Mining, Metallurgy & Exploration
https://doi.org/10.1007/s42461-026-01572-6

A Systematic Evaluation of Localisation Signals in the Advancing Open Pit Mine Aitik

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Received: 23 October 2024 / Accepted: 20 April 2026
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Abstract
Modern high-performance mining operations are under constant review for better to improve efficiency, increase productivity and reduce environmental impact. This can be achieved by introducing new automation and electrification technologies, such as the deployment of electric, autonomous drilling at Boliden's Aitik mine. Reliable, high precision localisation under all conditions, such as varying weather conditions and advancing geometry of the operation, is crucial for autonomous drilling. and the advancing mine geometry, is crucial for autonomous drilling. As part of a multistage project for the introduction of autonomous drilling, an assessment was conducted of localisation signals from satellite-based positioning and the mine-specific localisation infrastructure. This paper provides an overview of Aitik mine, its drilling operations, as well as the localisation system setup, before presenting the localisation evaluation procedure. The evaluation includes the determination of the influence of weather and time on satellite coverage. Further it covers an extensive recording and analysis of the position dependant availability of the different localisation systems within the different areas of a selected bench. The evaluation reveals the external influencing factors, displays the resulting accuracy level in the different parts of the bench, as well as its dependency on the different available satellite and locally installed localisation systems. Overall, this study serves as a practical example of how localisation quality and infrastructure can be evaluated, provides guidance for deciding whether additional localisation infrastructure is required for pit automation, and supports decisions on the appropriate timing of such an investment.

1 Introduction

Mining operations at Boliden Mineral AB are continuously evaluated to improve efficiency, productivity and reduce environmental impact. This ensures that operations are conducted as efficiently and sustainably as possible while also improving safety and environmental performance. Furthermore, the implementation of new technologies may increase machinery utilisation and availability. This is especially important for maintaining profitability and ensuring that raw material production meets current and future requirements for environmentally friendly, efficient, and socially acceptable resource extraction.

Boliden is currently pursuing several initiatives to test and implement new technologies, including at the open pit mine Aitik in Northern Sweden. Through the implementation of such technologies, with a particular focus on automation, Aitik is gradually moving towards an operation with reduced diesel emissions and improved safety and efficiency. Examples of automation projects at Aitik include the installation and testing of electrified dump trucks with a trolley line, as well as ongoing work **on** an autonomous haulage system and the automation of electric drill rigs.

The automation and electrification example addressed in this paper is the introduction of automated electric drilling, which formed part of a three-year phased programme beginning in April 2017. The drill rig (an Epiroc Pit Viper 351)

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Published online: 29 April 2026

has been operated successfully in automated mode under remote operator supervision and assistance, achieving a 30% increase in productivity compared with manned equipment (190 m/day) [9].

At the start of the project, Boliden aimed to increase the production at the Aitik operation from 39 Mtpa in 2017 to 45 Mtpa in 2020. This goal was accomplished and the production capacity was increased to this level. Despite the low ore grade of 0.22% copper and an increasing mining depth, Aitik is already considered the world's most efficient open pit copper mine. The targeted increase in production rate implied even further improvements in overall efficiency of the operation. Drilling, as an essential component of the drill and blast cycle, has a major role in the development of automation at Aitik. Drilling automation increases productivity, as time lost during shift changes and breaks can be minimized. As a first step of automation at Aitik, tele-remote operation of the drill rigs was established in 2018. The next step in development was the fully automated drilling of a complete drill row including navigation [1–3].

Drilling automation does not only include the drilling process itself, but also the precise navigation of the drill rig to the next borehole. Therefore, both tele-remote and fully automated drilling heavily depend on the accuracy of the localisation systems. Accurate localisation is a key factor in the automation of other processes as well. Automated hauling systems for example, as they are used at Rio Tinto's iron ore mines in the Pilbara region, also depend on reliable positioning systems for trucks. Furthermore, a high availability of localisation systems is essential for the development of non-interrupted autonomous processes [7, 13, 15].

As part of the multistage process for the introduction of autonomous drilling, different investigations and trials were conducted. One of these investigations focused on the quality of the localisation system as a key factor. This paper will reveal different insights on the approach that was used in this process but also having Aitik as an examplary mine facing different challenging factors. The available localisation system at Aitik needs to withstand extreme weather conditions, due to the mine's geographic position above the Arctic Circle. In addition, Aitik faces lower GNSS coverage than mining environments in more moderate latitudes. Given these circumstances, a successful implementation of localisation and thus automation systems are more challenging in Aitik compared to other mines. Furthermore, the applicability of any selected localisation system needs to be assessed with respect to the specific conditions of Aitik [12].

The localisation infrastructure at Aitik consists of the Global Navigation Satellite System (GNSS) with a corresponding improvement of the obtained position by correction signals obtained from a local base station (Differential GPS). In addition, a complementary Jigsaw Positioning System (JPS) is available within the deepest part of the mine ("Aitik-North"). JPS was implemented in order to compensate the decreased satellite coverage, related to mining depths of up to 420 m at the time of investigation in this area. The JPS consists of six masts transmitting a positioning signal, placed around the pit. This is discussed in detail in a later section in this paper.

As mentioned earlier, a prerequisite for autonomous drilling is a reliable and precise referenced localisation of the drill rig ("high-precision localisation") with high availability. Within this paper, a study on the coverage and accuracy regarding the available localisation infrastructure at Aitik is presented. The overarching goal of the investigation was to determine whether the localisation infrastructure fulfils the requirements of high-precision localisation and is thus sufficient for full drilling automation at current and intended future mining depths.

Reliable high precision localisation in an advancing open pit mine cannot be assessed only from operational outcomes, but it must also be understood from the principles of the positioning technologies involved. At Aitik, localisation is based on GNSS, which determines position from satellite signals but becomes less robust when pit depth, slope shadowing and restricted sky visibility reduce satellite availability and worsen the observation geometry. This GNSS solution is improved by differential corrections from local base stations, while the Jigsaw Positioning System (JPS/Locata) provides an additional terrestrial signal infrastructure that can complement satellite positioning in areas with limited sky view. Because these systems are affected differently by mine geometry, their combined behaviour must be evaluated in terms of signal availability and resulting localisation quality in order to determine whether the approximately 5 cm accuracy required for autonomous drilling can be achieved throughout the advancing pit [1, 2].

2 Aitik Open Pit Mine

This section introduces the Aitik mine and provides a detailed overview of the areas of operation, which are of importance for this study. A general overview of the mine is provided initially, followed by a discussion on current drilling operations and the state of drilling automation. At the end of this section, the installed localisation infrastructure, which forms the basis for the analysis and evaluation is presented.

2.1 Overview of Aitik

The open pit mine Aitik is located in Northern Sweden within the municipality of Gällivare - latitude 67º 07' 45''N

and longitude 20º 95' 00''E- and therefore is located above the Arctic Circle. The mine is operated by the Swedish company Boliden Mineral AB, which is hereafter referred to as Boliden in further reference. Aitik's main product is copper with chalcopyrite as the principal ore mineral. Gold and silver are produced as by-products.

Aitik's average copper grade in 2021 was 0.22%. To maintain profitability, despite this low copper grade, high production volume and an efficient processing plant are necessary. With an annual production of about 40.1 Mt of ore in 2021 and a total mining area of 4.55 km^2, excluding tailings, Aitik is Sweden's largest open pit mine. During processing, the recovery of copper is 90% and the final concentrate consists of about 25% copper. Aitik employed about 700 staff in 2018. With the production tonnage and staff numbers, Aitik is the world's most efficient open pit copper mine with respect to the produced tonnes per person hour [4].

Aitik applies the discontinuous mining technique of drilling and blasting with bench heights of 30 m. Mining of the main pit began in 1968. According to the current mine plan, operations will continue until 2043, reaching a final depth of 705 m. Figure 1 shows an aerial photograph of the mining area at Aitik. The photograph is orientated according to the local coordinate system used by Aitik, i.e. towards Aitik's local North, which is perpendicular to the strike of the main ore body. The deviation between Aitik's local North and geographic North is 73°. The currently deepest mining area is outlined in the picture and further referred to as "Aitik-North". The current study focuses on this part of the mine.

Due to the arctic geographic position of Aitik, winter conditions are harsh and temperatures can decrease as low as −37 °C. These arctic temperatures in winter lead to an increased downtime of operating resources. Furthermore, frozen ore is harder to excavate and to crush and conveyors operate less efficiently. This results in increased wear and tear. All these factors lead to a decrease in production during winter and thus decreased efficiency and increased operational cost.

2.2 Drilling Operations

Depending on the predominant geological and geotechnical situation, the pit walls can be formed using pre-splitting. Pre-splitting uses 127 mm (5") diameter drill holes with small spacing and little explosive charge (typically around 200 kg) to achieve a smooth wall with minimum damage to the remaining rock. In comparison, the explosive charge of a production drill hole is around 1000 kg. Ideally, re-splittings are detonated before consecutive drilling and blasting of the remaining drill sequences. The second batch of drill holes, i.e. the second row of drill holes as seen from the slope ("near-slope holes"), is drilled with a diameter of 159 mm (6¼") and closer spacing compared to the subsequent production drill holes to minimize damage to the slope caused by blasting. If the geological and geotechnical situation does not allow pre-splitting, e.g. due to heavy fracturing, the initial two rows of drill holes both have an equal true vertical depth of 15 m and a drilling angle varying between 75° and 85°. In this case, both drill sequences are separated by a drilling offset of 3 m. Production drill holes have a diameter of 311 mm (12¼").

Two different types of production drill rigs operate at Aitik, which are both manufactured by Epiroc. The pre-split holes and the near-slope holes (diameters 127 mm and 159 mm respectively) are drilled by SmartROC D65 drill rigs. Production holes with diameter 311 mm are drilled by PitViper-351 drill rigs. Both drill rigs are displayed in Fig. 2. At the time of this study, five PitVipers and five D65s operate



Fig. 1 Aerial photograph of Aitik (July 2019). (source: Boliden)



Fig. 2 (**a**) Smart Roc D65 and (**b**) Pit Viper 351 in use for drilling at Aitik open pit mine. (Photos taken: 16th January 2019)

at Aitik. This analysis focusses on the PitVipers, as mainly they are affected by ongoing development of automation.

2.3 Progress of Drilling Automation

Aitik has been progressing its drilling technology continuously, aiming to transform the entire drilling fleet into a fully autonomous production system. The goal is not only to increase productivity and availability of machines, but primarily to increase the safety of the operation and minimise the risks associated with manual operations in the mine. Since 2018, the PitViper fleet at Aitik has been remotely controlled from a central control room, as it can be seen in Fig. 3. In tele-remote operation, drilling itself is conducted autonomously whereas (tele-remote) movement of the drill rig to the next bore hole is executed by an operator. This first stage of drill rig automation resulted in a nearly 25% increase in utilization of the rigs. This is achieved through time savings during shift changes, breaks and blasting periods, as the monitoring and control from a central control room allow rapid operator handovers.

The next step of automation, which was established in one of the drill rigs in 2019, is the so-called "single-line autonomous mode". In single-line autonomous mode, a full row of drill holes (referred to as line) is drilled autonomously, including all accompanying processes, such as tramming and collaring. Only the movement of the rig to another line needs to be done tele-remotely. The limitation to single-line is due to complications in cable management for these electric rigs.

The next step of development at Aitik is to transform the entire fleet to single-line autonomous mode and eventually

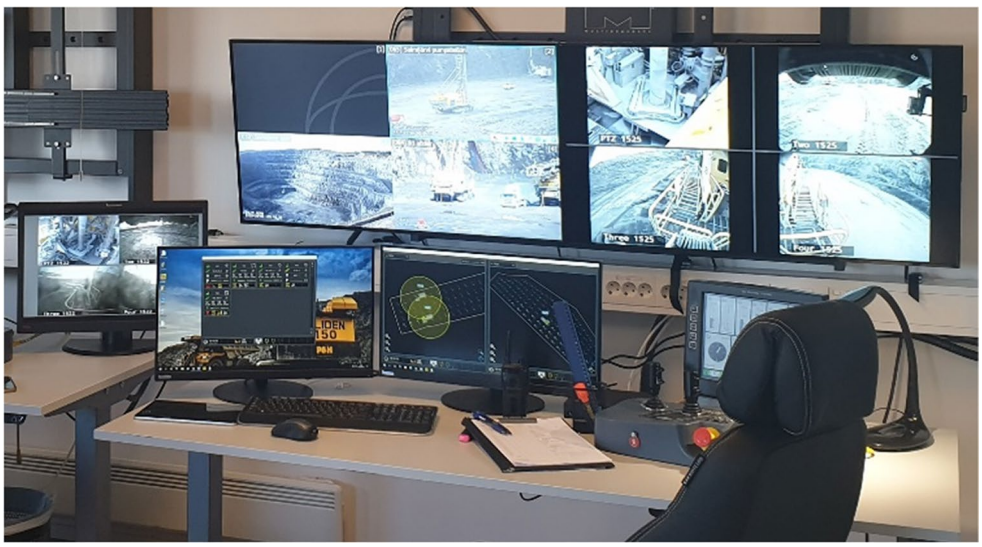


Fig. 3 Work place in a drill rig control room at Aitik (Photos taken: 10th March 2019)

to fully autonomous, with several machines controlled by a single operator, who mainly monitors the process rather than actively controls the drilling. This process is still ongoing.

A mandatory prerequisite for drilling automation is a continuous transmission of data between the drill rig and control room. At Aitik this is realised via a Wi-Fi network. Further, these steps of automation have utmost reliance on an accurate localisation system with high availability, which is necessary for correct positioning and navigation of the drill rig to the designated position of the next bore hole. The necessary localisation accuracy is a relative requirement depends on the required accuracy of a specific target. Drilling engineers at Aitik have empirically determined an accuracy of up to 5 cm in tramming and collaring to be acceptable. A localisation system fulfilling these requirements will be referred to as a system with "high-precision localisation".

For the automation of other fleets, such as trucks or dozers, the specific prerequisites for the necessary accuracy of localisation systems may vary. Nevertheless, regardless of precision and accuracy, reliability of such systems is of utmost importance if successful automation is desired. Availability and utilization of such systems are only as good as the system they depend on, including a high-speed network.

2.4 Localisation Concept and Setup

Localisation at Aitik is based upon three techniques: Global Navigation Satellite System (GNSS), Jigsaw Positioning System (JPS) and Differential GPS (DGPS). GNSS is defined as the collection of all satellite navigation systems. Drill rigs at Aitik use the American GPS and Russian GLONASS satellite navigation systems for localisation.

2.4.1 General Positioning Principles

Independent of the specific technology used, high-precision localisation is based on the same general principle: the position of a receiver is determined from signals transmitted by reference points whose coordinates are known. From these signals, the receiver derives range-related observations, for example from signal travel times or time differences, and computes its position by solving a geometric problem in three-dimensional space. The quality of the resulting position depends not only on the precision of the measurements themselves, but also on the spatial distribution of the available transmitters. If the observed transmitters are well distributed around the receiver, the position solution is geometrically strong; if they are clustered in a limited part of the visible field, the solution becomes weaker and more sensitive to errors. In practice, this means that localisation quality is controlled by two main factors: first, the quality of the signal observations, and second, the geometry of the available signal sources. Differential correction techniques mainly improve the observation quality by reducing common ranging errors, whereas complementary local positioning systems can additionally improve the available geometry in environments where satellite visibility is restricted.

This general principle forms the basis for the use of GNSS, DGPS/RTK and JPS at Aitik and explains why both signal availability and GDOP are central evaluation parameters in this study [3].

2.4.2 Fundamentals of GNSS

Global Navigation Satellite Systems (GNSS) consist of constellations of space-borne satellites (e.g., GPS, GLONASS, Galileo) that continuously broadcast code-modulated carrier signals. A GNSS receiver measures the pseudorange to each visible satellite and by solving the typically overdetermined system of equations for at least four satellites yields the three-dimensional position and the receiver clock offset. As satellite signals propagate from the satellite to the receiver, they are affected by atmospheric delays and multipath effects. In addition, various error sources arise from satellite-related biases (e.g., orbit and clock errors) as well as receiver-related biases, including receiver clock offset, inter-channel biases, antenna phase center variations, and receiver noise [18]. At Aitik the drill rigs therefore rely on the GPS and GLONASS constellations. At Aitik, high-precision localisation is achieved by combining three complementary positioning approaches: GNSS, differential GNSS corrections, and the Jigsaw Positioning System (JPS). GNSS provides the global satellite-based position solution, while differential corrections from local base stations improve the achievable accuracy by reducing common ranging errors. In addition, JPS provides a terrestrial positioning layer that can support or complement GNSS in areas where the open pit geometry limits satellite visibility. Because these three components are affected differently by pit depth, slope shadowing and local geometry, their technical principles must be briefly outlined before the localisation quality at Aitik can be evaluated in terms of signal availability and GDOP [1].

2.4.3 Differential GPS/Real-Time Kinematic (RTK)

Differential GPS (DGPS) improves a conventional GNSS solution by transmitting correction information from a reference station whose coordinates are known with high accuracy. A widely used high-precision implementation of this concept is Real-Time Kinematic (RTK), which uses carrier phase observations and real-time correction messages to achieve centimetre level positioning once the ambiguities are resolved (typically ≤ 5 cm) [12, 16].

At Aitik two permanent base stations transmit RTCM-3.2 correction messages, which are received by the drill-rig antennas. Because the RTK correction removes a large proportion of atmospheric errors, a geometric dilution of precision (GDOP) value of 8 (corresponding to a minimum of seven tracked satellites) satisfies the 5 cm accuracy requirement for autonomous drilling.

The correction can be classified as a local-area and absolute DGPS solutions. Accordingly, Aitik has two base stations transmitting correction signals [12, 16].

As mining depth increases, the visible sky above the receiver becomes progressively restricted and the probability of tracking a sufficiently large and well-distributed satellite set decreases. In such conditions, differential GNSS alone may no longer guarantee robust high precision localisation, which creates the need for an additional positioning system that is less dependent on open-sky satellite visibility.

2.4.4 Jigsaw Positioning System (JPS)

The JPS (also known as Locata) creates a local positioning network that works as a "localised autonomous terrestrial replica of GPS". Six ground-based transmitters – the *LocataLites* – are installed around the Aitik-North area and emit precisely timed signals. Because the masts are synchronised via a wired reference clock, a receiver can determine the time-difference of arrival to four or more LocataLites and compute a 3-D fix by multilateration [5, 14, 19].

JPS can be used to augment GNSS or to operate independently. The antennas mounted on the drill rigs detect both the LocataLite signals and the conventional GNSS signals. This dual-sensor setup guarantees high-precision localisation even in deep-bench zones where the sky view is severely limited.

Boliden implemented JPS at Aitik in 2015, being only the fourth mining environment worldwide where this technique has been applied. JPS was developed by the Australian company Locata Corporation. JPS creates a local positioning network functioning as a "localised autonomous terrestrial replica of GPS" [6]. It is generated by transmitting masts – "LocataLites" – placed around the area of coverage. The LocataLites can be regarded as local, ground-based reference transmitters analogous to stationary satellites. JPS antennas, mounted on the drill rigs, can detect LocataLite signals together with signals from conventional satellites. Their position on the drill rigs and a picture of a LocataLite are shown in Fig. 4. Six LocataLites are installed around Aitik-North, being the main area of coverage of the JPS system. Their positions are shown in Fig. 1 [5, 14].

In addition, the evaluation includes an extensive recording and analysis of the position-dependent availability of the different localisation systems across the different areas of a selected bench.

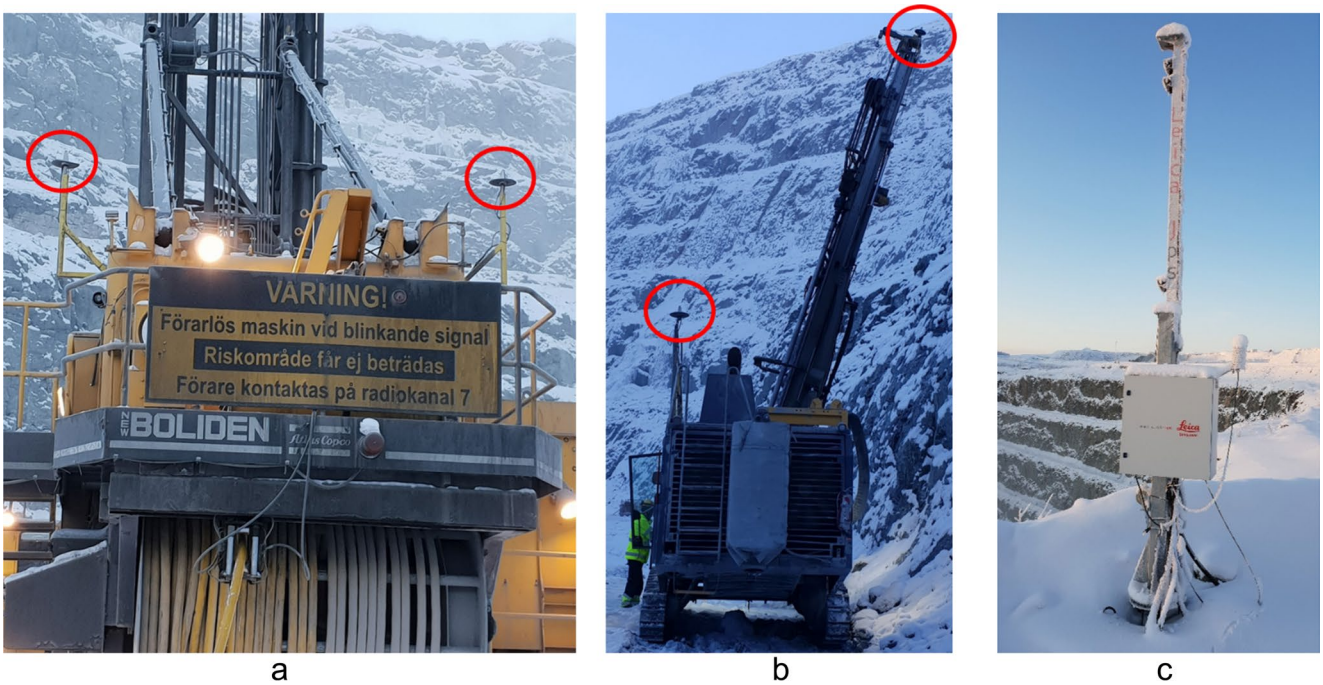


Fig. 4 Positions of the localisation antennas, as mounted on a (**a**) PitViper and (**b**) D65 (**b**). (**c**) shows an image of a LocataLite. (Photos taken: 30th January 2019)

3 Localisation Evaluation Procedure

In order to compare the prevailing localisation quality at Aitik with the high-precision localisation requirements for autonomous drilling, appropriate evaluation parameters must firstv be defined as localisation indicators. These influencing factors on localisation quality can thereupon be determined and examined, considering both external influencing factors, such as weather and time, and positional influences within the pit. Data can then be collected and validated. The required data and the associated processing steps are discussed at the end of this section.

3.1 GDOP as Evaluation Parameter of Localisation Quality

There are various parameters that can be considered as localisation indicators. When working with trilateration, a main factor is the "Geometric Dilution of Precision" (GDOP), that represents the geometric constellation of the localisation scenario. Another important factor is the range between a receiver to the GNSS satellites or JPS infrastructure. The determination of the range depends on the transmission of the signal itself, which is influenced by a variety of atmospheric effects, including astronomical and weather effects. These effects, resulting in an uncertainty in determination of the range, however are compensated by the available correction signal from an integrated differential base station with a known fixed position [12, 16].

Among the possible localisation indicators, GDOP was selected as the principal evaluation parameter because it describes the geometric strength of the positioning configuration independently of the underlying ranging technology. In positioning systems based on distance observations, GDOP is derived from the geometry matrix composed of the line-of-sight unit vectors to the observed transmitters and therefore expresses how strongly measurement errors are amplified by the spatial arrangement of the available signals. A low GDOP indicates a well-distributed constellation and a geometrically strong solution, whereas a high GDOP reflects poor geometry, for example when transmitters are clustered in a limited part of the visible field. This is particularly relevant in an open-pit environment, where slope shadowing, increasing depth and restricted sky visibility can degrade the available observation geometry even if differential corrections reduce a substantial part of the common range-related errors. For this reason, GDOP was chosen as the main indicator of localisation quality in this study, while the number of tracked satellites and LocataLites was used as a complementary measure of signal availability and robustness [3].

The GDOP is a parameter dependent on the constellation and number of the localisation infrastructure satellites/stations available. It is a universal variable and thus directly accessible from most localisation devices, requiring no calculations. Furthermore, a relationship between the GDOP and the accuracy and the number of satellites involved in the localisation process can be established as an indicator of accurate and robust localisation. As these parameters are of major importance for the present analysis, GDOP was chosen as the main evaluation parameter, thus allowing conclusions of the other factors. Additional error sources were not considered separately, as major range-related errors are substantially reduced by DGPS correction [12, 16].

The relation between the GDOP, number of satellites and resulting accuracy is not of a linear nature as it is dependent on the position of the satellites and the receiver's position on the earth. The relationship between GDOP and satellite availability was determined through measurements with a portable Trimble device, which has the ability to obtain a correction signal of its position. Therefore, the measurements generated the same position, precision and accuracy as a drill rig, which receives no additional JPS signals. For Aitik's accuracy requirements on localisation (difference of actual and planned position needs to be smaller than 5 cm) threshold values for the GDOP and the required number of satellites could be derived from the measurement results.

The accuracy of the boreholes has an important influence on the blasting result and resulting subsequent downstream process steps. Accurate drilling is vital for operation efficiency, efficient crushing of the material and cost per tonne ratio. By minimizing the localisation errors to the mentioned low levels, the localisation errors due to the localisation systems are being brought to a level where these can be neglected in comparison to the size of boreholes, machine accuracy and actual borehole path accuracy, which is comparatively difficult to control and evaluate [8].

A GDOP of 8 was proven to be the correct GDOP threshold to localise within the given accuracy range. In general, this value is only considered as a "sufficient" value for localisation [10]. However, thanks to the correction signal, the desired accuracy was achieved with a relatively small number of satellites. A minimum of seven satellites was sufficient, which corresponds to the stated GDOP.

3.2 Influences on Localisation Quality

The GDOP as the main quality and evaluation parameter is influenced by the mining environment. The influencing factors on localisation quality can be classified into factors caused by "external conditions" and factors related to the position within the pit ("positioning influences").

The external conditions considered for this study are weather, season and time of the day.

In addition to the external conditions, the following positional factors within the mine were found to be the main factors influencing the potential localisation quality at any given position:

- the geographic position within the mine (e.g. north/east/south/west).
- the mining depth and the corresponding bench level.
- the distance to the slopes.

The indicated influencing factors (external conditions and positioning influences) are each the focus of separate investigations with focus on their respective mentioned key factors.

3.3 Data Collection and Validation

In order to quantify the high-precision localisation availability within the mine, the above defined influencing factors are separately examined and sets of data are collected, validated and evaluated. Both the LocataLite and the operating drill rigs monitor various localisation indicators and obtain further metadata (e.g. drilling status) from the drilling process at a time interval of 1–3 min. This monitoring data provide a valuable basis for evaluating localisation indicators under the different influencing factors. The drill rig and LocataLite data were validated with an external Trimble GNSS device. The data from the external device, LocataLite and drill rig were highly consistent, with only minor deviations.

The logged localisation dataset comprised timestamped records from the drill rigs and the LocataLite infrastructure. The recorded variables included the number of tracked GNSS satellites, the number of tracked LocataLites, GDOP, machine position and process metadata relevant to the drilling state. Where available, the status of the differential GNSS correction was additionally considered. By combining these localisation records with the logged drill start and end times, the data points obtained during active drilling could be assigned to individual drill holes. Since the logging interval ranged from approximately 1 to 3 min, the data were aggregated per drill hole using average values and corresponding extrema to generate comparable evaluation parameters for the subsequent analysis.

For the analysis of the external conditions, a stationary point outside the pit – a LocataLite – was chosen as measuring point. Measurment data of the LocataLite were collected on certain days at different times, seasons and predominant weather conditions. These sets of data could then be compared to each other. The measurement data of the different LocataLites at equal timepoints and at timepoints with similar conditions were practically alike and corresponded to the measurements of the Trimble device, thus validating the input data of the analysis.

The positioning influences were analysed by collecting the logged data from all drill rigs and processing the logged positions combined with the localisation indicators and metadata. The drill rigs provided a large data set across multiple benches within the entire mine and also included process data, such as the drill start times. This made it possible to account for the respective machine states in the analysis.

With a recorded start and end time for drilling, the localisation indicators obtained during drilling can be associated to the corresponding drill hole. After this assignment, the average number of detected satellites, the average GDOP value, the corresponding extrema whilst drilling and other characteristic evaluation parameters could be obtained for each drill hole. For the study described here, the localisation indicators of those drill rigs operating at Aitik-North, during the period of 1 st January 2018 to 1 st February 2019, were assigned to their corresponding drill hole. Being the deepest part of the mine, the availability of high-precision localisation is most critical at Aitik-North, due to the overall lower localisation quality. The feasibility of autonomous drilling at Aitik thus especially relies on the availability of high-precision localisation at Aitik-North. Therefore, this area was chosen as main area of investigation and the rest of the pit was excluded from this study. Furthermore, JPS is only available at Aitik-North and an investigation on the localisation signals in this area can quantify the improvement of the localisation quality by this complementary system.

The described boundary conditions of analysis, resulted in a total number of 6322 drill holes contributing to the study, whereby each drill hole included about 5 to 15 datapoints on average. The drill holes were located at six different depths (360–420 m), with most of the drilling activity taking place at a depth of 405 m and 420 m. A comparison of the evaluation parameters generated from these drill holes allowed conclusions to be made on the lateral extent of the factors influencing the positioning accuracy. Differences in the localisation indicators regarding the different drill rigs were found to be negligible and their data sets were evaluated all together.

The results of the study are based on the interpretation of the obtained evaluation parameters, which are average values generated from the corresponding individual data points of a drill hole. However, the variance of the average values needs to be considered in the evaluation. Variation in the number of detected satellites normally occurs during the drilling period, which is about half an hour (refer to Sect. 4.1). A variance cannot be calculated consistently across holes and machines, due to the variation in the logging interval. The difference between the minimum and

maximum number of satellite connections at a drill hole ("satellite span") allows conclusions about the variance. For approximately 86% of all drill holes, the satellite span during the measurement time was three or less and for 96% of the drill holes the span was five or less. This is in accordance to the expectations on the satellite span, which can be derived from Fig. 5. Therefore, the average number of detected satellites can be used as an evaluation parameter, but potential variations have to be considered when reviewing the results. As the GDOP value correlates with the number of satellites, the use of the GDOP average is therefore also validated.

4 Analysis and Results

After data collection, pre-processing and validation, the data analysis was conducted. The results of the analysis are presented in this section. The collected data from the LocataLites, in respect to the influence of external conditions, were initially evaluated, followed by the analysis of the drill rig data regarding the influence of position within the pit.

4.1 External Conditions

A comparison of the number of detected satellites from a LocataLite on different days with similar weather conditions revealed recurring patterns of satellite availability, with a variance of up to 7 satellites. As the satellite orbit time is slightly less than 12 h there is a small change in the satellite coverage per day. This change of satellite coverage was determined to result in a shift of about 2 h per month. Based on the measured satellite coverage on a particular day, approximate conclusions can therefore be drawn regarding the local extrema of satellite detectability during another period [12].

Figure 5 shows the comparison between the satellite coverage for a cold, high pressure, dry winter day and a humid, low pressure summer day. In accordance to above finding, the displayed curves of satellite coverage are shifted by 2 h per month to best overlap each other.

The examination days differ regarding their temperature, barometric pressure and air humidity. These chosen weather characteristics impact the "tropospheric refraction", an effect potentially leading to a lower precision of localisation by a distortion of the travel of the satellite signal. As this error can largely be corrected via Differential GPS, it is not of importance for Aitik and this analysis [11, 17].

Figure 5 reveals there is no general difference between the two weather extremes in respect to the satellite coverage. The number of detected satellites varies without any systematics from the average at a given time. Furthermore, the displayed behaviour of satellite coverage is characteristic for the obtained results of days with similar conditions. Hence, weather conditions are considered not to significantly influence the detection of satellites and thus the localisation accuracy.

4.2 Positioning Influences

The results of the analysis regarding positioning influences are discussed in this section. The influence of geographic position within the mine and the influence of the depth with regards to GNSS and JPS are discussed separately. Additionally, the influence of JPS on the resulting GDOP

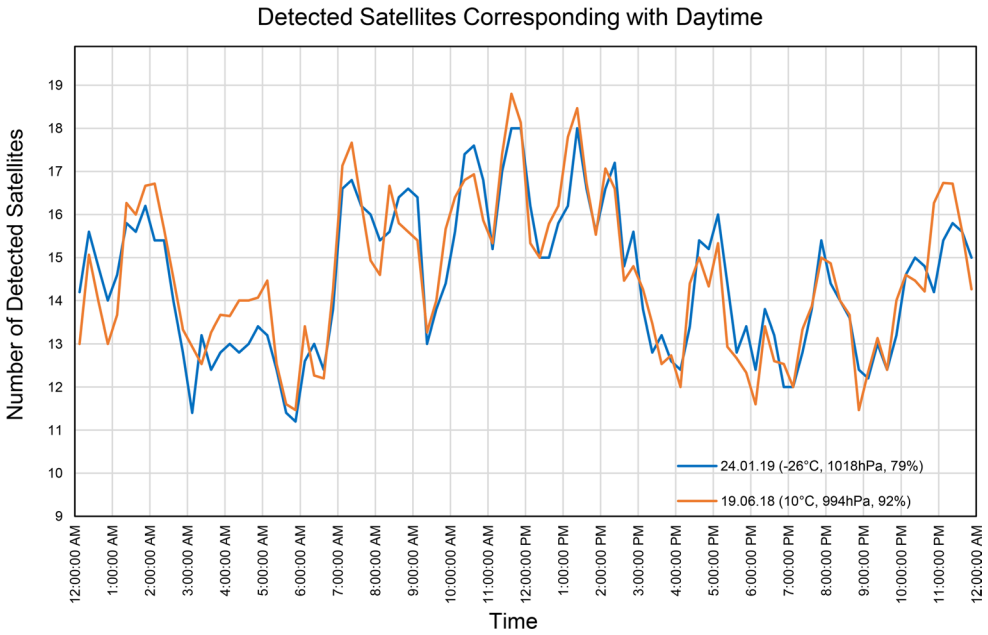


Fig. 5 Number of detected satellites, as measured on a LocataLite, on 24th January 2019 (cold, dry winter conditions) and 19th June 2018 (warm, humid summer conditions). The average number of detected satellites over a time period of 15 min is displayed, shifted by 2 h per month for best overlap

is described. The influence of the distance to the slopes on both positioning systems is discussed at the end of this section. (Figures 6 and 7).

For a better evaluation of the data, the drill holes at Aitik-North contributing to the analysis are distributed into the four areas North, East, South and West, referring to the local coordinate system. The discussion focusses on highlighting the differences of the positioning influences related to these different areas. The division of the drill holes on the 420 m bench into the four areas is visually illustrated in the Figs. 6 and 8. The drill holes on the other benches were distributed accordingly based on their positions, so as to correspond as closely as possible to the distribution shown.

4.2.1 GNSS

The calculated average number of tracked satellites, which correlates with the average GDOP value, is displayed in Fig. 6. It shows the drill holes on the 420 m bench at Aitik-North, which contributed to the analysis. All drill holes are coloured according to their average number of tracked satellites during drilling.

It is visible that the number of average tracked satellites depends on the positioning within the mine and also varies along each row, since the satellite availability varies over time. This number is higher in the eastern part (blue dots) and lower in the western part (red dots). The overall topography of the mine justifies this observation. The curvature of the mine results in a lower detection of satellite signals in the West compared with other areas, as the West is closely encircled by both the northern and western slopes. In contrast, the East benefits from a comparatively high surrounding open space. The East is located directly west of the two most eastern LocataLites (see Fig. 1). As shown, the distance to the nearest major slope (the southern slope) is greater than in the other areas. Further, this area is not significantly affected by its encircling slopes, whose upper levels are at the height of the junction between Aitik-North and the rest of the pit.

The threshold number of required satellites for high-precision localisation at Aitik is 7 (see Sect. 3.1). Due to the variance of the obtained average values, the data sets of the drill holes with an average of below 8 detected satellites are likely to contain measuring points with too few detected satellites for high-precision localisation. Hence, the availability of high-precision localisation on the 420 m level is most critical in the West. Similar observations can be made for the other examined benches, across the entire data set.

Figure 7 displays the average tracked satellites per drill hole, including variances and outliers on all examined benches and areas. The red line in the Figure illustrates the threshold value of 7 necessary satellites for high-precision localisation with a GNSS-only solution. In accordance with the above observation, the satellite coverage in the East was highest on all examined benches, whereas the West had the lowest coverage. Furthermore, this is the only area in which drill holes with an average satellite coverage below the threshold value were observed, i.e. drill holes where high-precision localisation was not achievable for most of the drilling period. This is consistent with the previous

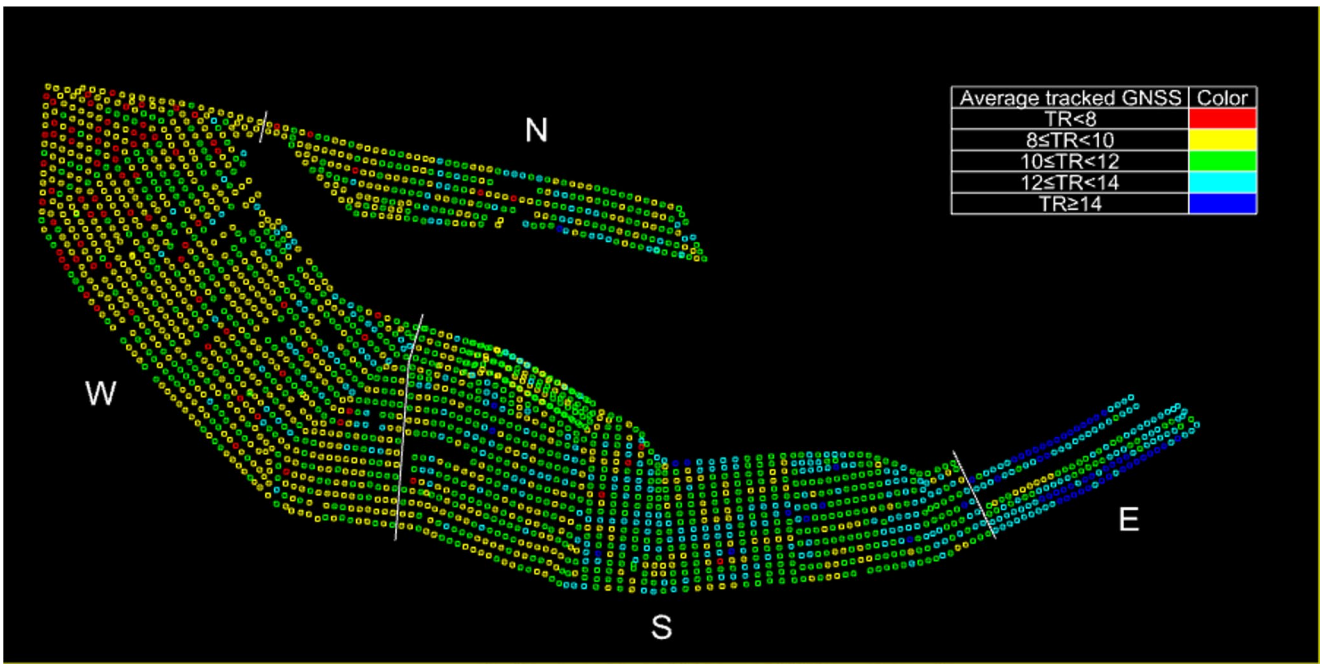


Fig. 6 Average tracked total satellites during drilling on the 420 m bench

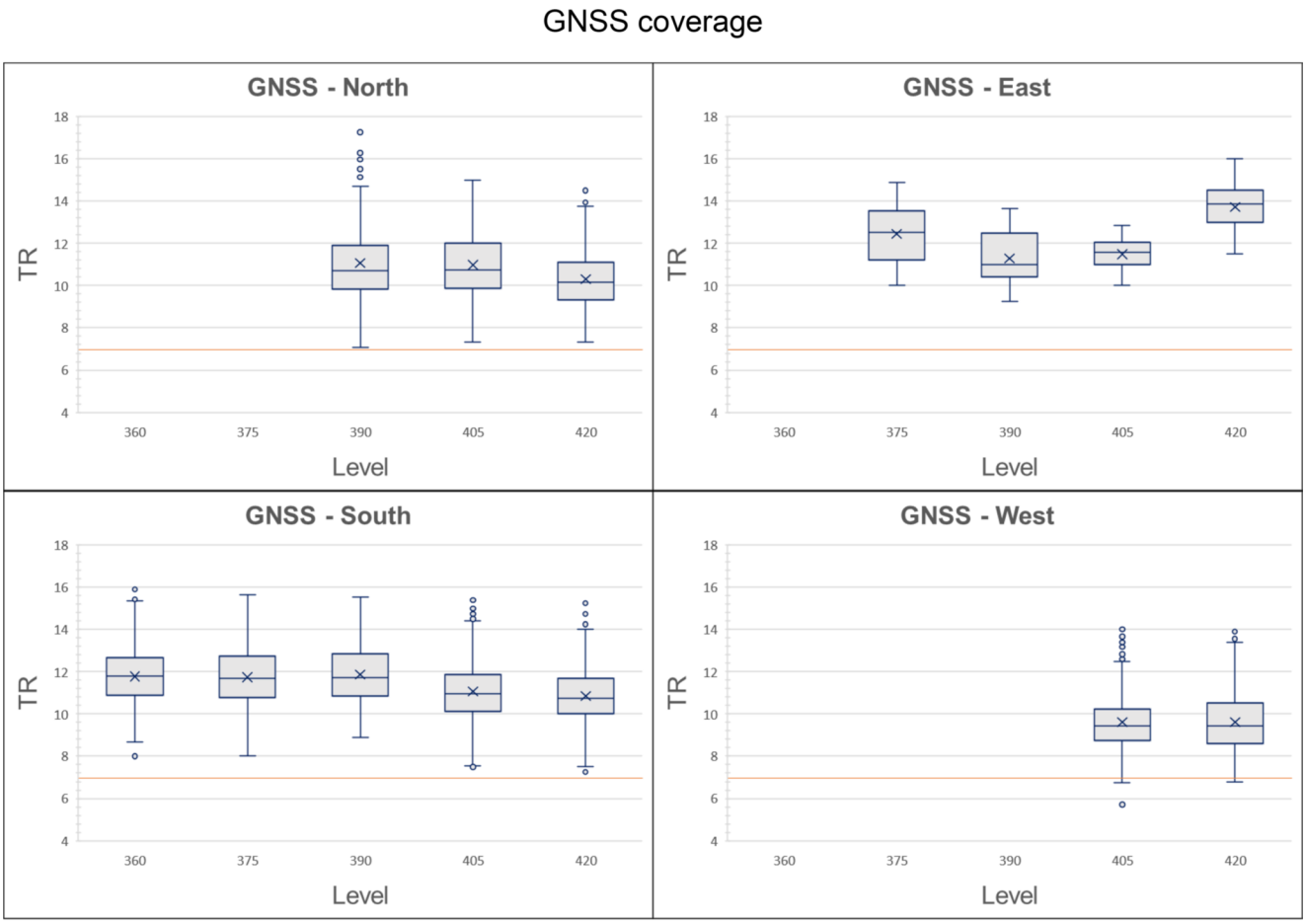


Fig. 7 The distribution of the average tracked satellites (TR) in each part and bench. The red line illustrates the threshold value of necessary satellites for high-precision localisation with a GNSS-only solution. West data is missing for higher benchesThe distribution of the average tracked satellites (TR) in each part and bench. The red line illustrates the threshold value of necessary satellites for high-precision localisation with a GNSS-only solution. West data is missing for higher benches

observation. Considering the variance of the average values, a lack of high-precision localisation can be anticipated to partially occur in the North and South. The East is the area most likely to provide high-precision localisation with a GNSS-based solution.

A deterioration of satellite coverage with increasing depth, and therefore increasing elevation angle, can be observed. However, a larger number of examined depths would be required to quantitively determine the number of fewer tracked satellites per bench, as the statistical variance cannot be calculated from the given data. Nevertheless, based upon the findings, it is likely, that a continuous availability of high precision localisation, as required for automated drilling, cannot be anticipated for upcoming mining operations at lower depths with a GNSS-only positioning solution.

Aitik is more reliant on GPS than on GLONASS, as revealed by a more detailed investigation on the number of detected satellites (e.g. average GPS and GLONASS on 420 m East: 6.9 and 5.9, respectively). Both satellite navigation systems have individual areas of relatively low and high coverage. This illustrates the individuality of each system (i.e. their different satellite ephemerides), leading to the above visualized total satellite distribution.

Overall, the observed spatial pattern of GNSS coverage can be explained directly by the pit geometry. In the western part of Aitik-North, the surrounding slopes restrict the visible sky more strongly and thereby reduce both the number and the geometric distribution of the tracked satellites. In contrast, the eastern part benefits from a comparatively larger open-sky sector and therefore shows a higher satellite availability and more favourable positioning conditions. With increasing mining depth, this geometric restriction becomes more pronounced, so that both the satellite count and the resulting GNSS geometry deteriorate progressively. Consequently, the localisation quality achievable with a GNSS-only solution is not constant across the pit, but degrades as a function of pit geometry, slope proximity and depth.

4.2.2 JPS and its Influence on the Resulting GDOP

The investigation on the complementary JPS positioning system revealed a different relation between the area and strength of coverage. Figure 8 shows the drill holes on the 420 m bench, coloured according to their average tracked LocataLites during drilling.

Whereas most drill holes had an average connection to more than four LocataLites, the East showed the lowest coverage. In this area, the number of on average tracked LocataLites ranged between two and four (yellow dots). This is related to the placement of the LocataLites, which were placed to be best available in the areas of low satellite coverage. The East is not within this area of optimal JPS coverage, i.e. the distance and the angle to the LocataLites from a drill rig is not as optimal as it is in the other parts of Aitik-North, which have worse satellite coverage. The JPS coverage in these areas only differs within the range of statistical deviation. Hence, the JPS coverage is equally good in all areas of Aitik-North with exception of the East. The drill holes with a very low JPS coverage of two or less (red dots) in the South and West were affected by JPS downtime, those in the East reflect genuinely poor JPS coverage.

No correlation between the increase of depth and the JPS coverage was observed as it can be seen in Fig. 9. Furthermore, the importance of JPS in order to achieve good and reliable GDOP values and to compensate varying satellite coverage is illustrated in this Figure. The GDOP values in the different areas and depths is displayed in dependence to the tracked satellites and LocataLites. Disregarding the observed differences in satellite coverage, the variation between the GDOP values in the different areas is minimal. The best localisation accuracy, i.e. the lowest GDOP, was achieved in the South, which profited from both a good JPS and satellite coverage. The East, being the area of best satellite coverage, has overall worse GDOP values. This indicates that the positive effect on the resulting GDOP of an additional LocataLite is generally larger than the one of an additional satellite. This is due to the placement of the LocataLites around the pit, which can be adjusted, in contrast to the satellite ephemerides, which cannot be influenced. An evaluation of the resulting GDOP values at discrete measurement points with each a different GNSS and JPS coverage verified this observation. This investigation was carried out on different drill patterns. It further showed that the minimum number of mandatory LocataLites for an excellent GDOP at low satellite coverage was proven to be four.

4.2.3 Distance to the Slopes

In order to examine the influence of the distance to the slopes on GNSS and JPS coverage, the drill holes in the investigated areas were divided into three groups. Near slope drill holes consist of the row of drill holes closest to the slopes, the outer group consists of the row of drill holes furthest away from the slope. The remaining drill holes situated between those groups compose the middle group. The

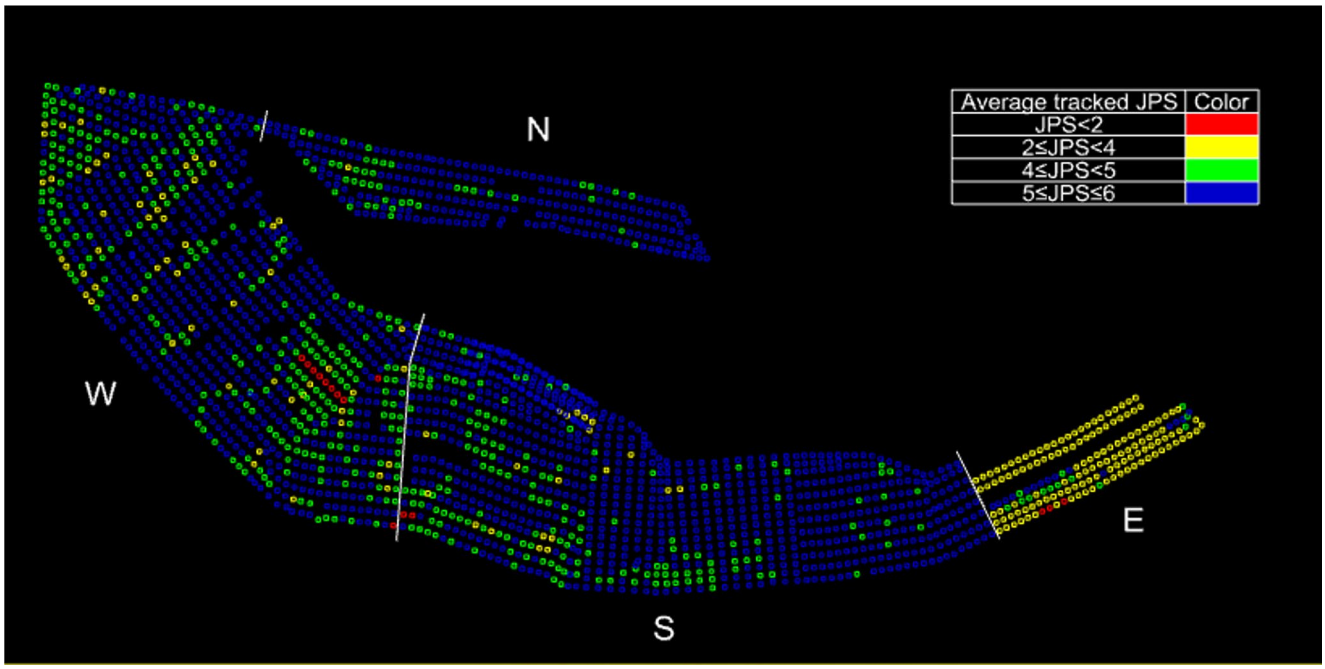


Fig. 8 Average tracked LocataLites during drilling on the 420 m bench, red row in the middle are false measuringsAverage tracked LocataLites during drilling on the 420 m bench, red row in the middle are false measurings

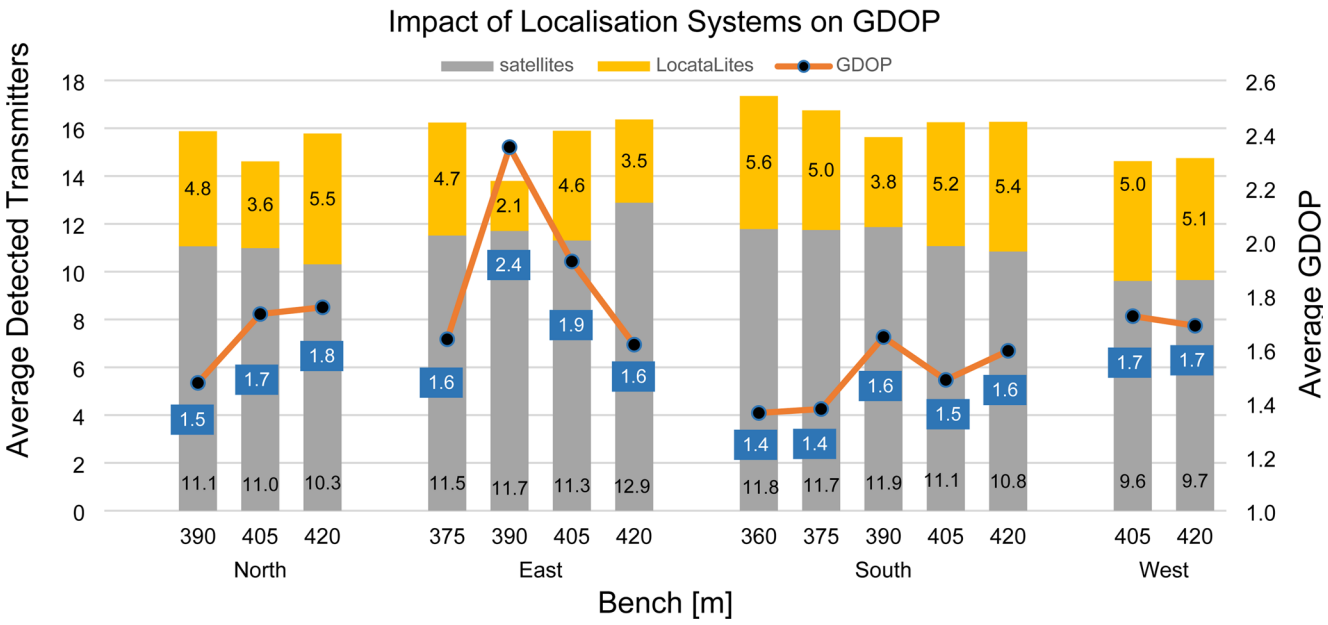


Fig. 9 GDOP in dependence of satellites and LocataLites. The presented values are rounded to the first digit

average number of detected satellites and LocataLites for each group on the 420 m bench is presented in Fig. 10. Due to the geographic particularity of the East being a wider open space, this area is excluded from analysis. A decrease in the number of detected satellites with increasing proximity to the slopes can be observed, as the proximity to slopes leads to a limitation of the visible sky and thus limits the potential number of detected satellites. The magnitude of this decline however depends on the area. As the North has the lowest number of drill rows, the decrease per row is greatest in this region. This is related to the local interramp slope angle, which is steepest in the North and hence with

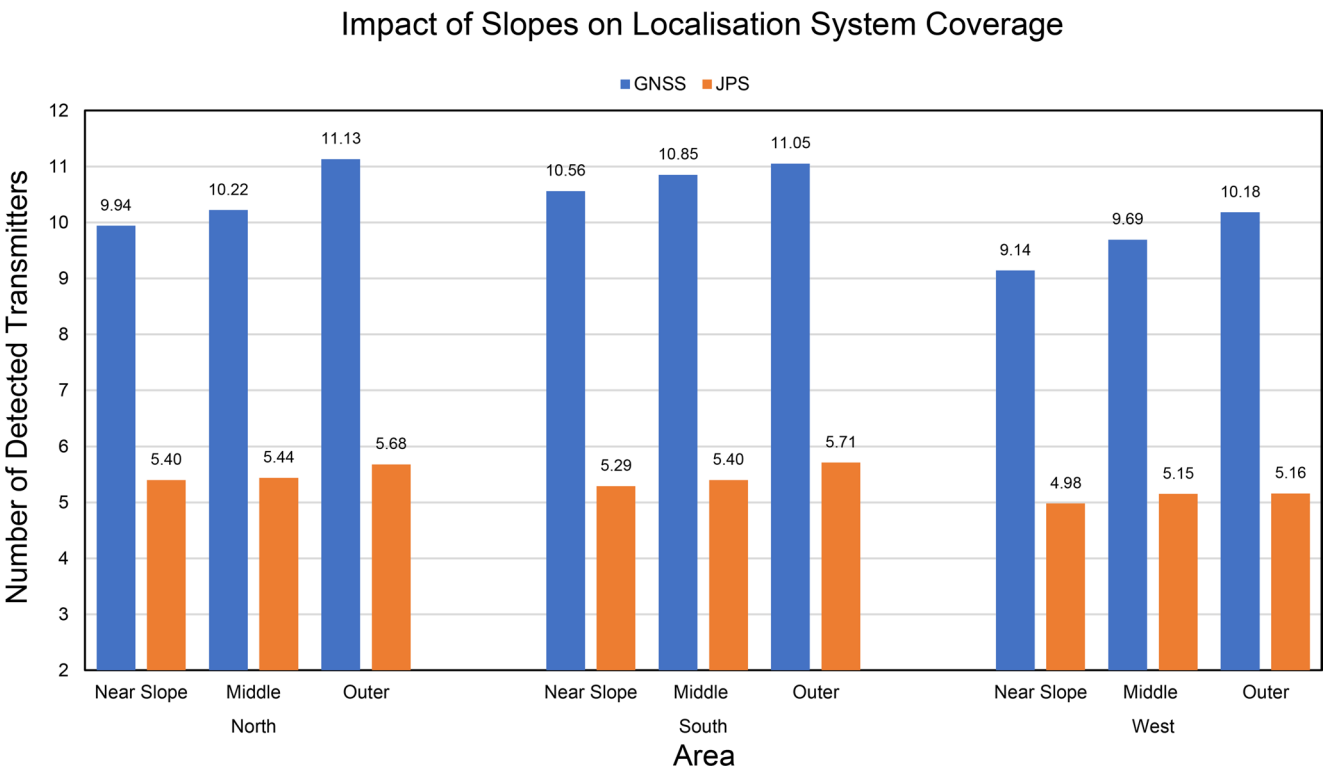


Fig. 10 Average detected satellites and LocataLites on the 420 m bench, in dependence of the distance towards slopes

decreasing distance to the slope the available sky becomes more restricted.

While the satellite coverage in the North at near slope positions equals about 89% of the coverage in the outer group, the JPS coverage near slopes is at about 95% of the coverage in the outer group. The respective values in the West are of the same magnitude with an approximate GNSS coverage of 90% and JPS coverage of 97% at near slope positions. Only in the southern part, the relative decline of average detected LocataLites near slopes is greater than of the detected satellites: the relative GNSS and JPS coverage at near slope positions is 96% and 93%, respectively. Hence, the effect of the slopes on JPS coverage is not as notable as it is on GNSS coverage in most positions of Aitik-North.

5 Conclusion

A highly robust and accurate localisation system with high availability ("high-precision localisation") is the backbone of any mobile and location-based automation process, such as drilling. In particular, drilling is a vital part of an efficient mining operation, and high-precision localisation, and thus the resulting positioning of drill rigs, constitutes a controllable and easily measurable performance parameter that can be maintained at a high level. GDOP was identified as the main parameter for evaluating localisation quality.

In addition, external influencing factors on localisation quality, including weather, date and time, and factors related to the position of the receiver, such as the relative position within the pit, depth and distance to the slopes were identified to be relevant. To fulfil the high-precision localisation requirements in combination with the corrected signal, the maximum GDOP value was determined to be 8, which in most cases correlates to 7 detected satellites. Different data sets have been collected for processing and analysis. In addition to GNNS recordings outside the pit, the localisation and process data of around 6300 drilled holes from the drill rigs were used.

The key results regarding the influence of the external factors can be described as follows: the coverage of the localisation system is robust with respect to weather conditions with mean values of 8–12 satellites (depending on the area of the bench) but varies regularly around the year and under different weather conditions with 7 satellites. This can lead to a low localisation (min. of 7 satellites) quality if the number of satellites and LocataLites is not high enough.

The key results regarding the positioning factors are: the quality of the localisation signal is found to be very dependent on the position within the pit. Different characteristics were found for four different geographic areas in the pit. The GNSS and JPS coverage was shown to have different areas of relatively high and low coverage: whereas, the quality of JPS mainly depends on and can be managed by the placement of the LocataLites, GNSS coverage is affected by the distance to the slopes and the depth. With decreasing distance to the slopes, the open surrounding space of a position is lowered and thus potentially less satellites are detected. The same effect occurs with increasing depth. JPS coverage was shown to be not affected by these factors.

Considering the above findings, the availability of JPS becomes increasingly essential with increasing depth of the mine to compensate for the decreasing number of visible satellites. The placement of the LocataLites is therefore of major importance to ensure that stable GDOP values are achievable throughout Aitik-North. This includes those areas with especially low satellite coverage, such as near slope positions or the western parts of the pit.

From a technical perspective, the results show that GNSS alone becomes increasingly limited with advancing pit depth and slope shadowing, because both factors reduce satellite visibility and worsen the positioning geometry. Although DGPS/RTK improves the achievable positioning accuracy by correcting common ranging errors, it cannot fully compensate for an unfavourable satellite constellation. The complementary JPS therefore plays a decisive role in maintaining robust high-precision localisation in the deeper and more geometrically restricted parts of the mine.

In summary, the Aitik pit fulfills the requirements of high-precision availability at future operations with the additional JPS localisation signal. Boliden proceeded in drilling automation that is fully introduced by today, contributing to the highly efficient operations far up north.

Overall, this paper shows how a study on GNSS and the integration of complementary localisation infrastructure can be conducted. This kind of research is of interest when an ongoing development of automation in a mining environment is confronted with an increase in mining depth and thus a potential shortcoming of localisation signals. Furthermore, this procedure can help in deciding whether additional localisation infrastructure for pit automation is required and in determining the appropriate timing of such an investment.

Funding Open Access funding enabled and organized by Projekt DEAL.

Data Availability The operational data used in this study are not publicly available.

Declarations

Conflict of Interest There is no conflict of interest.

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