smartrail4.0

Integrity Measures and Verification for Train Localisation

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1 Management Summary

When train localisation systems, such as existing odometry or future multi sensor systems, have to be evaluated for accuracy, reliability and safety, it is necessary to have an independent data source which generates highly accurate and reliable reference positions and timestamps. Such a data source is called a *ground truth*. The requirement for this ground truth is typically to be one order of magnitude more exact than the localisation system under consideration.

In this report we will address the challenge of generating such a dataset. We take advantage of the fact that a train is always running on a track for which an accurate and up-to-date digital map is available. By comparing map features on the planned route with the estimation results of a highly accurate inertial navigation system we can find discrepancies between these two independent data sources. Such discrepancies are called integrity violations. In such a case we can discard that data point, guaranteeing that we only have accurate data points with integrity in our Ground Truth dataset. We have analysed over two years of data from the SBB telecom measurement wagon MEWA12, which covers most of the Swiss normal gauge track network each year. The MEWA12 carries a highly precise inertial navigation system for localisation. With the here presented integrity monitoring approach it is possible to verify these data points.

Results show that of the recorded data points 92% had full integrity and can therefore be used for a ground truth dataset. As long as certain track selectivity criteria are fulfilled the integrity algorithm is track selective and the lateral error is $0m$. To filter out errors along the track a maximum distance error between two data points of is $0.9m$ specified. This enables the detection of single measurement outliers and results in a high relative accuracy of the integrity checked data points.

The generated ground truth data makes it possible to check other localisation information such as odometry based ETCS train position reports or new sensors in the railway environment, such as GNSS receivers, for accuracy, reliability and availability. This will provide valuable information for the improvement of existing localisation systems (e.g. odometry today in use with ETCS would benefit from further improvement) and the development of future localisation systems. It will in particular enable performance and safety evaluations of these systems.

2 Introduction

In ETCS Level 2 and ETCS Level 3 railway transportation systems it is necessary to provide real-time localisation information, in order to check whether the front-end of a train is within a given movement authority (MA). In the currently used ETCS Level 2 systems this is done through Train Position Reports (TPRs) that include the distance to a last relevant balise group (LRBG) measured by an odometry system. Installing and maintaining these balise groups as well as the trackside train detection systems is cost intensive and therefore undesirable. Hence, a major goal in ETCS Level 3 and the Swiss railway innovation project smartrail 4.0

is to reduce the need for track side equipment by 70% in the long term, what requires the use of a train borne localisation unit. This train borne localisation unit has to fulfil safety integrity level 4 (SIL 4) requirements, which means that the tolerable hazard rate has to be bellow $10^{-9}/h$. Thus, the accuracy and reliability of any future train borne localisation system has to be thoroughly assessed using a highly accurate and highly available reference measurement. This reference measurement has to include the used railway track, a position along that track, as well as accurate timestamps. We call such a reference measurement the ground truth. Such a dataset will allow an evaluation of both the currently used localisation system based on odometry and Eurobalise positions, as well as any future train borne localisation systems.

While evaluating different localisation sensor systems in our previous reports [1, 2], the availability, reliability and accuracy of a ground truth dataset has been identified as a major challenge and some ideas have been presented how to use an inertial navigation system to this end. To the best of our knowledge the generation of ground truth data by integrity monitoring has not yet been studied in depth in the literature. There exist however approaches to map-based integrity monitoring of train localisation systems. These have been mainly focused on geometric constraints either using the known route on the track [3] or determining the route online [4]. Using the yaw angle for integrity monitoring has been studied in [5]. An analysis of train motion and railway track characteristics with inertial sensors is presented in [6]. A train localisation solution combining GNSS and INS measurement in a Bayesian framework is presented in [7]. The paper only evaluates track selectivity but not along track accuracy due to a missing longitudinal ground truth.

Evolving on these ideas, in this report we will present a methodology to address this challenge by using a highly accurate inertial navigation system (INS), which is aided by a Global Navigation Satellite System (GNSS) receiver and odometry measurements. We will compare the INS estimates with track features in order to compute different measures of integrity. This allows us to only use reference points as ground truth that fulfil these integrity criteria, resulting in a highly reliable and accurate dataset that is available on most of the Swiss normal gauge railway network

3 Methodology

3.1 Coordinate Systems

Figure 1 shows the coordinate systems used in this report. The coordinate systems will be denoted by an exponent e, n or b when used to describe variables (i.e. v_x^n for a velocity component in north direction).

The first coordinate frame in use is the **earth-centred earth-fixed (ECEF) frame (e)**, which has its origin in the centre of the earth, its x-axis pointing towards the prime meridian, its z-axis pointing towards the north pole. The y-axis is constructed using the right-hand rule.

If we want to describe a section of railway track, a local flat coordinate system is useful. This coordinate system is called the **navigation or north-east-down frame (n)**. Its origin is a point on the earth's surface,

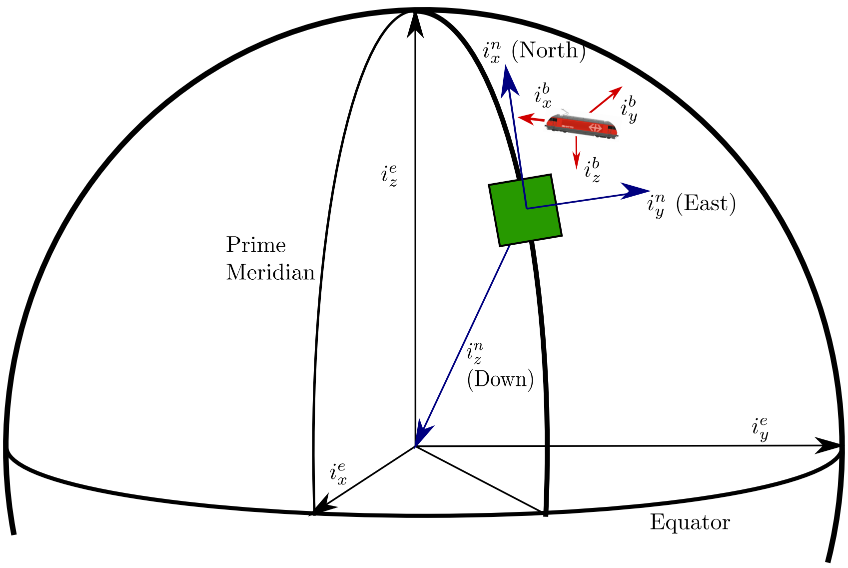

Figure 1: Coordinate Systems

i.e. the starting point of a train journey, its x-axis is pointing towards north pole, its y-axis towards east and the z-axis towards the centre of the earth. Note that both these coordinate frames are regarded as inertial frames, meaning that they are static and do not move with the vehicle.

The third coordinate frame regarded is the **body frame (b)**. This frame is attached to the moving train, often the front end of the train is chosen. In our case the origin of the body frame is defined as the position of the inertial measurement unit, which is mounted close to the centre of gravity of the measurement coach, making lever arm effect negligible. The x-axis of the body frame is pointing along the longitudinal axis of the train in moving direction, the z – axis is pointing downwards, and the y-axis is constructed using the right-hand rule.

3.2 Attitude and Track Geometry

The attitude of the train is defined through the Euler angles, roll (ϕ), pitch (θ) and yaw (ψ), which describe the rotation between the navigation frame and the body frame. Figure 2 shows the definition of the yaw angle as the angle between the x-axis in body frame i_x^b, projected onto the north – east plane, and the north direction i_x^n.

While the yaw angle ψ_d obtained from the database is defined as the angle between the local tangent and North, the Inertial Measurement Unit (IMU) on the SBB Telecommunications Measurement wagon MEWA12 is mounted in the carriage and not in the bogie. In turns, there is a rotation between the bogie and the carriage, leading to a difference in the yaw angle between the track database value and the IMU measurement. We are compensating for this effect following the description in [8] and define the track yaw angle as follows:

$$\psi_t = \psi_d + sin^{-1}\left(\kappa\frac{l}{2}\right) \tag{1}$$

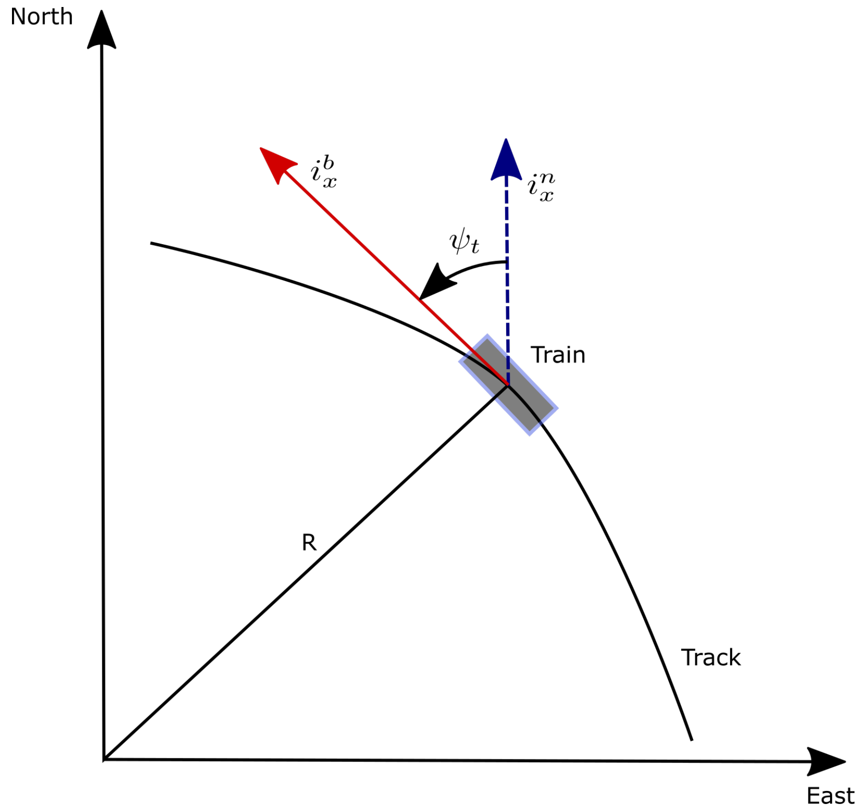

Figure 2: Definition of Yaw Angle and Curve Radius

Where κ is the track curvature, defined as the inverse of the curve radius R, and l is the distance between the two bogies of the MEWA12 carriage.

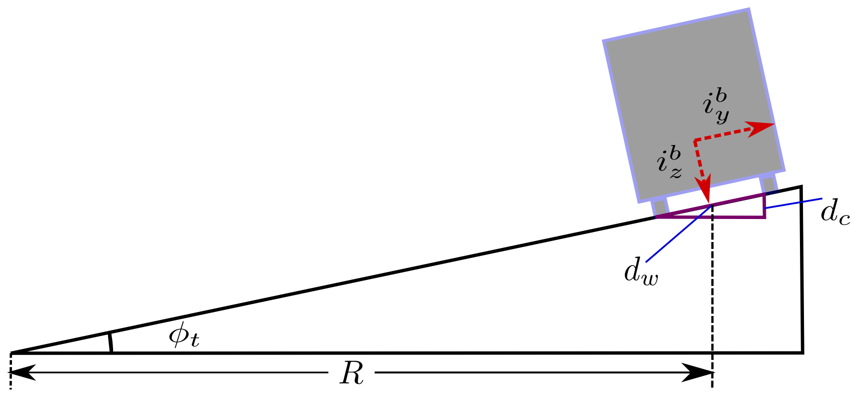

Figure 3: Definition of roll angle and cant

In Figure 3 the relationship between cant d_c, track width d_w, curve radius R and roll angle ϕ is shown. Since the train wagon is moving on a certain track, the roll angle ϕ_t of the vehicle can be calculated from the track's features as follows:

$$\phi_t = sin^{(-1)}\left(d_c/d_w\right) \tag{2}$$

In Figure 4 the definition of the pitch angle and the inclination is shown. The inclination d_h is normally given in per mill in the railway context. This denotes the change in height over a certain distance and can be

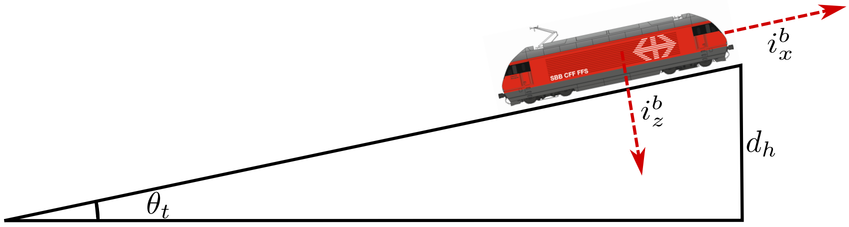

Figure 4: Definition of pitch angle and inclination

converted to a pitch angle as follows:

$$\theta_t = \tan^{-1}\left(\frac{d_h}{1000}\right) \tag{3}$$

3.3 High precision Inertial Navigation System (INS)

We are using a high precision IMU, which in combination with wheel odometry and a GNSS receiver, is able to estimate the attitude angles, its position in the ECEF frame and its speed along the track. The iMAR iNAT-RQT IMU used, is a ring laser gyro-based INS with MEMS accelerometers, a multi-frequency GNSS receiver and a wheel odometer. This sensor information is combined in an Extended Kalman Filter (EKF) to estimate the needed variables. It is important to note, that attitude, position and velocity are estimated simultaneously. This means that measurement errors in e.g. GNSS can appear in all estimated variables depending on the tuning of the EKF. The accuracies of the estimated variables, as stated by the manufacturer, are summarized in Table 1. In contrast to a classical odometry system, the accuracies are generally independent of the distance driven. Note that IMU calibration and GNSS reception are necessary to achieve these accuracies. For more information on the accuracies and drift we refer to the datasheet [9].

This INS is installed onboard the MEWA12, which is frequently used for SBB maintenance and certification surveys regarding railway telecommunication coverage. Therefore, it covers a large part of the Swiss normal gauge track network every year.

Table 1: INS accuracy [9]

Variable	**Accuracy**
Attitude Angles	$< 0.01^\circ$
Position	$< 1.6m$
Velocity	$< 5mm/s$

3.4 Data Pre-processing

We use the SBB Databases ANABEL and UNO to get the track features for a specific train run. First, we get from ANABEL a series of track elements the train has passed along its run. These track elements are trajectory segments specified as linestrings, taken from the SBB database DfA. These segments are used to construct the complete trajectory the train has taken. As shown in Figure 5 sometimes segments are missing resulting in gaps in the trajectory.

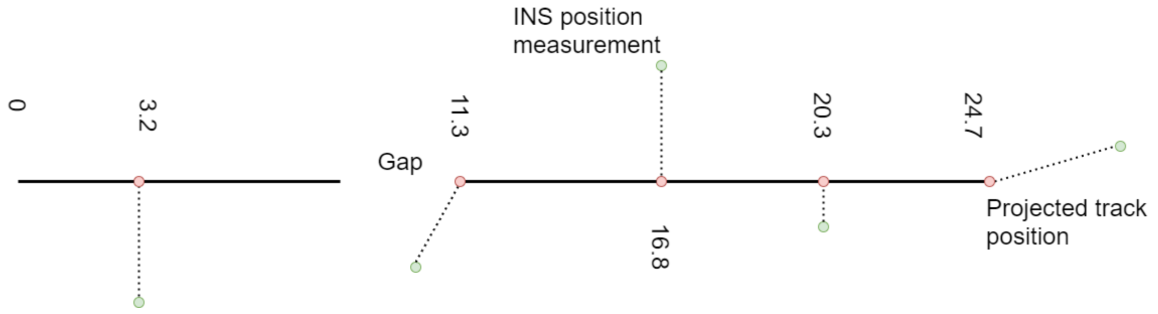

Figure 5: Matching Sensor Position and Track

We then project each position measurement of the INS onto the closest point on the trajectory. These projected points are called track points. In case of gaps the projected point will be either the end of the previous segment or the beginning of the next segment. This results in one or more INS position measurements being projected onto a wrong track point. Therefore, we have to use an integrity algorithm to detect these errors and identify the associated sensor data points and track points.

Afterwards we calculate the kilometrage along the trajectory from the start of mission for each of these track points. The result is a series of track points with kilometrage and timestamp for the regarded train run.

In addition, ANABEL supplies us with the IDs of the track edges the measurement train has passed. Based on this information, we use the database UNO to find the track features rail cant, inclination, curve radius and yaw angle for each track point. UNO provides this information at 10m intervals on each track edge. For each track point we find the closest UNO point, as shown in Figure 6. In case of ANABEL gaps the closest UNO point might not be on the current ANABEL track segment but in a gap. There can also be small errors between the DfA linestrings and the UNO points due to different representations of track elements, such as switches.

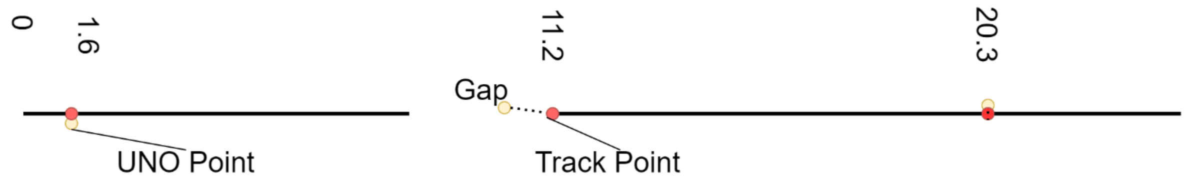

Figure 6: Matching Track and UNO Points

UNO uses a node – edge model to specify the track topology. For each edge a direction is specified, and the track features are defined along the edge direction. Therefore, we have to take the relationship between the driving and edge directions into account and compensate for that. If the driving direction and edge direction are opposite, the signs of the rail cant, inclination and curve radius have to be inverted and the yaw angle has to be rotated by 180 degrees.

Furthermore, unlike a car or an aeroplane the MEWA12 wagon does not have a predefined movement direction, as it can move in both directions indiscriminately. As mentioned in section 3.1 we define the x-axis in body frame as the forward movement direction, hence we are detecting the movement direction based on the wheel odometer and correct the attitude angles provided by the INS accordingly.

3.5 Integrity Measures

The goal of the integrity algorithm is to check for mismatches between the track features and the INS estimates. These mismatches can have different origins:

- Wrong track segments provided by the ANABEL database
- Wrong track features provided by the UNO or DfA database
- Measurement errors in the INS sensors leading to wrong position, velocity or attitude estimates
- Wrong calibration or mounting of the INS leading to faulty estimates

If we can detect these errors, we can exclude the affected track points from the ground truth dataset and increase the reliability and accuracy of the desired dataset. In the following we will define a set of integrity measures based on different indicators. In order to separate the different indicators, we will encode the different integrity measures with integrity values. These values are powers of 2. All integrity indicators are zero if the criterion is fulfilled and equal to their integrity value if it is not fulfilled.

3.5.1 Attitude based Integrity

In [5] an approach to finding GNSS errors by comparing the train yaw angle against the track yaw angle was presented. We build up on that approach but compare all three attitude angles calculated from the track features as described in section 3.2 with the attitude estimates of INS. We use the following criteria for roll integrity:

$$|\phi_{INS} - \phi_t| < 3\sigma_\phi \tag{4}$$

Where ϕ_{INS} is the roll angle estimated by the INS and ϕ_t is the track roll angle calculated using (2). If the criterion is not fulfilled for a track data point an integrity value $I_\phi = 1$ is associated with that point. Else the value is zero. The standard deviation of the measurement error σ_ϕ is calculated over one day of train operations:

$$\sigma_\phi = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left(e_\phi - \bar{e}_\phi\right)^2} \tag{5}$$

The roll error e_ϕ and the mean roll error $\bar{e}_\phi$ are defined as:

$$e_\phi = \phi_{INS} - \phi_t \tag{6}$$

$$\bar{e}_\phi = \frac{1}{N}\sum_{i=1}^{N} \phi_{INS} - \phi_t \tag{7}$$

Where N is the number of samples measured in an operating day. In some cases, the standard deviation can be distorted, due to unavailable track data. Therefore, we set an upper limit of $\sigma_\phi < 0.6^\circ$ and filter the input data for large outliers. This is done similarly for all other integrity indicators. This approach has two benefits:

- The statistical properties of the integrity detection (false-positive and false-negative rate) are static and do not depend on the operating conditions. This improves both availability and robustness of the integrity detection by using flexible thresholds.

- A maximum integrity threshold can be set, so that missing track data does not distort the detection.

The pitch and yaw integrity indicators have integrity values $\theta = 2$ and $I_\psi = 4$. The upper limits for the standard deviations are $\sigma_\theta < 0.12^\circ$ and $\sigma_\psi < 1^\circ$. These upper limits were found through data analysis of timespans without outliers.

3.5.2 Curvature based Integrity

If we assume that a train moving on a curve is following a circular motion the following relationship between curvature κ, the angular rate around the body z-axis ω_z^b and the train speed v holds:

$$\kappa_{INS} = \frac{1}{R} = \frac{cos\phi\,\omega_z^b}{v} \tag{8}$$

Note that the track radius is defined in the horizontal plane, therefore we need to compensate for the roll angle (see Figure 2). We are using track curvature and not the track radius to avoid infinite values on straight track segments. The curvature-based integrity measure is then calculated as

$$|\kappa_{INS} - \kappa_t| < 3\sigma_\kappa \tag{9}$$

The associated integrity value is $I_\kappa = 8$ if the criterion is not fulfilled and else zero. Again, we set an upper limit $\sigma_\kappa < 0.051/m$.

3.5.3 Longitudinal Integrity

An indication for along-track integrity is the difference between the train velocity and the calculated kilometrage of the track points. The distance between two track points can be calculated as follows

$$\Delta s_{ODO} = v\Delta t \tag{10}$$

Where v is the mean speed between the two points. This distance is compared to the difference of the projected track points Δs_t with the following criterion:

$$|\Delta s_{ODO} - \Delta s_t| < 3\sigma_s \tag{11}$$

$$\sigma_s < 0.3m \tag{12}$$

The associated integrity value is $I_s = 16$ if the criterion is not fulfilled and else zero. Note that this integrity indicator has some limitations, since Δs_t is based on the fused position estimate of the GNSS, odometer and accelerometer measurements. Consequently, Δs_{ODO} and Δs_t are not fully independent and certain errors can appear in both terms. Therefore, odometer errors due to i.e. slip and slide phenomena cannot be reliably detected. The occurrence of these errors is however assumed to be rare, since the odometer is installed on an unpowered axle and thus can only occur during breaking. This integrity measure is still able to detect along track GNSS outliers which disturb the INS solution.

3.5.4 Geometry-based Integrity

For lateral integrity we use the distance between the estimated INS position and the projected track point as shown in Figure 5. Since that error has a single sided distribution, a standard deviation can not be calculated using (5). Therefore, we use the root mean square error (RMSE) , denoted as σ_p, instead. The minimum distance between two adjacent tracks of $3.6m$ [10] is used as an upper limit for the integrity threshold. This provides limited track selectivity. A more strict limit would be desirable to ensure full track selectivity but is currently not possible due to the limited accuracy of the GNSS receiver used in the INS. A more detailed discussion of track selectivity follows in section 4.7.2

$$||\boldsymbol{p}_{INS} - \boldsymbol{p}_t|| < \sigma_p \tag{13}$$

Where $\boldsymbol{p}_{INS}$ is the INS position estimate and $\boldsymbol{p}_t$ is the corresponding track point (see Figure 5). The associated integrity value is $I_c = 32$ if the criterion is not fulfilled and else zero.

3.6 Total Integrity

The total integrity is the sum of the integrity values of the different criteria

$$I = I_\phi + I_\theta + I_\psi + I_\kappa + I_s + I_c \tag{14}$$

with a minimum value of 0, if the point has full integrity, and a maximum value of 63, if all integrity measures indicate a discrepancy. Depending on the application the user can now choose to only allow reference points with full integrity or relax the constraint and allow certain discrepancies. The result is a series of track points with exact INS timestamps which fulfil the integrity criteria and can be used as a ground truth.

4 Results and Discussion

As an example, we will use a train run from Domodossola (Italy) to Spiez (Switzerland) to demonstrate the use of the above defined integrity measures. The train run, shown in Figure 7, was chosen because it is especially challenging due to numerous tunnels, some of them helical tunnels, and poor GNSS coverage in the mountainous regions. The Swiss track part is operated by two different railway infrastructure managers, SBB and BLS. For the Italian part of the track no track data is available. Therefore, all sensor values are projected onto the closest available track point on the boarder to the Swiss network at the south end of the Simplon tunnel. These sensor position estimates and track points have to be identified as having no integrity by the integrity measures.

4.1 Attitude Angles

Figures 8 to 10 show the differences between the roll, pitch and yaw angles provided by the track database for the regarded train run and the INS estimate for a short timeframe and the integrity thresholds used. This window is on the section between Brig and Goppenstein and was chosen to illustrate the typical variations encountered. In addition we specify the minimum and maximum values of the track attitude angles over the entire train run. In general, the angles match very well, and errors are small.

For the roll error frequent errors of about one degree can be seen. This is due to the IMU being mounted in the carriage and not in the bogie. Due to the springs and dampeners in between the carriage and the bogie the carriage does not bank as much as one would expect from the track features leading to these errors. This is mainly visible on quick changes of direction as it is common on the “Lötschberg” line. This leads to some false positive integrity violations. These have to be accepted in order to achieve a high true-positive rate. The pitch angle shows the smallest variations over time of the three attitude angles. However, since the INS pitch angle is very sensitive to these small changes and follows the track pitch angle very closely it is still a valuable integrity indicator. The yaw angle shows the greatest amount of excitation and is therefore very suitable to

Figure 7: Train run from Domodossola to Spiez

detect losses of integrity. Track and INS yaw angle match very closely.

4.2 Curvature

Figure 11 shows the error between the track curvature and the curvature measured by the INS. For a normal gauge railway track the range of the curvature is typically quite small. The two signals match each other very well with small errors. This shows that it is possible to measure curvature accurately using the INS data. The benefit of this measure compared to the attitude is, that it is possible to distinguish between two parallel running tracks in curves because the track radii are different.

4.3 Longitudinal Integrity

In Figure 12 the error between the distance calculated from the track points and the velocity-based distance is shown. Notably, the error is below $0.25m$ for the entire window, but for one data point that exceeds the threshold. This indicates, that the point to point longitudinal distance is typically very precise but can have occasional outliers due to e.g. GNSS outliers or slip and slide phenomena.

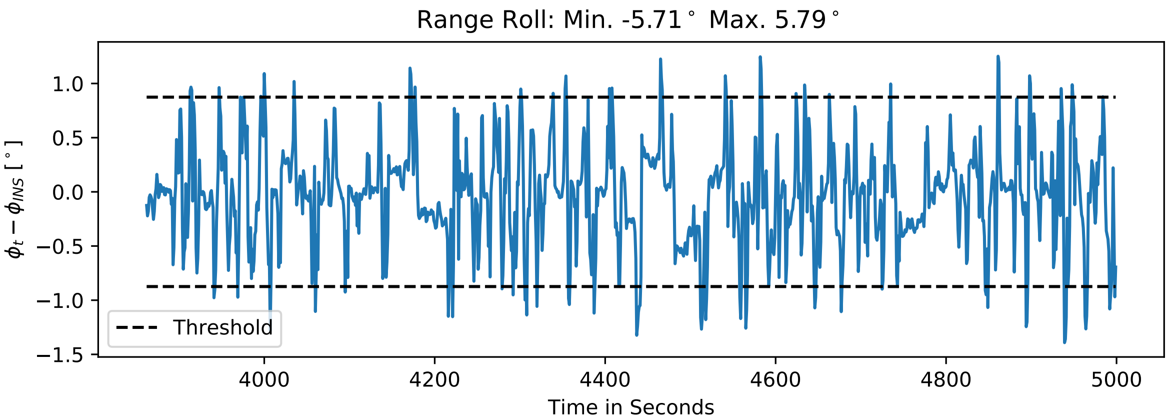

Figure 8: Error between track and INS roll angle

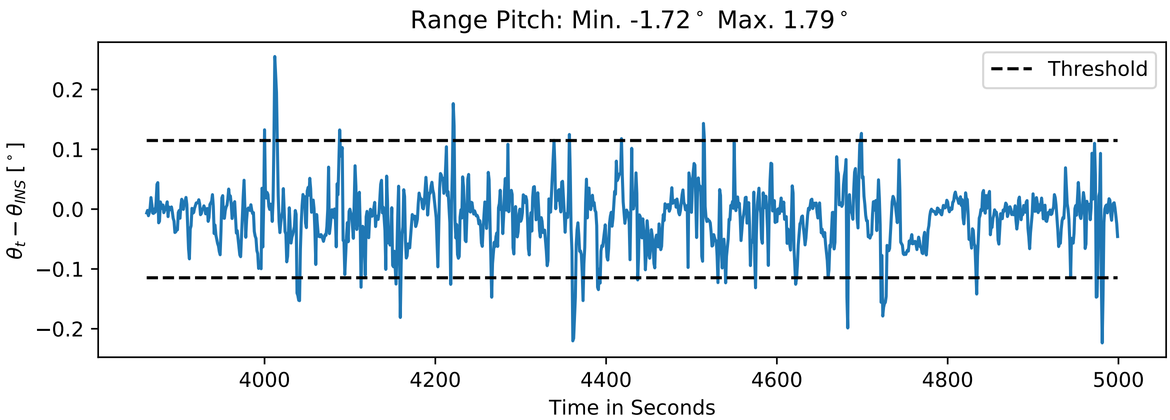

Figure 9: Error between track and INS pitch angle

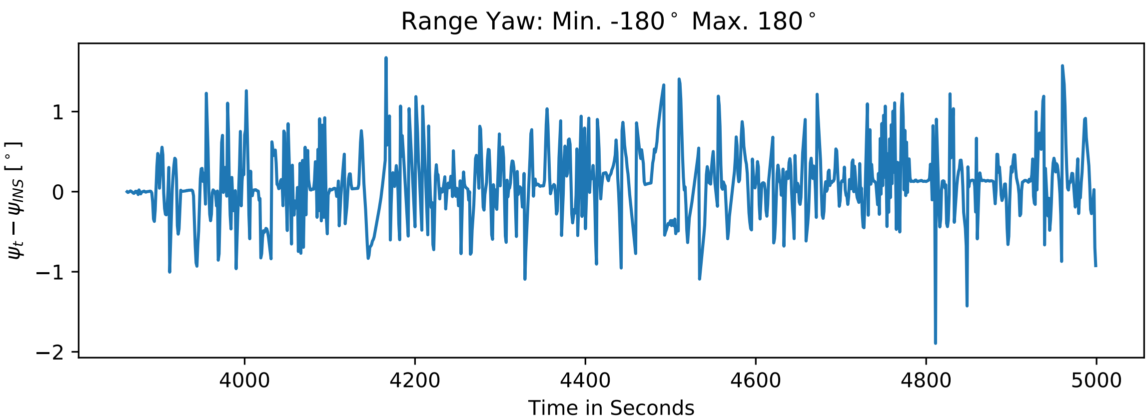

Figure 10: Error between track and INS yaw angle

4.4 Geometry-based Integrity

The error between INS position estimate and track point shown in Figure 13, which is typically the lateral error, is well within the threshold. The error is in the same range as the accuracy specified for the iNAT-RQT in the datasheet [9].

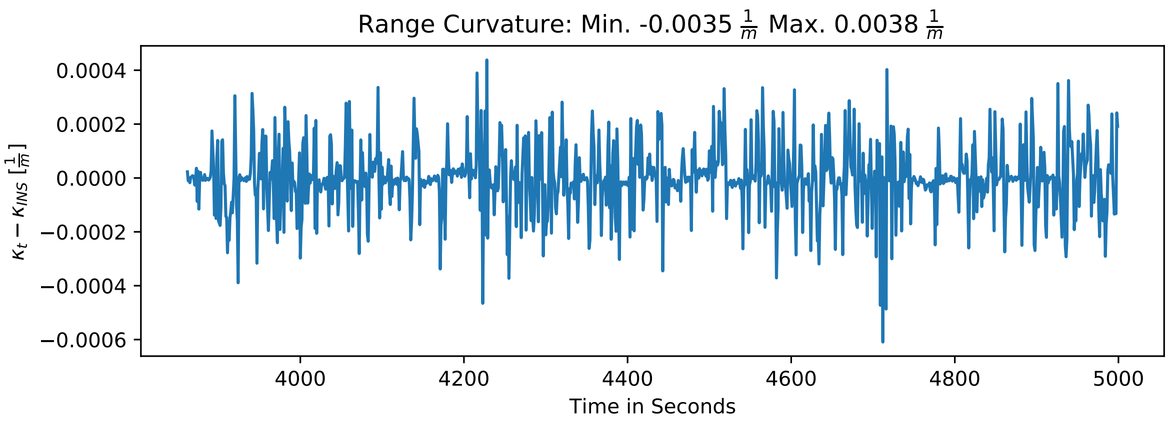

Figure 11: Error between track and INS curvature

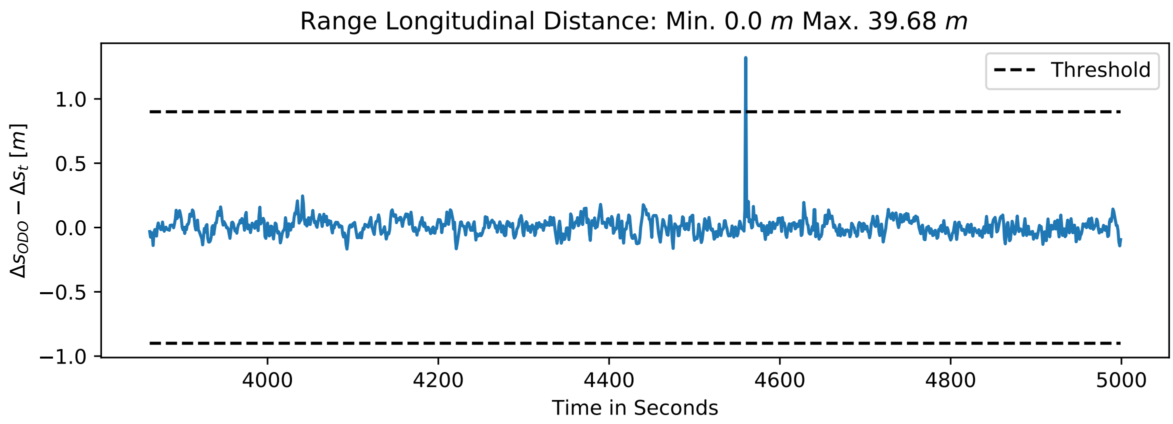

Figure 12: Error between track and INS distance

4.5 Correlation Analysis

In order to analyse the along track accuracy of the above presented integrity measured, we did a correlation analysis. The normalized cross correlation between the track and INS signals is calculated using the Numpy Python library. This shifts the signals against each other sample by sample and calculates the correlation coefficient for each point, giving a measure of similarity. The results of that analysis can be seen in Figure 14. One can see that for all four signals the maximum correlation is achieved at zero displacement. The peaks are sharpest for the roll and curvature correlations, indicating good longitudinal selectivity. For the pitch and yaw correlations, the peak at zero is less pronounced.

4.6 Integrity

Figure 15 shows the total integrity over the driven distance for the above described train run. The meaning of the integrity values and their thresholds are shown in Table 2. The number of simultaneously occurring integrity violations is shown in Figure 16.

As can be seen, the integrity is above zero for the entire Italian part of the train run where no track data

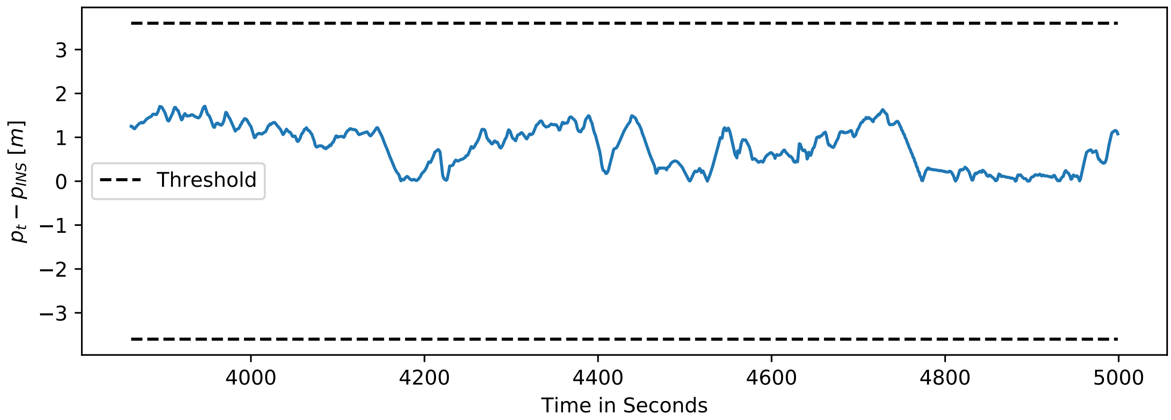

Figure 13: Error between track and INS position

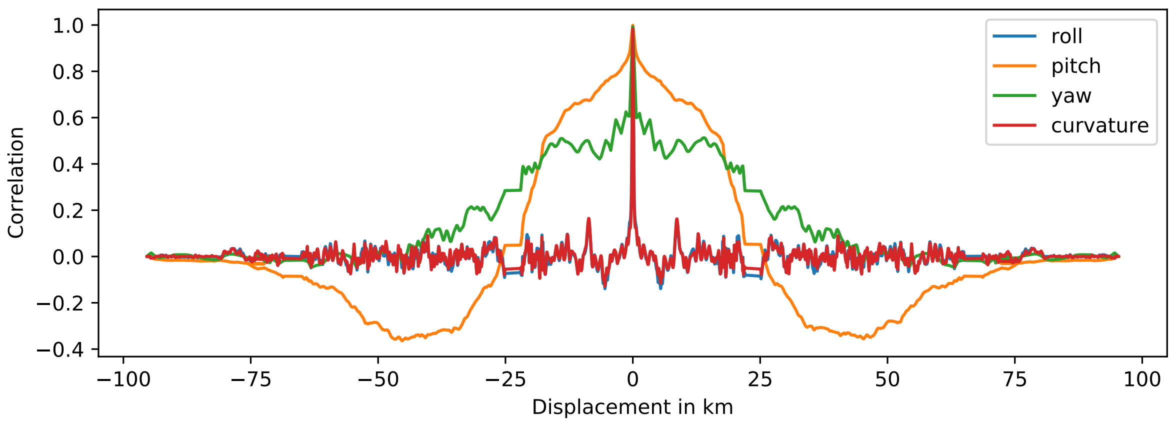

Figure 14: Correlation of roll, pitch, yaw and curvature signals of track and INS

is available and the sensor positions are mapped onto the closest Swiss track point. Notably, this is not only detected by the distance to the track point (value 32) but also by other indicators. More than three different integrity violation are detected on the Italian track section at all times, so that this segment can be easily excluded from a ground truth dataset. Note that the presence of the Italian segment in this train run results in a very high number of integrity violation which is not typically the case for purely Swiss train runs.

On the Swiss track section, the roll and pitch integrity indicators as well as longitudinal integrity indicator set alarms frequently. The roll integrity violations are a result of overall small error standard deviations. This leads to small thresholds, which are violated by the banking of the wagon in fast changes of direction. This is also visible in the histogram shown in Figure 17. The longitudinal integrity violations are mostly due to GNSS/INS outliers but can also be caused by slip and slide phenomena due to braking, resulting in odometry errors. There is also one data point that raises several integrity alarms. This point is wrongly projected onto a track point which has the same longitude and latitude but different altitude due to the helical tunnels. This is a result of the 2D mapping algorithm and will be addressed in the future. However, this is not of too great concern since those points can be easily detected by the integrity algorithm.

Table 2: Integrity Values

Integrity Value	Integrity Indicator	Integrity Threshold
0	No fault	-
1	Roll Integrity	$0.96°$
2	Pitch Integrity	$0.11°$
4	Yaw Integrity	$3°$
8	Curvature Integrity	$0.11m^{-1}$
16	Longitudinal Integrity	$0.2m$
32	Geometry-based Integrity	$3.6m$

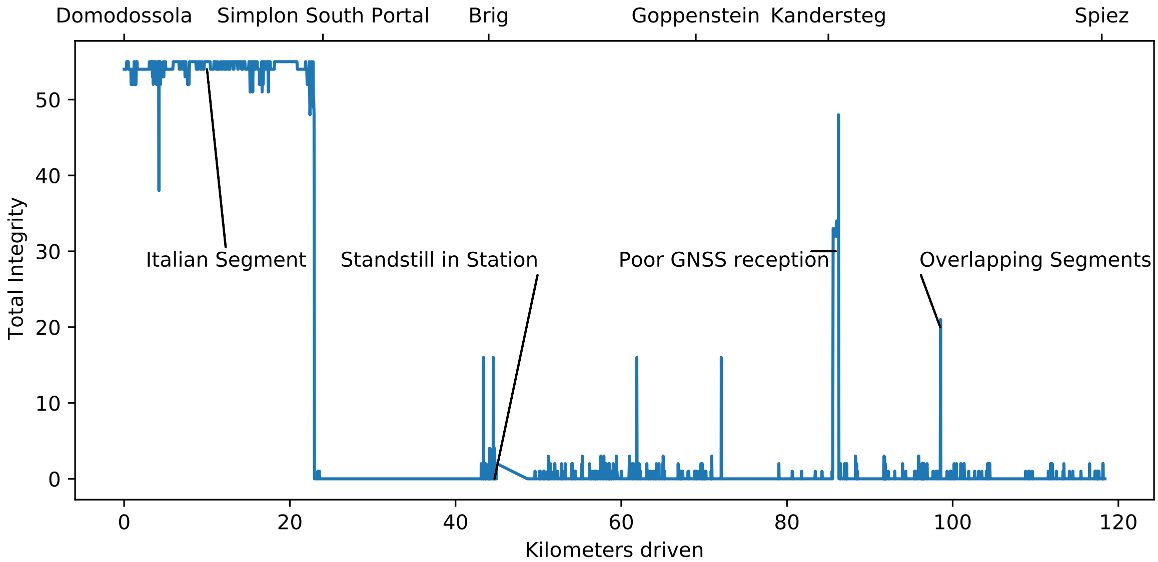

Figure 15: Integrity Values over Distance

The locations of the data points with non-zero integrity values are shown on a map in Figure 18. The roll and pitch integrity flags have been hidden for clarity. As discussed before all data points without corresponding track data are correctly identified as not having integrity. There is one segment on the "Lötschberg" line which has poor GNSS reception where the sensor points deviate from the track. This results in several violations of the geometry-based integrity constraint. In addition, integrity is lost during a longer stay at the Brig station. This might be due to GNSS multipath effects during the stay at the station, which cannot be compensated by INS because the vehicle is not moving and thus excitation is low. In general segments with poor GNSS reception cause more integrity violations than segments with no GNSS reception at all like the Simplon tunnel. This is due to the very small drift of the IMU used within the INS, enabling excellent dead reckoning capabilities.

4.7 Big Data Analysis

In a second step we analysed the train runs performed by the MEWA12 between 1.10.2018 and 31.12.2019. This dataset contains over 3 million data points from 860 hours of data.

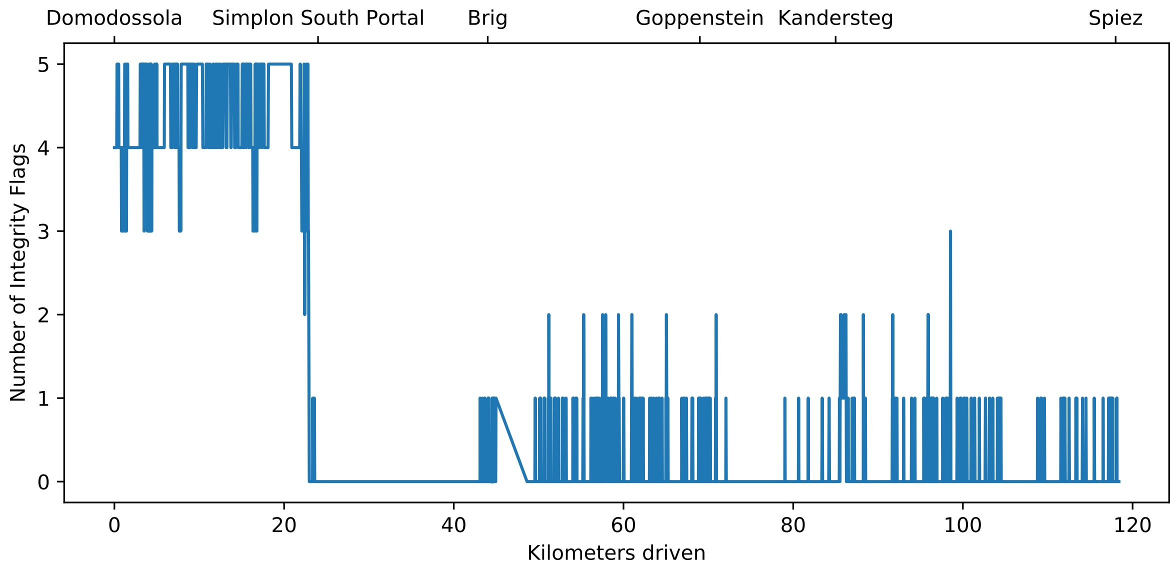

Figure 16: Number of Integrity Flags over Distance

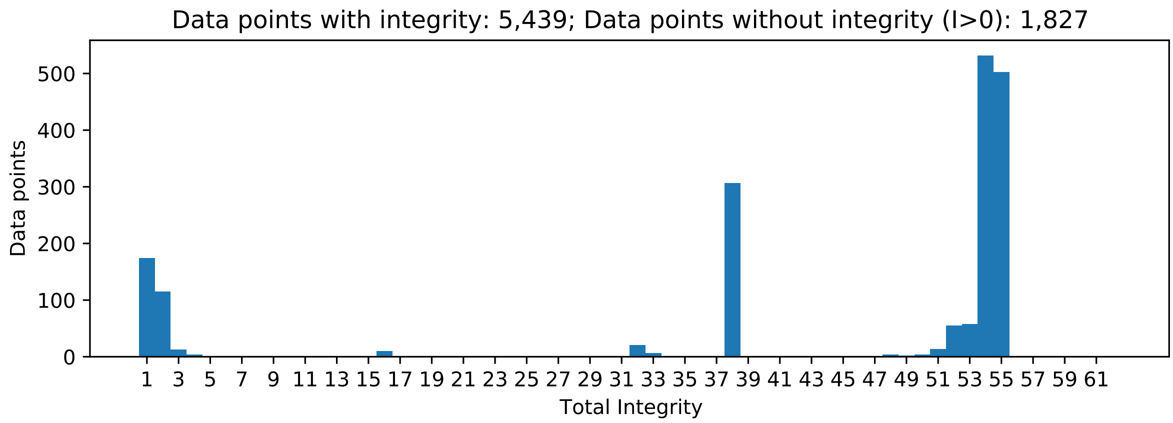

Figure 17: Integrity Histogram

4.7.1 Integrity

We have calculated integrity values for all data points in the dataset. The distribution of the integrity values is shown in Figure 19 on a logarithmic scale. It shows that attitude and geometry-based integrity violations are the most common. In Table 3 the occurrence of data points with multiple integrity flags is listed. 92% of the data points have full integrity, while only 0.1% have all six integrity flags. This shows that although the integrity measures are quite strict, a high availability of the ground truth dataset is given. Depending on the application one can increase the availability by requiring a certain number of integrity violation flags before discarding a data point. If high reliability is required one can discard data points for $I > 0$. In case even higher reliability is desired one can lower the maximum thresholds specified in Section 3. This puts higher demands on the INS and the track data if a certain availability is required.

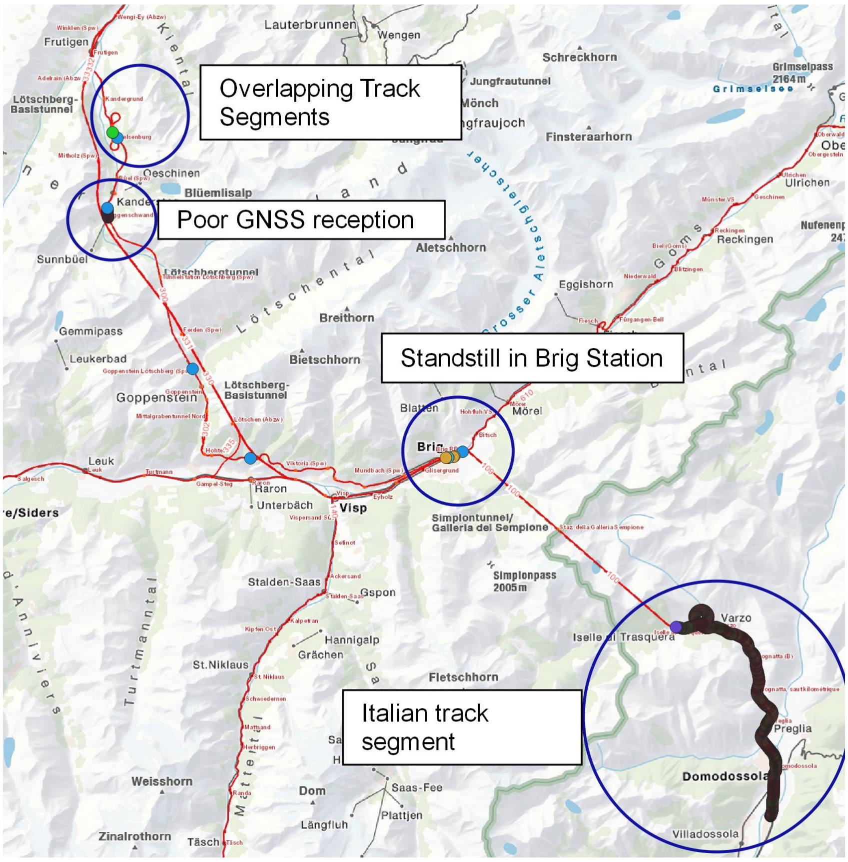

Figure 18: Integrity Map (roll and pitch integrity hidden)

4.7.2 Accuracy

The standard deviation for each integrity measure is calculated separately for each operating day. This is because the standard deviation changes depending on the calibration and operating conditions of the INS. The thresholds for the integrity measures are based on the calculated standard deviation, which is limited to the maximum values specified in Section 3. The distributions of the integrity thresholds for the different integrity measures are shown in Figure 20. It shows that the attitude and curvature integrity thresholds are typically smaller than the set upper limits. Indicating that the used INS is able to provide very accurate estimates that match the track database values very well.

The standard deviation in the longitudinal direction is typically larger than the set maximum value, so that the threshold is often limited to $0.9m$. This is due to the use of only single point solutions in the GNSS receiver as well as missing track segments which create large longitudinal errors as shown before.

The threshold for the position errors (geometry-based integrity) are typically close to the maximum value of $3.6,$. It is not possible to guarantee track selectivity with the current sensor setup solely based on the geometry-based integrity measure.

Wrong track selections are however guaranteed to be detected as long as at least one of the track features (roll, pitch, yaw, curvature and position error) of the wrong track deviates more from the corresponding feature of the correct track than the associated threshold. If this criterion is fulfilled the localisation is track selective

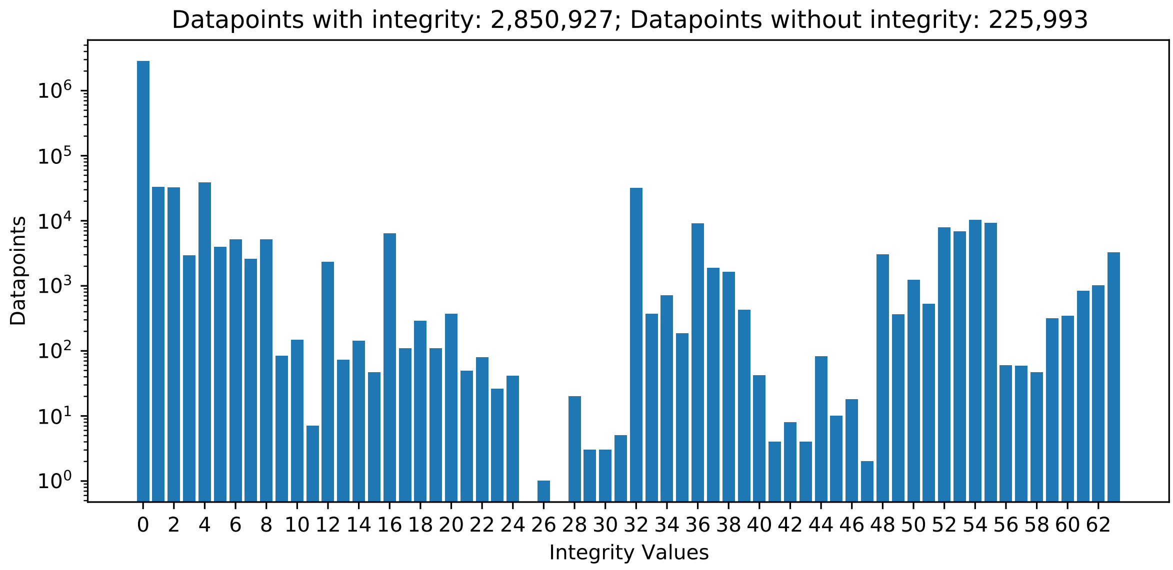

Figure 19: Big Data Integrity Histogram

Number of Integrity Violation Flags	Number of data points
0	2,850,927
1	147,661
2	28,613
3	16,413
4	18,565
5	11,470
6	3,271

Table 3: Multiple Integrity Flags

and the lateral error is zero. In case a wrong track is selected at a switch, the real and supposed track features deviate in the yaw angle, curvature and in lateral position, but can also deviate in roll and pitch depending on the type of switch.

An example for the detection of wrong track selections is shown in Figure 21. There ANABEL outputs a wrong track segment after a switch. Directly after the switch this deviation is detected by the yaw integrity measure, afterwards both yaw and geometry-based integrity measures are indicating errors.

All data points with integrity value zero have a relative longitudinal accuracy $< 0.9m$ between data points, due to the longitudinal integrity measure. With this integrity measure single GNSS/INS position errors above the threshold can be robustly detected. If GNSS reception is available the GNSS / INS system can be assumed to be drift free, since absolute position measurements are available. This means that GNSS/ INS errors typically do not accumulate over a given distance so that odometry drifts can be detected. In tunnels where no GNSS reception is available, drifts of the IMU and odometry based INS position solution can only be detected when the track features change. The typical drifts of the combined INS / odometry position estimate in tunnels are however quite small as shown in [1].

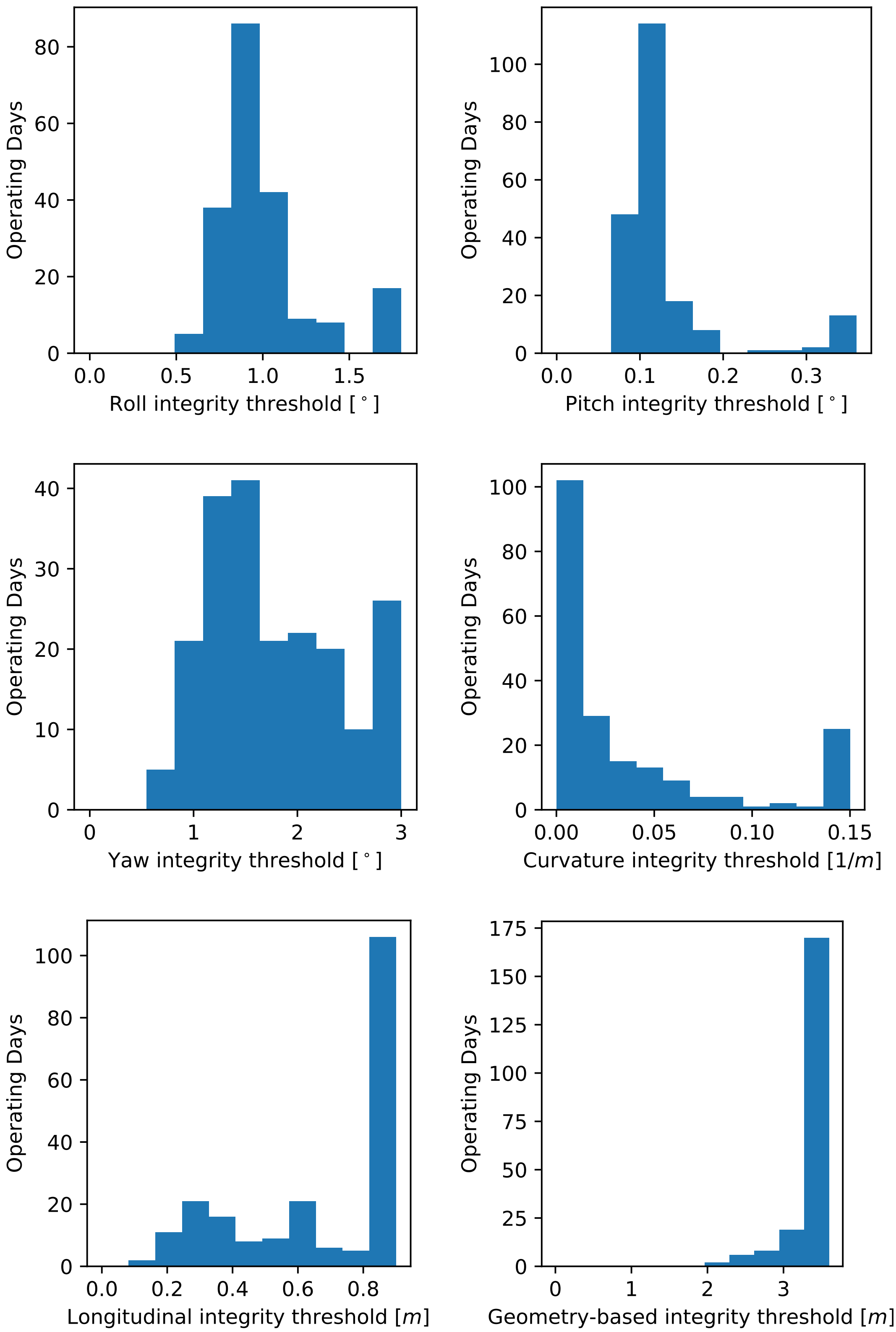

Figure 20: Integrity Thresholds

An absolute longitudinal accuracy is more difficult to assess, since multiple GNSS/INS position errors in the same direction along the track are possible (e.g. a shift of a series of position estimates along a

Figure 21: Example for a wrong track selection

straight track segment). Such errors can be detected if some of the track features vary enough between the supposed and real position to trigger integrity alerts (e.g. track curves). A possible solution to improve the absolute longitudinal accuracy and integrity is to use a Eurobalise reader as an additional source of absolute position measurements.

4.7.3 Availability

To evaluate how the data points with no integrity are distributed geographically, we have created a map showing the ratio of data points with no integrity to the total of data points on a track segment. This map is shown in Figure 22. It shows that overall the Swiss track network can be well covered with the here presented ground truth solution. 91% of the covered track kilometres (ca. 10000km) have more than 50% data points with integrity. The red marked sections with a high percentage of low integrity values are mainly at specific tracks in railway stations and shunting yards where either a combination of suboptimal GNSS reception and slow movements or wrong track data lead to conditions that violate the integrity conditions. Note that the map rendering emphasises red sections over green sections.

5 Conclusions and Future Work

We have presented a method to detect discrepancies between track features and train borne measurements. This method can judge the integrity of GNSS and odometry aided INS position estimates using a variety of different indicators. By mapping these measurements onto the track, a ground truth dataset with accurate

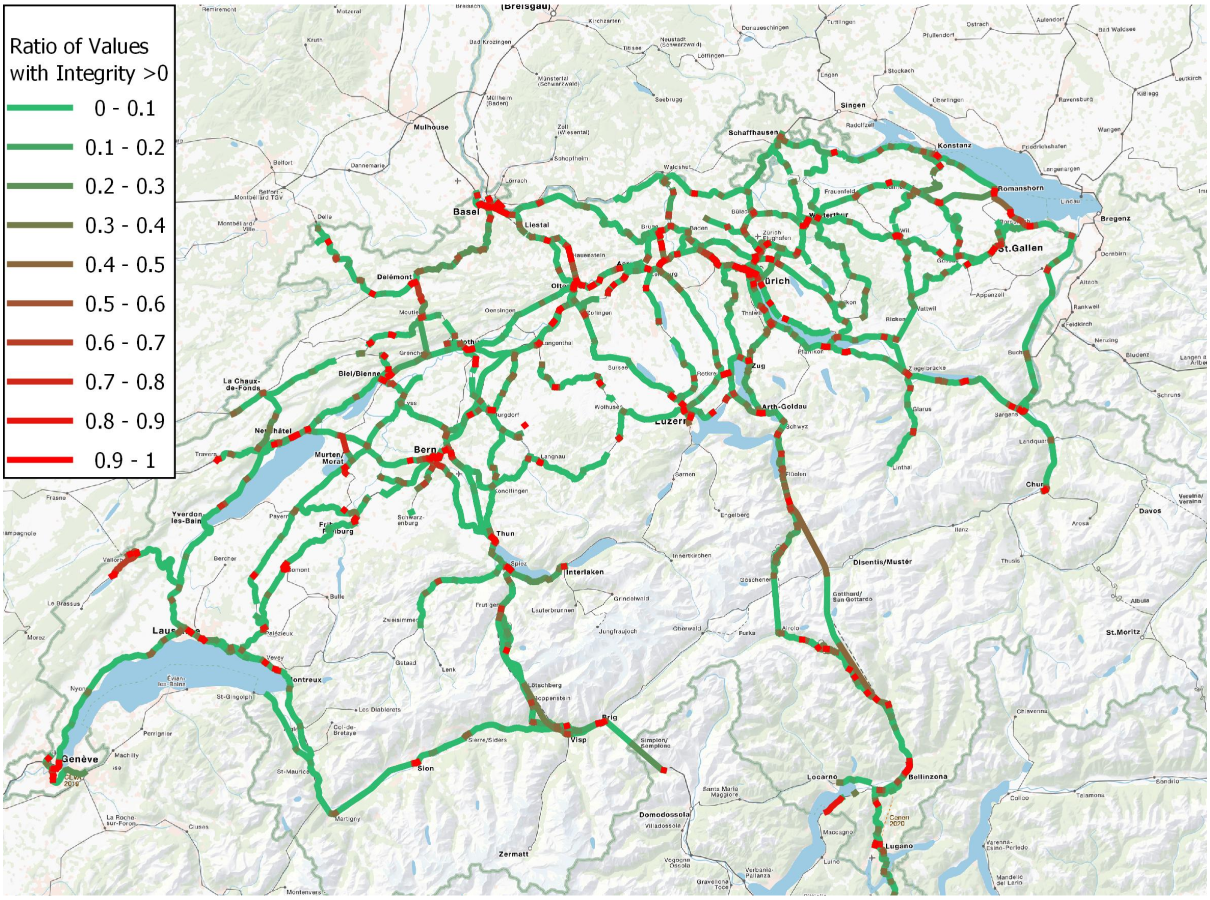

Figure 22: Availability Map

timestamps can be generated. Due to the integrity check, this ground truth data has increased accuracy and reliability, since it has been verified against two independent data sources using six different integrity indicators. The big data analysis showed that the presented integrity checking method provides a high accuracy and availability of ground truth data. There are also other applications where the here shown method would be of practical use. The quality of the data in the underlying databases could be improved if i.e. a certain track segment triggers errors repeatedly. It is also possible to use the INS with this algorithm to detect errors between the supposed position of a track in the database and the real position, which is subject to wear and tear. The method can also be used as part of a train borne localisation system where redundant sensor systems will need to be checked for integrity against a digital map.

There is of course room for improvements. At the moment we use 10m points from UNO to evaluate the track features. An improvement would be to use the geometric track segments stored in the SBB database DfA instead. This would improve the accuracy of the map data significantly, especially when the curve radii are changing frequently over short distances. This is mainly the case on slow track segments. A future planned extension of this method is the installation of a Eurobalise reader onboard the MEWA12 wagon. This will add an independent source of absolute longitudinal position information, enabling us to detect combined GNSS and odometry errors.

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Glossary

ANABEL	A database that contains all train runs on the Swiss normal gauge network
DfA	"Datenbank feste Anlagen": The SBB geoinformation database containing all static structures.
GNSS	Global Navigation Satellite System
IMU	Inertial Measurement Unit
INS	Inertial Navigation System
MEWA12	SBB Telecom Measurement Wagon
RMSE	Root Mean Square Error
UNO	"Unified Network Objects": The SBB train topology database