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ANALYSIS OF THE INFLUENCE OF THE OBJECT'S ELEVATION ON LASER MEASUREMENTS OBTAINED IN BOROWIEC IN 2016–2023

ANALIZA WPŁYWU ELEWACJI OBIEKTÓW NA POMIARY LASEROWE OTRZYMANE PRZEZ STACJĘ W BORÓWCU W LATACH 2016–2023

Abstract

This paper presents an analysis of how an object's position above the horizon affects laser measurements obtained in laser station in Borowiec. The objects used for this analysis were active satellites from LEO (Low Earth Orbit) and MEO (Medium Earth Orbit) regimes, as well as space debris from LEO regime. The data used for this analysis spanned from the second half of 2016 to the first half of 2023. The results of tests performed at the BORL station indicate that for LEO objects, it is least effective to make observations when the object is close to the zenith, i.e. 80–90 degrees above the horizon. The highest returns are obtained when the object is at an elevation of 20–39 degrees. These results apply to both active satellites and space debris objects from the LEO regime. In the case of MEO satellites the highest returns are received when the object is at an elevation of 50–79 degrees.

Keywords: elevation, satellite laser ranging, satellites, space debris

Streszczenie

Niniejszy artykuł przedstawia analizę wpływu pozycji obiektu nad horyzontem na pomiary laserowe otrzymane przez stację laserową w Borówcu. Obiektami wykorzystanymi do analizy są aktywne satelity z rejonu LEO (Niska Orbita Okołoziemska) oraz MEO (Średnia Orbita Okołoziemska), jak również śmieci kosmiczne z orbit LEO. Dane pomiarowe użyte do przeprowadzenia badania pochodzą z okresu pomiędzy drugą połową 2016 r. oraz pierwszą połową 2023 r. Otrzymane wyniki dla stacji BORL wykazują, że najmniej efektywne dla obiektów LEO jest wykonywanie pomiarów dla elewacji bliskich zenitu, tj. 80–90 stopni, zaś najwięcej powrotów pozyskano, gdy obiekty te znajdowały się nad horyzontem, czyli dla elewacji 20–39 stopni. Powyższe rezultaty odnoszą się zarówno dla aktywnych satelitów, jak i śmieci kosmicznych z rejonu LEO. W przypadku satelitów znajdujących się na orbitach MEO najwięcej odbić wiązki lasera zarejestrowano dla elewacji z przedziału 50–79 stopni.

Słowa kluczowe: elewacja, satelitarne pomiary laserowe, satelity, śmieci kosmiczne

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1. INTRODUCTION

The number of artificial satellites has been growing rapidly, and currently there are over 28 000 objects in orbit. Every day, thousands of space debris and active satellites fly over our heads. These numbers are well presented at the CELESTRACK service, which shows the increase of all catalogued orbital objects since 1957[1].

Since 2015, the Space Research Centre of the Polish Academy of Science has been regularly conducting measurements of active satellites and space debris from LEO and MEO regimes at the Borówiec Laser Station (BORL 7811)[2]. These measurements are necessary for determining the positions and the velocities of satellites laser ranging stations[3], tidal parameters[4], global geodetic parameters[5], precise orbit parameters[6]. In addition, laser ranging measurements support, global navigation satellite systems such as GLONASS or Galileo[7], which are crucial for the proper functioning of transport and logistics[8].

The purpose of this work is to present the results of analysing how the elevation of objects affects laser measurements taken by the laser station in Borowiec. The data used for this analysis spans from the second half of 2016 to the first half of 2023. The results presented in this paper focus on the BORL laser sensor.

Currently, the BORL station is tracking over 100 objects, which makes it impossible to measure each of them. The personnel responsible for these measurements must select objects in a way that ensures maximum effectiveness. Optimizing the measurement process is essential due to the large number of target objects. One of the factors that influence the effectiveness of this process is the elevation of the measured object. Analysing the object's position above the horizon in laser measurements allows us to examine each object individually and determine the optimal elevation for measurement.

1 https://celestrak.org/satcat/boxscore.php [access: 9.07.2023].

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2. OBJECTS AND METHODS

Artificial satellites orbiting the Earth are categorized according to their altitude. There are three main groups of satellites: Low Earth Orbit (LEO) satellites, which orbit at an altitude of approximately 2000 km above the Earth's surface; Medium Earth Orbit (MEO) satellites, which orbit between 2000 and 35 786 km; and Geostationary Earth Orbit (GEO) satellites, which orbit at an altitude of approximately 35 786 km. Due to their status, these objects are divided into operational satellites and space debris.

The objects used for this analysis are operational satellites belong to the group of objects regularly monitored by ILRS (International Laser Ranging Service)[9]. They are equipped with retroreflectors that ensure the return of the laser beam in the direction of emission[10]. Second group is non-functioning satellites, i.e. those that have been completed their mission or have been damaged and are also equipped with retroreflectors and regularly monitored by ILRS. The last group is space debris, i.e. defunct satellites, detached parts of rockets, pieces resulting from orbital collisions and anti-satellite weapons (ASAT) tests[11] as well as other cosmic remnants of orbital objects. The lack of retroreflectors, various sizes, irregular shapes and uncontrolled orbital motion make laser measurements of these objects difficult[12].

The analysis of the influence of the object's elevation on laser measurements obtained at the Borówiec Laser Station (BORL 7811) in 2016–2023 was made out for 14 objects, of which 10 are operational satellites[13], 2 space debris as non-operational (defunct) satellites[14] and 2 other space debris objects, typical rocket bodies, equipped likely with retroreflectors[15, 16]. The analysis is based on the result files from laser measurements of satellites and space debris at the BORL station. These files contain cleaned data, i.e. recorded returns without any noise. The elevation of each passing object is also recorded. We used our own software to sum up the number of returns for specific elevation intervals. Then, we averaged these values based on the number of passages during which returns were recorded within each elevation interval.

9 M.R. Pearlman et al., The ILRS: approaching 20 years and planning for the future, "Journal of Geodesy" 2019, vol. 93, DOI: https://doi.org/10.1007/s00190-019-01241-1.

10 J.J. Degnan, A Tutorial on Retroreflectors and Arrays Used in Satellite and Lunar Laser Ranging, "Photonics" 2023, vol. 10(11), DOI: https://doi.org/10.3390/photonics10111215.

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13 https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/index.html [access: 20.07.2023].

14 https://ilrs.gsfc.nasa.gov/missions/satellite_missions/past_missions/index.html [access: 20.07.2023].

15 P. Lejba et al., First laser measurements to space debris in Poland, "Advances in Space Research" 2018, vol. 61(10), DOI: https://doi.org/10.1016/j.asr.2018.02.033.

16 P. Lejba, Orbit determination of chinese rocket bodies from the picosecond full-rate laser measurements, "Artificial Satellites" 2023, vol. 58(4), DOI: https://doi.org/10.2478/arsa-2023-0010 [accepted for publication].

The objects were selected because of their varying orbital altitude, shape and purpose. The two objects that are farthest from the Earth's surface are GLONASS-128 and GLONASS-137 (attitude 19 140 km), Russian satellites that are part of the global navigation satellite system[17]. Data to analysis of GLONASS-128 have been obtained since May 2017, but for GLONASS-137 since August 2018. Two additional objects that are crucial for geodesy and geophysics are the LAGEOS-1 and LAGEOS-2 satellites, which are spherical and passive satellites located in the MEO regime at an altitude of 5850 km and 5625 km for LAGEOS-1 and LAGEOS-2, respectively[18]. In this paper, measurements since July 2016 for LAGEOS-1 and since August 2016 for LAGEOS-2 have been used. Six operational satellites were selected from the LEO regime. Starlette, with an altitude of 800–1100 km, and Stella, with an altitude of 815 km, are twin spherical passive satellites used for geodetic and geophysics purposes, for which data obtained from August and July 2016 was used for research. Sentinel-3A (data since July 2016), with an altitude of 814 km and Sentinel-6A (data since May 2018), with an altitude between 1340 and 1356 km, are used to measure sea surface topography[19]. Swarm-A and Swarm-B, with an altitude of 460 km, which have been analyzed using measurements obtained since July and August 2016, enable the study of the Earth's geomagnetic field and its temporal evolution[20]. Additionally, two defunct satellites were selected, namely OICETS[21] with an altitude of 610 km and the fast tumbling space object TOPEX/Poseidon[22,23] with an altitude of 1350 km. The last two space targets are space debris, specifically the Chinese CZ2C with NORAD numbers 28480 and 31114, which are typical rocket bodies. Analysis of space debris objects have been made using data received since August 2016 for OICETS, September 2016 for TOPEX/Poseidon, January 2016 for CZ2C-28480 and November 2016 for CZ2C-31114.

3. ANALYSIS

The BORL laser station measures various types of the space objects from different altitudes in orbit. Depending on this, different elevation ranges are used for the measurements. For instance, GLONASS satellites are measured at elevations higher than 50°.

17 https://ilrs.gsfc.nasa.gov/missions/satellite_missions/current_missions/g140_general.html [access: 20.07.2023].

18 M. Pearlman et al., Laser geodetic satellites: a high-accuracy scientific tool, "Journal of Geodesy" 2019, vol. 93, DOI: https://doi.org/10.1007/s00190-019-01228-y.

19 S. Mertikas et al., Jason-3 Using Transponder and Sea-Surface Calibrations with FRM Standards, "Remote Sensing" 2020, vol. 12(16), DOI: https://doi.org/10.3390/rs12162642.

20 D. Strugarek et al., Detector-specific issues in Satellite Laser Ranging to Swarm-A/B/C satellites, "Measurement" 2021, vol. 182, DOI: https://doi.org/10.1016/j.measurement.2021.109786.

21 Y. Fujiwara et al., Optical inter-orbit communications engineering test satellite (OICETS), "Acta Astronautica" 2007, vol. 61, DOI: https://doi.org/10.1016/j.actaastro.2007.01.021.

22 D. Kucharski et al., Photon Pressure Force on Space Debris TOPEX/Poseidon Measured by Satellite Laser Ranging, "Earth and Space Science" 2017, vol. 4(10), DOI: https://doi.org/10.1002/2017EA000329.

23 D. Kucharski et al., Full attitude state reconstruction of tumbling space debris TOPEX/Poseidon via light-curve inversion with Quanta Photogrammetry, "Acta Astronautica" 2021, vol. 187, DOI: https://doi.org/10.1016/j.actaastro.2021.06.032.

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GLONASS-128 is an object located approximately 20 000 km away. The average number of returns for different elevation ranges can be seen in Figure 1. In most cases, the average value of returns is above 250, except for the range of 70–79 degrees. For this range, there is a large deviation in the results, with values exceeding 400 returns. This is about 1.5 times higher than the average. The significant increase in returns is clearly due to the favourable positioning of the object in relation to the laser sensor. The data used to create Figure 1 is based on 71 passes.

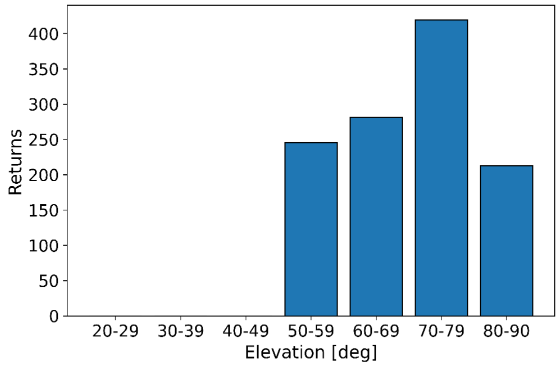

Fig. 1. Average number of returns of GLONASS-128 target, NORAD 37867
Source: own elaboration.

The results for GLONASS-137 are presented in Figure 2. In this case, the number of returns is close to the entire range of occurrence and falls within the range 350–400. This indicates that the orientation in orbit remains constant and equally favourable throughout the entire measurement period for the BORL station. The number of passes used to create Figure 2 is 79.

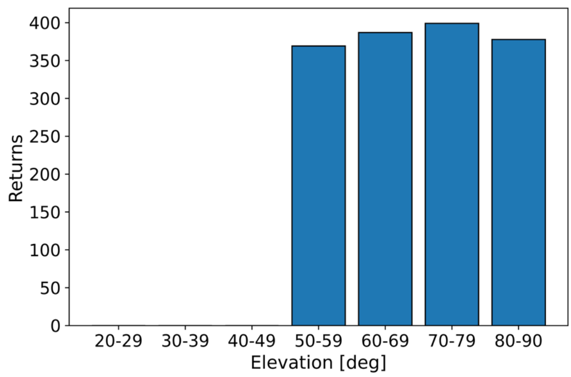

Fig. 2. Average number of returns of GLONASS-137 target, NORAD 42939
Source: own elaboration.

The histogram in Figure 3 displays the differences in elevation for LAGEOS-1. The range of elevations observed is from 20 to 90 degrees. The highest number of returns, exceeding 600, was obtained for elevations between 50 and 69 degrees. Conversely, the smallest number of returns, approximately 200, was obtained for elevations between 20 and 29 degrees. The number of returns rapidly increases from 20 to 29 degrees to 50 to 59 degrees. In the second half of the Figure, the number of returns gradually decreases to around 450 for elevations between 80 and 90 degrees. It should be noted that the LAGEOS-1 is spherical and has retroreflectors placed regularly, with its orientation towards the BORL station remaining constant throughout the entire pass. The data used to create Figure 3 is based on 593 passes.

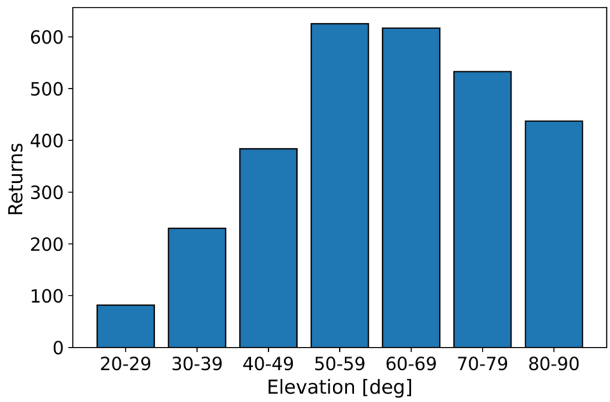

Fig. 3. Average number of returns of LAGEOS-1-1 target, NORAD 8820
Source: own elaboration.

A similar relationship can be seen in Figure 4 for the LAGEOS-2. The lowest number of returns below 100 is seen at elevations 20–29 degrees. The next increase occurs from 20 degrees to the range of 70–79 degrees, where the number of returns is approximately 330, the highest value. The number of returns for the next interval, near zenith, decreases to around 250. This pattern of returns is influenced by the accuracy of the ephemeris and limitations of the station apparatus. In the case of LAGEOS and GLONASS satellites, the observer cannot see the object on the monitor, so he must blindly search for the appropriate measurement area. The number of passes used to create Figure 4 is 376.

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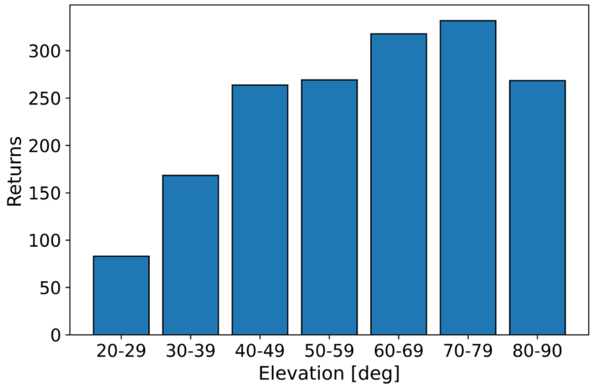

Fig. 4. Average number of returns of LAGEOS-2 target, NORAD 22195
Source: own elaboration.

The situation is different compared to earlier satellites, specifically with SWARM-A. SWARM-A is a trapezoidal object with a long boom that achieves the best results when the elevation is between 20 and 29 degrees near the horizon. The smallest value of returns is obtained when the elevation is between 70 and 79 degrees, as there is no value for near-zenith elevation. Figure 5 shows a steady decreasing trend as elevation increases. There is a small increase in the number of returns between 60 and 69 degrees, which is caused by a more favourable satellite orientation. When elevation is higher, then returns are less due to inaccuracies in the ephemeris and mount control issues. The telescope is usually too slow to track a LEO object near the zenith accurately. Furthermore, the object is not always visible through the sky viewing system. The are no returns in the range of 80–90 degrees. The number of passes used to create Figure 5 is 118.

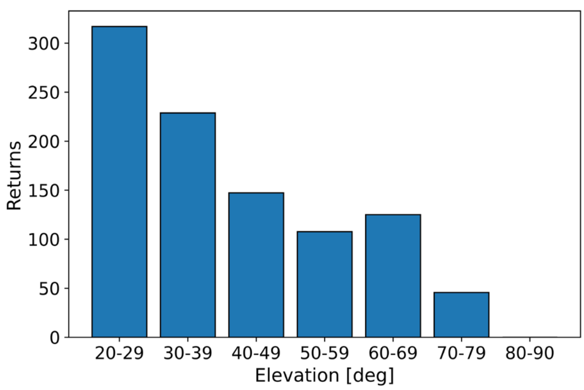

Fig. 5. Average number of returns of Swarm-A target, NORAD 39452
Source: own elaboration.

The histogram of the SWARM-B satellite (Figure 6) is very similar to the previous one. Like SWARM-A, SWARM-B is also a trapezoidal object with a long boom. The highest values range from around 300 for elevations between 20 and 29 degrees to about 10 for elevations between 80 and 90 degrees. The values generally decrease as the elevation increases. The number of passes used to create Figure 6 is 198.

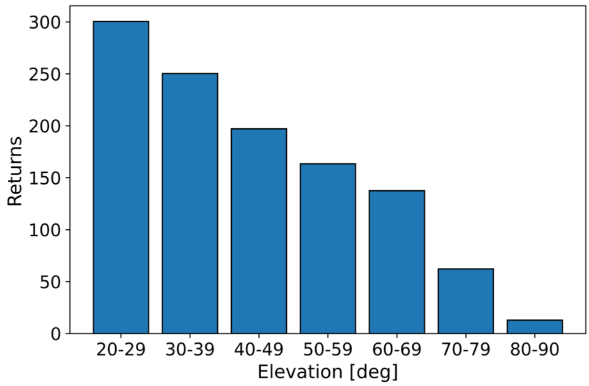

Fig. 6. Average number of returns of Swarm-B target, NORAD 39451
Source: own elaboration.

Figure 7 displays the results for SENTINEL-3A orbiting at an altitude of 814 km. The highest number of returns is observed for elevations between 30 and 39 degrees. With the exception of a minor anomaly, there is a clear decrease in value. The most favourable orientation towards the station is consistently repeated for elevations between 30 and 39 degrees. The number of returns for this range decreases from 320 to less than 50 for elevations between 80 and 90 degrees. The Figure 7 is based on data from 414 passes.

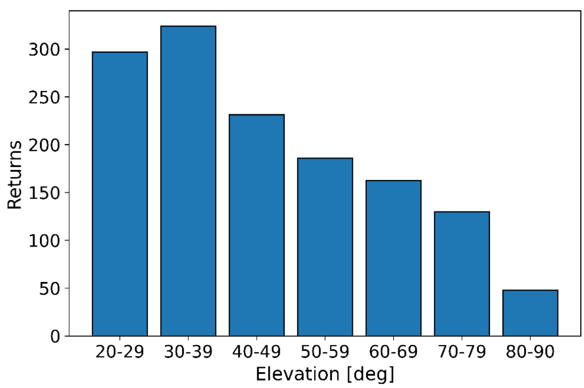

Fig. 7. Average number of returns of Sentinel-3A target, NORAD 41335
Source: own elaboration.

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In the case of non-spherical satellites, orientation of the tracked object is crucial for effective measurement, and this is clearly shown in Figure 8. The highest number of returns (around 420) is observed for elevations between 30 and 49 degrees. This indicates that the object is most favourably oriented towards the laser station at these elevations. This trend is easily noticeable since the number of reflections measured does not exceed 300 for other elevations. Figure 8 is based on 213 passes.

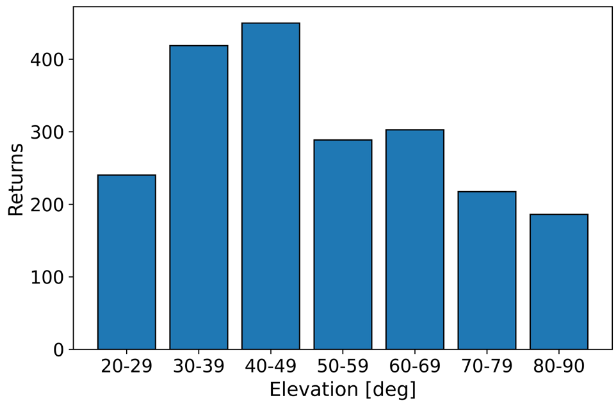

Fig. 8. Average number of returns of Sentinel-6A target, NORAD 46984
Source: own elaboration.

Starlette is a spherical object similar to LAGEOS satellites, but its orbits in the LEO regime at an altitude between 800 and 1100 km. The highest number of returns, close to 350, was obtained when the object was at a lower elevation. As the elevation increases, the number of returns decreases to about 130. There are no returns when the object is at elevations of 80–90 degrees. The Figure 9 was created using 462 passes.

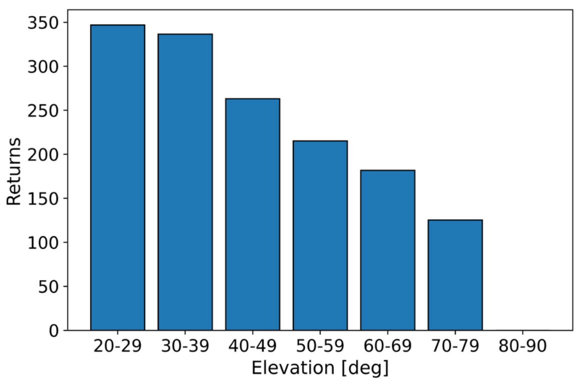

Fig. 9. Average number of returns of Starlette target, NORAD 7646
Source: own elaboration.

The next analysed satellite is Stella. Stella is the twin satellite of Starlette. The highest number of successful measurements occurs at lower elevation. If the object moves higher above the horizon, then the number of returns decreases. Starting from 400 returns for elevations between 20 and 29 degrees, this result decreases to less than 50 for elevations between 80 and 90 degrees. These LEO objects demonstrate the differences in results between spherical and non-spherical satellites very effectively. Non-spherical objects exhibit highly visible peaks in return values. The number of passes used to create Figure 10 is 113.

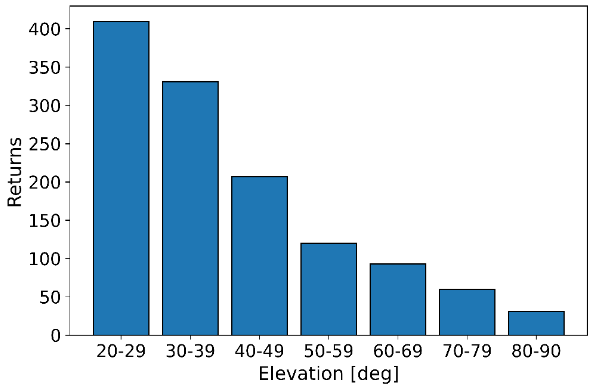

Fig. 10. Average number of returns of Stella target, NORAD 22824
Source: own elaboration.

The first analysed space debris objects are two CZ2C rocket bodies. The first object, with NORAD number 28480, is orbiting at an altitude of 709.5–913.9 km. The second object, with NORAD number 31114, is orbiting at an altitude 791–876 km. The most favourable elevations for taking successful measurements are between 20 and 39 degrees. As the elevation increases, the number of successful measurements decreases. For CZ2C-28480 (Figure 11), measurements taken at elevations between 40 and 79 degrees are similar because the orientation to the station is equally good for most of the pass. The significant difference in number of measurements at 80 to 90 degrees is due to the slow movement of the telescope, which is not enough to track targets near the zenith. Figure 11 is created using data from 119 passes.

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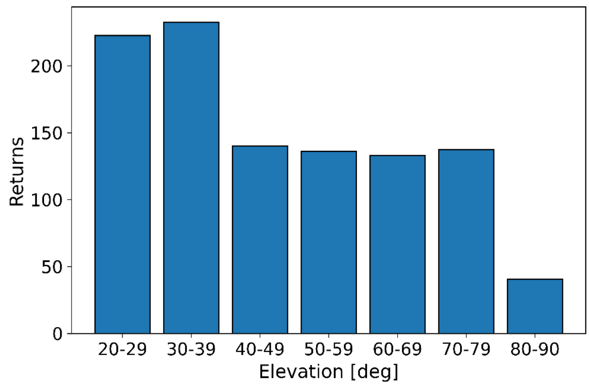

Fig. 11. Average number of returns of CZ2C target, NORAD 28480
Source: own elaboration.

In Figure 12, there is a gradual decline in the range of 40–90 degrees for the object CZ2C-31114. As the elevation of the satellite in the sky increases, its orientation towards the station worsens gradually, resulting in a decrease in the number of returns. The same problem is observed for other LEO satellites in the range of 80–90 degrees. The number of passes used to create Figure 12 is 275.

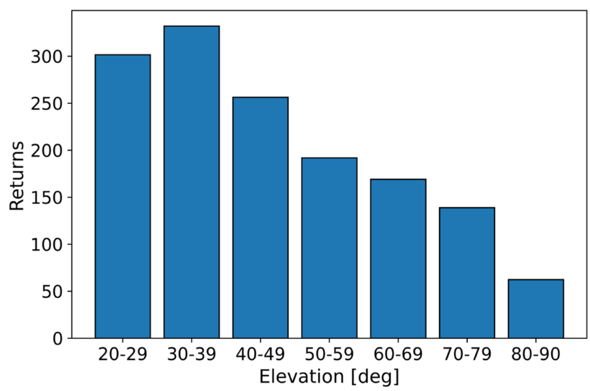

Fig. 12. Average number of returns of CZ2C target, NORAD 31114
Source: own elaboration.

The results are similar to those presented for other objects mentioned earlier. The highest value of returns is obtained for the elevation between 30 and 39 degrees, which is approximately 800. As the elevation increases, the number of returns decreases. Even when the satellite tumbles quickly, the results do not change. The biggest problems are the accuracy of the ephemeris and being able to see the target while measuring. Figure 3 is derived from data collected during 527 TOPEX/Poseidon flights over the BORL laser station.

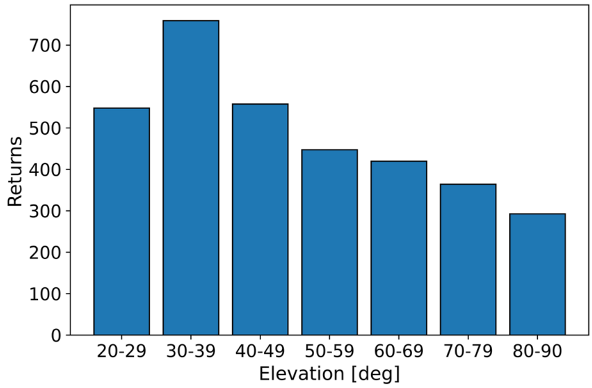

Fig. 13. Average number of returns of TOPEX/Poseidon target, NORAD 22076
Source: own elaboration.

The OICETS defunct satellite is orbiting at an altitude of 610 km. It has a high number of returns, with over 40 returns for all elevations and 120 returns at elevations between 30 and 39 degrees. The most favourable elevation for measurements is between 20 and 59 degrees, with over 100 returns obtained. Figure 14 was created using data from 215 passes and shows a histogram of the average number of returns for the OICETS object.

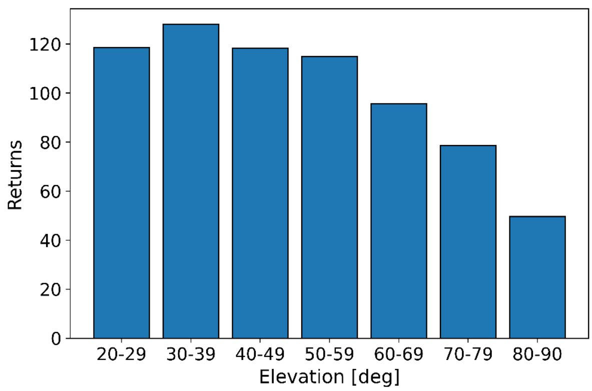

Fig. 14. Average number of returns of OICETS target, NORAD 28809
Source: own elaboration.

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4. CONCLUSIONS

The results presented in this study pertain specifically to the BORL laser sensor and cover data from June 2016 to July 2023. The analysis reveals that for objects from the LEO regime, the least effective approach is to take measurements near the zenith, specifically at elevations between 80 and 90 degrees. This inefficiency is due to technical limitations of the sensor, specifically the mechanical tracking inaccuracy. These limitations are primarily caused by the outdated hardware solutions used in the 3-ton telescope assembly, which dates back to the 1980s. The angular velocity of an object increases as its elevation increases. This causes difficulties for the BORL sensor's primary telescope in tracking a LEO object that is passing through or near the zenith. Among the ten analysed objects in LEO orbits, there is a clear correlation indicating that objects at higher elevations have the lowest number of returns. The Starlette, Stella, SWARM-A, and SWARM-B satellites have the highest number of returns when their elevations are between 20 and 29 degrees. The objects CZ2C-28480, CZ2C-31114, TOPEX/Poseidon, OICETS, and SENTINEL-3A had the highest number of returns when their elevation was between 30–39 degrees. On the other hand, SENTINEL-6A achieved the highest number of returns when its elevation was between 40–49 degrees. Spherical objects like Starlette or Stella have retroreflectors evenly distributed on their surface, making them advantageous for tracking at all times. However, there was no significant relationship found between the number of good measurements obtained and the elevation of both spherical and non-spherical objects being tracked.

The BORL primary telescope has no problem smoothly tracking MEO satellites. The least returns for LAGEOS-1 and LAGEOS-2 satellites were obtained at elevations between 20 and 39 degrees, while the most returns were obtained at elevations between 50 and 79 degrees. GLONASS objects orbiting at an altitude of approximately 20 000 km are tracked from an elevation of 50 degrees for a maximum of 30 minutes. This limitation is due to the long passes of these satellites over the station, which can last several hours. For GLONASS satellites, a similar number of returns was obtained for the entire elevation range of 50 to 90 degrees, except for the GLONASS-128 satellite. The GLONASS-128 satellite showed a peak in returns between 70 and 79 degrees, increasing from an average of approximately 250 returns to over 400. Observers face a challenge when trying to visually observe the sky while tracking objects in MEO regime. The telescope's technical limitations prevent the observer from seeing the tracked MEO objects on the monitor. Instead, they have to search for the photon trace, which provides clear evidence of the returns obtained. This task is difficult, and without experience in conducting satellite laser measurements, it may be challenging to successfully measure the tracked object.

The results of the research mentioned above are applicable only to the BORL sensors. They demonstrate the most effective way to measure satellites and space debris using the current equipment of the BORL station. It is important to maximize the use of each pass and avoid measuring when it is not efficient.

To enhance the efficiency of the BORL sensor and increase the number of measurements for different elevation ranges, several steps need to be taken. These include installing a more efficient sky view for observations (currently being worked on by installing a new guiding telescope and optical camera), improving the tracking accuracy of the telescope's mount control and motion, and replacing the current HAMAMATSU H5023 photodetector characterized by low quantum efficiency (QE).

It would be valuable to conduct additional analysis for other laser stations in the form of observational campaign. However, before conducting an observation campaign involving other stations, it is necessary to establish clearly defined conditions, including the objects to be observed and the conditions for measurement.

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