Precision on Track: Survey-grade Imagery and Positioning for Safer, Smoother Railways

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Key words: Uncrewed systems, cameras, GNSS, Railways, photogrammetry, LiDAR, AI

ABSTRACT

Railway environments present unique challenges for accurate and repeatable inspection: safety constraints limit on-track access, possessions are costly and disruptive, and many assets, particularly switches and crossings, require frequent monitoring to ensure operational reliability. Therefore, a solution that enables high-precision measurements without extensive ground access benefits both infrastructure owners and inspection teams by reducing risk, time spent on track, and overall inspection costs.

Ensuring the safety, sustainability, and efficiency of railway infrastructure depends on timely, survey-grade spatial data. Traditional ground surveys are often costly, risky, and disruptive to operations. This study introduces an advanced UAV-based workflow for railway inspection and mapping, combining high-accuracy aerial imagery with direct georeferencing to deliver sub-centimeter precision while eliminating the need for track access.

The paper presents advancements in rapid data acquisition and high-definition 3D reconstruction in railway infrastructure monitoring using ultra-high-resolution Phase One cameras integrated with Trimble Applanix GNSS and inertial systems, achieving millimeter-level ground sampling distances (GSDs) with less than 5 mm positional accuracy. This level of detail enhances the reliability of AI-driven feature extraction, enabling faster and more consistent detection of infrastructure anomalies. High-efficiency UAV platforms with customized hardware configurations were developed and deployed across multiple projects, demonstrating up to 30% cost savings and 20% faster data collection than traditional methods, while avoiding service disruption. The resulting datasets meet Network Rail's Band 1 accuracy requirements and support applications such as track alignment, structural gauging, and digital-twin modelling. This case exemplifies how advanced sensor fusion and streamlined workflows can transform railway inspection into a safer, faster, and more sustainable practice aligned with SDG 9 (Industry, Innovation & Infrastructure) and SDG 11 (Sustainable Cities & Communities), from Pixels to Perception™ (Miri, et al, 2025).

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1. INTRODUCTION

Traditional rail track surveys are costly, time-consuming, and risky. Not only do they require boots on ballast, but they also interrupt rail services and put workers in harm's way. Surveying large sections of track can take weeks or even months, often with significant delays due to access planning. That's where measurement trains & uncrewed Rail Track Survey UAV's come in (shown in Figure 1).

Figure 1: Uncrewed Rail Track Survey

1.1. Measurement Trains

Measurement trains, also known as Track Recording Vehicles (TRVs) or Automated Track Inspection (ATI) systems, are specialized rolling stock used to monitor the health of railway infrastructure. These high-tech laboratories on wheels use laser scanners, cameras, and positioning sensors to detect faults that are invisible to the human eye (as shown in Figure 2). The use of measurement trains represents a shift from reactive maintenance (fixing things when they break) to predictive maintenance (fixing things before they break). They offer significant improvements in safety, data quality, and operational efficiency over manual foot patrols or hand-pushed trolleys. They can capture multiple datasets simultaneously at speeds of up to 200km/h including track geometry, rail profile, overhead lines, and plain line pattern recognition (c.f., Malekjafarian, et al, 2019). However, while they can run at high speeds, they still require a *slot* in the timetable. On extremely busy networks, finding a window for a measurement run can be challenging. Furthermore, they may not be able to access narrow sidings or industrial yards where the curvature is too tight for a full-sized train.

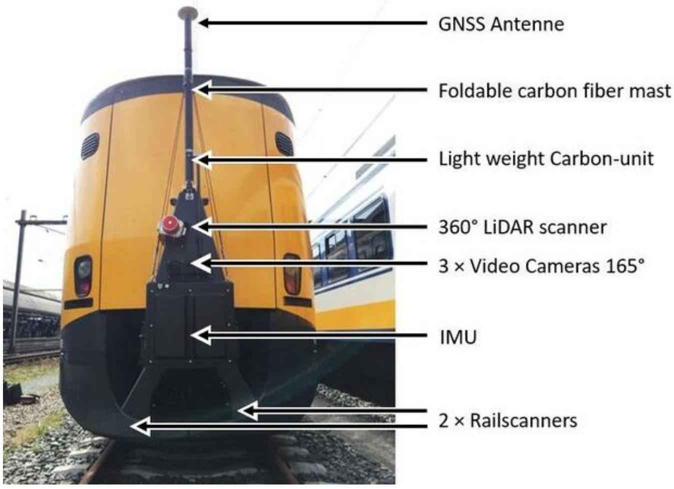

Figure 2: Measurement Trains - Courtesy of Wang & Berkers (2019)

1.2. Uncrewed Systems

Figure 3: Vogel Freedom Uncrewed System

Uncrewed systems, especially multi-rotor (Figure 3), can hover and maneuver in three dimensions with high stability, they are the only viable option for confined or complex geometries. This can ensure high-resolution, high-precision, and high-accuracy data acquisition needed for engineering-grade inspections without requiring shutting down the track. Today, multi-rotor drones evolved over the past decade, being optimized for weight, endurance, and stability in flight.

In busy depots or station entrances (like London Waterloo or NYC Penn Station), one cannot easily run a measurement train because the tracks are constantly occupied. Manual walking inspections are also dangerous and slow down traffic. Well equipped drones allow for getting those high-resolution measurements of the switch point and frog wear without ever having to step on the ballast or stop a train. Measuring and assessing switches and crossings (S&C) – often called turnouts – is one of the most critical safety tasks in rail maintenance. Because these components contain moving parts and endure 3 - 5 times more dynamic stress than straight track, they are inspected with much higher frequency and precision. Uncrewed Systems are the solution for this task, especially in complex and confined areas like station throats.

Today, UAV payloads include integrated multi-sensor systems including one or more cameras as the imaging sensor(s) in addition to GNSS/IMU integrated positioning systems for trajectory measurement during the drone journey. These multi-sensor system payloads, with the proper calibration, the right software tools, and best operational practices produce ground coordinate accuracies at the millimeter level without the need for ground control points (GCP's), except for geodetic datum calibration.

1.3. Direct Georeferencing

Direct Georeferencing (DG) is the key enabling technology in this work. In simple terms, DG allows each sensor measurement to be precisely positioned using GNSS and inertial data, without relying on dense GCP networks. This is especially important in rail environments, where installing GCPs on or near the track is often impractical, hazardous, or simply not permitted. By removing the dependency on heavy GCP use, DG makes high-accuracy rail mapping significantly more efficient and safer to conduct. This technique assigns coordinates to the pixels and points from a camera and LiDAR payload on a UAV using a GNSS and IMU. DG is a well-established method for mapping and surveying from mobile platforms such as crewed aircraft (c.f., Mostafa and Schwarz, 2001), land vehicles and marine vessels (c.f., Li et al, 2004), Uncrewed aerial systems (c.f., Mostafa, 2017). With the introduction of UAV's for surveying, purpose-built DG solutions for these platforms have been developed and integrated with several different sensors (c.f., Colomina and Molina, 2014). The Trimble APX-15 UAV is an example of such a system (Figure 4).

Figure 4: Trimble APX UAV

2. SYSTEM, DATA ACQUISITION AND WORKFLOW

The images used in this paper are captured by Phase One camera iXM-100, with 3.76 µm pixel size, 11,664 x 8,750 pixels, 80 mm lens, and High Dynamic Range (HDR) of 83DB. Data acquisition from 25 m hight flight speed of 6 m/s.

As photogrammetric image processing and image analysis is depended on the imagery and illumination condition, a homogeneous image scene plays an important role in AI-driven feature extraction. Phase One cameras keep the image content and quality within a significant high dynamic range (HDR). This information is smartly saved in a compressed raw data format, called Intelligent Image Quality (IIQ) format. This format provides keeping the image quality in different lighting condition on the object. Figure 5 shows the HDR capability of a Phase One camera (example of an iXM-GS120) in raw format and in adjusted dynamic range.

The Vogel system represents a high-end integration of an uncrewed airframe, a Phase One metric camera, and a Trimble APX UAV GNSS-Inertial system. Unlike consumer-grade sensors, the Phase One iXM series are professional metric cameras designed to produce survey-grade imagery characterized by superior resolution, radiometric consistency, high dynamic range, and geometric repeatability. The core strength of the system lies in Direct Georeferencing. By utilizing the Trimble APX to measure the precise position (X, Y, Z) and orientation (roll, pitch, yaw) of the camera at the exact moment of shutter release, the system bypasses many of the traditional requirements for extensive Ground GCPs. When this data is processed in a photogrammetric environment, it yields the highest possible spatial precision, enabling the generation of mapping products suitable for engineering-grade rail maintenance.

Upon proper flight planning, the drone is flown in the area of interest (AOI) to capture both nadir and oblique images. Initial data processing is then done before uploading the data to the cloud where the drone trajectory is computed and photogrammetric processing takes place.

The operational cycle of the Vogel system is divided into three distinct phases:

1. Mission Planning & Acquisition: Using optimized flight planning software, the UAV captures a combination of nadir and oblique imagery. This dual-perspective approach ensures that both the rail head and the vertical elements of the track (such as the web of the rail and the fastenings) are fully reconstructed in 3D.
2. Trajectory Computation: Initial post-processing focuses on refining the drone's trajectory. By utilizing post-processed kinematic (PPK) techniques, the system achieves centimeter-level positioning accuracy for the image centers.
3. Photogrammetric Cloud Processing (Figure 7): The refined trajectory and imagery are processed in a cloud-based environment. Here, dense point clouds and high-resolution orthomosaics (Figure 9) are generated for the rail corridor for remote analysis.

Machine learning (a branch of AI imitating the way humans learn, improving accuracy as experience grows) enables automating the detection of key assets within S&C. Once extracted, key assets are compared against previous surveys to detect change (as shown in Figure 8).

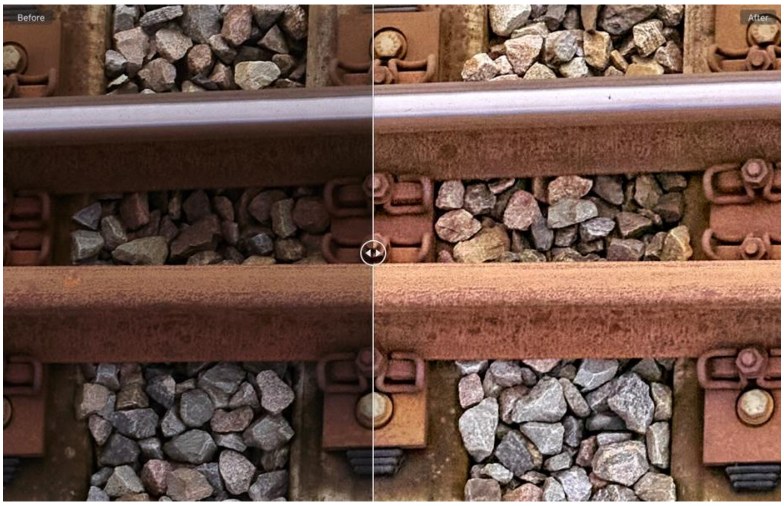

Figure 5: Raw IIQ image before (left) and after (right) radiometric adjustment shows the important of high dynamic range in extracting detailed information, needed for reliable and high-accuracy image processing

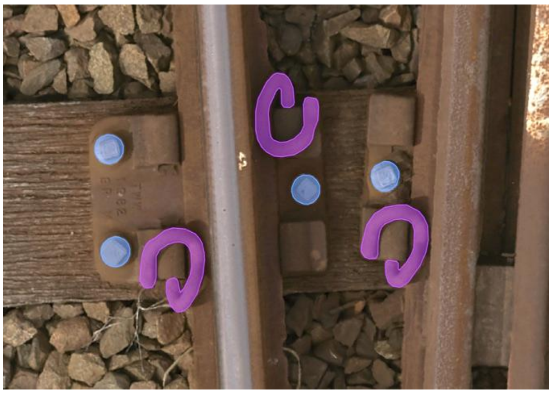

Figure 6: Accurate feature extraction based on adjusted HDR and homogeneous radiometry in images

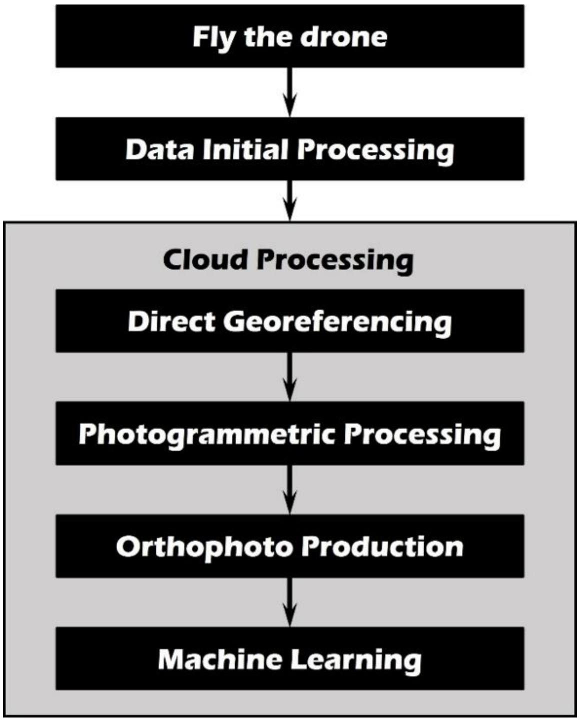

Figure 7: The Vogel System Workflow

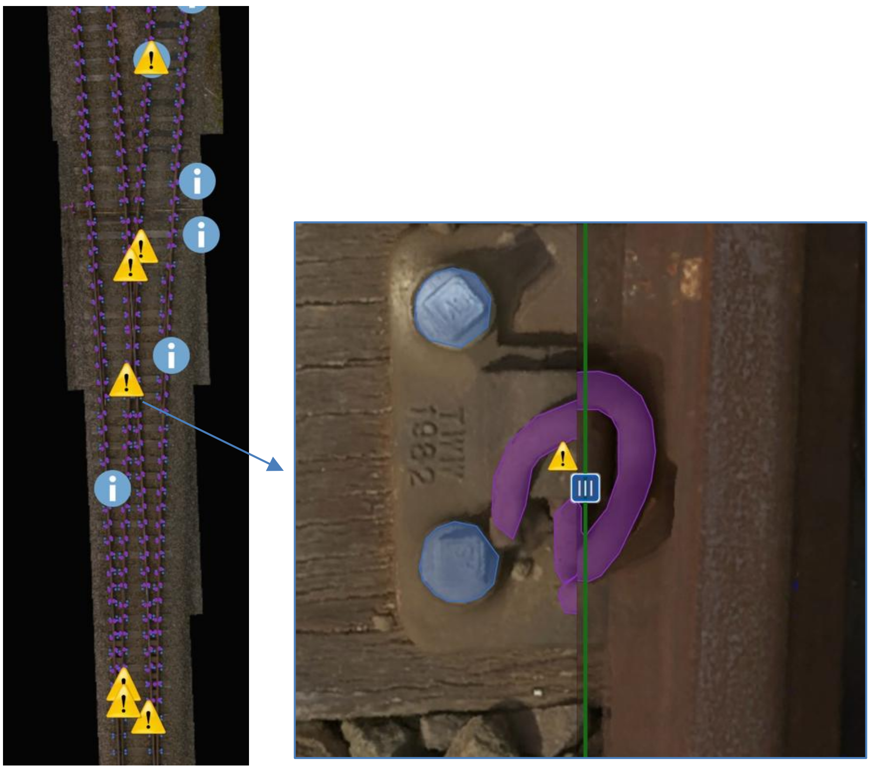
Figure 8: Automatic detection of high-risk changes (with yellow triangles) and medium-risk changes (with blue circles)

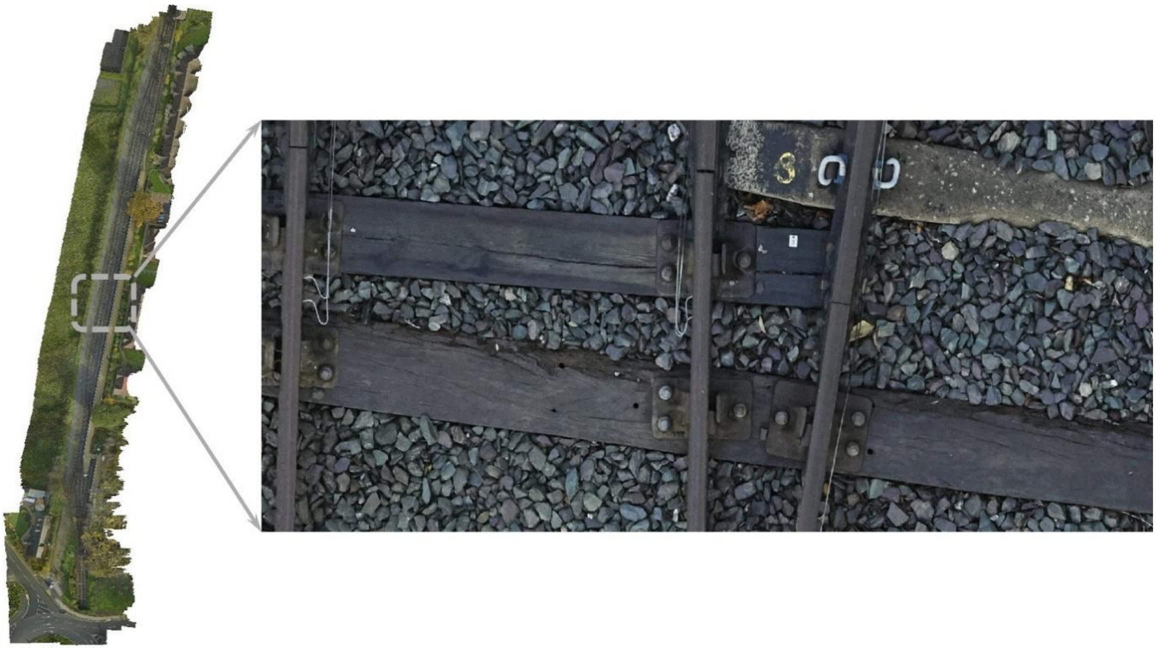

Figure 9: Orthophoto Mosaic of the Area of Interest (left) and a zoomed-in part of the mosaic showing S&C

3. DATA PROCESSING AND ACCURACY ASSESSMENT

Precision and absolute accuracy play a critical role for any railroad track maintenance flight. Therefore, a number of check points (CPs) are typically established in the AOI, in order to assess the accuracy of the orthophoto mosaic produced in this project. Figure 10 shows an example of a CP established on the track. Figure 11 shows automated CP measurement in the Applanix's software, Camera QC, which is used for system calibration and accuracy assessment.

Camera QC-computed coordinates of CPs are typically compared to the land-surveyed coordinates. The difference is the absolute accuracy of the orthophoto mosaic. Figure 12 shows the image footprint of 4 flights including nadir and oblique imagery ground footprint and the locations of CPs.

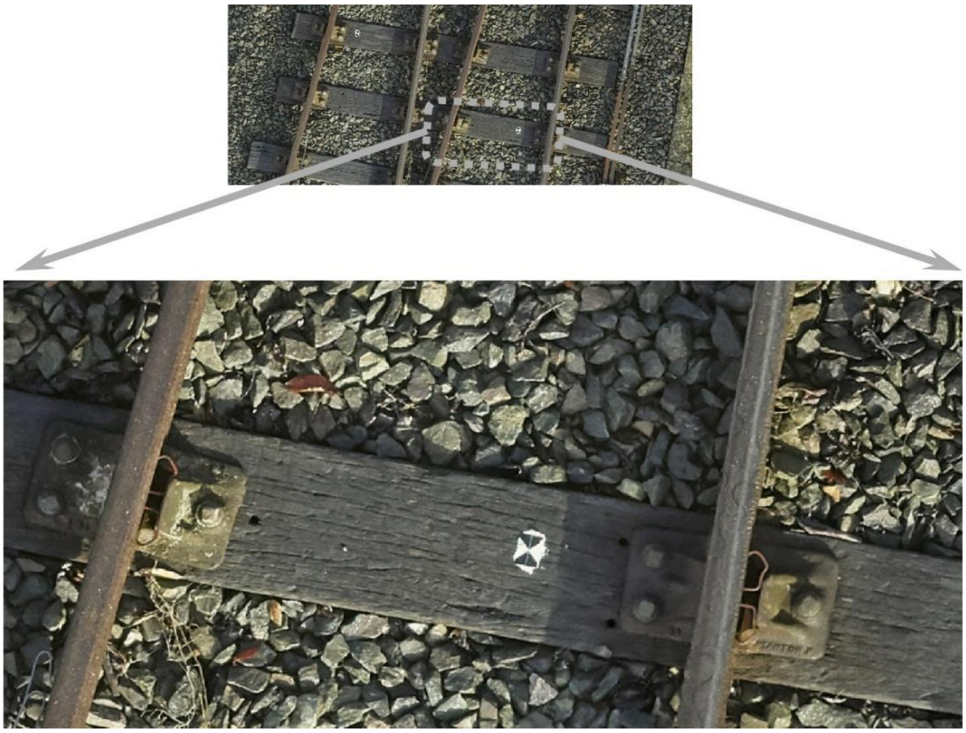

Figure 10: An Example of Check Point Location on the Track

Figure 11: Automated Checkpoint Measurement Using Camera QC

Table 1 lists the differences in 3D coordinates, dX, dY, and dZ for each check point and their associated statistical measures. It is clear from the ’Mean’ value that the system does not produce any biased check point coordinates. Since the GSD of this flight was 2 mm, the accuracy based on Root Mean Square (RMS) is at the level of 2 pixels.

This survey grade absolute accuracy enables the Vogel system to produce reliable change detection reports using machine learning techniques. Figure 13 and Figure 14 show the colorized point cloud for parts of the AOI at different resolutions. These colorized point clouds were produced using photogrammetric processing.

These accuracy results mean that the system can reliably detect changes mm. This level of sensitivity is critical for switches and crossings (S&C) monitoring, where small shifts in rails, bearers, or geometric alignment can indicate early-stage degradation requiring intervention.

Table 1: Check Point Residuals and Statistics

Check Pt	dX (m)	dY(m)	dZ(m)
Check_1	0.000	0.007	0.005
Check_2	-0.003	-0.013	-0.006
Check_3	0.000	0.004	-0.004
Check_4	-0.001	0.006	0.004
Check_5	0.001	0.008	-0.001
Check_6	0.000	0.012	-0.001
Check_7	0.000	0.008	-0.004
Check_8	0.001	0.006	-0.003
Check_9	0.002	0.005	0.000
Check_10	0.000	0.005	0.003
Check_11	0.003	0.004	0.002
Check_12	0.000	0.004	0.004
Check_13	-0.001	0.001	0.003
Check_14	0.000	0.002	0.004
Check_15	-0.001	-0.001	0.004
Check_16	0.003	0.000	0.003
Check_17	0.001	-0.002	0.003
Check_18	0.001	-0.006	0.002
Check_19	0.000	-0.005	0.002
Check_20	0.001	-0.007	0.001
Check_21	-0.003	-0.009	0.000
Check_22	-0.005	-0.009	0.000
Check_23	-0.002	-0.012	-0.001
Check_24	-0.002	-0.012	-0.004
Check_25	-0.004	-0.013	-0.002
Check_26	-0.002	-0.015	-0.003
Check_27	-0.004	-0.011	-0.004
Check_28	-0.005	-0.010	0.000
Check_29	-0.005	-0.012	-0.001
Check_30	-0.004	-0.011	0.000
Check_31	-0.004	-0.011	0.001
Check_32	-0.010	-0.009	0.008
Check_33	0.001	0.005	-0.003
Min	-0.010	-0.015	-0.006
Max	0.003	0.012	0.008
Mean	-0.001	-0.002	0.000
Sigma	0.003	0.007	0.003
RMS	**0.003**	**0.008**	**0.003**

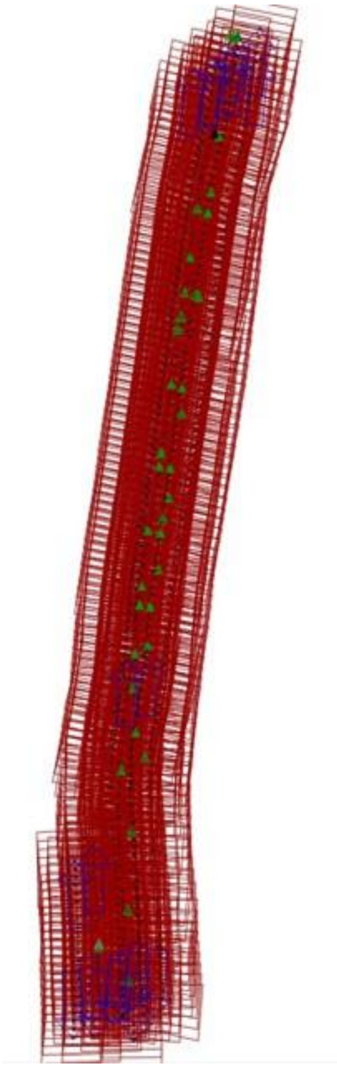

Figure 12: Image Footprint for 4 flights including Nadir and Oblique Camera footage and Check point locations

Figure 13: Colorized Photogrammetric Point Cloud

Figure 14: Colorized Photogrammetric Point Cloud

Modern uncrewed systems leverage multi-constellation, multi-frequency GNSS signals, including GPS (USA), Galileo (Europe), GLONASS (Russia), and BeiDou (China). This global coverage ensures optimal satellite geometry and a superior signal-to-noise ratio, which are critical for achieving high-precision positioning in the field. The geometric strength of these signals is quantified by the Position Dilution of Precision (PDOP). PDOP serves as a key indicator of the accuracy potential based on the relative positions of the satellites in the sky: the lower the PDOP value, the more robust the geometric distribution and, consequently, the higher the final positioning accuracy. As demonstrated in Figure 15, the combined PDOP for the flight mission presented in this study remains consistently below 1.5. A PDOP value within this threshold indicates an ideal sky geometric distribution. By maintaining such a low dilution of precision, the Vogel system can leverage the full potential of GNSS data, resulting in the centimeter-level positioning accuracy required for engineering-grade rail inspections.

The GNSS signal residuals are another indication of GNSS accuracy. For example, Figure 16 shows the GPS measurement residuals which are within a maximum of 2 cm. The RMS of 0.9 cm is an indication that the absolute positioning accuracy could be at the sub-centimeter level for a flight. Please note that Galileo's residuals have a 0.6 cm RMS and GLONASS residuals have a 1.2 cm RMS. Combining several factors allow the system to achieve a 1 cm level GNSS positioning accuracy. These factors are:

- Strong satellite geometry from all GNSS signals (low PDOP)
- Low satellite signal to noise ratio

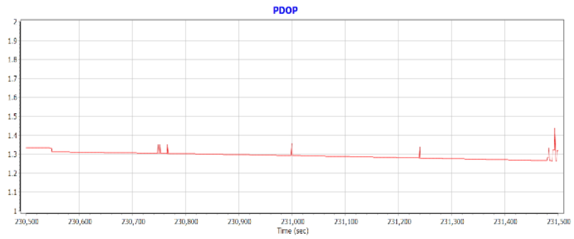

Figure 15: Drone Flight PDOP

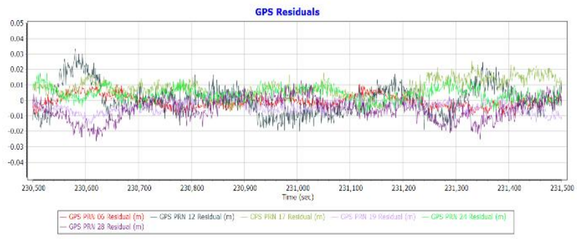

Figure 16: GPS Measurement Residuals

Figure 17 shows the estimated positioning accuracy at the level of 1 cm in horizontal and 2 cm in vertical. Figure 18 shows that the Forward/Reverse Separation is within 5 mm.

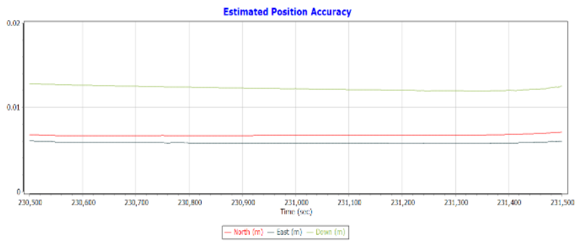

Figure 17: Estimated Positioning Accuracy

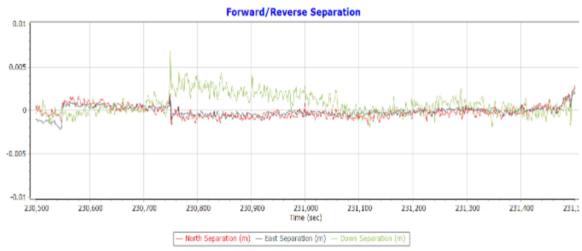

Figure 18: Forward - Reverse Separation

4. SUMMARY AND CONCLUSIONS

This paper has introduced the Vogel system as a transformative solution for railway infrastructure measurement and maintenance. By integrating surveying-grade metric camera with high-precision GNSS/Inertial navigation, the system overcomes the historical limitations of both manual inspections and traditional rolling stock surveys. We have detailed the system's hardware architecture, operational maneuvers, and the integrated data processing workflow, which bridges the gap between raw aerial acquisition and high-fidelity photogrammetric mapping. Rigorous accuracy assessments demonstrate that the Vogel system consistently achieves sub-centimeter precision, for repetitive and automatic change detection and risk analysis utilizing AI-based image processing algorithms. This level of accuracy provides rail operators with the "engineering-grade" data necessary for predictive maintenance, ensuring network safety and reliability without the need for track possessions or hazardous "boots on ballast" operations.

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