1.9	-4.9	-3.3	-11.6	-11.8
LONG L2	10.9	9.0	4.2	3.6	3.0	3.0	6.6	5.9	5.8	5.5	3.9	3.4	6.2	6.3
RMS L1	31.6	24.6	14.2	14.1	14.6	14.2	15.3	14.5	16.4	15.6	15.6	15.1	18.2	18.6
RMS L2	30.1	24.5	14.2	13.9	14.5	14.1	14.6	14.1	17.1	15.5	15.3	14.7	17.9	17.9
		86%		86%		64%		100%		100%		93%		29%

Source: own results.

All better results for ITRF2020 are marked in red. The last row of Tables 3 and 4 shows the percentage for which parameters the results for ITRF2020 are better. For two stations (7841, 7845) all results were improved for ITRF2020, for several stations the improvement was around 90%. The average improvement in results for ITRF2020 over ITRF2014 for all stations was 72%. It must therefore be concluded that the ITRF2020 results for SLR are much more accurate than the ITRF2014 results.

5. SUMMARY AND CONCLUSIONS

The basic task of this work was to assess the quality of 41 laser stations operating in 2020. The results were assessed on the basis of quantitative results presented in Figures 1-10 and station position charts for the N, E, U components. Too large qualitative and quantitative differences between the stations should be emphasized. A significant problem is the large number of systematic and random errors, especially in the vertical component. Only 13 SLR stations do not show significant deviations over the 10 years 2011-2020. The following types of errors were found in the N, E, U component charts: constant systematic shift of the station position relative to ITRF2020 for 10 stations, jumps in the station position of several cm for 8 stations, occurrence of an annual wave for 10, especially for more accurate stations, errors in stations velocity compared to ITRF2020 for 6 stations, increased random position errors for 19 stations. These errors also affect the best stations. The main cause of deviations are changes in the vertical component.

The most important parameter determining the accuracy of the station is the 3DRMS stability of the determined positions. The most accurate stations are Zimmerwald (4.4 mm), Herstmonceux (4.5 mm) and Graz (4.8 mm). To sum up, 16 stations had position stability in the range from 4 mm to 9 mm, 17 stations in the range from 10 mm to 15 mm, and 8 stations above 15 mm. A very important parameter is the number of normal points, which determines the precision of determining the position of the station. Achieving a high number of normal points requires 24-hour observations, high measurement frequency and ensuring reliable, continuous operation of the SLR system. The Yarragadee (±1.0 mm), Zimmerwald (±1.0 mm) and Matera (±1.3 mm) stations had the best precision. For core stations this value does not exceed ±2.5 mm, for other stations it is within 3-5 mm. Attention should be paid to maintaining a constant range bias of the station, which is decided by systematic errors, applying the principle of as few changes as possible to the SLR system is highly recommended. Noteworthy is the high consistency of the results obtained separately for both LAGEOS-1 and LAGEOS-2 satellites for long-term stability, orbital RMS and range bias.

The main goal of further work on improving the quality of SLR observations should be continuous monitoring of the positions of the N, E, U components for each station, which should ensure the detection of jumps, waves and increases in random scatter, as well as improving the position and velocity of several stations in ITRF2020 by introducing corrections to SLRF2020[32]. Further work is necessary to improve the technical parameters of individual stations and make them more uniform. According to the authors, the main reason for the low accuracy of SLR stations is insufficiently accurate consideration of the tropospheric delay. For this purpose, it is necessary to introduce two-color observations[33], unfortunately there are currently no appropriate detectors to determine the precise difference in the distance between two colors. Another method may be to introduce the horizontal gradient method[34, 35, 36]. The aim of all this work should be to achieve in the near future, in accordance with the recommendations of the Global Geodetic Observing System (GGOS), a positioning accuracy of 1 mm and a velocity of 0.1 mm/year.

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Due to the limited volume of this work, the results are not presented in graphical form (example in Fig. 11 and 12). This would require 123 charts illustrating topocentric changes in stations position. Charts in MS Excel format, including quantitative results of individual stations, are available from the main author of the work at sch@cbk.poznan.pl. At the request of interested persons, they will be sent for selected SLR station.

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