Alternative Positioning, Navigation and Timing (PNT) Services

D210 Technical Report

NextNav TerraPoiNT

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Submitted by:

David Knutson
SVP Network Operations and Deployment
NextNav, LLC
484 Oakmead Parkway
Sunnyvale, CA 94085
Tel. +1-703-622-3401
Email: dknutson@nextnav.com

Submitted to:

Lukasz Bonenberg
Space Programmes Policy and Scientific Officer
European Commission
1-2027 Ispra, Italy
Tel. +39 033278-9014
E-mail: Lukasz.BONENBERG@ec.europa.eu

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1 INTRODUCTION TO TEST REPORT

NextNav's Metropolitan Beacon System (MBS) technology, TerraPoiNT, was tested for the different use cases described in the Table 1.2 of the tender document including static position and timing, kinematic positioning, kinematic 3-D positioning, indoor positioning (static and dynamic), and indoor static timing. Due to deployment constraints at Ispra test area, Joint Research Centre (JRC), only some test cases could be conducted at JRC. The remaining tests were conducted in the San Jose, California (SJC) network. A 3-beacon network deployed at JRC was used to conduct short term timing and altitude (z-axis) tests, while the remaining 3-D static/kinematic positioning tests and longer timing tests were conducted in a 7-beacon network in the San Jose, California (SJC). Both networks were run in GNSS-free mode to demonstrate true Alternate PNT (APNT) performance.

2 INTRODUCTION TO THE TECHNOLOGY

2.1 System Description and Technology Overview

NextNav's TerraPoiNT provides both location (position and navigation) and timing information using a terrestrial radio beacon network as described below.

The TerraPoiNT solution infrastructure consists of:

1. A network of long-range, low-cost, and highly synchronized broadcast transmitters ("beacons") that transmit GNSS-compatible waveforms within a 5.115 MHz band
2. Appropriately equipped receivers that trilaterate the signal to compute time and/or position
3. Operations and maintenance functions hosted from a network operation center (NOC)

The beacons are typically deployed on cell towers or rooftops and can deliver PNT services with multi-layer reliability. Multi-layer reliability is achieved through the use of:

- Dual (primary/secondary) transmitters that provide unit level redundancy
- Multiple transmitters in a given geographical area for system level redundancy
- A power supply backup to ensure continuity during power outages
- A Rubidium based atomic clock in each transmitter and the ability for the transmitters to listen to each other
- A timing fusion architecture at beacons that uses a diverse set of time and frequency sources to enable a seamless transition between clock sources
- Encryption-ready signal for transmission

TerraPoiNT functions much like a terrestrial GNSS/GPS constellation and is designed to be as similar as possible to the L1 GPS Coarse/Acquisition (C/A) signal used in most civilian applications. The primary underpinnings of TerraPoiNT, like GNSS, are based on the broadcast transmission of highly synchronized timing signals.

This similarity of TerraPoiNT signals to GNSS signals reduces the integration effort for GNSS Integrated Circuit (IC) and receivers and allows transmission to be demodulated by the digital baseband of common GNSS receivers without significant hardware modifications. Details of the air interface are available in the MBS Interface Control Document (ICD) published by the Alliance for Telecommunications Industry Solutions (ATIS). ATIS is Equivalent to ETSI and is the US affiliate of 3GPP. ATIS is accredited by the American National Standards Institute (ANSI). The ICD can be obtained by sending an email to info@atis.org requesting ATIS Document 0500027.

The TerraPoiNT system is able to provide not only precise horizontal positioning (latitude and longitude) but also vertical positioning (altitude). To determine the altitude, the system leverages the barometric sensors from devices and applies differential barometric techniques to determine the height of the receiver precisely.

Unlike GNSS, which relies exclusively on range measurements to estimate position, TerraPoiNT also broadcasts hyper-local environmental data collected at each transmitter site. This allows devices equipped with optional, low-cost micro-electromechanical system ("MEMS") barometric pressure sensors to combine hyper-local environmental data with the MEMS pressure readings to accurately compute the device's altitude with floor-level accuracy.

Based on the data broadcast by TerraPoiNT transmitters, the receivers can determine an accurate position in a manner similar to GNSS but using terrestrial rather than space-based signals. In addition to outdoor operation, the terrestrial nature of the system also allows for operation in GNSS-challenged environments, such as urban canyons and indoors. The direct broadcast capabilities of the transmitters also support low latency positioning for applications such as autonomous vehicles and drones.

The transmitters utilize a combination of GNSS signals, the onboard atomic clock, and the ability to listen to each other to provide a very precisely synchronized transmitted signal. In the absence of, or, during jamming of GNSS signals, the transmitters can continue to provide a precise timing signal perpetually. A Leader/Follower beacon architecture is designed to provide an absolute time. The Leader beacon is synchronized to UTC using a Cesium clock or a timing reference such as Low Earth Orbit (LEO) Satellite based, Time over Fiber or other such system.

The TerraPoiNT signal design is very similar to the GNSS C/A signal and enables the signal to be processed by modified GPS chipsets and radios, thus enabling integration into mass market devices. A standalone GPS/GNSS chipset or an LTE based GPS/GNSS chipset, with modifications of similar complexity to adding a new GNSS constellation to a GPS chipset, can be used to process TerraPoiNT signals.

The TerraPoiNT receiver is typically implemented on a multi-constellation GNSS receiver. The GNSS receiver adapted to receive TerraPoiNT signals can receive both GNSS and TerraPoiNT signals and, thus, generate a fused solution for any application. The advantage of such a system enables applications to operate seamlessly when one or more of the GNSS signal is not available or jammed. This not only increases the resilience of the system but also allows it to operate in environments where GNSS does not work (e.g.: indoors and in urban areas) enabling new use cases.

Similar to GNSS, the TerraPoiNT system has unlimited capacity and can provide full PNT services to all devices within its footprint. Precision Timing and Frequency applications require only one transmitter to be in view, while Positioning and Navigation applications require signals from three or more transmitter locations. Typical transmitter range in a cluttered suburban environment for indoor reception to mobile phone type devices is 5~10 km. Greater site separation is possible:

- For outdoor-only reception
- With higher effective radiated power (ERP) limits, depending on what is permitted within the assigned licensed frequencies

In non-cluttered environments, the terrestrial range limitation is related to Transmit ("Tx") and Receive ("Rx") antenna heights.

TerraPoiNT Transmitters. Illustrated in Figure 1, the main components consist of a beacon transmitter (including data modem and network monitoring receiver), an omni antenna, and a weather station.

NextNav Beacon

Omni Antenna

Weather Station

Designed for deployment in unconditioned space

Small form factor 0.95m Ht x 0.78mW x 0.5m D

No special power requirements or backhaul

Management link via LTE or POTS
FCC certified

Low-impact omni antenna (typically 1.52m antenna)

Eases zoning, and creates placement flexibility

Omni antennas are ideal for location

Weather stations deployed across NextNav network

Data encoded in NextNav transmission

Enables high-accuracy pressure altitude

Figure 1: Equipment at a Typical Transmitter Site

2.2 User Segment: TerraPoiNT Receivers

TerraPoiNT
Position Receiver

- 3D Positioning receiver
- Small form factor
  9.4cm L x 6.7cm W x 1.9cm D
- External Power supply
- External GPS and MBS Antenna

TerraPoiNT
Timing Receiver

- Integrated GPS, MBS timing receiver
- Time better than 500nsec
- 10MHz and 1PPS output

Figure 2: Positioning and Timing Receivers

There were two types of TerraPoiNT receivers used during testing in this project. The TerraPoiNT timing NTR receiver (also referred to as NTR) is a timing receiver capable of providing time, synchronized to UTC, better than 100nsec. The TerraPoiNT positioning

LPRx receiver (also referred to as LPRx) is a 3D positioning receiver. These receivers are as shown in Figure 2.

The NTR and LPRx receivers come with separate antennas specified to have a gain 4 dBi, (length 5 cm) and use connector type TNC. While there are no special mechanical mounting features needed for operation, it is desirable to mount the receiver such that the antenna is at least 30 cm away from any mechanical plates to avoid any impact on antenna performance. The backside of the NTR hosts a fan that is required to be left unobstructed during operation to avoid heating issues.

Global Standards and Testing. Similar to GNSS, NextNav's TerraPoiNT Metropolitan Beacon System (MBS) solution is standardized as a terrestrial constellation, known as Terrestrial Beacon System (TBS), from Release 13 of the specifications managed by the 3rd Generation Partnership Projection organization (3GPP[1]), and is supported in the specifications of the Open Mobile Alliance (OMA[2]), including the Secure User-Plane Location protocol (SUPL) and the Mobile Location Protocol (MLP). Any wireless operator across the world supporting the above messaging protocols can provide MBS assistance and obtain MBS measurements from the receiver as well as transport these measurements through the standard core wireless infrastructure.

TerraPoiNT has undergone extensive independent testing and demonstrations by the US Government. These include:

- FCC/Communications Security, Reliability Interoperability Council (CSRIC) tests in 2016/2018, which formed the basis for the E911 rule making (FCC 4th Report and Order (R&O)
- DHS/MITRE testing of GPS backup technologies, which took place at NASA Langley Research Center (LaRC) in December 2018
- DOT /VOLPE Technology demonstration at NASA LaRC for Executive Branch agencies, Congressional staff, and PNT Advisory Board members in March 2020

In addition, TerraPoiNT has been tested by multiple tier 1 US operators. MBS technology is supported in Core wireless infrastructure servers (Enhanced-Serving Mobile Location Center (E-SMLC) and SUPL server) developed by Tier 1 network equipment providers implementing the 3GPP and OMA specifications, including Ericsson and Comtech. The Cellular Telecommunications Industry Association (CTIA[3]) is a trade association representing the wireless industry that develops test standards and operates certification programs for US wireless carriers. CTIA's Over-The-Air Test Plan version 3.8 (released in 2018) includes test procedures for MBS, which are supported by some of the commercial test equipment providers such as Rohde & Schwarz.

1 3GPP: Global Telecommunication Standard setting body (an affiliate of ITU)
2 www.openmobilealliance.org
3 www.ctia.org

2.3 Performance Parameters

Performance Parameter (X days after GNSS outage)	1 Day	14 days	100 Days	Comments
Horizontal Accuracy (95%) m	10 m	10	10 m	Note 1
Vertical Accuracy (95%) m	2 m	2 m	2 m	Note 1
Availability (%)	99.96%	99.96%	99.96%	Note 2
Continuity (per hour)	99.93%	99.93%	99.93%	Note 3
Integrity (per hour)	100%	100%	100%	Note 4
Time-To-Alarm (second)	60s	60s	60s	Note 4
Network Timing Accuracy to UTC (3sigma)	9 ns	*120 ns*	*900 ns*	Note 5
Network Time synchronisation (Allan Deviation)	9e-13	*3e-14*	*3e-14*	Note 6
Network Timing Stability (Allan Deviation)	4e-14	*2e-14*	*2e-14*	Note 7
First time to provide services upon cold start-up (including system and receiver contributions)	10s -- (PN receiver only)	10s -- (PN receiver only)	10s -- (PN receiver only)	Note 8
	7 minutes -- (T-receiver only)	7 minutes -- (T-receiver only)	7 minutes -- (T-receiver only)	Note 8
	15 minutes (System + receiver T-only)	15 minutes (System + receiver T-only)	15 minutes (System + receiver T-only)	Note 9
	43 minutes (System + receiver: PN or T)	43 minutes (System + receiver: PN or T)	43 minutes (System + receiver: PN or T)	Note 9

Table 1: Performance Levels of the Alternative PNT Service

Note 1 Horizontal and Vertical Accuracy: *The numbers are based on data from outdoor and indoor tests in San Jose City whose morphology is suburban/light urban. Using test data based on 10-day outage, the horizontal and vertical error is extrapolated for 14 days and 100 days since there is no expected increase in error during that time as relative synchronization is not affected by GNSS outage duration.*

Note 2 Availability: *Assumes reliable modem telemetry and power outages less than 24 hours, and normal SW maintenance windows and HW beacon mean-time-between-failures (MTBF) in present generation beacons. In this calculation, we have not considered fact that the TerraPoiNT network design incorporates additional beacon redundancy which would make actual system availability even higher.*

Note 3 Continuity per Hour: *Using similar assumptions as above for availability, continuity per hour is computed based on the dominant factor affecting continuity, i.e., the SW self-recovery/maintenance window assumptions.*

Note 4 Integrity per Hour: *Using similar assumptions as above for availability, network integrity of 100% can be achieved at time to alarm of 60s. Integrity is monitored by the TerraPoiNT control segment in the Network Operations Centre (NOC) for all the beacons and includes synchronization and transmission checks. The integrity alert/alarm can be provided within 60s in current implementation. Irrespective of the length of integrity failure event, the integrity alert/alarm can be provided within 60s from the time the integrity failure occurs. Techniques have been developed to further improve the time-to-alarm to ~12s for synchronization issues using automatic beacon health* *detection and indication on the beacon using over-the-air packets. Further improvements in time to alarm can be obtained if it can be assumed that the receiver is connected to the internet and can receive an alarm push from the control segment*

Note 5 Network Sync to UTC: *The numbers are driven by the quality of the absolute clock used at the leader beacon. In this case, a Cesium clock was used at the Leader beacon without any environment control assumptions. Further improvements can be obtained if Cesium is deployed in a temperature managed environment where the Cesium drift can be brought down to about 2-3 ns per day based on tests. Note that the numbers in the table for 100 days are based on the Cesium datasheet and there may be additional effects over 100 days, which may limit the extrapolation. If any alternate absolute timing source is available at one or more beacons in the area such as time over fiber, then the Cesium drift can be controlled as well. Note that the final timing error at receiver relative to UTC is dependent on the channel and adds to the network timing error.*

Note 6 Network Time Synchronization: *Computed using ADEV (Allen Deviation) based on 10 days of measured data and extrapolated to 14 days and 100 days in the same environment as in Note 1. The underlying synchronization was compared using GPS at beacons, assuming the GPS available at geographically separate beacons was providing the same pps (reasonable assumption due to common view and identical GPS receivers) and using local time interval counters at each beacon. The time interval differences were used as measure of synchronization error between beacons and ADEV was computed on this synchronization error. Note that raw GPS pps quality used for measuring the error may be limiting the 1-day ADEV performance shown here.*

Note 7 Network Time Stability: *Computed using ADEV based on 10 days of measured data and extrapolating to 14 days and 100 days in the same environment as in Note 1. Time stability was measured relative to GPS (which was assumed to be stable) and used in an ADEV computation. Note that time stability performance beyond 1 day is determined by the Cesium quality on the 'leader' beacon*

Note 8 First Time to Provide Services Upon Cold Start-Up (receiver only): *The TerraPoiNT PN receiver used in this test can provide an autonomous first fix from cold start within 10s. The TerraPoiNT timing receiver used in this test in autonomous mode can provide a good quality timing estimate in 7 minutes*

Note 9 First Time to Provide Services Upon Cold Start-Up (system + receiver): *When used for UTC time distribution TerraPoiNT depends on an absolute time source being available initially to obtain sync to UTC. In today's implementation, the overall system startup time is limited by the settling time of the timing synchronization loop of the system. At the time shown in the row 'System + receiver T-only', coarse position results (~50m error) can also be available. For best PN performance, the time shown in the row for 'System + receiver: PN or T' is desirable for best performance. Note that using conceptually well-known techniques, further reductions to the boot-strap time of the timing synchronization loop of the system and receiver can be made, as required by the application.*

3 TEST NETWORKS

3.1 JRC Network Configuration

A 3-beacon TerraPoiNT demonstration network, shown in Figure 3, was set up in the Ispra test area, which involved the installation of TerraPoiNT beacons at selected locations upon approval to transmit in the 920~928MHz band. The beacon locations were chosen using the 3D map of the test coverage area and determining the best geometry to serve the timing and Z test cases. The beacon at building 72C was set up to be the "Leader" beacon with access to absolute time source provided from the JRC timing lab. The other two beacons were set up to be "Follower" and maintain time relative to the "Leader" beacon either directly or via multiple hops.

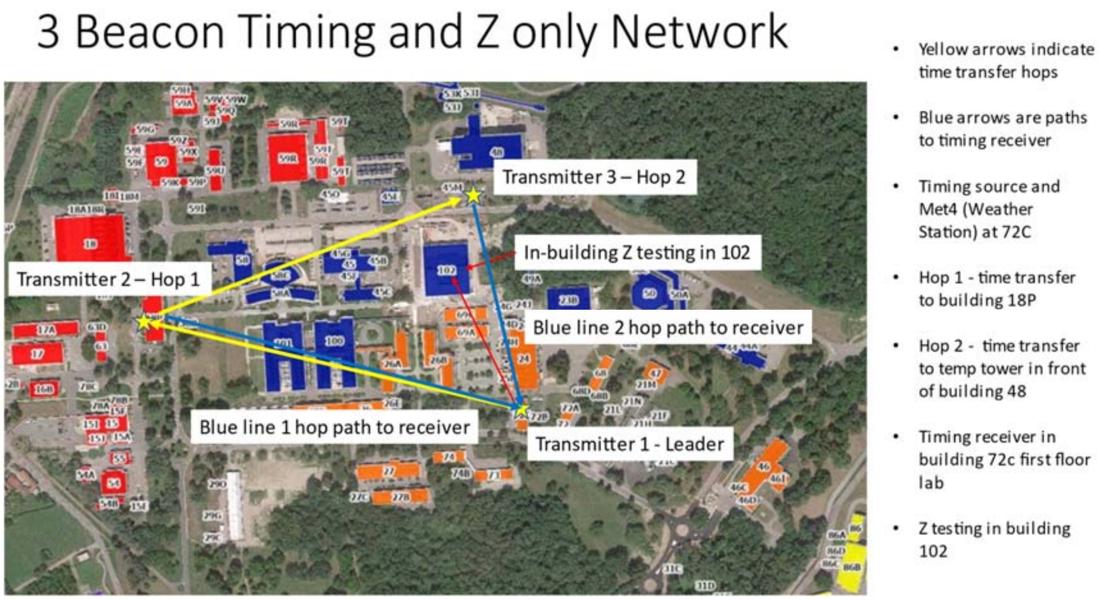


Figure 3: 3-Beacon Timing and Z-only Network at JRC

Note that TerraPoiNT beacons, in general, have redundant capability through primary and secondary dual transmitter configuration. However, in these tests for simplicity of deployment, only the primary transmitter was used.

3.2 SJC Network Configuration

A 7-beacon network was set up in San Jose (SJC) area, as shown in Figure 4, to demonstrate the positioning, navigation, and timing capabilities of the TerraPoiNT system. There is one "Leader" beacon which has access to absolute time source and a Cesium clock to maintain time during outages.

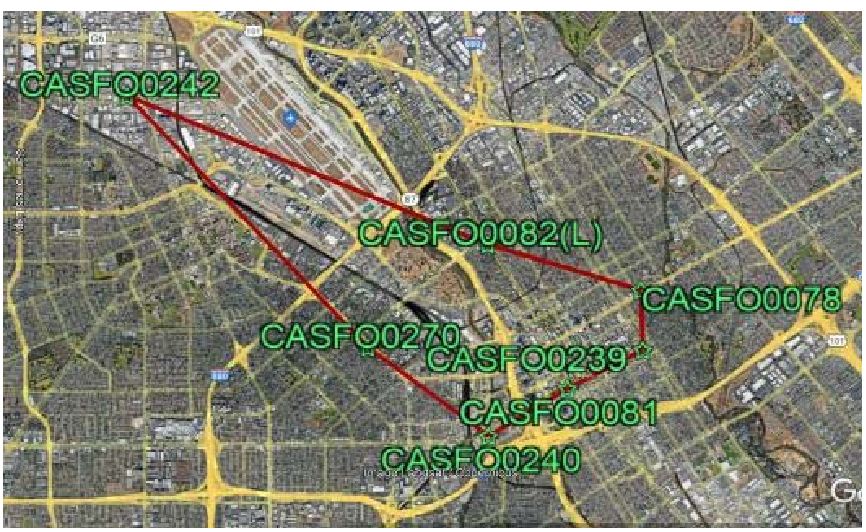


Figure 4: 7-Beacon SJC-APNT Network

The other beacons maintain relative time synchronization between themselves and the Leader using the best time transfer path among the various possibilities shown in the Figure 5. The possibilities of multiple paths per beacons adds redundancy in the network and provides resilience against any individual beacon getting compromised.

Figure 5: Time Transfer Paths Available in SJC Network

Note that TerraPoiNT beacons have redundant capability through primary and secondary dual transmitter configuration. However, in these tests for simplicity of deployment, only the primary transmitter was used.

4 TERRAPOINT RECEIVERS USED IN TESTS

NextNav has two different types of receivers available for testing: one for positioning and navigation (LPRx) and the other for timing applications (NTR).

4.1 TerraPoiNT Positioning and Navigation Receiver (LPRx)

TerraPoiNT has developed a positioning and navigation receiver (LPRx), shown in Figure 6, that can acquire and track TerraPoiNT signals. LPRx can track up to 20 beacons, and implements a sophisticated multipath resolution algorithm to provide an accurate and precise position. LPRx incorporates a barometer that can be used to compute altitude. The limitation of tracking up to 20 beacons is due to hardware implementation of the receiver and does not represent the limitation of the TerraPoiNT network. The LPRx platform interfaces include a UART interface, a Wi-Fi interface, a web-based interface for debugging and maintenance, and an LED-based user interface for operation status indication purposes. It provides a NMEA-style ASCII message (PVREP) output on the serial port, which contains the details of the timestamped user 3D-position, 3D-velocity along with their uncertainties.

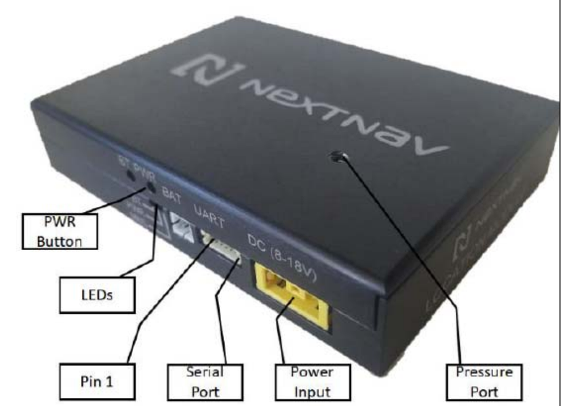
 Front and Right-Side view: These sides house all the customer interfaces, LEDs and Buttons. The pressure port is on the top of the unit.	 Rear and Side View: The rear panel has the USB ports reserved for NextNav use. The SMA connectors to connect to the TerraPoiNT and Wi-Fi antennas are located on the side.

Figure 6: TerraPoiNT Positioning Receiver (LPRx)

4.2 NextNav Timing Receiver (NTR)

NextNav Timing Receiver (NTR), shown in Figure 7, is used to derive timing and provide PPS + time of day (TOD) message using the TerraPoiNT signals along with a 10 MHz clock output. NTR automatically selects the best beacon signal for extracting timing or is configurable to select a particular beacon for timing. The NTR can do a self-survey to obtain a position estimate or accept a user-provided position. The NTR takes about 10 minutes to warm up and provides precise timing output after it is configured and powered on. NTR logs are stored on the device and can be extracted at the end of the test.

Figure 7: NextNav Timing Receiver

5 TEST PLAN

5.1 Test Scenarios

During the demonstration execution phase, a variety of field tests and lab tests were conducted as per the agreed upon test plan scenarios. The LPRx receiver supported 3D positioning applications in outdoor and indoor locations under stationary and dynamic conditions. The NTR receiver supported timing applications at outdoor and indoor locations, under stationary conditions. The test scenarios supported by the LPRx and NTR receivers are summarized in Table 2 along with the test category and KPI derived from the EU tender document.

Scenario	Category	KPI	NextNav comments
Static - position accuracy	Indoor and Outdoor location	Horizontal accuracy, short term stability	This test can be performed for Z-axis only at JRC using TerraPoiNT Position Receiver (LPRx) and for full 3D at SJC-APNT network Test details are provided under test category T7D
Static - Time synchronization, short term clock stability, traceability to UTC	Indoor and Outdoor location	Time synchronization, traceability to UTC	TerraPoiNT Timing Receiver (NTR) shall be used for this test and its usage is defined in the section 'Timing Testing using NTR' Test details are provided under test category T2I, T2J
Kinematic - position accuracy	Outdoor location	Horizontal accuracy short term stability	LPRx shall be used for this test and its usage is defined in the section 'Position and Navigation Testing using LPRx' Test details are provided under test category T6A
Kinematic - Time synchronization, traceability to UTC	Outdoor location	Not supported	NextNav TerraPoiNT technology can support this feature, but the current TerraPoiNT receiver implementation does not support this capability
Kinematic- 3D position accuracy	Outdoor location	Horizontal accuracy short term stability	LPRx shall be used for this test and its usage is defined in the section 'Position Testing using and Navigation LPRx'. Test details are provided under test category T6A
Kinematic- 3D Time synchronization, traceability to UTC	Outdoor location	Horizontal accuracy short term stability	NextNav TerraPoiNT technology can support this feature, but the current TerraPoiNT receiver implementation does not support this capability
Interference	Lab test	Horizontal accuracy Robustness to interference Signal Quality Time synchronization	As per discussion with JRC, this test is not applicable as the interference in GPS band does not impact TerraPoiNT technology
Stationary long-term test – position accuracy	Lab test	Horizontal accuracy long term stability	LPRx shall be used for this test and its usage is defined in the section 'Position and Navigation Testing using LPRx' Test details are provided under test category T7C, T7D
Stationary long-term test – time traceability to UTC	Lab test	Time synchronization, traceability to UTC	NTR receiver shall be used for this test and its usage is defined in the section 'Timing Testing using NTR'. Test details are provided under test category T3H

Table 2: NextNav Supported Scenarios

A list of surveyed test points at the JRC site for Z-accuracy testing are listed in Table 3.

Test location ID	Category	Test location description
JRC-GF	Indoor	Building-102: ground floor
JRC-FF	Indoor	Building-102: first floor
JRC-SF	Indoor	Building-102: second floor
JRC-TF	Indoor	Building-102: third floor
JRC-B	Indoor	Building-102: basement

Table 3: Test Locations at JRC

The list of tests point surveyed in the SJC area for static outdoor and indoor 3D are listed in Table 4 and shown on the map in Figure 8.

Test location ID	Category	Environment	Test location (Latitude, Longitude, Altitude)
SJC-E	Outdoor	Suburban	37.3414470, -121.9043278, -9.48
SJC-F	Outdoor	Suburban	37.343104, -121.8888754, -8.4582
SJC-G	Outdoor	Urban	37.339866, -121.883013, -6.4551
SJC-H	Outdoor	Urban	37.334805, -121.9011434, -6.494
SJC-I	Indoor	Urban	37.336561, -121.886200, 7.42
SJC-J	Indoor	Suburban	37.343157, -121.889431, -7.8
SJC-K	Indoor	Suburban	37.350561, -121.922312, -13.49
SJC-L	Indoor	Suburban	37.340314, -121.906491, -8.49

Table 4: Test Locations at SJC

The static points were chosen to cover different environments ranging from outdoor to indoor and suburban to urban. At these static locations, the signal power for the set of beacons is different, which demonstrated the performance of TerraPoiNT system under various conditions. Each test point has a different multipath and signal power profile.

Figure 8: Test Points at the SJC Site

5.2 Performed Tests Summary

5.2.1 Timing Test List

The list of timing tests performed are summarized in Table 5.

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T1C	System verification		1pps		Verify availability, generation of pps, 10MHz HW signals from NTR to Calnex and ToD message from NTR to laptop	JRC
T2I	Short term clock stability	limited to spectrum restrictions	1pps	TE	Timing Accuracy	JRC (Lab)
T3H	Medium term clock stability	14 days	1pps	TE, AVAR	Timing Accuracy with second hop	SJC (Sheltered building)
T4F	Resilience and network monitoring	1 hour	1pps	TE	Timing Accuracy	SJC (Sheltered building)

Table 5: Summary of Timing Tests Performed

5.2.2 Positioning Test List

The list of positioning tests performed are summarized in Table 6.

Test ID	Test name	Duration	Measurements	Metrics	Objective	Location
T5C	System verification				Verify the network	JRC
T6A	Kinematic	< 1 hour	3-D position	CDF of 2-D position, z error Time series of ENU errors, Estimated 2D position overlaid on map with Truth 2D	Verify Navigation accuracy	SJC
T7C	Kinematic – short and long term	< 1 day	Z-Position	CDF of z-error Time series of z-error	Verify Z-accuracy	JRC: Test on different floor of BG102 for Z-measurements

T7D	Static – short and long term	< 1 day	3-D position	CDF of 2-D position, z error Time series of ENU errors, Box plot	Verify short term position accuracy	SJC: 8 (4 indoor, 4 outdoor), each point test duration at 4 minutes and test repeated at least 2 times
T8J	Resilience and network monitoring	< 1 day	3-D position	CDF of 2-D position, z error Time series of ENU errors, Box plot	Verify short term position accuracy	Similar test as T7D at 2 outdoor and 1 indoor location with Beacons will be turned on/off to demonstrate resilient performance

Table 6: Summary of Positioning and Navigation Tests Performed

Additionally, box plots were generated to show the median value at 50%, first quartile at 25%, third quartile at 75%, with lower whisker at 10%, and upper whisker at 90%.

5.3 Customer Furnished Items (CFI)

NextNav provided the following during testing at JRC:

- Validated Beacon network for JRC and SJC as defined in section 3.0
- TerraPoiNT receivers as defined in the section 4.0
- Test equipment: Calnex for timing
- Laptop to control and configure the TerraPoiNT receivers

5.4 JRC Provided Items (JPI)

JRC provided the following during JRC tests:

- Timing Tests
    - o A stable reference PPS signal derived from an accurate clock source at each timing test location at JRC
    - o Time interval counter to compare the performance (in addition to NextNav provided Calnex equipment)
    - o Accurate test location co-ordinates of the test location
    - o Network connectivity to configure the NTR remotely.
- Altitude (Z-axis) Tests
    - o Accurate truth for the Z-test points for truth test location

5.5 Testing Platform Used in the SJC Test Network

5.5.1 Positioning and Navigation Test Setup

The tests were performed using the LPRx receiver for position and navigation performance. A truth system was used along with LPRx to obtain the positioning truth, which was used to determine the LPRx positioning performance.

5.5.1.1 Positioning Truth Setup at SJC

A truth system was used to obtain the truth data for each test. The positioning truth comprised of a system consisting of survey-grade GNSS receiver and high-grade IMU. The GNSS measurements were post processed using precise orbits to obtain a 'cm' level accurate truth position. The IMU was used to provide a truth position estimate in the regions where the GNSS solution accuracy was poor. Figure 9 shows the procedure used to obtain the truth for outdoor locations and kinematic tests. At indoor locations, the static test points were surveyed starting from outdoor truth using GNSS survey and then tape measures/laser distance measurement devices to the indoor locations to obtain the indoor truth location.

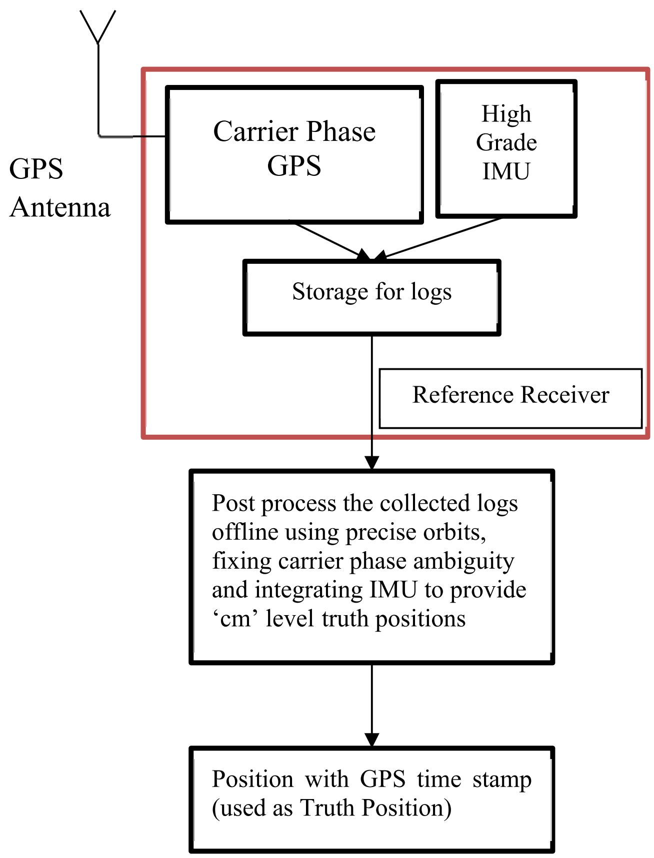


Figure 9: Outdoor Positioning Truth Determination Procedure

5.5.1.2 Positioning and Navigation Receiver Test Setup

LPRx was used for positioning and navigation tests along with a truth system (survey-GNSS and high grade IMU) for outdoor tests including kinematic tests as shown in Figure 10. The truth system was started in an open sky environment to allow precise GNSS receiver to track enough satellites to get an accurate position. The LPRx receiver was configured for the automotive mode and LPRx Position report (PVREP) was collected by the host port. The PVREP report provided GPS time-stamped position and velocity information which was logged on the Host PC and used to compare the GPS-timestamped data from the truth system.

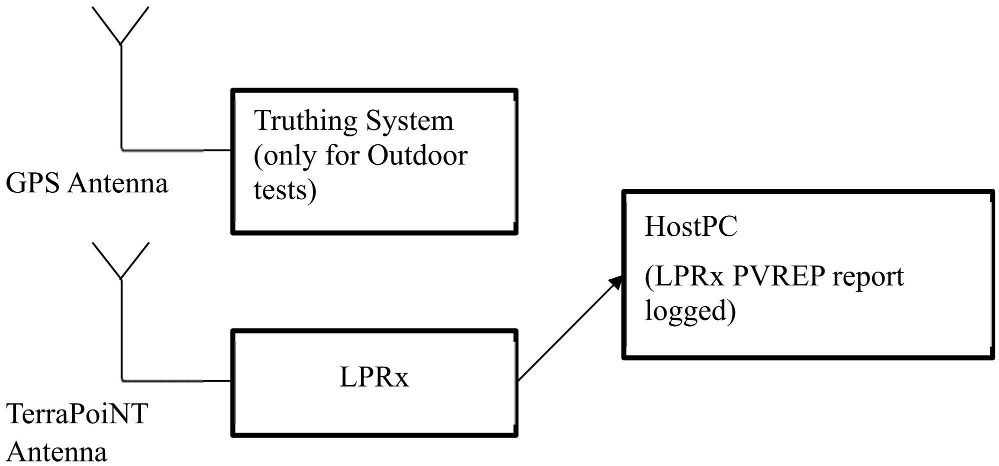


Figure 10: Positioning and Navigation Test Setup

The PVREP format is tabulated in Table 7. The highlighted cells in green indicate the fields providing GPS timestamp information and the cells marked in yellow indicate the position and velocity information.

Field	Name	Type	Unit	Description	Format (Max number of digits)	Range
1	PVREP	String	---	Report Name	5	---
2	LTime	Integer	Milliseconds	This is the local time based on the free-running counter (called fcount). It represents the local receiver time at which the PVREP message report and sent out over the serial interface to the host device	10	0 to 9999999999
3	FixAttempt	Integer	---	Number of times position and velocity fix has been attempted	5	---
4	NumPRanges	Integer	---	Number of beacon measurements used in the fix computation over the past one second	2	0 to 40
5	FixLTime	Integer	Milliseconds	Local receiver Fcount value at Fix instant. It	10	0 to 9999999999

				represents the time at beginning of the time window used for TOA measurement		
6	GPSWeekNum	Integer	---	GPS Week Number at the fix instant (full GPS week number including roll overs)	6	---
7	GPSTOW	Integer	Milliseconds	GPS Time of week in milliseconds at the fix instant	10	---
8	GPSStatusValid	Integer	---	Validity flag for GPS Time field, 1-> valid time in GPS Week Num and GPSTOW fields, else those two fields should not be used.	1	---
9	FixValid	Hexadecimal	---	This field represents binary bit field description and is represented as 4 hexadecimal digits. Bit0 -> position valid Bit Bit4-> velocity valid Bit Bit5Bit6 -> 00 => valid Altitude Bit9-> sensor solution valid	4	---
10	Lat	Float	Degrees	Latitude +/- 90 degrees	3.7	-90 to 90
11	Lon	Float	Degrees	Longitude +/- 180 degrees	4.7	-180 to 180
12	Alt	Float	Meter(s)	Height of the receiver above the WGS84 ellipsoid	5.2	---
13	2D quality	Float	---	2D measurement quality (Reserved for NextNav use)	4.2	---
14	AltUnc2D	Float	Meter(s)	Altitude Uncertainty in meters (confidence of 1-sigma)	4.2	---

15	PosUnc2D_majorAxis	Float	Meter(s)	Position Uncertainty Major Axis in meters (confidence of 1-sigma)	4.2	---
16	PosUnc2D_minorAxis	Float	Meter(s)	Position Uncertainty Minor Axis in meters (confidence of 1-sigma)	4.2	---
17	PosUnc2D_orientation	Float	Radians	Position Uncertainty Major Axis orientation in radians	4.2	---
18	Vel-N	Float	Meter(s)/ second	Velocity in North co-ordinate in meter/sec	4.2	---
19	Vel-E	Float	Meter(s)/ second	Velocity in East co-ordinate in meter/sec	4.2	---
20	Vel-D	Float	Meter(s)/ second	Velocity in Down co-ordinate in meter/sec	4.2	---
21	VelN-Unc	Float	Meter(s)/ second	Velocity North Uncertainty 1-sigma (meter/sec)	4.2	---
22	VelE-Unc	Float	Meter(s)/ second	Velocity East Uncertainty 1-sigma (meter/sec)	4.2	---
23	VelD-Unc	Float	Meter(s)/ second	Velocity Down Uncertainty 1-sigma (meter/sec)	4.2	---
24	CS	Hexadecimal	---	Byte wise Checksum (preceded by *). The checksum is computed as in NMEA	2	---

Table 7: PVREP Message Format

5.5.2 Timing Test Setup

The timing test setup consists of the NextNav Timing Receiver (NTR) and a timing truth equipment that measures error. Figure 11 shows the test setup for performing the timing tests. Details of this set up are discussed next.

The Calnex, which is standard timing truth equipment, was used to measure the timing accuracy of the system. It has an inbuilt GPS receiver which can generate a timing pulse when connected to the external antenna. Once the GPS-based PPS pulse is available, the equipment can be put into transport mode, wherein the internal Rubidium clock maintains the PPS pulse stability and allows the equipment to be moved into any desired location including indoors. The Calnex can also accept an external reference time pulse, and work as time interval counter to measure the time error between reference pulse and the TerraPoiNT time pulse. When the Calnex equipment is not available, a time interval counter can measure the difference between the estimated pps pulse and the truth reference pulse to compute the time error.

In the JRC tests, the Calnex was provided with the JRC timing truth pps pulse signal for comparison with the receiver pps since it was readily available in the lab at the timing test point. In the SJC tests, the Calnex was supplied with the GPS signal and used to generate a GPS-disciplined pps for comparison with the receiver pps.

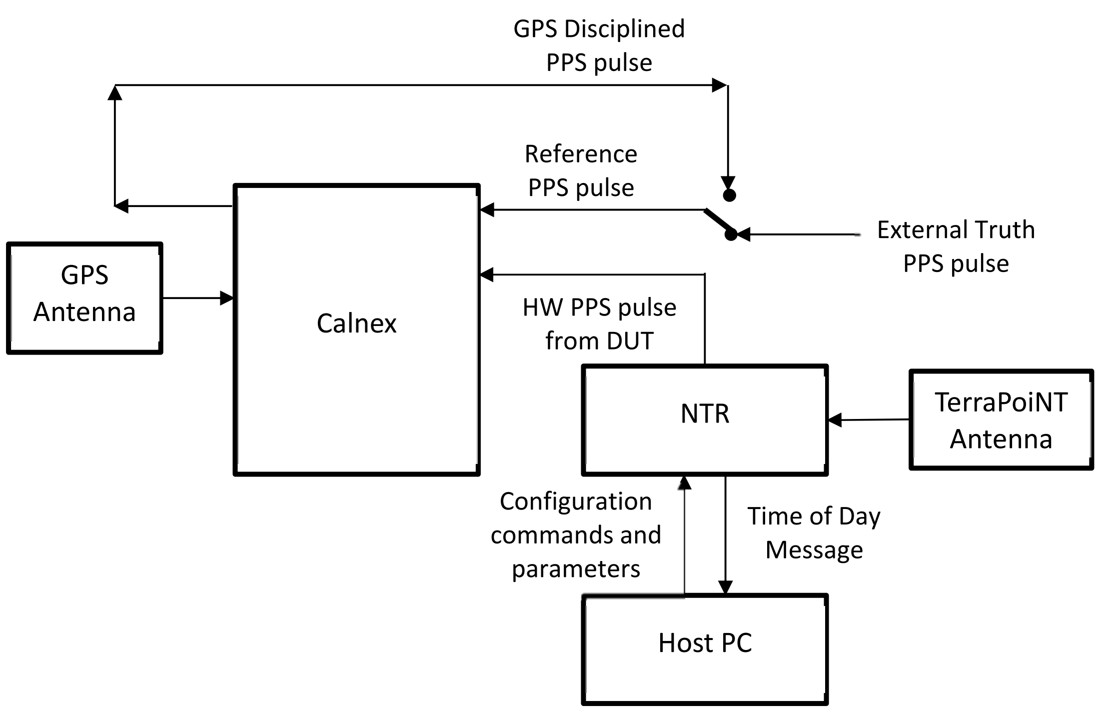


Figure 11: Timing Truth and Measurement Setup

The NTR reports UTC time at a second resolution through the time of day (TOD) message. This TOD message corresponds to the instant at which the PPS is generated, and the format of the message is tabulated in Table 8**Error! Reference source not found.**

Field	Name	Type	Description	Format (Max number of digits)
1	GPZDA	String	Report name	
2	Hhmmss	Integer	The first 2 digits represent hour information of the UTC time at the PPS Next 2 digits represent minute information of the UTC time at the PPS The last 2 digits represent second information of the UTC time at the PPS	6
3	dd	Integer	Day information of the UTC time at the PPS	2
4	mm	Integer	Month information of the UTC time at the PPS	2
5	yyyy	Integer	Year information of the UTC time at the PPS	4

Table 8: Time of Day Message from NTR (GPZDA)

The test points were pre-surveyed and provided to NTR as configuration during the tests. NTR was configured to select a particular beacon for deriving timing information. NTR outputs a time of day (TOD) message on the serial interface which is timestamped using the host PC connected to the NTR. The host PC time was synchronized to UTC time before the start of the test, so that PC timestamp latched with the TOD message can be used to compare the absolute time information.

6 TEST DESCRIPTION

6.1 Description of Timing Tests

6.1.1 Scenario T1C: System Verification

Table 9 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T1C
Test Name	System Verification
Objective	To assess the network is stable and operating as per specifications
Output	1-PPS and TOD message
Time to execute	1 hour
Metrics	None. This test is meant to verify functionality only
Location	JRC

Table 9: Scenario T1C - System Verification

The setup and procedure followed for the system verification test is described below:

- Setup the beacons and start transmission
- Allow the beacons to stabilize
- Verify the network data to ensure no alarms are reported for beacons
- Switch the TerraPoiNT network in GNSS-free mode 20 minutes before the test
- Use the timing measurement setup shown in Figure 11
- Configure the test location to the DUT
- Setup the DUT to track individual beacon in the network
- Collect data to measure the PPS error by comparing PPS with truth reference

Table 10 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 10: Risks for Scenario T1C

6.1.2 Scenario T2I and T2J: Short-Term Clock Stability

Table 11 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T2I, T2J
Test Name	Short term clock stability
Objective	To assess the short-term time stability and synchronization
Output	1-PPS
Time to execute	Maximum duration limited to spectrum restrictions
Metrics	TE
Location	T2I: Lab at JRC T2J: Backup test in Sheltered building in SJC

Table 11: Scenario T2I and T2J - Short-Term Clock Stability

The setup and procedure followed for short term clock stability test is described below:

- Ensure the beacons are setup and transmission are started
- Allow the beacons to stabilize
- Verify the network data to ensure no alarms are reported for beacons
- Switch the TerraPoiNT network to GNSS-free mode 20 minutes before the test
- Use the timing measurement setup shown in Figure 11
- Configure the DUT by providing the test location as input
    - For T2I, the test was done in the lab at JRC at location marked as ‘NTR’ in Figure 12
    - For T2J, the test was done at SJC in a room inside a sheltered building as shown in Figure 13
- Setup the DUT to track specific beacon in the network
- Collect data to measure the PPS error by comparing PPS with truth reference
- After the test is complete, use the collected data to obtain the test metrics

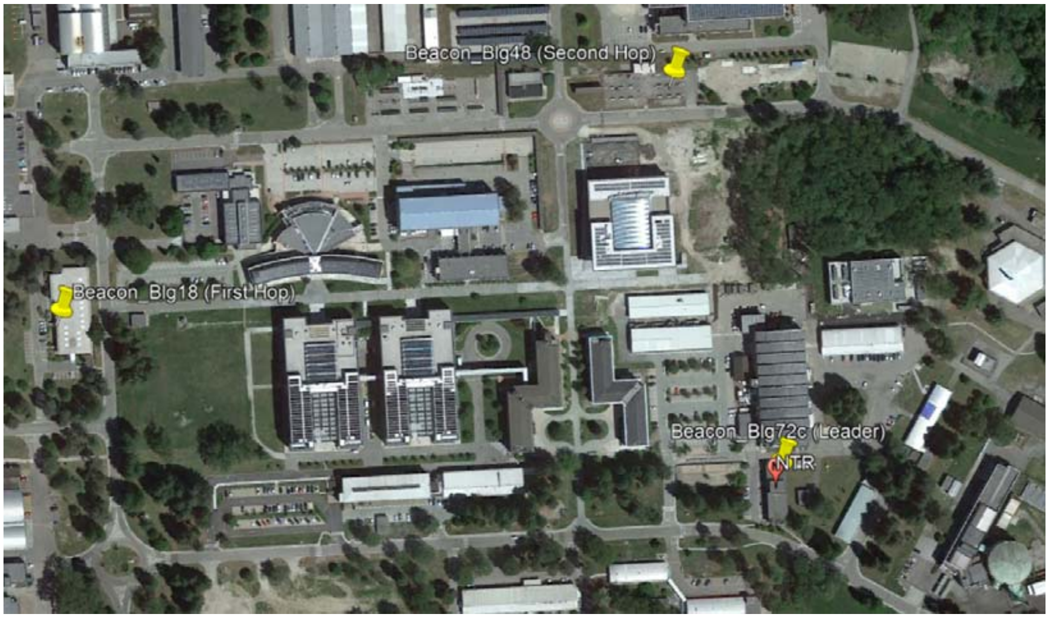


Figure 12: Timing Test Location at JRC Lab

Figure 13: Timing Test Location at SJC

Table 12 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 12: Risks for Scenario T2I and T2J

6.1.3 Scenario T3H: Medium-Term Clock Stability

Table 13 provides a tabular test summary including test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T3H
Test Name	Medium term clock stability
Objective	To assess the medium-term time stability and synchronization
Output	1-PPS
Time to execute	14 days
Metrics	TE, AVAR
Location	Sheltered building in SJC

Table 13: Scenario T3H: Medium-Term Clock Stability

The setup and procedure followed for medium term clock stability tests is described below:

- Ensure the beacons are setup and transmission are started
- Allow the beacons to stabilize
- Verify the network data to ensure no alarms are reported for beacons
- Switch the TerraPoiNT network in GNSS-free mode 48 hours before the test
- Use the timing measurement setup shown in Figure 11
- Configure the DUT by providing the test location as input
    - Test T3H was performed at SJC in a room inside a sheltered building as shown in Figure 13
- Setup the DUT to track specific beacon in the network
- Collect data to measure the PPS error by comparing PPS with truth reference
- After the test is complete, use the collected data to obtain the test metrics

Table 14 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 14: Risks for Scenario T3H - Medium-Term Clock Stability

6.1.4 Scenario T4F: Resilience and Network Monitoring

Table 15 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T4F
Test Name	Resilience and network monitoring
Objective	To assess the robustness of the system
Output	1-PPS
Time to execute	1 hour
Metrics	TE
Location	Sheltered building in SJC

Table 15: Scenario T4F - Resilience and Network Monitoring

The setup and procedure followed for Resilience and Network Monitoring test is described below:

- Ensure the beacons are setup and transmission is started
- Allow the beacons to stabilize
- Verify the network data to ensure no alarms are reported for beacons
- Switch the TerraPoiNT network in GNSS-free mode 48 hours before the test
- Use the timing measurement setup shown in Figure 11
- Configure the DUT by providing the test location as input.
    - The test location was the same as shown in Figure 13
- Setup the DUT to automatically select amongst beacons in the network
- Collect data to measure the PPS error by comparing PPS with truth reference
- Determine which beacon is used for obtaining time after 15 minutes from start of test
- Turn off the transmission of that beacon for 15-30 minutes and then turn on the transmission of the beacon
- After the test is complete, use the collected data to obtain the test metrics. The metrics were computed separately for segments corresponding to before and after beacon transmission turn off.

Table 16 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 16: Risks for Scenario T4F - Resilience and Network Monitoring

6.2 Description of Positioning and Navigation Tests

Static outdoor 3D, static indoor 3D and navigation tests were executed within the network coverage area to determine 3D positioning performance. The tests were repeated multiple times to assess the performance across time.

In the JRC network, Z-only accuracy was showcased at different floors in an indoor building. The JRC network had only 3 beacons due to which a full 3D performance could not be demonstrated in that network. The 3D tests were done in the SJC network.

6.2.1 Scenario T5C: System Verification

Table 17 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T5C
Test Name	System Verification
Objective	To assess the network is stable and operating as per specifications
Output	Measure the altitude output at two different floors in a building
Time to execute	1 hour
Metrics	None. This test is a functional test.
Location	JRC

Table 17: Scenario T5C - System Verification

The setup and procedure followed for the system verification test is as described below:

- Setup the beacons and start transmission
- Allow the beacons to stabilize
- Verify the network data to ensure no alarms are reported for beacons
- Switch the TerraPoiNT network to GNSS-free mode 20 minutes before the test
- Use the positioning setup shown in Figure 10
- Test the DUT at different floors of a building with pre-surveyed Z-coordinates and measure the Z-performance.
- Compute Z error by comparing estimated Z with truth Z and compute performance statistics
- Table 18 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 18: Risks for Scenario T5C - System Verification

6.2.2 Scenario T6A: Kinematic

Table 19 provides a summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T6A
Test Name	Kinematic
Objective	To assess the 3-D position performance under kinematic conditions
Output	3-D position report from the DUT
Time to execute	< 1 hour
Metrics	CDF of 2-D position, Z error Time series of ENU errors
Location	SJC

Table 19: Scenario T6A - Kinematic

The setup and procedure followed for kinematic positioning and navigation test is as described below:

- Verify the network data is stable (ensure no alarms are reported for beacons)
- Switch the TerraPoiNT network to GNSS-free mode 48 hours before the test
- Use the positioning setup shown in Figure 10 to obtain truth data along with receiver position estimates
- Drive the setup in the SJC area covering sub-urban and urban area using TerraPoiNT + IMU solution. The test route is shown in Figure 14.
- Collect PVREP reports from DUT and data from the truthing system during the drive
- Post process the collected truth data using the carrier phase measurements and sensor data from high grade IMU to obtain a 'cm' level accurate position, which is considered as truth for comparisons
- This truth data is compared with the LPRx output (PVREP) to compute the position error after aligning the GPS timestamp of the truth and LPRx
- The position error time series and its CDF are computed for each test and provided as the performance metrics

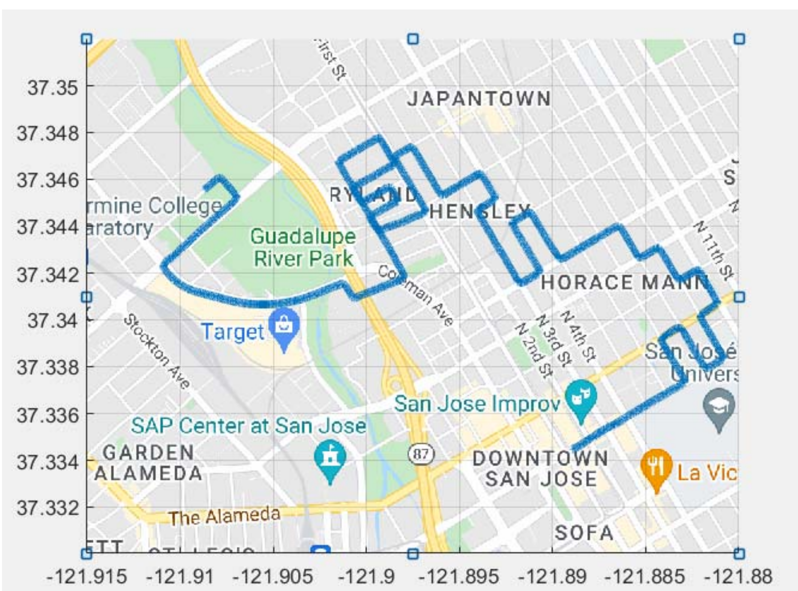


Figure 14: Kinematic Test Route

Table 20 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 20: Risks for Scenario T6A - Kinematic

6.2.3 Scenario T7C: Static Short-Term and Long-Term Z

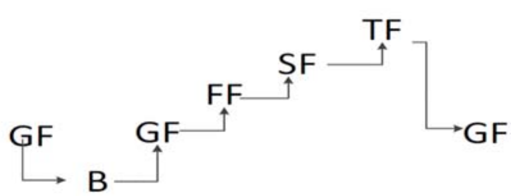
Table 21 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T7C
Test Name	Static tests – Z only
Objective	To assess the Z performance under static condition
Output	Z position report from the DUT
Time to execute	< 1-day
Metrics	CDF and Time series of Z error
Location	JRC (Building-102)

Table 21: Scenario T7C - Static Short-Term and Long-Term Z

The setup and procedure followed for z-tests is described below:

- Verify the network data is stable (ensure no alarms are reported for beacons)
- Switch the TerraPoiNT network to GNSS-free mode 20 minutes before the data capture
- Use the receiver setup shown in Figure 10
- Test at different test points in building BG102 and outdoor locations in the JRC campus as mentioned in Figure 3
- Move from one test point to another in a loop, collect data for 2 minutes at each test point



- The test was performed in the above sequence and then the path was re-traced back to the starting point
- Collect the PVREP reports from the DUT at each test point
- Compute Z error by comparing estimated Z with truth Z and compute performance statistics

- The time series and CDF of the Z error are provided as performance metrics

Table 22 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 22: Risks for Scenario T7C - Static Short-Term and Long-Term Tests

6.2.4 Scenario T7D: Static Short-Term and Long-Term 3D

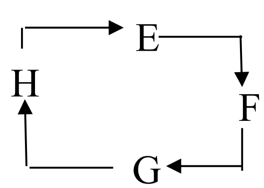
Table 23 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T7D
Test Name	Static tests – 3-D only
Objective	To assess the 3-D performance under static condition
Output	3-D position report from the DUT
Time to execute	< 1-day
Metrics	CDF and Time series of 2D error and Z error
Location	SJC

Table 23: Scenario T7D - Static Short-Term and Long-Term 3D

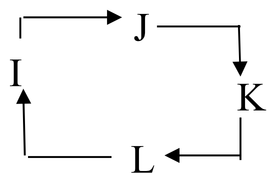
The setup and procedure followed for the 3D static tests is described as follows:

- Verify that the network data is stable (ensure no alarms are reported for beacons)
- Switch the TerraPoiNT network to GNSS-free mode 48 hours before the test
- Use the receiver setup shown in Figure 10
- The test was done at different outdoor test points in the SJC campus listed in Figure 8.
  - Move from one test point to another in a loop, collect data for 5 minutes at each test point



  - Repeat the test loop at least 2 times
- Indoor test points were located inside different buildings
  - A loop of tests was performed as shown below

- The loop of tests was repeated twice at the same test points



- Collect the PVREP reports from the DUT at each test point
- Compare the 3D position estimates from the DUT to the truth 3D data
  - Static test points are surveyed to obtain the truth 3D data
- The CDF of 2D error and Z error along with time series of the ENU errors are provided as performance metrics.

Table 24 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 24: Risks for Scenario T7D - Static Short-Term and Long-Term 3D

6.2.5 Scenario T8J: Resilience and Network Monitoring

Table 25 provides a tabular summary of the test including the test ID, test name, objective of the test, the key outputs, the time required to execute the test, the test metrics, and the test location.

Test ID	T8J
Test Name	Resilience and network monitoring
Objective	To assess the 3-D performance
Output	3-D position report from the DUT
Time to execute	< 1-day
Metrics	CDF and Time series of 2D error and Z error
Location	SJC

Table 25: Scenario T8J - Resilience and Network Monitoring

The setup and procedure followed for Resilience and Network Monitoring Test is described as follows:

- Tests were performed at one outdoor and one indoor location similar to Test T7D
- TerraPoiNT network was switched to GNSS-free mode 48 hours before the test
- Beacons were turned ON/OFF during the tests
- Collect the PVREP reports from the DUT at each test point.
- Compare the 3D position estimates from the DUT to the truth 3D data
  - Static test points are surveyed to obtain the truth 3D data

- The CDF of 2D error and Z error along with time series of the ENU errors are provided as performance metrics

Table 26 summarizes the risks that were considered in this test, and the actions that were taken to mitigate the risks. None of these risks materialized during this test.

Risk	Probability	Severity	Action
Receiver connectivity failure	Low	Medium	Monitor connectivity, Use the internal logs stored on the receiver
Beacon hardware failure	Low	High	Monitor network beacon status and stop/reset the beacon
Beacon connectivity failure	Medium	Low	Monitor data frequently
Receiver failure	Low	High	Monitor receiver health and use spare receiver if needed

Table 26: Risks for Scenario T8J - Resilience and Network Monitoring

7 TEST RESULTS

The measured data collected during the tests were compared with the truth data using the UTC timestamp to obtain the error estimates for each scenario. The network logs were used to demonstrate the network synchronization performance during the tests.

7.1 Timing Test Results

7.1.1 Scenario T2I: Short-Term Clock Stability Test Results at JRC

The short-term clock stability test was performed in the JRC campus. A 3-beacon network was deployed in the JRC campus and timing tests were performed to derive timing using first and second hop beacons as shown in Figure 15. The timing performance of NTR was compared against the timing reference from the JRC lab using Calnex equipment. The test time was restricted to a duration of 30 minutes per timing hop due to constraints on TerraPoiNT signal transmission the JRC campus.

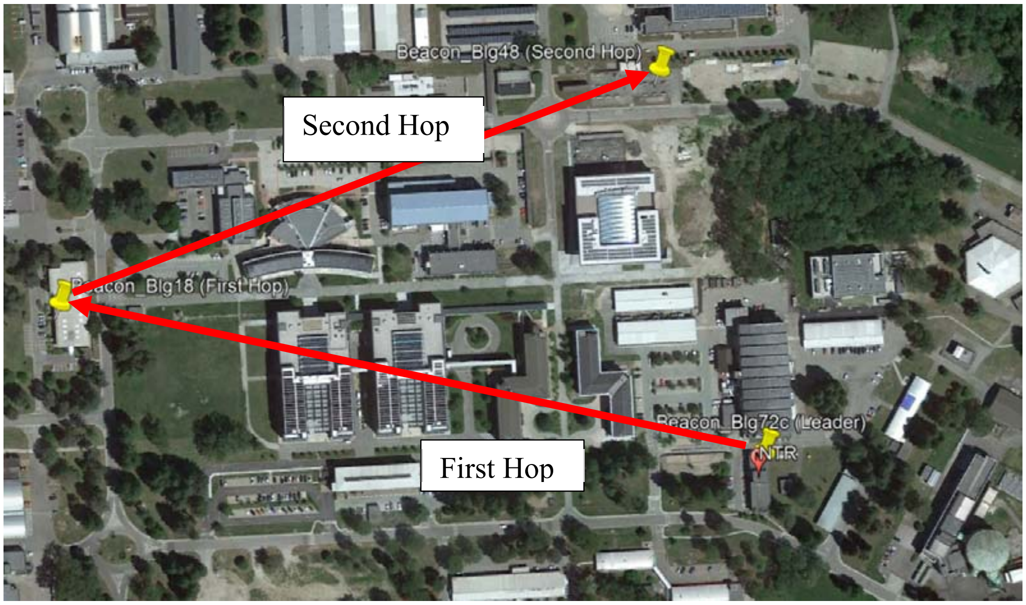


Figure 15: Timing Test Location at JRC

The test results for short term clock stability are shown in Figure 16 and Figure 17 with the statistics tabulated in Table **27**. The results indicate that the TerraPoiNT receiver is able to provide a very stable and accurate timing solution. The signal path from the first hop beacon to the timing receiver was blocked by a building resulting in absence of any line of sight (LOS) path and hence the result shows higher time error compared to the timing error from second hop. While the multipath added a bias error to time solution, the variability of time error (representing stability) was within 10ns for both the tests. The results indicate the TerraPoiNT system can provide accurate and stable timing results relatively insensitive to the number of timing paths(hops) in the system.

Note that the short-term spikes observed in the timing result are likely an artifact of the time interval counter within the Calnex equipment and not an artifact of the NTR receiver. The NTR receiver uses a stable OCXO clock, and the update rate is much slower than the rate of occurrence of spikes. Therefore, the spikes do not come from the NTR receiver.

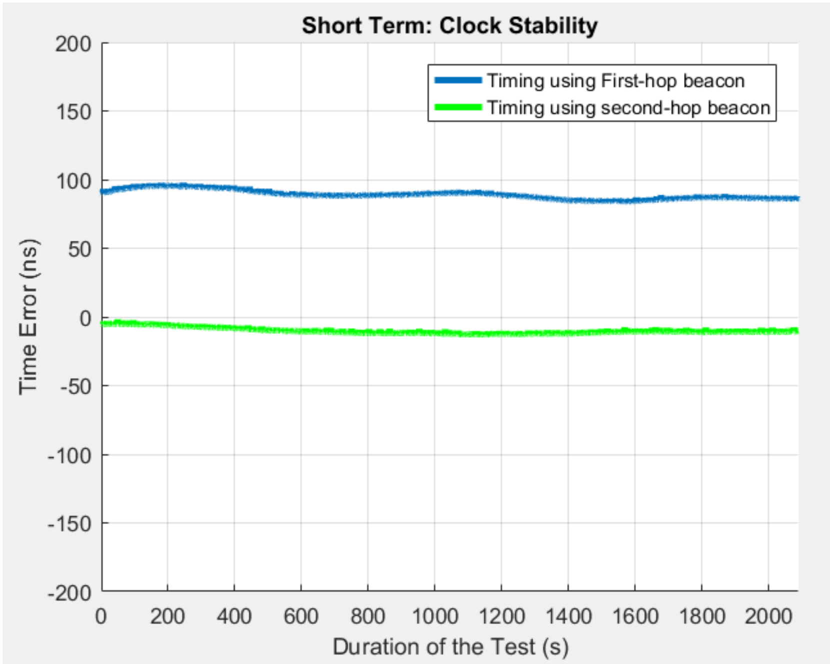


Figure 16: Time Series of Time Error for Short-Term Clock Stability Test at JRC

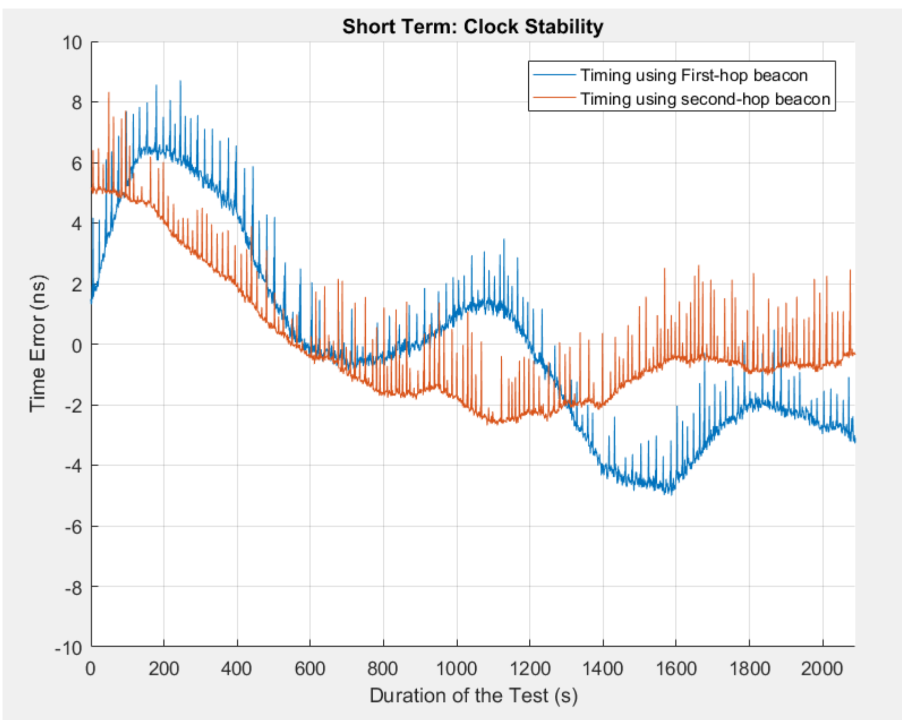


Figure 17: Time Series of Time Error (mean removed) for Short-Term Clock Stability Test at JRC

Test Case ID	Test Time in UTC	Duration of the test (s)	Time Error (ns)				
			10%	25%	50%	75%	90%
T2I-1 (Second-hop)	26-Jan-2022 18:10:32 to 26-Jan-2022 18:45:51	2120	-12	-12	-11	-9	-6
T2I-2 (First-hop)	26-Jan-2022 18:53:20 to 26-Jan-2022 19:13:08	2088	85	86	89	90	95

Table 27: Time Error Statistics for Short-Term Clock Stability Test at JRC.

7.1.2 Scenario T2J: Short-Term Clock Stability Test Results at SJC

The short-term clock stability timing test was performed in the SJC-APNT network for a duration of 2 hours. The NTR was set up in a sheltered building and RB-smoothened GPS time was used as the truth reference to compare the timing performance. The NTR was configured to derive timing from a beacon after two timing hops in the network as shown in Figure 18. Specifically, the receiver located at the yellow pin derived timing from beacon labelled CASFO0239, with the time derivation shown as blue line with the arrow pointing from source to destination in Figure 18. The beacon CASFO0239 derived timing indirectly from leader beacon CASFO0082 through two hops of time transfer (shown as white lines in Figure 18). The first hop of time transfer was from the leader (CASFO0082) to Follower 1 (CASFO0242), and the second hop of time transfer was from Follower1 (CASFO0242) to Follower2 (CASFO0239). The time-error at the NTR was computed relative to the truth timing derived from GPS. The leader beacon in the APNT network utilized Cesium clock and provided a very stable time to the network. The time error of the NTR PPS observed over a 2-hour test is shown in Figure 19 with the statistics tabulated in Table 28**Error! Reference source not found.**.

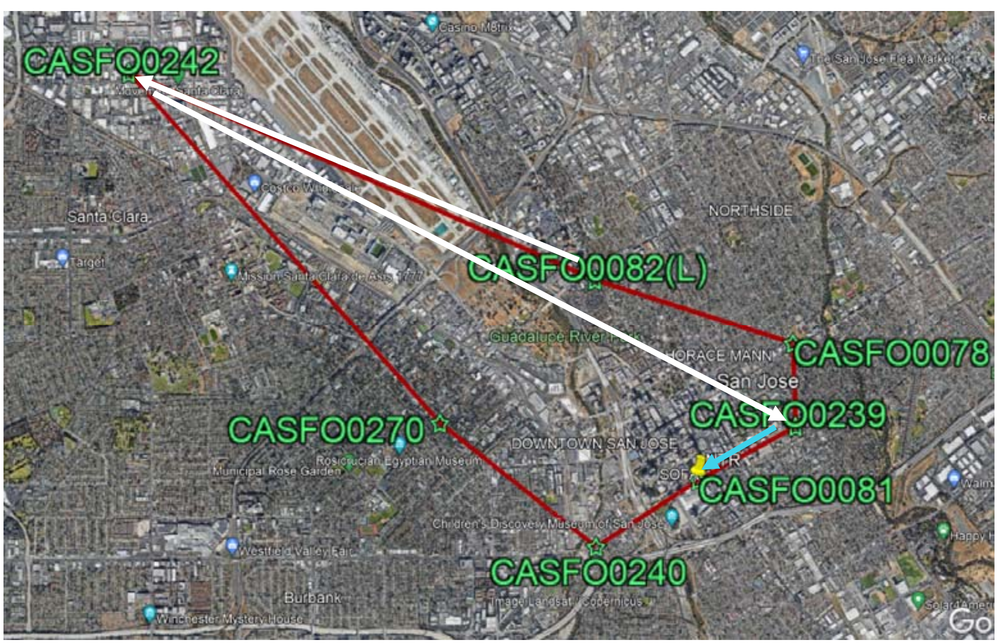


Figure 18: Short and Medium-Term Clock Stability Test Configuration at SJC

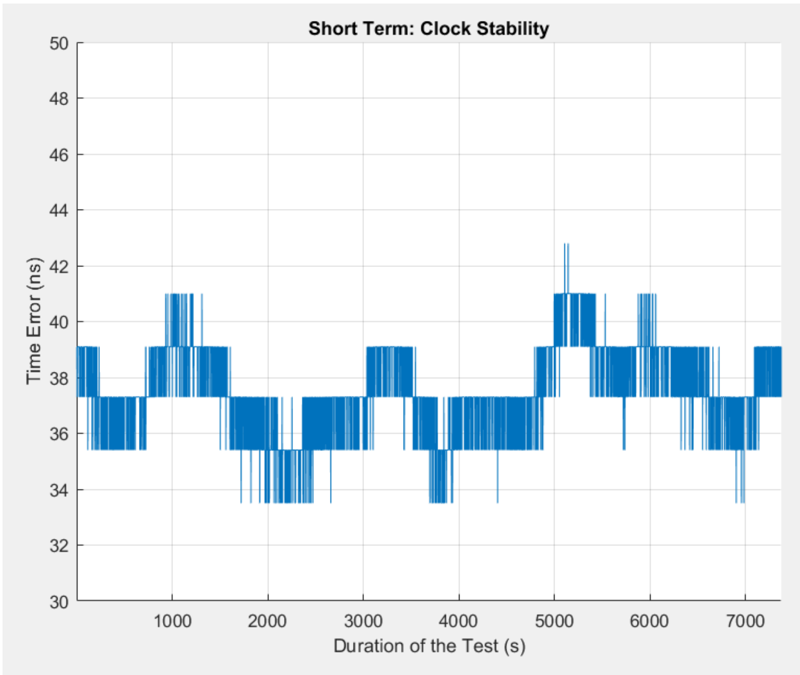


Figure 19: Time Error for Short-Term Clock Stability Test at SJC

Test Case ID	Start Test Time in UTC	Duration of the test (hours)	Time Error (ns)				
			10%	25%	50%	75%	90%
T2J	16-Mar-2022 17:19:47	2	35	37	39	39	39

Table 28: Time Error Statistics for Short-Term Clock Stability Test at SJC

7.1.3 Scenario T3H: Medium-Term Clock Stability Test Results

The medium-term clock stability timing test was performed over ~10-days in the SJC APNT network to showcase the medium-term timing performance. The NTR was setup in a sheltered building and RB-smoothened GPS time was used as the truth reference to compare the timing performance. The NTR was configured to derive timing from a beacon after two timing hops in the network as shown in Figure 18. Specifically, the receiver located at the yellow pin derived timing from beacon labelled CASFO0239, with the time derivation shown as blue line with the arrow pointing from source to destination in Figure 18. The beacon CASFO0239 derived timing indirectly from leader beacon CASFO0082 through two hops of time transfer (shown as white lines in Figure 18). The first hop of time transfer was from the leader (CASFO0082) to Follower 1 (CASFO0242), and the second hop of time transfer was from Follower1 (CASFO0242) to Follower2 (CASFO0239). The time series of time error for medium-term clock stability at shown in Figure 20. The x-axis in Figure 20 shows the duration in the seconds from the start of the test. The corresponding Allan deviation is shown in Figure 21 and statistics are tabulated in Table 29**Error! Reference source not found.**. The results indicate a stable timing performance over ~10-day period indicating TerraPoiNT system can provide an accurate time over a long-term interval.

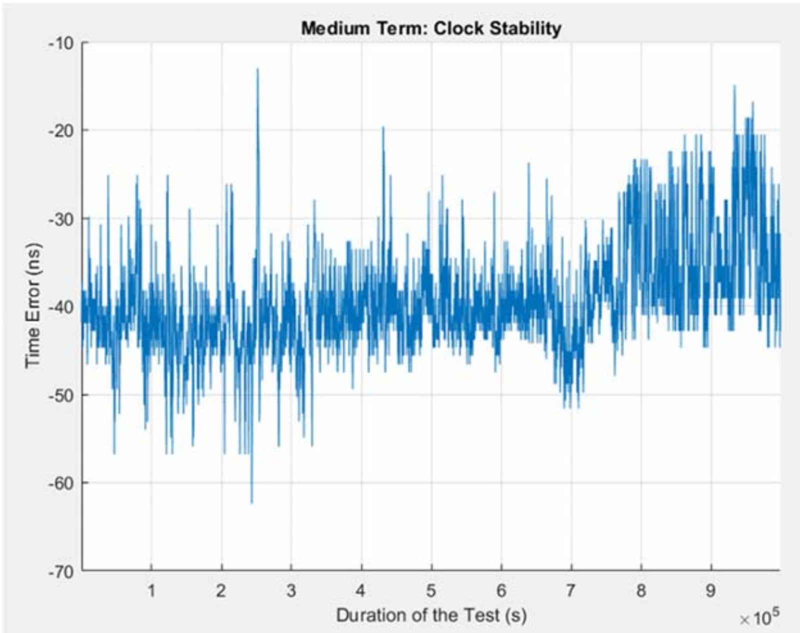


Figure 20: Time Series of Time Error in Medium-Term Clock Stability Test

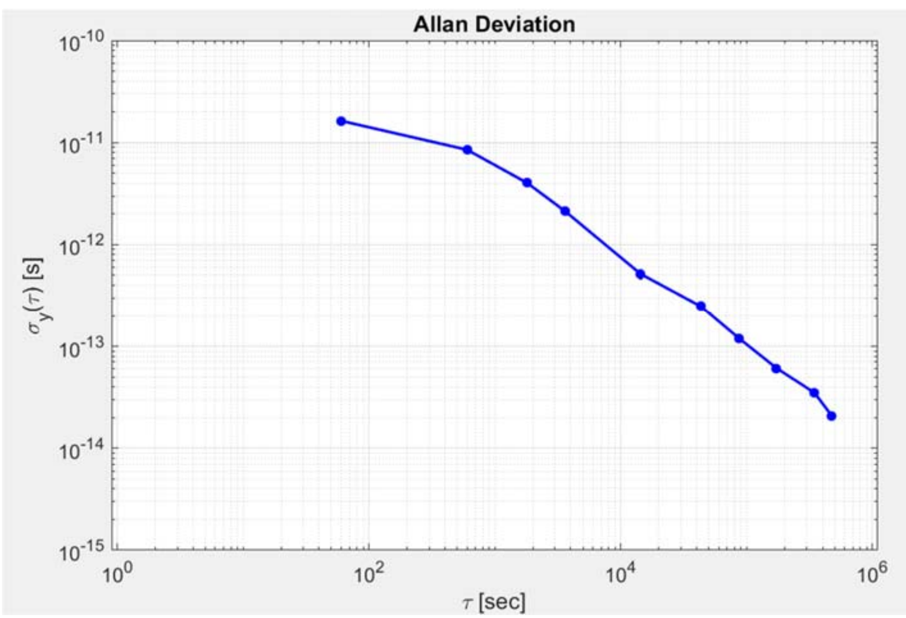


Figure 21: Allan Variance of Time Error in Medium-Term Clock Stability Test

Test Case ID	Start Test Time in UTC	Duration of the test (days)	Time Error (ns)				
			10%	25%	50%	75%	90%
T3H	25-Feb-2022 19:25:07	11.55	-45	-43	-40	-37	-32

Table 29: Time Error Statistics for Medium-Term Clock Stability Test

7.1.4 Scenario T4F: Resilience and Network Monitoring Test Results

The resilience timing test was performed to demonstrate the resiliency and stability of TerraPoiNT network and the NTR. The test was performed to showcase the continuity of timing performance during outage of any beacons in the network. The test was setup to stop transmission of the beacons of up to 2 beacons, which were used by the NTR to derive timing. The test was started with NTR setup to derive timing using a combination of measurements from 3 beacons (referred as Beacon-1, Beacon-2 and Beacon-3). After 30 minutes, the Beacon-1 was forced to stop transmission and the NTR continued to derive timing from two beacons (Beacon-2 and Beacon-3). Another 30 minutes later, Beacon-2 was forced to stop transmission and NTR continued to derive timing from Beacon-3. Figure 25 shows the timing error of the NTR during the entire test. The x-axis in Figure 25 shows the duration in the seconds from the start of the test. The result demonstrates the resilience of the TerraPoiNT system and the NTR, which in combination, provide accurate timing even during any partial network outage if at least one beacon is detectable at the NTR. The NTR makes a smooth transition (intentionally spread over ~500s) in switching its timing source from one beacon to another beacon as shown in Figure 25.

Table 30 shows the time error statistics over the duration of the test. Note that the test started at UTC time 15-Mar-2022 19:44:51 with the NTR using all the 3 beacons to provide a timing pulse. Beacon-1 was forced to stop transmission at UTC time 15-Mar-2022 20:14:50 (1800s after start) and later, Beacon-2 was forced to stop transmission at UTC time 15-Mar-2022 20:44:50 (3600s after start). At UTC time 15-Mar-2022 21:44:50 (7200s after start), both the Beacon-1 and Beacon-2 were made to start transmission.

TerraPoiNT SJC-APNT network has 7 beacons and has multiple time transfer paths to derive and maintain time with respect to the leader beacon as shown in Figure 22. Each beacon has multiple paths to derive and maintain relative time which builds in an inherent robustness into the network. Figure 23 shows the time transfer paths available after Beacon-1 has stopped transmission. Any beacon using Beacon-1 to maintain relative time synchronization will switch to another time transfer path through another beacon in the network. Figure 24 shows the time transfer paths available after Beacon-1 and Beacon-2 are stopped transmission. The beacons continue to maintain relative time synchronization to the leader allowing the NTR to provide accurate timing across any outages.

The results indicate the TerraPoiNT system can provide accurate and precise timing even during outage of few beacons in the system indicating the resiliency of the system against outages.

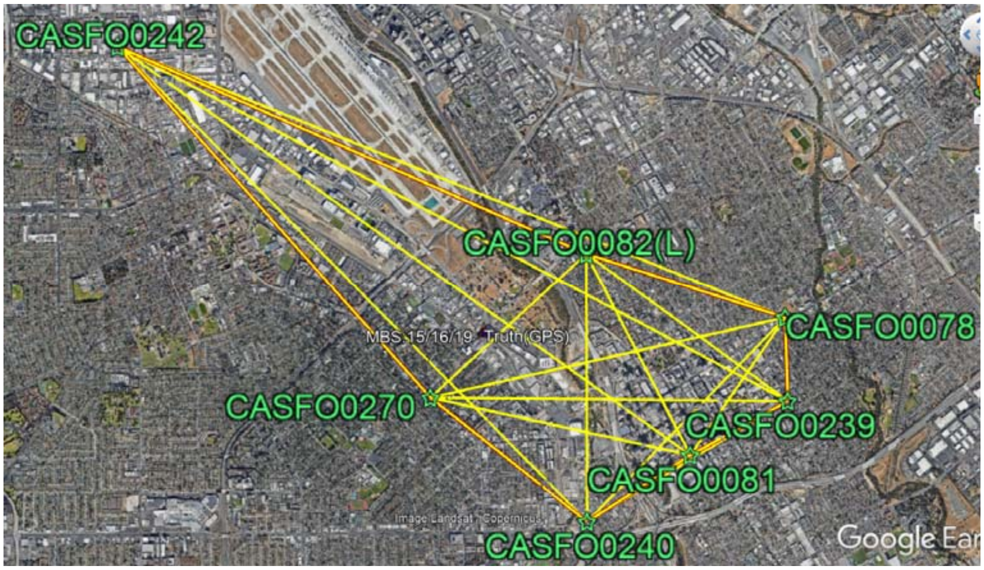
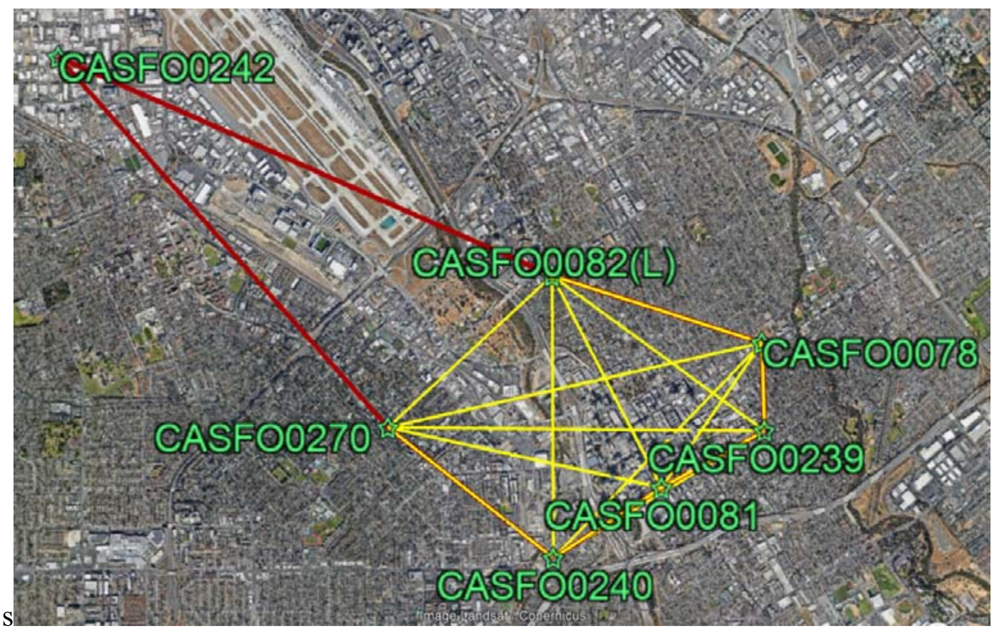


Figure 22: Time Transfer Paths for SJC Network across all beacons



S

Figure 23: Time Transfer Paths for SJC Network after Stopping Beacon-1 (CASFO0242)

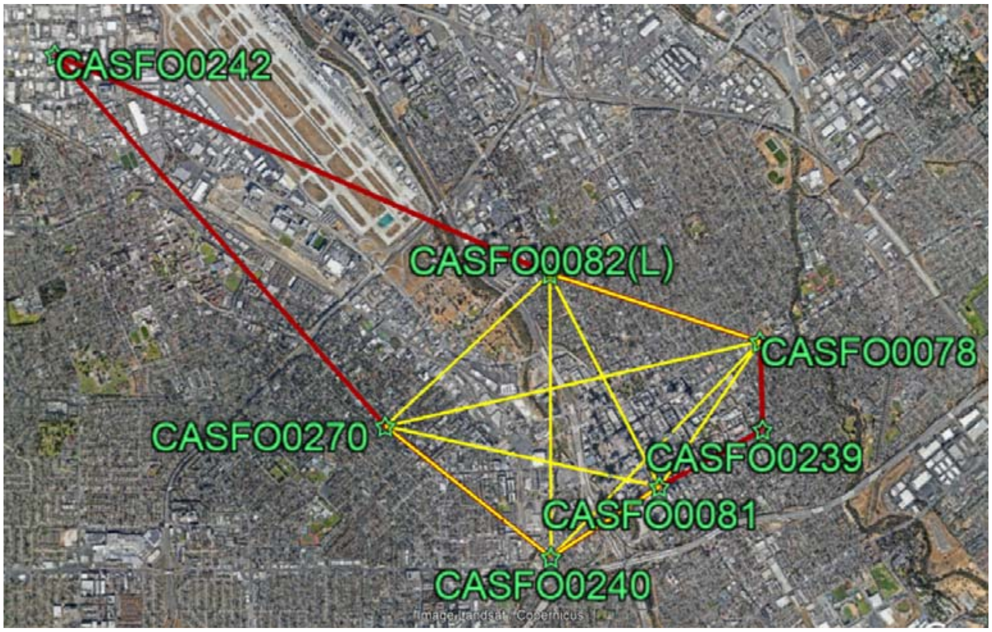


Figure 24: Time Transfer Paths for SJC Network after Stopping Beacon-1 (CASFO0242) & Beacon-2 (CASFO0239)

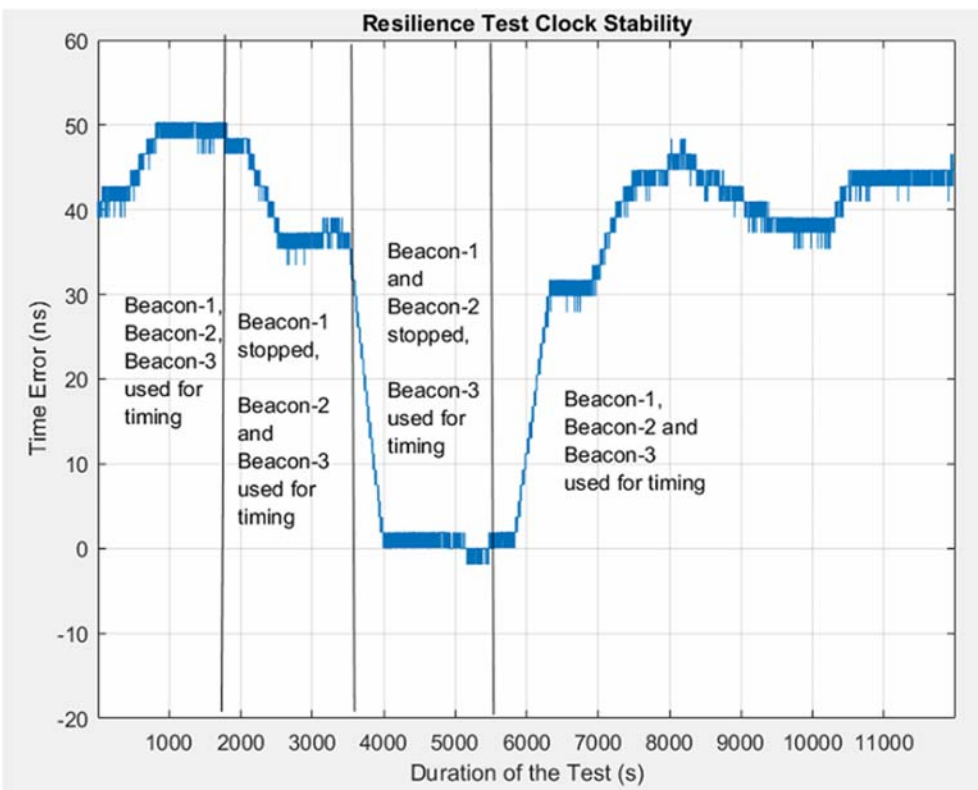


Figure 25: Time Series of Time Error for Resilience and Network Monitoring Test at SJC

Test Case ID	Start Test Time in UTC	Duration of the test	Time Error (ns)				
			10%	25%	50%	75%	90%
T4F	15-Mar-2022 19:44:51	3.33 hours	2	32	41	45	48

Table 30: Time Error Statistics for Resilience and Network Monitoring Test at SJC

7.2 Positioning and Navigation Test Results

7.2.1 Scenario T6A: Kinematic Tests

The kinematic test was conducted in the SJC-APNT network. LPRx receiver was used for this test and drive was performed over a duration of 20 minutes with two trials along the same route. The route used for this test is shown in the Figure 26. The test route includes sub-urban and urban environments allowing to measure the performance in different environments. The truth trajectory was determined by using the Truthing system (as shown in Figure 10). Truthing system provides a post processed time stamped solution using PPS-correct carrier phase measurements providing “cm” level accurate position. This truth position was matched in time with the LPRx output to compute the position error. TerraPoiNT position performance over two trials are shown in Figure 27 and Figure 28. Figure 29 and Figure 30 show the CDFs for the two trials with the corresponding statistics shown in tabular form in Table 31 and Table 32**Error! Reference source not found.Error! Reference source not found.**, respectively. The 2-D error time series for the two trials are shown in Figure 31, while the z-error time series for the two trials are shown in Figure 32.

The results indicate the TerraPoiNT position 2D performance is within 10m (90%) throughout the entire drive and is repeatable across both the trials.

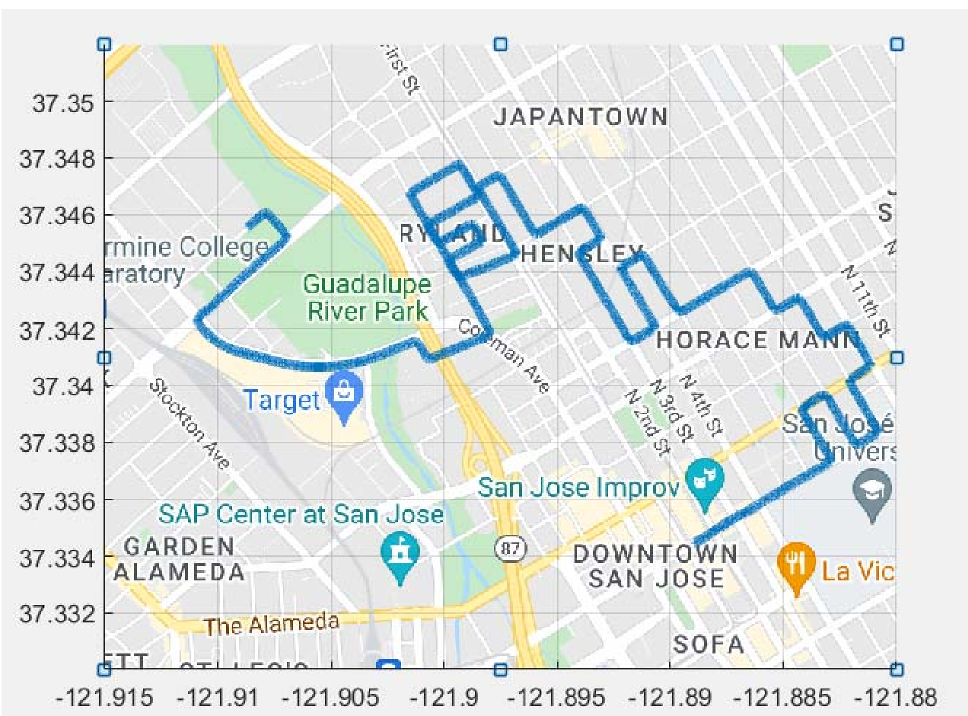


Figure 26: Route for Kinematic Test

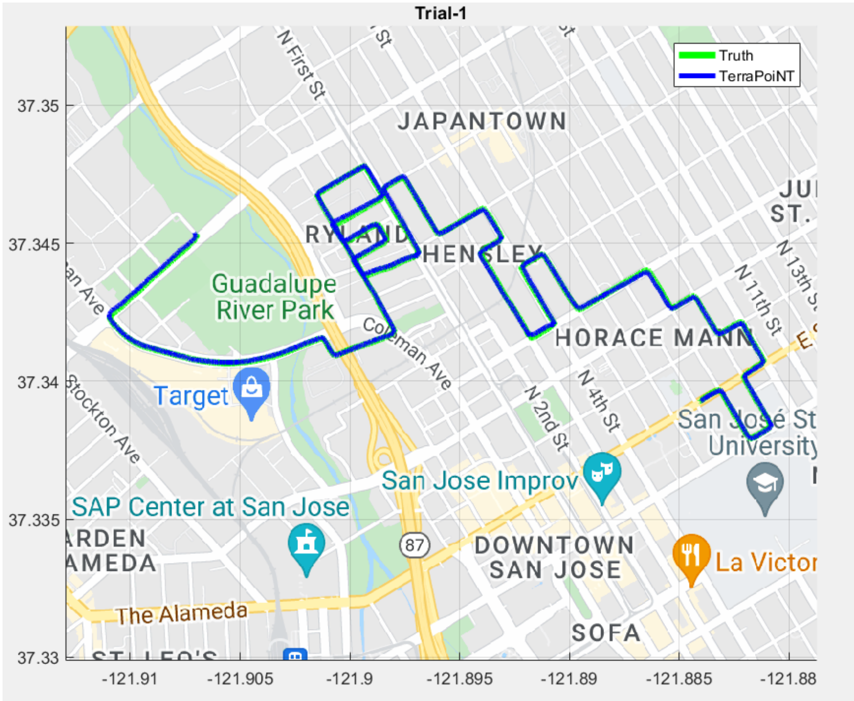


Figure 27: Kinematic Drive 2D Error on map for Trial 1

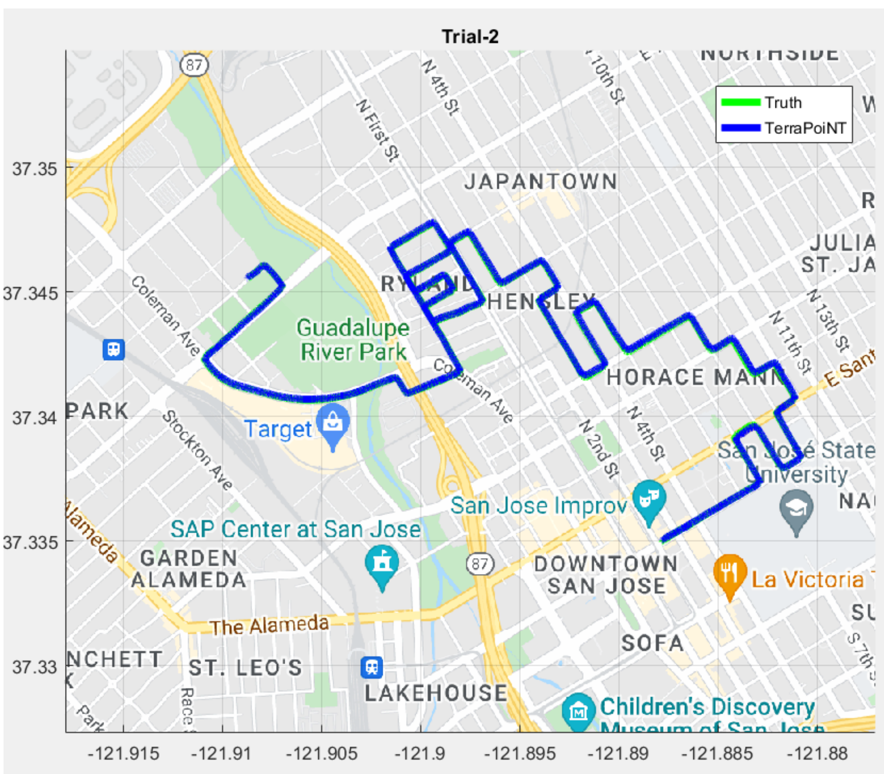


Figure 28: Kinematic Drive 2D Error on map for Trial 2

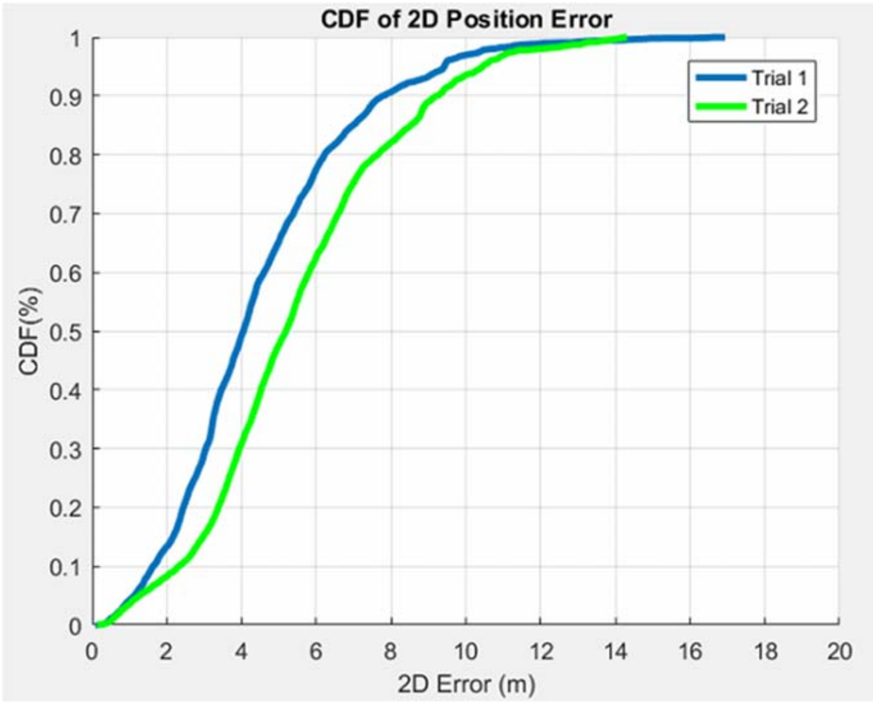


Figure 29: CDF of 2D Position Error for Kinematic Test at SJC

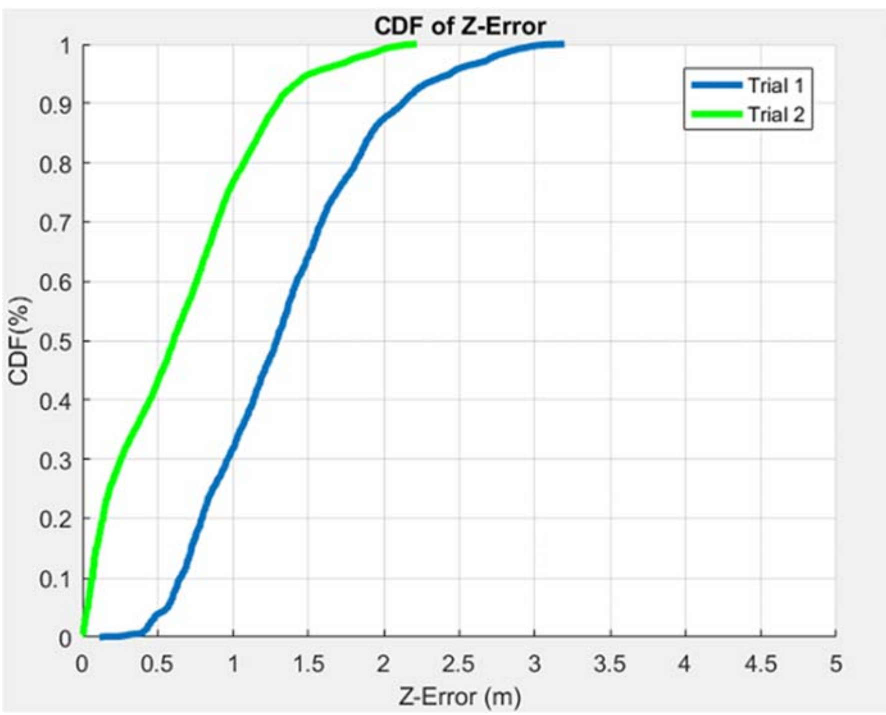


Figure 30: CDF of Z Error for Kinematic Test at SJC

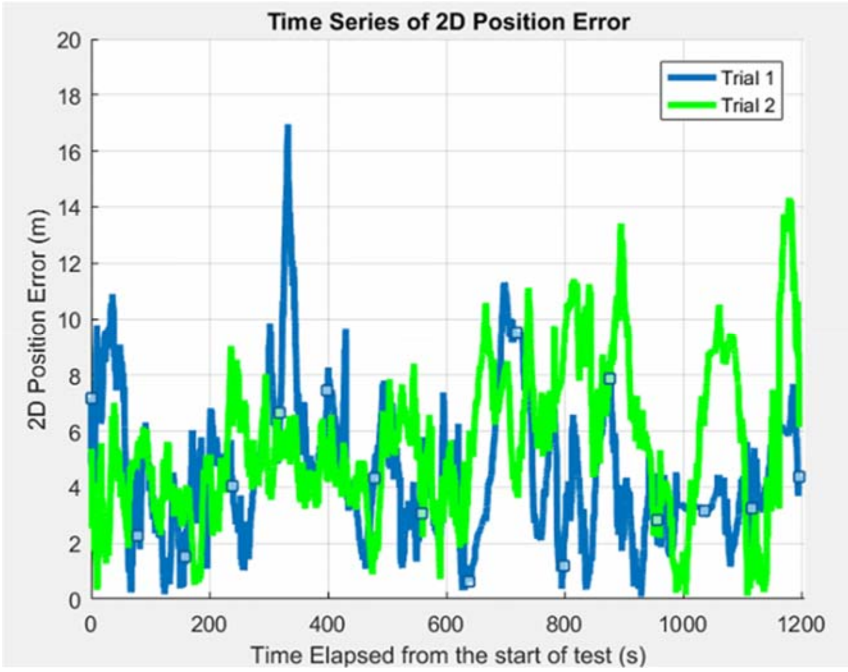


Figure 31: Time series of 2D Position Error for Kinematic Test at SJC

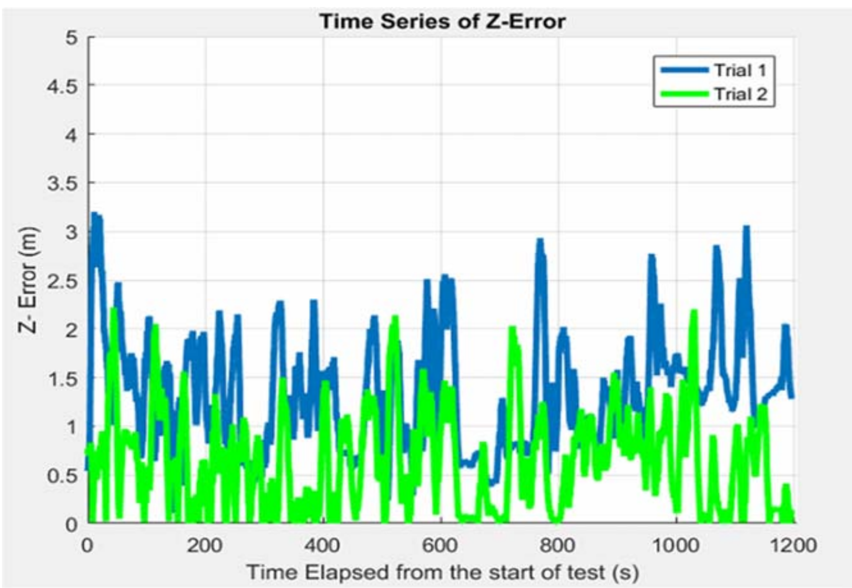


Figure 32: Time series of Z Error for Kinematic Test at SJC

Test Case ID	UTC Start time	Trial Number	Test Duration (s)	Number of fixes	Position Error 2D (m)				
					50 %	25 %	75 %	10 %	90 %
T6A	18-Feb-2022 22:31:33	1	1200	11964	4	3	6	2	8
	09-Feb-2022 19:08:41	2	1200	11962	5	4	7	2	9

Table 31: 2D Position Error Statistics for Kinematic Test at SJC

Test Case ID	UTC Start time	Trial Number	Test Duration (s)	Number of fixes	Z Error (m)				
					50 %	25 %	75 %	10 %	90 %
T6A	18-Feb-2022 22:31:33	1	1200	11964	1.3	0.9	1.7	0.6	2.1
	09-Feb-2022 19:08:41	2	1200	11962	0.6	0.2	1.0	0.1	1.3

Table 32: Z Position Error Statistics for Kinematic Test at SJC

7.2.2 Scenario T7C: Static Short-Term Z-Tests

The static Z-test was performed in the JRC campus at different floors in building 102 inside the JRC campus. LPRx was used to provide Z-information using the 3-beacon network deployed in the JRC campus. Two different walk tests were performed with stationary period per floor as per path shown in Figure 33 and Figure 34.

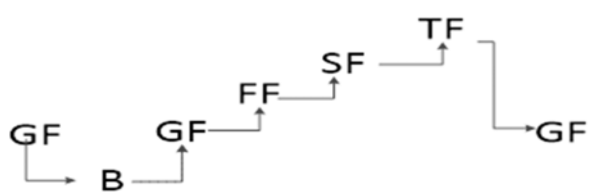


Figure 33: Trajectory for Trial-1 (GF: Ground Floor, B: Basement, FF: 1st Floor, SF: 2nd Floor, TF: Top Floor)

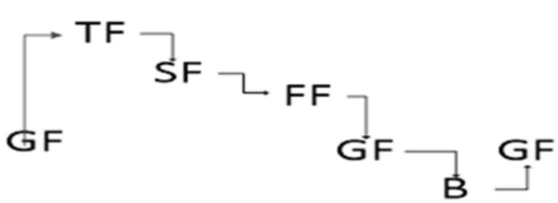


Figure 34: Trajectory for Trial-2 (GF: Ground Floor, B: Basement, FF: 1st Floor, SF: 2nd Floor, TF: Top Floor)

The truth altitude at each floor was measured independently and used to determine the Z-performance. The transition period between floors was skipped for the performance measurement. The Z-performance for Trial1 and Trial 2 are summarized in a box plot in Figure 35. The time series of z-estimates for Trial 1 and Trial 2 shown in Figure 36 and Figure 37, respectively. Figure 38 shows the time series of absolute error z-error for the two trials. The absolute z-error statistics for each floor are tabulated in Table 33**Error! Reference source not found.**. The results indicate Z accuracy is within 1m.

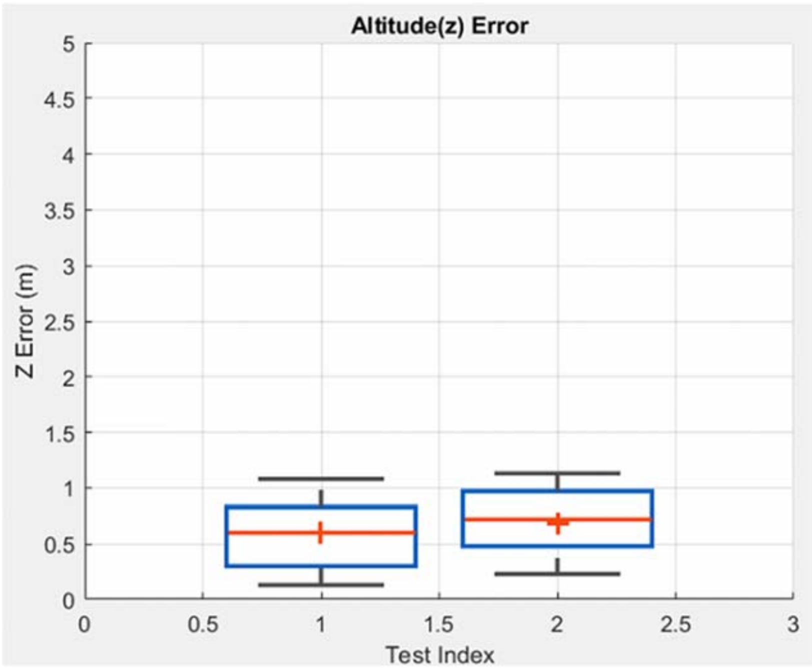


Figure 35: Box Plot of Z Error

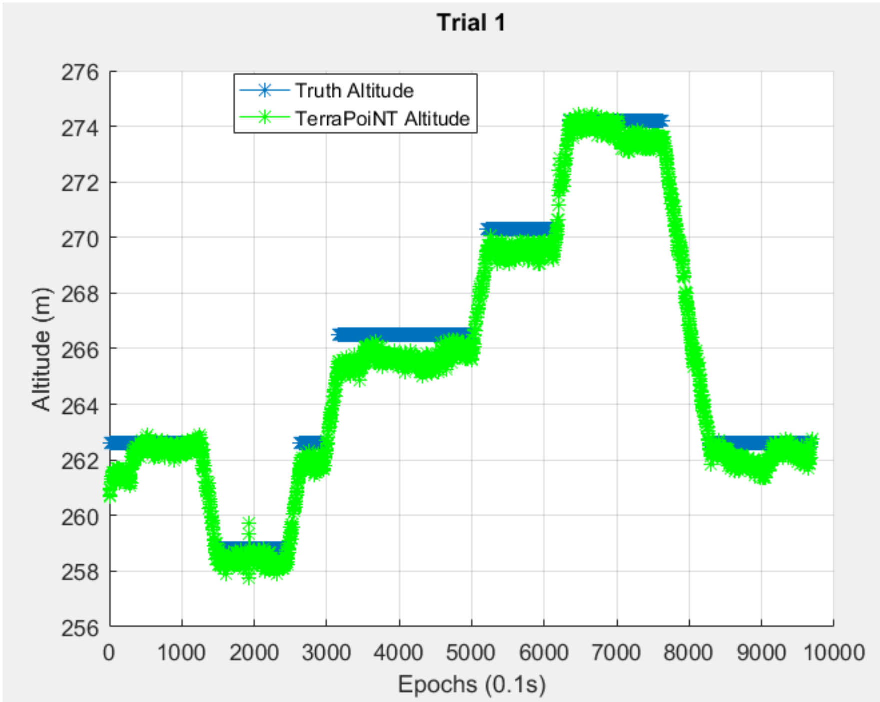


Figure 36: Z Performance for Trial 1 for Z-Test at JRC

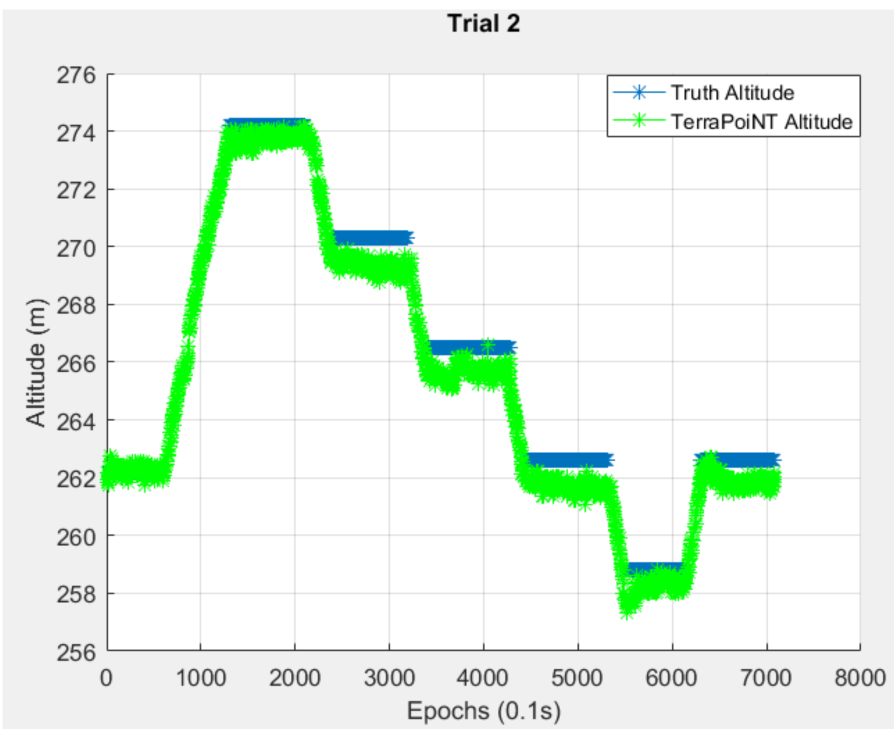


Figure 37: Z Performance for Trial 2 for Z-Test at JRC

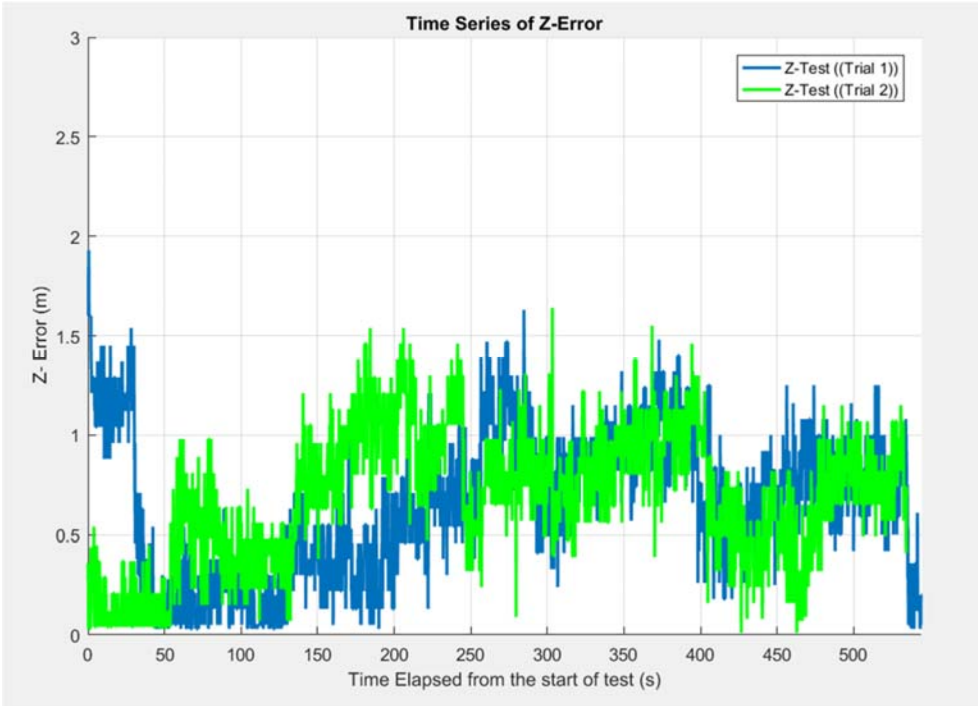


Figure 38: Time series of absolute Z Error for Trial 1 and 2 of Z-Test at JRC

Test Case ID	Number of points	Test Duration (s)	Z Error (m)				
			50%	25%	75%	10%	90%
T7C – Trial 1	8059	969	0.6	0.3	0.8	0.1	1.1
T7C – Trial 2	5346	709	0.7	0.5	1.0	0.2	1.1

Table 33: Z Error Statistics for Z-Test at JRC

7.2.3 Scenario T7D: Static Short-Term 3D Test Results

Static position accuracy tests were performed using LPRx at different outdoor and indoor test points in the SJC-APNT network. Each test was repeated twice per test location.

7.2.3.1 Scenario T7D1: Static Outdoor Test Results

The tests were conducted at four outdoor test locations (E, F, G, H) for 10 minutes each. The tests were performed by going to test locations in the sequence (E → F → G → H → E) and repeating this loop twice. The location coordinates shown in Table 34**Error! Reference source not found.** were used to compute the position accuracy performance. Each location test point was selected to have a diverse signal power profile for each beacon as well as a different multipath profile.

Test Point	Location (Latitude, Longitude, Altitude in HAE)
E	37.3414470, -121.9043278, -9.48
F	37.343104, -121.8888754, -8.4582
G	37.339866, -121.883013, -6.4551
H	37.334805, -121.9011434, -6.494

Table 34: Outdoor Test Point Coordinates

Figure 39: Outdoor Static Locations at SJC

The static position accuracy performance for the TerraPoiNT system is shown in the form of box plots and error time series from Figure 40 to 43. The error statistics are tabulated in Table 35 and Table 36**Error! Reference source not found.**. Figure 40 (box plot) and Figure 42 (error time series) show that the TerraPoiNT system has a position 2D accuracy within 10m (95%) across all the test points and different trials. Figure 41 (box plot) and Figure 42 (error time series) show the TerraPoiNT altitude (Z) accuracy is within 2m across all the test points and trials.

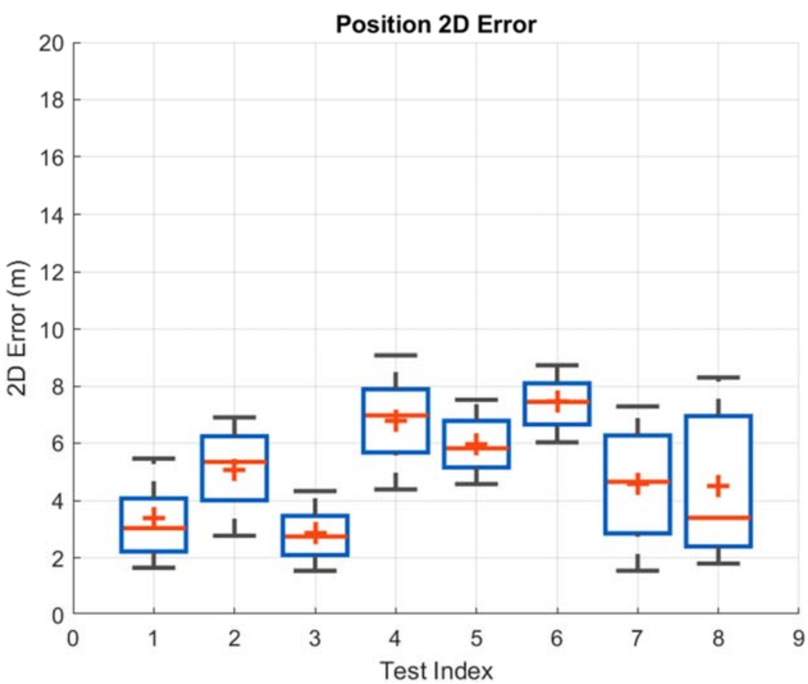


Figure 40: Box Plot of Position 2D Error for Outdoor Static Points

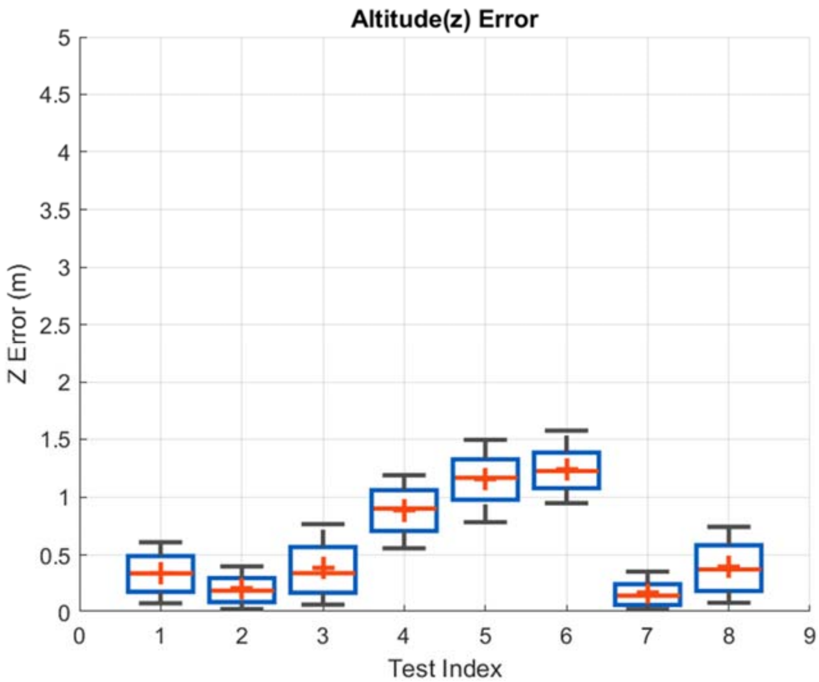


Figure 41: Box Plot of Z error for Outdoor Static Points for Static Outdoor Test at SJC

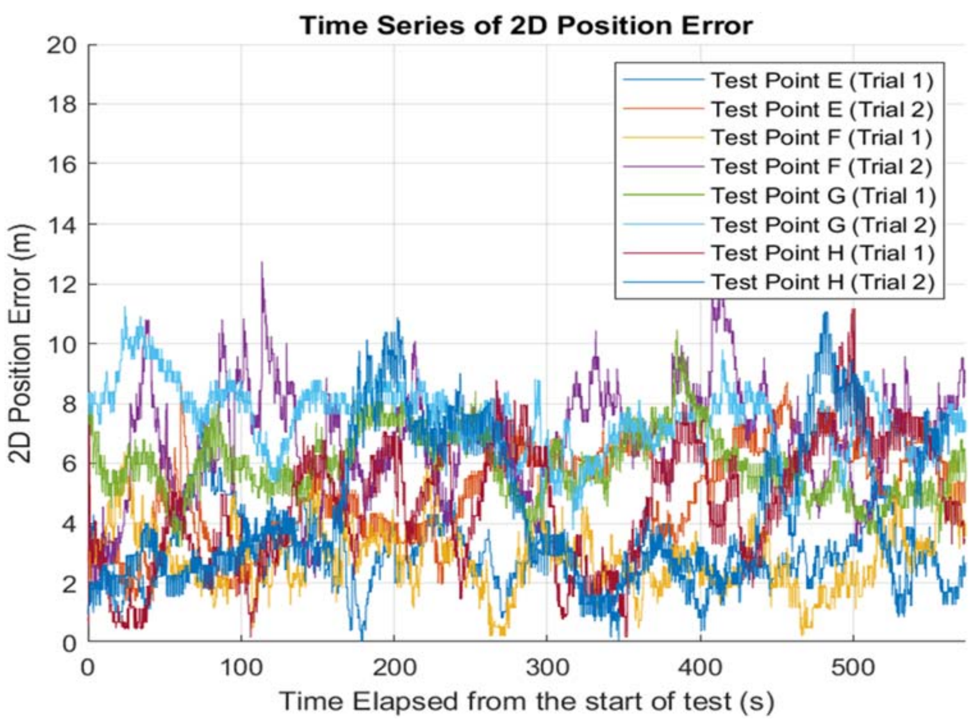


Figure 42: Time Series of Position 2D Error for Static Outdoor Test at SJC

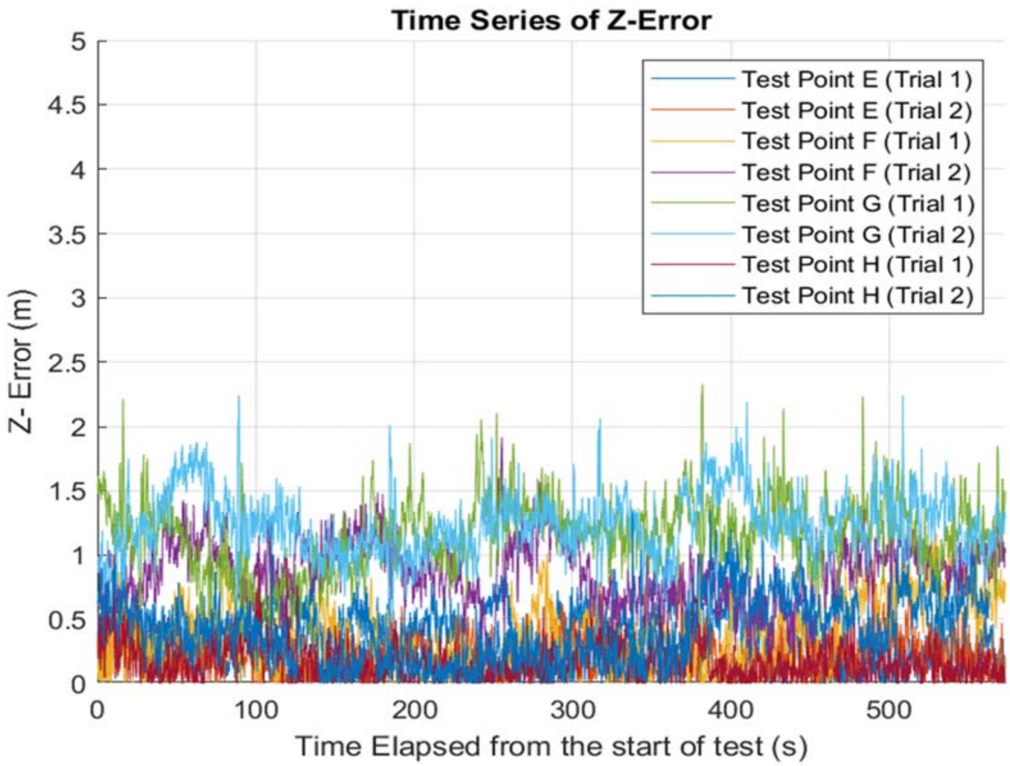


Figure 43: Time series of Z Error for Static Outdoor Test at SJC

Test Case ID	UTC Start time	Trial Number	Test Index	Test Duration(s)	Number of fixes	Position Error 2D (meters)				
						50%	25%	75%	10%	90%
T7D-E	14-Dec-2021 14:43:52	1	1	660	6496	3	2	4	2	5
T7D-E	14-Dec-2021 16:50-06	2	2	610	6090	5	4	6	3	7
T7D-F	14-Dec-2021 13:58:01	1	3	610	6022	3	2	3	2	4
T7D-F	14-Dec-2021 15:03:41	2	4	610	6007	7	6	8	4	9
T7D-G	14-Dec-2021 15:19:00	1	5	600	5831	6	5	7	5	8
T7D-G	14-Dec-2021 16-20-38	2	6	620	6146	7	7	8	6	9
T7D-H	08-Feb-2022 16-34-56	1	7	600	5951	5	3	6	2	7
T7D-H	14-Dec-2021 14-30-39	2	8	580	5632	3	2	7	2	8

Table 35: Position 2D Error Statistics for Static Outdoor Test at SJC

Test Case ID	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Z Error (meters)				
						50 %	25%	75%	10%	90%
T7D-E	14-Dec-2021 14:43:52	1	1	660	6496	0.3	0.2	0.5	0.1	0.6
T7D-E	14-Dec-2021 16:50-06	2	2	610	6090	0.2	0.1	0.3	0	0.4
T7D-F	14-Dec-2021 13:58:01	1	3	610	6022	0.3	0.2	0.6	0.1	0.8
T7D-F	14-Dec-2021 15:03:41	2	4	610	6007	0.9	0.7	1.1	0.6	1.2
T7D-G	14-Dec-2021 15:19:00	1	5	600	5831	1.2	1	1.3	0.8	1.5
T7D-G	14-Dec-2021 16-20-38	2	6	620	6146	1.2	1.1	1.4	0.9	1.6
T7D-H	08-Feb-2022 16-34-56	1	7	600	5951	0.1	0.1	0.2	0	0.4
T7D-H	14-Dec-2021 14-30-39	2	8	580	5632	0.4	0.2	0.6	0.1	0.7

Table 36: Z Error Statistics for Static Outdoor Test at SJC

7.2.3.2 Scenario T7D2: Static Indoor Test Results

The tests were conducted at four indoor test locations (labelled as I, J, K, L) for a duration of 10 minutes each. The location coordinates for the indoor test points are tabulated in Table 37 and shown in Figure 44. Each indoor location test point is selected to have diverse signal power profile for each beacon as well as a different multipath profile. The tests were performed going from test point I, J, K L in a sequence and entire sequence was repeated for the second trial. The results are plotted and tabulated with two trials for each point next to each other.

Test Point	Location (Latitude, Longitude, Altitude in HAE)
I	37.336561, -121.886200, 7.42
J	37.343157, -121.889431, -8.8
K	37.350561, -121.922312, -11.49
L	37.340314, -121.906491, -8.00

Table 37: Indoor Test Point Coordinates

Figure 44: Indoor Static Locations at SJC

The static position accuracy performance for TerraPoiNT system is shown in Figure 45, Figure 46, Figure 47, and Figure 48. The corresponding error statistics are tabulated in Table 38 and Table 39, respectively. The tests were performed going from test point E, F, G H in a sequence and entire sequence was repeated for the second trial. The results are plotted and tabulated with two trials for each point next to each other.

Figure 45 (box plot) and Figure 47 (error time series) show the TerraPoiNT position 2D accuracy is within 10m (90%) across all the test points and different trials. Figure 46 (box plot) and Figure 48 (error time series) show the TerraPoiNT altitude (Z) accuracy is within 2m for all the trials. Altitude spikes correspond to temporary pressure disturbances due to opening and closing of door. In a system solution, such non-physical changes can be removed/reduced by appropriate filtering, which we have not implemented in present solution.

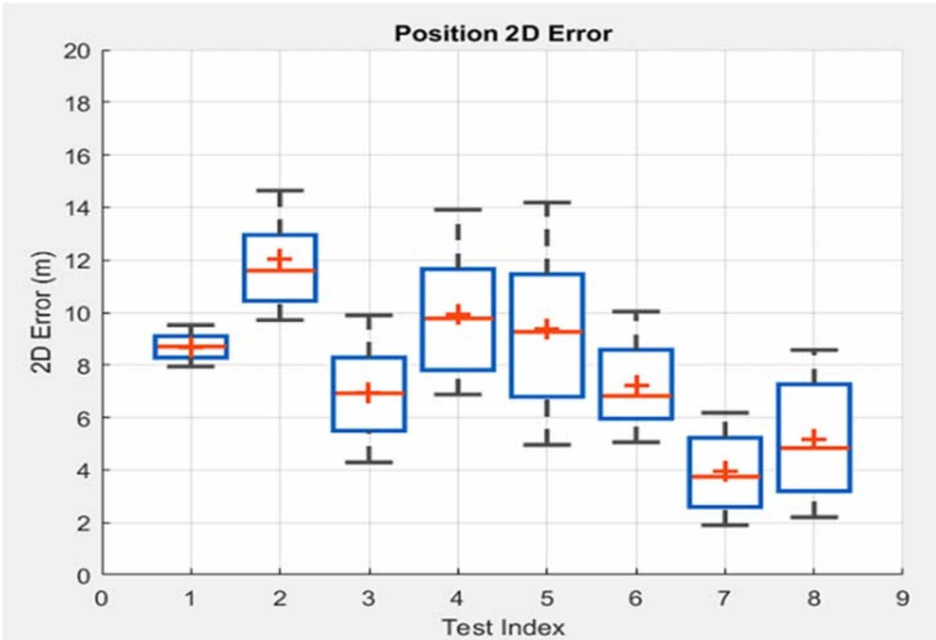


Figure 45: Box Plot of Position 2D Error for Static Indoor Test at SJC

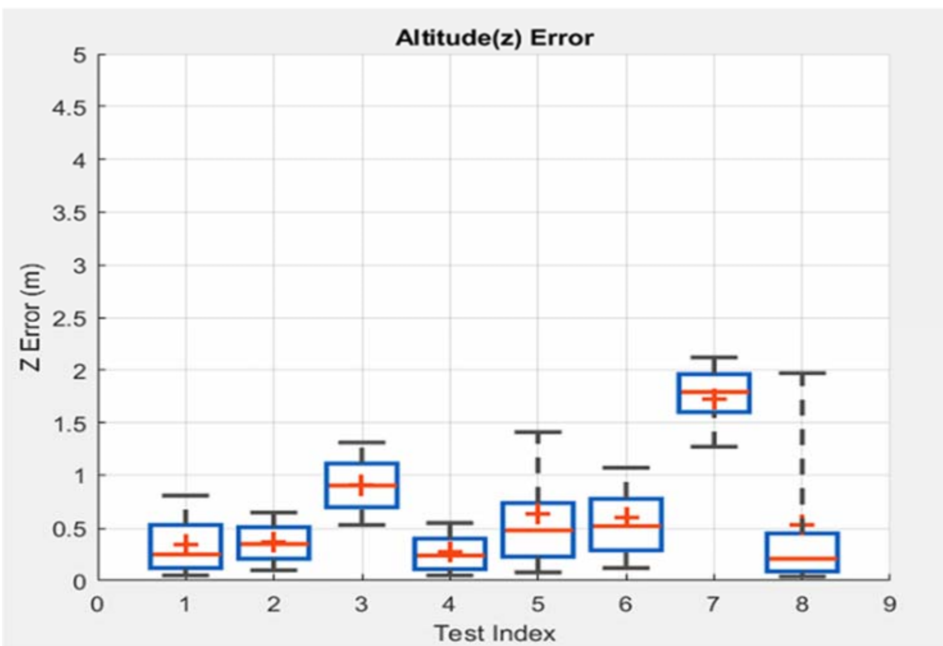


Figure 46: Box Plot of Z error for Static Indoor Test at SJC

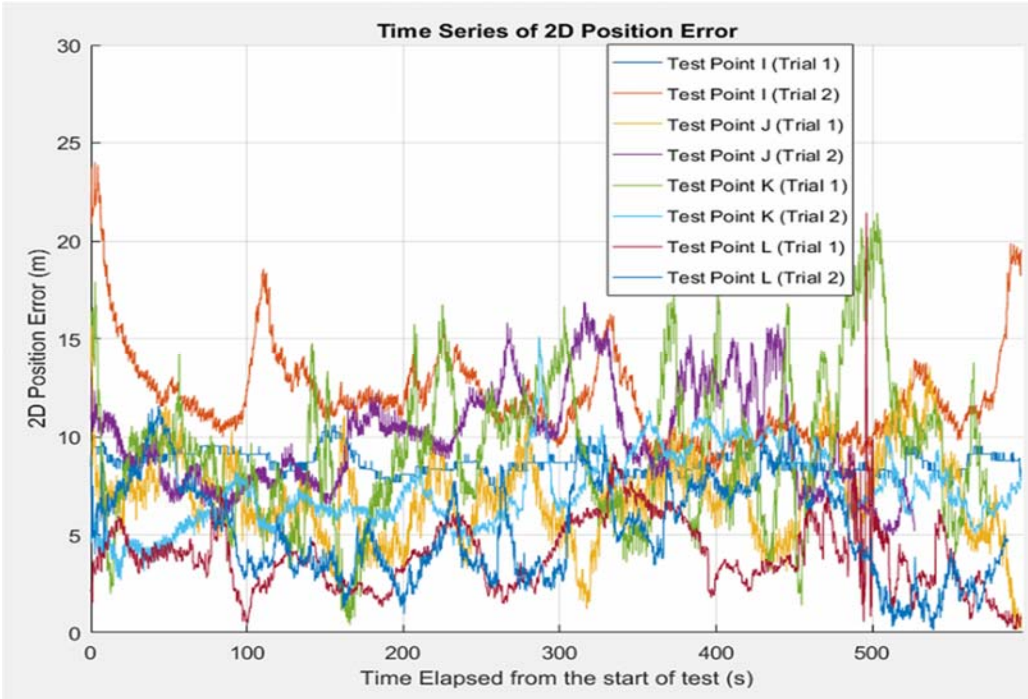


Figure 47: Time Series of Position 2D Error for Static Indoor Test at SJC

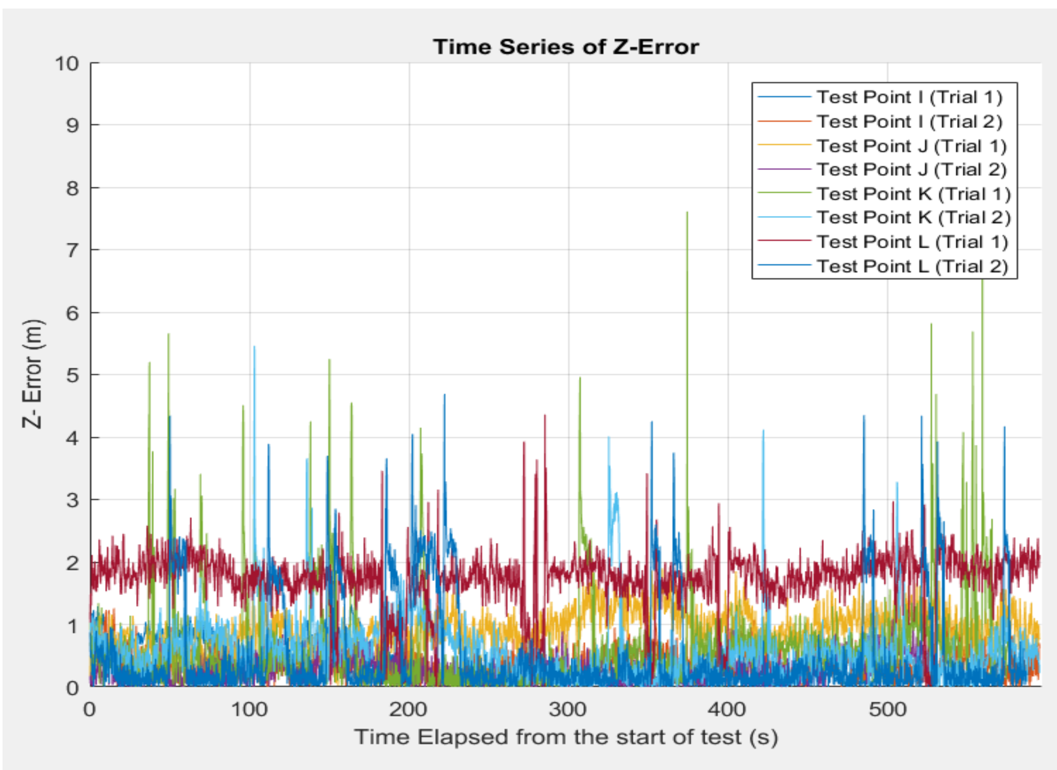


Figure 48: Time Series of Z Error for Static Indoor Test at SJC

Test Case ID	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Position Error 2D (meters)				
						50 %	25 %	75 %	10 %	90 %
T7D-I	11-Feb-2022 00:10:52	1	1	600	5948	9	8	9	8	10
T7D-I	04-Mar-2022 00:30:19	2	2	600	5951	12	10	13	10	15
T7D-J	17-Feb-2022 19:10:35	1	3	600	5951	7	5	8	4	10
T7D-J	17-Feb-2022 20:48:51	2	4	600	5270	10	8	12	7	14
T7D-K	02-Mar-2022 20:51:19	1	5	530	5757	9	7	11	5	14
T7D-K	02-Mar-2022 22:41:39	2	6	580	5951	7	6	9	5	10
T7D-L	02-Mar-2022 23:24:11	1	7	600	5951	4	3	5	2	6
T7D-L	03-Mar-2022 22:37:11	2	8	600	5867	5	3	7	2	9

Table 38: Position 2D Error Statistics for Static Indoor Test at SJC

Test Case ID	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Z Error (meters)				
						50 %	25 %	75 %	10 %	90 %
T7D-I	11-Feb-2022 00:10:52	1	1	600	5948	0.3	0.1	0.5	0.1	0.8
T7D-I	04-Mar-2022 00:30:19	2	2	600	5951	0.4	0.2	0.5	0.1	0.7
T7D-J	17-Feb-2022 19:10:35	1	3	600	5951	0.9	0.7	1.1	0.5	1.3
T7D-J	17-Feb-2022 20:48:51	2	4	600	5270	0.2	0.1	0.4	0.0	0.6
T7D-K	02-Mar-2022 20:51:19	1	5	530	5757	0.5	0.2	0.7	0.1	1.4
T7D-K	02-Mar-2022 22:41:39	2	6	580	5951	0.5	0.3	0.8	0.1	1.1
T7D-L	02-Mar-2022 23:24:11	1	7	600	5951	1.8	1.6	2.0	1.3	2.1
T7D-L	03-Mar-2022 22:37:11	2	8	600	5867	0.2	0.1	0.5	0.0	2.0

Table 39: Z Error Statistics for Static Indoor Test at SJC

7.2.4 Scenario T8J: Resilience and Network Monitoring Test Results

This test was intended to demonstrate the performance of the network under circumstances when a part of the network is not operating due to various reasons like maintenance and jammers. In this test, two beacons (CASFO0240 and CASFO0078) from the seven beacon SJC-APNT network had their transmission stopped and position accuracy was estimated at one outdoor and one indoor location. Two trials were performed at each test location with each trial for a duration of about 10 minutes. Table 40 lists the coordinate of the test points and Figure 49 shows them on the map.

Test Point	Category	Location (Latitude, Longitude, Altitude in HAE)
M	Outdoor	37.343541, -121.889079, -8.43
N	Indoor	37.341465, -121.911599, -8.49 (Baseline Test Truth: 37.340336, -121.903719, -6.8)

Table 40: Test Point Coordinates for Resilience and Network Monitoring Test

The baseline test and resilience tests were done on different days. The test location N was slightly different between baseline tests and resilience tests as the baseline test location was not accessible on the day of resilience tests. Hence, another building with similar features in the near-by area was chosen.

Figure 49: Resilience and Network Monitoring Test Locations

LPRx was used for these tests and its output was compared with the truth location and position accuracy was determined. The results for static point M are shown in Figure 50, Figure 51, Figure 52, and Figure 53. The error statistics are tabulated in Table 41 and Table 42. Figure 50 (box plot) and Figure 52 (error time series) show that the TerraPoiNT position 2D error is not impacted significantly by partial outage of the network. The results indicate the position results across different trials vary within the statistical accuracy expected from changing wireless channel, multipath profile during each test. In these tests, the accuracy during resilience trials is slightly better than the baseline result which could be due to slightly different multipath profile during the tests. Figure 51 (box plot) and Figure 53 (error time series) show the altitude (Z) errors are not impacted by the partial network outage across different trials.

The results for static indoor point N are shown in Figure 54, Figure 55, Figure 56 and Figure 57 and the statistics are tabulated in Table 43 and Table 44. Figure 54 (box plot) and Figure 56 (error time series) show the TerraPoiNT position 2D error is not severely impacted with reduced network as long as there are sufficient beacons to compute the position. The altitude performance mainly comes from barometer sensor which is minimally impacted by the partial network outage. The baseline and resilience trials indicate the position 2D accuracy shown some variation across trails which are within the statistical variation expected. The variation could result from the RF channel changes across time as well as multipath profile. Figure 55 (box plot) and Figure 57 (error time series) show the altitude (Z) errors are not impacted by the partial network outage across different trials.

The results indicate the TerraPoiNT can provide good position accuracy despite partial network outage if there are at least 3 beacons available for trilateration. Note that the TerraPoiNT network design builds-in this resiliency by ensuring that greater than 3 beacons (e.g., 4) are available within the network coverage area. For example, a design which targets 4 beacon availability can handle one beacon outage.

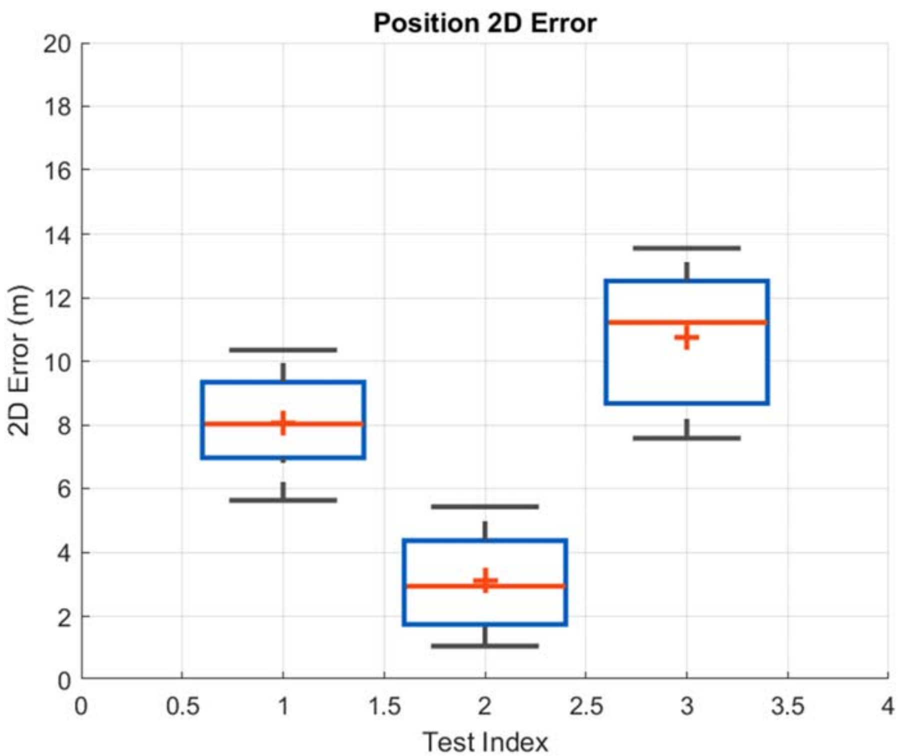


Figure 50: Box Plot of Position 2D error at Point M for Resilience and Network Monitoring Test

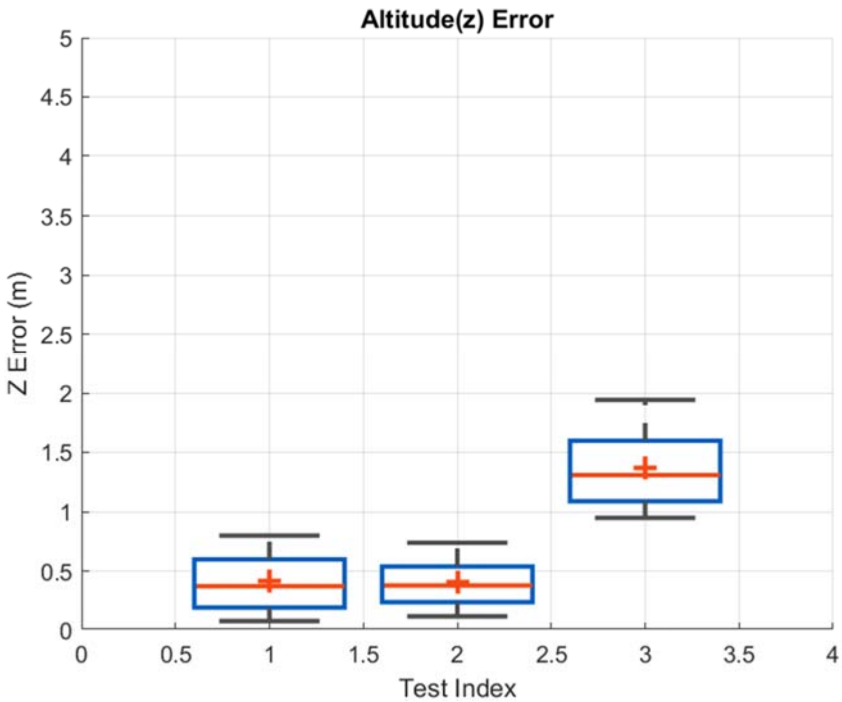


Figure 51: Box Plot of Z Error at Point M for Resilience and Network Monitoring Test

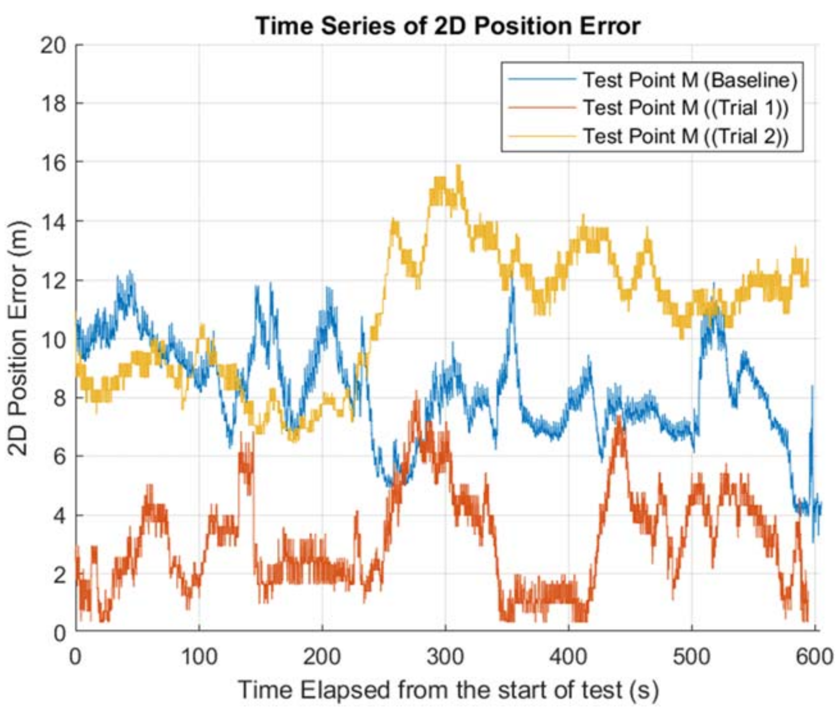


Figure 52: Time series of Position 2D Error at Point M for Resilience and Network Monitoring Test

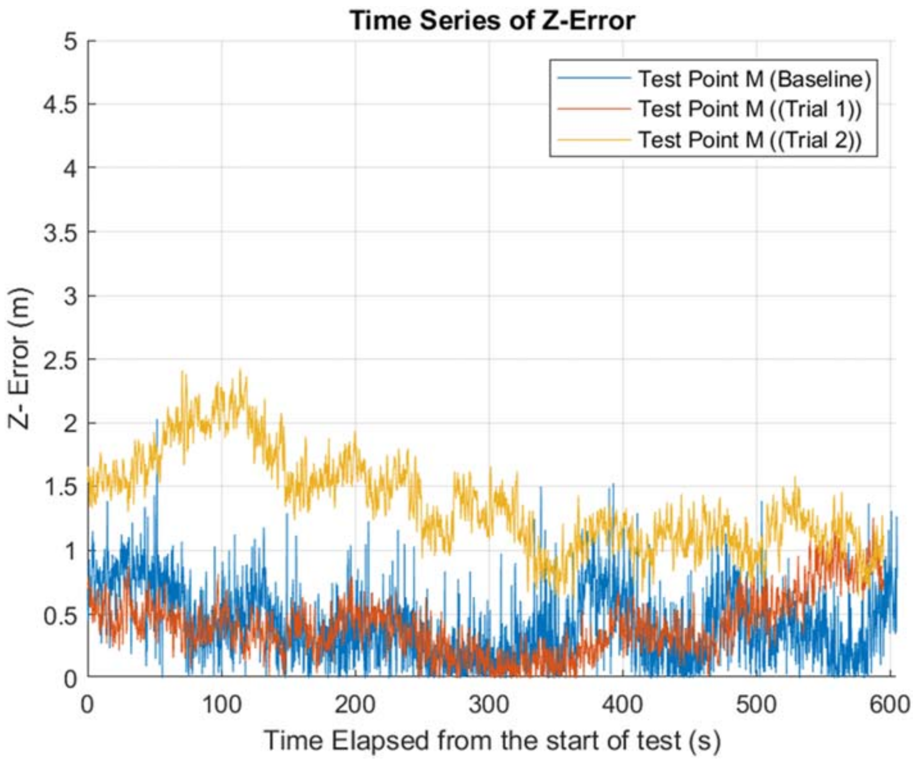


Figure 53: Time series of Z Error at Point M for Resilience and Network Monitoring Test

Test Case ID - location	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Position Error 2D (meters)				
						Median (50%)	First Quartile (25%)	Third Quartile (75%)	Lower whisker (10%)	Upper whisker (90%)
T8J-M	2022-02-09:14:26:26	Baseline	1	630	6201	8	7	9	6	10
T8J-M	2021-12-21:10:36:43	1	2	600	5951	3	2	4	1	5
T8J-M	2021-12-21:12:37:07	2	3	600	5951	11	9	13	8	14

Table 41: Position 2D Error Statistics at Point M for Resilience and Network Monitoring Test

Test Case ID - location	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Z Error (meters)				
						Median (50%)	First Quartile (25%)	Third Quartile (75%)	Lower whisker (10%)	Upper whisker (90%)
T8J-M	2022-02-09:14:26:26	Baseline	1	630	6201	0.4	0.2	0.6	0.1	0.8
T8J-M	2021-12-21:10:36:43	1	2	600	5951	0.4	0.2	0.5	0.1	0.7
T8J-M	2021-12-21:12:37:07	2	3	600	5951	1.3	1.1	1.6	0.9	1.9

Table 42: Z Error Statistics at Point M for Resilience and Network Monitoring Test

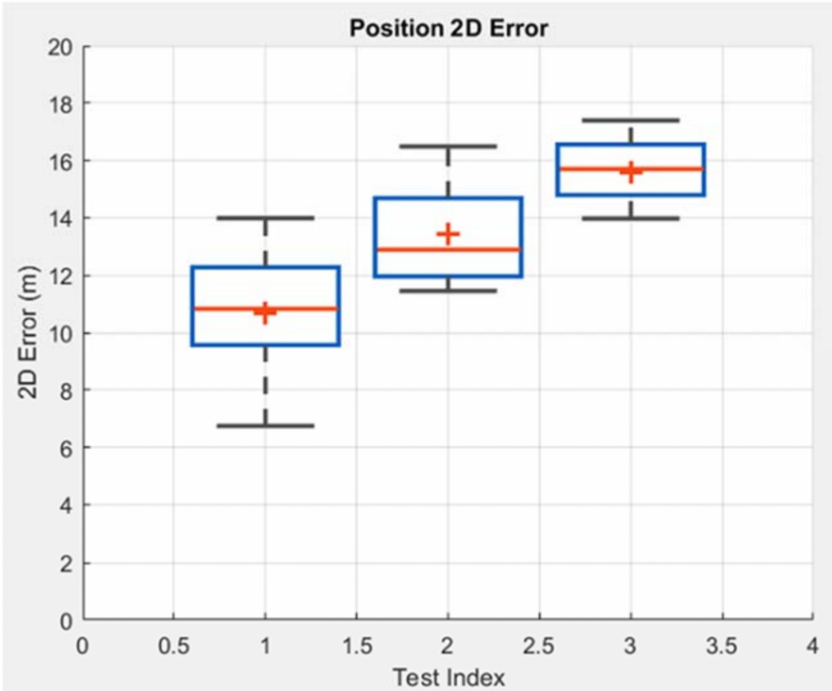


Figure 54: Box Plot of Position 2D error at Point N for Resilience and Network Monitoring Test

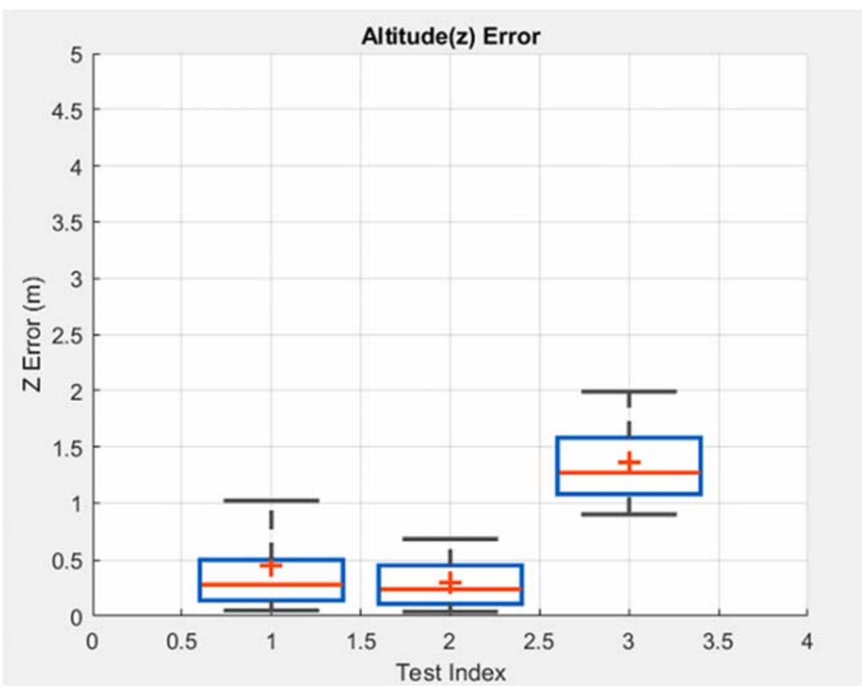


Figure 55: Box Plot of Z Error at Point N for Resilience and Network Monitoring Test

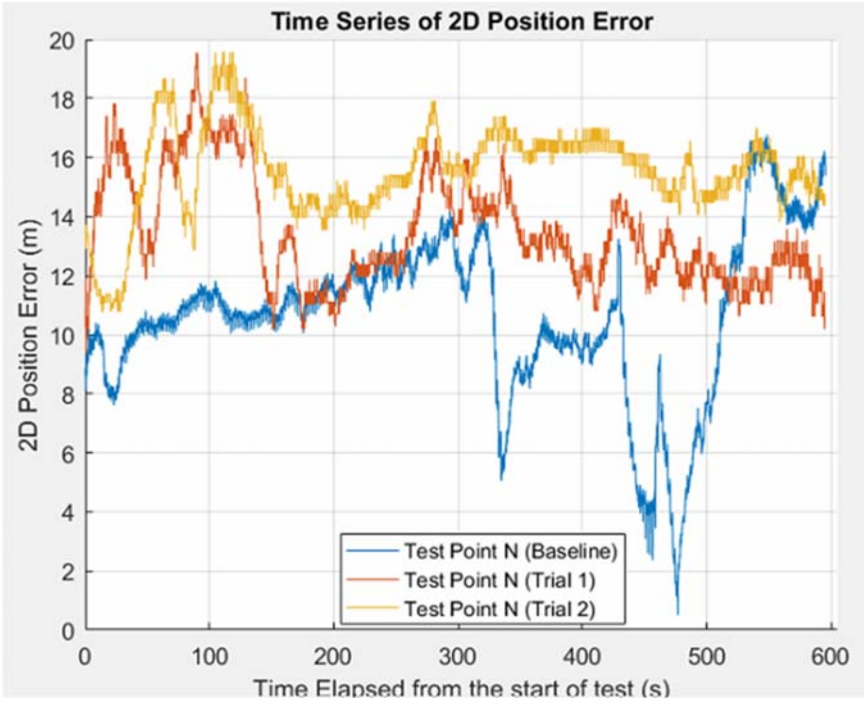


Figure 56: Time Series of Position 2D Error at Point N for Resilience and Network Monitoring Test

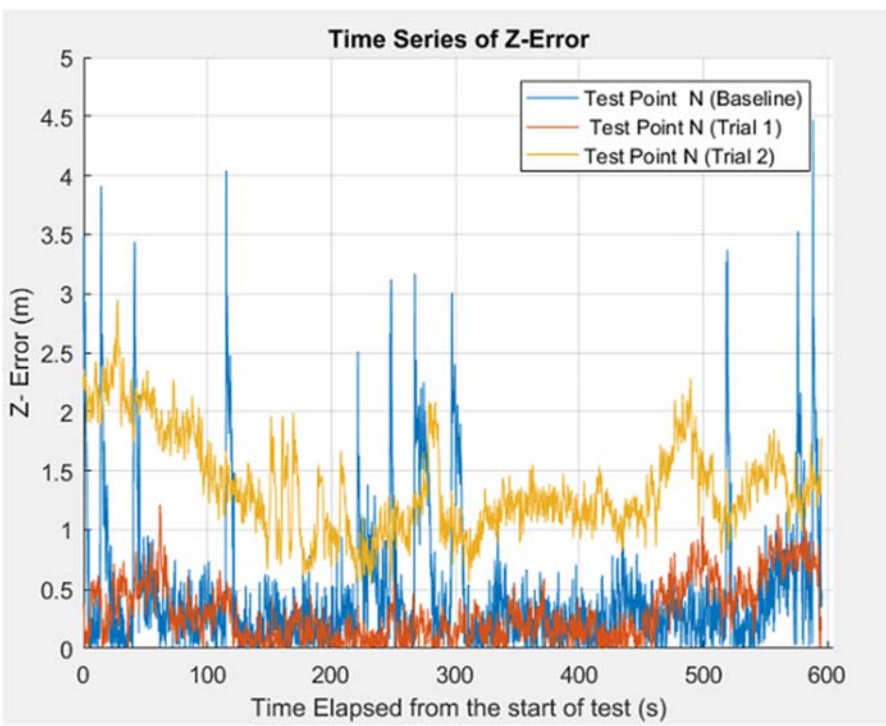


Figure 57: Time Series of Z Error at Point N for Resilience and Network Monitoring Test

Test Case ID - location	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Position Error 2D (meters)				
						50%	25%	75%	10%	90%
T8J-N	17-Feb-2022 02:11:17	Baseline	1	600	5952	11	10	12	7	14
T8J-N	21Dec-2021 03:43:21	1	2	600	5951	13	12	15	11	16
T8J-N	2021-12-21 07:49:00	2	3	600	5951	16	15	17	14	17

Table 43: Position 2D Error Statistics at Point N for Resilience and Network Monitoring Test

Test Case ID - location	UTC Start time	Trial Number	Test Index	Test Duration (s)	Number of fixes	Z Error (meters)				
						50%	25%	75%	10%	90%
T8J-N	17-Feb-2022 02:11:17	Baseline	1	600	5952	0.3	0.1	0.5	0.1	1.0
T8J-N	21-Dec-2021 03:43:21	1	2	600	5951	0.2	0.1	0.5	0.0	0.7
T8J-N	21-Dec-2021 07:49:00	2	3	600	5951	1.3	1.1	1.6	0.9	2.0

Table 44: Z Error Statistics at Point N for Resilience and Network Monitoring Test