Complementary PNT and GPS Backup Technologies Demonstration Report

Sections 1 through 10

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IEEE ABBREVIATIONS AND LETTER SYMBOLS FOR UNITS			
Unit or Term	**Abbreviation**	**Unit or Term**	**Abbreviation**
alternating current	ac	lumen second	lm · s
American wire gauge	AWG	lux	lx
ampere	A	magnetohydrodynamics	MHD
ampere hour	Ah	magnetomotive force	MMF
ampere turn	A	medium frequency	MF
amplitude modulation	AM	megaelectronvolt	MeV
antilogarithm	antilog	megahertz	MHz
audio frequency	AF	megavolt	MV
automatic frequency control	AFC	megawatt	MW
automatic gain control	AGC	megohm	MΩ
automatic volume control	AVC	metal-oxide semiconductor	MOS
average	avg	meter	m
backward-wave oscillator	BWO	meter-kilogram-second	MKS
baud	Bd	microampere	µA
beat-frequency oscillator	BFO	microfarad	µF
binary coded decimal	BCD	microgram	µg
bit	b	microhenry	µH
British thermal unit	Btu	micrometer	µm
calorie	cal	micromho	µmho
candela	cd	microsecond	µs
candela per square foot	cd/ft^2	microwatt	µW
candela per square meter	cd/m^2	mile (statute)	mi
cathode-ray oscilloscope	CRO	mile per hour	mi/h
cathode-ray tube	CRT	milliampere	mA
centimeter	cm	milligram	mg
circular mil	cmil	millihenry	mH
continuous wave	CW	milliliter	ml
coulomb	C	millimeter	mm
cubic centimeter	cm^3	millisecond	ms
cubic foot per minute	ft^3/min	millivolt	mV
cubic meter	m^3	milliwatt	mW
cubic meter per second	m^3/s	minute (plane angle)	...'
decibel	dB	minute (time)	min
decibel referred to one milliwatt	dBm	nanofarad	nF
degree (plane angle)	...°	nanometer	nm
degree (temperature interval or difference)	deg	nanosecond	ns
degree Celsius	°C	nanowatt	nW
degree Fahrenheit	°F		

IEEE ABBREVIATIONS AND LETTER SYMBOLS FOR UNITS

Unit or Term	Abbreviation	Unit or Term	Abbreviation
degree Rankine	°R	neper	Np
diameter	diam	newton	N
direct current	dc	newton meter	Nm
electromagnetic compatibility	EMC	ohm	Ω
electromagnetic unit	EMU	ounce (avoirdupois)	oz
electromotive force	EMF	pulse(s) per second	pps
electronic data processing	EDP	per unit	pu
electronvolt	eV	phase modulation	PM
electrostatic unit	ESU	picoampere	pA
extra-high voltage	EHV	picofarad	pF
extremely high frequency	EHF	picosecond	ps
extremely low frequency	ELF	picowatt	pW
farad	F	pound	lb
field-effect transistor	FET	pound per square inch§	lb/in^2
foot	ft	poundal	pdl
foot per minute	ft/min	pound-force	lbf
foot per second	ft/s	pound-force foot	lbf · ft
foot pound-force	ft · lbf	pound-force per square inch§	lbf/in^2
frequency modulation	FM	power factor	PF
gallon	gal	pulse per second	pps
gallon per minute	gal/min	radian	rad
gauss	G	radio frequency	RF
gigaelectronvolt	GeV	radio-frequency interference	RFI
gigahertz	GHz	resistance-capacitance	RC
gram	g	resistance-inductance-capacitance	RLC
henry	H	revolution per minute	r/min
hertz	Hz	revolution per second	r/s
high voltage	HV	roentgen	R
high-frequency	HF	root-mean-square	rms
hour	h	second (plane angle)	…"
inch	in	second (time)	s
inch per second	in/s	short wave	SW
inductance-capacitance	LC	siemens	S
inertia	$kg \cdot m^2$ or $lb \cdot ft^2$	signal-to-noise ratio	SNR
infrared	IR	silicon controlled rectifier	SCR
inside diameter	ID	square foot	ft^2

IEEE ABBREVIATIONS AND LETTER SYMBOLS FOR UNITS

Unit or Term	Abbreviation	Unit or Term	Abbreviation
intermediate frequency	IF	square inch	in^2
joule	J	square meter	m^2
joule per degree	J/deg	square yard	yd^2
kelvin	K	standing-wave ratio	SWR
kiloelectronvolt	keV	television interference	TVI
kilogram	kg	tesla	T
kilohertz	kHz	thousand circular mils	kcmil
kilohm	kQ	transverse electric	TE
kilojoule	kJ	transverse electromagnetic	TEM
kilometer	km	transverse magnetic	TM
kilometer per hour	km/h	traveling-wave tube	TWT
kilovar	kvar	vacuum-tube voltmeter	VTVM
kilovolt	kV	var	var
kilovoltampere	kVA	variable-frequency oscillator	VFO
kilowatt	kW	very-high-frequency	VHF
kilowatthour	kWh	very-low-frequnecy	VLF
lambert	L	volt	V
liter	L	voltage controlled oscillator	VCO
liter per second	L/s	voltage standing-wave ratio	VSWR
logarithm	log	voltampere	var
logarithm, natural	ln	watt	W
low-frequency	LF	watt per steradian	W/sr
lumen	lm	watt per steradian square meter	$W/(sr \cdot m^2)$
lumen per square foot	lm/ft^2	watthour	Wh
lumen per square meter	lm/m^2	weber	Wb
lumen per watt	lm/W	yard	yd

SI* (MODERN METRIC) CONVERSION FACTORS

APPROXIMATE CONVERSIONS TO SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
in	inches	25.4	millimeters	mm
ft	feet	0.305	meters	m
yd	yards	0.914	meters	m
mi	miles	1.61	kilometers	km
		AREA		
in^2	square inches	645.2	square millimeters	mm^2
ft^2	square feet	0.093	square meters	m^2
yd^2	square yard	0.836	square meters	m^2
ac	acres	0.405	hectares	ha
mi^2	square miles	2.59	square kilometers	km^2
		VOLUME		
fl oz	fluid ounces	29.57	milliliters	mL
gal	gallons	3.785	liters	L
ft^3	cubic feet	0.028	cubic meters	m^3
yd^3	cubic yards	0.765	cubic meters	m^3
		NOTE: volumes greater than 1000 L shall be shown in m^3		
		MASS		
oz	ounces	28.35	grams	g
lb	pounds	0.454	kilograms	kg
T	short tons (2000 lb)	0.907	megagrams (or "metric ton")	Mg (or "t")
oz	ounces	28.35	grams	g
		TEMPERATURE (exact degrees)		
°F	Fahrenheit	5 (F-32)/9 or (F-32)/1.8	Celsius	°C
		ILLUMINATION		
fc	foot-candles	10.76	lux	lx
fl	foot-Lamberts	3.426	candela/m^2	cd/m^2
		FORCE and PRESSURE or STRESS		
lbf	poundforce	4.45	newtons	N
lbf/in^2	poundforce per square inch	6.89	kilopascals	kPa

APPROXIMATE CONVERSIONS FROM SI UNITS

Symbol	When You Know	Multiply By	To Find	Symbol
		LENGTH		
mm	millimeters	0.039	inches	in
m	meters	3.28	feet	ft
m	meters	1.09	yards	yd
km	kilometers	0.621	miles	mi
		AREA		
mm^2	square millimeters	0.0016	square inches	in^2
m^2	square meters	10.764	square feet	ft^2
m^2	square meters	1.195	square yards	yd^2
ha	hectares	2.47	acres	ac
km^2	square kilometers	0.386	square miles	mi^2
		VOLUME		
mL	milliliters	0.034	fluid ounces	fl oz
L	liters	0.264	gallons	gal
m^3	cubic meters	35.314	cubic feet	ft^3
m^3	cubic meters	1.307	cubic yards	yd^3
mL	milliliters	0.034	fluid ounces	fl oz
		MASS		
g	grams	0.035	ounces	oz
kg	kilograms	2.202	pounds	lb
Mg (or "t")	megagrams (or "metric ton")	1.103	short tons (2000 lb)	T
g	grams	0.035	ounces	oz

SI* (MODERN METRIC) CONVERSION FACTORS				
		TEMPERATURE (exact degrees)		
ºC	Celsius	1.8C+32	Fahrenheit	ºF
		ILLUMINATION		
lx	lux	0.0929	foot-candles	fc
cd/m²	candela/m²	0.2919	foot-Lamberts	fl
		FORCE and PRESSURE or STRESS		
N	newtons	0.225	poundforce	lbf
kPa	Kilopascals	0.145	poundforce per square inch	lbf/in²

*SI is the symbol for the International System of Units. Appropriate rounding should be made to comply with Section 4 of ASTM E380. (Revised March 2003)

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Abbreviation	Term
2D	Two-Dimensional
3D	Three-Dimensional
AIS	Automatic Identification System
AP	Access Point
APS	Augmented Positioning System
AV	Automated Vehicles
AWRF	Aviation Weather Research Facility
BLE	Bluetooth Low Energy
C&DH	Command and Data Handling
CDF	Cumulative Distribution Function
CDMA	Code Division Multiple Access
CERTAIN	City Environment for Range Testing of Autonomous Integrated Navigation
CI	Critical Infrastructure
CISA	DHS Cybersecurity and Infrastructure Security Agency
COA	Certificate of Authorization
COTS	Commercial-Off-the-Shelf
CRADA	Cooperative Research and Development Agreement
CSRIC	Communications Security, Reliability and Interoperability Council
CW	Continuous-Wave
DGPS	Differential GPS
DHS	Department of Homeland Security
DHS S&T	DHS Security Science and Technology Directorate
DOD	Department of Defense
DOT	Department of Transportation
EIRP	Effective Isotopic Radiated Power
eLORAN	Enhanced LORAN
ENU	East, North, and Up
EO	Executive Order
ESG	Executive Steering Group
EXCOM	National Space-Based PNT Executive Committee
FAA	Federal Aviation Administration
FAR	Federal Acquisition Regulations
FCC	Federal Communications Commission
FFRDC	Federally Funded Research and Development Center
FHWA	Federal Highway Administration
FOC	Full Operational Capability
FRP	Federal Radionavigation Plan
GDOP	Geometric Dilution of Precision
GFE	Government-Furnished Equipment
GNSS	Global Navigation Satellite System
GPS	Global Positioning System
HSN	Hyper Sync Net
HSOAC	Homeland Security Operational Analysis Center

Abbreviation	Term
HSSEDI	Homeland Security Systems Engineering and Development Institute
IEEE	Institute of Electrical and Electronics Engineers
IIHS	Insurance Institute for Highway Safety
IMU	Inertial Measurement Unit
IOC	Initial Operational Capability
JBCC	Joint Base Cape Cod
LaRC	NASA Langley Research Center
LEO	Low Earth Orbit
LF	Low-Frequency RF
LOP	Letter of Procedure
LORAN	Long-Range Navigation
LSU	LORAN Support Unit
LTE	Long-Term Evolution
MBS	Metropolitan Beacon System
MEO	Medium Earth Orbit
MF	Medium-Frequency RF
MoE	Measure of Effectiveness
MTBF	Mean Time Between Failures
NASA	National Aeronautics and Space Administration
NATO	North Atlantic Treaty Organization
NavCen	USCG Navigation Center
NDAA	National Defense Authorization Act
NDGPS	Nationwide Differential Global Positioning System
NIHS	National Institute for Hometown Security
NIST	National Institute of Standards and Technology
NRMC	National Risk Management Center of DHS
NSPD	National Security Presidential Directive
NTI	National Timing Institute (U.S.)
NTP	Network Time Protocol
NTRSA	National Timing Resiliency and Security Act
OCXO	Oven-Controlled Crystal Oscillator
OST-R	Office of the Assistant Secretary of Transportation for Research and Technology
OSTP	Office of Science and Technology Policy (Executive Office of the President)
PL	Public Law
PLS	Precision Location System
PNT	Positioning, Navigation, and Timing
PO	Purchase Order
PPK	Post-Process Kinematic
PPP	Precise Point Positioning
PPS	Pulses Per Second
PTIC	Precise Time Interval Counter
PTP	Precision Time Protocol

Abbreviation	Term
PVT	Position-Velocity-Time
RF	Radio Frequency
RFQ	Request for Quotation
RFI	Request for Information
R-mode	Ranging mode of the NDGPS MF spectrum
RMS	Root-Mean-Square
RSSI	Received Signal Strength Indicator
RTT	Round-Trip Time
SCOAR	Support for Communications and Operations Research and Analysis (Volpe Center)
SI	Static Indoor
SI5	Static Indoor Point 5 (example)
SMC	Space and Missile System Center
SME	Subject Matter Expert
SO	Static Outdoor
SO3	Static Outdoor Point 3 (example)
SOFITS	Support On-Site for Information Technology (Volpe Center)
SOOP	Signal-of-Opportunity
SPS-PS	Standard Positioning Service Performance Standard
SSA	Sector-Specific Agency
STL	Satellite Time and Location
sUAS	Small Unmanned Aerial System
SV	Satellite Vehicle
SWAP-C	Size-Weight-Power-Cost
TASE	Time Analysis and Selection Engine
TCXO	Temperature Controlled Crystal Oscillator
TDOA	Time-Difference-of-Arrival
TFDS	Time and Frequency Distribution System
TIC	Time Interval Counter
TOA	Time-of-Arrival
TRL	Technical Readiness Level; Technology Readiness Level
UAS	Unmanned Aerial Systems; Unmanned Aircraft System (drone)
UE	User Equipment
UHF	Ultra-High-Frequency RF
USAF	U.S. Air Force
USCG	U.S. Coast Guard
USNO	United States Naval Observatory
UTC	Universal Time Coordinated / Coordinated Universal Time
UWB	Ultra-Wideband
VHF	Very-High-Frequency RF
Volpe Center	Volpe National Transportation Systems Center
WAAS	Wide-Area Augmentation System
WPS	WiFi Position System
WR	White Rabbit (synchronization technology)

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Executive Summary

Resilient PNT is not only important to support critical infrastructure in the transportation sector, but is also essential for national and economic security. The primary and most recognizable PNT service supporting critical infrastructure is the Global Positioning System (GPS). However, because GPS relies on signals broadcast from satellites in Medium Earth Orbit (MEO), signal strength at the receiver is low and thus vulnerable to intentional and unintentional disruptions.

The impact areas identified in DOT's 2001 report, "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," have, if anything, increased the scope and exposure to public sector economic and safety losses in the event of a GPS disruption:

- Transportation service disruption;
- Environmental damage;
- Property damage;
- Serious injury or fatality;
- Loss of confidence in a transportation mode; and
- Liability to the service provider.

Since 2001, neither the vulnerabilities of, nor the dependence on, PNT service from GPS have decreased significantly for the public sector. Federal departments and agencies across the Federal Government have reinforced this assessment with findings on critical infrastructure, emergency services, consumer and business processes, and automated systems. [1] A clear common denominator in reducing economic and safety risk exposure due to dependence on GPS is to consider investment in complementary PNT services.

Section 1606 of Public Law 115–91 (also known as the National Defense Authorization Act for Fiscal Year 2018 [FY18 NDAA]), directed the Secretary of Defense, the Secretary of Transportation, and the Secretary of Homeland Security (referred to in this section as the "Secretaries") to jointly develop a plan for carrying out a backup GPS capability and complementary PNT demonstration. This report provides the details and results of DOT activities covering demonstration planning, the PNT technologies demonstrated, the government reference system used to collect and verify results, and an information framework to convey measures of effectiveness of the demonstrated technologies.

Based on the requirements of the FY18 NDAA, the DOT Office of the Assistant Secretary for Research and Technology (OST-R) Volpe National Transportation Systems Center (Volpe Center) conducted field

[1] *Resilient PNT for Critical Infrastructure*, Washington, DC: U.S. Dept. of Homeland Security, 2020, available at https://www.dhs.gov/sites/default/files/publications/resilient_pnt_for_critical_infrastructure_fact_sheet_508.pdf. See also Sarah Mahmood, "Critical Infrastructure Vulnerabilities to GPS Disruptions," Washington, DC: Homeland Security Advanced Research Projects Agency, July 2014, available at https://www.gps.gov/governance/advisory/meetings/2014-06/mahmood.pdf.

demonstrations of candidate PNT technologies that could offer complementary service in the event of GPS disruptions. The purpose of the demonstration was to gather information on PNT technologies that are at a high Technology Readiness Level (TRL) that can work in the absence of GPS. The Government Team comprised Federal staff from OST-R, the Volpe Center, the NASA Langley Research Center, and the United States Coast Guard. In addition, contractor support was provided by The MITRE Corporation, Zeta Associates Inc., KBR, and Changeis, Inc.

Ongoing input and feedback from stakeholders before, during, and after the demonstration were recognized as essential from the outset of the demonstration. DOT obtained input from external stakeholders with regard to PNT technologies at a high level of technical readiness to inform the demonstration through a variety of external public and private activities that included:

- March 20, 2019: DOT industry roundtable with chief executive officers and chief technology officers from a number of PNT technology companies
- April 8, 2019: DOT industry roundtable with representatives from the wireless industry
- May 3, 2019: DOT Request for Information (RFI) to seek information from the PNT Industry
- March 13, 2020: A DOT-hosted VIP tour of the demonstration site at NASA LaRC for Executive Branch agencies, Congressional staff, and PNT Advisory Board members

The demonstration planning process also allowed repeated opportunities for DOT to receive input and feedback from the participating PNT industry vendors. These resulted in adjustments to the demonstration implementation that improved the conditions under which the technologies could exhibit their positioning or timing performance capabilities.

The Volpe Center, through a competitive acquisition process, selected 11 candidate technologies to demonstrate positioning or timing functions in the absence of GPS:

- Two vendors demonstrated Low Earth Orbit satellite PNT technologies, one L-band, one S-band
- Two vendors demonstrated fiber-optic timing systems, both based on the White Rabbit Precision Time Protocol (PTP) technology
- One vendor demonstrated localized database map matching database, Inertial Measurement Unit (IMU), and ultra-wideband (UWB) technologies
- Six vendors demonstrated terrestrial RF PNT technologies across, Low-Frequency (LF), Medium-Frequency (MF), Ultra-High Frequency (UHF), and WiFi/802.11 spectrum bands

Five of the technologies were demonstrated at Joint Base Cape Cod (JBCC) and six were demonstrated at NASA LaRC. This demonstration was a scenario-based implementation consisting of a series of scenarios modeled on critical infrastructure use cases under various operating conditions.

The purpose of the timing scenarios was to assess the time transfer capability of participating vendor systems to a static location. The scenarios assessed four attributes considered relevant to transportation, communication, and other infrastructure applications requiring synchronization with a time source traceable to a GPS or Coordinated Universal Time (UTC) time standard:

1. Coverage (for wireless time transfer service only); service availability and uniformity within an appropriate area
2. Accuracy and stability across an appropriate area
3. Long-term accuracy and stability of time transfer to a fixed location
4. Time transfer availability and accuracy to a fixed location under challenged GPS signal conditions

Five timing scenarios were developed to assess vendor systems based on these four attributes: 72-Hour Bench Static Timing, Static Outdoor Timing, Static Indoor Timing, Static Basement Timing, and eLORAN Reference Station Offset.

- The 72-Hour Bench Static Timing scenario was designed to support characterization of a technology's time transfer error over an extended period of continuous transmission. Each vendor technology was required to provide a one-pulse-per-second (1-pps) output connection that could then be measured against the timing standard produced by the appropriate static timing reference system.

- The Static Outdoor Timing scenario was designed to collect continuous 60-minute timing data at three separate predetermined points in the demonstration area to assess vendor technology performance in relation to the parameters recognized in the rationale. These would be the same three points that would be used in the Static Outdoor Positioning scenario.

- The Static Indoor Timing scenario was designed to enable a continuous 60-minute time transfer data collection. In this scenario, participating vendor technology's time transfer data was collected at three surveyed indoor points to assess each system's signal availability and time transfer accuracy at a fixed location under challenged GPS signal conditions. The points used in this scenario would be the same used for the Static Indoor Positioning scenario.

- The Static Basement Timing scenario was designed to collect time transfer data simultaneously from all participating vendor technology over a 60-minute period at a single location indoors and below grade.

- The eLORAN Reference Station Offset scenario was designed to demonstrate timing error characteristics and short-term stability of specific eLORAN vendor technologies at locations with progressively larger baseline distances between the UE and reference stations antennae locations. These baseline distancese chosen to be approximately 15, 30, and 60 miles. It comprised a vendor transmitter positioned at LSU (Wildwood, NJ), and one reference station at JBCC used to provide corrections to the vendor's technology during data collection. As in the Static Outdoor Timing scenario, demonstration of system stability, and the sensitivity of time error to the outdoor vendor technology antenna location, were performed. The objective was to verify the availability and to assess the uniformity of the coverage of each of the participating eLORAN systems.

The purpose of the positioning scenarios was to exemplify the following five positioning system attributes, which are relevant to multimodal transportation and other critical infrastructure applications:

1. Coverage: Service availability within a defined region
2. Two-dimensional (2D) and three-dimensional (3D) dynamic positioning: Service availability and accuracy under constant and changing dynamic variables (*e.g.*, linear/angular velocity and acceleration under normal and challenged GPS signal conditions)
3. Static positioning: Service availability and accuracy
4. Static positioning: Long-term service availability and accuracy under normal conditions
5. Static positioning: Long-term service availability and accuracy under challenged GPS signal conditions

Four positioning scenarios were developed to assess vendor systems based on these five attributes: Dynamic Outdoor Positioning with Holds, 3D Positioning, Static Outdoor Positioning, and Static Indoor Positioning.

- The Dynamic Outdoor Positioning with Holds scenario was developed to fulfill the 2D outdoor positioning rationale. The scenario comprised one figure-eight shape, one propeller shape, one double-circle shape (two circular patterns were traced in opposite directions to sample additional dynamics), one rectangle shape, and a general route with segments along paved and unpaved roads. Six Static Outdoor (SO) hold points were identified; three of the six were located on the segment route, and the remaining three on the figure-eight, propeller, and double-circles shapes.
- Two routes for 3D positioning were developed.
    - The first was a multi-level polygon route. With multiple straight segments, this route enabled sampling a large part of the scenario execution area at three different altitudes to assess coverage, availability, and accuracy across the area. This route was designed to sample a larger range of line-of-sight angles between the receiver antenna and transmitter antennae than was the case for 2D.
    - The second was a multi-level propeller route. This route was intended for an area smaller than the polygon route and with a higher range of dynamic variables, including varying linear and angular velocities and accelerations. As with the multi-level polygon route, this scenario allowed sampling a larger range of azimuthal angles of the lines of sight between receiver antenna and all ground transmitter antennae than was the case in 2D.
- The Static Outdoor Positioning comprised three surveyed static points. This allowed for 60 minutes of simultaneous and continuous data collection from all participating technology vendors at each static point.
- The Static Indoor Positioning scenario was designed with five surveyed static points located indoors and below grade. The scenario included 2 minutes of continuous data collection repeated three times. Additionally, a continuous 60-minute data collection was carried out at three of the five points.

In total, Government Team, with vendor support, conducted nine scenarios: eight at both sites and one at JBCC only for eLORAN. The nine scenarios are summarized in Table ES.1.

Table ES.1. Scenario Demonstration Matrix

Scenario	Positioning				
	2D		3D		
	Static	Dynamic	Static	Dynamic	
Dynamic Outdoor Positioning With Holds	X	X			
Static Outdoor Positioning	X				
Static Indoor Positioning	X				
3D Positioning			X	X	
Scenario	**Timing**				
	Long-Term	**Short-Term**			
	Indoor	**Indoor**	**Outdoor**	**Basement**	**Offset**
72-Hour Bench Static Timing	X				
Static Indoor Timing		X			
Static Outdoor Timing			X		
Static Basement Timing		X		X	
eLORAN Reference Station Offset					X

PNT technology vendors were encouraged to participate in all timing and positioning scenarios that they felt would show their technology in its best light. Table ES.2 lists the vendors, technologies, and scenarios in which each was demonstrated.

Table ES.2. PNT Technology Vendor Participation in Scenarios

Vendor	PNT Technology	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LEO commercial S-band (2483.5 – 2500 MHz)	LaRC					N/A		X		
Hellen Systems, LLC	eLoran terrestrial RF (90-110 kHz)	JBCC	X			X	X				
NextNav LLC	UHF terrestrial RF (920-928 MHz)	LaRC	X	X	X	X	N/A	X	X	X	X
OPNT B.V.	fiber optic time service (white rabbit PTP)	LaRC	X				N/A				
PhasorLab Inc.	802.11 terrestrial RF (2.4 GHz)	JBCC	X	X	X		N/A	X	X		X
Satelles, Inc.	LEO commercial L-band (1616-1626.5 MHz)	JBCC	X	X	X	X	N/A		X		
Serco Inc.	R-mode terrestrial RF (283.5-325 KHz)	JBCC					N/A	X	X		
Seven Solutions S.L.	fiber optic time transfer (white rabbit PTP)	LaRC	X				N/A				
Skyhook Wireless, Inc.	802.11 terrestrial RF (900 MHz, 2.4 GHz, & 5 GHz)	LaRC					N/A	X	X	X	X
TRX Systems, Inc.	UWB & IMU map matching (3.1-5 GHz)	LaRC					N/A	X	X	X	
UrsaNav Inc.	eLoran terrestrial RF (90-110 kHz)	JBCC	X		X	X	X				

Based on vendor participation in the positioning and/or timing scenarios, the results of the demonstration were analyzed to provide 14 Measures of Effectiveness (MoEs), structured as rubrics. “Rubric” as used in this report means a scoring guide that sets defined levels for use in assessment and scoring. The 14 MoEs, along with their respective rubrics, were:

MoE-1: Technical Readiness–System (TRL 6–9)
MoE-2: Technical Readiness–User Equipment (TRL 6–9)
MoE-3: Timing and Positioning Accuracy as residual error (m, ns)
MoE-4: Spectrum Protection (protected, owned, leased, shared)
MoE-5: Service Deployment Effort (low, medium, high)
MoE-6: Service Coverage per Unit of Infrastructure as number of transmitters per area covered (units/km^2)
MoE-7: Service Synchronization (UTC, cascade, self-synchronizing)
MoE-8: PNT Signal Robustness (strong, weak)
MoE-9: Service Resilience (fail-safe, -over, -soft, -hard)
MoE-10: PNT Distribution Mode (terrestrial RF, orbital RF, fiber, database)
MoE-11: Service Interoperability (high, low)
MoE-12: PNT Information Security (high, medium, low)
MoE-13: Time to Service Implementation (short, medium, long)
MoE-14: PNT System/Service Longevity (long, medium, short)

The MoEs are grouped into two logical subsets:

- Capability subset (MoE-1 through MoE-9). These MoEs are evaluated using inherently more quantitative rubrics.
- Suitability subset (MoE-10 through MoE-14). The MoEs in this group are evaluated using inherently more qualitative rubrics.

Subject Matter Experts (SMEs) employed the MoE rubrics to assess the strengths of a given technology as demonstrated under a given scenario. The results of the MoE assessment were then collated into an information framework. The framework conveys the demonstration information in a convenient format, and provides weighted scoring functions for needs and/or requirements. Decision-makers can effectively apply these weightings against the 14 MoEs to evaluate candidate technologies suitable for their local situations.

Figure ES.1 is a graphic representation of the scoring process, which illustrates values for each scenario that a given technology demonstrated across each metric. Each demonstrated PNT technology was assessed in the same way by the government SMEs to generate MoE “scorecards.” Those scorecards represent points that can be weighted and summed to express a given technology’s strengths. Four scorecards (MoE-1, MoE-3, MoE-5, and MoE-6) are included in this Executive Summary to support the main findings from the demonstration.

MoE-1: Technical Readiness–System

Rubric: Technical Readiness Level (TRL)

Values: TRL 1–TRL 9; TRL 6 or above considered valid for demonstration

Quantification %: TRL 1–5 = 0%, TRL 6 = 20%, TRL 7 = 40%, TRL 8 = 70%, TRL 9 = 100%

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		8		
Hellen Systems, LLC	JBCC	8			8	8				
NextNav LLC	LaRC	9	9	9	9	N/A	9	9	9	9
OPNT B.V.	LaRC	9				N/A				
PhasorLab Inc.	JBCC	8	8	8		N/A	7	7		7
Satelles, Inc.	JBCC	9	9	9	9	N/A		9		
Serco Inc.	JBCC					N/A	5	5		
Seven Solutions S.L.	LaRC	9				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	9	9	9	9
TRX Systems, Inc.	LaRC					N/A	7	7	7	
UrsaNav Inc.	JBCC	9		9	9	9				

Rubric:	level
	9
	8
	7
	6
	5

Figure ES.1. MoE-1: Technical Readiness–System Government Consensus Scorecard

MoE-3: Timing and Positioning Accuracy as Residual Error

Rubric: Residual error in positioning (m) or timing (ns) against government reference system.

Values: Scalar; largest 95% bound across all runs in a scenario

Quantification %: Proportional inverse error in the range over all participating technologies

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					**N/A**		**333.2**		
Hellen Systems, LLC	JBCC	**114.9**			**failed to close**	**3.4**				
NextNav LLC	LaRC	**23.1**	**7.1**	**5.8**	**17.5**	**N/A**	**15.6**	**6.7**	**8.9**	**3.8**
OPNT B.V.^	LaRC	**0.2**				**N/A**				
PhasorLab Inc.	JBCC	**9.4**	**17.4**	**18.7**		**N/A**	**11.7**	**7.4**		**8.6**
Satelles, Inc.	JBCC	**75.5**	**75.0**	**9.0**	**117.0**	**N/A**		**9.0**		
Serco Inc.	JBCC					**N/A**	**DNQ**	**39.4**		
Seven Solutions S.L.^	LaRC	**0.1**				**N/A**				
Skyhook Wireless, Inc.	LaRC					**N/A**	**7.6**	**1.8**	**23.5**	**14.6**
TRX Systems, Inc.	LaRC					**N/A**	**9.7**	**6.2**	**9.8**	
UrsaNav Inc.	JBCC	**80.1**		**57.4**	**failed to close**	**9.7**				

Rubric:

positioning: max 95%{runs} (m)

1.8 to 333

timing: max 95%{runs} (ns)

0.1 to 117

Figure ES.2. MoE-3: Timing and Positioning 95% Accuracy Government Consensus Scorecard

MoE-5: Service Deployment Effort

Rubric: Observed effort/resource for demonstration

Values: Low, medium, high

Quantification %: low = 100%, medium = 66%, high = 33%

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		low		
Hellen Systems, LLC	JBCC	medium			medium	medium				
NextNav LLC	LaRC	high	high	high	high	N/A	high	high	high	high
OPNT B.V.	LaRC	low				N/A				
PhasorLab Inc.	JBCC	high	high	high		N/A	high	high		high
Satelles, Inc.	JBCC	low	low	low	low	N/A		low		
Serco Inc.	JBCC					N/A	medium	medium		
Seven Solutions S.L.	LaRC	low				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	low	low	low	low
TRX Systems, Inc.	LaRC					N/A	medium	medium	medium	
UrsaNav Inc.	JBCC	medium		medium	medium	medium				

Rubric:

low
medium
high

Figure ES.3. MOE-5: Service Deployment Effort Government Consensus Scorecard

MoE-6: Service Coverage per Unit of Infrastructure

Rubric: Infrastructure per covered area, affine model of baseline + marginal

Values: Number of transmitters in target coverage area (units per square kilometer)

Quantification %: Proportional inverse unit coverage in range over all participating technologies

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning	scale
Echo Ridge LLC	LaRC					N/A		24			0
Hellen Systems, LLC	JBCC	2			2	2					0.0001
NextNav LLC	LaRC	11	11	11	11	N/A	17	17	17	17	0.1
OPNT B.V.	LaRC	in situ				N/A					N/A
PhasorLab Inc.	JBCC	21	21	21		N/A	29	29		32	0.2
Satelles, Inc.	JBCC	66	66	66	66	N/A		66			0
Serco Inc.	JBCC					N/A	8	8			0.05
Seven Solutions S.L.	LaRC	in situ				N/A					N/A
Skyhook Wireless, Inc.	LaRC					N/A	14	14	14	14	0.08
TRX Systems, Inc.	LaRC					N/A	in situ	in situ	in situ		N/A
UrsaNav Inc.	JBCC	2		2	2	2					0.0001

Rubric:

units/km^2

2

to

66

in situ

target coverage area (km^2): 100

Figure ES.4. MoE-6: Service Coverage per Unit of Infrastructure Government Consensus Scorecard

The Government Team applied a wide range of stakeholder weighting vectors and technology constraints. Examples of those results, with weights, constraints, and yielded scores, represent six hypothetical constructs:

1. **Timing Performance.** This construct constrains the weighted scoring function for technologies to their demonstrated TIMING PERFORMANCE only.
2. **Positioning Performance.** This construct constrains the scoring function for technologies to their demonstrated POSITIONING PERFORMANCE only.
3. **Timing-terrestrial broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND the technology be a terrestrial RF broadcast.
4. **PNT-terrestrial broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND a positioning function AND the technology be a terrestrial RF broadcast.
5. **Timing-broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND the technology be a RF broadcast.
6. **PNT broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND a positioning function AND the technology be a terrestrial RF broadcast.

These six constructs as implemented in the information framework are graphically depicted in Figure ES.5. Each construct maps by name to one of the six rows of weights in the bottom block of the worksheet. The corresponding scoring results for each construct appear in the six columns on the right end of the vendor/MoE matrix.

PNT Technology Vendor	MoE01: System TRL	MoE02: User Equipment TRL	MoE03a: Accuracy (timing)	MoE03b: Accuracy (2D positioning)	MoE0c: Accuracy (3D positioning)	MoE04: Spectrum Protection	MoE05: Deployment Effort	MoE06a: Unit Coverage (timing)	MoE06b: Unit Coverage (2D positioning)	MoE06c: Unit Coverage (3D positioning)	MoE07: System Synchronization	MoE08: Signal Robustness	MoE09: Service Resilience	MoE10: PNT Mode	MoE11: System Interoperability	MoE12: PNT Info. Security	MoE13: Time to Capability	MoE14: Service Longevity
Echo Ridge	70.0	40.0	0.0	4.8	0.0	100.0	100.0	0.0	65.6	0.0	0.0	0.0	40.0	80.0	100.0	100.0	66.0	66.0
Hellen Systems	70.0	40.0	33.8	0.0	0.0	100.0	66.0	100.0	0.0	0.0	100.0	100.0	0.0	100.0	0.0	75.0	33.0	66.0
NextNav	100.0	100.0	88.9	97.8	99.2	75.0	33.0	86.0	76.6	76.6	75.0	100.0	60.0	100.0	100.0	100.0	100.0	100.0
OPNT	100.0	100.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	100.0	100.0	60.0	100.0	75.0	100.0	100.0
PhasorLab	70.0	70.0	87.4	97.6	97.8	25.0	33.0	70.3	56.3	53.1	75.0	0.0	60.0	100.0	0.0	25.0	66.0	100.0
Satelles	100.0	100.0	53.1	97.7	0.0	100.0	100.0	0.0	0.0	0.0	100.0	100.0	60.0	80.0	100.0	100.0	100.0	66.0
Serco	0.0	0.0	0.0	44.5	0.0	100.0	66.0	0.0	90.6	0.0	75.0	100.0	0.0	100.0	0.0	25.0	33.0	100.0
Seven Solutions	100.0	100.0	100.0	0.0	0.0	0.0	100.0	0.0	0.0	0.0	100.0	100.0	60.0	60.0	100.0	75.0	100.0	100.0
Skyhook	100.0	100.0	0.0	96.9	96.1	25.0	100.0	0.0	81.3	81.3	0.0	0.0	40.0	100.0	100.0	25.0	100.0	100.0
TRX Systems	40.0	70.0	0.0	97.8	0.0	25.0	66.0	0.0	0.0	0.0	0.0	100.0	0.0	40.0	0.0	75.0	66.0	33.0
UrsaNav	100.0	70.0	44.4	0.0	0.0	100.0	66.0	100.0	0.0	0.0	100.0	100.0	0.0	100.0	0.0	75.0	33.0	66.0
GPS (SPS PS)	100.0	100.0	75.1	98.7	98.3	100.0	100.0	65.6	65.6	65.6	100.0	0.0	0.0	80.0	100.0	25.0	100.0	100.0
Stakeholder Weights																		
timing performance	10%	10%	10%	0%	0%	0%	0%	10%	0%	0%	10%	10%	10%	0%	0%	10%	10%	10%
positioning performance	10%	5%	0%	10%	5%	15%	5%	0%	10%	5%	0%	10%	10%	0%	5%	5%	0%	5%
timing ground broadcast	10%	-	10%	-	-	10%	10%	10%	-	-	10%	10%	10%	-	5%	5%	5%	5%
PNT ground broadcast	10%	-	5%	5%	-	10%	10%	5%	5%	-	10%	10%	10%	-	5%	5%	5%	5%
timing broadcast	10%	-	10%	-	-	10%	10%	10%	-	-	10%	10%	10%	-	5%	5%	5%	5%
PNT broadcast	10%	-	5%	5%	-	10%	10%	5%	5%	-	10%	10%	10%	-	5%	5%	5%	5%

Figure ES.5. Application of Scoring Functions with Weighting and Explicit Requirement Filters

DOT sought input and feedback on the data evaluation process and on the presentation of findings on successive occasions from the members of the National Executive Committee for Space-Based Positioning, Navigation, and Timing (EXCOM) and the DOT operating administrations:

- February 24, 2020 – Briefing to the EXCOM Executive Steering Group (ESG)
- April 9, 2020 – Briefing to the PNT Advisory Board (SG)
- May 28, 2020 – Briefing to the EXCOM Steering Group (SG)
- June 9, 2020 – Briefing to DOT Operating Administration Staff
- June 15, 2020 – Briefing to the Extended Positioning & Navigation Working Group
- July 10, 2020 – Briefing to the EXCOM ESG
- August 21, 2020 – Briefing to the EXCOM

Through these various engagements, DOT was able to gain valuable suggestions and recommendations that it subsequently folded into the demonstration and evaluation process. As an example, during the ESG meeting, a representative from the Office of Science and Technology Policy (OSTP) recommended that the MoE analysis build in the assessment of stand-alone GPS as a point of reference; this was implemented as shown in Figure ES.5 with the additional "vendor" row of GPS Standard Positioning Service Performance Standard (SPS-PS).

In addition to the DHS December 2018 demonstration findings, there are four key findings from the DOT technology demonstration:

1. All TRL-qualified vendors demonstrated some PNT performance of value, but only one vendor demonstrated PNT performance in all applicable use case scenarios.
2. Neither eLORAN technology succeeded in the Static Basement Timing scenario.
3. One technology, R-Mode ranging in the MF band, did not meet the minimum Technology Readiness Level (TRL) of 6.
4. Deployment effort and coverage (infrastructure per unit area) are both significant cost factors.

The findings indicate that the best strategy for achieving resilient PNT service is to pursue multiple technologies to promote diversity in the PNT functions that support transportation and other critical infrastructure sectors.

The demonstration team has constructed a decision support capability with the MoE information framework. The MoE framework can serve as a strategic, planning, and programmatic support tool. The MoE framework is also capable of incorporating information from other sources or demonstrations to broaden the base of information fed up through the framework.

As communicated during the August 21, 2020 briefing to the EXCOM, DOT makes two recommendations:

1. DOT should develop system requirements for PNT functions that support safety-critical services.

2. DOT should develop standards, test procedures, and monitoring capabilities to ensure that PNT services, and the equipage that utilizes them, meet the necessary levels of safety and resilience identified in Recommendation 1.

Recognizing that the transportation sector has some of the most stringent performance requirements in terms of accuracy, integrity, availability, and reliability, developing system requirements that focus on safety and resilience will allow determination of which requirements are currently met, and which requirements may require further commercial innovation. DOT supports open safety standards to promote private-sector innovation and commercial product development.

1 Background

Safety is the U.S. Department of Transportation's (DOT) top priority. DOT must ensure that accurate and reliable sources of Positioning, Navigation, and Timing (PNT), such as the Global Positioning System (GPS), are available to meet current and emerging applications and supporting infrastructures (*e.g.*, communications, energy, and information systems), with the goal of reducing deaths and injuries within all modes of transportation, ensuring that America's transportation network continues to be the safe and technologically advanced, and generally protecting all critical infrastructure that depend on reliable PNT services.

PNT technology research and development is vital to the efficiency and safety of all transportation modes. The safety of critical infrastructure sectors such as communication, banking, the electric grid, and dams, among many others, relies on the promise of improved accuracy and resilience of PNT technologies. Improved PNT systems comprising both space-based and ground-based technologies are also needed for the safety of autonomous platforms, such as Automated Vehicles (AV) and Unmanned Aerial Systems (UAS). Infrastructure and transportation safety also depend on sound, efficient spectrum management policies allowing the harmonious coexistence of various communication and PNT systems.

Resilient PNT is not only important to support critical infrastructure in the transportation sector, but is also essential for national and economic security. The primary and most recognizable PNT service supporting critical infrastructure is GPS. However, because GPS relies on signals broadcast from satellites in Medium Earth Orbit (MEO), signal strength at the receiver is low and thus vulnerable to intentional and unintentional disruptions.

1.1 Threats to GPS

As GPS technology advances, the number of threats to the system increases. Two of these threats are jamming and spoofing. As explained in a DHS report,[2] "jamming is intentionally produced RF waveforms that have the same effect as interference; the only difference is the intent to degrade or deny a target receiver's operation", and "spoofing is caused by RF waveforms that mimic true signals in some ways, but deny, degrade, disrupt, or deceive a receiver's operation when they are processed."

Jamming has long been a threat to GPS due to the weak signal power from GPS satellites. Last year, North Atlantic Treaty Organization (NATO) military drills in the Baltic Sea, with 40,000 troops and all 29 NATO countries participating, experienced GPS jamming.

[2] Department of Homeland Security, Improving the Operation and Development of Global Positioning system (GPS) Equipment Used by Critical Infrastructure. Undated. At https://www.navcen.uscg.gov/pdf/gps/Best%20Practices%20for%20Improving%20the%20Operation%20and%20Development%20of%20GPS%20Equipment.pdf

Spoofing was discounted as a realistic threat for many years because it is complicated to perform. However, high-profile demonstrations at the University of Texas that spoofed a drone and a sophisticated yacht brought spoofing into the public eye. The 2017 incident in the Black Sea, in which over 20 ships reported their positions inland at an airport, was likely a spoofing attack. The number of separate vessels that reported the same false position, as well as the characteristic jumping between the false and true position of the ships, is strong evidence of a large-scale spoofing attack.

Teenagers have figured out ways to spoof the Global Navigation Satellite System (GNSS) in Pokémon GO, an app-based augmented reality game based on GPS, using chips in their phones. If teenagers have figured out how to spoof the GPS on their phones, others with more malicious intentions most certainly have done the same. The rise of the low-cost, software-defined radio has enabled, if not "spoofing for everyone," spoofing for many. When people buy small, software-defined radios that cost around $200 and are equipped with open-source GPS simulation software, they have obtained a basic spoofer.

The impact areas identified in the DOT 2001 report, "Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System," have, if anything, increased the scope and exposure to public sector economic and safety losses in the event of a GPS disruption:[3]

- Transportation service disruption
- Environmental damage
- Property damage
- Serious injury or fatality
- Loss of confidence in a transportation mode
- Liability to the service provider

Since 2001, neither the vulnerabilities of, nor the dependence on, GPS service have decreased significantly for the public sector. Over the last two decades, Federal departments and agencies across the Federal Government have reinforced this assessment with findings on critical infrastructure, emergency services, consumer and business processes, and automated systems.[1] Even commercial entities, such as timing services, are slowly gaining awareness.[4] The ubiquity of GPS in everyday consumer, commercial, and public-agency devices to enable Positioning, Navigation, and Timing functions is due in large part to its highly favorable price and performance points under normal conditions.

For an open service, such as the public side of GPS, the risks lie in the disruptions to and potential manipulation of the broadcast service. Improving GPS service by adding new functionality—for example, authenticated or encrypted signals—renders older user equipment obsolete or unprotected because it

[3] John A. Volpe National Transportation Systems Center, *Vulnerability Assessment of the Transportation Infrastructure Relying on the Global Positioning System*, Washington, DC: U.S. Department of Transportation, 2001, available at https://rosap.ntl.bts.gov/view/dot/8435.
[4] Paul Tullis, "The World Economy Runs on GPS. It Needs a Backup Plan," Bloomberg Businessweek, July 25, 2018, available at https://www.bloomberg.com/news/features/2018-07-25/the-world-economy-runs-on-gps-it-needs-a-backup-plan.

cannot apply new functions. The GPS paradox lies in its wide adoption, which has made the service very difficult to improve to ensure signal reception under degraded operating conditions or resilience to threats. To date, GPS service has been too expensive to change. However, the economic and safety risk of GPS dependence is quickly becoming too large to accept.

A clear common denominator in reducing economic and safety exposure due to dependence on GPS is to consider investment in complementary PNT services. Not only does this approach ease the cost side of the GPS paradox by protecting against degraded or interrupted performance with additional technologies; if designed properly, complementary technologies can also add a layer of resilience to GPS service itself. Through the former, users can achieve needed resilience by balancing between required PNT performance and investment cost. Through the latter, devices can improve GPS performance with a comparator function, an authentication mechanism, or in the extreme case a back-up PNT function.

1.2 National Security Presidential Directive 39

The Secretary of Transportation, under 49 U.S.C. § 301, has overall leadership responsibility for, and broad authority over, transportation matters, including policy, programs, and technological development. PNT is an important part of carrying out these responsibilities. The Office of the Assistant Secretary for Research and Technology (OST-R) coordinates PNT issues and planning that affect multiple modes of transportation, including those that are intermodal in nature.

Under National Security Presidential Directive 39 (NSPD-39)[5], issued in December 2004 and still in force, the United States is committed to developing, maintaining and modernizing GPS, including providing a backup capability in the event of a GPS disruption. The directive gives DOT lead responsibility over the full range of civil uses of GPS, and it makes DOT co-chair, along with DOD, of the National Space Based Positioning, Navigation, and Timing Executive Committee. DOT is working closely with DHS, DOD, and other federal departments and agencies to address policy and technical issues, including the security of resilience of GPS receivers. NSPD-39 designated DOT as the lead agency for representing U.S. non-military stakeholders—and, increasingly, for resilient use of foreign GNSS services.

DOT is the focal point for PNT policy, which has centered primarily on GPS, used across the Nation in all modes of transportation. The Federal Aviation Administration (FAA) is responsible for supporting all aviation users of GPS and of FAA’s associated Wide Area Augmentation System (WAAS), which is a real-time overlay to GPS providing safety-of-life navigation based on the open signals broadcast by GPS. These and other economic activities in transportation, among other civil sectors, are dependent on space-based PNT for maintaining normal operations both within and outside U.S. territory.

[5] The White House, National Security Presidential Directive 39 (NSPD 39): U.S. Space-Based Position, Navigation, and Timing Policy (Dec. 8, 2004).

DOT, including FAA, works in close coordination with DHS, including the U.S. Coast Guard (USCG) Navigation Center (NavCen), to serve civil GPS users. NavCen provides GPS operational advisories and maintains the GPS Problem Reporting web-based portal for all positioning and timing users.

1.3 Legislation

This report supports the response to three directives from Congress that seek to strengthen the overall resilience of U.S PNT capabilities. The three legislative initiatives are described below; the complete text of each may be found in Appendix A. Two of the initiatives involved joint efforts of the Department of Defense (DOD), DOT, and the Department of Homeland Security (DHS). Research and evaluation of issues involving sensitive information or classified national security matters are addressed in separate reports by DOD and DHS.

1.3.1 National Defense Authorization Act for Fiscal Year 2017 (FY17 NDAA)

Section 1618 of the FY17 NDAA (Public Law 114–328) directed the Secretary of Defense, the Secretary of Transportation, and the Secretary of Homeland Security jointly to conduct a study to assess and identify the technology-neutral requirements to back up and complement the PNT capabilities of GPS for national security and critical infrastructure. The resultant report is described in detail in section 1.5.[6]

1.3.2 National Defense Authorization Act for Fiscal Year 2018 (FY18 NDAA)

Section 1606 of Public Law 115–91 (also known as the National Defense Authorization Act for Fiscal Year 2018 [FY18 NDAA]), directed the Secretary of Defense, the Secretary of Transportation, and the Secretary of Homeland Security (referred to in this section as the "Secretaries") to jointly develop a plan for carrying out a backup GPS capability and complementary PNT demonstration.[7] The FY18 NDAA language specifies four actions:

- PLAN: A jointly developed demonstration plan ("Plan") shall be based on the results of the study conducted under Section 1618 of the National Defense Authorization Act for Fiscal Year 2017 (Public Law 114–328; 130 Stat. 2595); and include the activities that the Secretaries determine necessary to carry out such demonstration.
- BRIEFING: Appropriate congressional committees shall be briefed on the Plan identifying the sectors that would be expected to participate in the backup GPS capability demonstration, an estimate of the costs of implementing the demonstration in each identified sector, and explanation of the extent to which the demonstration may be carried out with the funds appropriated for such purpose.
- IMPLEMENTATION: Jointly initiate the backup GPS capability demonstration to the extent described under the Plan.
- REPORT: Appropriate congressional committees shall be provided a report on the backup GPS capability demonstration carried out under subsection (c) that includes—(1) a description of

[6] 130 Stat. 2595–2596, available at https://www.congress.gov/114/plaws/publ328/PLAW-114publ328.pdf.
[7] 131 Stat. 1725–1726, available at https://www.congress.gov/115/plaws/publ91/PLAW-115publ91.pdf.

the opportunities and challenges learned from such demonstration; and (2) a description of the next actions the Secretaries determine appropriate to backup and complement the Positioning, Navigation, and Timing capabilities of the Global Positioning System for national security and critical infrastructure, including, at a minimum, the timeline and funding required to issue a request for proposals for such capabilities.

Further, the FY18 NDAA Section 1606 language specifies that the costs to develop and execute the plan shall be consistent with the responsibilities established in NSPD-39. The term "backup GPS capability demonstration" means a proof-of-concept demonstration of capabilities to back up and complement the Positioning, Navigation, and Timing capabilities of the Global Positioning System for national security and critical infrastructure. Ten million dollars were authorized to conduct the demonstration, which is the amount that was appropriated in the FY 2018 Omnibus Appropriations (Consolidated Appropriations Act, 2018; P.L. 115-141 March 23, 2018).

Under this mandate from Congress, OST-R tasked the John A. Volpe National Transportation Systems Center (Volpe Center) with preparing and conducting the required GPS backup demonstration with funds appropriated by DOD.

1.3.3 The National Timing Resilience and Security Act of 2018

Subsequent to the FY18 NDAA legislation, the Frank LoBiondo Coast Guard Authorization Act of 2018 (Public Law 115–282) included Section 514, "Backup National Timing System," also known as the National Timing Resilience and Security Act of 2018 (NTRSA).[8] The NTRSA required that, "Subject to the availability of appropriations, the Secretary of Transportation shall provide for the establishment, sustainment, and operation of a land-based, resilient, and reliable alternative timing system" within two years, with a nominal 20-year operational life. The goals of this measure were to reduce critical dependency on GPS, to provide a complement to GPS, and to ensure availability of uncorrupted and non-degraded timing signals.

DOT has been working with DOD and DHS on GPS backup and complementary PNT activities for several years, most recently in response to requirements in the FY17 NDAA and the FY18 NDAA. For clarification, a GPS backup capability provides equal or lesser performance in terms of accuracy, availability, coverage, etc., whereas a complementary PNT capability may provide coverage in environments where GPS performance typically is limited (*e.g.*, indoors, underground, etc.).

The goal of the NTRSA is to reduce critical dependency on, and to provide a complement to, GPS, and to ensure the availability of uncorrupted and non-degraded timing signals, especially for national security and critical infrastructure purposes. Specific actions in the NTRSA require the Secretary of Transportation to prepare a plan to develop, construct, and operate the GPS backup system within 180 days, and to submit an implementation plan to the Committee on Commerce, Science, and Technology of the Senate and the Committee on Transportation and Infrastructure of the House of Representatives.

[8] 132 Stat. 4276–4278, available at https://www.congress.gov/115/plaws/publ282/PLAW-115publ282.pdf.

1.4 DOT PNT Resilience Roadmap

DOT has established a PNT Resiliency Roadmap for achieving the goals laid out in the FY17 and FY18 interagency NDAA efforts and the NTRSA. The roadmap sets objectives that leverage the joint technical work conducted by DOT, DOD, and DHS over several years, and most recently in response to the requirements of the FY17 NDAA and FY18 NDAA. Section 1618 of the FY17 NDAA requires DOD, DOT, and DHS to "conduct a study to assess and identify the technology-neutral requirements to backup and complement the Positioning, Navigation, and Timing capabilities of the Global Positioning System for national security and critical infrastructure," and to conduct an analysis of alternatives to determine the "best mix" of technologies.

Further, DOT coordinates across Federal departments and agencies to publish jointly the Federal Radionavigation Plan (FRP).[9] The FRP is the official source of PNT policy and planning for the Federal Government. It is required by the National Defense Authorization Act for Fiscal Year 1998, as published under Title 10 United States Code, Section 2281, paragraph (c). The FRP is prepared jointly by DOD, DOT, and DHS with the assistance of other Government agencies, and is published not less than every two years. DOT has aligned work conducted on this complementary PNT demonstration under the FY18 NDAA Section 1606 with the FRP to serve transportation and critical infrastructure needs for the public good.

1.5 FY17 NDAA Report

The National Risk Management Center (NRMC), within the Cybersecurity and Infrastructure Security Agency (CISA) of DHS, conducted a study to fulfill the mandate of the FY17 NDAA. This study was supported by additional research by the Homeland Security Operational Analysis Center (HSOAC) and the National Institute for Hometown Security, Inc. (NIHS).[10] The study generated a report, "Positioning, Navigation, and Timing (PNT) Backup and Complementary Capabilities to the Global Positioning System (GPS)" (hereafter referred to as the FY17 NDAA Report).[11] The key findings and recommendations from the DHS FY17 PNT Report were:

1. GPS is not the only source of PNT data. Other sources are currently available for purchase, and include alternate space-based systems and constellations, terrestrial beaconing systems, time-over-fiber, cellular and wireless signals, and local terrestrial systems.
2. Whatever the source of the PNT, it is incumbent on users to apply the principles found in Executive Order 13905, "Strengthening National Resilience through Responsible Use of

[9] *2019 Federal Radionavigation Plan*, Washington, DC: Departments of Defense, Transportation, and Homeland Security, available at https://rosap.ntl.bts.gov/view/dot/43623.

[10] HSOAC is a federally funded research and development center operated by the RAND Corporation. NIHS provides research and operational support for the DHS Cybersecurity and Infrastructure Security Agency. The specific study conducted by NIHS to support this effort was subcontracted by NIHS to the Civil Systems Group of The Aerospace Corporation.

[11] Cybersecurity and Infrastructure Security Agency, *Report on Positioning, Navigation, and Timing (PNT) Backup and Complementary Capabilities to the Global Positioning System (GPS)*, Washington, DC: U.S. Department of Homeland Security, 2020, available at: https://www.cisa.gov/publication/pnt-backup-report.

Positioning, Navigation, and Timing Services." By applying these principles users can reduce the risk associated with the disruption or manipulation of PNT services.
3. Unless non-GPS PNT sources are free or low-cost or provide a unique benefit deemed valuable by the user and not found in GPS and other currently available sources, there is no reason to assume users will adopt new non-GPS PNT sources more widely than they have today. However, user behavior could be modified through subsidies or regulatory requirements.
4. The critical infrastructure sectors heavily reliant on PNT (meaning disruption would cause significant costs, delays, or degradation of functions and service) include communications, information technology, transportation, emergency services, energy, surveying and mapping, and financial services.
5. The critical infrastructure sectors highlighted in this report are heavily reliant on PNT services, but their requirements differ significantly. Some sectors require very precise timing, while in others position and navigation precision is more important.
6. Critical infrastructure systems that would cease to operate due to GPS disruptions will do so because of design choices associated with a lack of information, cost, efficiency, and other considerations—not because of a lack of available options. In other words, business decisions, the lack of a Federal mandate, and potentially an under-appreciation of the risk associated with GPS dependence are factors in the lack of resilience to GPS disruption.
7. New non-GPS PNT systems that are designed without considering existing PNT systems—including their capabilities, limitations, and why they were adopted in some industries and not others—may simply compete with existing systems rather than fill perceived backup gaps.
8. DHS could not identify generic specifications for a national backup. Position and navigation backups must be application-specific and must be developed in coordination with industry owners and operators.
9. While position and navigation requirements are complex, timing requirements are simple, with a minimal acceptable precision of anywhere between 65 and 240 nanoseconds. This level of precision supports all critical infrastructure requirements and is expected to meet future requirements, including 5G.

<u>Recommendations</u>

The FY17 NDAA Report contained four broad recommendations that seek to address the Nation's PNT requirements and backup or complementary PNT capability gaps. The results of the demonstration effort mandated by NDAA FY18 will inform the Federal Government's efforts in carrying out these recommendations and promoting PNT resilience for critical infrastructure.

1. **Temporary GPS Disruptions:** End users should be responsible for mitigating temporary GPS disruptions. For example, the Federal Aviation Administration maintains sufficient PNT capabilities to assure the continued safe operation of the national airspace, albeit at a reduced capacity, during GPS disruptions. The Federal Government can facilitate this mitigation for various critical infrastructure sectors, but should not be solely responsible for it.
2. **PNT Diversity and Segmentation:** The Federal Government should encourage adoption of multiple PNT sources, thus expanding the availability of PNT services based on market drivers. Encouraging critical infrastructure owners and operators to adopt multiple PNT systems will diffuse the risk currently concentrated in wide-area PNT services, such as GPS. Federal actions should focus on facilitating the availability and adoption of PNT sources in the open market.
3. **System Design:** PNT provisioning systems, assets, and services must be designed with inherent security and resilience features. Critical Infrastructure systems that use PNT services must be

designed to operate through interference and to identify and respond to anomalous PNT inputs. These attributes are applicable to the PNT receivers and the systems that use them.

4. **Pursue Innovation that Emphasizes Transition and Adoption:** Incorporating PNT signal diversity into the PNT ecosystem should be pursued with an emphasis on research and development that prioritizes successful transition and adoption into existing GPS receivers, taking into account factors such as business case considerations, financial costs, technical integration, and logistical deployment.

1.6 Policy on Responsible Use of PNT Services

On February 12, 2020, the President issued Executive Order (EO) 13905, "Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services."[12] The order establishes U.S. policy to ensure that disruption or manipulation of PNT services does not undermine the reliable and efficient functioning of its critical infrastructure. EO 13905 expressly calls for Federal departments and agencies to implement plans, tests, and profiles for all critical infrastructure utilizing or depending on PNT services.

EO 13905 seeks to ensure that disruption or manipulation of PNT services does not undermine the reliability or efficiency of critical infrastructure by:

- Raising awareness of the extent to which critical infrastructure depends on PNT services
- Ensuring critical infrastructure can withstand disruption or manipulation of PNT services
- Engaging public and private sectors to promote responsible use of PNT services.

EO 13905 assigned responsibilities across the Executive Branch to raise awareness of critical infrastructure dependence on GPS and other GNSS services, including the transportation sector. The responsibilities include development of PNT profiles describing the usage and dependence of Sector-Specific Agency (SSA) critical infrastructure, conducting testing of PNT services, and, as directed by the Office of Science and Technology Policy, integrating multiple PNT services that are not dependent on GNSS.

The complementary PNT technologies demonstrated by DOT in this FY18 NDAA effort will directly inform the OSTP National PNT R&D plan, as well as the pilot programs required under EO 13905. Further, the decision framework described in this report provides pertinent information and candidate capabilities for GNSS-independent PNT service options that increase critical infrastructure resilience against GPS disruptions or manipulation.

[12] 85 FR 9359, available at https://www.govinfo.gov/content/pkg/FR-2020-02-18/pdf/2020-03337.pdf.

2 GPS Backup and Complementary PNT Demonstration Overview

Resilience against PNT service disruption or manipulation is an important safety and economic concern for critical infrastructure owners, operators, and users. This demonstration was designed to identify the set of PNT technologies that increase resilience of critical infrastructure through candidate acquisition of provided services. This is in parallel with the "protect and toughen" aspects of the "Protect-Toughen-Augment" guidance developed by the Space-Based Positioning, Navigation, and Timing Advisory Board with respect to spectrum policy and receiver designs.[13]

2.1 Goals and Objectives

Based on the requirements of the FY18 NDAA, OST-R directed the Volpe Center to conduct field demonstrations of candidate PNT technologies that could offer complementary service in the event of GPS disruptions. The purpose of the demonstration was to gather information on PNT technologies at a high Technology Readiness Level (TRL) that can work in the absence of GPS. As noted in section 1, the effort was undertaken in accordance with the FY18 NDAA, Section 1606, for DOD, DOT, and DHS jointly to develop a plan for demonstration of PNT capabilities in the absence of GPS.

The Volpe Center, through a competitive acquisition process, selected 11 candidate technologies to demonstrate positioning and timing functions in the absence of GPS at two demonstration sites. Five of the technologies were demonstrated at Joint Base Cape Cod and six were demonstrated at NASA Langley Research Center. The Government Team (discussed below), with vendor support, conducted eight scenarios at both sites; an additional ninth scenario was conducted at JBCC for eLORAN.

The Government Team established nine demonstration scenarios. Each PNT vendor was encouraged to demonstrate under all scenarios suitable for their technology and TRL. All PNT vendors were required to choose and to demonstrate at least one of the nine scenarios. The Complementary PNT and GPS Backup Technologies Demonstration Plan defined the scenarios prescribed in the demonstrations. The motivation for a scenario-based, rather than technology-based, demonstration drew from the Plan's two-fold PNT policy and strategy:

1. To broaden Positioning, Navigation, and Timing functional performance (rather than focusing on the technology itself)
2. To provide a common demonstration platform with an independent/confirmation reference system.

[13] Space-Based Positioning, Navigation, and Timing Advisory Board, "Protect, Toughen, and Augment Global Positioning System for Users," September 2018, available at https://www.gps.gov/governance/advisory/recommendations/2018-09-topic-papers.pdf.

The Government's reference systems used Differential GPS (DGPS) for positioning and a cesium- or rubidium-based atomic frequency standard initialized with GPS for timing, along with data collection equipment and mobile land and aerial host vehicles. The central objective of the overall demonstration was to have each complementary PNT technology demonstrated and verified in its best light. With that objective in mind, the Government Team sought to identify measures that aid in understanding what that "best light" was and how the demonstration scenarios bring that understanding forward.

2.2 Measures of Effectiveness

The range of potential complementary PNT technologies is wide and varied. Consequently, an important outcome of the demonstration project was to develop a framework that conveys pertinent information relevant to the Government's policy and decision-making strategy. That framework must channel information from a diverse set of PNT technologies into a clear, tractable set of statements about any given technology's suitability to fulfill complementary PNT functions. The approach established by the Government team was to develop a set of Measures of Effectiveness (MoEs) that scope the needs or notional requirements of PNT services that the Government could invest in or endorse.

The challenge of this approach is that any particular measure must be capable of taking in broad information from the range of technologies being demonstrated. That this effort was a demonstration rather than a system acquisition provided some additional flexibility. The Government Team made use of this flexibility, structuring the MoEs as rubrics. "Rubric" as used here means a scoring guide that sets defined levels for use in assessment and scoring.

The team defined 14 MoEs, along with their respective rubrics:

- MoE-1: Technical Readiness–System (TRL 6-9)
- MoE-2: Technical Readiness–User Equipment (TRL 6-9)
- MoE-3: Timing and Positioning Accuracy (as residual error; meters, nanoseconds)
- MoE-4: Spectrum Protection (protected, owned, leased, shared)
- MoE-5: Service Deployment Effort (low, medium, high)
- MoE-6: Service Coverage per Unit of Infrastructure (number of transmitters per unit area covered (units/km^2)
- MoE-7: Service Synchronization (UTC, cascade, self-synchronizing)
- MoE-8: PNT Signal Robustness (strong, weak)
- MoE-9: Service Resilience (fail-safe, -over, -soft, -hard)
- MoE-10: PNT Distribution Mode (terrestrial RF, orbital RF, fiber, database)
- MoE-11: Service Interoperability (high, low)
- MoE-12: PNT Information Security (high, medium, low)
- MoE-13: Time to Service Implementation (short, medium, long)
- MoE-14: PNT System/Service Longevity (long, medium, short)

These MoEs fall into two logical subsets:

- Capability subset (MoE-1 through MoE-9). These MoEs can be evaluated using inherently more quantitative rubrics.
- Suitability subset (MoE-10 through MoE-14). The MoEs in this group which can be evaluated using inherently more qualitative rubrics.

The government Team's Subject Matter Experts (SMEs) employed the MOE rubrics to assess the strengths of a given technology as demonstrated under a given scenario.

2.3 Funding

Funding for conducting the Complementary PNT and GPS Backup Demonstration was provided through the United States Air Force (USAF) Space and Missile System Center (SMC), based primarily on $10,000,000 authorized to conduct the demonstration, which is the amount that was appropriated in the FY 2018 Omnibus Appropriations (Consolidated Appropriations Act, 2018; P.L. 115-141 March 23, 2018). In addition, approximately $1,150,000 in supplementary resources from the 2018-2019 regular appropriations of the Office of the Assistant Secretary for Research and Technology also supported the demonstration.

2.4 The Government Team

The Government Team comprised Federal staff from OST-R, the Volpe Center, the NASA Langley Research Center, and the United States Coast Guard. In addition, contractor support was provided by The MITRE Corporation, Zeta Associates Inc., KBR, and Changeis, Inc. Throughout this report, references to the "DOT" or "Government Team" mean Federal staff, contract personnel, or both.
The MITRE Corporation was selected to support the demonstration due to its experience with the previous GPS backup demonstration effort conducted by DHS. Given an aggressive schedule, it was advantageous to leverage MITRE's experience, including a previously developed reference truth and data collection system.

Zeta Associates was selected to support the demonstration due to its experience with other PNT activities, including support to DOT on the GPS Adjacent Band Compatibility Assessment[14]and work for the FAA WAAS Program. The Zeta Associates team supported the demonstration at NASA LaRC and the MITRE Corporation supported the demonstration at JBCC.

KBR provides technical expertise to the Volpe Center via the Support On-Site for Information Technology (SOFITS) contract. Through this relationship, the NDAA GPS Backup and Complimentary PNT Program was able to secure key technical assets with subject matter expertise in data acquisition systems and GNSS applications for small Unmanned Aerial Systems (sUAS).

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[14] https://www.transportation.gov/pnt/global-positioning-systemgps-adjacent-band-compatibility-assessment.

Changeis, Inc., provides technical expertise to the Volpe Center via the Support for Communications and Operations Research and Analysis (SCOAR) contract. For the GPS Backup and Complementary PNT Demonstration, Changeis contributed work breakdown analysis, expert management of document development and production, and both technical and copy editing.

2.5 OST Outreach and Request for Information (RFI)

An important consideration in DOT's evaluation to implement a GPS backup and/or complementary PNT capability was to incorporate input from external stakeholders with regard to PNT technologies that are at a high level of technological readiness. This input was to be used to identify scenarios that would satisfy user needs in the event of a GPS disruption.

DOT held two industry roundtable discussions in early 2019 to receive this input on technology options to be considered as part of a DOT-led demonstration program, as well as to identify technologies that would likely be adopted into end-user equipment to ensure PNT resilience. Using input from the roundtable discussions, DOT issued an RFI requesting information for DOT's use in developing a plan to demonstrate candidate technologies.

2.5.1 PNT Technology Vendor Roundtable

The DOT industry roundtable on March 20, 2019, included chief executive officers and chief technology officers from a number of PNT technology vendors potentially interested in demonstrating GPS backup and/or complementary PNT technologies. Key takeaways from this technology vendor roundtable were:

- An ecosystem of PNT technologies exists; no single system can meet all user application needs when GPS service is degraded or denied.
- Radiofrequency spectrum that is protected from interference is required for effective deployment of GPS backup/complementary PNT technologies.
- Commercial PNT systems are available and deployed to meet specific needs/applications.
- GPS dependence is a by-product of system design choices driven by cost, reliability, and efficiency considerations, all of which are also key considerations for the implementation of GPS backup/complementary PNT technologies.
- Size, weight, and power of GPS backup/complementary PNT end-user equipment, as well as availability and cost of that equipment, will be a key factor for user adoption.
- Industry supports DOT conducting a demonstration of GPS backup/ complementary PNT technologies that includes industry participation in the demonstration.
- Participants recommended that analysis of DOT results be based on tiered levels of PNT service.

2.5.2 Wireless Industry Roundtable

DOT hosted a second industry roundtable on April 8, 2019, with representatives from the wireless industry to understand considerations for network deployment and end-user equipment adoption of

GPS backup/complementary PNT technologies. Key takeaways from the wireless industry roundtable were:

- Modern communications networks require precise time and frequency standards to operate efficiently, with GPS being the most commonly deployed source of precise frequency control and absolute time distribution.
- The current baseline for time holdover is +/- 1.5 microseconds. 5G will push the limit into the hundreds of nanoseconds.
- Wireless network providers are aware of GPS vulnerabilities and support the findings and recommendations of the Communications Security, Reliability and Interoperability Council (CSRIC) V Working Group 4 Subgroup B in their "Network Timing Single Source Risk Reduction Final Report" (December 2016).[15]
- Existing and emerging technologies can meet commercial timing requirements, at a cost, and with their own set of limitations and risks, depending on how long GPS is disrupted.
- Use of local holdover capabilities can mitigate short-term disruptions.
- There is no clear indication that network providers will be willing to pay a subscription fee for a GPS backup timing capability.

2.5.3 Request for Information

Based on feedback from the two industry roundtables, DOT developed a Request for Information (RFI) to seek levels of interest and additional information from PNT technology vendors on participation in the demonstration. DOT worked with DHS and DOD to develop the RFI, which requested information for DOT's use in developing a plan to demonstrate candidate technologies capable of serving as a backup and/or complement to GPS to ensure resilient PNT services for U.S. critical infrastructure (CI) operations. The RFI requested that a vendor interested in participating provide information about its proposed technology and include at minimum:

1. A description of the technology(ies) and CI application(s), including cybersecurity and other security measures inherent in the system, and statement of whether the technology(ies) is/are for timing only, location only, or both timing and location.
2. Identify the TRL for the proposed technology(ies).
3. Identify whether the vendor is willing to participate in the demonstration by providing material (hardware and user equipment when applicable), engineering (technology deployment, configuration, and data collection support), and logistical support during the preparation and execution phases of the demonstration.
4. Identify whether this support is contingent on the government providing funding.
5. Provide information about the needed infrastructure (e.g., power, network, etc.) that would be necessary to deploy the vendor technology(ies) at a DOT-furnished demonstration site.
6. Identify any constraints on participation such as lead-time, demonstration timelines, funding, infrastructure (HVAC, power, shelter, and equipment space, etc.).
7. Identify radiofrequency bands and transmit power levels in terms of peak Effective Isotropic Radiated Power (EIRP). This is needed during the planning phase depending on the selected demonstration site(s).

[15] CSRIC V, Working Group 4: Communications Infrastructure Resiliency, Subgroup B: Network Timing Single Source Risk Reduction, Final Report, December 2016, Washington, DC: Federal Communications Commission, available at https://transition.fcc.gov/bureaus/pshs/advisory/csric5/WG4B_FinalReport_122116.docx

8. Identify where the technology(ies) is/are currently deployed and in use, if applicable. Provide location, date of deployment, and if the deployment is available for examination.

The RFI was issued on May 3, 2019, with responses due June 3, 2019.[16] Twenty-one unique responses to the RFI were received by the deadline (see Table 1). The responses confirmed that there existed a large number of diverse candidate technologies that could participate in a GPS backup/complementary PNT capability demonstration.

Table 1. Respondents to DOT RFI on GPS Backup/Complementary PNT

Number	Submitter
1	Alion Science and Technology Corporation
2	Arbiter Systems, Inc.
3	CTIA – The Wireless Association
4	GlobalStar, Inc. and Echo Ridge, LLC
5	GPS Innovation Alliance
6	Hellen Systems, LLC
7	InfiniDome Ltd.
8	Intelligent Material Solutions, Inc.
9	iPosi, Inc.
10	Jackson Labs Technologies, Inc.
11	Locata Corporation Pty Ltd.
12	Lockheed Martin Corporation
13	Merlin Technology Inc.
14	NextNav, LLC
15	OPNT B.V.
16	Qualcomm Technologies, Inc.
17	Satelles, Inc.
18	Seven Solutions S.L.
19	Skyhook Wireless, Inc.
20	Ursa Navigation Solutions, Inc. (d.b.a. UrsaNav, Inc.)
21	Viziv Technologies, LLC

2.6 DHS FY18 NDAA Report

To meet the short timelines in the FY18 NDAA Section 1606 requirements, DHS conducted a Phase 1 demonstration in December 2018. This demonstration was executed through the DHS Science and Technology Directorate (S&T) and utilized DHS S&T funds to contract support from the test facility (NASA Langley Research Center) and the Homeland Security Systems Engineering and Development

[16] 84 FR 19154, available at https://www.govinfo.gov/content/pkg/FR-2019-05-03/pdf/2019-09092.pdf.

Institute (HSSEDI).[17] DHS demonstrated a combination of position and timing use cases for dynamic vs. static and indoor vs. outdoor applications, along with a time-transfer use case for critical infrastructure applications. DHS demonstration plans, results, and lessons learned were shared with DOT to help inform their Phase 2 demonstration.

Due to schedule constraints, DHS selected three PNT technologies that could be readily demonstrated under similar conditions and routes: NextNav Metropolitan Beacon System (MBS), Locata, and Satelles Satellite Time and Location (STL). Other technologies, such as eLORAN, were not included as part of that demonstration because there were insufficient transmitters in the region to support position/navigation demonstration of the technology. However, DHS had previously studied eLORAN performance under a Cooperative Research and Development Agreement (CRADA) with Harris Corporation and UrsaNav and had an understanding of its capabilities.

The primary demonstration site was the NASA Langley Research Center in Hampton, Virginia, which had existing NextNav and Locata deployments. An additional demonstration of the Locata system was performed at the Insurance Institute for Highway Safety (IIHS) Vehicle Research Center in Ruckersville, Virginia, which had a permanent Locata installation for autonomous vehicle research.

2.7 Volpe Request for Quotation and Final Vendor Awards

Utilizing information from the various external stakeholder outreach efforts, the Government Team developed technical elements for a Request for Quotation (RFQ) so that companies with candidate technologies could participate in a GPS backup demonstration. The Volpe Center issued the RFQ and conducted the subsequent acquisition process.

2.7.1 Request for Quotation

The Volpe Center issued a combined synopsis/solicitation for commercial items on September 13, 2019. The solicitation (No. 6913G619Q300177) was issued as a Request for Quotation RFQ, titled Backup Global Positioning System (GPS) Technical Consulting Services—Technology Demonstration.[18] This was a full and open competition, in accordance with applicable Federal Acquisition Regulations (FAR), and utilized NAICS code 541690.

The RFQ requested commercial services to support a GPS backup capability and complementary PNT demonstration, and requested technical consulting services related to vendor participation. It further indicated that no equipment would be purchased by the Government. Further, data collected under the RFQ would support DOT's congressionally mandated obligations. The RFQ limited the total possible number of firm-fixed-price Purchase Orders (POs) to twenty (20).

[17] HSSEDI is a federally funded research and development center (FFRDC) operated by The MITRE Corporation on behalf of DHS. For more information, see https://www.dhs.gov/science-and-technology/hssedi.

[18] The legacy announcement can be found at the General Service Administration's website, available at https://beta.sam.gov/opp/5ae798c95fb3358e1af2967bf366393d/view.

The following is a list of key requirements/specifications issued under the RFQ:

Contractors must be able to demonstrate a solution within the following parameters:

1. GPS backup technology, henceforth referred to as the Solution, must be at a Technology Readiness Level (TRL) of six or higher as described in the Federal Highway Administration (FHWA)'s Technology Readiness Level Guidebook: TRL 6: Prototype demonstrated in relevant environment, operational environment fully known, tested outside the laboratory, satisfying all operational requirements when confronted with realistic problems.[19]
2. The solution must provide either timing information, position information, or both.
3. The solution must be capable of operating independently of GPS/GNSS. Specifically, the solutions must operate in absence of GPS/GNSS broadcast signals and provide more than just interference mitigation of GPS/GNSS broadcast signals or provide resilience to those specific signals.
4. The solution must be capable of interfacing with the Government's data collection system; specifically, serial connections (e.g., RS-232, i2c, SPI), USB based, or other standard interfaces, e.g., Institute of Electrical and Electronics Engineers (IEEE), 802.11, etc.
5. Demonstration of the solution must meet regulatory compliance and be without any proprietary licensing agreement restrictions.
6. The solution must not produce information requiring protections against disclosure in the interest of national defense of the U.S. commensurate with Executive Order 13526, Classified National Security Information.

Listed below is additional information issued under the RFQ:

Demonstration of the solution is expected to occur at either of two locations (henceforth referred to as the demonstration site):

1. The Volpe Center's Aviation Weather Research Facility located on Joint Base Cape Cod (JBCC); or
2. The National Aeronautics and Space Administration's (NASA) Langley Research Center (LaRC).

The Government intends to demonstrate tunnel, underground and/or degraded environment scenarios.

The Government shall provide a furnished site for the purposes of the demonstration. The furnishings include:

1. Electrical power
2. Internet
3. Tower locations, sizes, payloads, and mounting options determined by the Government considering inputs from offerors
4. HVAC
5. Mobile host platforms for User Equipment (UE) demonstration

[19] *Technology Readiness Level Guidebook*, Washington, DC: Federal Highway Administration, 2015, p. 8, available at https://www.fhwa.dot.gov/publications/research/ear/17047/17047.pdf.

The Government expects to provide access to eLORAN transmitter sites commensurate with proposed solutions, meeting the Government demonstration scenarios.

The Government intends to conduct demonstration scenarios for the Solution including but not limited to the following categories:

1. Stationary positions
2. Dynamic routes
3. Indoors
4. Outdoors
5. On and off road
6. Three-dimensional position
7. Tunnel, underground, and/or degraded environments
8. Highway corridor
9. Ports and/or oceans

Each solution is expected to be capable of demonstration by the Government in at least one of the scenarios. Participation in all suitable scenarios is encouraged, but quotes will not be evaluated on the number or type of scenarios that can be demonstrated. Deployment of the solution, specifically local infrastructure, is expected to remain stationary after set up for the entirety of the demonstration.

The Government Team evaluated all proposals that were submitted. On November 4, 2019, a total of 11 POs were awarded to the following vendors, ordered alphabetically:

1. Echo Ridge LLC
2. Hellen Systems, LLC
3. NextNav LLC
4. OPNT B.V.
5. PhasorLab Inc.
6. Satelles, Inc.
7. Serco Inc.
8. Seven Solutions S.L.
9. Skyhook Wireless, Inc.
10. TRX Systems, Inc.
11. Ursa Navigation Solutions, Inc. (d.b.a. UrsaNav, Inc.)

The total award dollar amount to the 11 vendors was $2,507,499.

2.7.2 Vendors and Technologies

This section briefly describes the 11 vendors and PNT technologies selected for participation in the DOT GPS Backup Demonstration of March 2020. Appendix B provides additional information regarding the implementation of the demonstration for each vendor.

These technologies comprised terrestrial and satellite systems, wireless and wired (optical fiber) systems, networked and autonomous systems, and standardized and customized systems. Regarding positioning, the prevalent approach was multilateration (determining the distance of the user from multiple signal sources at known locations), but there was also a system using dead reckoning (determining the user path after a known initial position).

The technologies are presented in alphabetical order by vendor name.

2.7.2.1 Echo Ridge, LLC

Echo Ridge, LLC (Sterling, Virginia) submitted an Augmented Positioning System (APS), which the company developed with Globalstar, Inc. of Covington, Louisiana.

This APS is a Time-of-Arrival (TOA) multilateration system offering 3D positioning and timing by using Signal-of-Opportunity (SOOP) measurements from the transmissions of the Globalstar satellite communication system. The Globalstar constellation consists of 24 Low Earth Orbit (LEO) satellites at about 1,410-km altitude. The APS user equipment has access to the Globalstar uplink frequency band signals (1,610–1,621.35 MHz) and to the downlink frequency band signals (2,483–2,500 MHz). This positioning system can derive ranging information from the communication signals transmitted from the satellites in their normal operations without the use of any other special signals or modifications to the Globalstar satellite communication system.

2.7.2.2 Hellen Systems, LLC

The technology submitted by Hellen Systems, LLC (Middleburg, Virginia) is based on the enhanced LORAN (eLORAN) system. The Hellen Systems team comprised L3Harris Technologies, Inc.; Microsemi Corp.; Continental Electronics Corp.; Booz Allen Hamilton Inc.; and Crown Consulting, Inc.

eLORAN is a TOA multilateration system offering 2D positioning and timing through a dedicated primary terrestrial network of eLORAN transmitters, which operate in the frequency band of 90-110 kHz, and which can be separated by up to 1,000 km. The eLORAN radio signal is approximately 3 million times (65 dB) stronger than GPS, making it nearly impossible to jam or spoof. eLORAN is an evolution of LORAN-C, which was a Time-Difference-of-Arrival (TDOA) positioning system, and which itself evolved from the initial World War II Long-Range Navigation (LORAN) system.

The main enhancement provided by eLORAN is the inclusion of one or more data channels. These provide low-rate data messaging, added integrity, differential eLORAN and/or DGPS corrections to improve accuracy, and additional data, including navigation messages. These improvements require a dedicated secondary terrestrial network of reference stations, which are spaced up to 50 km apart.

2.7.2.3 NextNav LLC

NextNav LLC (Sunnyvale, California) submitted a technology referred to as the Metropolitan Beacon System (MBS) geolocation platform.

MBS is a TOA multilateration system offering 2D positioning and timing through a dedicated terrestrial network of synchronized transmitters operating in the 920–928 MHz frequency band, using Code Division Multiple Access (CDMA) spread-spectrum signals (as does GPS). MBS also offers vertical positioning through integration with a barometric altimeter and environmental reference information provided over the data payload of the beacon. The Federal Communications Commission (FCC) authorized MBS transmitter EIRP at 30 watts (45 dBm), resulting in typical received signal power of approximately 80 dBm at 1-km range. This is about 100,000 times (50 dB) higher than the nominal received signal power for GPS.

The transmitters are typically synchronized through GPS, but in the absence of GPS, they can revert to non-satellite timing sources (cesium clock or time-over-fiber). The MBS receiver technology has been licensed to several integrated circuit manufacturers (Broadcom, GCT Semiconductor, Intel), and it has been integrated in their standalone GPS chipsets or Long-Term Evolution (LTE)-based GPS chipsets.

2.7.2.4 OPNT B.V.

OPNT B.V. (Amsterdam, The Netherlands) submitted a technology that is embedded within OPNT timing switches for the purpose of real-time analysis and controlled selection of an appropriate timing source.

In the U.S., the OPNT system provides timing services nationwide by leveraging existing telecommunication fiber networks to connect multiple National Timing Institute (NTI) timing sources to a stationary user. For this demonstration, the OPNT system used a hardware simulation of the National Institute of Standards and Technology (NIST) Boulder site and two US Naval Observatory (USNO) sites in the U.S.

The OPNT technology embedded in its timing switches is referred to as the Time Analysis and Selection Engine (TASE). A TASE-equipped timing switch monitors multiple timing sources and performs real-time signal analysis and time correction to determine the output timing signal.

2.7.2.5 PhasorLab Inc.

The technology submitted by PhasorLab Inc. (Nashua, NH) is based on a wireless high-precision Time and Frequency Distribution System (TFDS) called Hyper Sync Net (HSN).

HSN is a TOA multilateration system offering 2D positioning and timing through a dedicated terrestrial network of adaptively synchronized transmitters, which can be stationary or mobile. HSN requires just one grand master reference node, which calibrates its timing to a reference PPS input (such as PPS signals from atomic reference clock or GPS) and acts as a time reference for all the other nodes in the network. HSN can also provide low-altitude vertical positioning, depending on the height of the reference transmitters.

2.7.2.6 Satelles, Inc.

The technology submitted by Satelles, Inc. (Reston, Virginia) is referred to as the Satellite Time and Location (STL) service.

STL is a TOA multilateration system offering 3D positioning and timing using dedicated satellite signals designed by Satelles for the Iridium satellite communication system. The STL signals are broadcast by the LEO 66-satellite Iridium® constellation, which orbits at about 780-km altitude and transmits in the frequency band 1621.35–1626.5 MHz (uplink and downlink). Due to the proximity of LEO satellites (in orbit 25 times closer to the Earth than GNSS satellites) and a high-power satellite signal, the STL signals are about 1,000 times (30 dB) stronger than GPS. In addition, STL exploits the complex and overlapping beam patterns of the Iridium satellite signals and employs cryptographic techniques to mitigate spoofing.

2.7.2.7 Serco Inc.

Serco Inc. (Herndon, Virginia) submitted its R-Mode (Ranging Mode) technology.

Serco's R-Mode is a multilateration system offering 2D-positioning dedicated constant-frequency continuous-wave (CW) retrofitted in existing DGPS transmitters (i.e., R-Mode is not a signal-of-opportunity system). R-Mode targets maritime positioning applications. The DGPS transmitters operate in the Medium Frequency (MF) band (283.5–325 kHz maritime channels). Regarding the method of ranging, an R-Mode receiver measures the phase of the received signal and equates that to distance from the transmitter. Future versions of R-Mode (not demonstrated) are expected to include the use of existing Very High Frequency (VHF) Automatic Identification System (AIS) signals in the maritime channels AIS-1 at 161.975 MHz and AIS-2 at 162.025 MHz or VDE Terrestrial signals. For the DOT demonstration, R-Mode used three custom CW transmitters simulating the operation of MF band Differential GPS (DGPS).

2.7.2.8 Seven Solutions S.L.

The technology demonstrated by Seven Solutions S.L. (Granada, Spain) provides timing services based on the White Rabbit (WR) protocol for time distribution over optical fiber networks.

WR is a standardized technique for high-accuracy (sub-nanosecond) time transfer. It was created to enhance the IEEE 1588 Precision Time Protocol (PTP), used for demanding scientific requirements, and it has evolved as part of the new IEEE 1588-2019 standard that provides precise synchronization of clocks in packet-based networked systems.

Currently, WR is considered the reference synchronization technology in scientific and financial applications. The WR approach can be deployed using existing telecommunication optical fiber infrastructures without requiring modifications to that infrastructure, instead using instead calibration at the user site through commercially available equipment for links longer than 120 km.

2.7.2.9 Skyhook Wireless, Inc.

Skyhook Wireless, Inc. (Boston, Massachusetts) submitted its Precision Location System (PLS) technology for demonstration.

PLS is a multilateration system offering 2D-positioning through SOOP range measurements from the signals of the world-wide network of WiFi access points (AP). The power approach for WiFi ranging uses the Received Signal Strength Indicator (RSSI) of a passive transmission or a probe response from a WiFi AP, which is obtained at the UE. The timing approach for WiFi ranging uses the Round Trip Time (RTT) calculation, which is retrieved from an AP. RTT measurements are standardized and require support from both UE and AP chipset. New UEs and APs are expected to support this feature widely in the future. In addition to 2D-positioning, PLS can provide low-altitude vertical positioning by integrating a barometric pressure sensor in the UE.

2.7.2.10 TRX Systems, Inc.

TRX Systems, Inc. (Greenbelt, Maryland) submitted its NEON® Personnel Tracker.

NEON Personnel Tracker is a dead reckoning system offering 2D positioning (plus low-altitude vertical positioning) of personnel through an estimate of the initial position of a user and integration over time of his subsequent estimated velocity. This is accomplished through an Android-based software application deployed with a body-worn accessory that uses an accelerometer, compass, pressure sensor, gyroscope, and other sensors to compute an estimated relative path of the user. These relative path data are passed via Bluetooth to an Android Smartphone running the NEON Location Service, where the path data are fused with last known GPS and available map information (terrain data, 3D building shape files, and building data). TRX's UWB beacons and/or third-party Bluetooth Low Energy (BLE) beacons can also be deployed to further enhance location accuracy. UWB beacons typically range 30-m line-of-sight, and can be placed at choke points or in an area of initialization. If set up for an area of initialization, two to three UWB beacons are needed, and they should be placed at least 10-m apart. The NEON UWB beacons use a hybrid approach to range to NEON Tracking Units. The NEON UWB beacon detects that a tracking unit is nearby using a BLE range, and then initiates a time-of-flight UWB range.

2.7.2.11 Ursa Navigation Solutions Inc. (d.b.a. UrsaNav Inc.)

UrsaNav Inc. (North Billerica, Massachusetts) submitted its eLORAN technology for demonstration.

eLORAN is a TOA multilateration system offering 2D positioning and timing through a dedicated terrestrial network provided by eLORAN transmitters, which operate in the frequency band of 90–110 kHz, and which can be separated by up to 1,000 km. The eLORAN radio signal is approximately 3 million times (65 dB) stronger than GPS, making it nearly impossible to jam or spoof from a distance. eLORAN is an evolution of LORAN-C, which was a TDOA positioning system, and which itself evolved from the initial World War II LORAN system. The main enhancement provided by eLORAN is the inclusion of one or more data channels. These provide low-rate data messaging, added integrity, differential eLORAN, and/or differential GPS corrections to improve accuracy and additional data, including navigation messages. These improvements require a secondary terrestrial network of reference stations, which are spaced up to 50 km apart.

3 Demonstration Plan

The Congressionally mandated demonstration was scheduled for completion by the end of March 2020. In preparation, the Volpe Center developed a detailed demonstration plan,[20] which addressed:

1. Selection and preparation of demonstration sites
2. Development of Government PNT reference and data collection systems
3. Opportunities for vendor site visits to inform their required site plans, and
4. The demonstration schedule.

The Government Team shared the demonstration plan with the participating vendors on March 6, 2020, in advance of the start of the demonstration.

Section 3.1 describes the selection of sites and their general characteristics, and Section 3.2 discusses the rationale behind necessary components of each scenario. The scenarios had to be designed to support use cases from the critical infrastructure sectors, as required by the Congressional mandate. Therefore, developing a sound rationale for each of the demonstration scenarios that would exhibit the backup and complementary capabilities of the vendor technologies was an essential element of demonstration planning.

3.1 The Demonstration Plan: Sites

The Government Team selected two locations for the demonstration, both already familiar to the team: the NASA Langley Research Center (LaRC), located in Virginia, and Joint Base Cape Cod (JBCC), located in Massachusetts. In addition, because it was anticipated that there would be vendors who would want to demonstrate eLORAN, the Government Team coordinated with the United States Coast Guard (USCG) to gain access to the legacy LORAN Support Unit (LSU) site in Wildwood, New Jersey.

3.1.1 NASA Langley Research Center

LaRC is located in Hampton, Virginia, approximately 77 miles southeast of Richmond. Several compelling reasons factored in the selection of LaRC as a demonstration site:

1. LaRC had been used by DHS in the Phase 1 effort
2. Experienced NASA staff were available to support the demonstration
3. LaRC provided a large open area with flexibility to install multiple transmitters

In Figure 1, the large blue polygon is the area in which vendors installed their equipment. The smaller red area within the blue perimeter indicates the scenario execution area in which user equipment (UE) was located during data collection.

[20] DOT, John A. Volpe National Transportation Systems Center, "GPS Backup Demonstration Plan," March 2020.

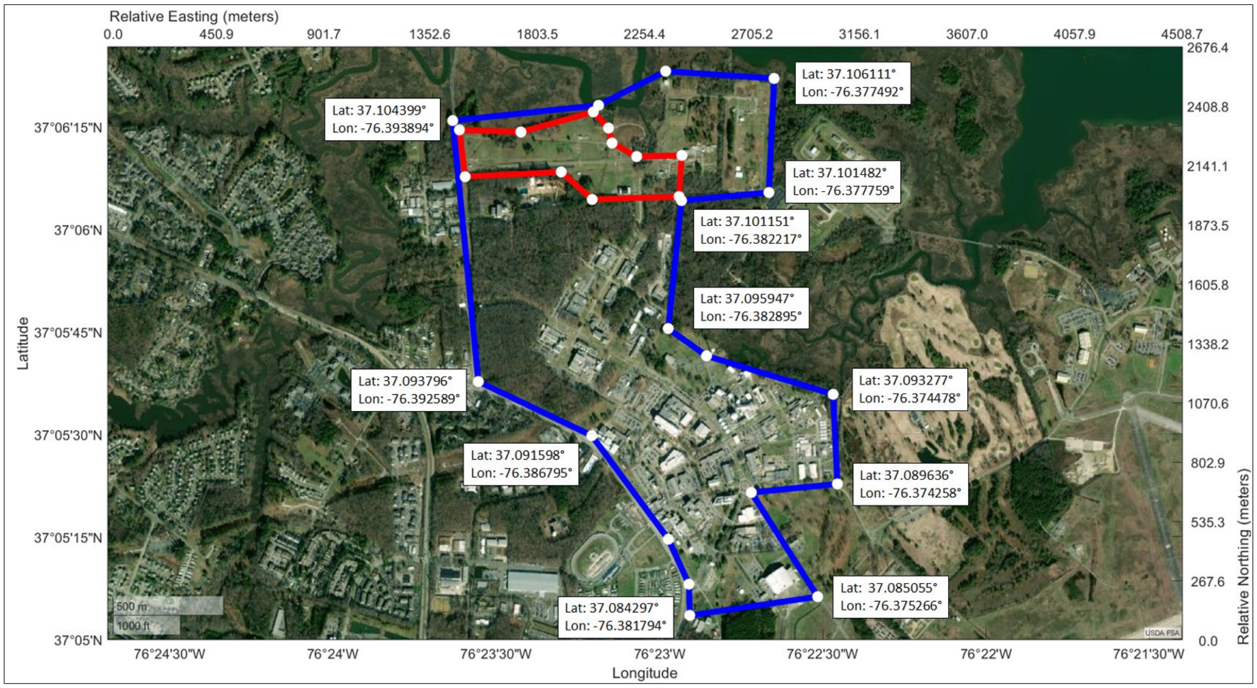


Figure 1. LaRC: Area Used for Demonstration

3.1.2 Joint Base Cape Cod

JBCC is located in Buzzards Bay, Massachusetts, approximately 65 miles south-southeast of Boston. For some years, the Volpe Center has operated the Aviation Weather Research Facility (AWRF), which is a 155-acre test range and an operations building located within JBCC. Due to the site's expansive acreage allowing for flexible equipment placement, the generally flat landscape, and its supportive leadership, Volpe concluded the AWRF (JBCC is used interchangeably in this report) was an ideally suited site for the demonstration.

In Figure 2, the large blue polygon depicts the region where vendors installed their equipment. The smaller red area within the blue perimeter indicates the scenario execution area in which User Equipment (UE) was located during data collection. Additional locations outside of JBCC were identified to support a scenario to demonstrate eLORAN reference station effects.

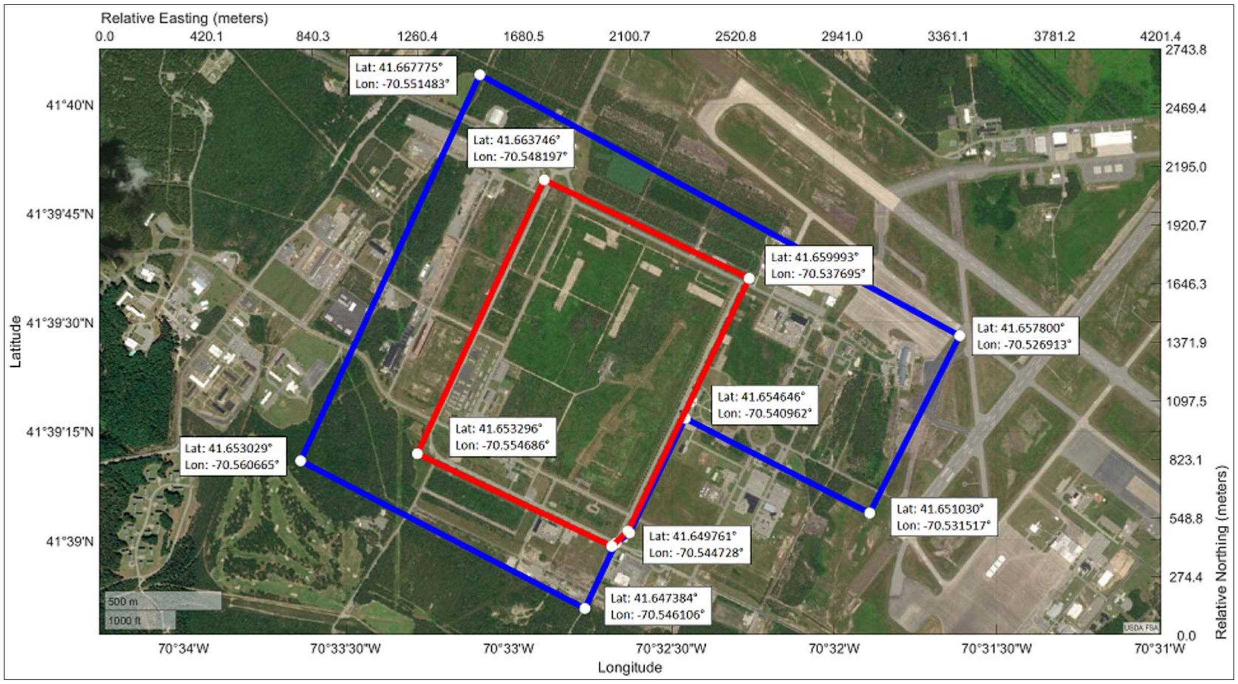


Figure 2. JBCC: Area Used for Demonstration

3.1.3 LORAN Support Unit, Wildwood, NJ

The USCG established the LORAN Support Unit in 1997 as the headquarters for long-range navigation (LORAN) equipment and support. The LSU is located adjacent to the Atlantic Ocean and on the southern tip of New Jersey, just north of Cape May. The LSU was officially decommissioned in 2010; however, a 625-foot tower remains (see Figure 3), including a patch panel and transmission equipment.

Figure 3. 625-Foot Transmission Tower at LSU

3.2 Demonstration Scenarios: Rationales and Plans

The Government Team developed a series of scenarios, modeled on Critical Infrastructure use cases under various positioning and timing conditions, which were used to demonstrate the performance of the participating vendors' technology.

3.2.1 Positioning Scenarios

The purpose of the positioning scenarios was to exemplify the following five positioning system attributes, which are relevant to multimodal transportation and other critical infrastructure applications.

1. Coverage: Service availability within a defined region
2. 2D and 3D dynamic positioning: Service availability and accuracy under constant and changing dynamic variables (e.g., linear/angular velocity and acceleration and under normal and challenged GPS conditions)
3. Static positioning: Service availability and accuracy
4. Static positioning: Long-term service availability and accuracy under normal conditions
5. Static positioning: Long-term service availability and accuracy under challenged GPS signal conditions

Four positioning scenarios were developed to assess vendor systems based on the aforementioned five attributes: Dynamic Outdoor Positioning w/Holds, 3D Positioning, Static Outdoor Positioning, and Static Indoor Positioning. The rationale and design of each scenario are discussed below.

All positioning scenarios were to be carried out at both demonstration sites.

3.2.1.1 Two-Dimensional Outdoor Positioning

Rationale

Because GPS is used to determine position at ground level by people and vehicles moving outdoors for various purposes, the use-case scenario would need to assess technology performance over a variety of movement two-dimensional (2D) paths, both while in motion and during a short-term stop.

Design

Dynamic Outdoor Positioning with Holds scenario was developed to fulfill the 2D outdoor positioning rationale. The Government Team planned the scenario to comprise one figure eight shape, one propeller shape, one double-circle shape (two circular patterns were traced in opposite directions to sample additional dynamics), one rectangle shape, and a general route with segments along paved and unpaved roads. Six Static Outdoor (SO) hold points were to be identified; three of the six were to be located on the segment route, and the remaining three on the figure eight, propeller, and double circles shapes.

Rectangular Shape: This is the least complex shape, comprising four segments with minimal changes in angular velocities and accelerations along each of the four segments (Figure 4).

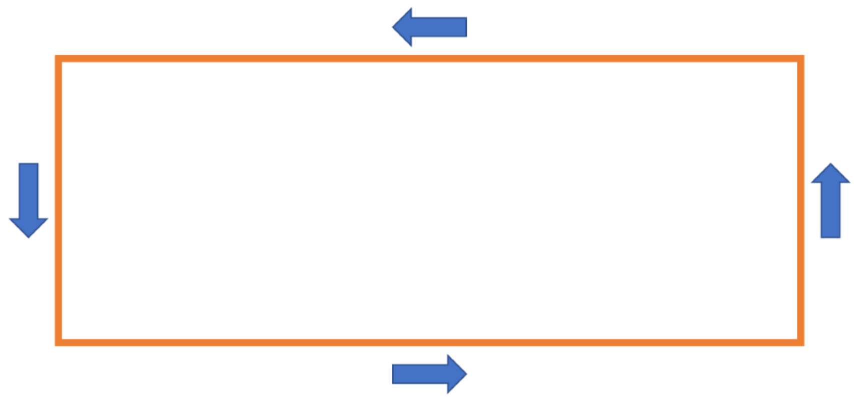


Figure 4. Rectangular Pattern

Circular Shape: A circular shape (Figure 5) allows the sampling of all receiver antennae azimuthal look angles relative to each transmitter. Further, this shape represents a near-constant angular acceleration. In the case of terrestrial positioning systems, a circular pattern also allows data collection as the positioning system antenna moves closer to and farther from each ground transmitter. Two circular patterns were traced in opposite directions to sample additional dynamics.

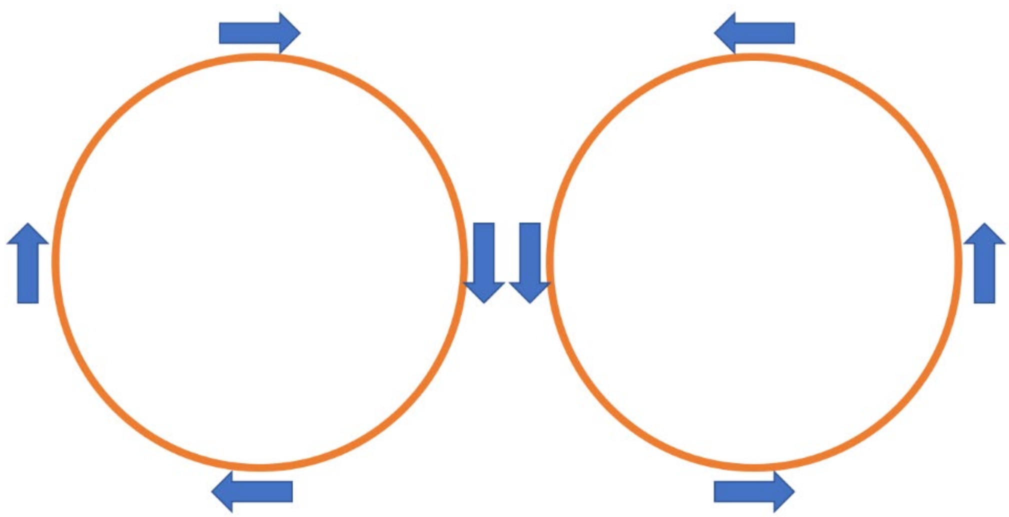


Figure 5. Circular Shapes

Figure Eight Shape: In comparison with a circular shape, a figure eight shape also allows for the sampling of all azimuthal look angles, but with a greater range of linear and angular velocities and accelerations. Additionally, tracing this shape results in sampling two different azimuthal look angles between the receiver antenna and each of the transmitter antennas from the same point at the center of the pattern (Figure 6).

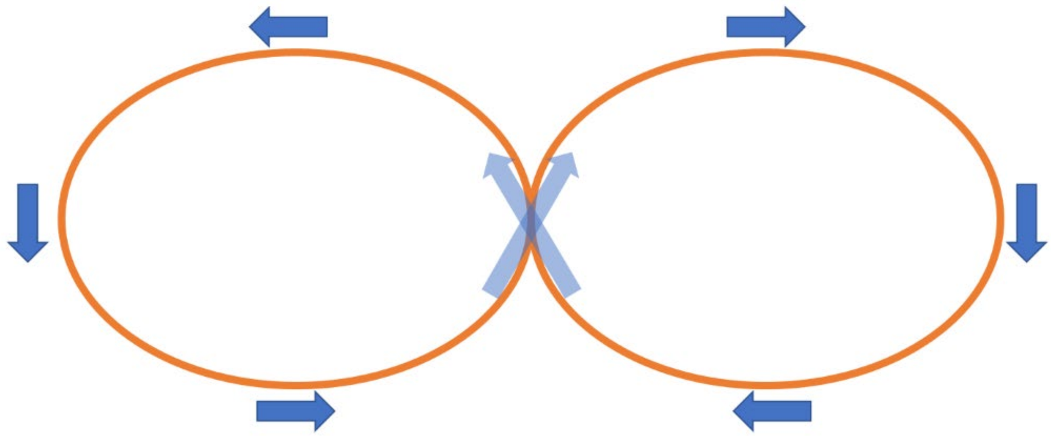


Figure 6. Figure Eight Shape

Propeller Shape: In addition to the advantages of the figure eight shape, tracing a three-lobe propeller shape results in a wider range of angular velocities and accelerations. Doing so also results in three receiver-antenna azimuthal look angles at the center of the pattern relative to each of the transmitting antennas (Figure 7).

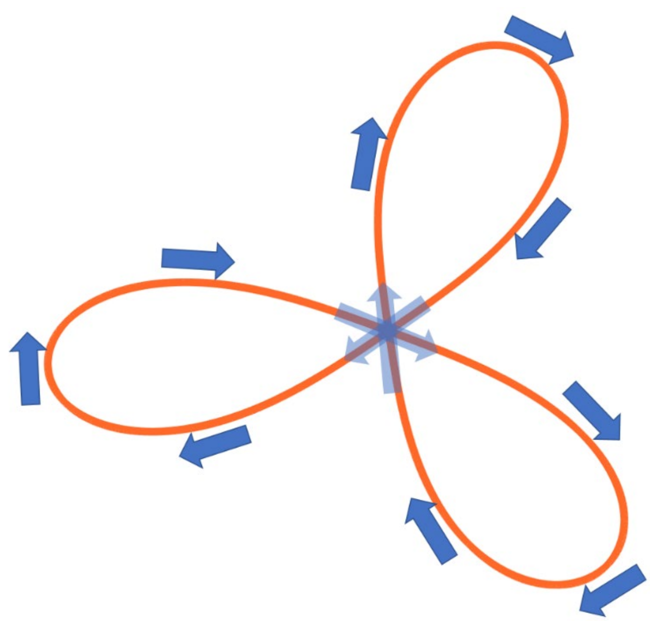


Figure 7. Propeller Shape

General (Segment) Route with Holds: In addition to the four shapes discussed above, a general (segment) route with holds was intended to emulate the dynamic conditions of a vehicle driving on a suburban road. The objective was to assess coverage, availability, and accuracy. Traversing this route enabled signal sampling across a large portion of both the center and perimeter of the site execution area. This route had no arbitrarily predefined shape, but instead, was to be defined as the driveable route within the scenario execution area at each site (see the areas defined in Figure 1 and Figure 2, above).

The assessments were to comprise positioning service coverage, availability, and accuracy under varying transmitter-receiver geometries and signal conditions throughout the scenario execution area. These progressively higher levels of complexity were achieved by placing routes in a variety of conditions that included flat area and open sky, adjacent trees and structures, and different vehicle dynamics.

3.2.1.2 3D Positioning

Rationale

This scenario was needed to assess the coverage, availability, and accuracy of vendor positioning systems with complex dynamics under 3D conditions created by UE placement on a UAS. Two routes would support this: they should be in different shapes and dynamic complexity, and include additional dynamic variables for 3D, including vertical velocity and acceleration. This scenario should address the higher-order dynamics associated with six degrees of freedom. Three degrees of freedom represented translation or changes in position along perpendicular axes—(1) forward/backward, (2) up/down, and (3) left/right—while another three represented changes in orientation through rotation about those axes—(4) yaw (vertical axis), (5) pitch (transverse axis), and (6) roll (longitudinal axis).

Design

The Government Team designed two routes for 3D positioning to conform to the rationale. The first was a **multi-level polygon route**. With multiple straight segments, this route enabled sampling a large part of the scenario execution area at three different altitudes to assess coverage, availability, and accuracy across the area. This route was designed to sample a larger range of line-of-sight angles between the receiver antenna and transmitter antennae than was the case for 2D.

The second was a **multi-level propeller route**. This route was intended for an area smaller than the polygon route and with a higher range of dynamic variables, including varying linear and angular velocities and accelerations. As with the multi-level polygon route, this scenario allowed sampling a larger range of azimuthal angles of the lines of sight between receiver antenna and all ground transmitter antennae than was the case in 2D.

3.2.1.3 2D Positioning Under Static Outdoor Conditions

Rationale

A scenario was needed to assess long-term availability, accuracy, and stability at various outdoor locations.

Design

The Static Outdoor Positioning scenario comprised three surveyed static points. This allowed for 60 minutes of simultaneous and continuous data collection from all participating UEs at each static point.

3.2.1.4 2D Positioning Under Static Indoor Conditions

Rationale

Indoor environments result in degraded GPS signal conditions due to strong GPS signal attenuation and multipath conditions. A scenario was needed to assess the short- and long-term performance capability and accuracy of participating vendor UEs under specified GPS-challenged conditions.

Design

The *Static Indoor Positioning* scenario was planned for five surveyed static points located indoors and below grade. The scenario included 2 minutes of continuous data collection repeated three times. Additionally, a continuous 60-minute data collection was to be carried out at three of the five points.

3.2.2 Timing Scenarios

The purpose of timing scenarios was to assess the time transfer capability of participating vendor systems to a static location. The scenarios should assess four UE attributes considered relevant to transportation, communication, and other infrastructure applications requiring synchronization with a time source traceable to a GPS or UTC time standard:

1. Coverage (for wireless time transfer service only); service availability and uniformity an appropriate area
2. Accuracy and stability across an appropriate area
3. Long-term accuracy and stability of time transfer to a fixed location
4. Time transfer availability and accuracy to a fixed location under challenged GPS signal conditions

The following five timing scenarios were developed to assess vendor systems based on the aforementioned four attributes: 72-Hour Bench Static Timing, Static Outdoor Timing, Static Indoor Timing, and Static Basement Timing, and eLORAN Reference Station Offset.

With the exception of the eLORAN Reference Station Offset scenario, all timing scenarios were to be carried out at both demonstration sites. The eLORAN Reference Station Offset Scenario was to be carried out only at JBCC.

3.2.2.1 *Indoor Static Extended Time Transfer*

Rationale

A scenario was needed to assess the timing service availability and time transfer accuracy and stability of vendor UEs. In addition to stability due to timing system design and implementation, for the case of wireless RF based systems, measure of time transfer error over an extended period would allow for the impact of atmospheric variations on signal propagation to be observed and for the time transfer error to be characterized.

Design

The *72-Hour Bench Static Timing* scenario was designed to support characterization of a technology's time transfer error over an extended period of continuous transmission. Each UE would be required to provide a one-pulse-per-second (1-pps) output connection that could then be measured against the timing standard produced by the appropriate static timing reference system. All UEs would be placed indoors.

3.2.2.2 *Outdoor Static Time Transfer*

Rationale

A scenario was needed to verify each participating UE's time transfer service coverage, availability, and uniformity, as well as the accuracy and stability over time of the time transfer error across the scenario execution area.

Design

The *Static Outdoor Timing* scenario was designed to collect continuous 60-minute timing data at three separate predetermined points in the demonstration area to assess UE performance in relation to the parameters recognized in the rationale. These would be the same three points that would be used in the Static Outdoor Positioning scenario.

3.2.2.3 *Static Indoor Time Transfer*

Rationale

An indoor environment is a moderately challenging signal environment for GPS due to high signal attenuation and potential multipath conditions encountered inside buildings and other structures. A scenario was needed to demonstrate each participating technology's signal availability and time transfer accuracy to a fixed location under signal-challenged GPS conditions.

Design

The *Static Indoor Timing* scenario was designed to enable a continuous 60-minute time transfer data collection In this scenario participating vendor time transfer data were collected at three surveyed indoor points to assess each system's signal availability and time transfer accuracy at a fixed location under challenged GPS signal conditions. The points used in this scenario would be the same used for the Static Indoor Positioning scenario.

3.2.2.4 Below-Grade Time Transfer

Rationale

A below-grade environment (basement) is a severely challenging signal environment for RF technologies due to very high signal attenuation and the potential to experience multipath conditions. A scenario was needed to demonstrate each participating technology's signal availability and time transfer accuracy to a fixed location under passively denied GPS conditions.

Design

The *Static Basement Timing* scenario was designed to collect time transfer data simultaneously from all participating UEs over a 60-minute period at a single location indoors and below grade.

3.2.2.5 eLORAN Time Transfer

Rationale

A scenario was needed to demonstrate timing error characteristics and short-term stability of specific eLORAN vendor technologies at locations with progressively larger baseline distances between the UE and reference stations antennae locations. These baseline distances were chosen to be approximately 15, 30, and 60 miles.

Design

The *eLORAN Reference Station Offset* scenario was designed to demonstrate vendor eLORAN systems. It comprised a vendor transmitter positioned at LSU (Wildwood, New Jersey), and one reference station at JBCC used to provide corrections to the UE during data collection.

As in the *Static Outdoor Timing* scenario, demonstration of system stability, and the sensitivity of time error to the outdoor UE antenna location, was to be performed. The objective was to verify the availability and assess the uniformity of the coverage of each of the participating eLORAN systems.

4 Government Reference and Data Acquisition Systems

The Government Team fielded an overall demonstration that comprised reference systems, platforms, and a team to operate them. At both LaRC and JBCC, three component subsystems (Fixed, Rover, and Airborne–R3) collectively constituted the Reference and Data Acquisition System. Stated generally, the Fixed subsystem at each location acted as the reference clock for all timing measurements, as well as the positioning base station for Global Navigation Satellite Systems (GNSS) kinematic post-processing. The Rover subsystem acted as the platform (Mercedes Sprinter van) for 2D position and time scenarios, and the Airborne–R3 subsystem acted as the platform for 3D (UAS) position scenarios.

Each reference system collected PNT outputs from participant user equipment (UE), while simultaneously recording signals from GNSS to provide a truth reference. The systems deployed at LaRC and JBCC were tailored for different UE and installation requirements but provided fundamentally the same functions and performance capabilities. The following sections describe the attributes of each system and, where needed, specific data processing from those systems necessary for UE performance characterization.

4.1 LaRC Reference and Data Acquisition System

4.1.1 Fixed Subsystem

The LaRC Fixed subsystem was positioned by the Government Team in Building 1230 with the reference GNSS antenna mounted on the roof. The key components of the Fixed subsystem were:

1. A cesium (Cs) atomic frequency standard providing 10-MHz and 1-pps reference signals
2. A Time-Interval-Counter (TIC) to measure 1-pps differences between the vendor UE under test and the 1-pps reference signal
3. A GPS time server to correct 1-pps measurements in post-processing to UTC
4. A GPS reference receiver[21] functioning as a base station to support kinematic position post-processing for the Rover as well as to function as a secondary source for determining UTC offsets
5. A mechanical switch to allow measurement of up to 24 1-pps signals
6. Data collection and control computers

Figure 8 is a high-level diagram of the LaRC Fixed subsystem, Table 2 provides a detailed list of the subsystem's key equipment, and Table 3 presents the associated cable delays and switch locations.

[21] Surveyed phase center location was 37° 05' 15.75593"N, -76° 22' 43.36370"E, -23.547 m --WGS84, 2020.155a[22] 37° 06' 5.12579"N, -76° 23' 5.39722"E, -30.325 m --WGS84/ITRF2014, ITRF project epoch

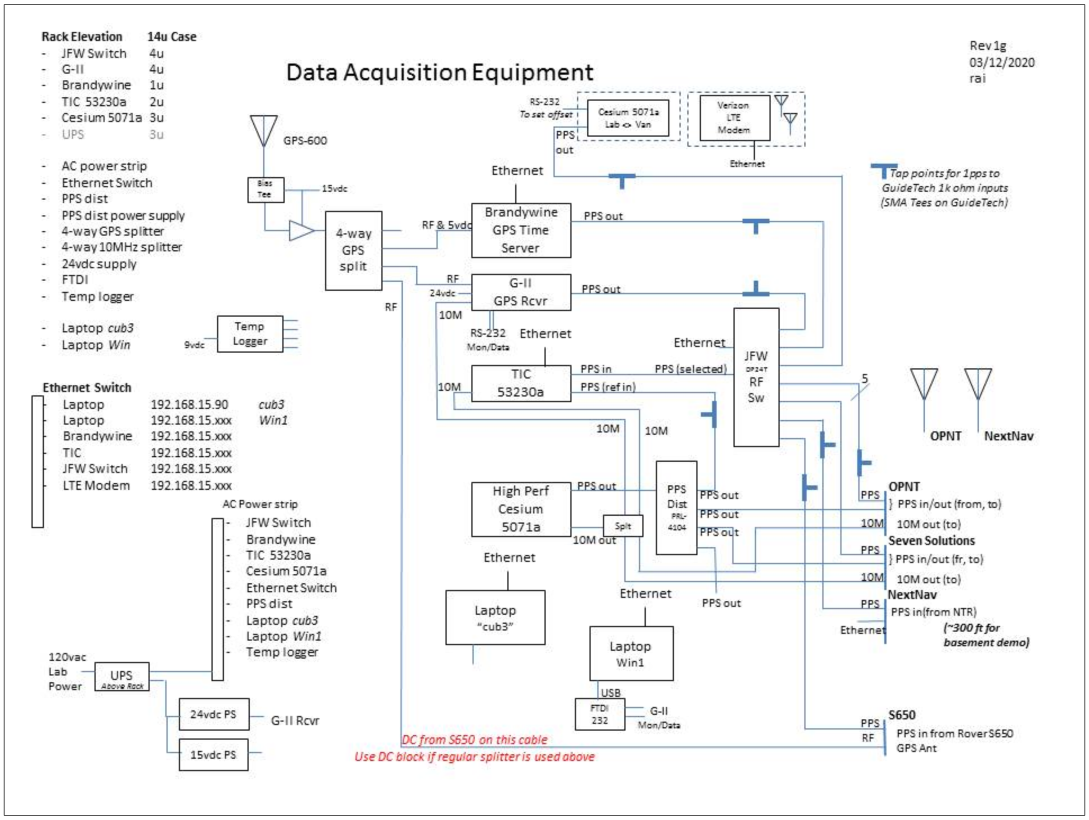


Figure 8. Diagram of the LaRC Fixed Subsystem

Table 2. LaRC Fixed Subsystem Key Components

Fixed Subsystem Equipment	Manufacturer	Model
GPS Antenna	NovAtel	GPS-600
GPS Time Server	Brandywine (BW)	ENTA-II
GPS Reference Receiver (G-II)	NovAtel	107260
Cesium (Cs) Atomic Frequency Standard	Microsemi	5071A
Time Interval Counter	Keysight	53230A
RF Switch, DP24T	JFW Industries	2P24T-DC-4GHZ
Collection Laptop (Linux)	Dell	Latitude E5450
Collection Laptop (Windows)	Dell	Latitude E6500
Temperature Logger	TekcoPlus	THTK-6

Table 3. Measured Cable Delays for Fixed Subsystem and Vendor UE

Device	Switch	Description	Delay (ns)
Brandywine	1	TIC-4’- Sw-3’- 6’	20
G-II	2	TIC-4’- Sw-3’- 6’	20
S650	3	TIC-4’- Sw-3’- 50’-12’	106
2nd Cesium	4	TIC-4’- Sw-3’- 6’	20
NTR	5	4’- Sw-3’- 300’	472
OPNT1	6	TIC-4’- Sw-3’- 50’-50’-quadPPSdist-3’	178
OPNT2	7	TIC-4’- Sw-3’- 50’-50’-quadPPSdist-3’	178
OPNT3	8	TIC-4’- Sw-3’- 50’-50’-quadPPSdist-3’	178
OPNT4	9	TIC-4’- Sw-3’- 50’-50’-quadPPSdist-3’	178
Seven	10	TIC-4’- Sw-3’- 50’-50’-quadPPSdist-3’	178
OPNT5	11	TIC-4’- Sw-3’- 50’-50’-quadPPSdist-3’	178

The Fixed subsystem measured UE 1-pps outputs for the 72-Hour Static Bench Timing and Static Basement Timing scenarios. The vendor UE and reference equipment 1-pps outputs were connected to the mechanical switch, which was commanded to sequentially step through devices and capture a 1-pps measurement every 14 seconds from each connected device.

The Government Team enabled two vendors (OPNT and Seven Solutions) to use the Fixed subsystem 1-pps and 10-MHz signals as the master timing reference. Those two vendors were demonstrating the time distribution capabilities of their technologies rather than performance as an independent time source.

The key reference data post-processing of the Fixed subsystem for time characterizations was correction to UTC using the GPS time server information (also applicable to the Rover subsystem, discussed below in section 4.1.2). Post-processing was concerned only with removing the deterministic drift of the cesium frequency standards relative to UTC, because an absolute UTC time calibration of the subsystems’ reference time could not be accomplished prior to the LaRC and JBCC demonstrations. The correction to UTC was estimated from a least squares fit of the difference between cesium and GPS time server 1-pps observations.

Figure 9 shows the drift of the Fixed subsystem cesium 1-pps signal relative to the GPS time server and the UTC correction fit (the slope) along with the fit residuals. The figure shows that the Fixed subsystem reference time is well represented by this linear fit.

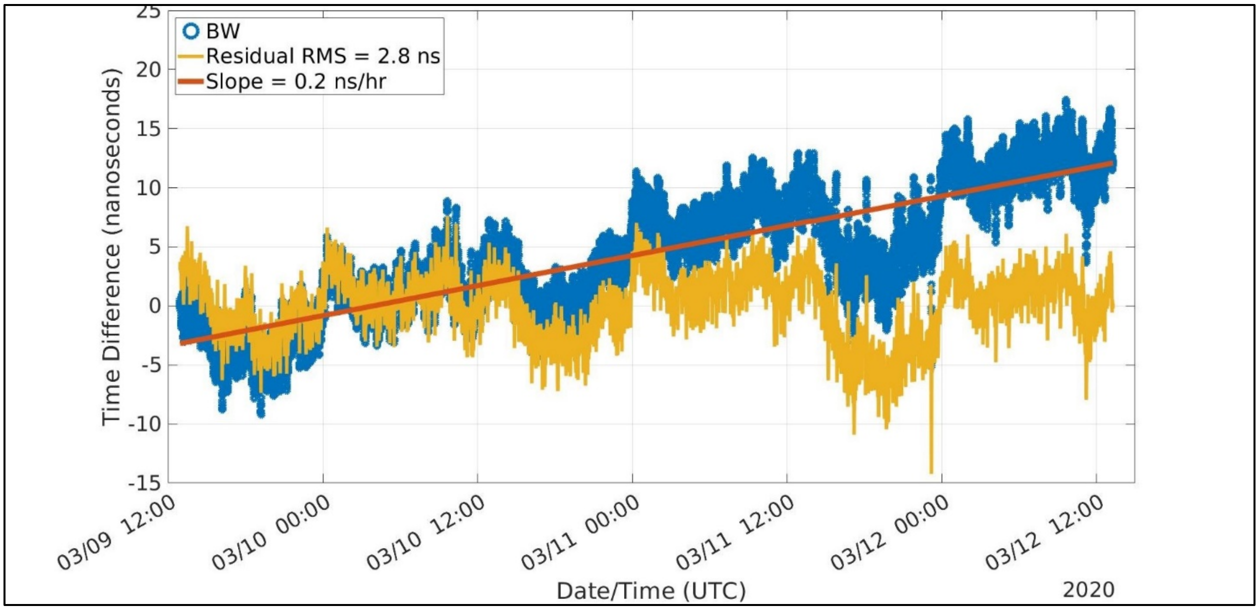


Figure 9. UTC Drift over 72-Hour Collection Period: Fixed Cs Standard Against GPS Time Server

4.1.2 Rover Subsystem

The Rover subsystem implemented at LaRC provided both 2D position and time reference measurements to verify vendor UE performance. The key components of the Rover subsystem were:

1. A dual-antenna-input GPS receiver with an integrated inertial measurement unit (IMU) for post-processed position and heading information
2. GPS time server with integrated rubidium frequency standard, which provided 10-MHz and 1-pps reference signals
3. A cesium frequency standard used as a 1-pps source for UTC adjustment
4. A time-interval-counter to measure 1-pps differences between the vendor UEs under test and the reference signal
5. Mechanical switch to allow measurements from multiple 1-pps signals
6. Data collection and control computers

Figure 10 is a picture of the LaRC data collection van, Figure 11 is a high-level diagram of the Rover subsystem, and Table 4 is a detailed list of key subsystem equipment.

The dual antenna GPS receiver/IMU that was key for 2D positioning performance was physically located on top of the van in the center rear. This location was the reference point that all GPS and UE antenna offsets were measured from.

When not in use for Rover activities, the Rover subsystem cesium frequency standard and Rover GPS time server (S650) were connected to the Fixed subsystem. This allowed the Rover timing measurements to be corrected to UTC using the Fixed subsystem reference time.

Figure 10. LaRC Rover Transport Van, with GPS/IMU Mounted Top Center Rear of Van Roof

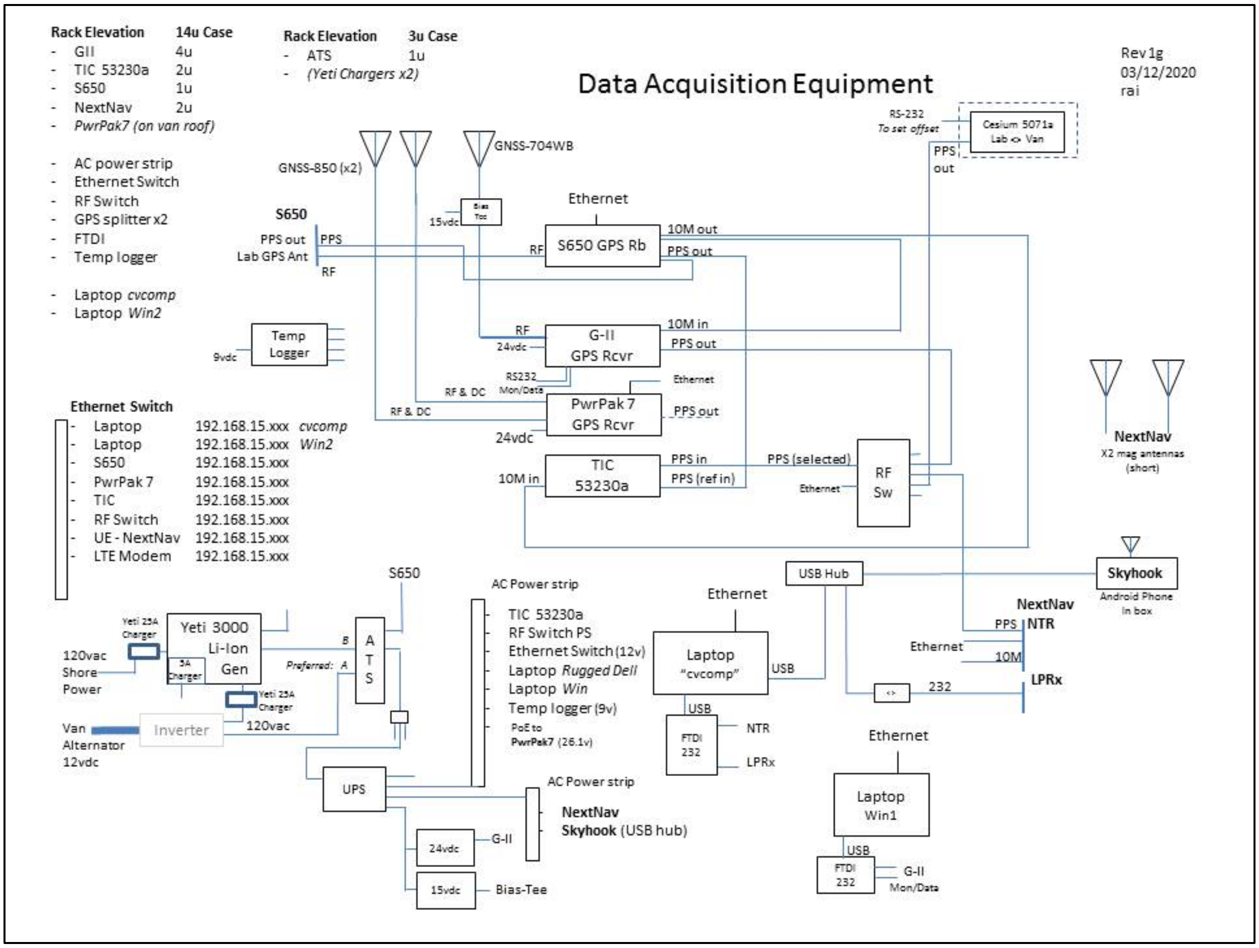


Figure 11. Diagram of LaRC Rover Subsystem

Table 4. LaRC Rover Subsystem Key Components

Rover Subsystem Equipment	Manufacturer	Model
GPS Antenna	NovAtel	GNSS-704WB
GPS Antenna	NovAtel	GNSS-850
GPS Antenna	NovAtel	GNSS-850
Dual GPS/INS Receiver (PwrPak7)	NovAtel	PW7720E2-GDD-RZN-TBN-P1
GPS Reference Receiver (G-II)	NovAtel	107260
GPS Frequency Standard/Time Server	Microsemi	SyncServer S650
Atomic (Cesium) Frequency Standard	Microsemi	5071A
Time Interval Counter	Keysight	53230A
RF Switch, SP6T	Mini-Circuits	RC-1SP6T-A12
Collection Laptop (Linux)	Dell	G5590
Collection Laptop (Windows)	Panasonic	CF-53
Temperature Logger	TekcoPlus	THTK-6

A separate cesium frequency standard was required for the LaRC Rover because the van was taken into a hangar to conduct the indoor timing and positioning scenarios. The Fixed subsystem was physically distant from the hangar, so its cesium frequency standard could not be used. The initial Rover reference concept considered estimating UTC time with an additional GPS receiver. However, that configuration would not have achieved adequate performance given the long dwell periods in the hangar, where GPS reception was not adequate.

Another important aspect of the Rover subsystem design was the ability to precisely position the van over pre-surveyed points along the outdoor routes to demonstrate 2D positioning accuracy against an external position reference. This was accomplished through the deployment of an externally-mounted camera and internal display system that enabled the driver to accurately position the vehicle. The positioning and alignment of the van using this system were critical for indoor positioning scenarios conducted in the hangar, because the GPS reference system could not provide position or heading truth. Lastly, an additional GPS reference receiver and antenna were included in the LaRC Rover subsystem to allow further validation of reference positioning, and as a means of independent lever arm validation.

4.1.2.1 Rover Subsystem Position Estimation

The key post-processing for the Rover subsystem was position estimation for outdoor scenarios. This post-processing combined the Rover GPS measurements (L1 and L2), the IMU heading information, and the base station GPS measurements from the Fixed subsystem. The processing at LaRC used a commercial software package (NovAtel Waypoint Inertial Explorer [Waypoint]), which fuses traditional GPS Post-Process Kinematic (PPK) methods with the IMU measurements.

The open-source RTKLIB software package was also used as an independent consistency check with this Waypoint processing. The RTKLIB software package was developed at the Tokyo University of Marine Science and Technology and is widely used in academia, industry, and government. RTKLIB was used for LaRC Airborne–R3 position estimation and for all position processing at JBCC. As mentioned above, the reference position for the van was the GPS/IMU receiver, which was located on the top of the van at the center-rear. The lever arm offsets to GPS and vendor antennas from this location are provided in Table 5.

Table 5. Lever Arm Offsets Measured Relative to the Center of the IMU in the ProPak7

Antenna	x-right (m)	y-fwd (m)	z-up (m)
ANT1 (NOV850)	-1.140	0.006	0.000
ANT2 (NOV850)	1.130	0.000	0.000
USER (704-WB)	0.784	2.920	0.033
NextNav left (NTR)	0.657	1.410	0.080
NextNav right (LPRX)	0.476	1.410	0.080
Skyhook	0.546	1.829	0.159

The positioning performance of the Rover reference was confirmed, as shown in Figure 12 and Figure 13. In Figure 12, the Rover subsystem reference antenna (ANT1—left rear antenna) was positioned, using the camera system, over the pre-surveyed point SO3. The graphic illustrates that the Rover positioning, as separately estimated using Waypoint and RTKLIB, was within approximately 1 cm (horizontal) of this point.

In Figure 13, the top plot shows the estimated Rover position using measurements from RTKLIB from the validation GPS receiver compared with measurements from Waypoint and the GPS/IMU receiver. The bottom plot shows the difference in these position estimates and the 2-σ error predicted by the Waypoint software from its solution. The key point is the GPS/IMU receiver (used as the reference) provided a position solution for the entire route with an estimated 2- σ error well within 20 cm, and generally closer to a few cm. These two examples indicate that the Rover subsystem provided centimeter-level 2D accuracy for UE antenna positions during all scenarios.

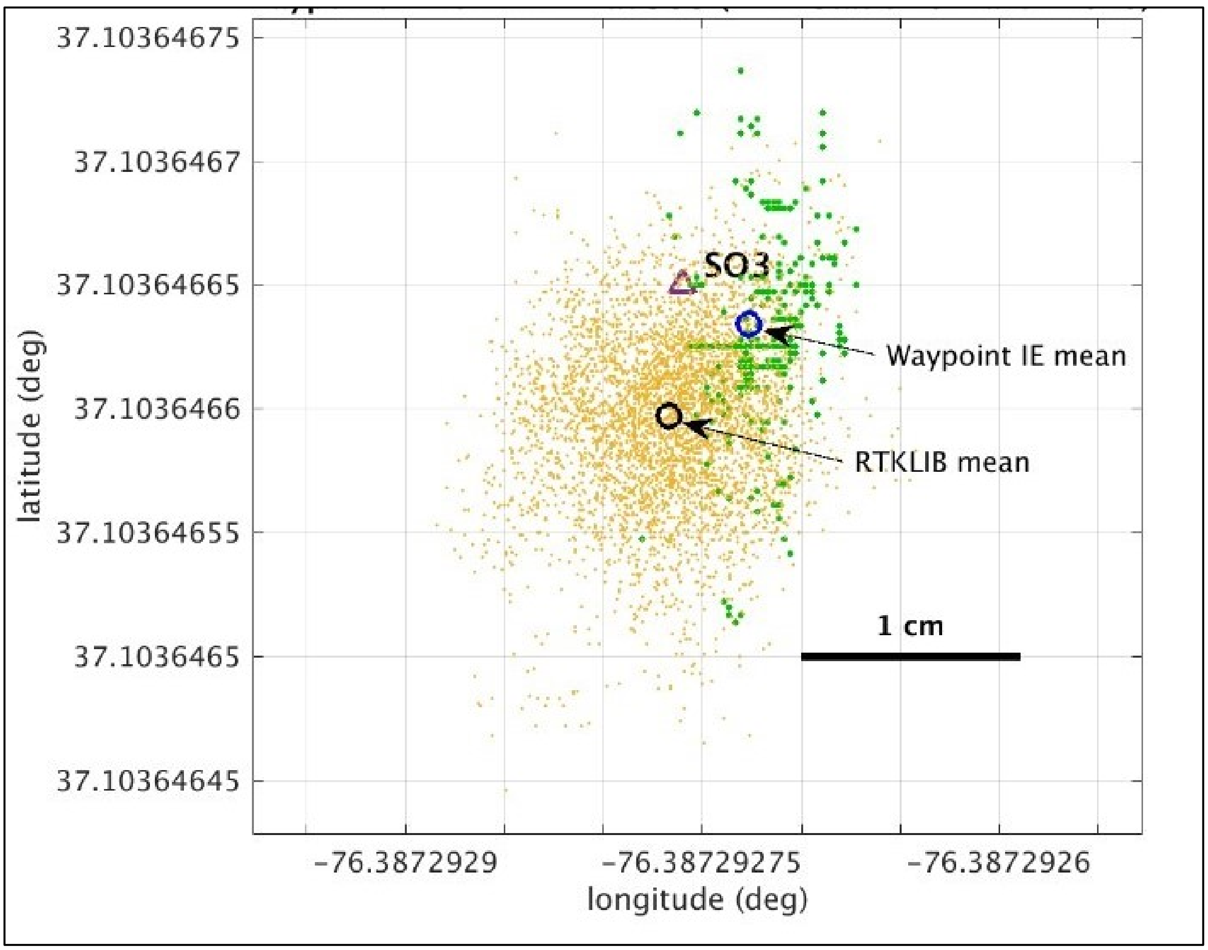


Figure 12. Comparison of Surveyed Reference Point SO3 with Estimates from Waypoint and RTKLIB

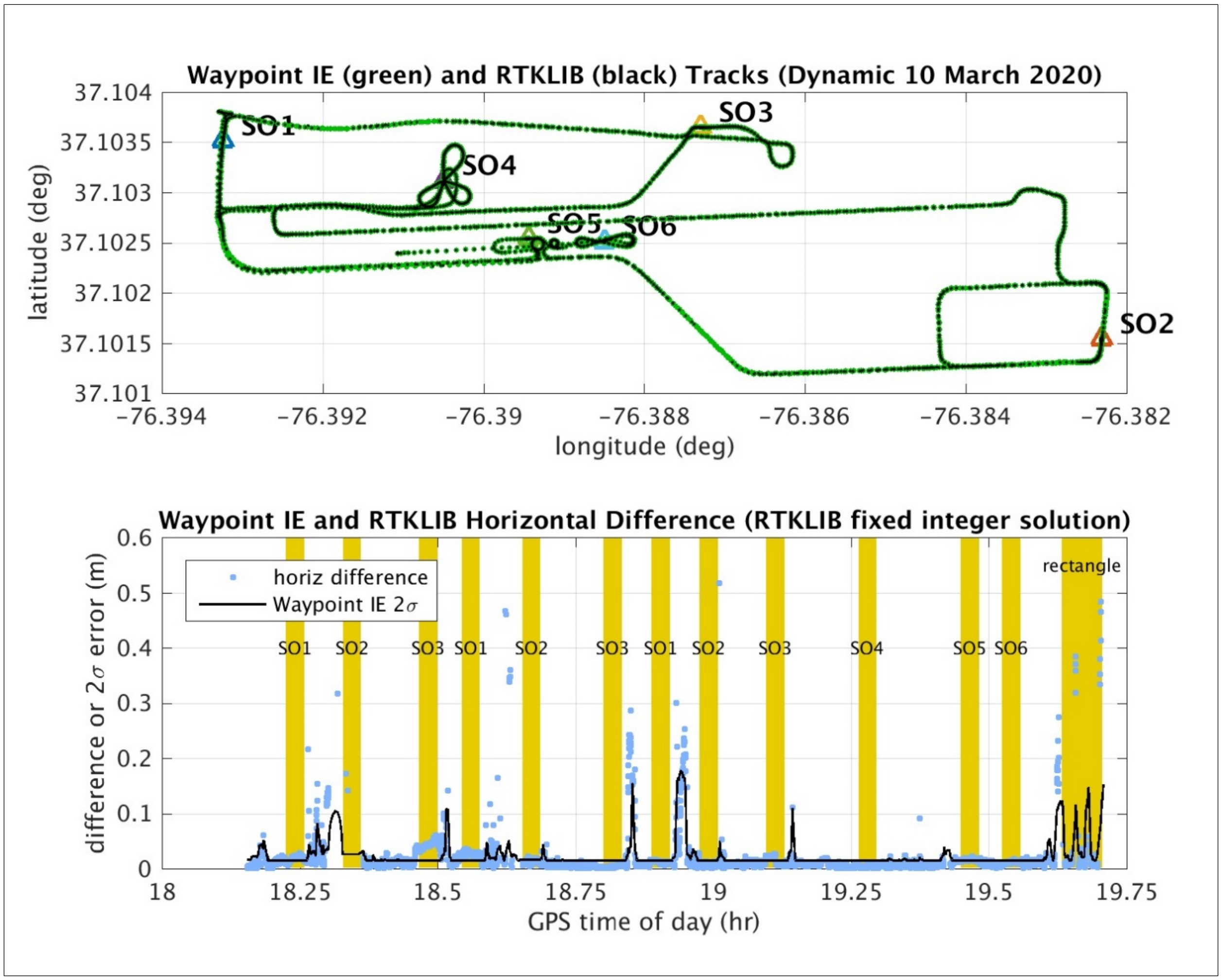


Figure 13. Comparison of Dynamic Positioning with Waypoint and RTKLIB

4.1.2.2 Rover Time Measurement Correction

In addition to Rover position estimation, the other key post-processing step was correction of UE time estimates to UTC. Figure 14 is the graphic for the Rover subsystem cesium frequency standard, and is equivalent to Figure 11 for the Fixed subsystem. The missing 1-pps measurements in Figure 16 were the result of disconnecting the Rover cesium frequency standard from the Fixed subsystem. Both cesium standards' 1-pps differences relative to UTC are well represented by the linear fit. As was presented in Figure 11, above, the Fixed cesium standard showed a drift (slope) of approximately 0.2 ns/h; the drift for the Rover cesium standard (Figure 14) was approximately 2.3 ns/h.

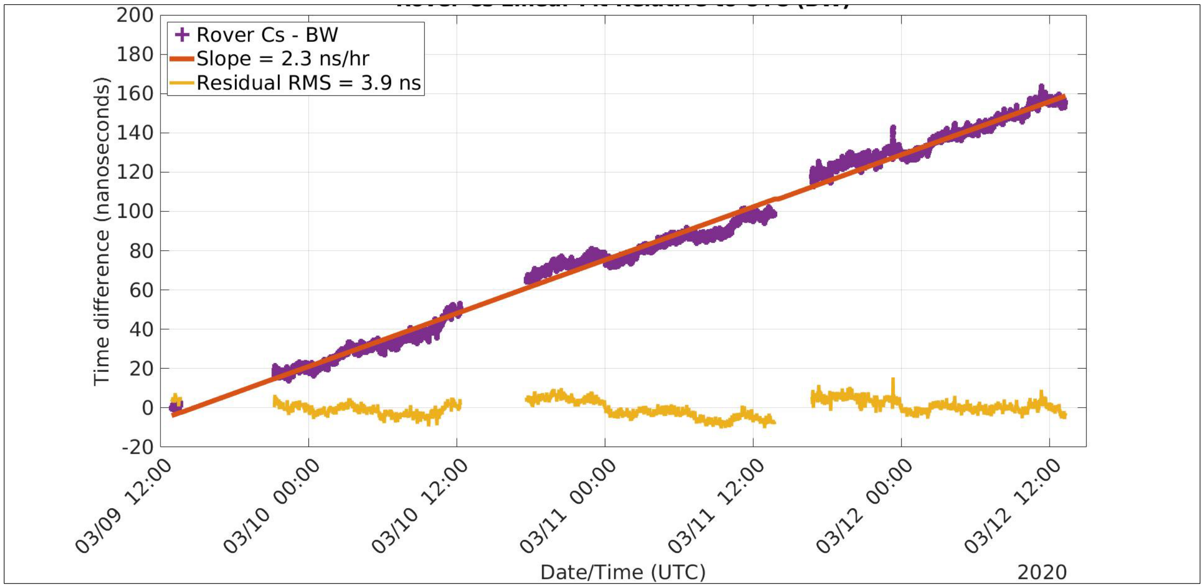


Figure 14. UTC Drift over 72-Hour Collection: Rover Cs Against GPS Time Server

An example of the time correction approach used for Rover UE time measurements is provided for SI1 below. Figure 15 shows the collected 1-pps measurements of the NextNav and Rover cesium 1-pps outputs (biased to 0 at T=0). Note that the S650 time server in the Rover subsystem provided the reference 10-MHz and 1-pps signals for the TIC, and that this receiver was not connected to a GPS antenna for Rover operations.

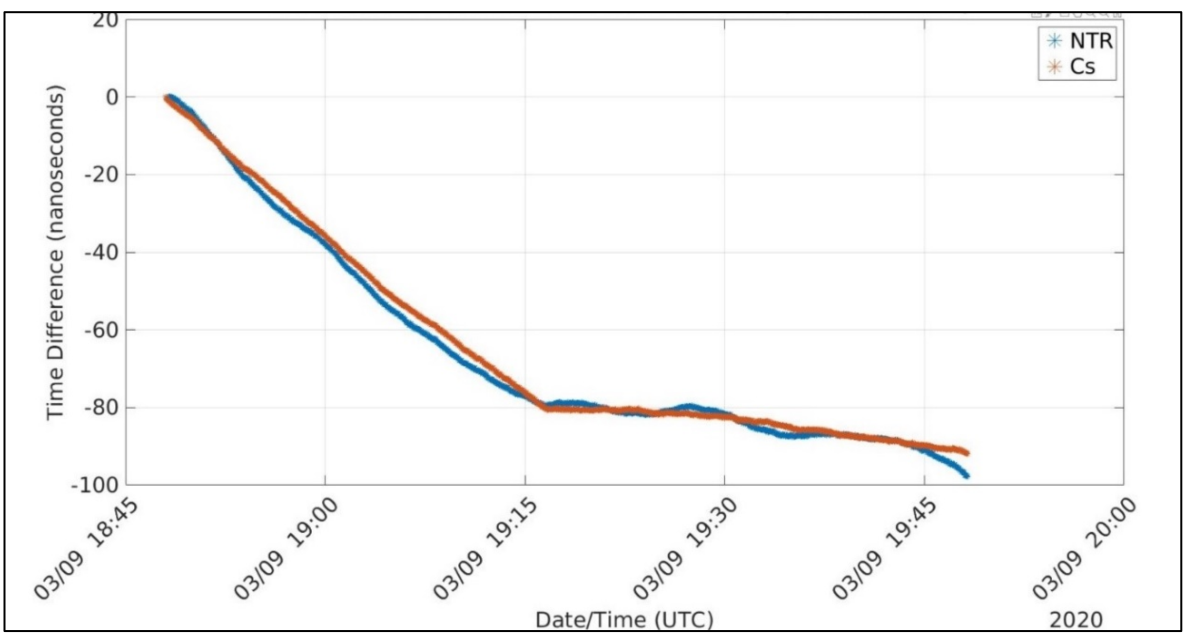
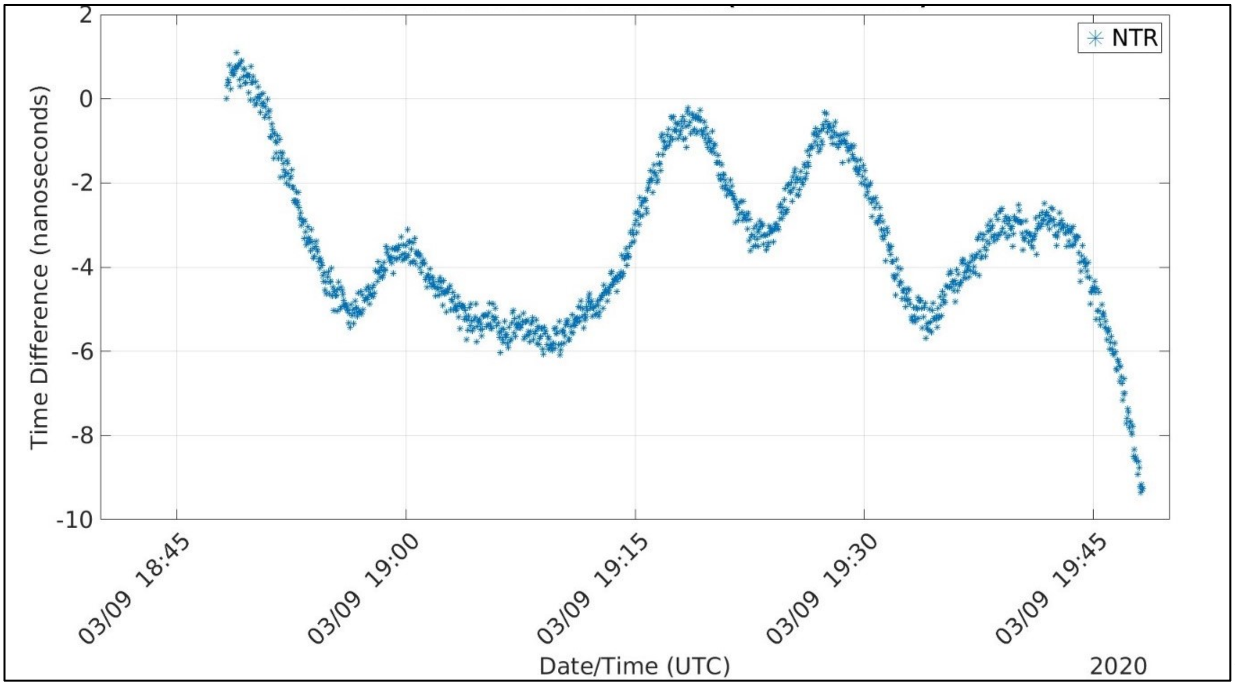


Figure 15. Example: Comparison of NextNav NTR and Rover Cs 1-pps Outputs for Location SI1

The piecewise linear drift evident in the plot for both the NextNav NTR and cesium 1-pps measurements resulted from the S650 attempting to maintain UTC alignment from its holdover model. The correction technique first adjusted the Rover subsystem cesium to UTC, based on the slope measurements discussed in relation to the Fixed subsystem, and then subtracted those values from the NextNav 1-pps measurements, effectively canceling the S650 drift and correcting the NextNav measurements to UTC. The first corrected NextNav data point was then referenced to a value of zero for the initial time estimate of the data collection, as shown in Figure 16.



7

Figure 16. Example: NextNav NTR and Cs 1-pps Output Relative to UTC for Location SI1

4.1.3 Airborne–R3 Subsystem

The Airborne–R3 subsystem used at LaRC was deployed on an unmanned aircraft system (UAS) to collect 3D flight data. The vehicle, shown below in Figure 17, is a 7.4-kg commercial-off-the-shelf (COTS) octocopter with a maximum payload of 8 kg. Autonomous data collection flights were conducted using this vehicle throughout the specified LaRC demonstration area at various altitudes up to 400 feet.

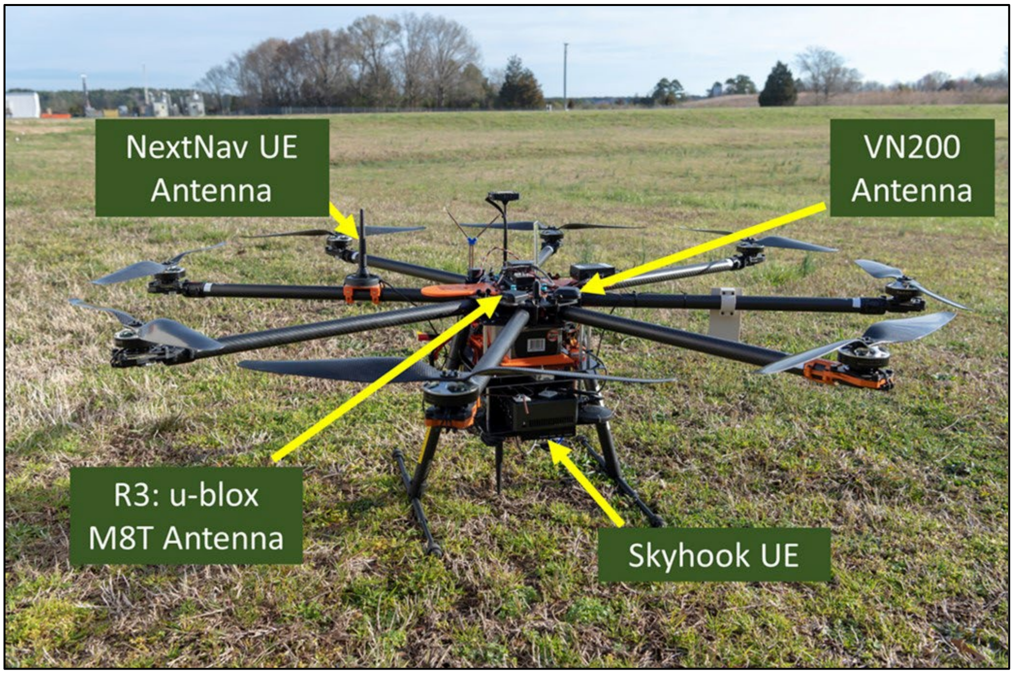


Figure 17. UAS Carrying LaRC Airborne—R3 Subsystem

Figure 18 is a diagram of the Airborne–R3 subsystem equipment on the LaRC UAS. The primary flight controller for the UAS was a Pixhawk autopilot. The Airborne–R3 subsystem used a u-blox M8T GNSS receiver as the primary positioning source. A ruggedized VectorNav VN200 (GPS receiver with integrated IMU) was mounted on the LaRC UAS as a secondary positioning source to provide redundancy and validation of results. Due to hardware failure of the initial UAS (Tarot) during the demonstration, a second UAS (DJI) was used at LaRC to complete the airborne demonstrations. Static positioning and the polygon routes were conducted using the Tarot UAS. The DJI vehicle was used to run the propeller route demonstration.

Table 6 and Table 7 list the lever arm offsets to the Airborne–R3 subsystem antennas and the vendor UE antennas relative to the autopilot's GPS antenna for the Tarot UAS and DJI UAS.

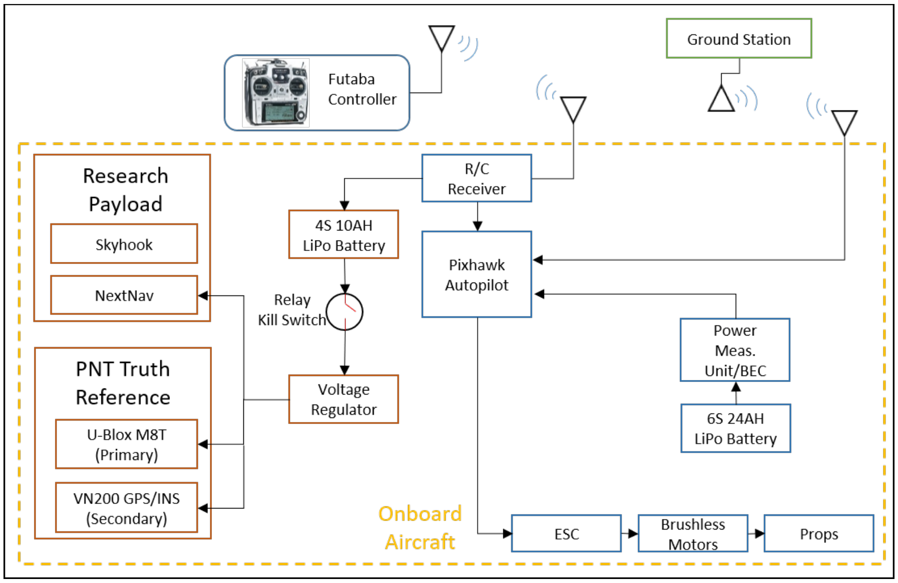


Figure 18. LaRC Airborne–R3 Subsystem Diagram

Table 6. Lever Arm Offsets Relative to the UAS GNSS Antenna Phase Center for Tarot UAS

Antenna	x-right (cm)	y-fwd (cm)	z-up (cm)
VN200 Antenna	-4.0	22.5	-15.0
u-blox M8T Antenna	4.0	22.5	-15.0
NextNav UE Antenna	30.0	-5.0	-14.5
SkyHook UE	0.0	8.0	-36.5

Table 7. Lever Arm Offsets Relative to the UAS GNSS Antenna Phase Center for DJI UAS

Antenna	x-right (cm)	y-fwd (cm)	z-up (cm)
VN200 Antenna	10.0	-15.0	-13.0
u-Blox M8T Antenna	-9.0	-2.0	-13.0
NextNav UE Antenna	27.5	3.0	-10.5
SkyHook UE	0.0	-12.5	-32.75

Using a similar procedure to that used for the LaRC Rover position estimation (see section 4.1.2.1), the Airborne–R3 GPS measurements (L1) from the u-blox M8T were post-processed with base station measurements from a u-blox receiver temporarily installed adjacent to demonstration area. These base station measurements were used instead of the Fixed subsystem measurements due to closer proximity to flight operations and GPS receiver commonality.[22] This processing was completed with the RTKLIB software package.

[22] 37° 06' 5.12579"N, -76° 23' 5.39722"E, -30.325 m --WGS84/ITRF2014, ITRF project epoch

In application, the LaRC Airborne–R3 positioning accuracy varied by the specific scenario executed. The best-performing static position accuracy for individual points was approximately 0.5 meters horizontal and 2 meters vertical. Therefore, the static positions did not rely on the reference system and instead utilized the pre-surveyed points over which the UAS was placed.

4.2 JBCC System

4.2.1 Fixed Subsystem

The JBCC Fixed subsystem was located in Building 2410 with the reference GNSS antenna mounted on the roof. The Fixed subsystem comprised:

1. A cesium atomic frequency standard that provided both 10-MHz and 1-pps reference signals
2. A GNSS reference receiver[23] functioning as a base station and with capability to measure and log the differences between a PPS input and its internal GPS-derived reference
3. Twelve (12) time-interval counter channels to measure 1-pps differences with support for Command and Data Handling (C&DH) interfaces via Ethernet or serial bus as needed by each vendor UE technology
4. Data collection and control computers

Figure 19 shows a high-level diagram of the equipment. The open port labeled “GNSS IF” represents the reception of signals at the receiver antenna interface. Table 8 presents a detailed list of the reference equipment and additional logical components involved in measuring and recording signals from vendor technologies.

[23] Antenna location was 41° 39' 23.82646"N, -70° 32' 41.52160"E, +12.612 m --WGS84, 2020.155).

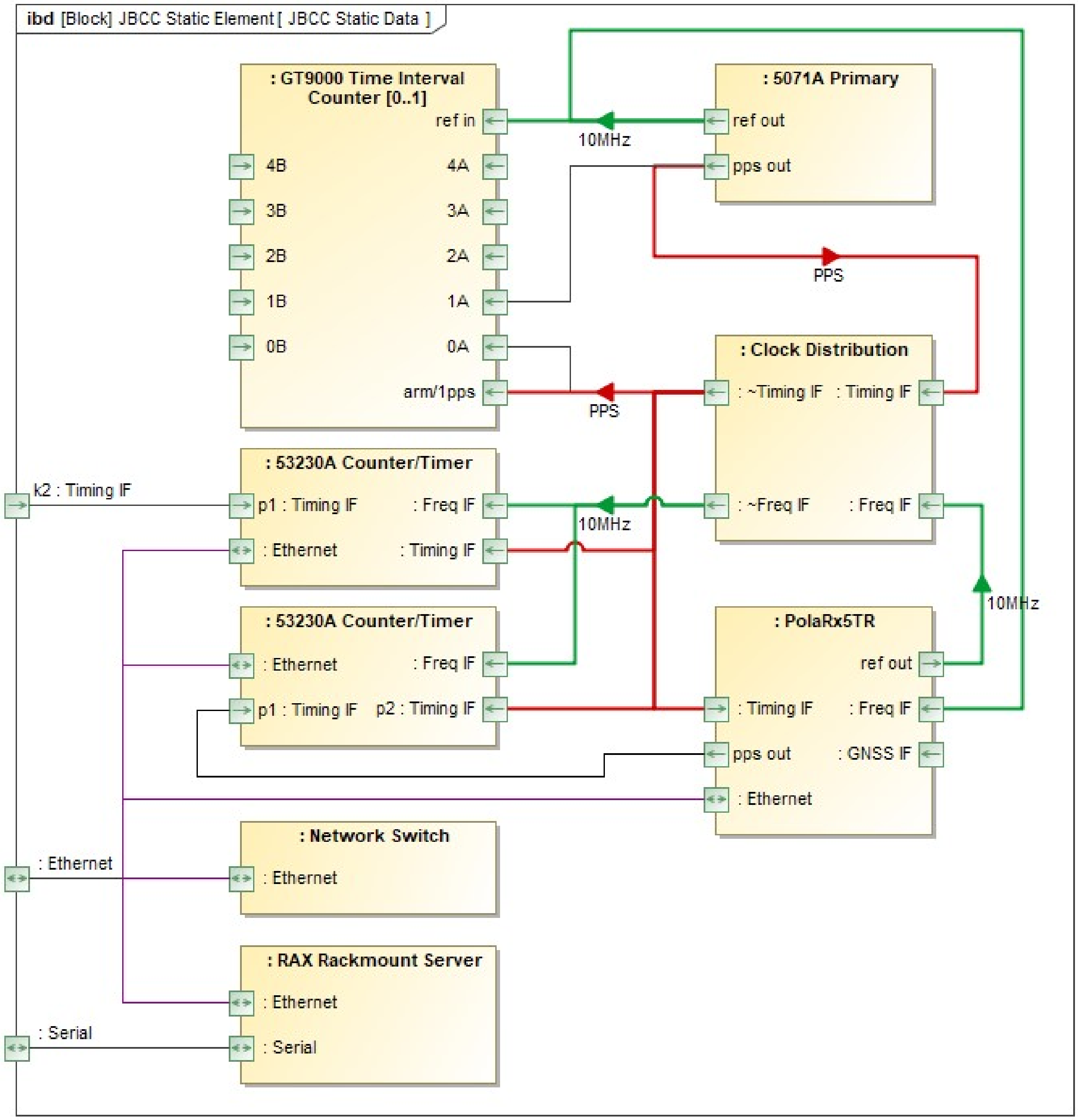


Figure 19. JBCC Fixed Subsystem Components and Interfaces

Table 8. JBCC Fixed Subsystem Key Components

Component	Manufacturer	Model
GNSS Antenna	NovAtel	GNSS - 850
GNSS Reference Receiver	Septentrio	PolaRx5TR FULL
Atomic (Cesium) Frequency Standard	Microsemi	5071A
10-Channel Time Interval Counter	GuideTech	GT9000
Time Interval Counter	Keysight	53230A
Network Switch	NETGEAR	XS512EM
8-Channel Clock Distribution Module	National Instruments	CDA-2990
Rackmount Server	Thinkmate	RAX XF2-11S1-SH

The system distributed the 10-MHz frequency reference and 1-pps output from the free-running cesium to all TICs, providing a stable reference frequency and periodic trigger from which to measure participant UE timing outputs.

At the request of some vendors, the Fixed subsystem also provided a reference 1-pps output to their systems. For example, the eLORAN technologies used the reference 1-pps to calibrate and lock onto transmitter signals, then disconnected from the reference for the actual scenario measurement periods. The reference 1-pps also allowed explicit measurement of a participant system to distribute time over a network without having to account for independent time sources simultaneously. For internal diagnostics, the system dedicated two TIC channels to measure 1-pps distribution (monitoring to detect cycle slips); a third TIC channel monitored the GNSS reference receiver 1-pps output, redundantly logging the difference between the cesium and GNSS-derived timing reference.

At JBCC, the cesium-based primary frequency standard was not disciplined to UTC throughout the entire period of dry runs and demonstrations. The drift of the cesium frequency standard 1-pps output was measured against UTC 1-pps output of the PolaRx5TR GNSS reference receiver, connected as shown above in Figure 19.

This drift was calculated and removed in post-processing via a least squares trend line, as shown in Figure 20. This post-processing yielded a correction that established UTC reference time as the standard against which to measure the output of vendor systems with their own UTC-traceable time source (*i.e.*, vendors with a clock source that is other than the reference system cesium clock).

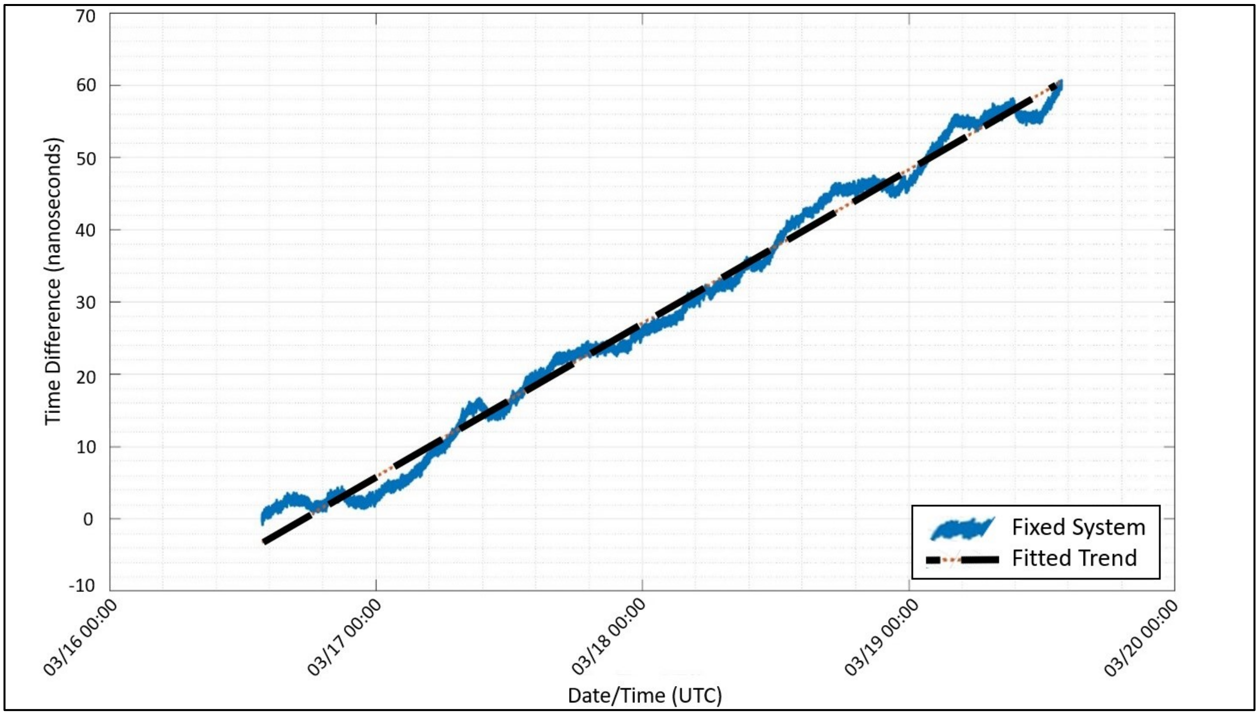


Figure 20. UTC Drift over 72-Hour Static Bench Timing Scenario

4.2.2 Rover Subsystem

The Rover subsystem used at JBCC provided co-located positioning and timing reference measurements for verification of vendor UE 2D positioning and timing performance. The Rover subsystem was installed in a Sprinter van (Figure 21); this van was identical in make and model to that used at LaRC. At JBCC, the bar-mounted antenna above the passenger compartment that extended to the left above the driver was the reference antenna; the antenna mounted above and to the right of the passenger seat position was the auxiliary antenna. Table 9 presents a list of key subsystem components and Figure 22 presents a high-level diagram of the JBCC Rover subsystem components and interfaces.

Figure 21. Rover Subsystem with Antennas as Installed in Sprinter Van at JBCC

Table 9. JBCC Rover Subsystem Key Components

Component	Manufacturer	Model
GNSS Antenna	NovAtel	GNSS-850
GNSS Antenna	NovAtel	GNSS-850
GNSS Reference Receiver	Septentrio	PolaRx5TR FULL
GNSS Reference Receiver (heading capable)	Septentrio	AsteRx-U M
GPS Frequency Standard/Time Server	Microsemi	SyncServer S650
Frequency Counter/Timer	Keysight	53230A
RAX Rackmount Server	Thinkmate	RAX XF2-11S1-SH
Network Switch	NETGEAR	XS512EM

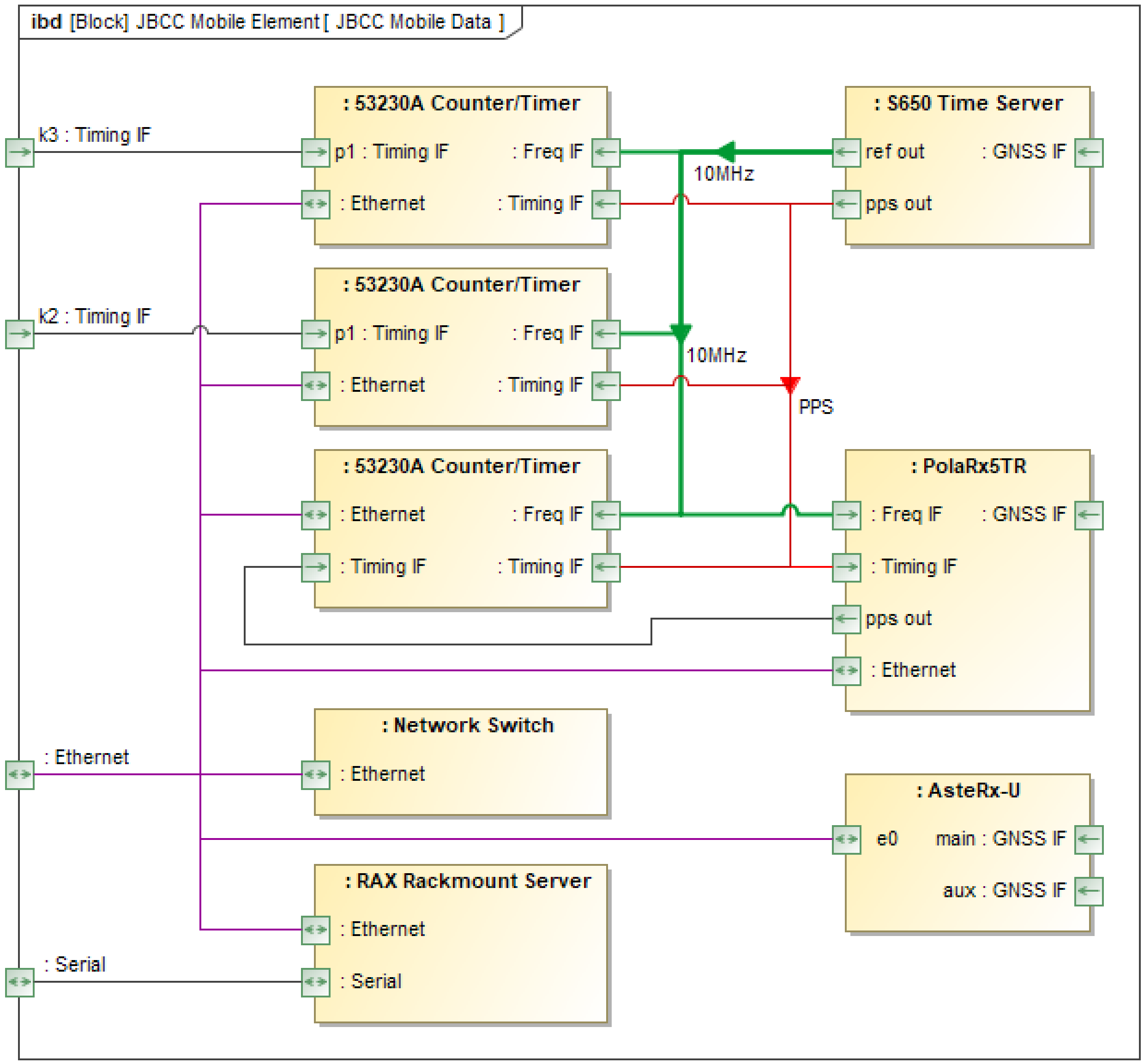


Figure 22. JBCC Rover Subsystem Components and Interfaces

The JBCC Rover subsystem paralleled the JBCC Fixed subsystem in that both had a co-located reference time source, a GNSS receiver and antenna, and input channels for participant UE measurements. However, the Fixed subsystem used a stand-alone cesium frequency standard, whereas the Rover used an integrated rubidium frequency standard (S650).

4.2.2.1 Rover Subsystem Position Estimation

For 2D positioning scenarios, the Rover subsystem was designed to determine the position of each vendor's UE antenna. The position determination task involved two steps: (1) determine both position and orientation of a local platform-fixed coordinate system; and (2) transform the UE antenna position from platform-fixed to geodetic coordinates. The AsteRx-U reference receiver collected real-time GNSS signals from each UE antenna sequentially to support Step 1.

Transforming the UE antenna position for Step 2 involved measuring the platform-fixed offsets relative to the GNSS reference and auxiliary antennas. In Figure 23, the origin coincides with the "Ref" (Reference) antenna, with the positive x-axis aligned in the direction of the "Aux" (Auxiliary) antenna and positive y-axis oriented forward in the van direction of travel. The measurements, shown in meters, between the Rover and UE antennas were made with a multi-point laser level and a portable laser rangefinder.

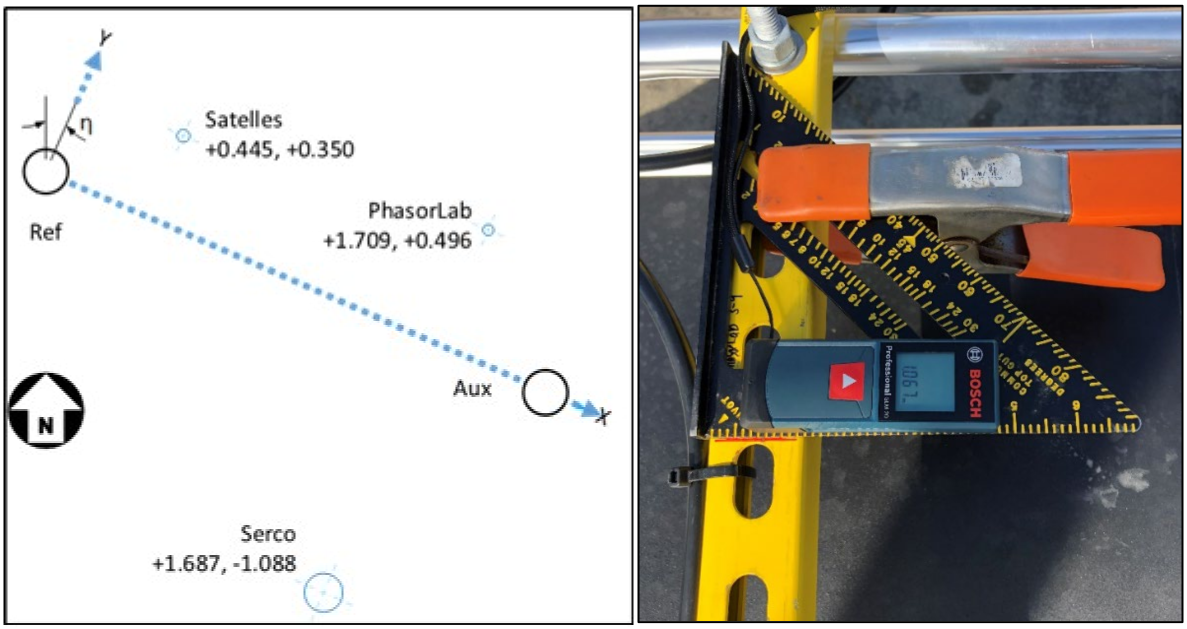


Figure 23. JBCC Van Layout: Rover Subsystem Reference and Auxiliary Antenna Positions, and Vendor UE Antenna Positions (in m), Determined Using Laser Rangefinder to Measure Offsets

While the AsteRx-U heading measurement was sufficiently accurate (less than 1.5 mrad) for direct use, its position measurement underwent post-processing using the known Fixed subsystem base station. The post-processing for the Rover position estimation for outdoor scenarios used base-station GNSS measurements from the Fixed subsystem with the open-source RTKLIB software package. Figure 24 shows the comparison between the 2D Rover RTKLIB mean with the scatter of 2D Rover position estimates for Scenario 2: Dynamic Outdoor Positioning with Holds at static point SO1. For reference, the 3D Airborne–R3 RTKLIB mean is shown when this subsystem as placed exactly on static point SO1, revealing that the difference in positions after post-processing using two separate subsystems was on the order of 2 cm. The figure also shows the reference line of 0.33 cm to provide distance scale for these comparisons.

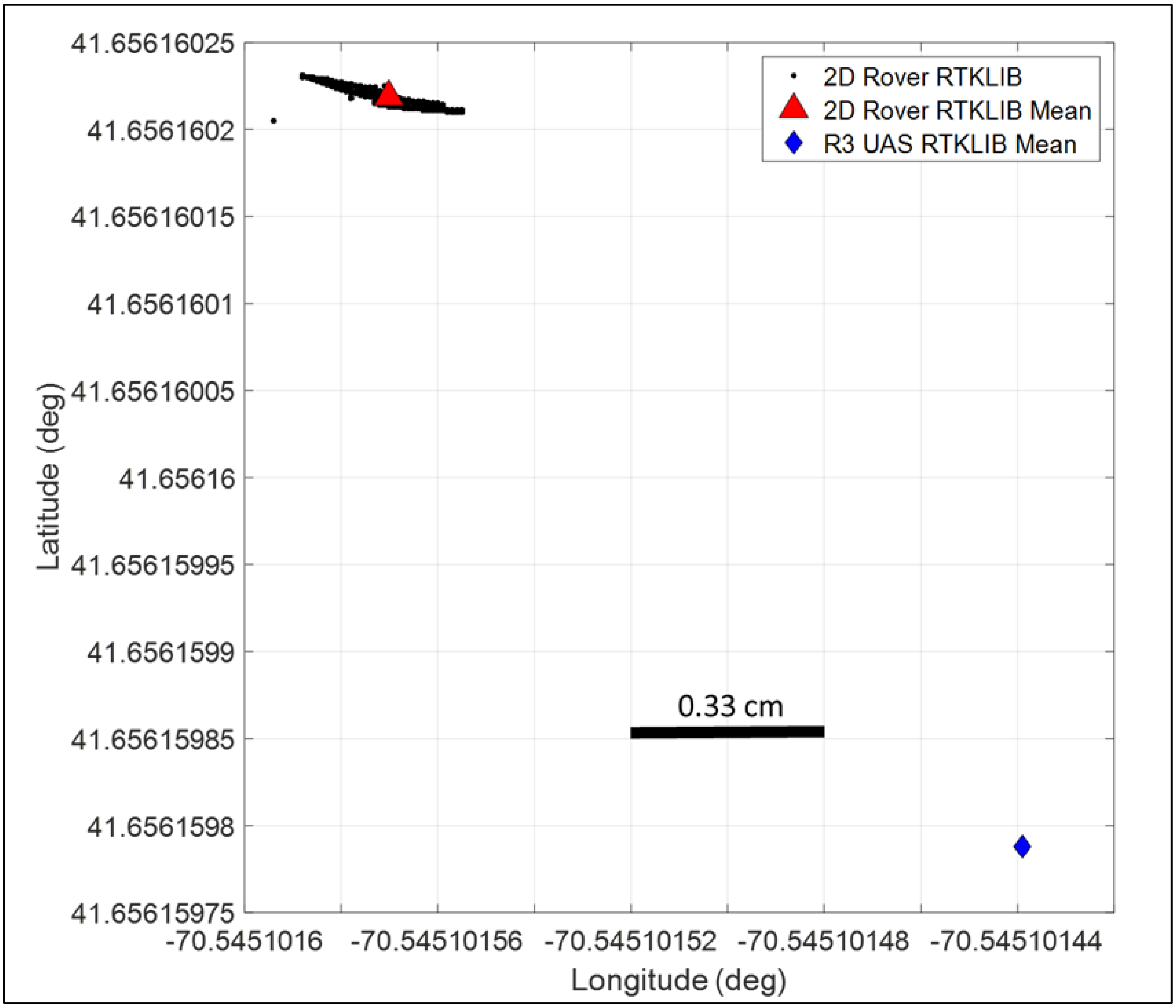


Figure 24. RTK Reference Positions from Rover and Airborne–R3 Subsystems

When the specific scenario called for repeatable positioning over a pre-surveyed point, the team used a laser level to ensure vertical alignment of the "Ref" antenna within a few centimeters. The tripod-mounted laser level projected points both up and down. Easily placed by hand over the desired point, the upward beam provided a visible reference point for the driver, yielding final positioning repeatability, as shown in Figure 25.

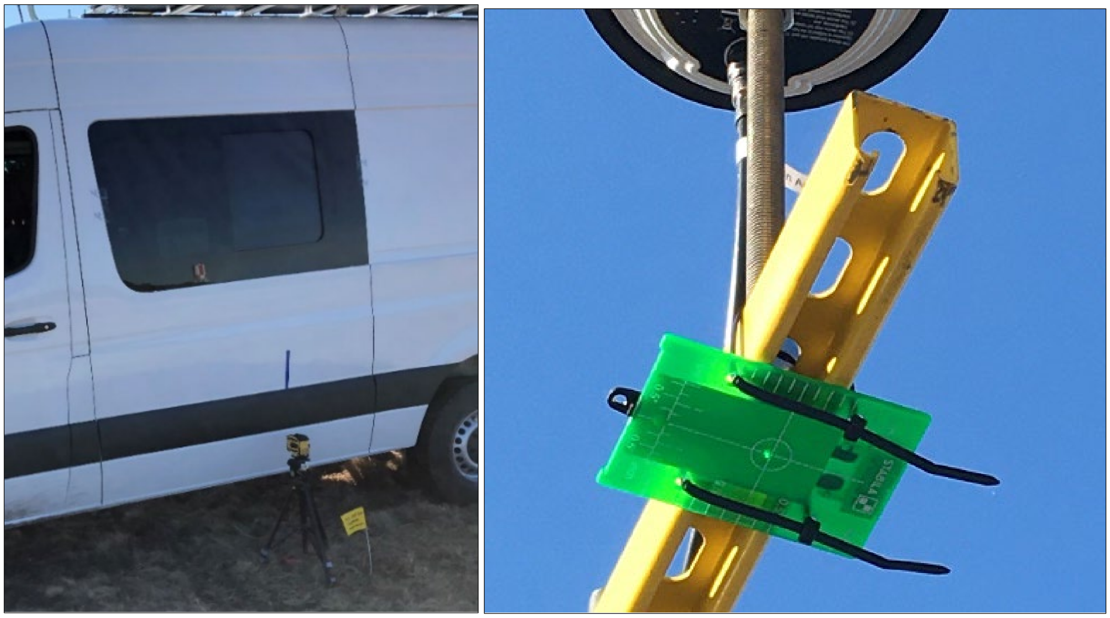


Figure 25. Tripod-Mounted Laser Level for Vertically Aligned Positioning of the Rover Reference Antenna

4.2.2.2 Rover Time Measurement Correction

For Scenario 4: Static Outdoor Timing, Scenario 7: Static Basement Timing, Scenario 9: eLORAN Reference Station Offset, and some vendor participants in Scenario 6: Static Indoor Timing, the Rover subsystem provided the UTC timing reference for participant UE. For these measurements, the S650 time server provided a 1-pps reference output. The S650 was disconnected from its GPS antenna for all scenario data collection involving the Rover subsystem.

For outdoor scenarios, the S650 1-pps output was measured against the UTC 1-pps output of the PolaRx5 receiver. Figure 26 shows the measured drift of S650 and corresponding least squares fitted curves that were used to detrend the UE measurements for Scenario 4: Static Outdoor Timing. For the basement and indoor demonstrations using the Rover subsystem, a valid GPS signal was too weak under those degraded conditions to be detectable by the Rover subsystem. The S650 holdover algorithm resulted in piecewise linear drifts relative to UTC, as was similarly shown in Figure 15 for LaRC. Therefore, measurements before loss of GPS reception and after signal reacquisition were used to extrapolate the S650 1-pps drift and provide a UTC reference for indoor and basement timing scenarios.

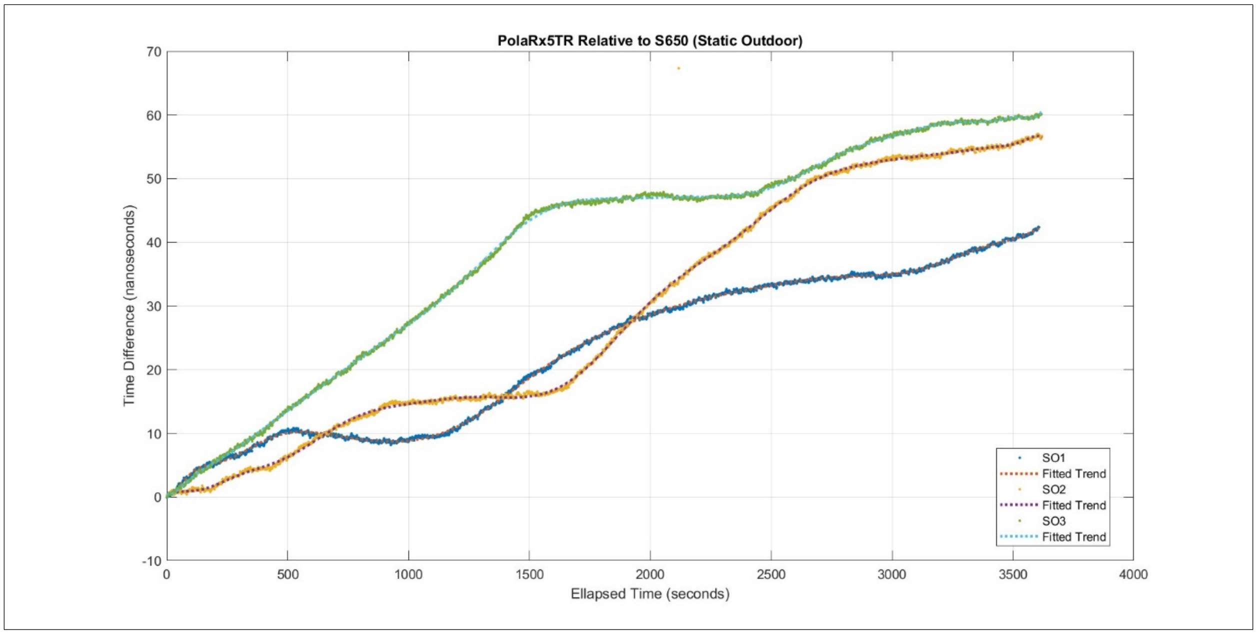


Figure 26. S650-Fitted Trend for JBCC Static Outdoor Scenarios

4.2.3 JBCC Airborne–R3 Subsystem

The Airborne–R3 subsystem deployed at JBCC was developed by the Volpe Center for the purpose of deriving precise positioning information from UAS and other small automated platforms. It comprised primarily COTS products configured for the purpose of collecting and storing satellite observations suitable for applying carrier-phase-based correction methods, as used for all positioning data in this demonstration. Data were collected simultaneously at the Airborne–R3 subsystem and a stationary differential GNSS receiver (Base Station).

The UAS platform at JBCC was a Tarot X6 v1.0 UAS owned and operated by a participating vendor, PhasorLab. Figure 27 is a picture of the UAS with the Airborne–R3 subsystem mounted on-board. (Note the addition of a top-mounted wooden platform to accommodate elements of the payload.) The Tarot X6 is a 6-kg hexacopter with a maximum payload capacity of 5 kg. Flight tracks for autonomous operation were created by the Government Team and subsequently loaded to the UAS flight controller by PhasorLab personnel. 3D scenarios were conducted using this vehicle throughout the specified JBCC demonstration area at various altitudes up to 350 ft. Figure 28 presents the JBCC Airborne–R3 subsystem equipment diagram.

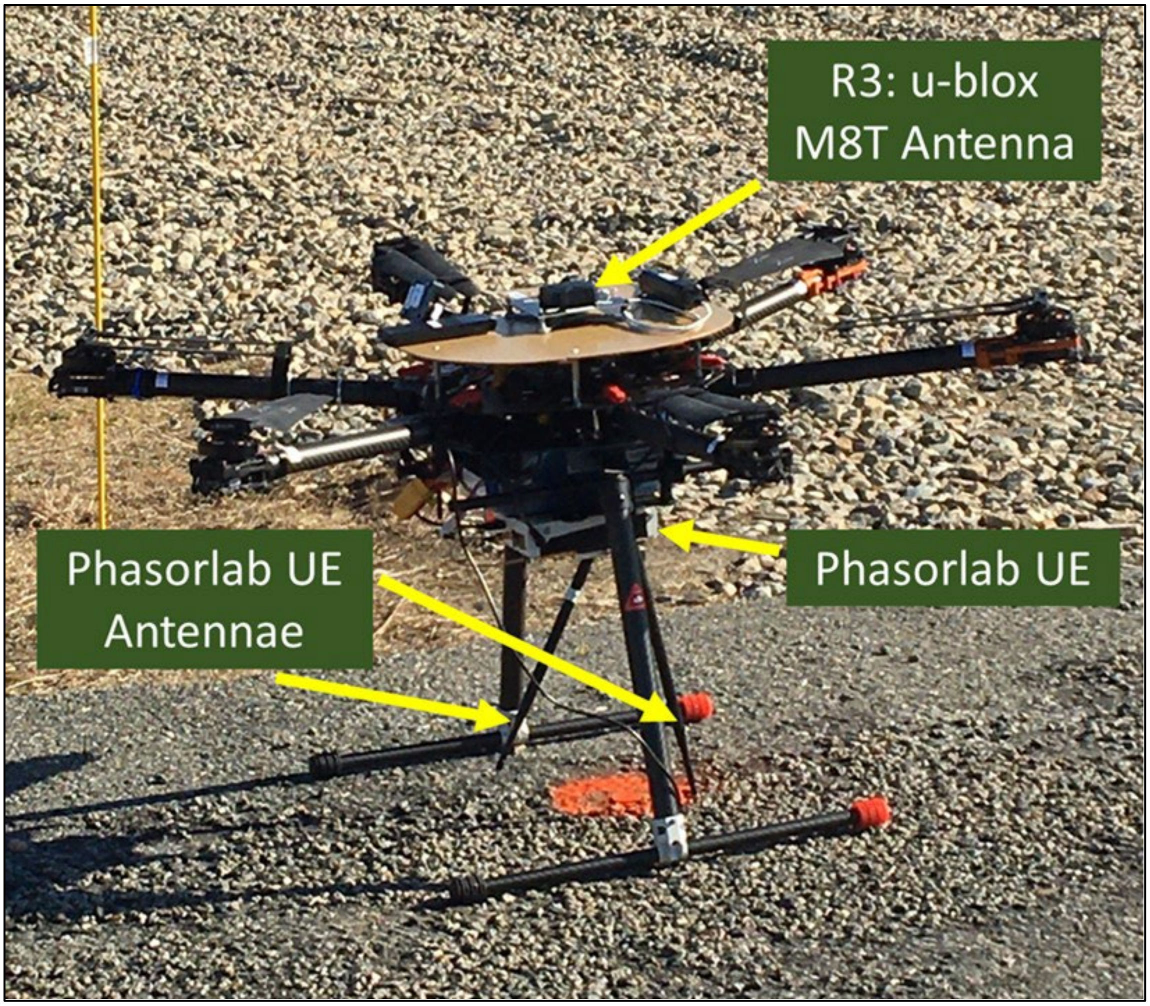


Figure 27. Tarot X6 Carrying JBCC Airborne–R3 Subsystem

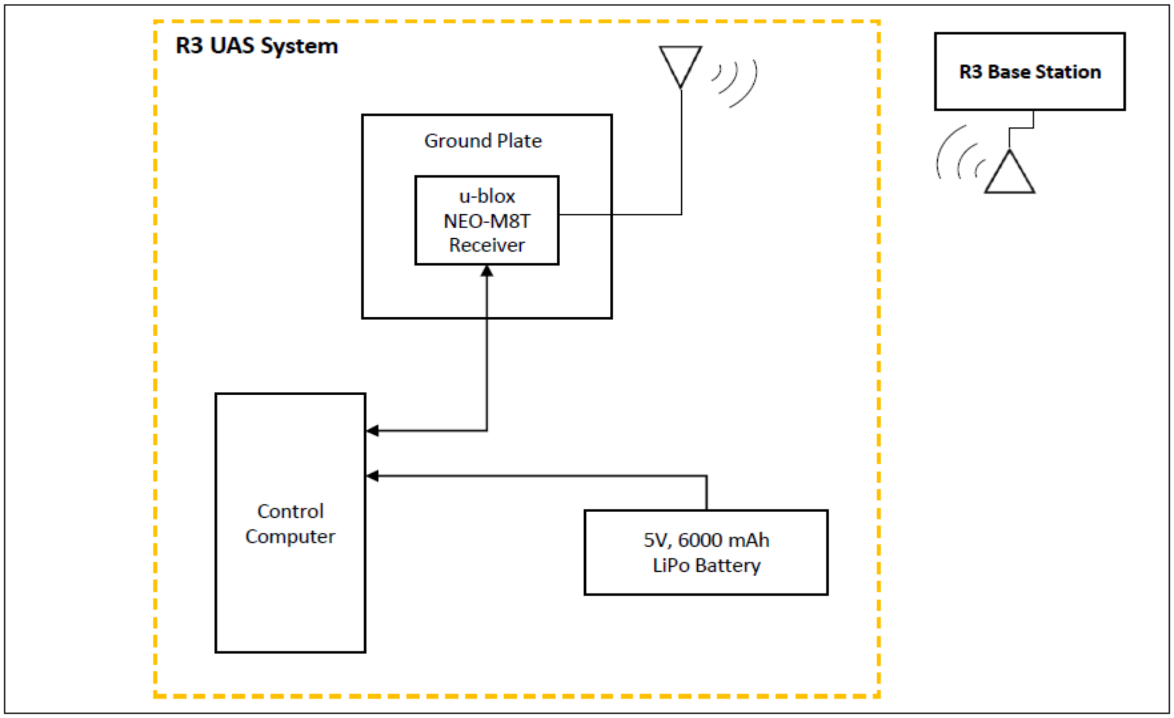


Figure 28. JBCC Airborne–R3 Subsystem Equipment Diagram

The core components of the R3 UAS, along with weights and dimensions, are presented in Table 10. The JBCC Airborne–R3 comprised a u-blox NEO-M8T receiver integrated onto a grounding plate along with an active, dual-feed, ceramic patch antenna. The system was configured and data were stored using a miniature computer. Power was provided by a 5-V, 2-A, 6000-mAh USB power bank.

Table 10. JBCC Airborne–R3 Subsystem: Key Components with Weights and Dimensions

Function	Component	Wgt (g)	Length (mm)			Comments
			X	Y	Z	
Receiver	u-blox NEO-M8T receiver assembly	80	100	100	25	integrated antenna + ground plate
Rover Control Computer	Intel Compute Stick	60	113	38	12	COTS
Rover Battery	6000 mAH Batteries	148	99	47	22	COTS
u-blox Mount	Custom mounting apparatus (plastic/metal)	31	90	90	58	3D printed

4.2.3.1 R3 Base Reference Position Estimation

The JBCC Airborne–R3 subsystem used a dedicated stationary differential GNSS receiver (Base Station), rather than the Fixed subsystem. The JBCC R3 base station employed the same GNSS receiver as the

Airborne–R3, but a laptop was substituted for the microcomputer, and a Tallysman TW2710 dual-feed ceramic patch antenna was substituted for the integrated antenna.

The R3 base station was set up in the vicinity of where the 3D scenarios were to be demonstrated approximately six weeks prior to the demonstration so that multiple surveys of its antenna position could be completed. The surveys were compared to verify accuracy because of the critical dependency between the error associated with this position estimate and the global positioning accuracy of the Airborne–R3 subsystem. All surveys were in agreement within a horizontal tolerance of 2.5 cm and a vertical tolerance of 3.0 cm, regardless of the specific days sampled, the duration of the survey, or, where applicable, the Precise Point Positioning (PPP) products used (i.e., rapid or final).[24]

4.2.3.2 UAS Vendor UE

PhasorLab was the only vendor at JBCC to participate in Scenario 8: 3D Outdoor Positioning. The PhasorLab UE functioned as a discrete system relative to both the Airborne–R3 subsystem and the Tarot X6 UAS. The UE was mounted to the bottom of the aircraft with the antennas oriented toward the ground. The R3 subsystem's antenna was mounted directly above the vendor UE. In this configuration, the lever arm offsets were vertical (Table 11). PhasorLab UE positioning data were collected and stored on the UE, and offloaded to the Fixed subsystem data acquisition equipment after the 3D scenarios were performed.

Table 11. Lever Arm Offsets Measured Relative to the Center of the R3 UAS Antenna

Antenna	x-right (cm)	y-fwd (cm)	z-up (cm)
PhasorLab UE	0	0	-39.5

[24] The final determination of the JBCC Airborne–R3 Base Station reference position was 41° 39' 21.84885", -70° 32' 35.70267", 8.389 m – ITRF14 (2020.0).

5 Demonstration Implementation

To demonstrate the GPS backup and complementary PNT capabilities of the 11 vendors in a methodical manner, the Government Team had developed a set of positioning and timing scenarios to model the real-world conditions under which complementary and backup technologies would need to operate. Vendors were encouraged to participate in any scenario they felt provided the Government with relevant information about the applications and/or domains for which their system provided valid GPS backup solutions.

5.1 Vendor Assignments

Taking vendor preferences into account, the Government Team assigned six technology vendors to LaRC and five vendors to JBCC.

The vendors assigned to LaRC (listed alphabetically) were:

- Echo Ridge, LLC
- NextNav LLC
- OPNT B.V.
- Seven Solutions S.L.
- Skyhook Wireless, Inc.
- TRX Systems, Inc.

Those assigned to JBCC were:

- Hellen Systems LLC
- PhasorLab Inc.
- Satelles, Inc.
- Serco Inc.
- UrsaNav Inc.

The Government Team arranged LSU access and service for the two vendors demonstrating eLORAN technologies:

- Hellen Systems, LLC
- UrsaNav Inc.

5.2 Locations

5.2.1 NASA Langley Research Center

Three primary locations at LaRC were used as part of this demonstration (see Figure 29): (1) Building 1230, (2) a portion of NASA Langley's City Environment for Range Testing of Autonomous Integrated Navigation (CERTAIN) range, and (3) Building 1262. Building 1230 was the primary hub for much of the work completed at LaRC. Lab space was made available in this building for the Government Team and vendors to install and work on their respective equipment.

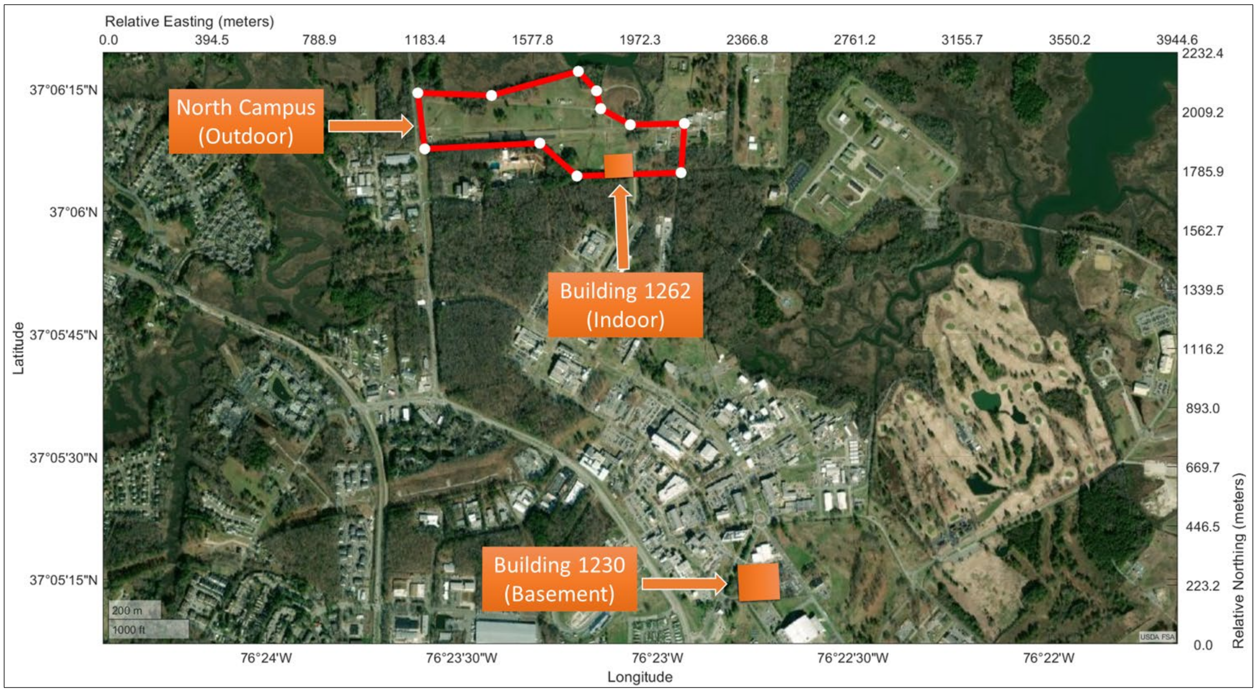


Figure 29. LaRC Campus Layout

The CERTAIN range at LaRC spans much of the facility.[25] The portion of the CERTAIN range used for this demonstration is a large, sparsely populated portion of the facility referred to as CERTAIN I. This area was utilized to collect ground-based dynamic and static data for both positioning and timing via the data collection van, as well as 3D positioning data by means of unmanned aircraft system (UAS) flights.

Situated within the CERTAIN I range is Building 1262, which was utilized for indoor data collection. A portion of Building 1262 is a hangar, which was large enough to allow the data collection van to perform dynamic and static data collection indoors.

5.2.2 Joint Base Cape Cod

Three primary locations at JBCC were used as part of this demonstration (Figure 30): (1) the AWRF Demonstration Range, (2) Building 2410, and (3) Building 2822. In addition, three off-site locations approximately 15, 30, and 60 miles northwest of JBCC were used to support the eLORAN Reference System Offset scenario.

[25] The CERTAIN range is designed to allow for unmanned flight operations in a variety of dissimilar environments under an FAA-issued Certificate of Authorization (COA) and a Letter of Procedure (LOP) with Langley Air Force Base.

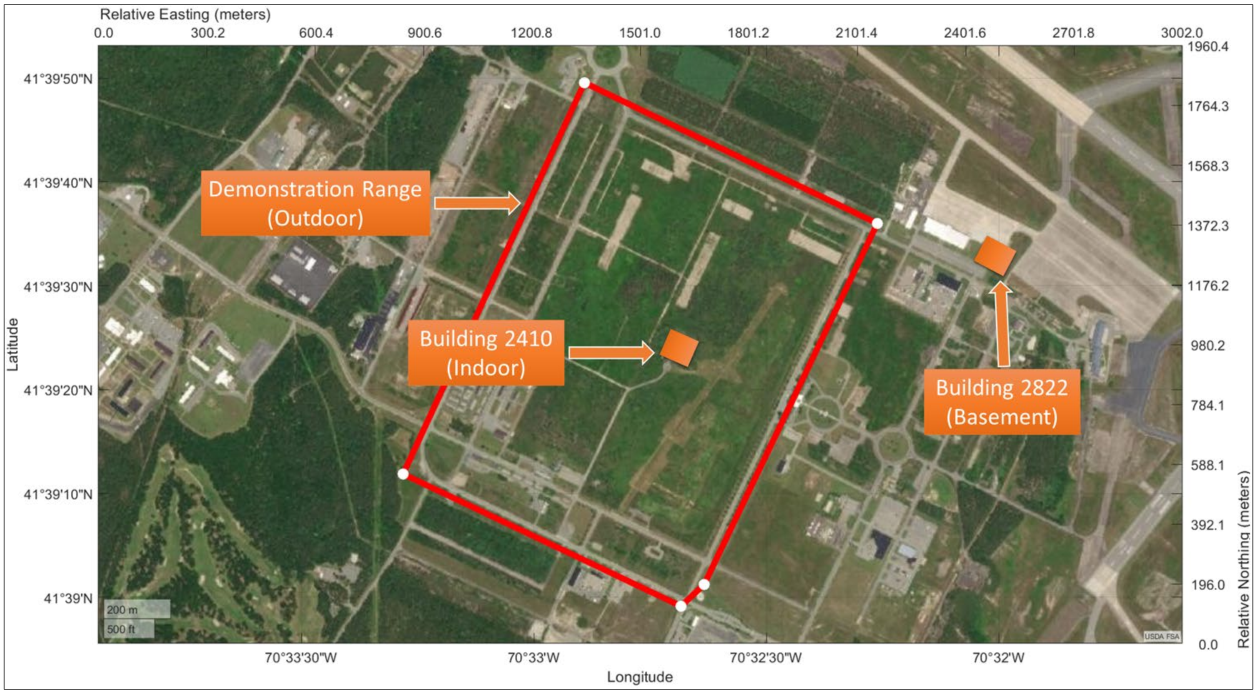


Figure 30. JBCC Campus Layout

Building 2410 was reconfigured to support vendor personnel and equipment during the demonstration, including removal of unneeded equipment and sensors. Each vendor was provided equal space: five vendor work station areas were partitioned and each set up with two workstation tables and a storage cabinet. An electrician was brought in to provide each vendor area with a dedicated 15A circuit. The network was upgraded to support the increased number of users.

To accommodate the increased traffic and usage in the demonstration range, a variety of physical improvements were completed. The demonstration routes were cleared of all stumps, low branches, and potential hazards, and low points filled in with gravel. The demonstration points and patterns for each scenario were marked with spray paint and flags.

5.2.3 U.S. Coast Guard LORAN Support Unit

Figure 31 shows the location of LSU in relation to JBCC.

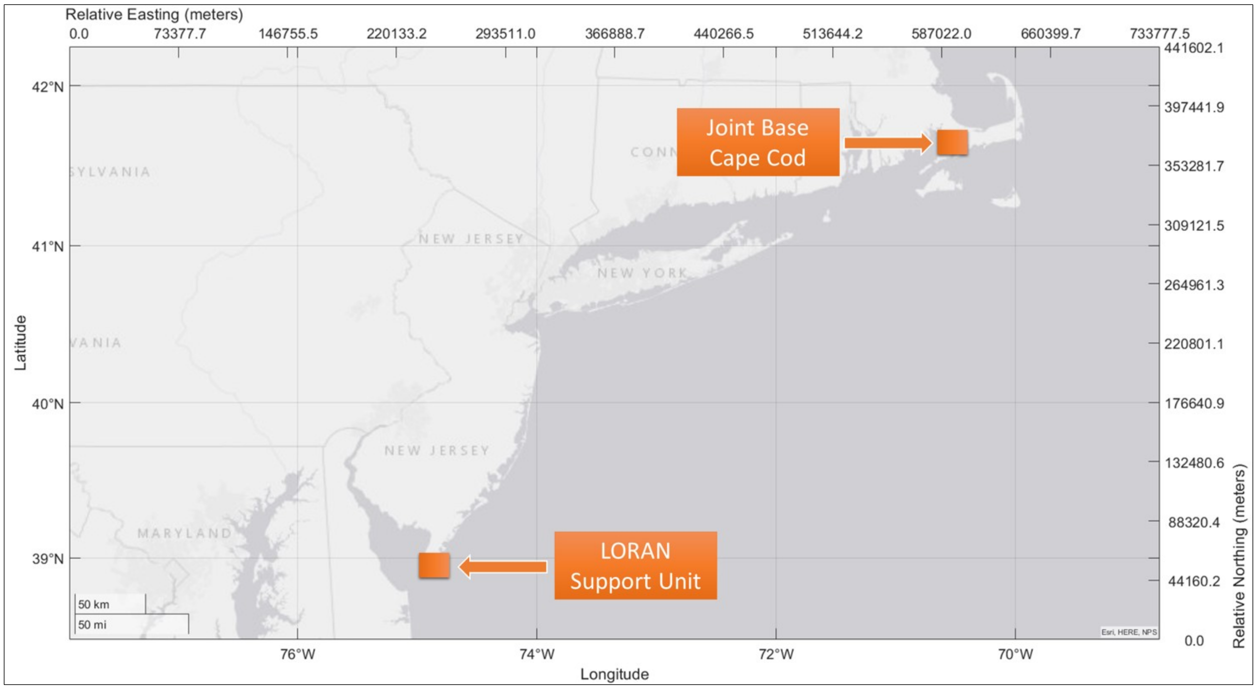


Figure 31. Position of LSU Relative to JBCC

The LSU facility contained several interconnected structures (Figure 32). The buildings and surrounding parking lots had not been used for many years and were overgrown and in poor condition. However, much of the existing equipment was still operational including the patch panel, the antenna connection points (from both old and new solid-state transmitter rooms), the Megapulse transmitters, the transmitter feed, and the 625-foot antenna.

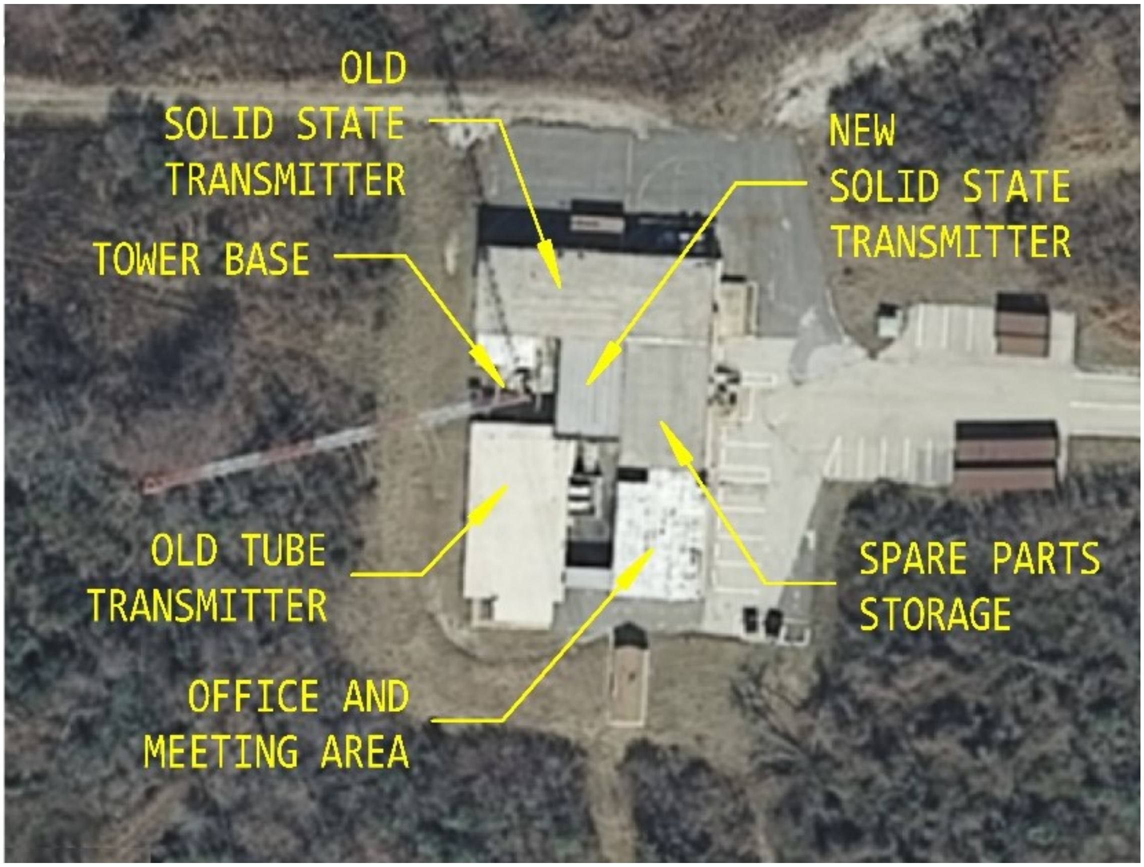


Figure 32. LSU Buildings

5.3 Vendor Site Visits and Demonstration Plans

In November 2019, the vendors selected through the RFQ were asked to conduct visits to their assigned sites at LaRC, JBCC, and LSU. The site visits included tours of the test range, labs, and buildings and basements where the scenarios were to be conducted. The site visits provided an opportunity for the vendors to assess their assigned site for information needed as input into a required site plan.

The plans were to inform the Government Team how each vendor intended to set up and operate its equipment. The required information included the physical size of each transmitter, AC power requirements, the location needed for each transmitter, HVAC requirements (if any), and any other special considerations. Site plans were submitted to the Government Team by December 2, 2020.

5.4 UE Integration and Verification

An essential pre-implementation component of the demonstration was interfacing vendor user equipment (UE) with the Government's reference and data collection systems. Interfacing UEs directly with the Government's systems enabled real-time data collection of time, position, and other metadata supporting the comparison of results produced by the Government reference system and vendor user equipment.

In December 2019, the Government Team hosted the UE integration and verification task at The MITRE Corporation in Bedford, Massachusetts, to establish the compatibility of each vendor's UE with the Government-furnished data collection system. All vendors were required to participate; each was to provide the UE, associated support, and all relevant information needed for the Government Team to read and understand the positioning and timing results produced by the UEs.

During this task, it was determined that the Echo Ridge and TRX UEs could not integrate with the Rover reference and data collection subsystem to enable real-time positioning data collection. The target market for both of the vendors is dismount applications, in which the UE is hand-held and the holder's GPS data reflect movement while on foot. The dynamic positioning scenarios in which these vendors had asked to participate would be using a mobile reference system mounted in a vehicle; there would therefore be no way to establish reference positions for comparison against the UEs' results.

After careful consideration, and in the spirit of wanting to demonstrate a wide variety of technologies in response to the Congressional mandate, the Government Team offered these vendors the option to instead participate in static positioning scenarios. The rationale behind this decision was that static position points would have been well established, surveyed locations against which to compare the data. Echo Ridge and TRX Systems accepted this alternative, and loosened the definition of real-time data collection to mean providing the Government with data logs immediately after completion of the demonstrations.

Table 12 below lists the timing and positioning UEs and total UE quantity provided by the vendors. More details regarding vendor technology setup and configuration can be found in Appendix B.

Table 12. Vendor UE List and Quantity

Vendor	Timing Scenarios UE (Quantity)	Positioning Scenarios UE (Quantity)	Total Quantity
Echo Ridge LLC	N/A	ER310 (1)	1
Hellen Systems, LLC	ATS-6500 (1)	N/A	1
NextNav LLC	NTR (2)	LPRx (2)	4
OPNT B.V.	OPTC (2)	N/A	2
PhasorLab Inc.	HSN Node (2)	HSN Node (2)	3
Satelles, Inc.	EVK2-OCXO (4), EVK2-Rb (2), Orolia SecureSync-Rb (2)	EVK2-OCXO (1)	8
Serco Inc.	N/A	Prototype Windows OS Device (1)	1
Seven Solutions S.L.	WR-ZEN TP-32BNC (1)	N/A	1
Skyhook Wireless, Inc.	N/A	Android OS Device (1)	1
TRX Systems, Inc.	N/A	Neon/Android OS Device (2)	2
UrsaNav Inc.	UN-155 (2)	N/A	2

Note: Only those UEs transmitting data that were analyzed for the demonstration are shown.

5.5 Equipment Installation

Over the course of several months leading up to the demonstration, the vendors were given access to their assigned sites to deploy their systems. These installations were in accordance with the submitted site plans. More details regarding vendor technology setup and configuration can be found in Appendix B.

5.5.1 LaRC

Lab space in building 1230 was made available to host the vendor equipment and the government-provided Fixed reference subsystem. Additional areas were also made available in the basement and on the roof of building 1230 to mount antennas that could connect to equipment in the lab. Vendor equipment was also installed in the CERTAIN range. This included dispersing over 20 towers of different types on which to mount antennas, as well as battery- and generator-powered UEs at various locations. Vendor UEs were also deployed inside building 1262.

5.5.2 JBCC

The Government Team had intended vendors to install equipment in the blue area shown in Figure 2 of Section 3. However, several of the vendors requested transmitter locations outside of the test range. This request was allowed by the Government Team, but required additional coordination with JBCC leadership and corresponding site owners. In total, 21 antennas and associated antenna mounts, cabling, equipment, and UEs were installed.

5.5.3 LSU

The Government Team coordinated with the USCG to permit access to LSU by two vendors to ensure equal access at separate times.

The Hellen System team brought in a Conex box containing their equipment and installed a coaxial cable between the Conex box and antenna connection point in the old solid-state transmitter room. Hellen utilized the existing antenna feed, patch panel, and antenna.

UrsaNav used the new solid-state transmitter room and installed additional electronics for controlling the existing Megapulse transmitter. In addition, UrsaNav used the existing antenna feed, patch panel, and antenna.

5.6 Demonstration Vehicles

Two identical Mercedes Sprinter vans, one for each demonstration site, were purchased through GSA to serve as mobile platforms for the Government reference rover subsystem and vendor data collection. Each van was outfitted with a 3,000-Watt pure sine wave inverter for powering equipment, an upgraded alternator, a roof rack, rear ladder, and tie-down points inside the van. The Government Team outfitted the van at each site by mounting antennas on the roof and equipment inside, based on considerations pertaining to the demonstration site and the vendor equipment.[26] Detailed descriptions of the Government reference equipment fitted in each van can be found in section 4.1.2 for LaRC and Section 4.2.2 for JBCC.

5.7 Schedule

Table 13 lists the vendors, their assigned demonstration location, and the scenarios in which they elected to participate.

[26] At LaRC the team routed cabling through the back of the van, while at the JBCC the team routed cables through the passenger side window. Due to more challenging topography at JBCC, the team upgraded the tires on that van to “all-terrain.”

Table 13. Vendor Location and Scenario Participation

Vendor	Site	1: 72-Hour Bench Static Timing	2: Dynamic Outdoor Positioning with Holds	3: Static Outdoor Positioning	4: Static Outdoor Timing	5: Static Indoor Positioning	6: Static Indoor Timing	7: Static Basement Timing	8: 3D Positioning	9: eLORAN Reference Station Offset
Echo Ridge LLC	LaRC			X						
Hellen Systems, LLC	JBCC	X						X		X
NextNav LLC	LaRC	X	X	X	X	X	X	X	X	
OPNT B.V.	LaRC	X								
PhasorLab Inc.	JBCC	X	X	X	X		X		X	
Satelles, Inc.	JBCC	X		X	X		X	X		
Serco Inc.	JBCC		X	X						
Seven Solutions S.L.	LaRC	X								
Skyhook Wireless, Inc.	LaRC		X	X		X			X	
TRX Systems, Inc.	LaRC		X	X		X				
UrsaNav Inc.	JBCC	X					X	X		X

Each vendor was given a week for a dry run and a week for the demonstration. For scheduling and logistics, the vendors at JBCC were divided into Groups A and B because it was not feasible for both eLORAN vendors to transmit at the same time utilizing the same antenna. Thus, Group A consisted of all JBCC-assigned vendors with the exception of Hellen Systems, the sole participant in Group B. Group C consisted of all vendors assigned to NASA LaRC. Table 14 presents the members of all three groups.

Table 14. Vendor Group Assignments by Site

Site	Vendor	Group
JBCC	PhasorLab	A
JBCC	Satelles	A
JBCC	Serco	A
JBCC	UrsaNav	A
JBCC	Hellen Systems	B
LaRC	Echo Ridge	C
LaRC	NextNav	C
LaRC	OPNT	C
LaRC	Seven Systems	C
LaRC	Skyhook	C
LaRC	TRX	C

Two weeks of dry runs and two weeks of demonstrations were conducted (Table 15). For reasons of efficiency, the demonstration was conducted in reverse order of the dry-run. Groups B and C demonstrated their technologies concurrently at their respective sites

Table 15. Dry Run and Demonstration Dates

Event	Location	Group	Week of
Dry Run	JBCC	Group A	February 17, 2020
	JBCC	Group B	February 24, 2020
	LaRC	Group C	February 24, 2020
Demonstration	JBCC	Group B	March 9, 2020
	LaRC	Group C	March 9, 2020
	JBCC	Group A	March 16, 2020

The demonstration schedules are detailed below. The demonstration of Group B vendor technology was conducted the week of March 9, 2020;

Table 16 provides the daily schedule.

Table 16. Demonstration Scenario Schedule, Week of March 9, 2020: JBCC Group B

Scenario	Monday	Tuesday	Wednesday	Thursday	Friday
1: 72-Hour Bench Static Timing	X	X	X	X	
7: Static Basement Timing				X	
9: eLORAN Reference Station Offset				Offset Point 3	Offset Points 1 & 2

The demonstration for Group C was conducted at LaRC, also during the week of March 9, 2020. Table 17 provides the daily schedule.

Table 17. Demonstration Scenario Schedule, Week of March 9, 2020: LaRC Group C

Scenario	Monday	Tuesday	Wednesday	Thursday	Friday
1: 72-Hour Bench Static Timing	X	X	X	X	VIP Tour and Demonstra-tions Day
2: Dynamic Outdoor Positioning w/Holds	TRX Only	X			
3: Static Outdoor Positioning	Echo Ridge & TRX Only	SO1 & SO2 Only	SO3 Only		
4: Static Outdoor Timing		SO1 & SO2 Only	SO3 Only		
5: Static Indoor Positioning	X	TRX Only			
6: Static Indoor Timing	X				
7: Static Basement Timing				X	
8: 3D Positioning	X	X	X	X	

TRX and Echo Ridge participated separately from the other vendors. In addition, for all other vendors participating in Static Outdoor and Indoor Positioning, not all points were completed in a single day.

The demonstration at JBCC for Group A was the last conducted during the week of March 16, 2020; Table 18 provides the daily schedule.

Table 18. Demonstration Scenario Schedule, Week of March 16, 2020: JBCC Group A

Scenario	Monday	Tuesday	Wednesday	Thursday	Friday
1: 72-Hour Bench Static Timing	X	X	X	X	
2: Dynamic Outdoor Positioning with Holds	X				
3. Static Outdoor Positioning	X				
4: Static Outdoor Timing	X				
5. Static Indoor Positioning (no vendor participated)					
6: Static Indoor Timing		X			
7: Static Basement Timing		X			
8: 3D Positioning	X				
9: eLORAN Reference Station Offset		Offset Point 1	Offset Points 2 & 3		

DOT hosted a VIP tour and demonstration day on Friday, March 13, 2020, for Executive Branch agencies, Congressional staff, and PNT Advisory Board members. Tours, briefings, and demonstrations were conducted by the combined Government and vendor personnel.

5.8 Scenario Implementation

To prepare for the demonstration, two weeks of dry runs were conducted to make sure that the end-to-end readiness of both the Government Team and vendors could be verified. Lessons learned during the dry runs were then folded into the demonstration. These included allowing vendor system parameter changes, improvements in scenario work flows, and accommodating weather impacts on scenario scheduling. The demonstration for record was then conducted the following three weeks according to the schedules described in section 5.7.

5.8.1 Positioning

Four positioning scenarios were conducted during the demonstration: Dynamic Outdoor Positioning with Holds, Static Outdoor Positioning, Static Indoor Positioning, and 3D Positioning (see section 3.2.1 for the rationale and design of each of these scenarios). This section discusses the implementation of these scenarios, including the actual routes driven (for dynamic scenarios) and static positions (for static scenarios).

5.8.1.1 Scenario 2: Dynamic Outdoor Positioning with Holds

In this scenario, the five dynamic routes described in section 3.2.1 were implemented at both sites. This implementation maintained the general shape of each route to the extent practicable under local conditions. The exact adherence to the geometric shapes with high precision was not necessary because the assessment based on their attributes imposed no stringent requirements on linear or angular speed profiles.

Figure 33 and Figure 34 show the implementation of the general (segment) routes at LaRC and JBCC. Six static points were defined on each route. The implementation of the remaining four routes at the two sites is shown in Figure 35 and Figure 36. These figures were generated using data recorded by the Rover positioning reference subsystem at each site during scenario execution. This scenario also included regions with typical signal challenges due to naturally occurring obstructions such as trees and structures along some route segments. Three of the six static points were located on the General (Segment) route and the remaining three were on the figure eight, propeller, and circular routes.

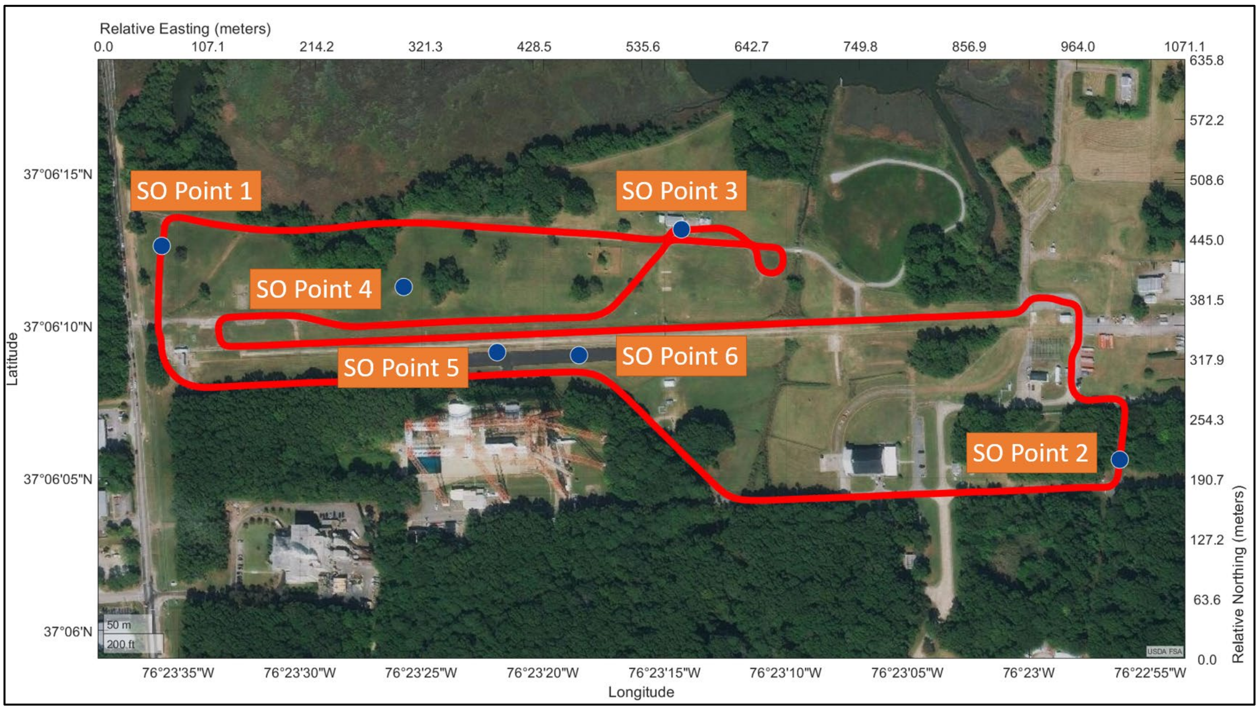


Figure 33. Scenario 2: Dynamic Positioning with Hold – General (Segment) Route (LaRC)

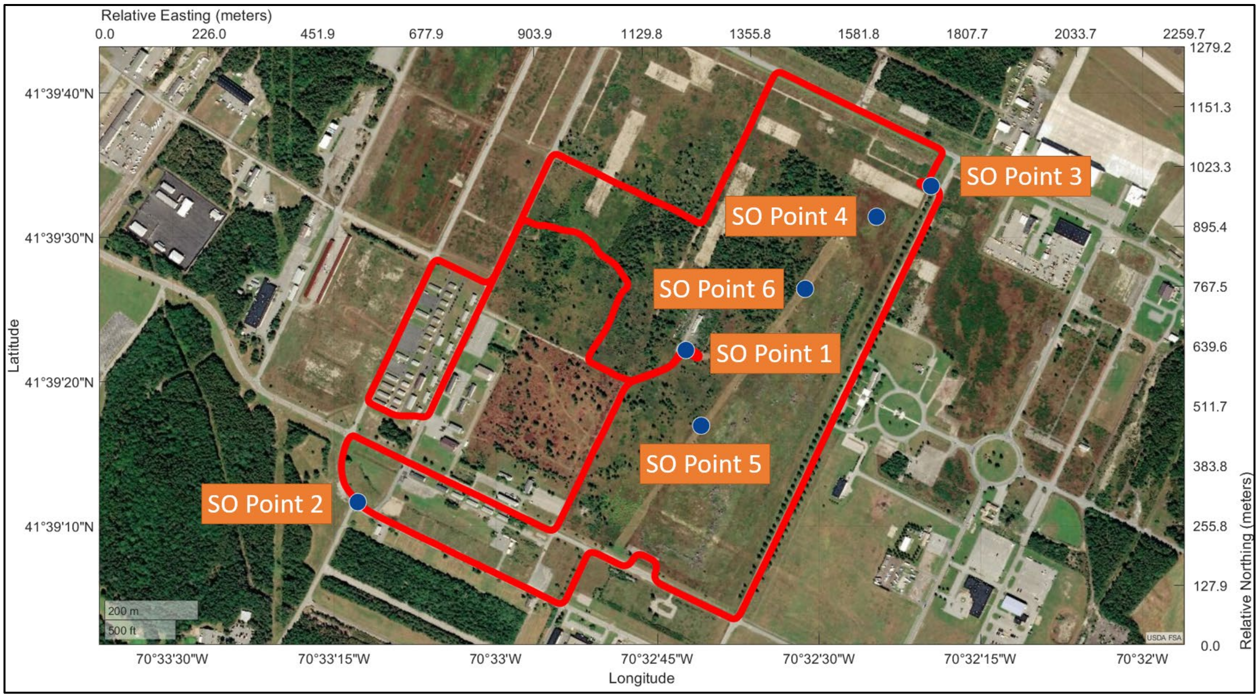


Figure 34. Scenario 2: Dynamic Positioning with Hold – General (Segment) Route (JBCC)

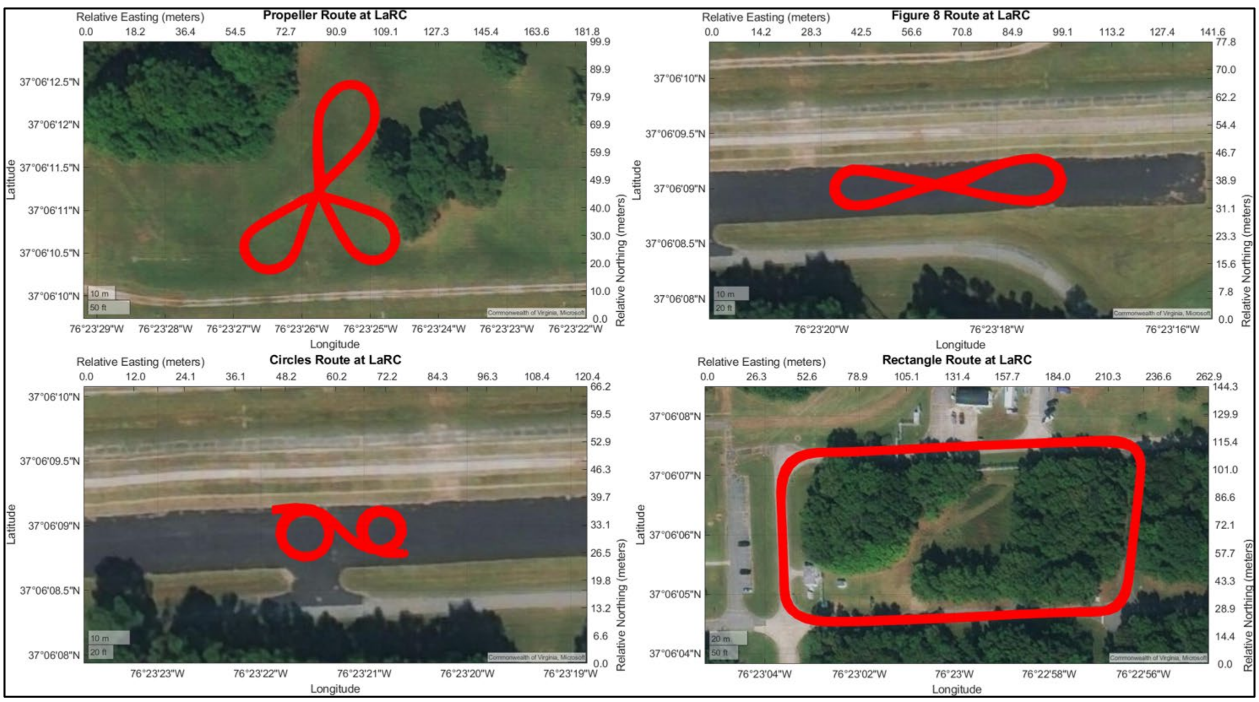


Figure 35. Scenario 2: Dynamic Positioning with Hold – Propeller, Figure Eight, Circular, and Rectangular Routes (LaRC)

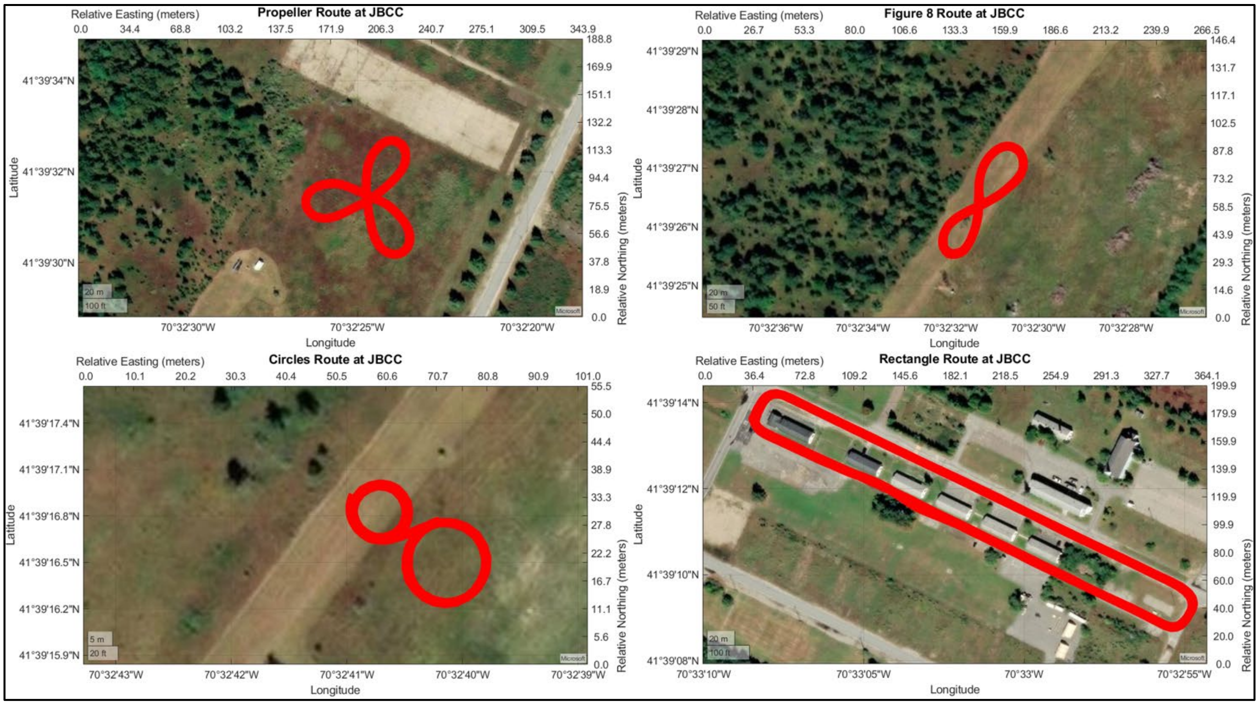


Figure 36. Routes for Scenario 2: Dynamic Positioning with Hold – Propeller, Figure Eight, Circular, and Rectangular Routes (JBCC)

The UEs of all vendors participating in demonstration of dynamic positioning were placed inside the respective site's demonstration van and properly configured for data collection. Sufficient settling time for each UE (based on the vendor's recommendation) was allocated prior to the start of the data collection. During each scenario run, positioning data were collected simultaneously both for all UEs and for the Rover reference subsystem.

The demonstration van traced the general (segment) route three times, stopping on each run to collect data at static points SO1, SO3, and SO5 for two minutes each. The van then traced the rectangle route three times. For the propeller, figure eight, and circular routes, the van first stopped at the center point of the shape for two minutes of continuous data collection before tracing the shape three times. The result was three runs for all routes.

As noted in Section 5.4, because TRX System's UE is a dismount unit, it could not be integrated into the Rover reference and data collection subsystem. Without concurrent data from the Rover subsystem to assess dynamic positioning performance, TRX Systems could only participate in the short-duration static holds of the Dynamic Positioning with Hold scenario (*i.e.*, at static points SO1, SO2, and SO3). Consequently, the TRX Systems demonstration was conducted separately, outside the van.

5.8.1.2 Scenario 3: Static Outdoor Positioning

This scenario involved data gathering at three surveyed static points designated SO1, SO2, and SO3, as shown previously above in Figure 33 for LaRC and Figure 34 for JBCC. The UEs for all vendors participating in this scenario were placed in the demonstration van (except for TRX and Echo Ridge, as discussed in Section 5.4). Sufficient settling time for each UE (based on the vendor's recommendation) was allocated prior to the start of the data collection. The van was aligned to each static point using methods described in Section 4. The Rover reference subsystem then collected UE data for 60 minutes.

5.8.1.3 Scenario 5: Static Indoor Positioning

In this scenario, the demonstration van carried out three 2-minute data collection runs at each of five surveyed static indoor points (SI1, SI2, SI3, SI4, and SI5); this same layout was used for Scenario 7. Additionally, a 60-minute data collection was carried out at 3 of those 5 points (SI1, SI3, and SI5). At LaRC, this scenario was conducted in Building 1262, which permitted the van to drive in and align with the static locations on the building floor.

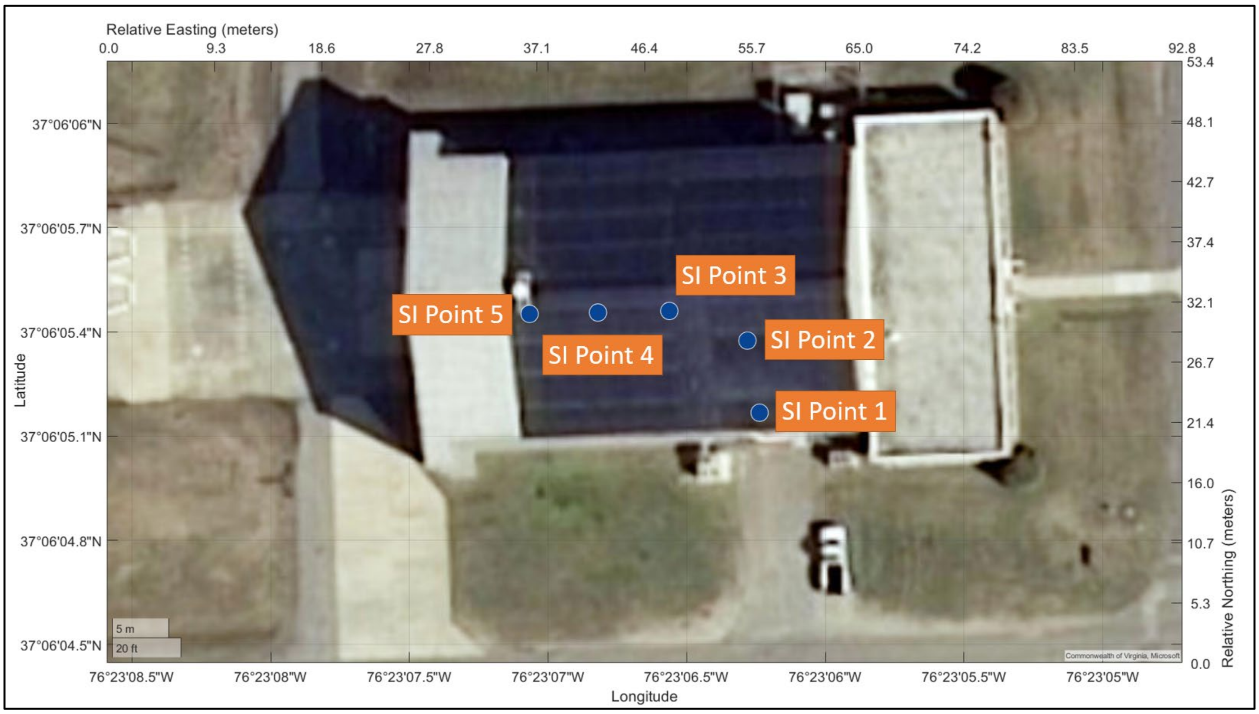


Figure 37. Scenario 5 – Static Indoor Positioning Static Point Locations (LaRC)

No vendor participated in this scenario at JBCC.

5.8.1.4 Scenario 8: 3D Positioning

As discussed in section 3.2.1.2, a part of the 3D positioning scenario rationale was the need to have the ability to assess the vertical (z component) measurement capabilities of a demonstrated positioning system under more complex dynamics. This scenario implemented the 3D routes described in section 3.2.1.1. All UEs were placed and flown simultaneously on a UAS platform. The actual 3D positioning scenario routes are shown in Figure 38 for LaRC and Figure 39 for JBCC. The routes shown in these figures were plotted from the data collected by the Airborne-R3 reference subsystem at each site.

Note that the positioning of the survey point on the Propeller shape used for 3D positioning at the two sites appears to be different. At LaRC, there were trees near the edge of the Route. The pilot felt uncomfortable risking flight operations near the trees, which forced the Government Team to shift the propeller shape down slightly. However, the survey point itself was not shifted, because it was the center point of the 2D propeller shape.

Figure 38. Scenario 9 – 3D Positioning Layout (LaRC)

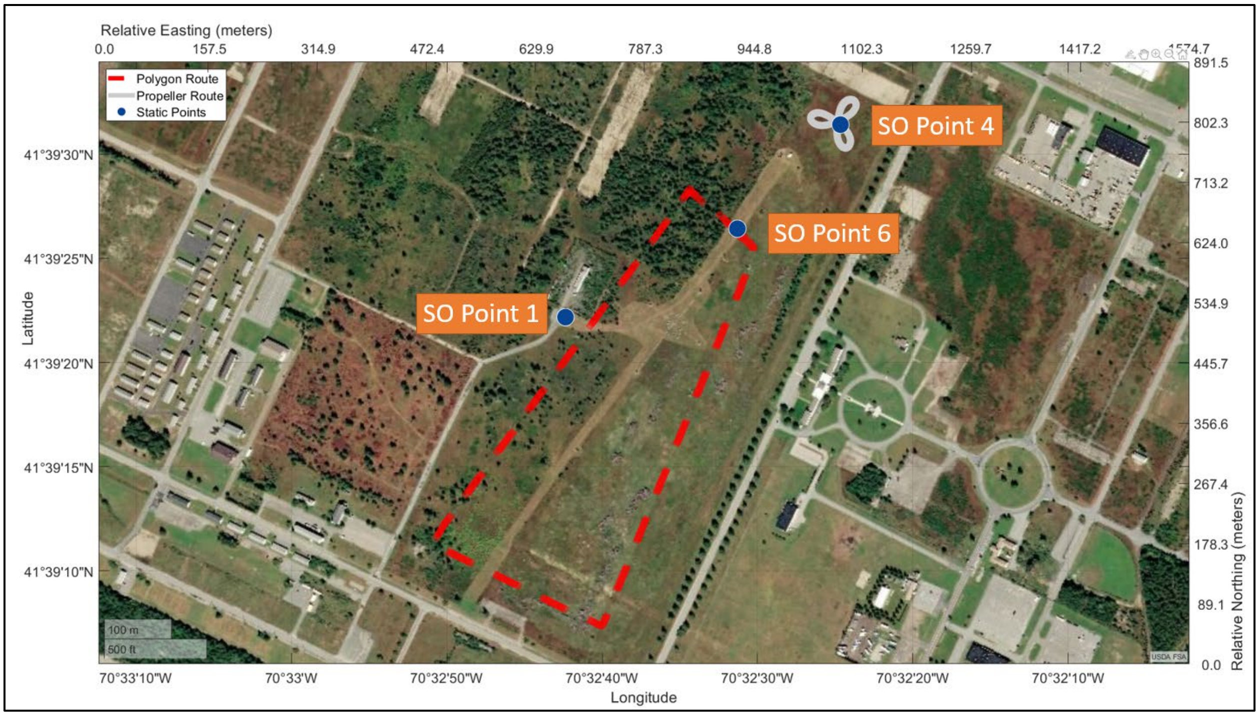


Figure 39. Scenario 9 – 3D Positioning Layout (JBCC)

The following maneuvering sequence was performed during the execution of this scenario at each site:

1. The UAS platform was successively placed at points SO1, SO4, and SO6, first at ground level and then an elevated flat surface (*e.g.*, a table) and positioning measurements were collected for one minute each.
2. The UAS platform traced the polygon at three fixed altitudes (100 ft., 200 ft., and 300 ft.). One run per altitude was made.
3. The UAS platform traced the propeller route three times at a fixed 50-ft. altitude.
4. The UAS platform traced the propeller route once while transitioning from 50 ft. to 350 ft.
5. The UAS platform traced the propeller route three times at a constant altitude of 350 ft.

For the propeller route (Figure 40), the overall scenario sequence consisted of the UAS taking off and flying to 50 ft.; then tracing the propeller route three times at 50 ft.; transitioning from 50 ft. to 350 ft. while tracing the propeller route; then tracing the propeller route three times at a constant 350-ft altitude, followed by a slow vertical descent to the ground while holding for short periods of time at specified lower altitudes.

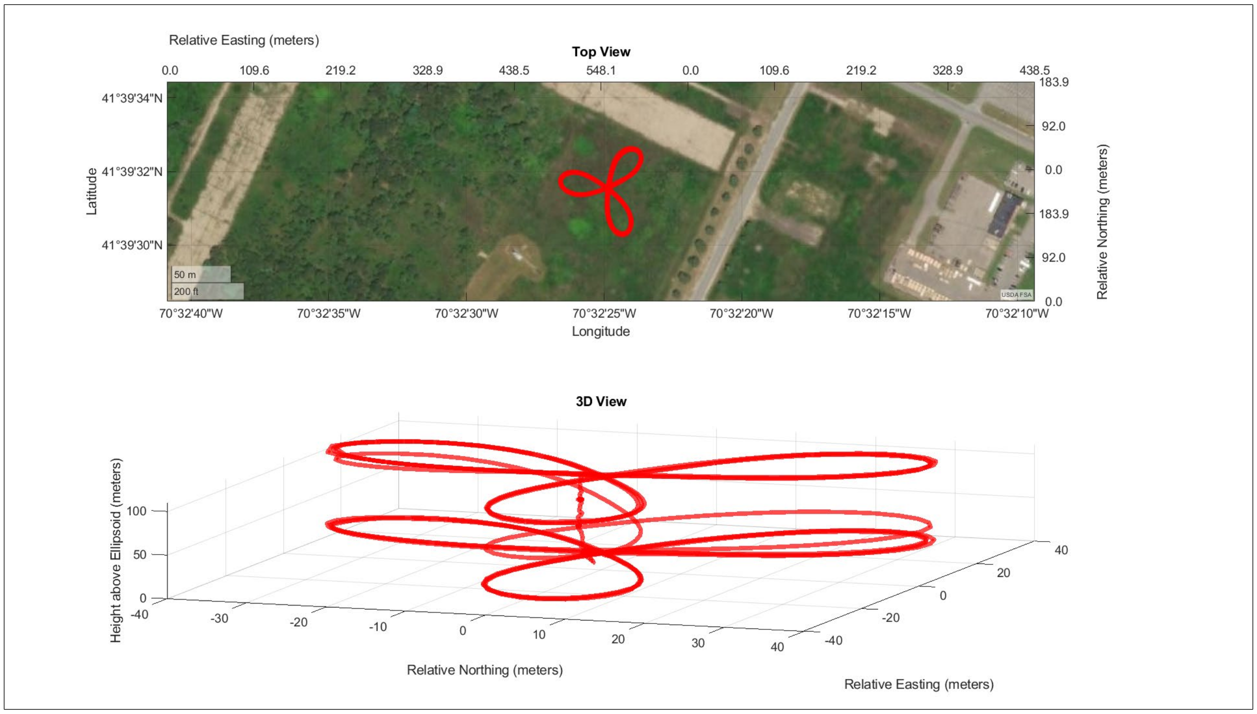


Figure 40. Scenario 9 – 3D Positioning Propeller Route

5.8.2 Timing

Five timing scenarios were developed as described in section 3.2.2. Four of those scenarios were conducted at both LaRC and JBCC: Scenario 1: 72-Hour Bench Static Timing, Scenario 4: Static Outdoor Timing, Scenario 6: Static Indoor Timing, and Scenario 7: Static Basement Timing. The fifth timing scenario, Scenario 9: eLORAN Reference Station offset, was conducted solely at JBCC. Each participating vendor's UE received signals from LSU as well as correction signals from two reference stations located at JBCC.

5.8.2.1 Scenario 1: 72-Hour Bench Static Timing

As discussed in Section 3.2.2.1, this scenario was developed to assess the long-term timing service availability and time transfer accuracy and stability of the participating UEs. For RF wireless systems, the 72-hour period allows the impact of atmospheric variations to be included. Each UE was required to provide a 1-pps output data signal that could then be measured against the Fixed timing reference system. All UEs were placed indoors. The UE antennae for systems with RF wireless time transfer capabilities were placed outdoors, on a mast or on the building. The antenna location was at the discretion of the vendor within the practical limitations of the two 72-hour scenarios building sites. In most instances, cabling was run to an outdoor antenna mast. For LaRC, this scenario was conducted in a lab located in Building 1230 and for JBCC it was conducted in Building 2410.

5.8.2.2 Scenario 4: Static Outdoor Timing

In this scenario, one-hour timing data were collected at three static surveyed points (SO1, SO2, and SO3) to verify the time transfer service coverage (or availability and uniformity) as well as the accuracy and stability of the time transfer error across the scenario execution region. These points are shown in Figure 41 and Figure 42 for LaRC and JBCC, respectively. Sufficient settling time for each UE (based on the vendor's recommendation) was allocated prior to the start of the data collection. The van containing the participating UEs was aligned to the static point with a known location on the van. Once positioned, the Rover reference subsystem collected UE data for one hour.

5.8.2.3 Scenario 6: Static Indoor Timing

In this scenario participating vendor time transfer data were collected at three surveyed indoor points (SI1, SI3, and SI5) to assess that system's availability and time transfer accuracy to a fixed location under challenged GPS signal conditions. These points are shown in Figure 41 for LaRC and Figure 42 for JBCC.

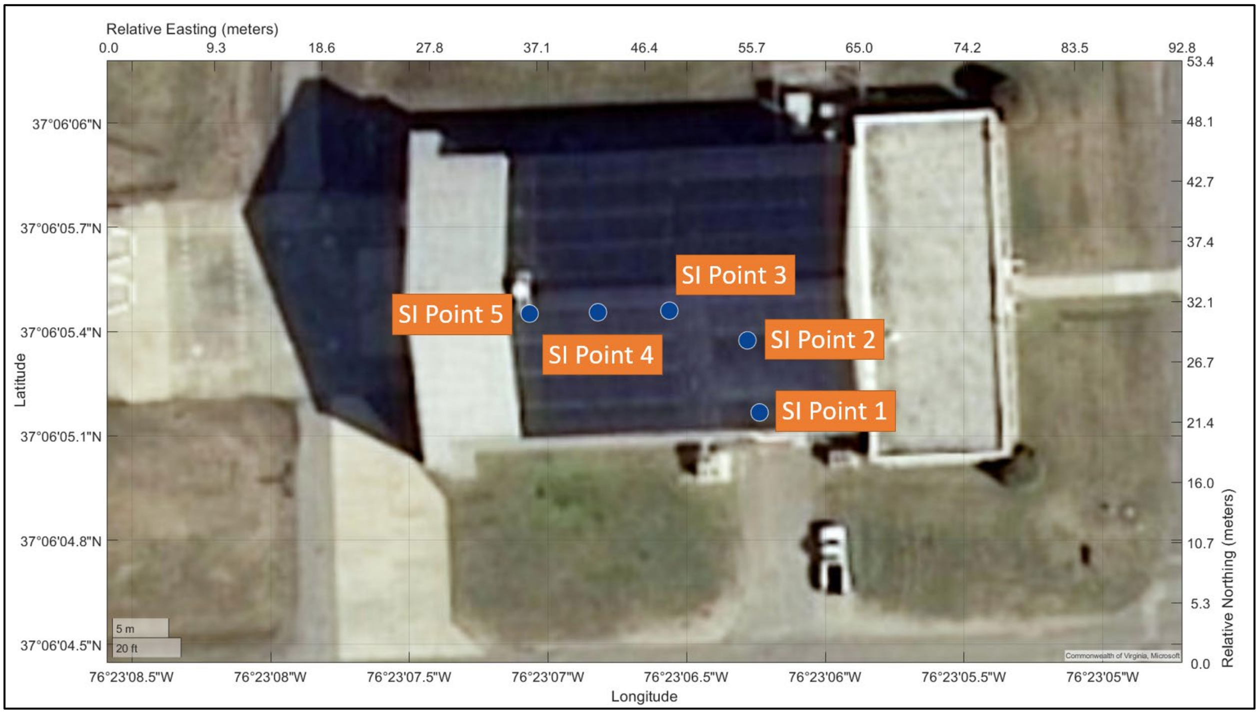


Figure 41. Scenario 6 – Static Indoor Timing Static Point Locations (LaRC)

Figure 42. Scenario 6 – Static Indoor Timing Static Point Locations (JBCC)

At LaRC, this scenario was conducted concurrently with and in the same manner as Scenario 5: Static Indoor Positioning in Building 1262 (see section 3.2.1.4). At JBCC, this scenario was conducted in Building 2410; UE antennae were evenly spaced on a 2-foot-radius circle centered at the static point. Sufficient settling time for each UE (based on the vendor's recommendation) was allocated prior to the start of the data collection. Data were then collected using the Fixed reference and data acquisition subsystem.

5.8.2.4 Scenario 7: Static Basement Timing

In this scenario, participating vendor system time transfer data were collected for a one-hour single indoor, below-grade location (*i.e.*, in a basement). Its purpose was to assess the service availability and time transfer accuracy and stability in a GPS denied environment. At LaRC this scenario was conducted in the basement of Building 1230; at JBCC it was conducted in the basement of Building 2822 (see Figure 41 and Figure 42).

5.8.2.5 Scenario 9: eLORAN Reference Station Offset

This scenario was developed to assess timing error characteristics and stability at larger baseline distances between the UE and reference subsystem antennae locations. These baseline distances were chosen to be approximately 15, 30, and 60 miles.

In this scenario, time transfer measurements were collected for one hour at each of three locations. Points SOF1, SOF2, and SOF3 (Figure 43) were at surveyed distances of 15, 30, and 60 miles to the northwest of JBCC; the exact geographic coordinates of these points are shown in Table 19.

Vendor UEs were placed inside the van and connected to the Rover reference system. Prior to the start of the scenario, UEs were powered, configured (if applicable), and data collection was initiated. Each UE was allowed the time advised by the vendor as necessary for settling before the start of each one-hour data collection.

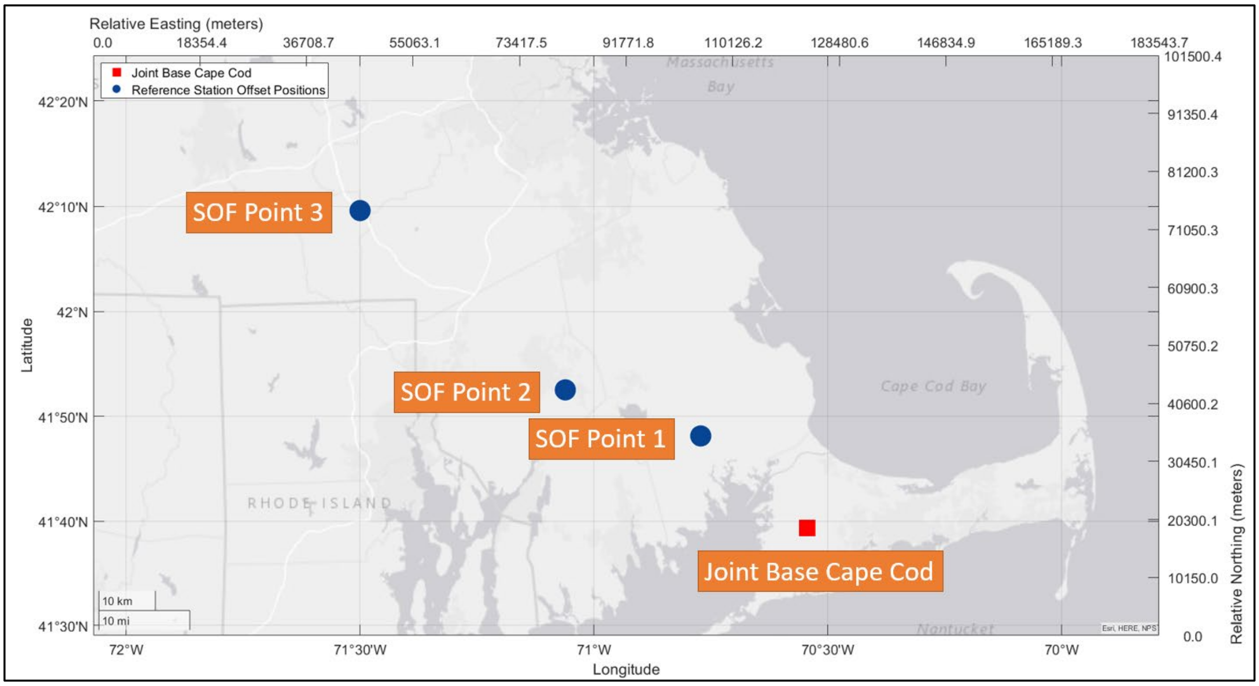


Figure 43. Scenario 9: eLORAN Reference Station Offset – Offset Point Positions (JBCC)

Table 19. Scenario 9: eLORAN Reference Station Offset – Offset Positions

Point	Latitude	Longitude
SOF1	41.8023075°	-70.7716867°
SOF2	41.8755816°	-71.0611791°
SOF3	42.1600761°	-71.4999733°

6 Positioning: Analytical Methods and Summary of Results

6.1 Positioning: Analytical Methods

This analysis quantified the accuracy of the position data collected by the Government Team from the vendor UEs for each scenario in comparison with the relevant Government reference system. The analysis methodologies objectively assessed the positioning capabilities of the vendor technologies. The Government Team's analysis did not speculate regarding the causes of missing data or inaccuracies in the vendor data.

The reference system and vendor UE position data were collected for each positioning scenario. To prepare the data for comparative analysis:

1. Each vendor's UE data were filtered based on quality-check parameters specified by that vendor.
2. Each vendor UE's positioning data were compared with the post-process-corrected reference position to quantify their accuracy. To align the data for comparison, the reference and vendor UE position results were converted to a local tangent plane coordinate frame with local east, north, and up (ENU) Cartesian coordinate system axes. For UE positioning data that did not contain a valid altitude, a nominal altitude was used to convert the latitude and longitude to northing and easting, respectively.
3. For dynamic positioning scenarios only, time alignment of the Government's reference positions and each vendor's UE positions was also necessary to be able to compare the results. Using a one-dimensional interpolation, each component of the vendor UE position (easting, northing, and, for the 3D scenario, up) was time-aligned to the reference position updates.[27]
4. A lever-arm correction was applied to account for the relative position offsets between the reference system antenna and vendor UE antennas, thus removing the constant position bias caused by the placement of vendor UE antennas separate from the reference system antenna.
5. The position error for each vendor UE as compared with the reference system was derived. The mean error and standard deviation were calculated for the positioning error to show the overall results for each scenario. In addition, the 95th percentile error and maximum deviation were calculated.
6. To provide the reader with an understanding of the frequency of position reports, an average update rate and a data availability percentage were calculated for static and dynamic positioning scenarios, respectively.[28,29]

[27] Interpolation for sample time alignment required a vendor UE's position logs to contain a valid position data point within 1.5 seconds before and after the reference position time.
[28] For static position scenarios, the average update rate is the average rate at which the UE position is updated with valid position reports that pass the vendor's data filters.
[29] For dynamic position scenarios, data availability shows the percentage of times the UE provided valid position reports that pass vendor data filters and able to be interpolated to align with reference position times.

6.2 Positioning: Summary of Results

Vendor participation in the positioning scenarios is shown in Table 20.

Table 20. Vendor Participation in Positioning Scenarios

Vendor	Location	Scenario 2: Dynamic Outdoor Positioning with Holds	Scenario 3: Static Outdoor Positioning	Scenario 5: Static Indoor Positioning	Scenario 8: 3D Positioning
Echo Ridge[A]	LaRC		X		
NextNav	LaRC	X	X	X	X
PhasorLab	JBCC	X	X		X
Satelles	JBCC		X		
Serco	JBCC	X	X		
Skyhook[B]	LaRC	X	X	X	X
TRX Systems[A]	LaRC	X	X	X	

A UE provided by Echo Ridge and TRX Systems did not integrate with the Government's Rover reference and data collection subsystem, so therefore, there are no data available to compare for dynamic scenarios. For static scenarios, the UEs were placed directly onto the static survey points and the vendor's data were provided to the government after the demonstrations and compared with the Government survey results.

B Skyhook's UE reported position information derived from two different protocols: round-trip time (RTT) and Wi-Fi position system (WPS) based on received signal strength indication (RSSI); both were considered in the analysis.

In addition, three of the vendors participating in the Positioning scenarios required a settling time for their UEs prior to the execution of each scenario to allow for the UE initialization and calibration necessary to provide useable positioning data. The quantity of time for each vendor is shown below in Table 21.

Table 21. Vendor-Requested UE Settling Times

Vendor	Settling Time
Echo Ridge	About 5 minutes
Satelles	15 minutes
TRX Systems	About 3 minutes

The discussions of the scenario outcomes that follow are organized to give context to the tabular data. First, the overall purpose of each scenario as described in section 3.2 is restated. Second, the images from section 5.8 showing the scenario plots are repeated. Third, a sample plot of the data collected for that scenario is offered.[30] This is followed by tabular summaries of positioning results; each table is cross-referenced to the location in Appendix C of the related data plot figures. Tables presenting data

[30] In each instance, the example given is of data for the vendor UE with the lowest mean error for that scenario.

from multiple vendor UEs and successive tables containing data for a single vendor's UE under multiple conditions are organized in alphabetical order by vendor.

6.2.1 Scenario 2: Dynamic Outdoor Positioning with Holds

Scenario 2: Dynamic Outdoor Positioning with Holds was intended to assess UE positioning service coverage, availability, and accuracy under varying transmitter-receiver geometry and signal conditions throughout the scenario execution area, under generally open sky conditions, and with minimal GPS signal challenges. It comprised 1) a general route with six specified points for data collection during a static 2-minute hold; and 2) a set of dynamic routes in a variety of shapes—a segment, a propeller, a figure eight, a double circular figure, and a rectangle—over which the UEs traveled, while mounted on and/or in the demonstration vehicle, to permit continuous data collection. (See section 5.8.1.1 for the description of how this scenario was implemented.)

The vendor participants in this scenario were NextNav, PhasorLab, Serco, Skyhook (RTT and WPS protocols), and TRX Systems.

Furthermore, Echo Ridge and TRX Systems UEs did not integrate with the Government's Rover reference and measurement collection system. The target market for Echo Ridge and TRX Systems is dismount applications, in which the UE requires a count of the number of steps taken to estimate distance. Therefore, for static hold points the UEs were placed directly onto the surveyed points and were then transported between points on foot by the vendors. The vendors did not participate in the dynamic portion of this scenario.

6.2.1.1 General Route: Static 2-Minute Hold Results

The images for the general routes at LaRC and JBCC are shown in Figure 44 and Figure 45, respectively.

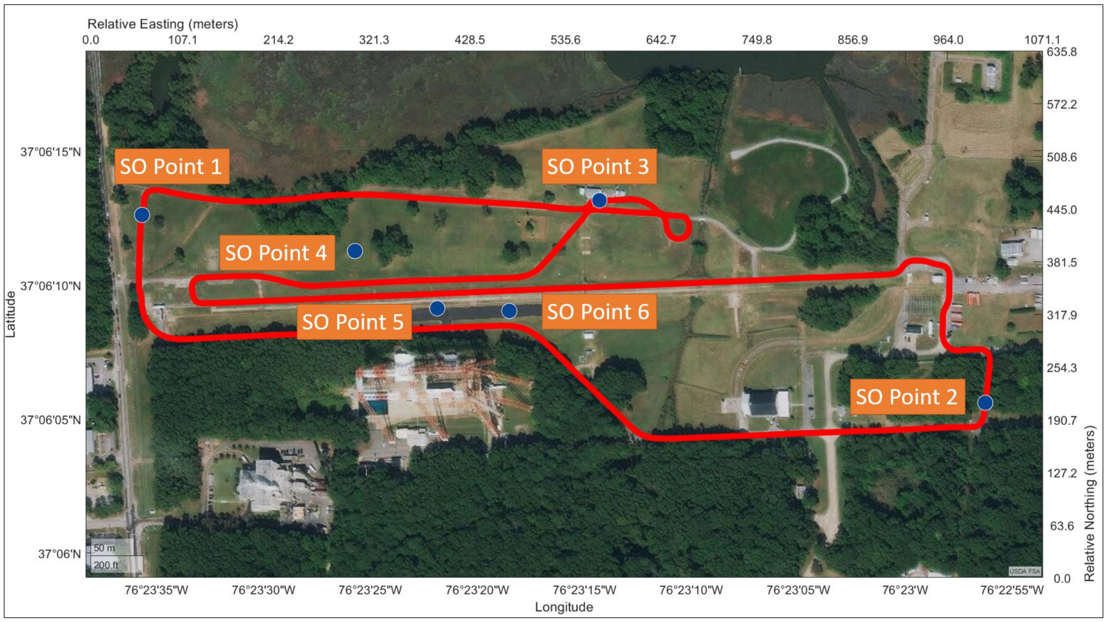


Figure 44. Dynamic Outdoor Positioning with Hold: General Route (LaRC)

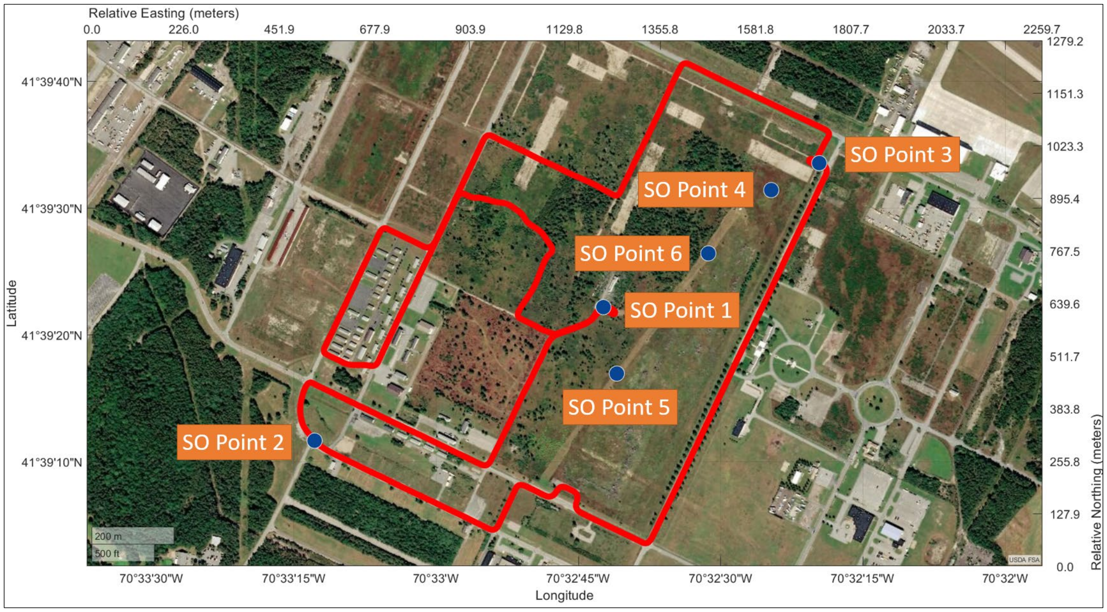


Figure 45. Dynamic Outdoor Positioning with Hold: General Route (JBCC)

Figure 46 is a sample graphic of the NextNav results for SO3 - Run 3.[31] The image on the left indicates the horizontal position error in meters. The image on the top right shows the horizontal position error distribution with a histogram (bars), the empirical cumulative distribution function (CDF) with a solid line, and the 95th percentile error with a dashed line. The image on the bottom right depicts the

[31] In this three-character notation, the first character, always S, stands for “static point”. The O signifies “outdoor”, and I, “indoor”. The third character, a number, is assigned to that unique point.

horizontal position error versus time with a solid line comprising time point markers, and the 95th percentile error with a dashed line.

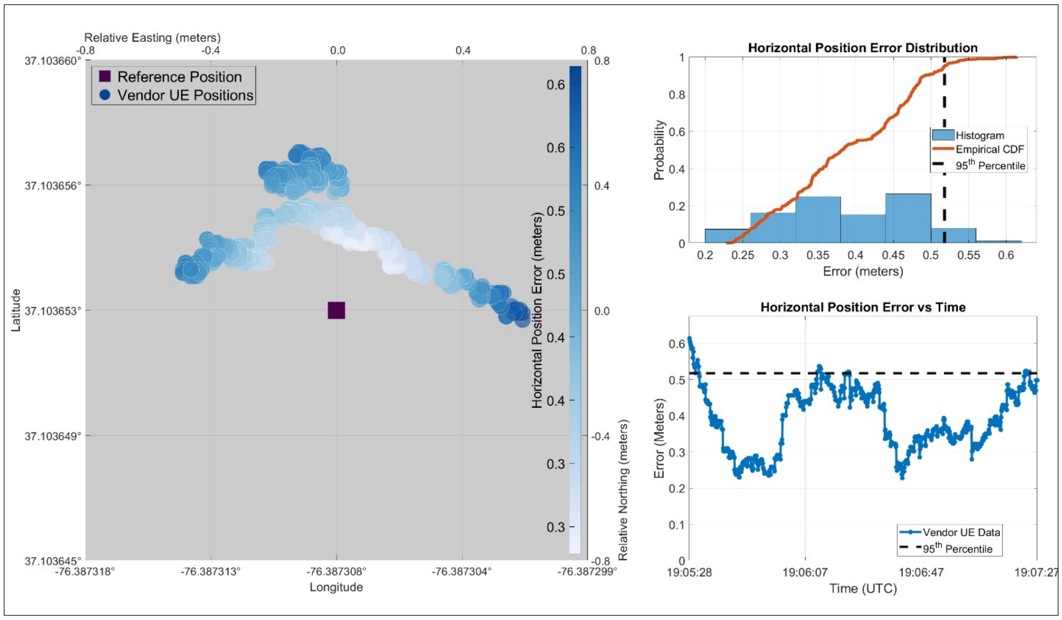


Figure 46. NextNav: Static 2-Minute Outdoor Hold Point 3 - Run 3

Table 22, Table 23, Table 24, Table 25, Table 26, and Table 27 each give the positioning results for a single vendor's UE, by static point and run, under the following parameters: mean error, 95th percentile, standard deviation, and maximum deviation of the error (all in meters); the demonstration duration; and the average update rate. If "no data" is the value in a field, it indicates that either the vendor UE failed to provide usable data or the data collected did not pass the data quality filter(s) specified by the vendor.

Table 22. NextNav Static 2-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point - Run 1	1.6	1.9	0.2	2.1	0:02:00	0.1
SO1 Point - Run 2	0.9	1.6	0.4	1.7	0:02:00	0.1
SO1 Point - Run 3	0.6	0.9	0.2	0.9	0:02:00	0.1
SO2 Point - Run 1	4.0	4.5	0.3	4.6	0:02:00	0.1
SO2 Point - Run 2	3.6	4.4	0.5	4.5	0:02:00	0.1
SO2 Point - Run 3	4.8	5.6	0.5	5.8	0:02:00	0.1
SO3 Point - Run 1	1.7	1.9	0.1	2.1	0:02:00	0.1
SO3 Point - Run 2	1.7	2.2	0.3	2.3	0:02:00	0.1
SO3 Point - Run 3	0.4	0.5	0.1	0.6	0:02:00	0.1
SO4 Point	3.6	3.8	0.2	3.9	0:02:00	0.1
SO5 Point	11.5	11.7	0.1	11.8	0:02:00	0.1
SO6 Point	15.2	15.3	0.1	15.4	0:02:00	0.1

See C.1.1.1 in Appendix C for corresponding figures.

Table 23. PhasorLab Static 2-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point - Run 1	0.8	0.8	0.0	0.9	0:02:00	1.0
SO1 Point - Run 2	1.1	1.2	0.1	1.3	0:02:00	1.0
SO1 Point - Run 3	0.9	1.0	0.0	1.1	0:02:00	1.0
SO2 Point - Run 1	7.6	11.7	2.9	12.4	0:02:00	1.0
SO2 Point - Run 2	4.7	6.6	0.9	7.2	0:02:00	1.0
SO2 Point - Run 3	4.2	5.8	0.7	6.2	0:02:00	1.0
SO3 Point - Run 1	2.3	2.4	0.1	2.4	0:02:00	1.0
SO3 Point - Run 2	2.2	2.2	0.0	2.3	0:02:00	1.0
SO3 Point - Run 3	2.0	2.6	0.4	3.3	0:02:00	1.0
SO4 Point	2.4	4.2	0.6	4.5	0:02:00	1.0
SO5 Point	1.2	1.3	0.1	1.9	0:02:00	1.0
SO6 Point	1.7	1.8	0.1	2.4	0:02:00	1.0

See C.1.1.2 in Appendix C for corresponding figures.

Table 24. Serco Static 2-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point - Run 1	No Data	No Data	No Data	No Data	0:02:00	No Data
SO1 Point - Run 2	No Data	No Data	No Data	No Data	0:02:00	No Data
SO1 Point - Run 3	25.9	35.2	5.2	38.6	0:02:00	1.0
SO2 Point - Run 1	No Data	No Data	No Data	No Data	0:02:00	No Data
SO2 Point - Run 2	No Data	No Data	No Data	No Data	0:02:00	No Data
SO2 Point - Run 3	1131.4	1150	12.2	1156.6	0:02:00	1.0
SO3 Point - Run 1	No Data	No Data	No Data	No Data	0:02:00	No Data
SO3 Point - Run 2	No Data	No Data	No Data	No Data	0:02:00	No Data
SO3 Point - Run 3	No Data	No Data	No Data	No Data	0:02:00	No Data
SO4 Point	No Data	No Data	No Data	No Data	0:02:00	No Data
SO5 Point	No Data	No Data	No Data	No Data	0:02:00	No Data
SO6 Point	No Data	No Data	No Data	No Data	0:02:00	No Data

See C.1.1.3 in Appendix C for corresponding figures.

Table 25. Skyhook RTT Static 2-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point - Run 1	1.7	2.3	0.5	2.4	0:02:00	1.1
SO1 Point - Run 2	1.6	2.3	0.7	6.8	0:02:00	1.1
SO1 Point - Run 3	1.8	2.1	0.3	3.3	0:02:00	1.1
SO2 Point - Run 1	5.3	5.4	0.3	5.4	0:02:00	1.1
SO2 Point - Run 2	6.4	6.6	0.8	7.6	0:02:00	1.1
SO2 Point - Run 3	6.6	7.6	0.2	7.6	0:02:00	1.1
SO3 Point - Run 1	0.6	1.1	0.2	1.2	0:02:00	1.2
SO3 Point - Run 2	1.1	4.2	2.3	14.8	0:02:00	1.1
SO3 Point - Run 3	1.1	2.1	0.5	2.4	0:02:00	1.1
SO4 Point	3.1	4.0	0.6	7.2	0:02:00	1.1
SO5 Point	1.5	1.4	2.4	25.3	0:02:00	1.1
SO6 Point	1.1	1.9	0.4	2.0	0:02:00	1.2

See C.1.1.4 in Appendix C for corresponding figures.

Table 26. Skyhook WPS Static 2-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point - Run 1	66.8	76.9	5.6	77.3	0:02:00	1.0
SO1 Point - Run 2	58.9	69.5	6.4	70.5	0:02:00	1.0
SO1 Point - Run 3	74.3	90.0	7.9	93.5	0:02:00	1.0
SO2 Point - Run 1	23.2	32.3	6.5	35.2	0:02:00	1.0
SO2 Point - Run 2	21.8	29.4	3.8	29.4	0:02:00	1.0
SO2 Point - Run 3	22.3	30.0	4.4	31.7	0:02:00	1.0
SO3 Point - Run 1	50.6	65.8	8.4	66.6	0:02:00	1.0
SO3 Point - Run 2	61.8	71.3	6.6	74.4	0:02:00	1.0
SO3 Point - Run 3	56.7	64.0	5.3	64.7	0:02:00	1.0
SO4 Point	18.9	31.0	6.8	34.5	0:02:00	1.0
SO5 Point	56.3	61.0	2.5	66.5	0:02:00	1.0
SO6 Point	83.1	101.1	10.8	106.0	0:02:00	1.0

See C.1.1.5 in Appendix C for corresponding figures.

Table 27. TRX Systems Static 2-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point - Run 1	2.4	2.8	0.3	4.4	0:02:00	0.5
SO1 Point - Run 2	3.1	3.1	0.0	3.1	0:02:00	0.5
SO1 Point - Run 3	3.5	3.6	0.0	3.6	0:02:00	0.5
SO2 Point - Run 1	9.0	9.7	1.0	9.8	0:02:00	0.5
SO2 Point - Run 2	6.1	8.7	2.0	8.8	0:02:00	0.5
SO2 Point - Run 3	3.3	3.4	0.0	3.4	0:02:00	0.5
SO3 Point - Run 1	3.4	3.5	0.2	3.6	0:02:00	0.5
SO3 Point - Run 2	3.7	3.8	0.0	3.8	0:02:00	0.5
SO3 Point - Run 3	4.2	4.2	0.0	4.2	0:02:00	0.5
SO4 Point	9.1	9.2	0.0	9.2	0:02:00	0.5
SO5 Point	5.8	5.8	0.0	5.8	0:02:00	0.5
SO6 Point	3.9	6.3	1.3	6.8	0:02:00	0.5

See C.1.1.6 in Appendix C for corresponding figures.

6.2.1.2 Dynamic Shape Route Results

The images for the shape dynamic routes at LaRC and JBCC are shown in Figure 47 and Figure 48. The segment routes for the two sites are those shown in Figure 45 and Figure 46, above.

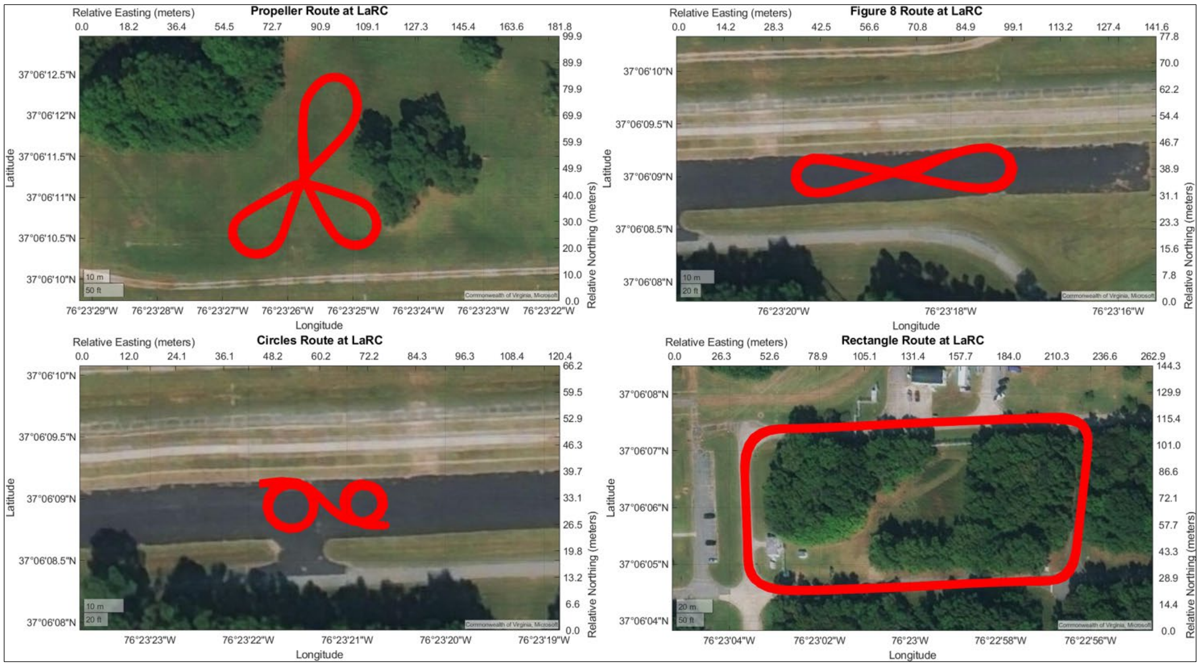


Figure 47. Dynamic Outdoor Positioning with Hold: Shape Routes (Clockwise: Propeller, Figure Eight, Rectangular, and Circular) (LaRC)

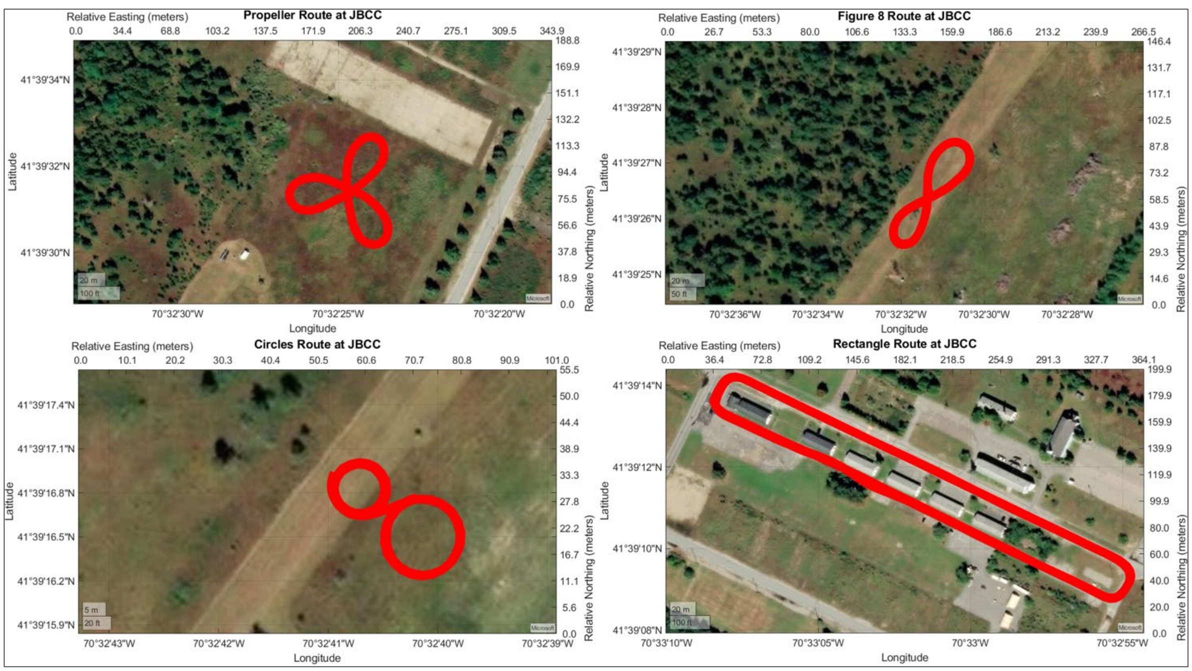


Figure 48. Dynamic Outdoor Positioning with Hold: Shape Routes (Clockwise: Propeller, Figure Eight, Rectangular, and Circular) (JBCC)

Sample figures for each of the dynamic route positioning results appear below. In each figure, the image on the left indicates the horizontal position error in meters. The image on the top right shows the horizontal position error distribution with a histogram (bars), the empirical cumulative distribution function with a solid line, and the 95th percentile error with a dashed line. The image on the bottom right depicts the horizontal position error broken down by the relative northing and relative easting components.

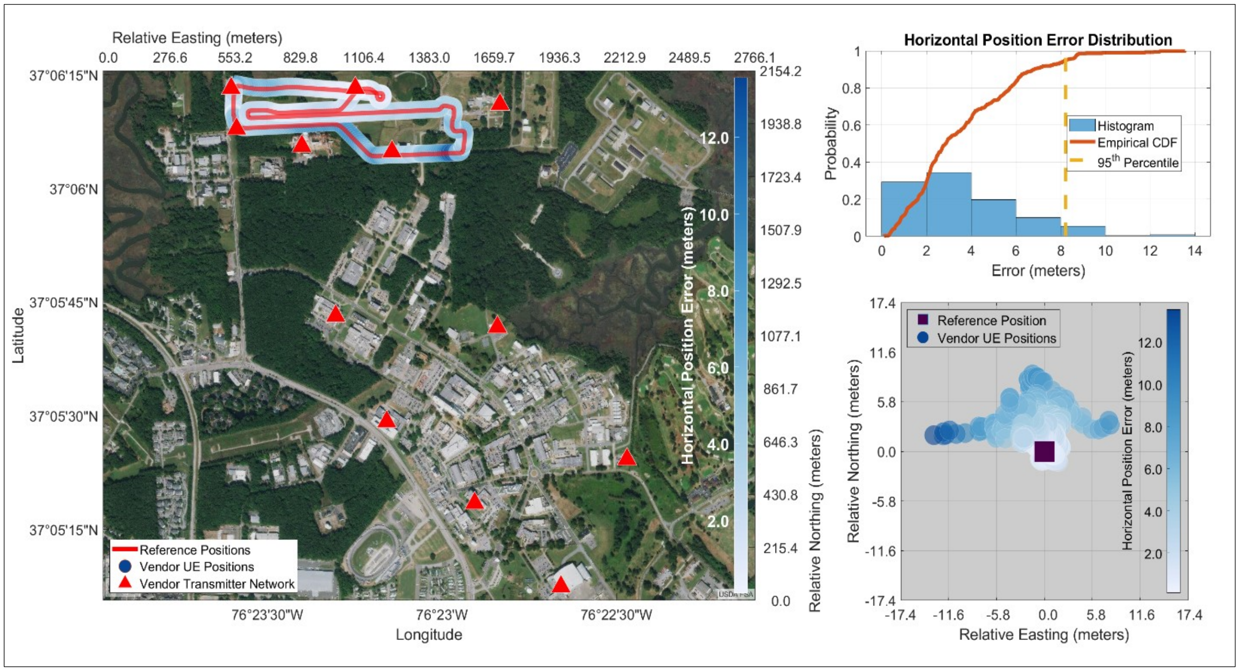


Figure 49. NextNav: Segment Route - Run 3

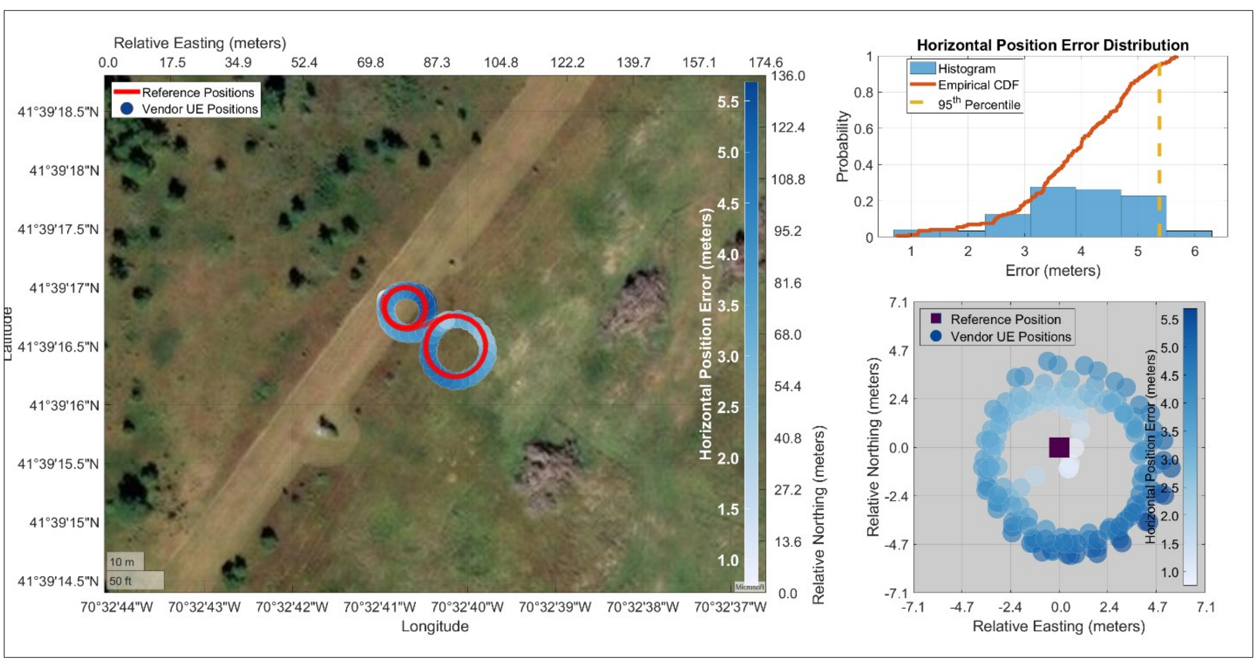


Figure 50. PhasorLab: Circles Route

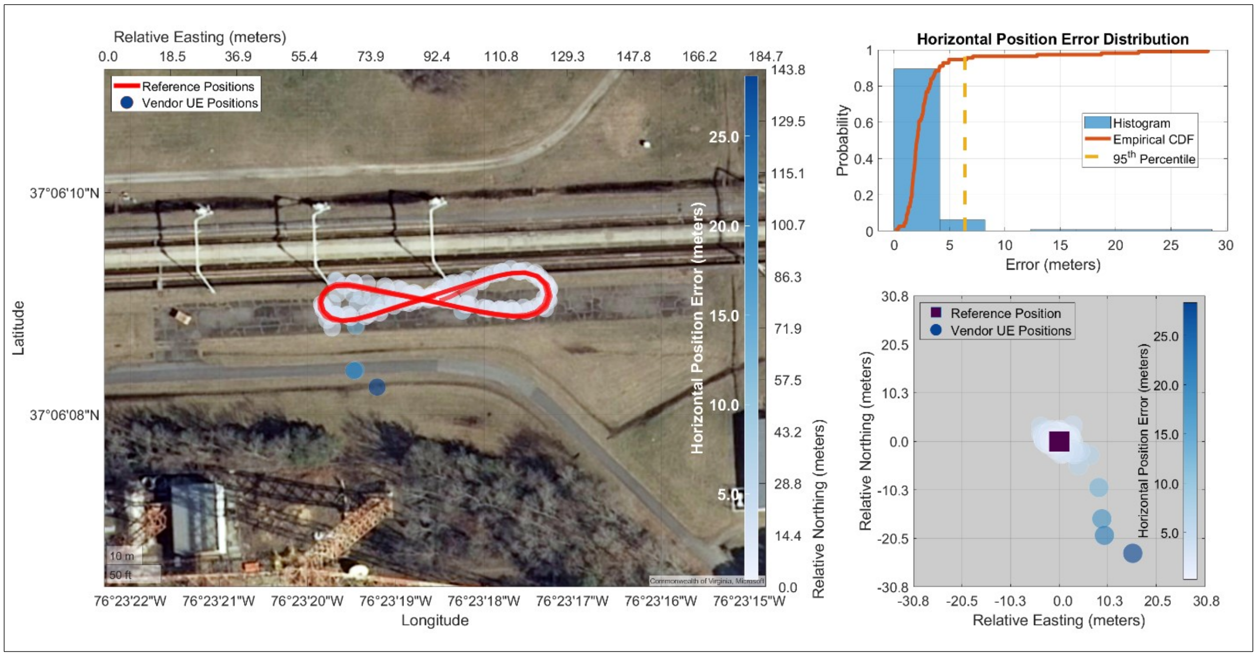


Figure 51. Skyhook RTT: Figure Eight Route

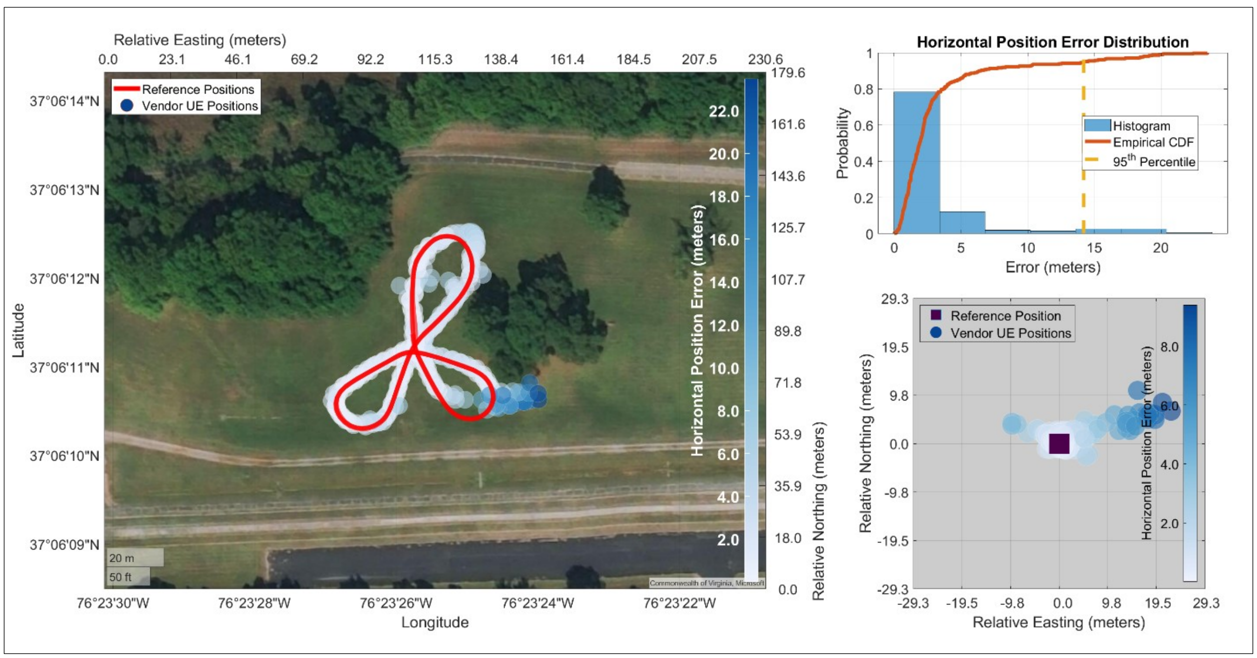


Figure 52. Skyhook RTT: Propeller Route

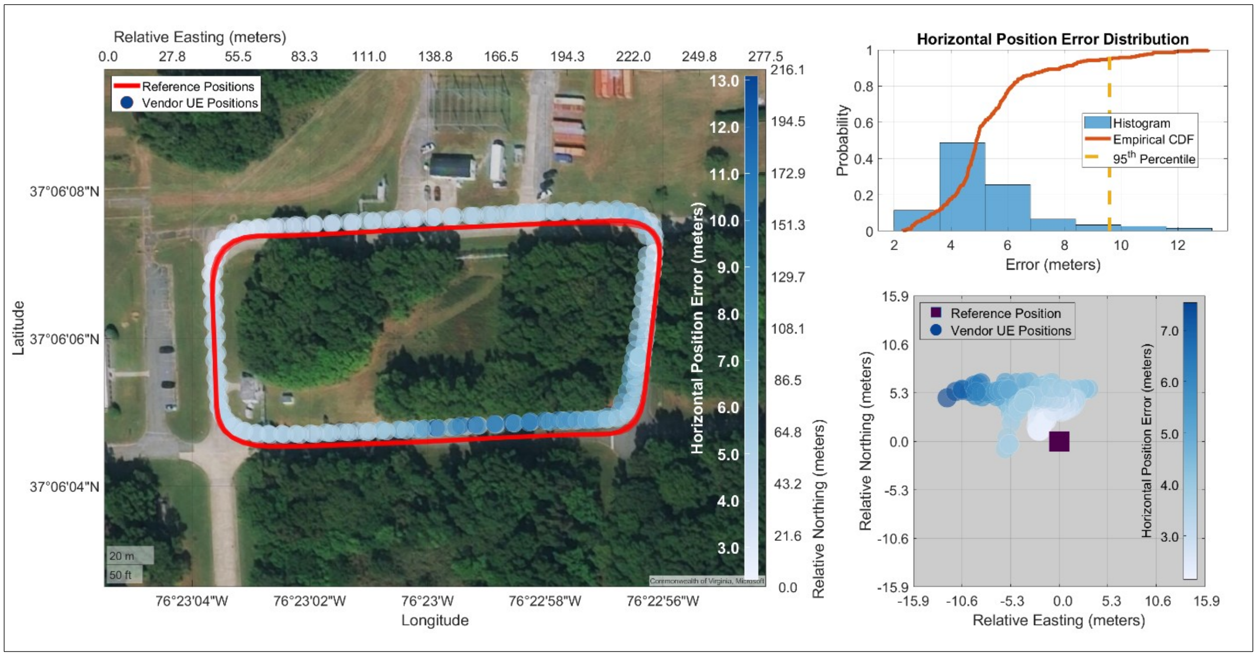


Figure 53. NextNav: Rectangle Route

Table 28, Table 29, Table 30, Table 31, and Table 32 each give the positioning results for a single vendor's UE for the shape dynamic routes. The results represent performance on three runs over the segment route, and one run each for the circular, figure eight, propeller, and rectangle routes under the following parameters: mean error, 95th percentile, standard deviation, and maximum deviation of the error (all in meters); the demonstration duration; and data availability. If "no data" is the value in a field, it indicates that either the vendor UE failed to provide usable data or the data collected did not pass the data quality filter(s) specified by the vendor.

Table 28. NextNav Dynamic Outdoor Routes: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Data Availability (percent)
Segment Route - Run 1	4.1	9.4	2.5	19.3	0:09:55	100.0
Segment Route - Run 2	4.3	9.0	2.7	18.1	0:10:37	100.0
Segment Route - Run 3	3.6	8.2	2.4	13.5	0:09:01	100.0
Circles Route	13.0	14.0	0.7	14.2	0:01:40	100.0
Figure Eight Route	13.9	15.6	1.0	16.0	0:01:52	100.0
Propeller Route	7.8	11.0	2.3	11.7	0:05:09	100.0
Rectangle Route	5.4	9.6	1.9	13.1	0:04:20	100.0

See C.1.2.1 in Appendix C for corresponding figures.

Table 29. PhasorLab Dynamic Outdoor Routes: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Data Availability (percent)
Segment Route - Run 1	13.6	27.0	8.0	34.2	0:16:40	100.0
Segment Route - Run 2	14.0	28.5	8.6	58.9	0:16:31	100.0
Segment Route - Run 3	15.4	29.2	13.5	135.1	0:16:28	100.0
Circles Route	3.9	5.4	1.1	5.7	0:02:24	100.0
Figure Eight Route	5.7	8.9	2.3	12.1	0:03:23	100.0
Propeller Route	5.8	8.4	1.8	9.5	0:05:10	100.0
Rectangle Route	13.3	22.6	5.8	26.4	0:05:56	100.0

See C.1.2.2 in Appendix C for corresponding figures.

Table 30. Serco Dynamic Outdoor Routes: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Data Availability (percent)
Segment Route - Run 1	No Data	No Data	No Data	No Data	0:16:40	0.0
Segment Route - Run 2	No Data	No Data	No Data	No Data	0:16:31	0.0
Segment Route - Run 3	548.9	1156.6	549.3	1180.2	0:16:28	2.2
Circles Route	No Data	No Data	No Data	No Data	0:02:24	0.0
Figure Eight Route	No Data	No Data	No Data	No Data	0:03:23	0.0
Propeller Route	No Data	No Data	No Data	No Data	0:05:10	0.0
Rectangle Route	No Data	No Data	No Data	No Data	0:05:56	0.0

See C.1.2.3 in Appendix C for corresponding figures.

Table 31. Skyhook RTT Dynamic Outdoor Routes: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Data Availability (percent)
Segment Route - Run 1	9.6	49.3	18.5	196.5	0:09:55	99.3
Segment Route - Run 2	7.4	31.6	12.2	88.7	0:10:37	99.4
Segment Route - Run 3	9.1	43.0	18.4	218.8	0:09:01	99.6
Circles Route	5.0	17.4	6.2	32.7	0:01:40	99.0
Figure Eight Route	3.0	6.4	3.7	28.4	0:01:52	99.1
Propeller Route	3.2	14.2	4.1	23.5	0:05:09	100.0
Rectangle Route	5.5	13.0	5.8	42.0	0:04:20	99.2

See C.1.2.4 in Appendix C for corresponding figures.

Table 32. Skyhook WPS Dynamic Outdoor Routes: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Data Availability (percent)
Segment Route - Run 1	48.5	97.1	26.7	136.5	0:09:55	90.3
Segment Route - Run 2	46.5	88.8	23.6	125.9	0:10:37	89.2
Segment Route - Run 3	50.7	101.7	28.6	156.3	0:09:01	88.6
Circles Route	44.2	86.1	23.5	107.5	0:01:40	81.2
Figure Eight Route	65.2	101.0	26.8	104.1	0:01:52	93.8
Propeller Route	31.4	57.6	14.8	69.0	0:05:09	92.3
Rectangle Route	34.6	62.5	16.7	88.4	0:04:20	85.8

See C.1.2.5 in Appendix C for corresponding figures.

6.2.2 Scenario 3: Static Outdoor Positioning

Scenario 3: Static Outdoor Positioning was developed to assess the long-term availability, accuracy, and stability of the static positioning solution. Data were collected continuously for 60 minutes at each of three surveyed static points, SO1, SO2, and SO3, which are shown in Figure 45 and Figure 46, above. The vendor participants in this scenario were Echo Ridge, NextNav, PhasorLab, Satelles, Serco, Skyhook, and TRX Systems. (See section 5.8.1.2 for the description of how this scenario was implemented.)

Figure 54 presents as an example the Skyhook RTT SO3 positioning results. The image on the left indicates the horizontal position error in meters. The image on the top right shows the horizontal position error distribution as a histogram, the empirical CDF with a solid line, and the 95th percentile error with a dashed line. The image on the bottom right depicts the horizontal position error versus time as a solid line with time point markers, and the 95th percentile error as a dashed line.

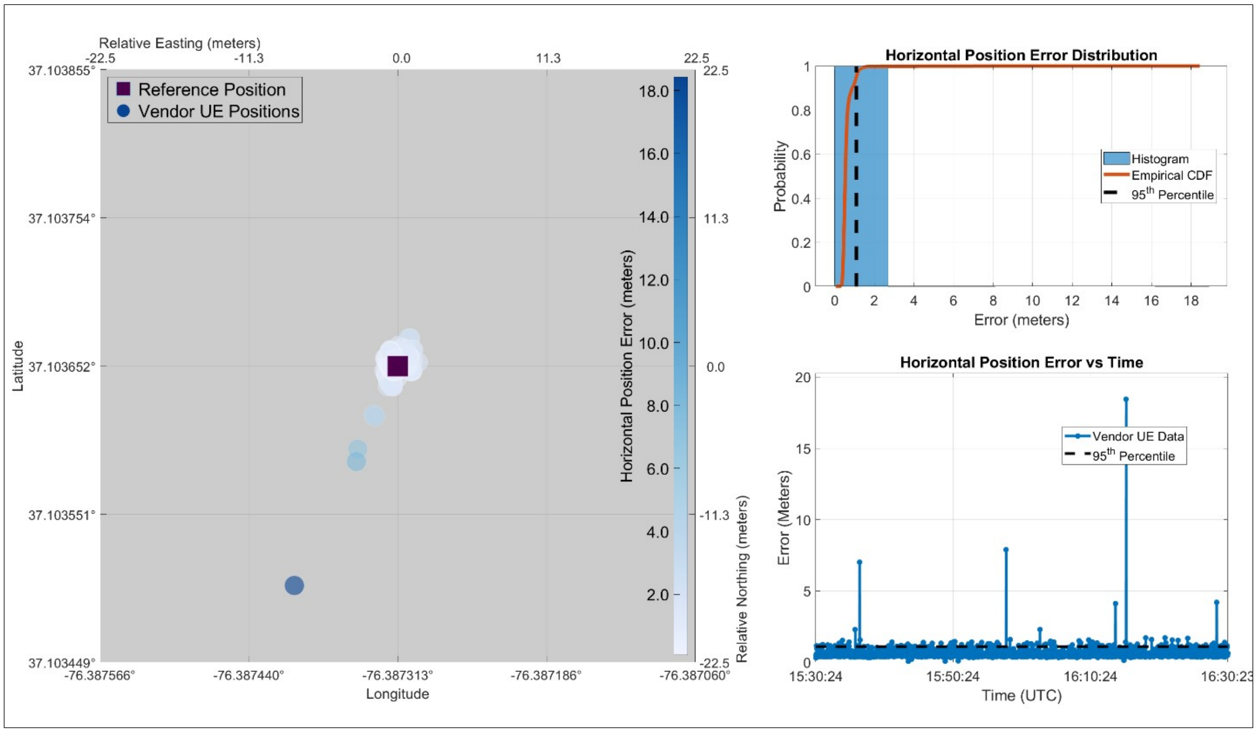


Figure 54. Skyhook RTT: Static 60-Minute Outdoor Point 3 (SO3)

The tables below each give the positioning results for a single vendor's UE for the static 60-minute outdoor hold at points SO1, SO2, and SO3. The results represent UE performance under the following parameters: mean error, 95th percentile, standard deviation, and maximum deviation of the error (all in meters); the demonstration duration; and the average update rate. If "no data" is the value in a field, it indicates that either the vendor UE failed to provide usable data or the data collected did not pass the data quality filter(s) specified by the vendor.

Table 33. Echo Ridge Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	105.2	246.0	69.3	364.1	1:00:00	7.3
SO2 Point	184.0	333.2	124.7	541.9	1:00:00	10.5
SO3 Point	116.5	255.8	83.3	365.9	1:00:00	6.3

See C.2.1.1 in Appendix C for corresponding figures.

Table 34. NextNav Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	3.3	4.4	0.7	5.5	1:00:00	0.1
SO2 Point	4.8	6.7	1.1	9.2	1:00:00	0.1
SO3 Point	3.9	5.5	1.6	18.2	1:00:00	0.1

See C.2.1.2 in Appendix C for corresponding figures.

Table 35. PhasorLab Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	0.9	1.0	0.1	1.5	1:00:00	1.0
SO2 Point	4.5	7.4	1.5	10.3	1:00:00	1.0
SO3 Point	2.1	2.2	0.1	3.1	1:00:00	1.0

See C.2.1.3 in Appendix C for corresponding figures.

Table 36. Satelles EVK2-OCXO Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	23.3	27.6	3.8	27.9	1:00:00	1.0
SO2 Point	20.1	26.9	2.5	30.4	1:00:00	1.0
SO3 Point	30.9	38.3	4.3	40.6	1:00:00	1.0

See C.2.1.4 in Appendix C for corresponding figures.

Table 37. Serco Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	No Data	No Data	No Data	No Data	1:00:00	No Data
SO2 Point	17.7	39.4	10.5	50.8	1:00:00	1.0
SO3 Point	No Data	No Data	No Data	No Data	1:00:00	No Data

See C.2.1.5 in Appendix C for corresponding figures.

Table 38. Skyhook RTT Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	1.1	1.8	0.7	24.0	1:00:00	1.1
SO2 Point	0.7	1.5	0.7	6.5.0	1:00:00	1.1
SO3 Point	0.6	1.1	0.4	18.4	1:00:00	1.1

See C.2.1.6 in Appendix C for corresponding figures.

Table 39. Skyhook WPS Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	58.7	66.1	6.0	88.9	1:00:00	1.0
SO2 Point	19.4	27.9	4.6	39.3	1:00:00	1.0
SO3 Point	35.4	61.3	15.8	75.2	1:00:00	1.0

See C.2.1.7 in Appendix C for corresponding figures.

Table 40. TRX Systems Static 60-Minute Outdoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SO1 Point	6.1	6.2	0.1	6.2	1:00:00	0.5
SO2 Point	2.7	2.8	0.0	2.8	1:00:00	0.5
SO3 Point	3.5	3.5	0.1	3.6	1:00:00	0.5

See C.2.1.8 in Appendix C for corresponding figures.

6.2.3 Scenario 5: Static Indoor Positioning

Scenario 5: Static Indoor Positioning was designed to assess the availability and accuracy of vendor UEs under specified GPS-challenged conditions, as exemplified by an indoor environment. It comprised 1) three runs of 2-minute holds at five static points (SI1, SI2, SI3, SI4, and SI5); and 2) one 60-minute data collection at each of three of those same static points (SI1, SI3, and SI5). No vendors that had been assigned JBCC elected to participate in this scenario; the locations of the five static points used in this scenario at LaRC are shown in Figure 55, below. (See section 5.8.1.3 for the description of how this scenario was implemented.) The vendor participants in this scenario were NextNav, Skyhook (RTT and WPS), and TRX Systems.

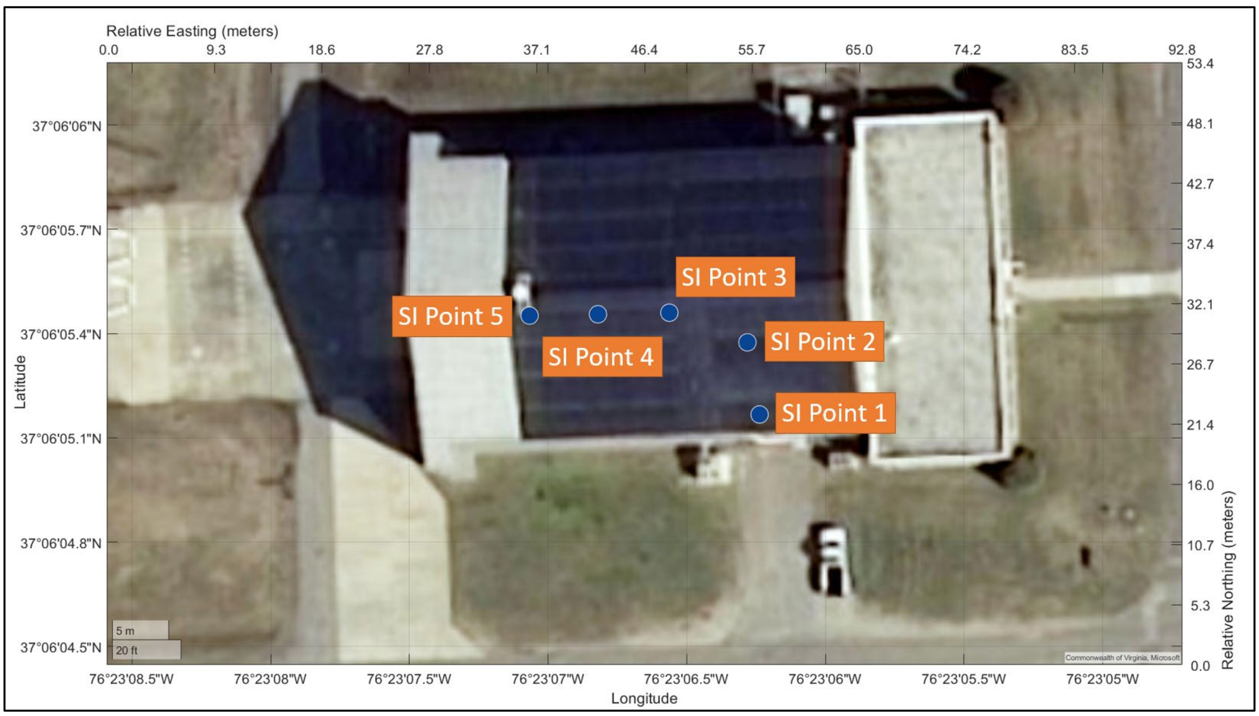


Figure 55. Scenario 5 Static Indoor Positioning Static Points (Building 1262, LaRC)

6.2.3.1 Static Indoor Positioning: Static 2-Minute Hold Results

Figure 56 presents as an example the NextNav static indoor point 4 (SI4) - Run 1 positioning results. The image on the left indicates the horizontal position error in meters. The image on the top right shows the horizontal position error distribution as a histogram, the empirical CDF as a solid line, and the 95th percentile error as a dashed line. The image on the bottom right depicts the horizontal position error versus time as a solid line with time point markers, and the 95th percentile error as a dashed line.

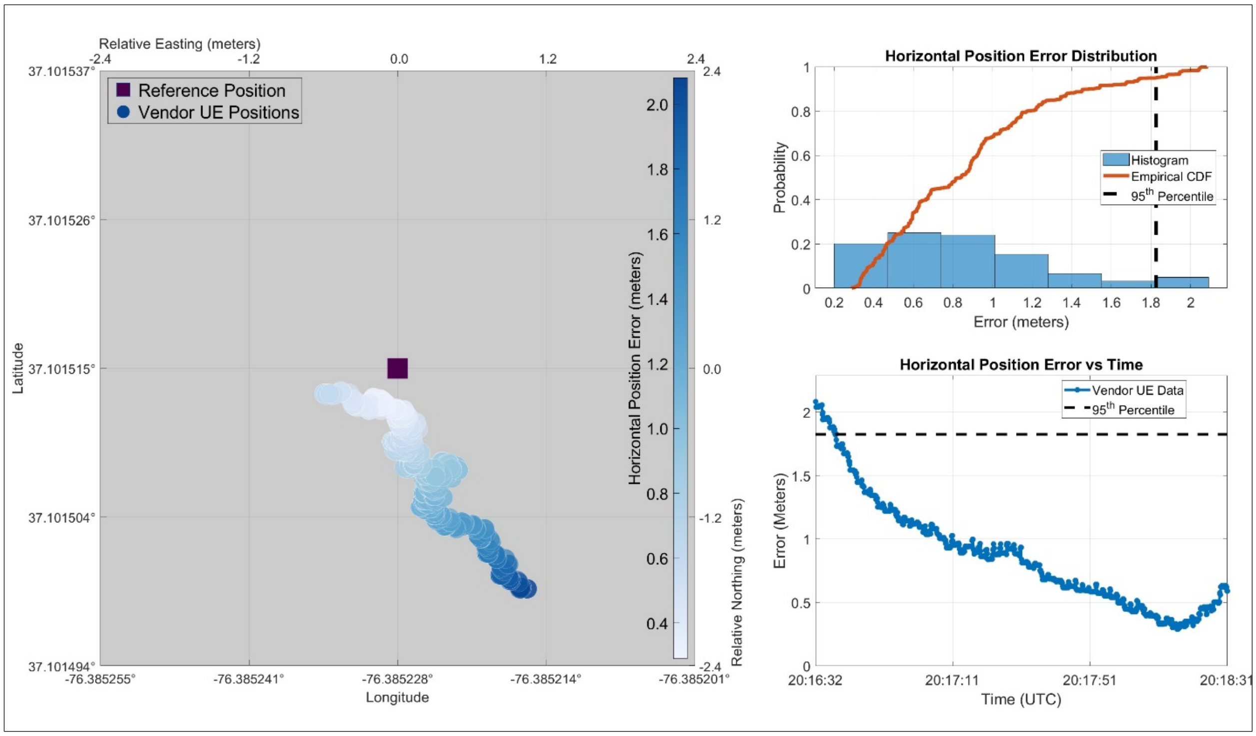


Figure 56. NextNav: Static 2-Minute Indoor Hold Point 4 - Run 1

Table 41, Table 42, Table 43, and Table 44 each give the positioning results for a single vendor's UE for the static 2-minute indoor hold at points SI1 through SI5. The results represent UE performance under the following parameters: mean error, 95th percentile, standard deviation, and maximum deviation of the error (all in meters); the demonstration duration; and the average UE position update rate.

Table 41. NextNav Static 2-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1 Hold - Run 1	6.9	8.7	1.3	8.8	0:02:00	0.1
SI1 Hold - Run 2	8.1	8.9	0.7	9.0	0:02:00	0.1
SI1 Hold - Run 3	7.3	8.5	0.9	8.7	0:02:00	0.1
SI2 Hold - Run 1	6.3	7.8	0.7	8.1	0:02:00	0.1
SI2 Hold - Run 2	6.2	7.4	0.6	7.8	0:02:00	0.1
SI2 Hold - Run 3	5.5	6.2	0.3	6.4	0:02:00	0.1
SI3 Hold - Run 1	2.7	3.4	0.7	3.4	0:02:00	0.1
SI3 Hold - Run 2	1.9	2.5	0.4	2.5	0:02:00	0.1
SI3 Hold - Run 3	3.3	3.6	0.1	3.7	0:02:00	0.1
SI4 Hold - Run 1	0.9	1.8	0.4	2.1	0:02:00	0.1
SI4 Hold - Run 2	1.0	2.6	0.7	2.8	0:02:00	0.1
SI4 Hold - Run 3	2.6	3.4	0.4	3.6	0:02:00	0.1
SI5 Hold - Run 1	5.2	7.6	1.7	7.8	0:02:00	0.1
SI5 Hold - Run 2	5.0	7.0	1.3	7.2	0:02:00	0.1
SI5 Hold - Run 3	5.5	7.4	1.3	7.5	0:02:00	0.1

See C.3.1.1 in Appendix C for corresponding figures.

Table 42. Skyhook RTT Static 2-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1 Hold - Run 1	10.9	12.7	2.3	26.7	0:02:00	1.2
SI1 Hold - Run 2	7.8	17.4	4.3	29.8	0:02:00	1.2
SI1 Hold - Run 3	12.1	12.5	0.7	12.6	0:02:00	1.2
SI2 Hold - Run 1	6.4	8.8	1.9	9.8	0:02:00	1.2
SI2 Hold - Run 2	6.8	9.8	1.8	18.1	0:02:00	1.2
SI2 Hold - Run 3	10.0	11.6	1.3	12.6	0:02:00	1.2
SI3 Hold - Run 1	13.5	14.3	0.6	14.9	0:02:00	1.2
SI3 Hold - Run 2	13.5	14.3	0.5	14.3	0:02:00	1.2
SI3 Hold - Run 3	14.1	14.3	0.2	14.3	0:02:00	1.2
SI4 Hold - Run 1	4.5	5.6	0.7	6.4	0:02:00	1.2
SI4 Hold - Run 2	8.6	19.0	6.7	19.0	0:02:00	1.2
SI4 Hold - Run 3	12.4	21.1	7.5	23.0	0:02:00	1.2
SI5 Hold - Run 1	15.9	20.9	4.7	23.0	0:02:00	1.2
SI5 Hold - Run 2	22.9	23.0	0.2	23.0	0:02:00	1.2
SI5 Hold - Run 3	22.7	23.5	0.6	24.0	0:02:00	1.2

See C.3.1.2 in Appendix C for corresponding figures.

Table 43. Skyhook WPS Static 2-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1 Hold - Run 1	28.5	31.5	2.8	32.2	0:02:00	1.0
SI1 Hold - Run 2	22.4	28.7	4.4	29.9	0:02:00	1.0
SI1 Hold - Run 3	31.7	34.0	1.7	35.5	0:02:00	1.0
SI2 Hold - Run 1	22.2	26.6	2.2	27.1	0:02:00	1.0
SI2 Hold - Run 2	26.1	28.8	1.6	29.2	0:02:00	1.0
SI2 Hold - Run 3	23.1	26.1	2.9	27.4	0:02:00	1.0
SI3 Hold - Run 1	13.2	19.0	2.6	21.0	0:02:00	1.0
SI3 Hold - Run 2	13.6	18.2	2.5	24.9	0:02:00	1.0
SI3 Hold - Run 3	14.0	17.3	1.7	18.9	0:02:00	1.0
SI4 Hold - Run 1	32.8	34.7	2.1	35.6	0:02:00	1.0
SI4 Hold - Run 2	27.2	32.4	6.1	32.8	0:02:00	1.0
SI4 Hold - Run 3	21.7	30.5	5.5	30.9	0:02:00	1.0
SI5 Hold - Run 1	24.7	34.6	9.4	35.5	0:02:00	1.0
SI5 Hold - Run 2	16.1	23.9	3.8	25.4	0:02:00	1.0
SI5 Hold - Run 3	16.2	21.2	3.0	23.9	0:02:00	1.0

See C.3.1.3 in Appendix C for corresponding figures.

Table 44. TRX Systems Static 2-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1 Hold - Run 1	5.7	5.8	0.1	5.8	0:02:00	0.5
SI1 Hold - Run 2	7.5	9.3	1.1	9.3	0:02:00	0.5
SI1 Hold - Run 3	5.7	6.1	0.5	6.1	0:02:00	0.5
SI2 Hold - Run 1	2.9	2.9	0.0	3.4	0:02:00	0.5
SI2 Hold - Run 2	9.8	9.8	0.0	9.8	0:02:00	0.5
SI2 Hold - Run 3	8.9	8.9	0.0	8.9	0:02:00	0.5
SI3 Hold - Run 1	3.3	3.4	0.1	3.9	0:02:00	0.5
SI3 Hold - Run 2	7.4	7.7	0.1	8.0	0:02:00	0.5
SI3 Hold - Run 3	1.3	1.3	0.0	1.4	0:02:00	0.5
SI4 Hold - Run 1	2.6	7.3	2.0	8.8	0:02:00	0.5
SI4 Hold - Run 2	5.6	6.6	0.4	7.2	0:02:00	0.5
SI4 Hold - Run 3	3.2	3.2	0.0	3.2	0:02:00	0.5
SI5 Hold - Run 1	2.9	3.7	0.4	4.2	0:02:00	0.5
SI5 Hold - Run 2	1.5	2.1	0.6	2.8	0:02:00	0.5
SI5 Hold - Run 3	2.6	4.1	0.7	4.4	0:02:00	0.5

See C.3.1.4 in Appendix C for corresponding figures.

6.2.3.2 Static Indoor Positioning: Static 60-Minute Collection Results

Figure 57 shows the data collected over 60 minutes from the TRX Systems UE at Static Indoor Point 5 (SI5). The image on the left indicates the horizontal position error in meters. The image on the top right shows the horizontal position error distribution as a histogram, the empirical CDF as a solid line, and the 95th percentile error as a dashed line. The image on the bottom right depicts the horizontal position error versus time as a solid line with time point markers, and the 95th percentile error as a dashed line.

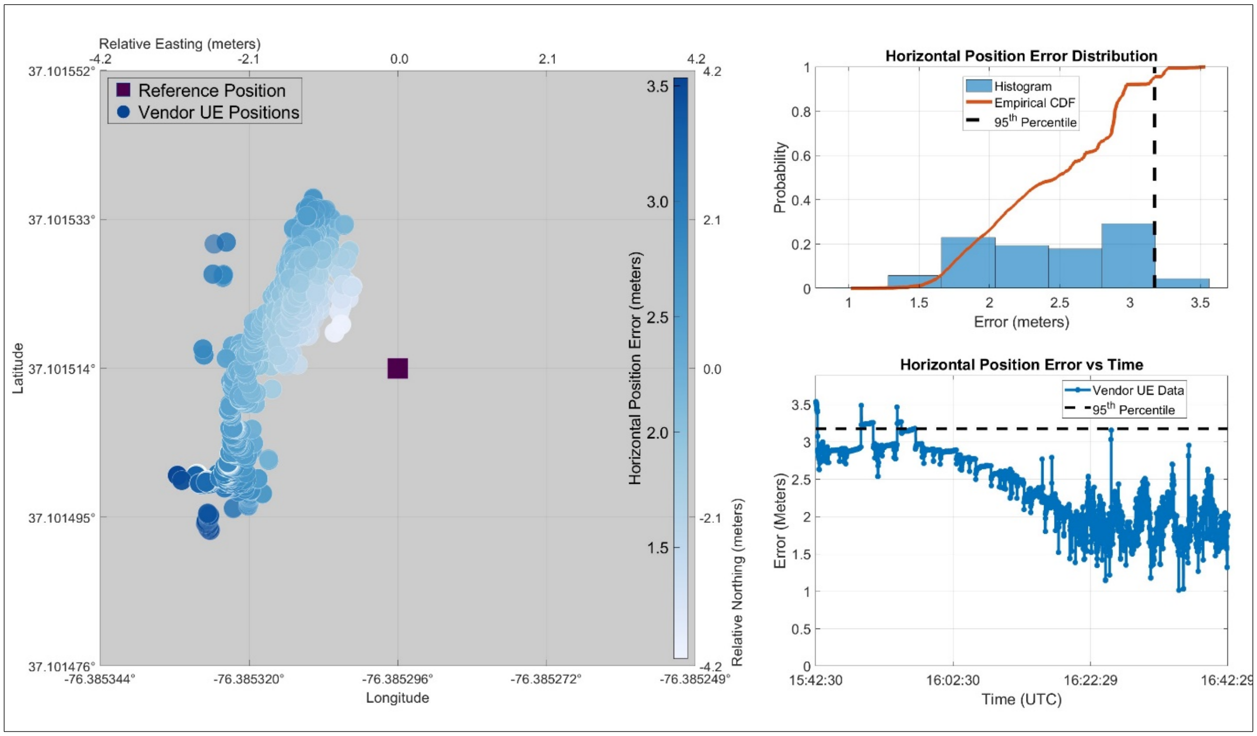


Figure 57. TRX Systems: Static 60-Minute Indoor Point 5 (SI5)

Table 45, Table 46, Table 47, and Table 48 give the positioning results for a single vendor's UE for the static 60-minute indoor hold at points SI1, SI2, and SI3. The results represent UE performance under the following parameters: mean error, 95th percentile, standard deviation, and maximum deviation of the error (all in meters); the demonstration duration; and average update rate.

Table 45. NextNav Static 60-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1	6.3	13.5	3.5	23.4	1:00:00	0.1
SI3	8.5	13.4	2.7	21.4	1:00:00	0.1
SI5	56.3	67.0	11.8	72.3	1:00:00	0.1

See C.3.2.1 in Appendix C for corresponding figures.

Table 46. Skyhook RTT Static 60-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1	7.7	8.1	0.6	9.5	1:00:00	1.2
SI3	11.8	12.5	0.6	15.2	1:00:00	1.2
SI5	13.8	17.8	2.7	18.3	1:00:00	1.2

See C.3.2.2 in Appendix C for corresponding figures.

Table 47. Skyhook WPS Static 60-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1	11.9	22.1	5.8	34.7	1:00:00	1.0
SI3	19.9	23.9	2.7	28.7	1:00:00	1.0
SI5	34.9	39.5	3.2	52.0	1:00:00	1.0

See C.3.2.3 in Appendix C for corresponding figures.

Table 48. TRX Systems Static 60-Minute Indoor Hold: Positioning Results

Collection	Mean Error (meters)	95th Percentile (meters)	Standard Deviation (meters)	Max Deviation (meters)	Demo Duration (H:MM:SS)	Average Update Rate (seconds)
SI1	5.5	5.6	0.0	5.6	1:00:00	0.5
SI3	3.4	3.6	0.5	3.6	1:00:00	0.5
SI5	2.4	3.2	0.5	3.5	1:00:00	0.5

See C.3.2.4 in Appendix C for corresponding figures.

6.2.4 Scenario 8: 3D Positioning

Scenario 8: 3D Positioning was designed to assess the coverage, availability, and accuracy of positioning systems with more complex dynamics and height changes such as experienced in UAS flight. UEs were placed and flown on a UAS platform. The scenario comprised 1) data collection during 1-minute static holds at each of three points, SO1, SO4, and SO6, on the ground and then on a table; and 2) data collection at various altitudes while the UAS followed each of two routes—a polygon and a propeller route—that introduced dynamically complex additional variables. (See section 5.8.1.4 for a description of scenario implementation.) The vendor participants in this demonstration scenario were NextNav, PhasorLab, and Skyhook (RTT only).

Figure 58 and Figure 59 below show the layouts for this scenario at LaRC and JBCC.

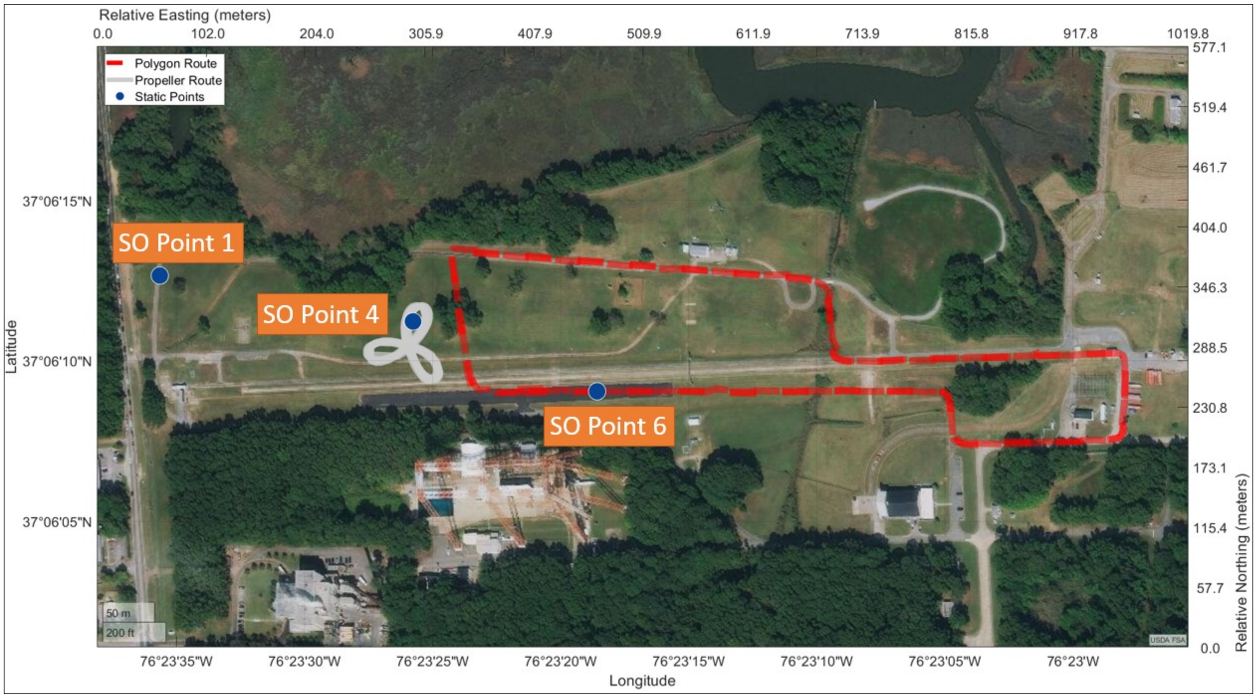


Figure 58. Scenario 8: 3D Positioning Demonstration Layout (LaRC)

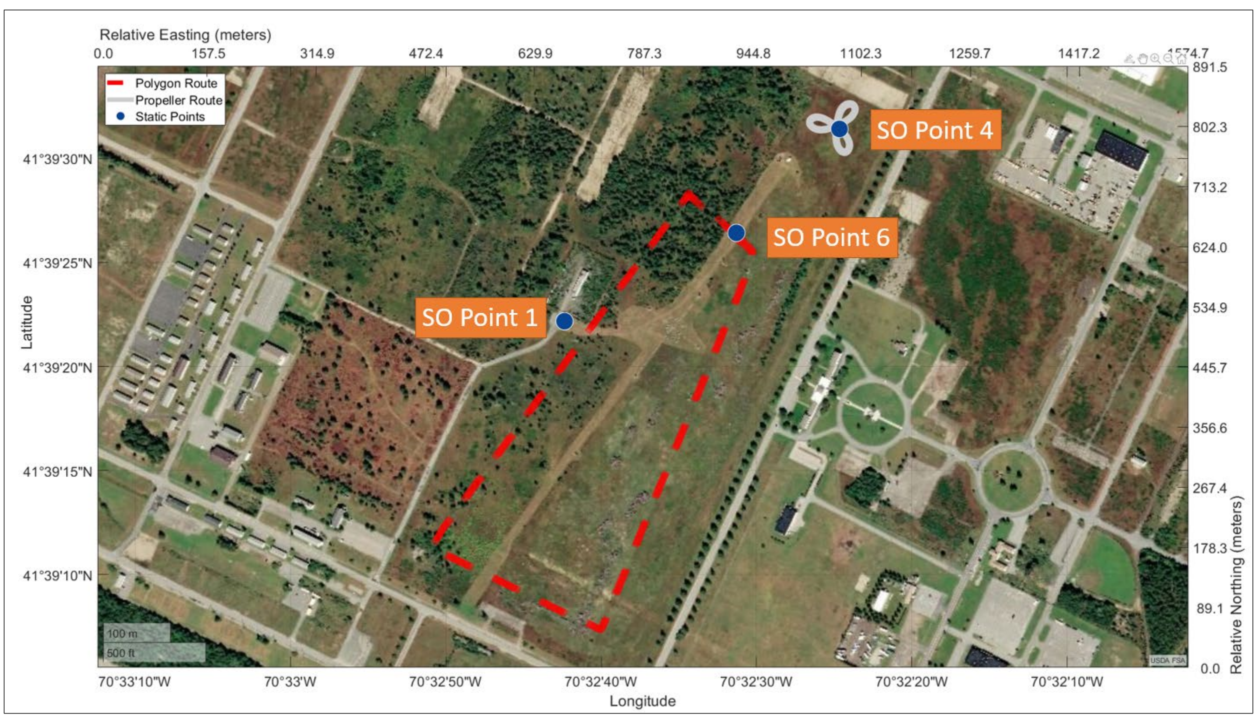


Figure 59. Scenario 8: 3D Positioning Demonstration Layout (JBCC)

6.2.4.1 *Scenario 8: 3D 1-Minute Static Hold Results*

Figure 60 below shows the 3D 1-minute, static point 6, ground hold positioning results for the Skyhook UE RTT protocol. The image on the left indicates the horizontal position error in meters. The image on the top right shows the horizontal position error distribution as a histogram, the empirical CDF as a solid line, and the 95th percentile error as a dashed line. The image on the bottom right depicts the horizontal position error versus time as a solid line with time point markers, and the 95th percentile error as a dashed line.

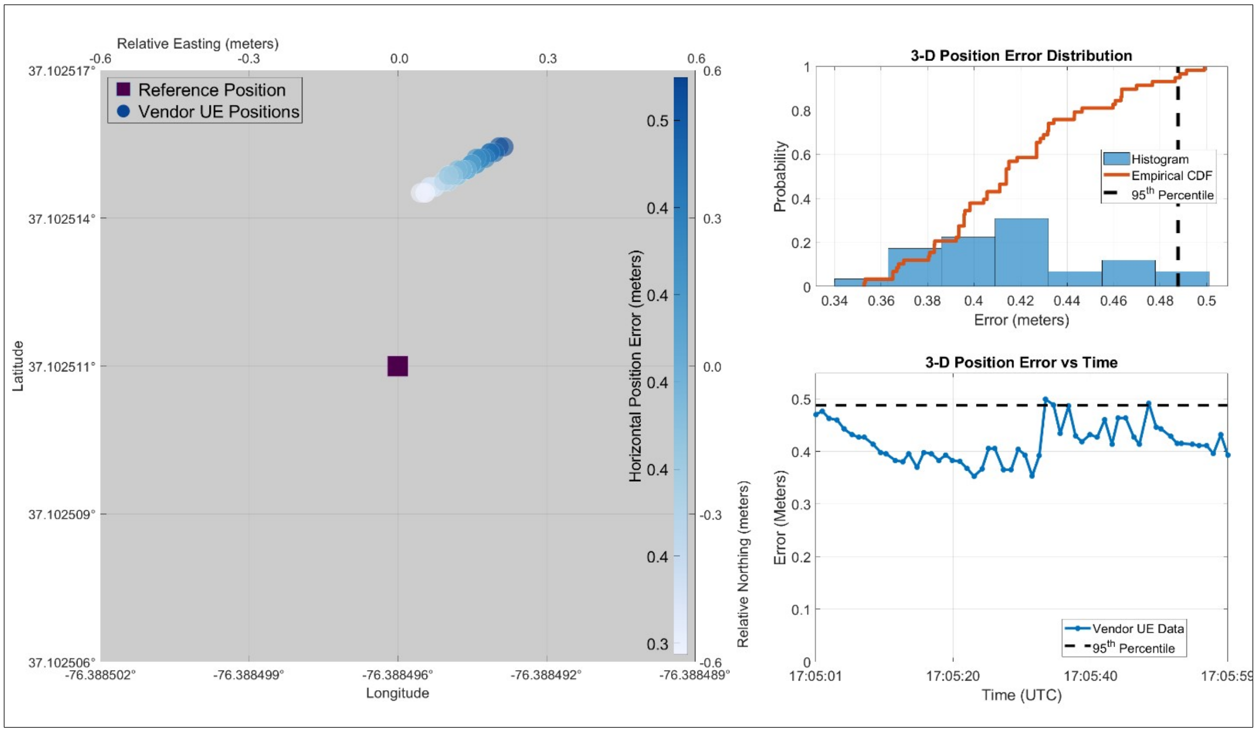


Figure 60. Skyhook RTT: 3D Static 1-Minute Hold Point SO6 – Ground

Table 49, Table 50, and Table 51 each give the positioning results for a single vendor's UE for the 3D static 1-minute outdoor hold at points SO1, SO4, and SO6. The results represent UE performance under the following parameters: mean error, 95th percentile, standard deviation, and maximum deviation of the error (all in meters); the demonstration duration; and 3D data availability. If "No Data" is the value in a field, it indicates that either the vendor UE failed to provide usable data or the data collected did not pass the data quality filter(s) specified by the vendor.

Table 49. NextNav 3D 1-Minute Static Hold: Positioning Results

Collection	Mean Height Error (meters)	Height Error Standard Deviation (meters)	3D Mean Error (meters)	3D Standard Deviation (meters)	Demo Duration (H:MM:SS)	3D Data Availability (percent)
SO1 Ground Hold	1.7	0.2	6.7	1.2	0:01:00	100.0
SO1 Table Hold	2.6	0.1	10.0	1.6	0:01:00	100.0
SO4 Ground Hold	1.2	0.1	3.9	0.6	0:01:00	100.0
SO4 Table Hold	2.6	0.2	10.9	0.9	0:01:00	100.0
SO6 Ground Hold	1.4	0.1	7.9	0.9	0:01:00	100.0
SO6 Table Hold	1.7	0.2	9.3	1.2	0:01:00	100.0

See C.4.1.1 in Appendix C for corresponding figures.

Table 50. PhasorLab 3D 1-Minute Static Hold: Positioning Results

Collection	Mean Height Error (meters)	Height Error Standard Deviation (meters)	3D Mean Error (meters)	3D Standard Deviation (meters)	Demo Duration (H:MM:SS)	3D Data Availability (percent)
SO1 Ground Hold	No Data	No Data	No Data	No Data	0:01:00	0.0
SO1 Table Hold	No Data	No Data	No Data	No Data	0:01:00	0.0
SO4 Ground Hold	No Data	No Data	No Data	No Data	0:01:00	0.0
SO4 Table Hold	No Data	No Data	No Data	No Data	0:01:00	0.0
SO6 Ground Hold	No Data	No Data	No Data	No Data	0:01:00	0.0
SO6 Table Hold	No Data	No Data	No Data	No Data	0:01:00	0.0

See C.4.1.2 in Appendix C for corresponding figures.

Table 51. Skyhook RTT 3D 1-Minute Static Hold: Positioning Results[32]

Collection	Mean Height Error (meters)	Height Error Standard Deviation (meters)	3D Mean Error (meters)	3D Standard Deviation (meters)	Demo Duration (H:MM:SS)	3D Data Availability (percent)
SO1 Ground Hold	0.2	0.1	1.9	0.0	0:01:00	91.7
SO1 Table Hold	0.2	0.1	3.3	0.0	0:01:00	91.7
SO4 Ground Hold	0.2	0.1	57.1	0.0	0:01:00	85.0
SO4 Table Hold	0.1	0.2	0.9	0.4	0:01:00	86.7
SO6 Ground Hold	0.1	0.1	1.9	0.0	0:01:00	85.0
SO6 Table Hold	-0.1	0.1	1.7	1.1	0:01:00	76.7

See C.4.1.3 in Appendix C for corresponding figures.

6.2.4.2 Scenario 8: 3D Dynamic Routes

Figures 61 and 62 present the NextNav results, as examples, for the polygon route at 100-ft altitude and for the overall propeller route. In each figure, the top left image shows the horizontal position error from a top view. The bottom left image shows a 3D view of the route with the UE height error. The image on top right shows the 3D position error distribution with a histogram, empirical cumulative distribution function with a solid line, and the 95th percentile error with a dashed line. The image on the bottom right depicts the 3D position error with dot intensity broken down by relative northing and relative easting component axes.

[32] Height data provided by the Skyhook UE was offset using reference position height information at the beginning of each scenario.

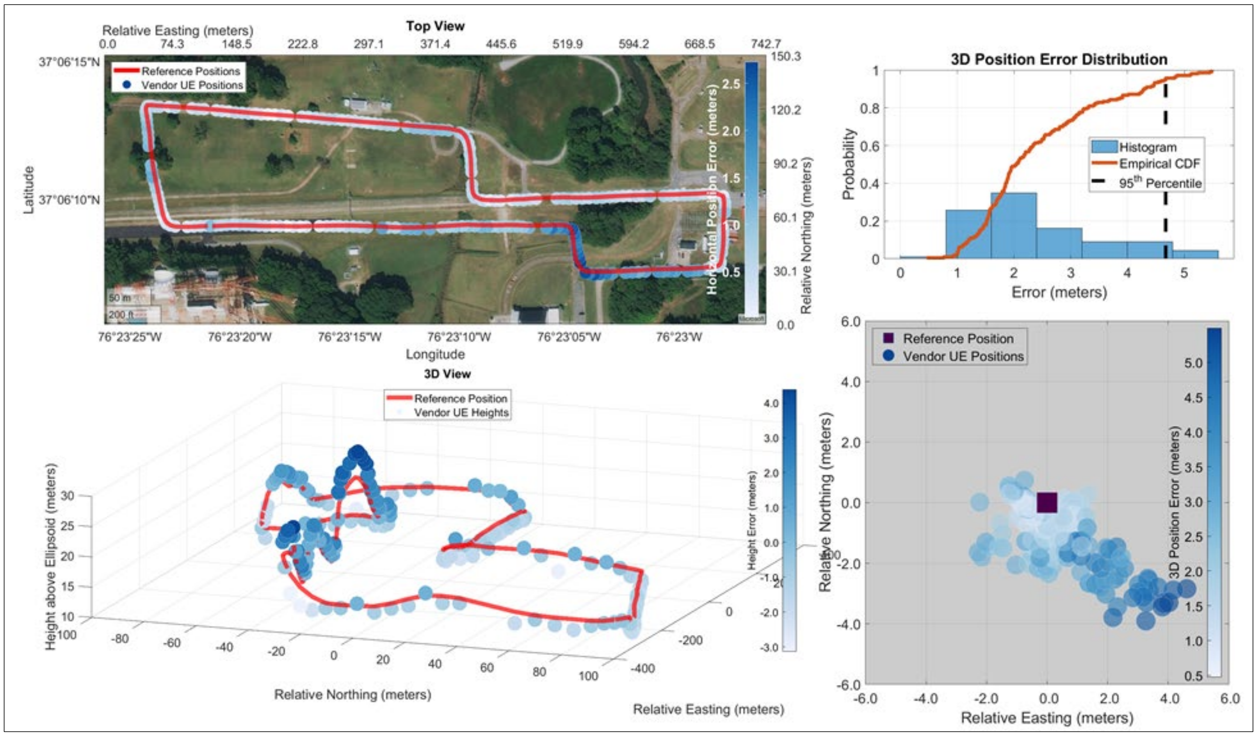


Figure 61. NextNav: Polygon – 100-ft Altitude

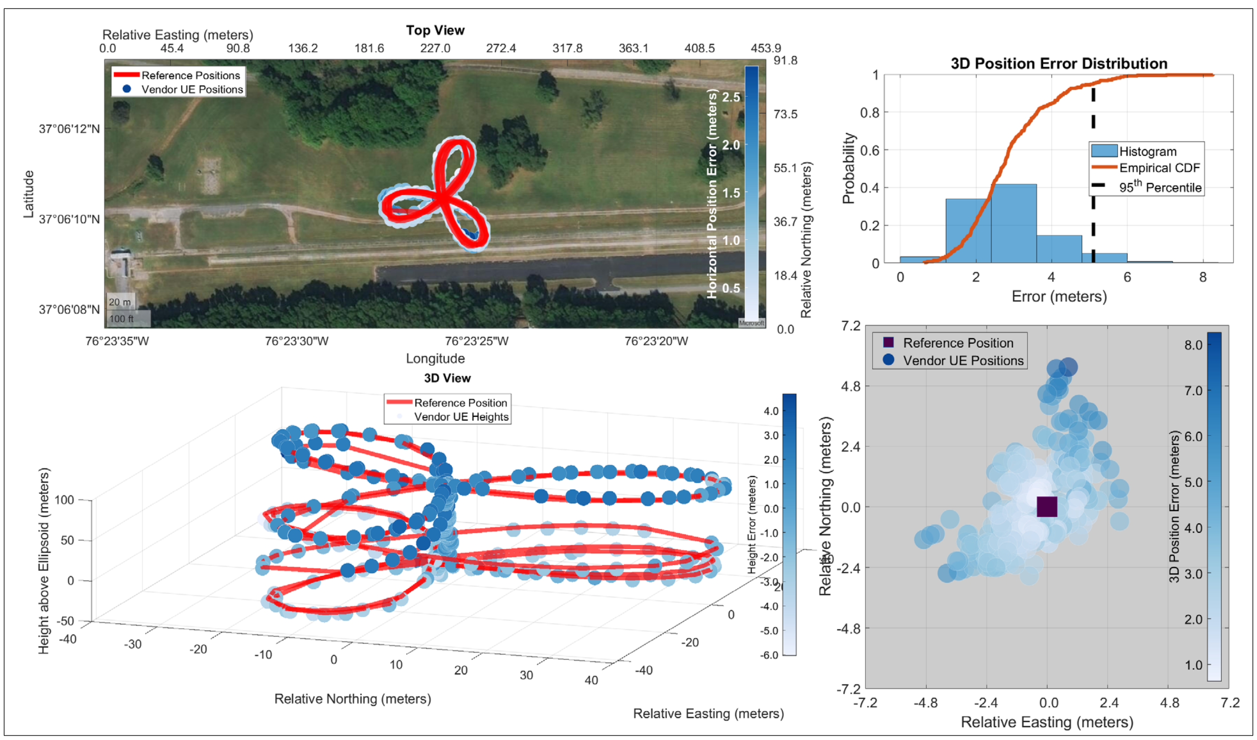


Figure 62. NextNav: Propeller Route – Overall

Table 52, Table 53, and Table 54 give the positioning results for a single vendor's UE for the 3D dynamic polygon and propeller routes. The results represent UE performance under the following parameters: mean height error, height error standard deviation, 3D mean error, and 3D standard deviation (all in meters); the demonstration duration; and 3D data availability.

Table 52. NextNav 3D Dynamic Routes: Positioning Results

Collection (altitude)	Mean Height Error (meters)	Height Error Standard Deviation (meters)	3D Mean Error (meters)	3D Standard Deviation (meters)	Demo Duration (H:MM:SS)	3D Data Availability (percent)
Polygon – 100 ft	-0.2	1.7	2.4	1.1	0:04:04	100.0
Polygon – 200 ft	-0.2	1.8	2.3	0.9	0:04:12	100.0
Polygon – 350 ft	6.6	4.0	7.3	3.8	0:03:56	100.0
Propeller Route – Overall	0.1	2.1	2.8	1.1	0:07:35	100.0
Propeller Route – 50 ft	-2.5	1.3	3.6	1.4	0:01:47	100.0
Propeller Route – 350 ft	1.8	1.0	2.4	0.6	0:01:45	100.0
Propeller Route – 50-ft to 350-ft Transition	0.4	2.4	2.9	1.1	0:00:59	100.0

See C.4.1.4 in Appendix C for corresponding figures.

Table 53. PhasorLab 3D Dynamic Routes: Positioning Results

Collection (altitude)	Mean Height Error (meters)	Height Error Standard Deviation (meters)	3D Mean Error (meters)	3D Standard Deviation (meters)	Demo Duration (H:MM:SS)	3D Data Availability (percent)
Polygon – 100 ft	0.2	5.1	16.4	7.1	0:05:56	56.6
Polygon – 200 ft	-1.2	2.7	18.5	6.0	0:04:23	26.3
Polygon – 300 ft	-1.7	2.9	24.4	8.6	0:04:22	29.5
Propeller Route – Overall	-1.5	3.3	8.6	4.6	0:15:20	80.2
Propeller Route – 50 ft	-2.6	1.7	11.3	2.4	0:03:48	97.8
Propeller Route – 350 ft	0.0	0.8	11.6	2.8	0:03:50	70.8
Propeller Route – 50-ft to 350-ft Transition	-7.6	1.3	14.0	2.2	0:01:10	88.6

See C.4.1.5 in Appendix C for corresponding figures.

Table 54. Skyhook RTT 3D Dynamic Routes: Positioning Results[33]

Collection (altitude)	Mean Height Error (meters)	Height Error Standard Deviation (meters)	3D Mean Error (meters)	3D Standard Deviation (meters)	Demo Duration (H:MM:SS)	3D Data Availability (percent)
Polygon – 100 ft	-3.6	1.4	5.8	1.9	0:04:04	100.0
Polygon – 200 ft	1.4	1.5	5.4	4.3	0:04:12	100.0
Polygon – 350 ft	2.7	3.8	6.2	2.9	0:03:56	94.9
Propeller Route – Overall	-0.7	1.5	5.7	8.6	0:07:35	96.1
Propeller Route – 50 ft	-0.3	1.4	3.4	2.2	0:01:47	98.8
Propeller Route – 350 ft	-0.9	0.8	12.0	14.8	0:01:45	94.4
Propeller Route – 50-ft to 350-ft Transition	2.3	1.6	6.5	5.9	0:00:59	93.5

See C.4.1.6 in Appendix C for corresponding figures.

[33] Height data provided by the Skyhook UE were offset at the beginning of each scenario using reference position height information.

7 Timing: Analytical Methods and Results

This section describes the analytical methods used to generate the numerical results from the data, and provides a summary of those results, organized by scenario. The data considered in this section correspond to the timing scenarios described in section 3.2.2 and implemented as described in section 5.8.2 of this report.

The primary objective of the data analysis was to quantify the accuracy and stability metrics for the participating vendor timing systems as they were configured during the Demonstration. The reference systems were tested and validated before and throughout the Demonstration, as described in section 4.

Table 55 presents vendor participation in the timing scenarios.

Table 55. Vendor Participation in Timing Scenarios

Vendor	Site	1: 72-Hour Bench Static Timing	4: Static Outdoor Timing	6: Static Indoor Timing	7: Static Basement Timing	9: eLORAN Reference Station Offset
Hellen Systems, LLC	JBCC	X			X*	X
NextNav LLC	LaRC	X	X	X	X	
OPNT B.V.	LaRC	X				
PhasorLab Inc.	JBCC	X	X	X		
Satelles, Inc.	JBCC	X	X	X	X	
Seven Solutions S.L.	LaRC	X				
Ursa Navigation Solutions, Inc. (d.b.a. UrsaNav, Inc.)	JBCC	X		X	X*	X

*Participated, but no valid signal received.

7.1 Timing: Analytical Methods

All UE 1-pps timing output signals were measured against a reference atomic frequency standard using a TIC, as described in section 4.

The timing scenarios used two of the three reference systems described in section 4. The Fixed reference subsystem at each demonstration site provided the source clock for vendor systems for vendors who requested it (OPNT and Seven Solutions at LaRC, and PhasorLab at JBCC), and served as the differential base station for Global Navigation Satellite Systems (GNSS) kinematic post-processed positioning.

The Fixed and Rover subsystems were also designed to perform data collection (see section 4). The Government Team's decision on whether the Fixed reference subsystem or the Rover subsystem was used to collect data from a particular vendor system UE for a particular scenario at each location was based on practical considerations, such as proximity of UE location to the Fixed reference subsystem and the availability of measurement channels. This choice did not affect the quality of the data, because all measurement systems were designed to have equivalent performance after measurements were detrended (see section 4 for a description of the detrending process). Table 56 shows the subsystem used to collect timing data for each combination of vendor UE and scenario.

Table 56. Government Reference Subsystem Used to Collect Vendor UE 1-pps Measurements by Timing Scenario

Vendor UE	Site	1: 72-Hour Bench Static Timing	4: Static Outdoor Timing	6: Static Indoor Timing	7: Static Basement Timing	9: eLORAN Reference Station Offset
Hellen Systems, LLC	JBCC	Fixed			Rover*	Rover
NextNav LLC	LaRC	Fixed	Rover	Rover	Fixed	
OPNT B.V.	LaRC	Fixed				
PhasorLab Inc.	JBCC	Fixed	Rover	Rover		
Satelles, Inc.	JBCC	Fixed	Rover	Fixed	Rover	
Seven Solutions S.L.	LaRC	Fixed				
Ursa Navigation Solutions, Inc. (d.b.a. UrsaNav, Inc.)	JBCC	Fixed		Rover	Rover*	Rover

*Participated, but no valid signal received

Table 57 shows the reference clock used for each participating vendor UE in each scenario. The table also indicates whether the system source clock was provided by the Government reference system, and whether the detrending process was needed and performed.

Table 57. Vendor UE Use of Government Reference System Atomic Clock by Timing Scenario

Vendor UE	Site	1-pps and/or 10-MHZ Signal Sourced from Government Reference System	1: 72-Hour Bench Static Timing	4: Static Outdoor Timing	6: Static Indoor Timing	7: Static Basement Timing	9: eLORAN Reference Station Offset
Hellen	JBCC	No	Cs §			S650*	S650 §
NextNav	LaRC	No	Cs §	Cs §	Cs §	Cs §	
OPNT	LaRC	Yes (Cs)	Cs				
PhasorLab	JBCC	Yes (Cs)	Cs	S650 §	S650 §		
Satelles	JBCC	No	Cs §	S650 §	Cs §	S650 §	
Seven Solutions	LaRC	Yes (Cs)	Cs				
UrsaNav	JBCC	No	Cs §		S650 §	S650*	S650 §

“ § ” indicates that detrending was needed and performed.

***Participated, but no valid signal received.**

The first step in the Timing analysis was to detrend the 1-pps UE data output where applicable. In general, when a vendor system and measurement system source clock signals are distributed from the same atomic frequency standard, no trend characterization is needed; the source clock drift is a mode error common to both the reference and vendor system timing signals, and is subtracted out when the TIC difference measurement is performed. This was the case for the collection of UE data for Scenario 1: 72-hour Bench Static Timing for OPNT, PhasorLab, and Seven Solutions.

However, in the case of vendor systems with UTC-traceable time sources, or when the source reference clock signal for the TIC measurement is different than the one provided to the vendor, detrending is needed to minimize the reference clock drift error.

Atomic clocks provide a reference 1-pps signal that is smooth (*i.e.*, with a small Allan Deviation relative to a GPS receiver 1-pps output signal) and slow-drifting with a measureable trend relative to a UTC-traceable timing signal. For the cesium reference standard, a linear trend was found to characterize long-term drift for up to 72 hours. [34] This was the case for Scenario 1 UE data from the Hellen, NextNav, Satelles, and UrsaNav UEs. It was also the case for NextNav UE data collected during Scenarios 4, 6, and 7. For the rubidium-based S650 standard, a higher-order polynomial fit was required for each 60-minute data collection with concurrent GPS 1-pps data, as described in section 5.2.2. This was the case for Hellen and UrsaNav UE data in Scenario 9, PhasorLab UE data in Scenarios 4 and 6, and Satelles UE data in Scenarios 4 and 7.

[34] See sections 4.1.1 and 4.1.2. 72 hours in Scenario 1 was the longest continuous timing data collection implemented during this demonstration.

For timing scenarios during which concurrent GPS 1-pps data from the Rover reference system were not available, as discussed in sections 4.1.2.2 and 4.2.2.2, the reference clock drift characterization before and/or after the scenario was used for detrending. This was necessary for NextNav UE data collected in Scenarios 4, 6, and 7, PhasorLab and UrsaNav data in Scenario 6, and Satelles data in Scenario 7. After detrending, the initial timing offset relative to the reference system clock was subtracted out from each scenario run data.

Next, the stability of the vendor timing system was characterized by estimating the drift rate as the slope from the linear fit to the detrended measurements. Long-term stability was assessed by characterizing the drift rate over the 72-hour collection period in Scenario 1, while short-term stability and its sensitivity to UE location was checked by calculating that drift rate over the 60-minute collection period in Scenarios 4, 6, and 7.

Additionally, the following four statistics were calculated for each UE data set in each scenario to assess time transfer accuracy:

$$Med = median[Dt],$$

$$\sigma = \left[\frac{1}{N-1}\sum_{i=1}^{N}[Dt[i] - \mu_{Dt}]^2\right]^{\frac{1}{2}}$$

$$MaxDev = Max\{|Dt|\}, \text{ and}$$

$$p_{95}(|Dt|).$$

In the four expressions above, σ is the sample standard deviation, *Dt* (“difference in time”) represents the TIC measurements with initial time offset removed[35] (and detrended when applicable), N represents the total number of TIC measurements in a scenario run, *Dt[i]* is measurement sample *i*, μ_{Dt} is the sample mean of Dt, $|Dt|$ is the absolute value of Dt, and $p_{95}(|Dt|)$ represents the 95[th] percentile of Dt.

During the 72-Hour Bench Static Timing scenario, a small number of data anomalies were detected that were related to temporary cabling issues at LaRC, and occasional cycle slips on the frequency counter at the JBCC Fixed reference system. Any detected UE data anomalies observed throughout the demonstration were corrected or discarded from the analysis to ensure the reported statistics were not contaminated by such events.

[35] For Scenario 1, the initial time offset was calculated as the median of the initial first 2 hours of the 72-hour collection period, and was calculated as the value for the first point offset for all other timing scenarios. This is more consistent with how a fixed timing infrastructure system would be initialized.

Each of the two eLORAN systems (Hellen and UrsaNav) broadcasted time offset corrections between the vendor's onsite reference station and the corresponding UE in all scenarios in which they were demonstrated.[36] The results are presented below in section 7.2.

The demonstration relied on the vendors to provide the corrections to the UE data in real time. UrsaNav's broadcast signals corrections were processed in real time within the UE hardware by its supporting software, and were incorporated in the results.

In the case of Hellen, the recorded time offset corrections were not applied to the UE data in real time, and therefore were not reflected in the reported results. If applied in post processing, these corrections can potentially further improve the accuracy and stability of the Hellen Systems Scenario 1 72-hour data collection results due to atmospheric pressure and temperature profile changes throughout the day and from day to day. However, for Scenario 9, it can be reasonably assumed that the pressure and temperature profiles along the signal path did not change significantly over the course of the 60-minute data collection at any of the three signal offset locations.

7.2 Timing: Results

The methods for data pre-processing and analysis described in section 7.1 were used to characterize the performance of each vendor's timing system in the respective scenarios they chose to demonstrate. Each of the following scenario subsections starts with the tabulated summary of analytical results followed by the graphical results for all participating vendors. The tabulated results consist of the estimated first order drift and statistical values calculated as described in section 7.1. The graphical results for each vendor's data comprise 1-Hz time series TIC measurements[37] that are detrended (when applicable) and with initial time offset removed, followed by a distribution of these same measurements in terms of percentages of total samples.

7.2.1 Scenario 1: 72-Hour Bench Static Timing

The purpose of the 72-Hour Bench Static Timing scenario was to assess the timing service availability and long-term time transfer error and stability (see section 5.8.2.1). The data analysis described in section 7.1 was performed, resulting in a statistical characterization of the long term data using the metrics defined in that same section. With the exception of OPNT and Satelles, vendors participating in Scenario 1 used one UE configuration. As shown in section 6.4, Table 12, and described in Appendix B, OPNT offered two UE configurations, and Satelles three, for demonstration in this scenario. A summary of the 72-Hour Bench Static Timing Scenario results for all participating vendor systems appears in Table 58.

[36] Both vendors participated in Scenarios 1 (72-Hour Bench Static Timing), 7 (Static Basement Timing), and 9 (eLORAN Reference Station Offset); in addition, UrsaNav participated in Scenario 6 (Static Indoor Timing).
[37] The TIC in the reference and data collection system measured 1-pps differences between the vendor UE under test and the reference 1-pps reference signal.

Table 58. Scenario 1: 72-Hour Bench Static Timing Statistical Results

Vendor UE	Slope (ns/hr)	Median (ns)	SD (ns)	Max Deviation (ns)	95th Percentile (|.|) (ns)
Hellen §	0.095	82.08	38.24	215.12	114.47
NextNav §	0.16	6.88	9.52	63.45	22.03
OPNT1	0.014	0.053	0.99	4.07	1.88
OPNT2	0.0045	0.087	0.062	1.43	0.15
PhasorLab	0.0072	1.35	4.46	23.33	9.40
Satelles SecureSync1-Rb (Ch2A) §	0.34	-39.72	118.85	698.25	243.57
Satelles EVK2-Rb (Ch3A) §	-0.42	25.44	30.89	91.63	75.47
Satelles EVK2-OCXO (Ch4A) §	0.00020	34.25	40.87	208.72	107.38
Seven Solutions	0.00030	0.014	0.052	0.55	0.10
UrsaNav §	0.57	-35.48	37.81	171.46	94.93

§ Indicates that detrending was necessary and performed.

The figures that follow immediately below are presented to support the tabular data. They show paired time series plots and distributions of the same measurements for each vendor UE as the percentages of total samples that are detrended (when applicable) and with initial time offset removed. They are Figure 63 and Figure 64 (Hellen); Figure 65 and Figure 66 (NexNav); Figure 67 and Figure 68 (OPNT1); Figure 69 and Figure 70 (OPNT2); Figure 71 and Figure 72 (PhasorLab); Figure 73 and Figure 74 (Satelles SecureSync 1-Rb [Ch2A]); Figure 75 and Figure 76 (Satelles EVK2-Rb [Ch3A]); Figure 77 and Figure 78 (Satelles EVK2-OCXO [Ch4A]); Figure 79 and Figure 80 (Seven Solutions); and Figure 81 and Figure 82 (UrsaNav).

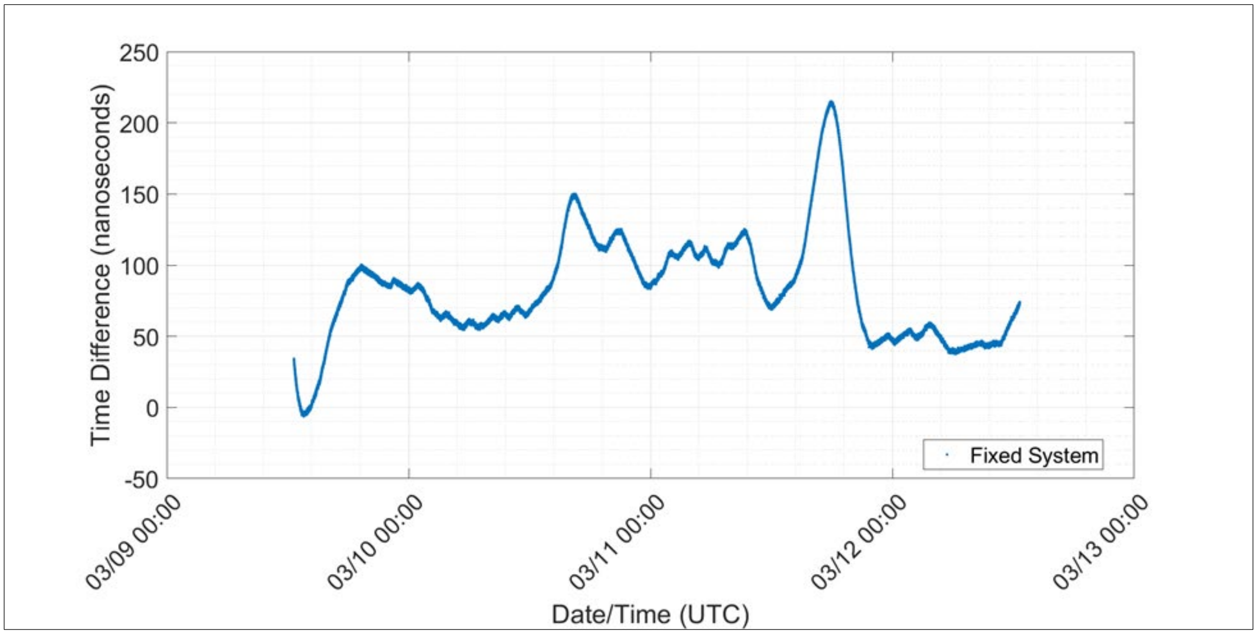


Figure 63. 72-Hour Bench Static Timing: Hellen – 1-pps Time Difference (ns) Relative to UTC (detrended)

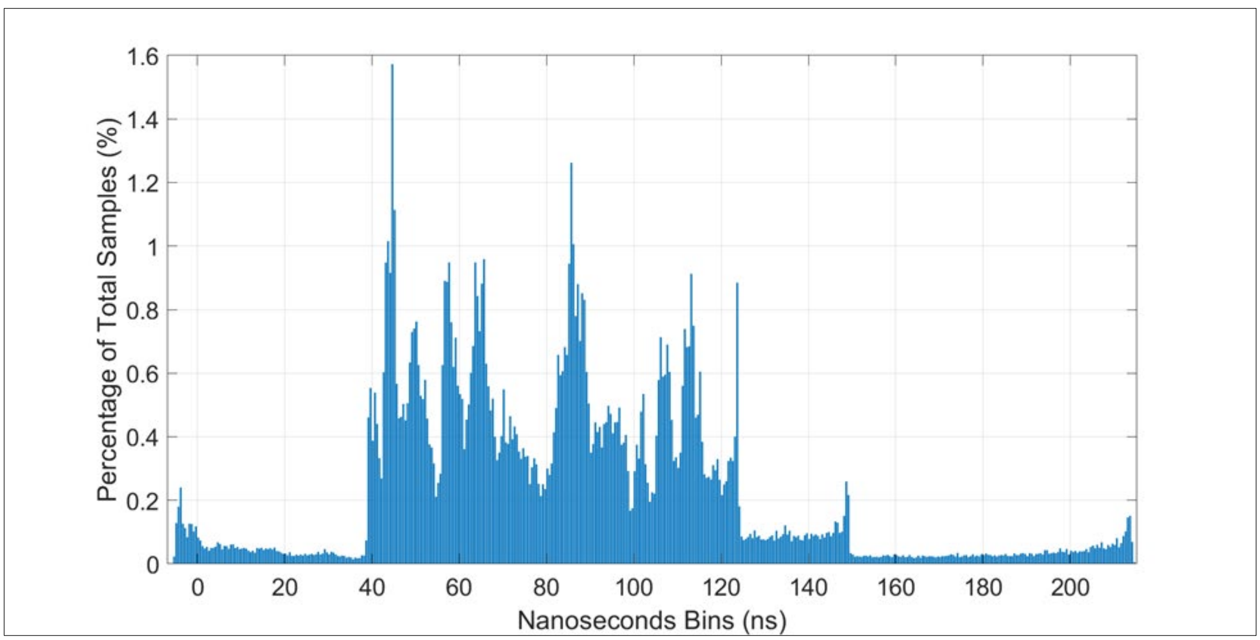


Figure 64. 72-Hour Bench Static Timing: Hellen – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

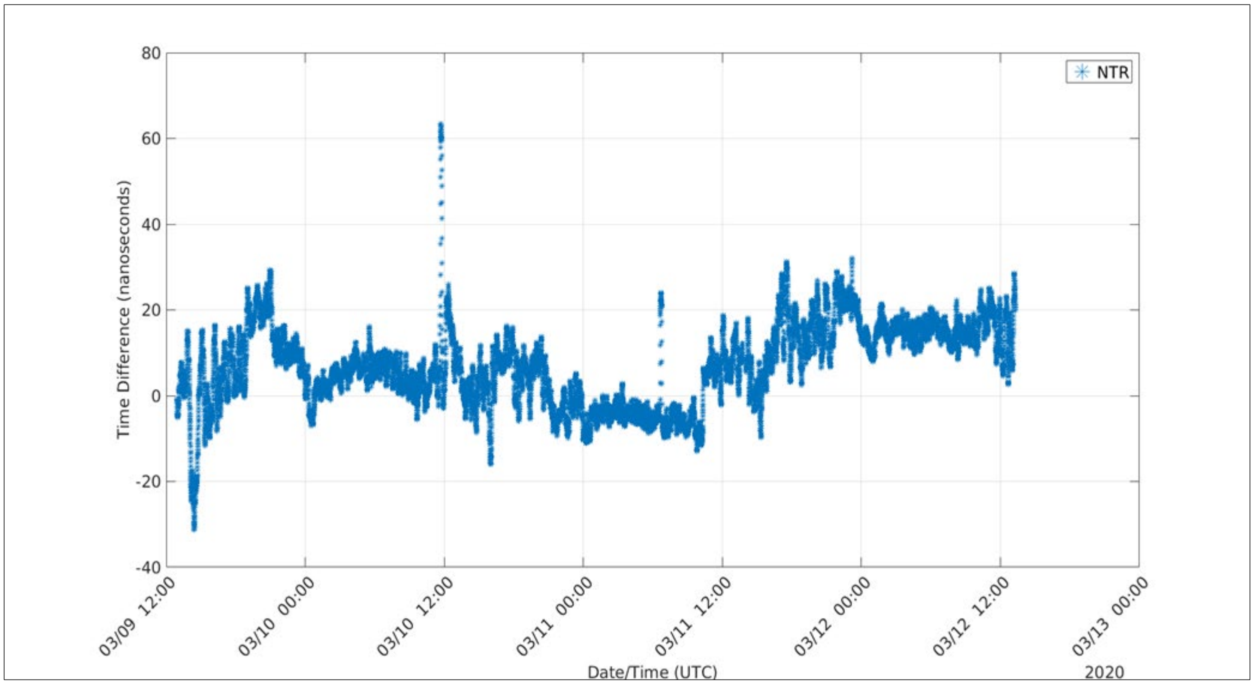


Figure 65. 72-Hour Bench Static Timing: NextNav – 1-pps Time Difference (ns) Relative to UTC (detrended)

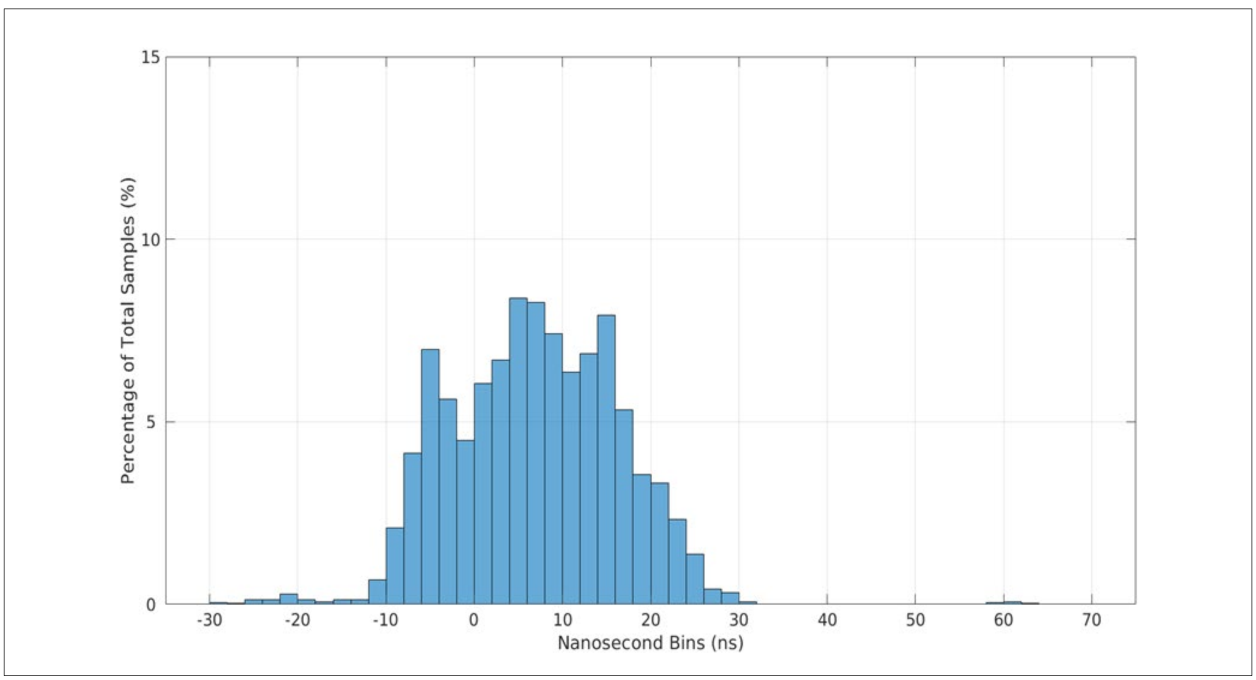


Figure 66. 72-Hour Bench Static Timing: NextNav – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

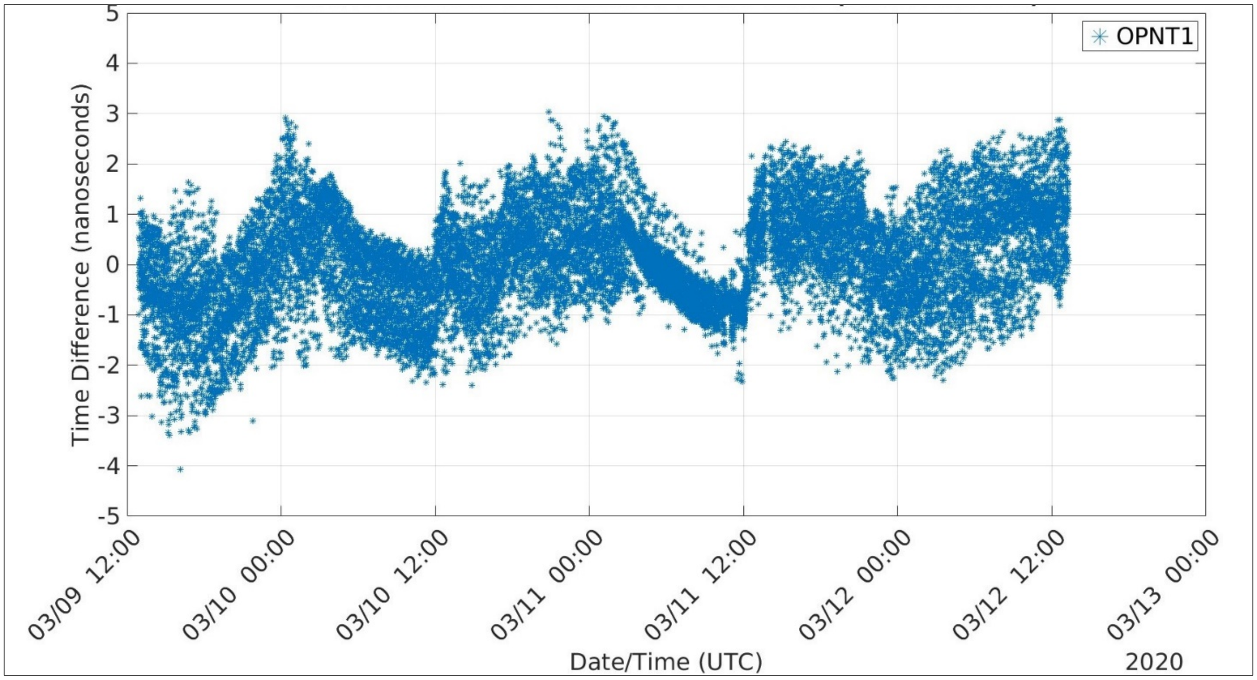


Figure 67. 72-Hour Bench Static Timing: OPNT1 – 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

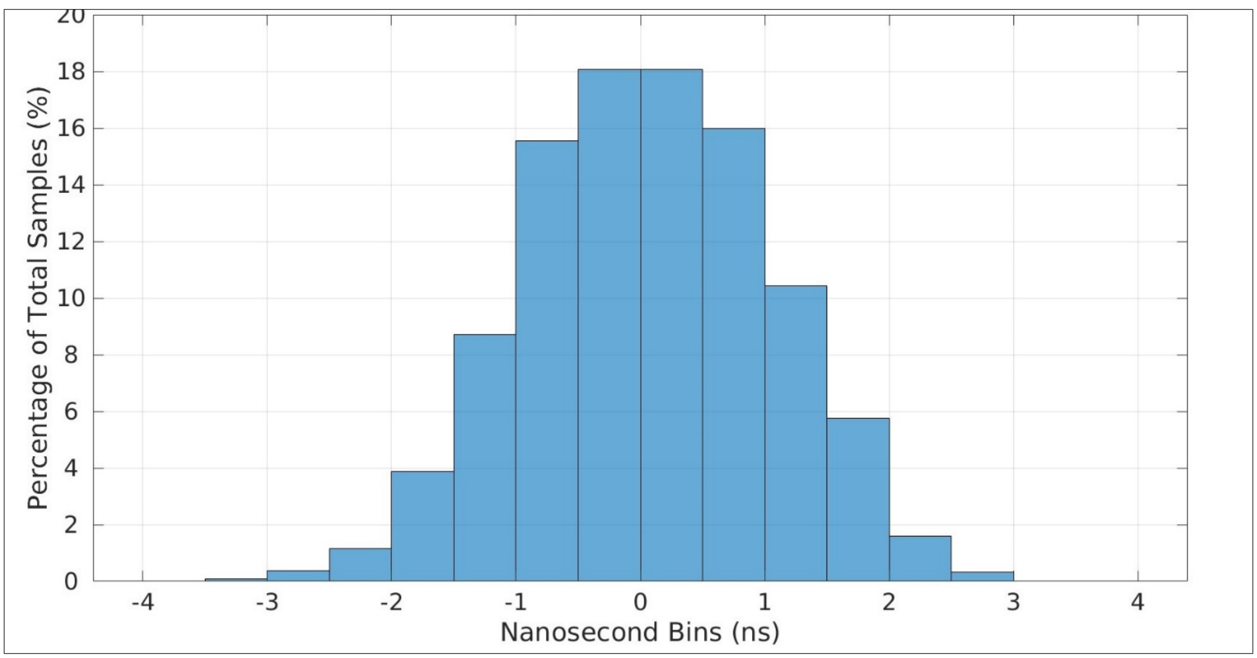


Figure 68. 72-Hour Bench Static Timing: OPNT1 – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

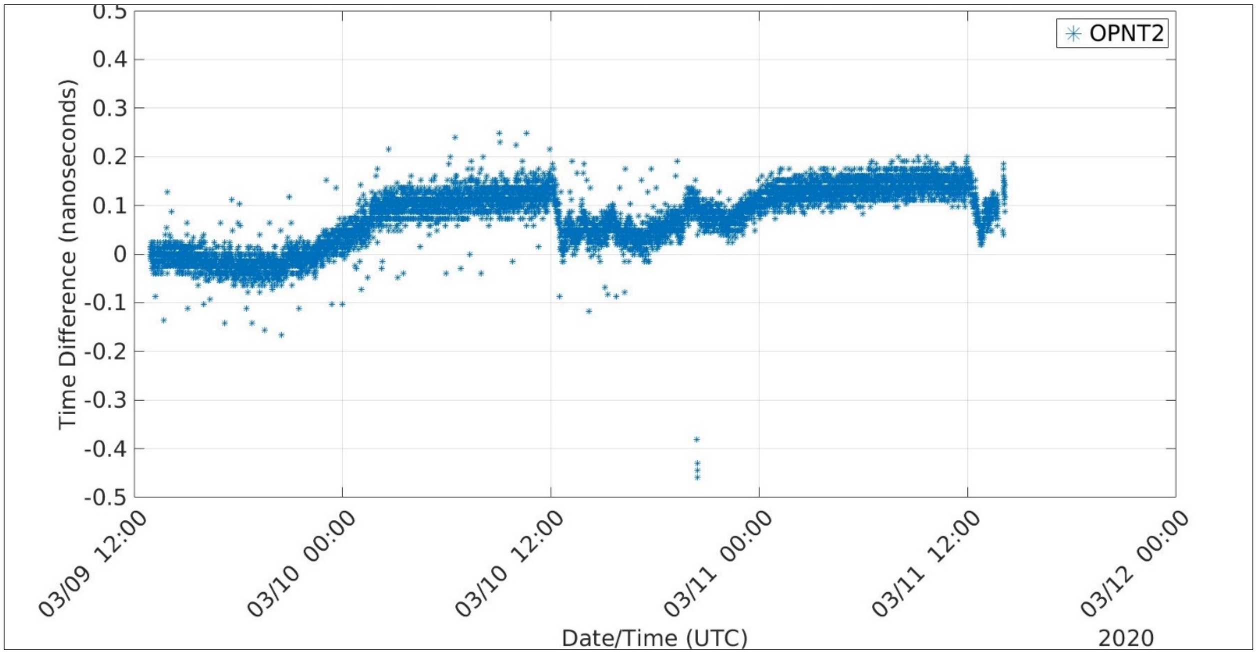


Figure 69. 72-Hour Bench Static Timing: OPNT2 – 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

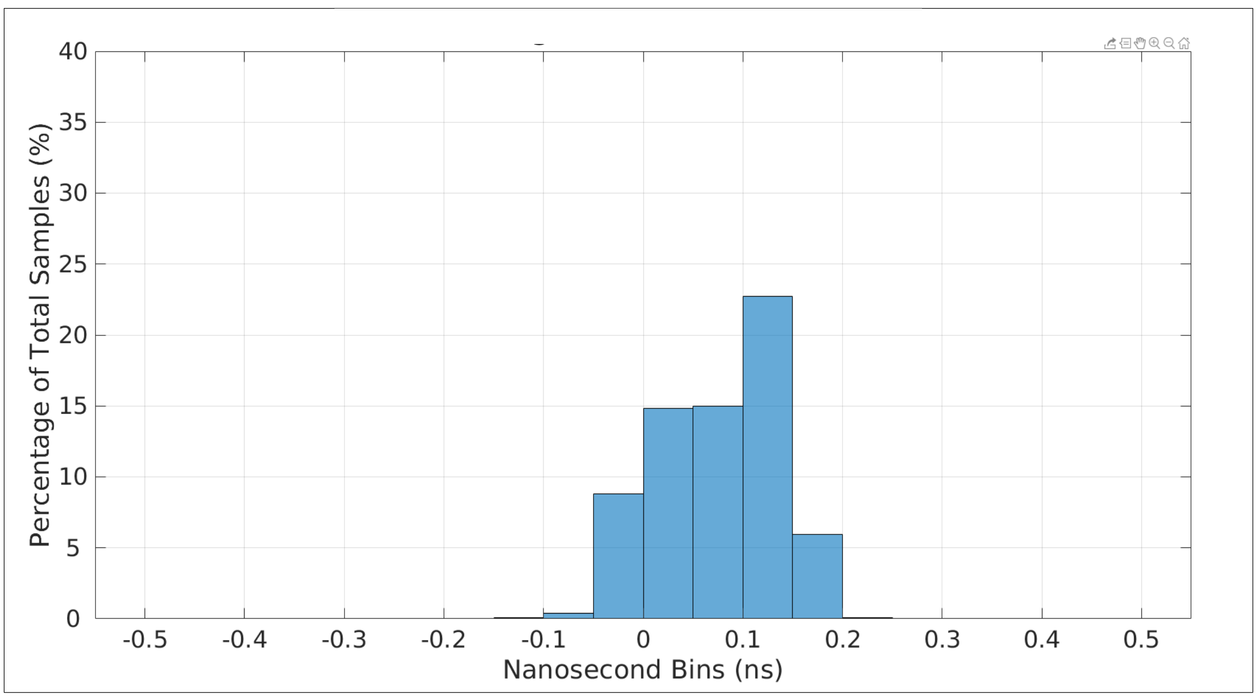


Figure 70. 72-Hour Bench Static Timing: OPNT2 – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

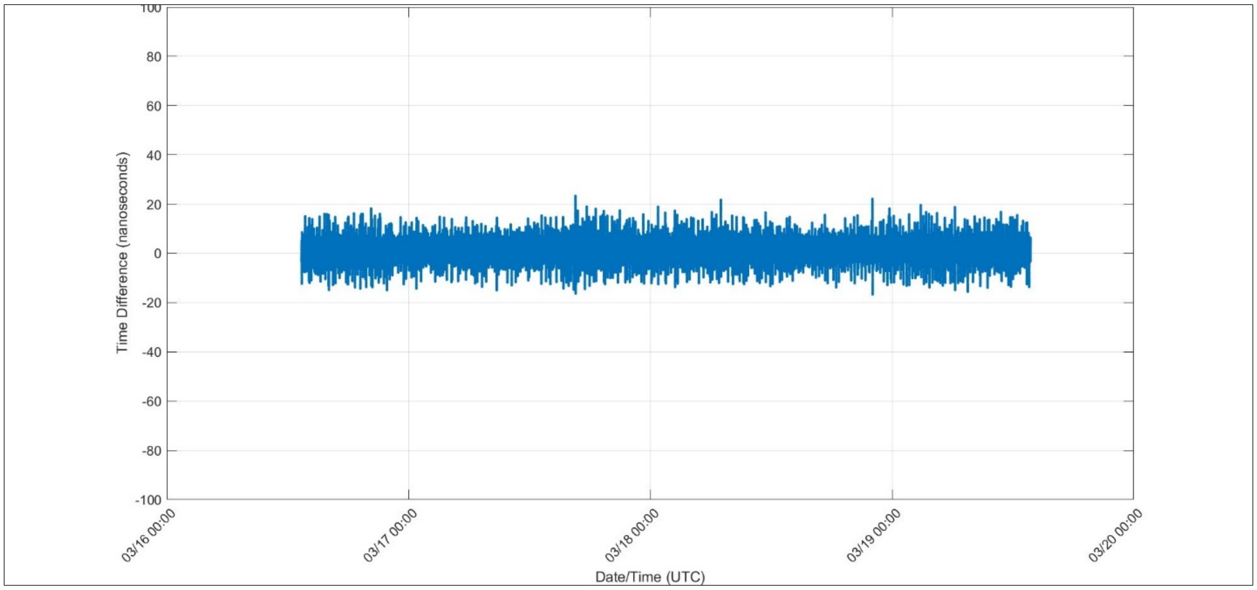


Figure 71. 72-Hour Bench Static Timing: PhasorLab – 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

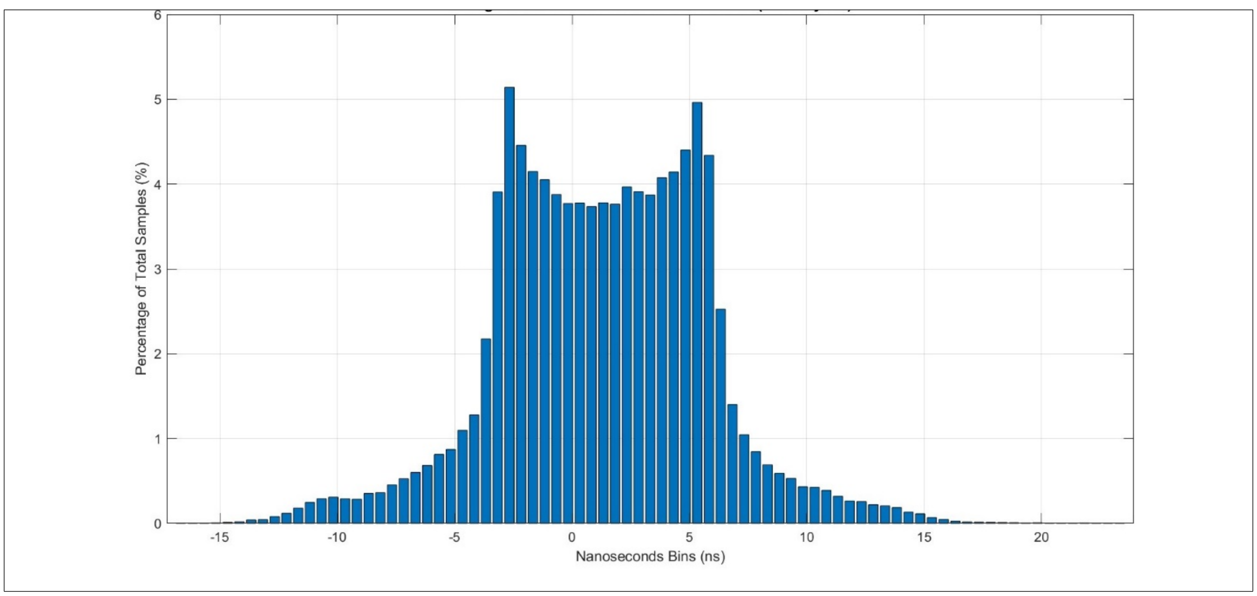


Figure 72. 72-Hour Bench Static Timing: PhasorLab – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

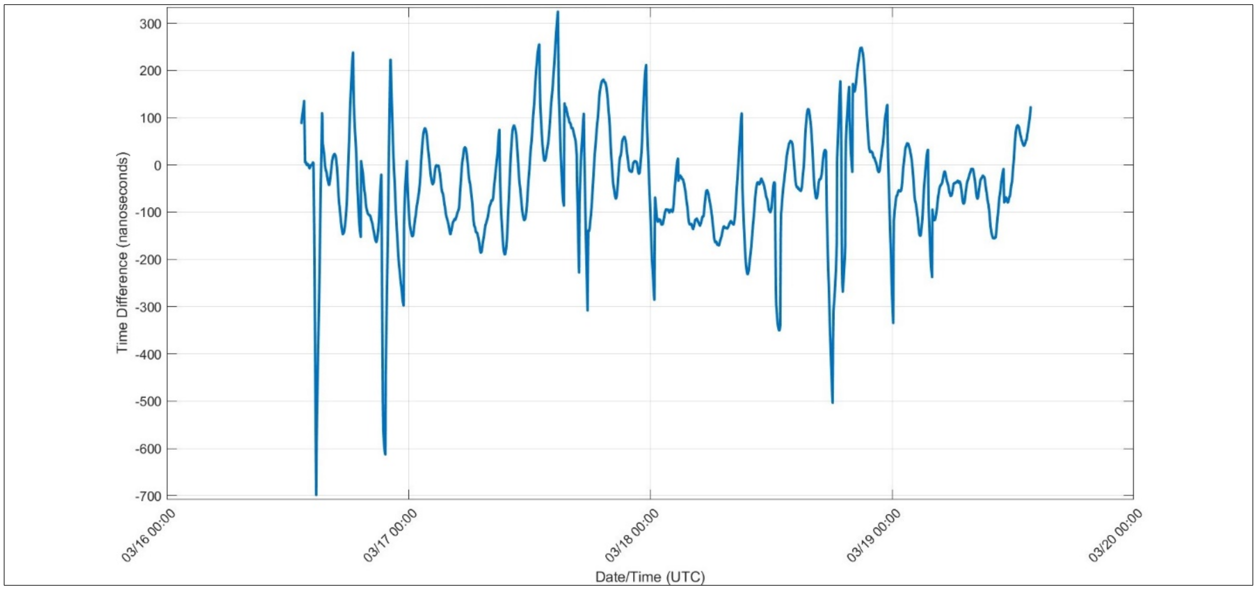


Figure 73. 72-Hour Bench Static Timing: Satelles SecureSync 1-Rb (Ch2A) – 1-pps Time Difference (ns) Relative to UTC (detrended)

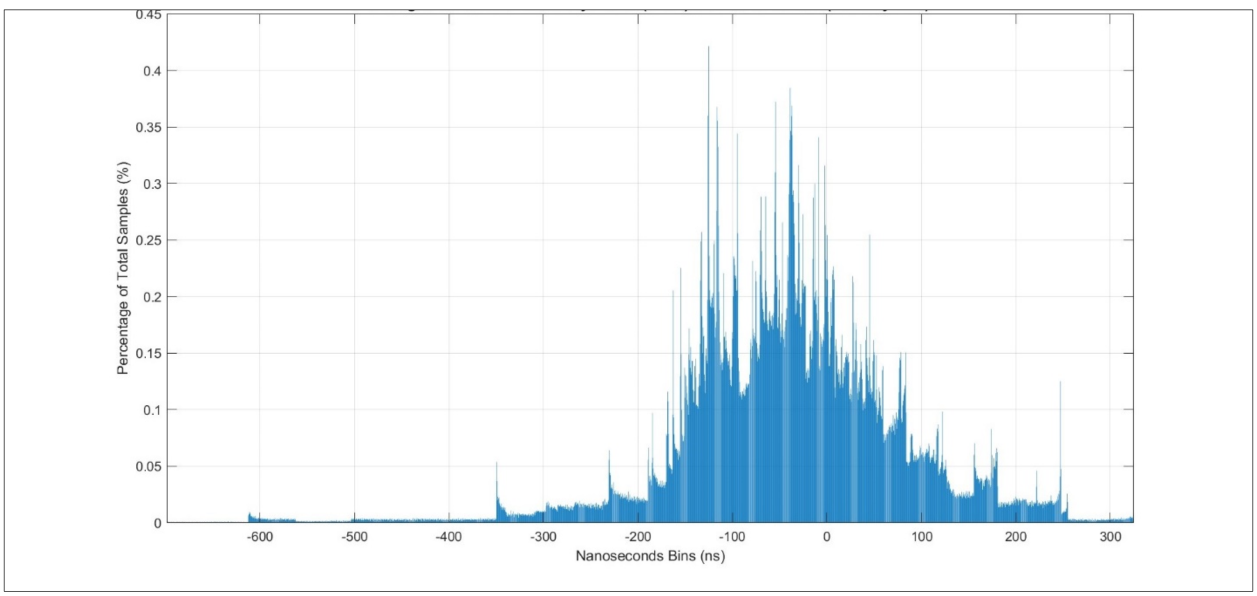


Figure 74. 72-Hour Bench Static Timing: Satelles SecureSync1-Rb (Ch2A) – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

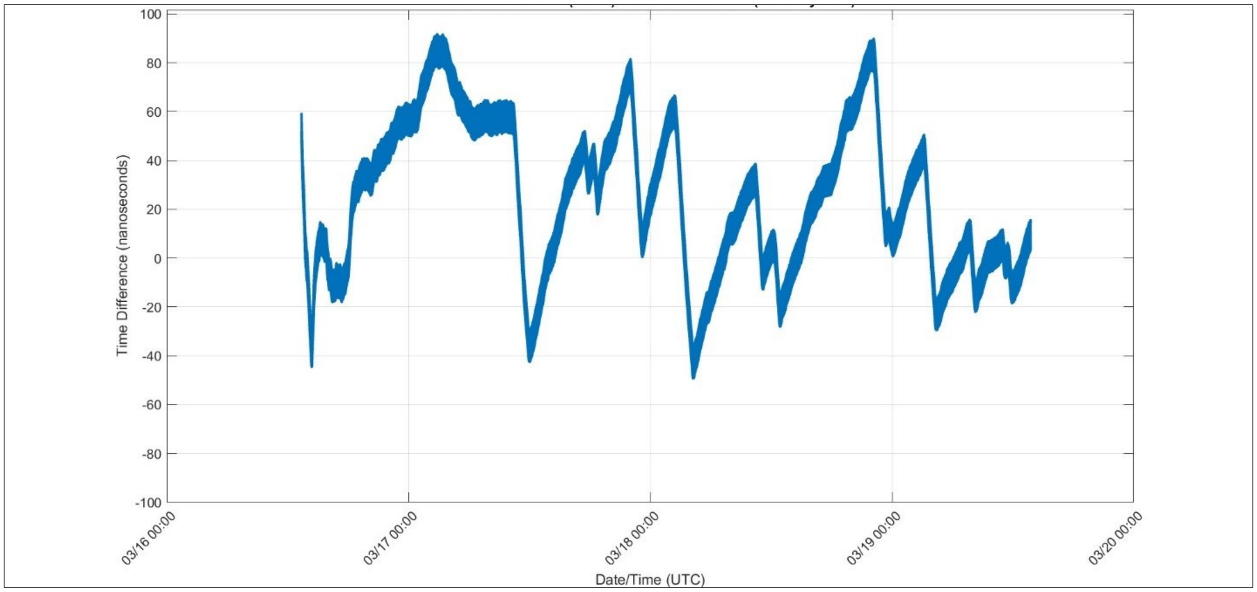


Figure 75. 72-Hour Bench Static Timing: Satelles EVK2 -Rb (Ch3A) – 1-pps Time Difference (ns) Relative to UTC (detrended)

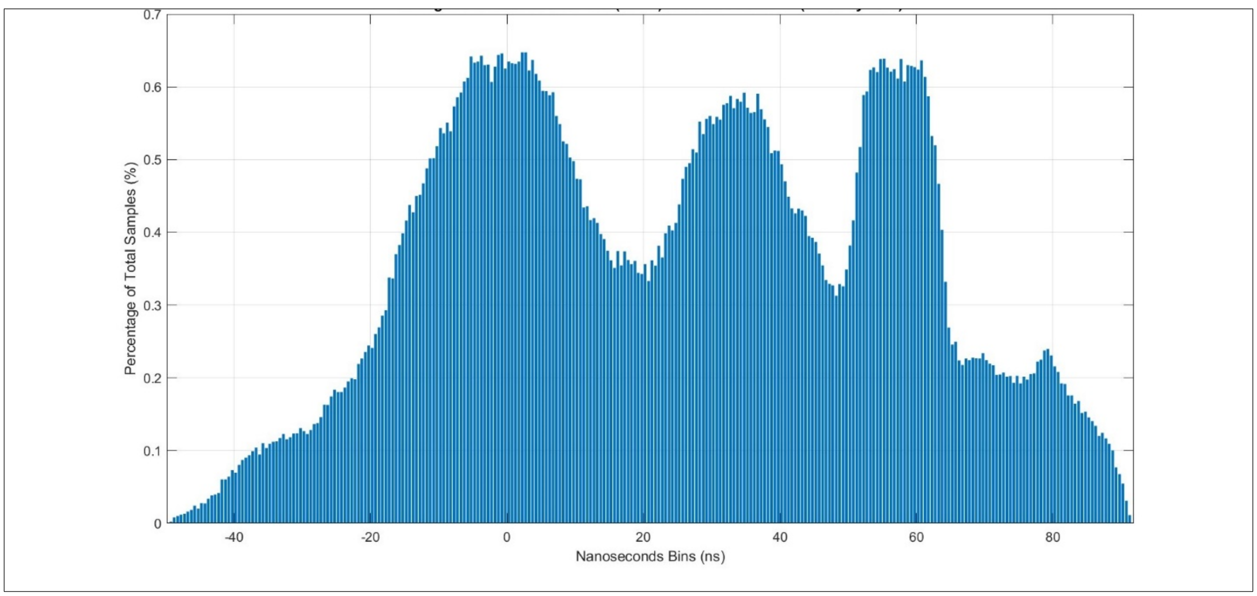


Figure 76. 72-Hour Bench Static Timing: Satelles EVK2-Rb (Ch3A) – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

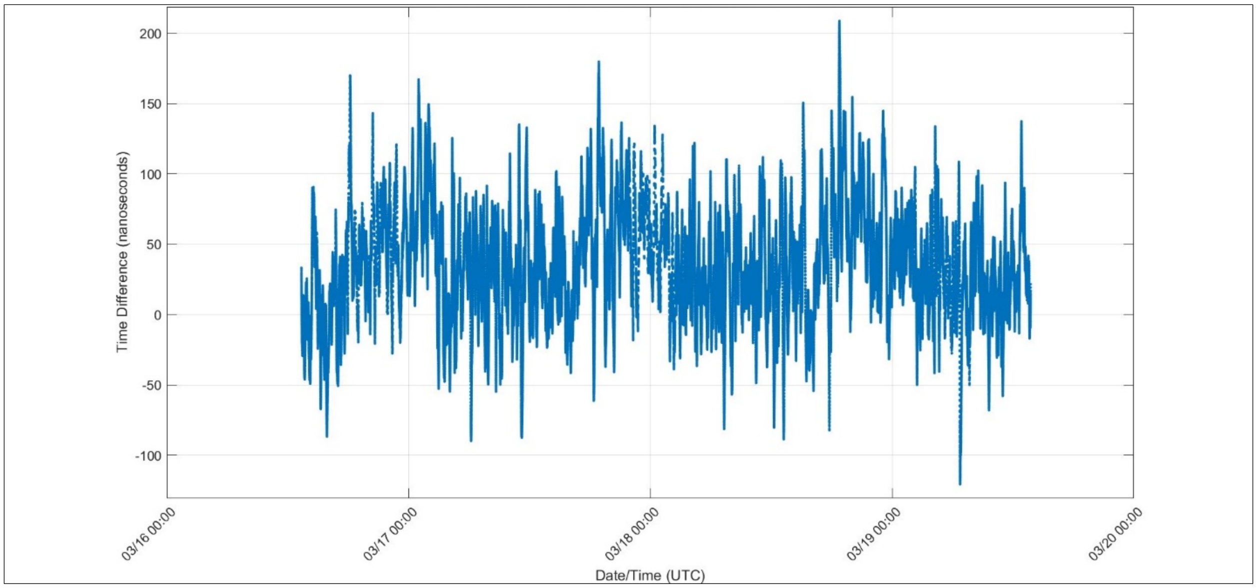


Figure 77. 72-Hour Bench Static Timing: Satelles EVK2-OCXO (Ch4A) – 1-pps Time Difference (ns) Relative to UTC (detrended)

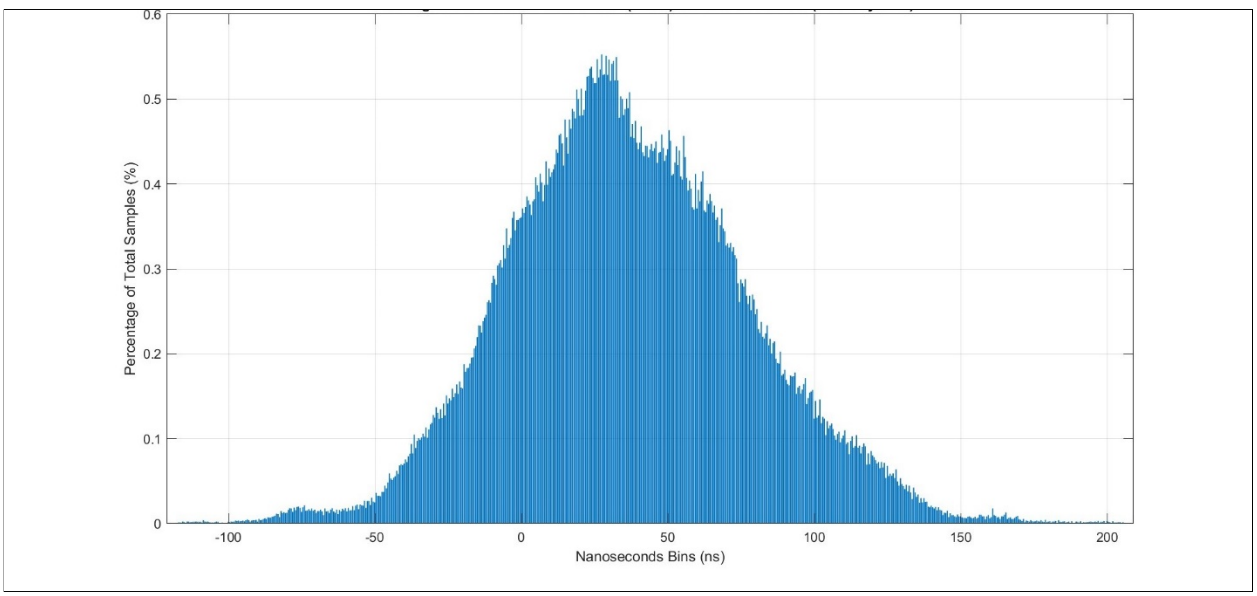


Figure 78. 72-Hour Bench Static Timing: Satelles EVK2-OCXO (Ch4A) – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

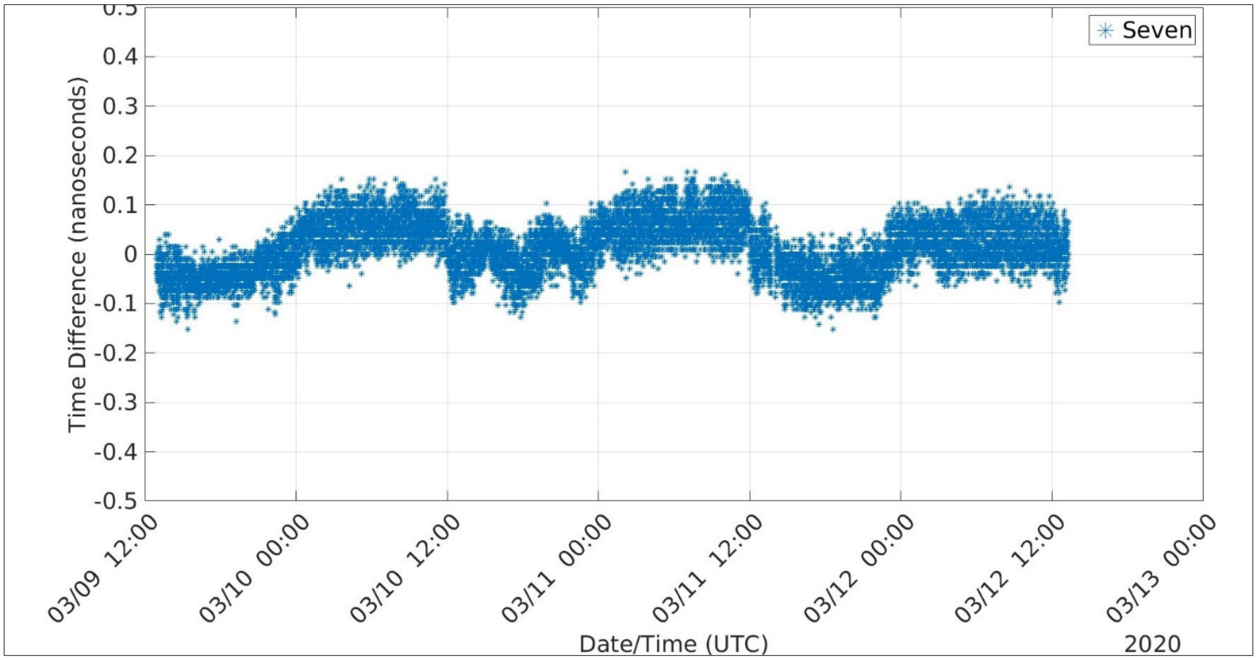


Figure 79. 72-Hour Bench Static Timing: Seven Solutions – 1-pps Time Difference (ns) Relative to Fixed Reference Subsystem Cs 1-pps Signal

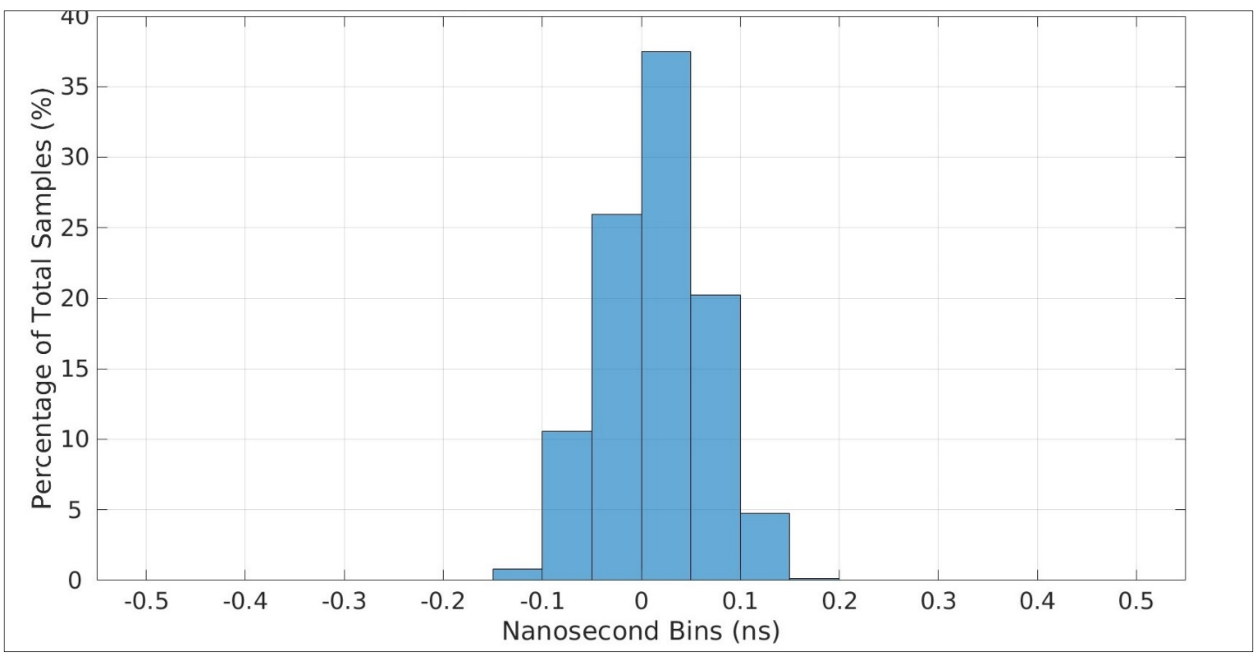


Figure 80. 72-Hour Bench Static Timing: Seven Solutions – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to Cs

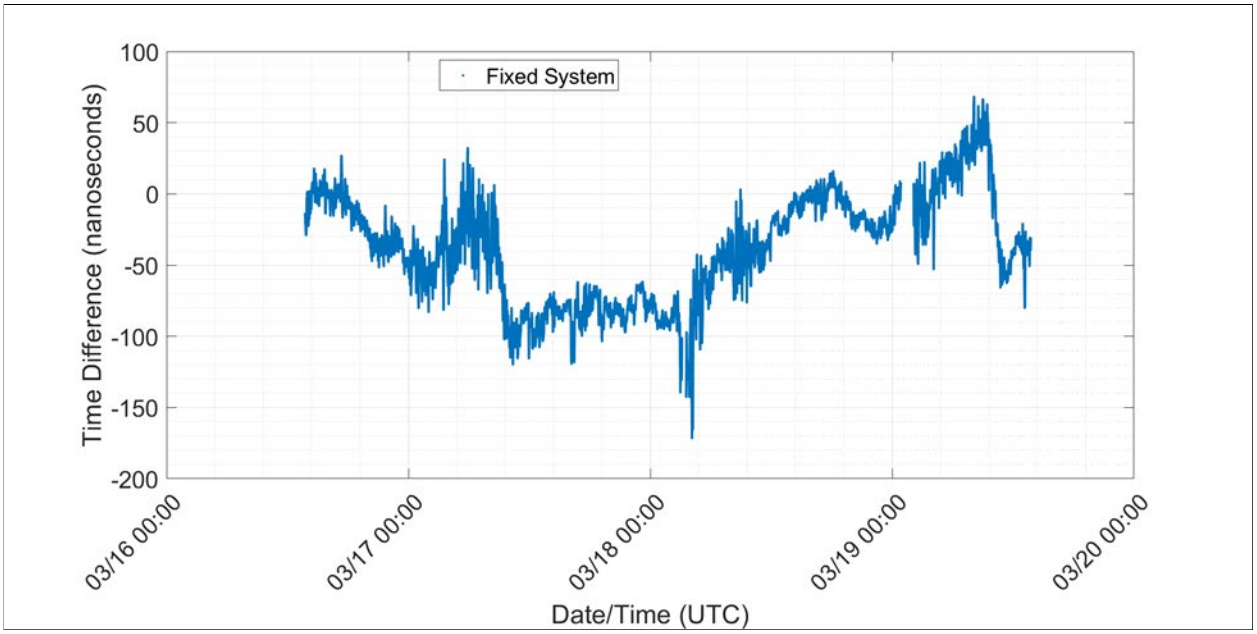


Figure 81. 72-Hour Bench Static Timing: UrsaNav – 1-pps Time Difference (ns) Relative to UTC (detrended)

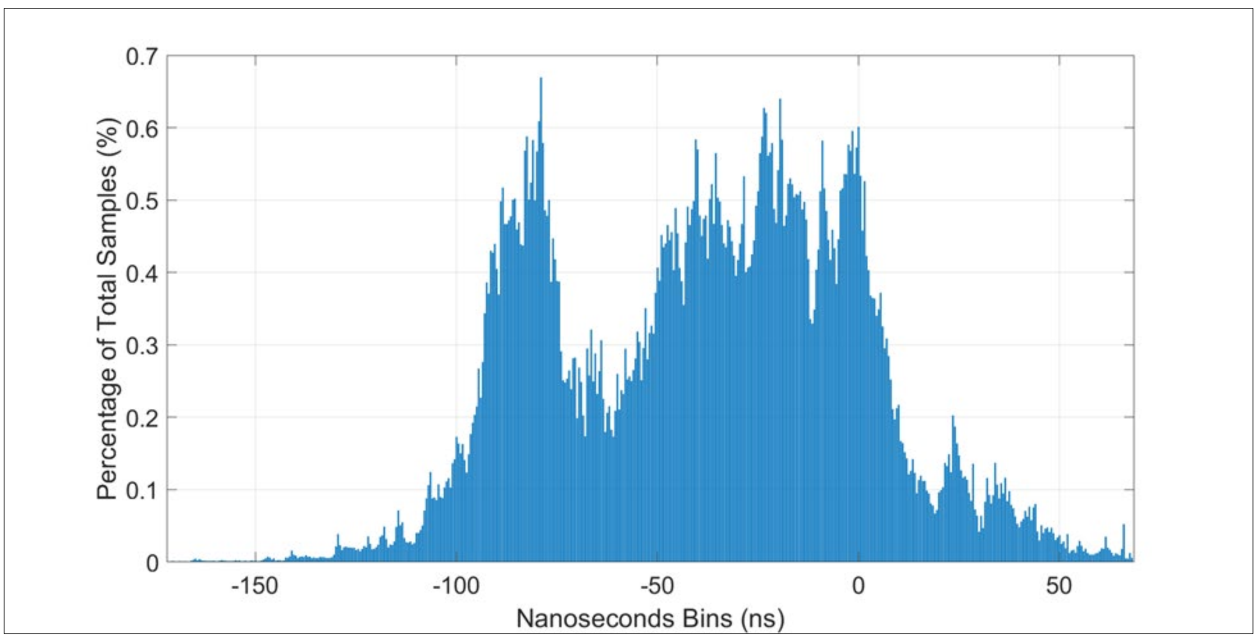


Figure 82. 72-Hour Bench Static Timing: UrsaNav – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

7.2.2 Scenario 4: Static Outdoor Timing

In this scenario (described in section 3.2.2.2), the sensitivity of time error and short-term stability to outdoor UE antenna location were demonstrated to verify availability and to assess uniformity of coverage within the demonstration region. A 60-minute data collection was performed at each of three static positions. Table 59 presents the statistical results for each participating vendor at each location.

Table 59. Scenario 4 – Static Outdoor Timing Scenario Statistical Results

Vendor	Location	Slope (ns/hr)	Median (ns)	SD (ns)	|Max Deviation| (ns)	95th Percentile (|.|) (ns)
NextNav §	**SO1**	-7.37	-4.23	2.34	9.05	8.48
	SO2	-11.86	-9.33	5.08	15.13	14.41
	SO3	-8.39	-3.57	2.53	8.16	7.10
PhasorLab §	**SO1**	2.36	-1.60	8.63	25.91	17.43
	SO2	4.39	24.82	8.22	41.88	33.29
	SO3	-3.73	7.90	8.45	27.79	17.81
Satelles EVK2-OCXO §	**SO1**	-22.57	-9.87	31.92	87.61	74.99
	SO2	111.15	71.40	37.55	129.09	116.00
	SO3	45.85	-44.77	40.15	132.11	114.48

§ Indicates that detrending was needed and performed.

For each vendor system, the detrended time series from each of the three static positions was overlaid with initial time offset removed for each position. The corresponding histogram for each vendor system UE was calculated by aggregating plotted time-series data from the three positions. The time series and histogram are shown for each participating vendor in paired Figure 83 and Figure 84 (NextNav); Figure 85 and Figure 86 (PhasorLab); and Figure 87 and Figure 88 (Satelles).

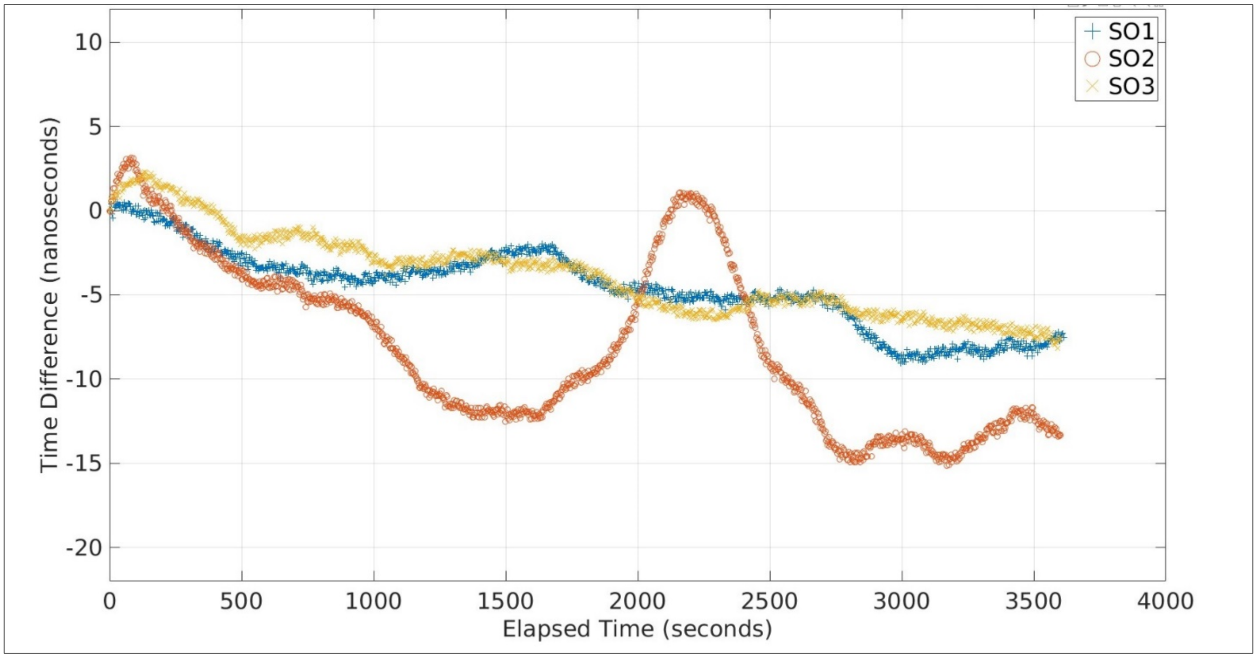


Figure 83. Static Outdoor Timing: NextNav – 1-pps Time Difference (ns) Relative to UTC (detrended)

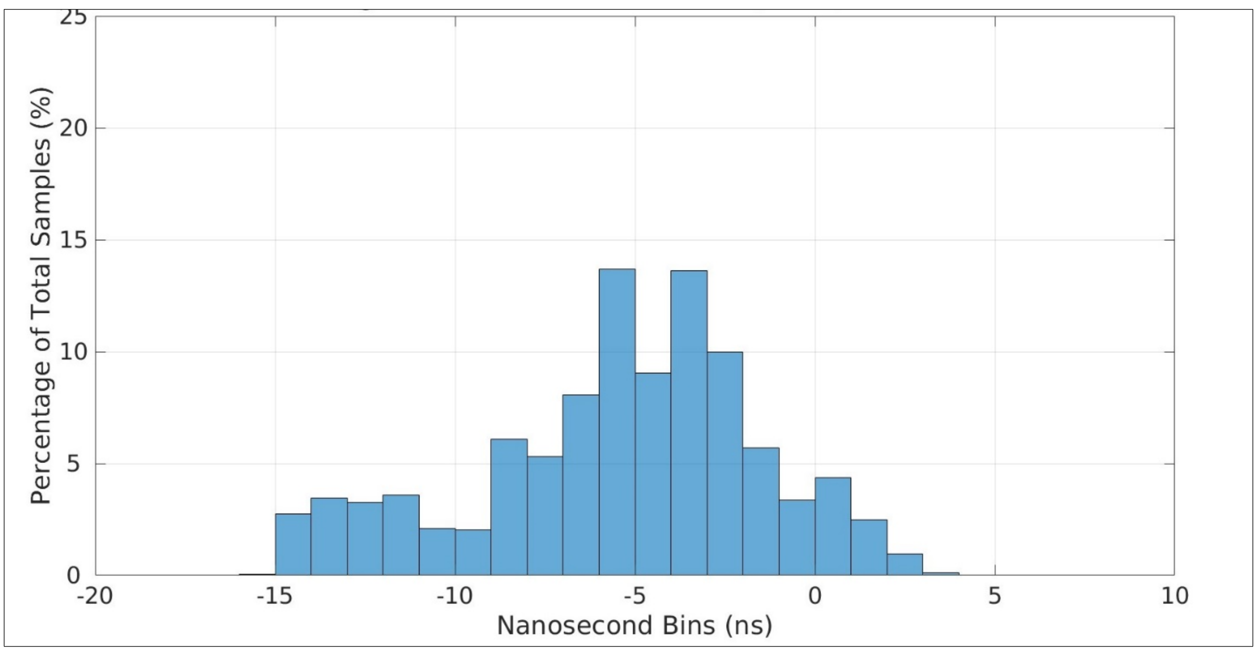


Figure 84. Static Outdoor Timing: NextNav – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

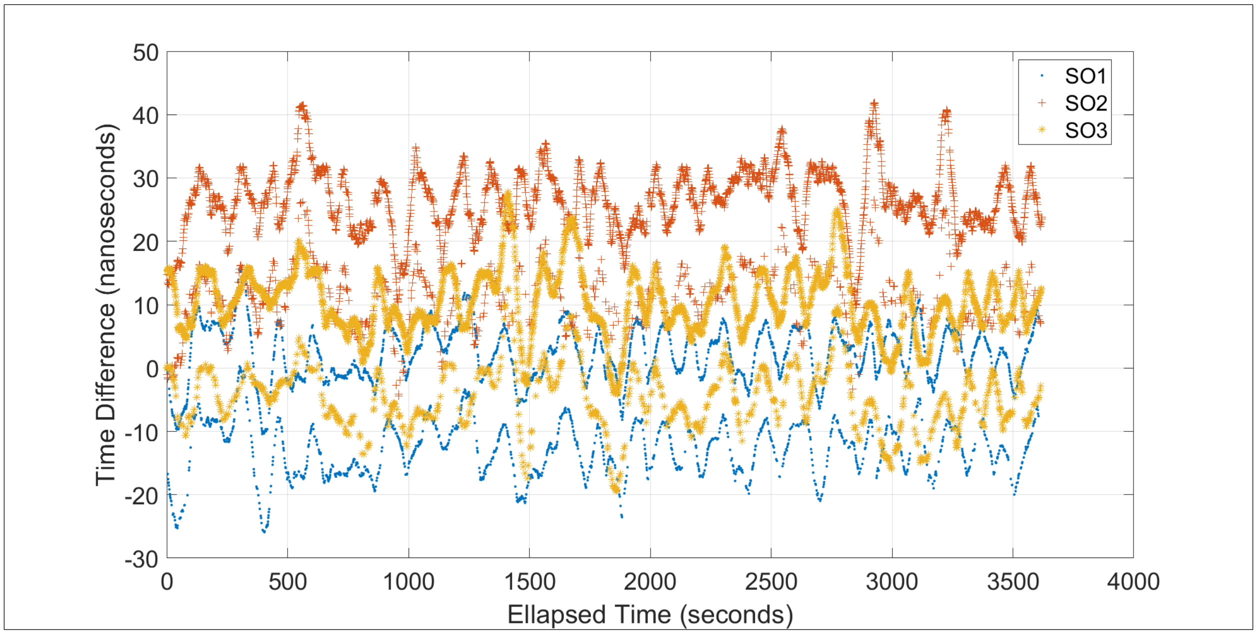


Figure 85. Static Outdoor Timing: PhasorLab – 1-pps Time Difference (ns) Relative to UTC (detrended)

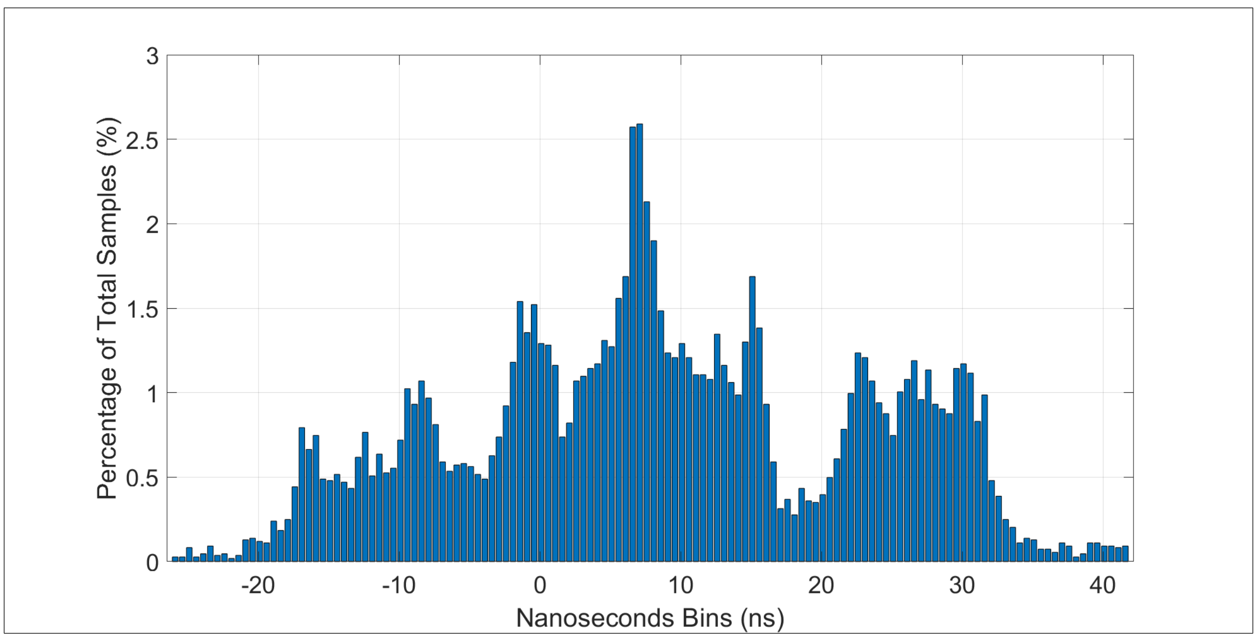


Figure 86. Static Outdoor Timing: PhasorLab – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

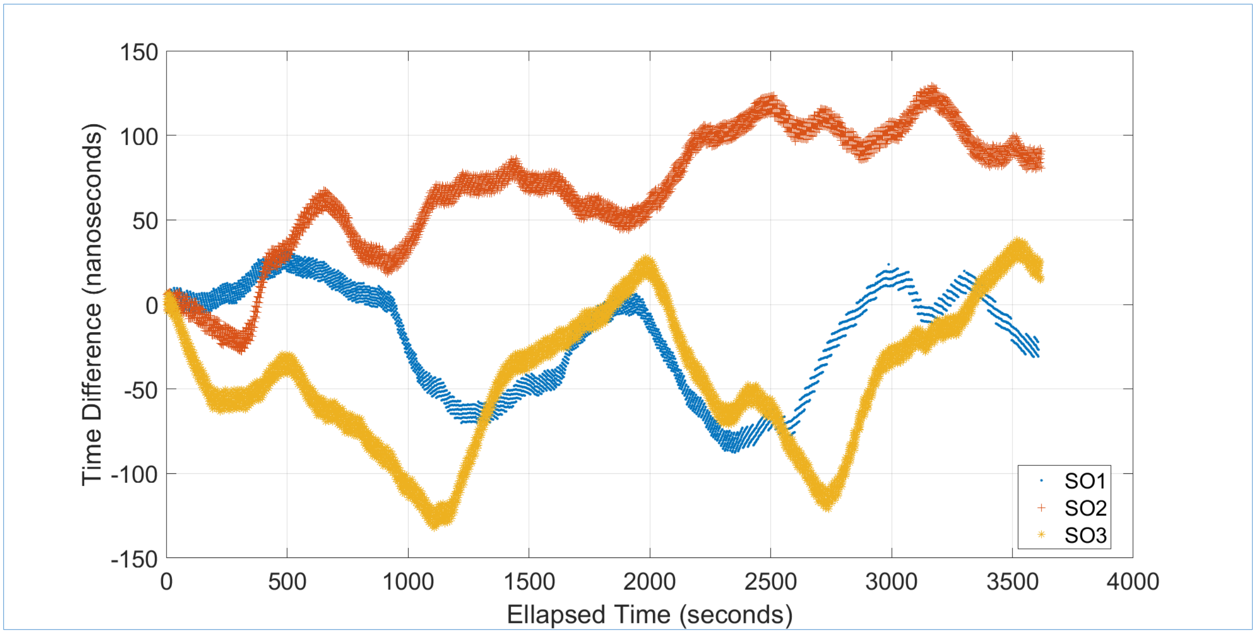


Figure 87. Static Outdoor Timing: Satelles – 1-pps Time Difference (ns) Relative to UTC (detrended)

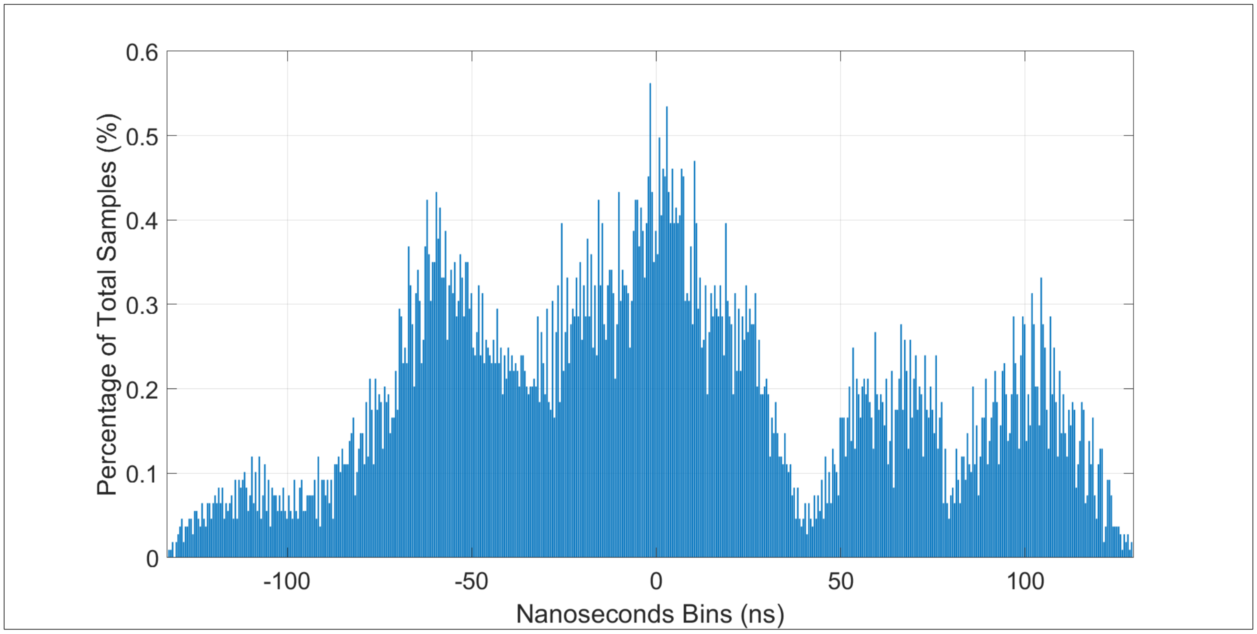


Figure 88. Static Outdoor Timing: Satelles – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

7.2.3 Scenario 6: Static Indoor Timing

This scenario was designed to assess the time transfer capability to challenged signal environment due to high signal attenuation and potential multipath conditions encountered inside buildings and other structures. A 60-minute continuous data collection was performed at three static indoor locations for each participating vendor system (see section 5.8.2.3). For each of these UEs, the three locations' detrended time series with initial time offset removed were overlaid. As discussed in section 7.1, for indoor data collection, when valid GPS signal was available the trends for the rover reference clocks were estimated based on observations before and/or after the data collection to characterize the atomic clocks (Cs for LaRC; Rb-based S650 for JBCC). The results are shown in Table 60.

Table 60. Scenario 6 – Static Indoor Timing Statistical Results

Vendor UE	Point	Slope (ns/hr)	Median (ns)	SD (ns)	|Max Deviation| (ns)	95th Percentile (|.|) (ns)
NextNav §	SI1	-1.01	-3.59	1.84	9.34	5.80
	SI3	-5.04	-1.47	2.53	17.29	6.13
	SI5	-17.73	-3.08	6.43	16.53	15.32
PhasorLab §	SI1	2.54	-5.23	6.43	43.77	18.66
	SI3	-18.45	-6.94	8.92	45.13	23.44
	SI5	-5.33	-15.53	6.44	42.51	24.57
Satelles SecureSync2-Rb (Ch2B) §	SI1	-318.72	-331.21	111.51	466.15	450.67
	SI3	161.50	39.93	61.42	154.92	142.06
	SI5	187.68	105.73	54.37	179.47	168.18
Satelles EVK2-Rb (Ch3B) §	SI1	2.74	6.74	3.95	17.76	13.40
	SI3	8.62	0.96	4.64	13.8	9.04
	SI5	6.12	5.38	4.20	17.24	13.20
Satelles EVK2-OCXO (Ch4B) §	SI1	29.77	-28.03	19.45	80.35	64.60
	SI3	5.77	60.71	22.08	124.56	98.47
	SI5	29.66	48.61	26.66	110.29	91.39
UrsaNav §	SI1	64.04	13.39	36.78	118.55	74.88
	SI3	-33.19	-9.05	27.51	87.29	57.37
	SI5	-23.86	-19.89	13.32	62.78	41.38

" § " indicates that detrending was needed and performed.

A time-series plot and corresponding histogram supporting the data in Table 60 are shown below for each of the participating vendors: Figure 89 and Figure 90 (NextNav); Figure 91 and Figure 92 (PhasorLab); Figure 93 and Figure 94 (Satelles SecureSync 1-Rb [Ch2A]); Figure 95 and Figure 96 (Satelles

EVK2-Rb [Ch3A]); Figure 97 and Figure 98 (Satelles EVK2-OCXO [Ch4A]); and Figure 99 and Figure 100 (UrsaNav).

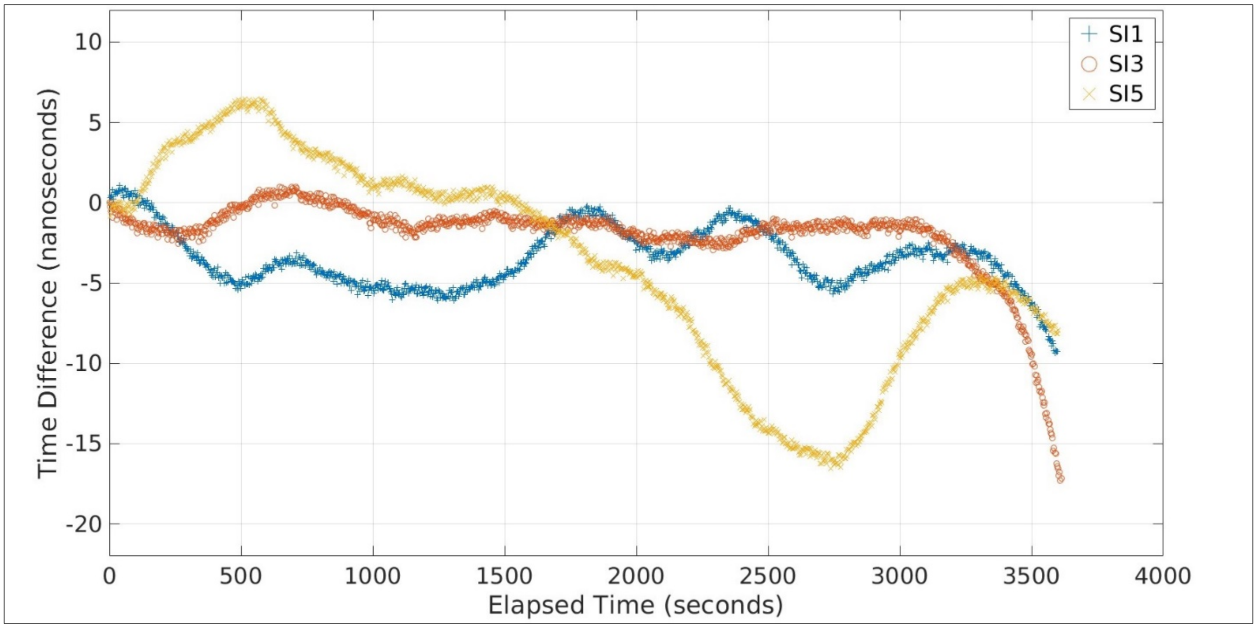


Figure 89. Static Indoor Timing: NextNav – 1-pps Time Difference (ns) Relative to UTC (detrended)

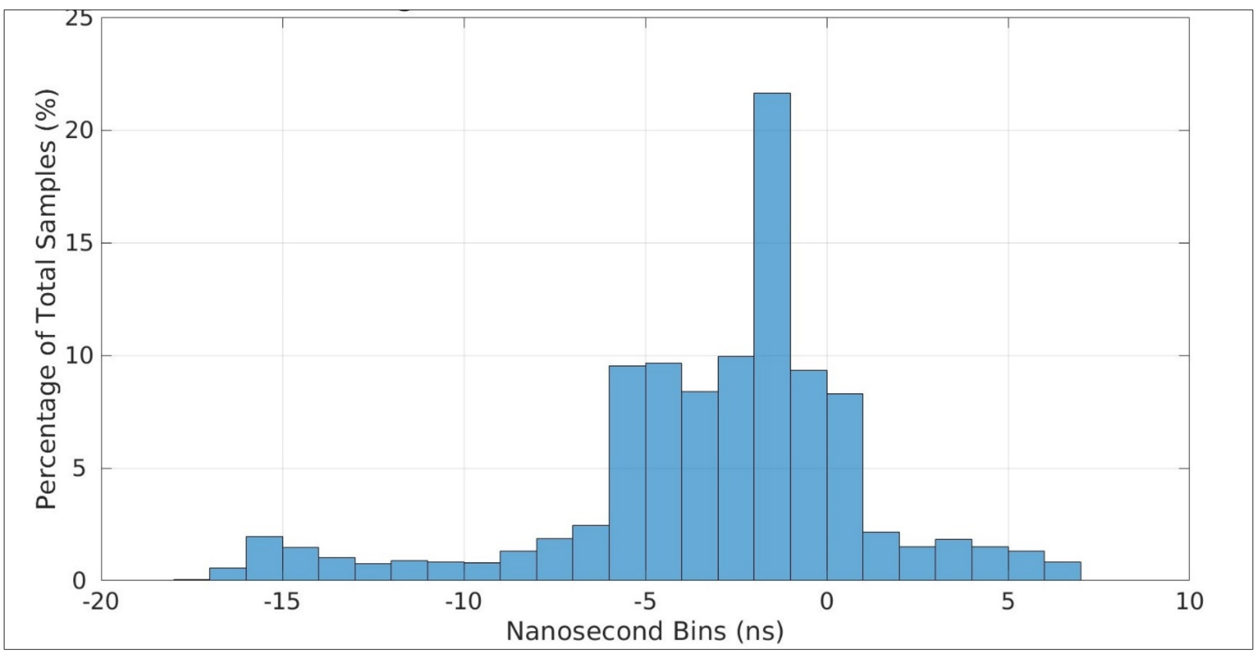


Figure 90. Static Indoor Timing: NextNav – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

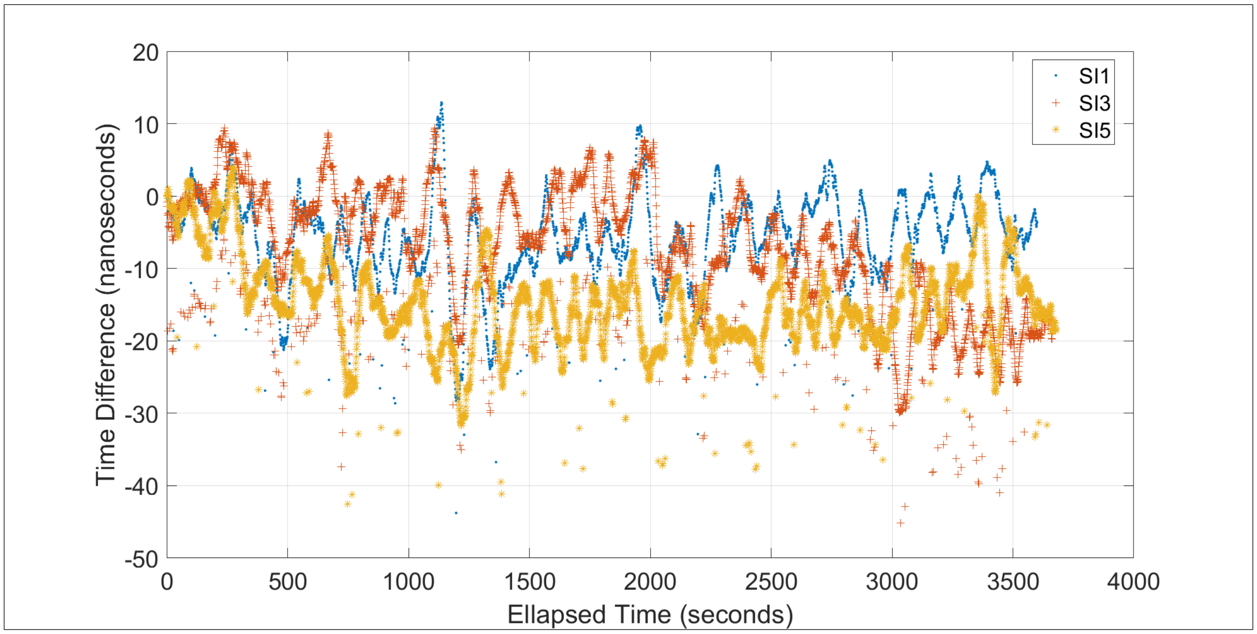


Figure 91. Static Indoor Timing: PhasorLab – 1-pps Time Difference (ns) Relative to UTC (detrended)

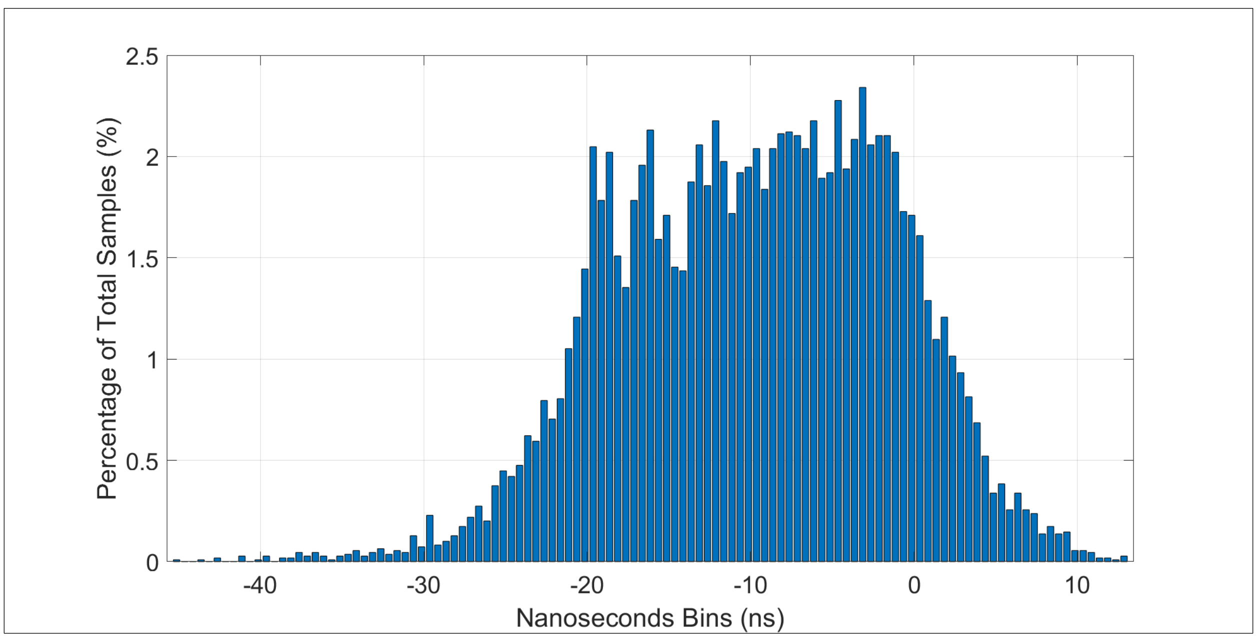


Figure 92. Static Indoor Timing: PhasorLab – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

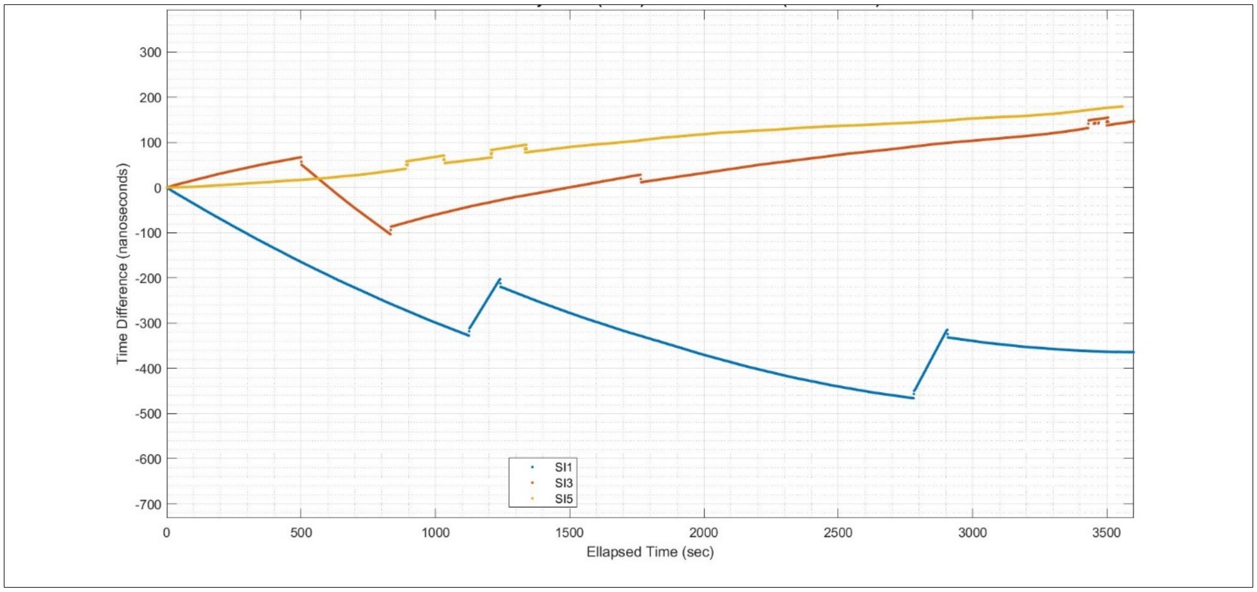


Figure 93. Static Indoor Timing: Satelles SecureSync2-Rb (Ch2B) – 1-pps Time Difference (ns) Relative to UTC (detrended)

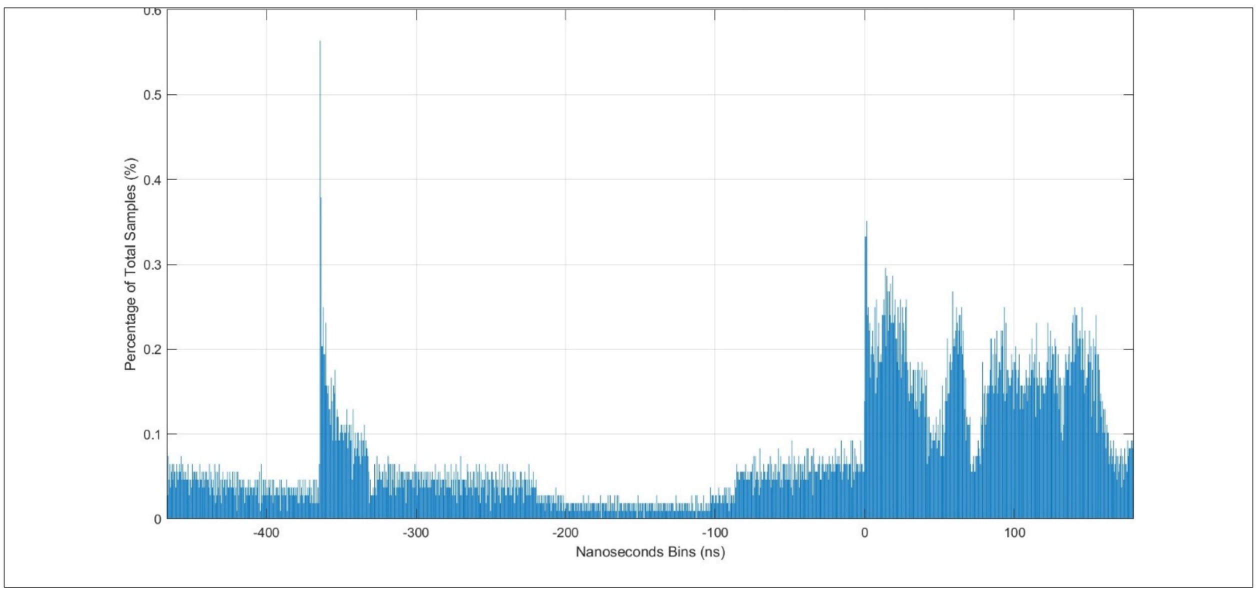


Figure 94. Static Indoor Timing: Satelles SecureSync2-Rb (Ch2B) – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

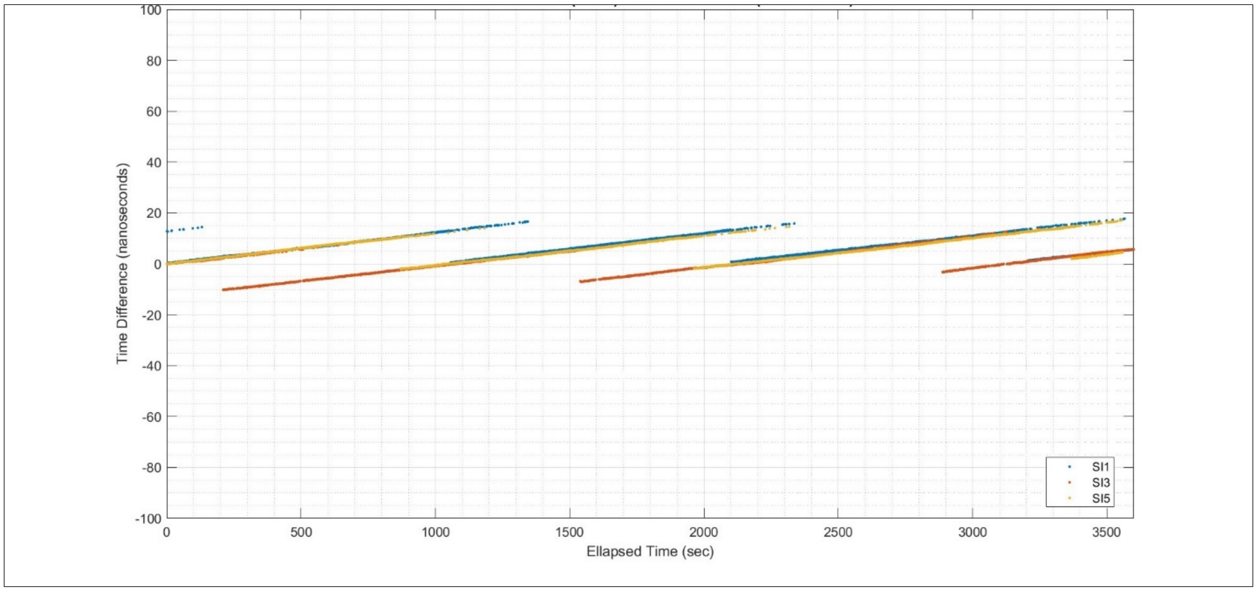


Figure 95. Static Indoor Timing: Satelles EVK2-Rb (Ch3B) – 1-pps Time Difference (ns) Relative to UTC (detrended)

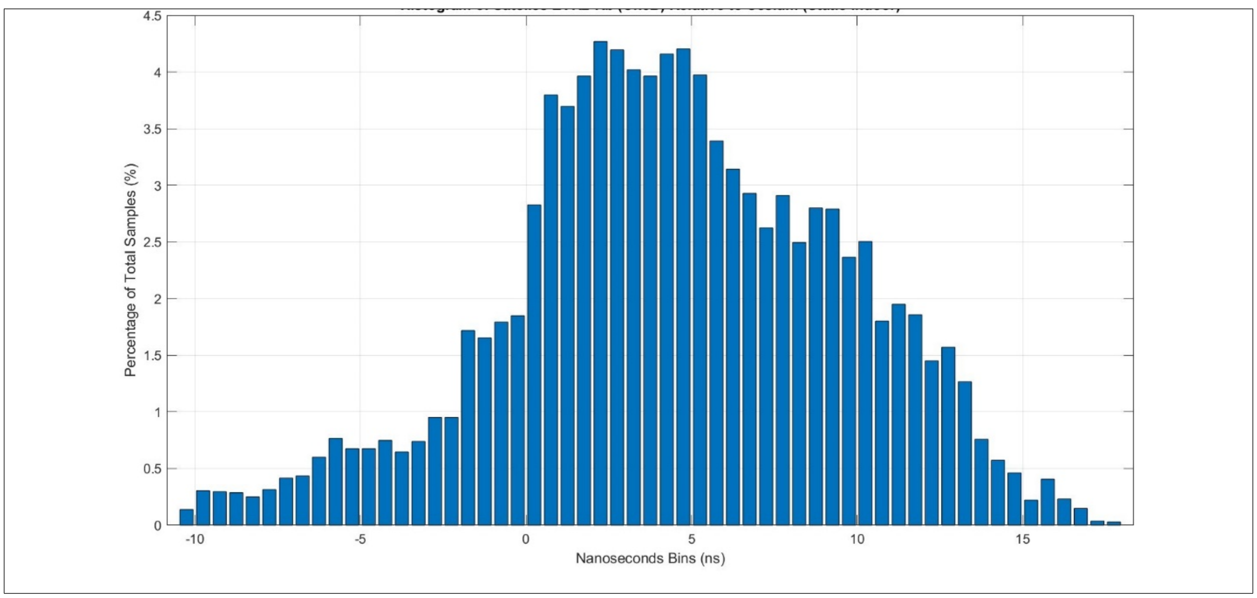


Figure 96. Static Indoor Timing: Satelles EVK2-Rb (Ch3B) – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

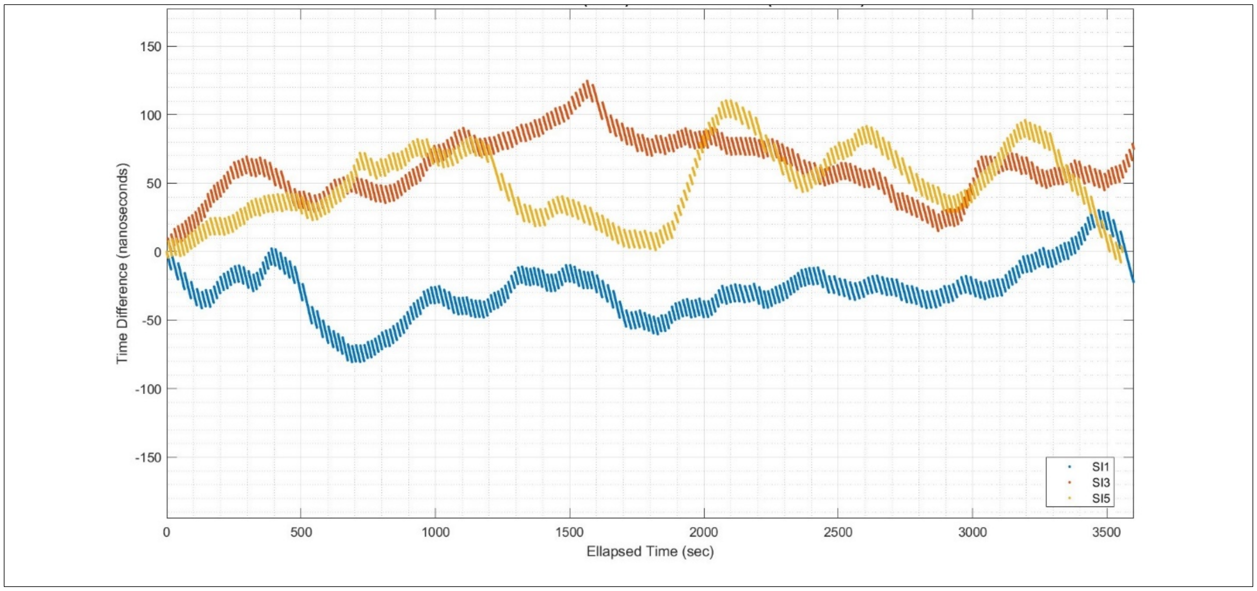


Figure 97. Static Indoor Timing: Satelles EVK2-OCXO (Ch4B) − 1-pps Time Difference (ns) Relative to UTC (detrended)

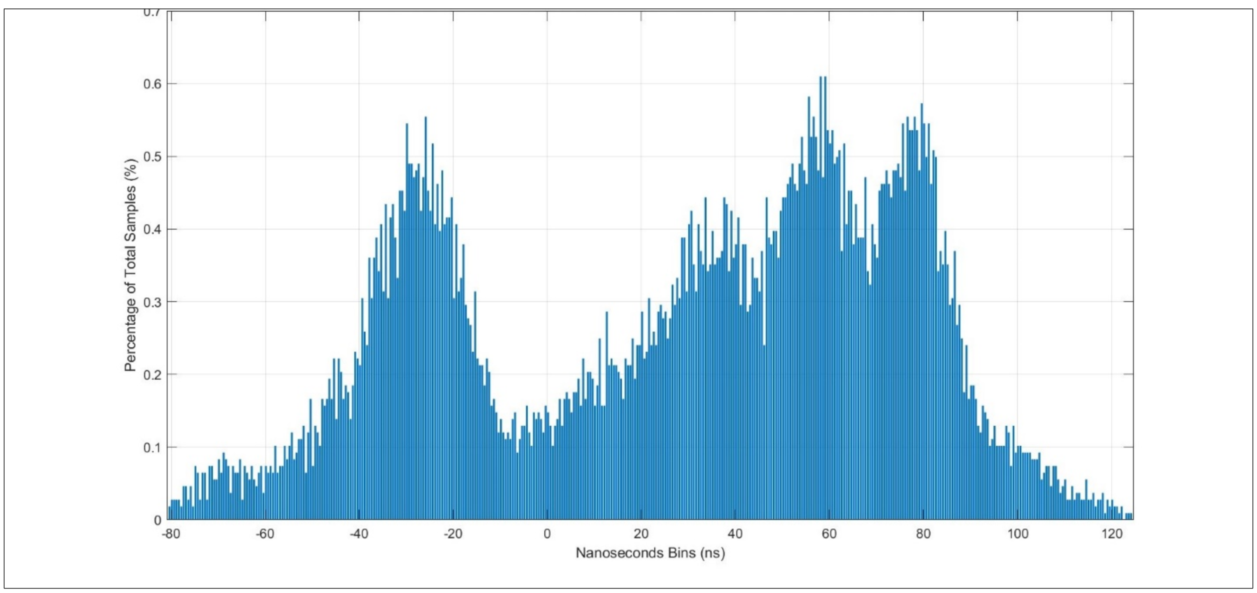


Figure 98. Static Indoor Timing: Satelles EVK2-OCXO (Ch4B) − Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

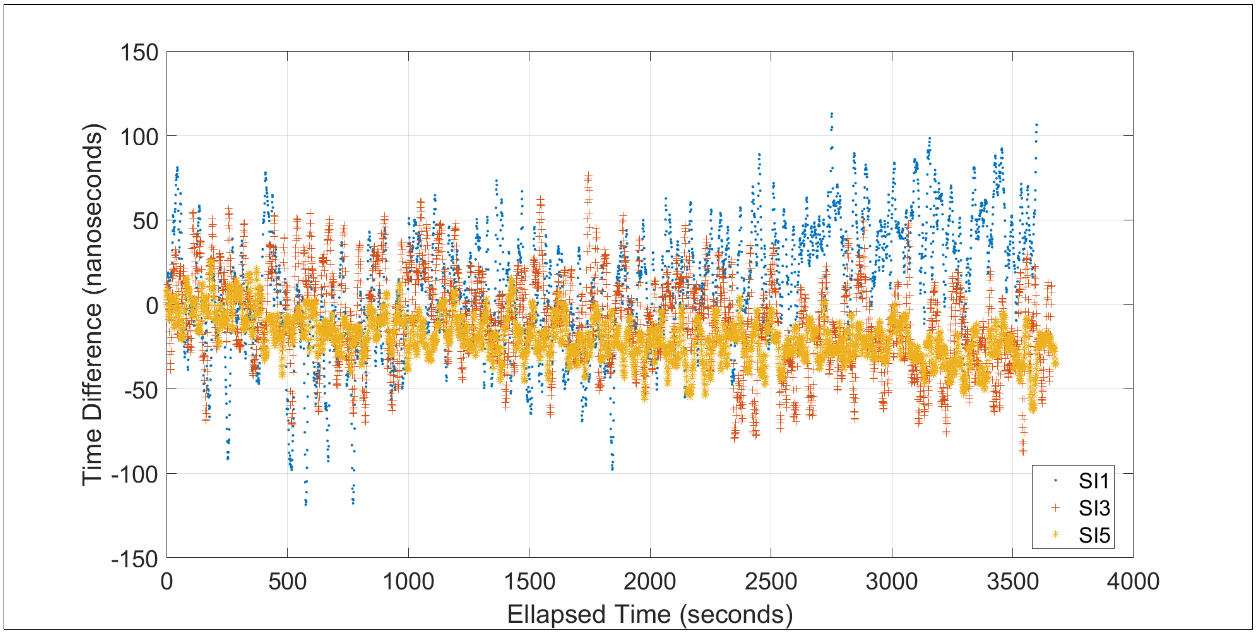


Figure 99. Static Indoor Timing: UrsaNav – 1-pps Time Difference (ns) Relative to UTC (detrended)

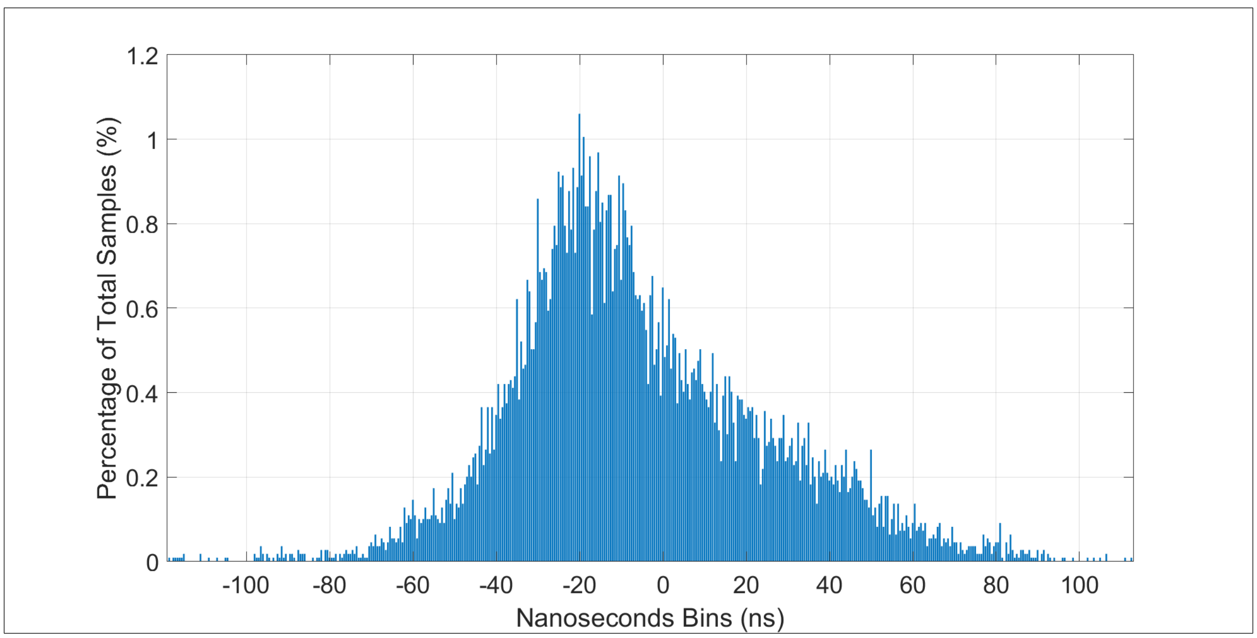


Figure 100. Static Indoor Timing: UrsaNav – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

7.2.4 Scenario 7: Static Basement Timing

This scenario was designed to assess the service availability and time transfer accuracy and stability in a GPS denied environment with potentially strong signal attenuation and multipath conditions encountered deep inside multistory buildings and below grade. Data collection was performed for one hour at one static, indoor, below-grade location for each participating vendor system. The Static Basement Timing scenario was conducted in the basement of Building 1230 for vendors demonstrating at LaRC and in the basement of Building 2822 for vendors demonstrating at JBCC.

Hellen and UrsaNav participated in this scenario, but no valid signal was received by the UE. For each of the other two vendor UEs, the detrended time series from the corresponding static location was plotted with initial time offset removed. As discussed in section 7.1, for basement data collection, the trends for the JBCC Rover reference subsystem clocks were estimated based on observations made by the Government Team before and/or after the data collection period, when valid GPS signal was available to characterize the atomic clocks. (Rb-based S650 for JBCC). For LaRC, the fixed reference subsystem and its associated Cs was used since the test location was in the same building. The corresponding histogram was calculated from the time series data at each corresponding location. The statistical results are shown in Table 61.

Table 61. Scenario 7 – Static Basement Timing Scenario Statistical Results

Vendor UE	Location	Slope (ns/hr)	Median (ns)	SD (ns)	|Max Deviation| (ns)	95th Percentile (|.|) (ns)
Hellen	SI7	No data	No data	No data	No data	No data
NextNav §	SI7	36.77	7.78	17.54	37.44	35.77
Satelles EVK2-OCXO §	SI7	-150.28	-272.62	117.01	485.68	460.47
UrsaNav	SI7	No data	No data	No data	No data	No data

“ § ” indicates that detrending was needed and performed.

A time series plot and corresponding histogram are shown for the NextNav UE in Figure 101 and Figure 102, and for the Satelles UE in Figure 103 and Figure 104.

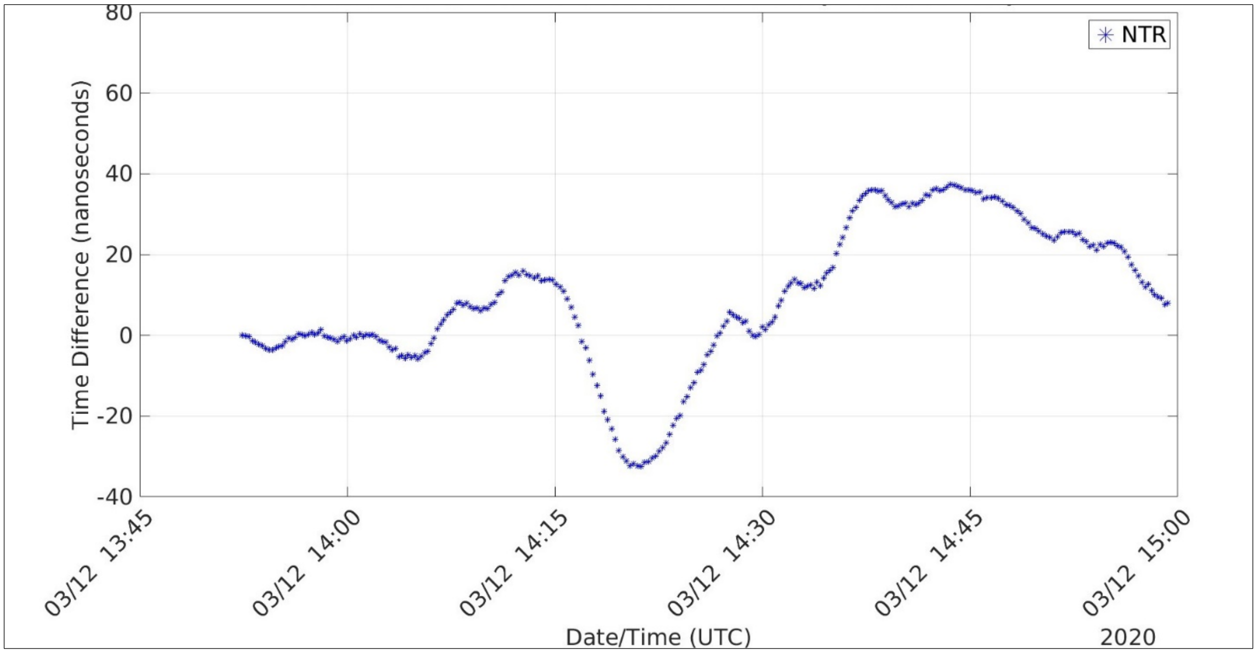


Figure 101. Static Basement Timing: NextNav – 1-pps Timing Difference (ns) Relative to UTC (detrended)

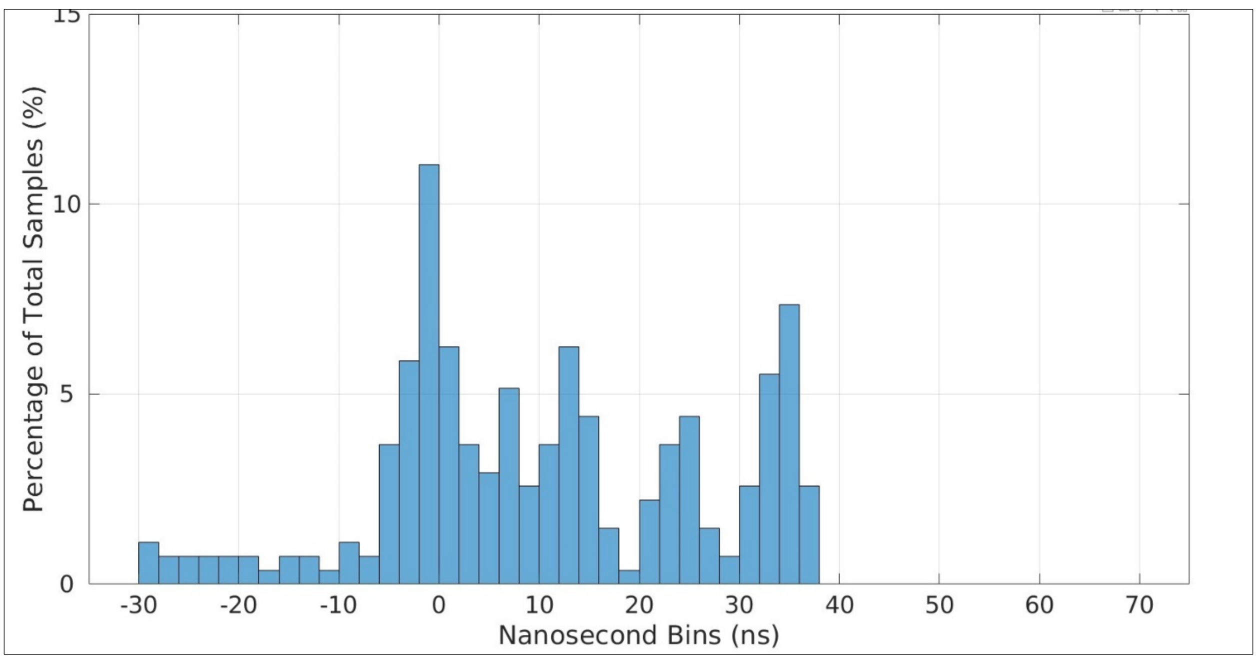


Figure 102. Static Basement Timing: NextNav – Distribution (% of Total Samples) of 1-pps Timing Difference (ns) Relative to UTC (detrended)

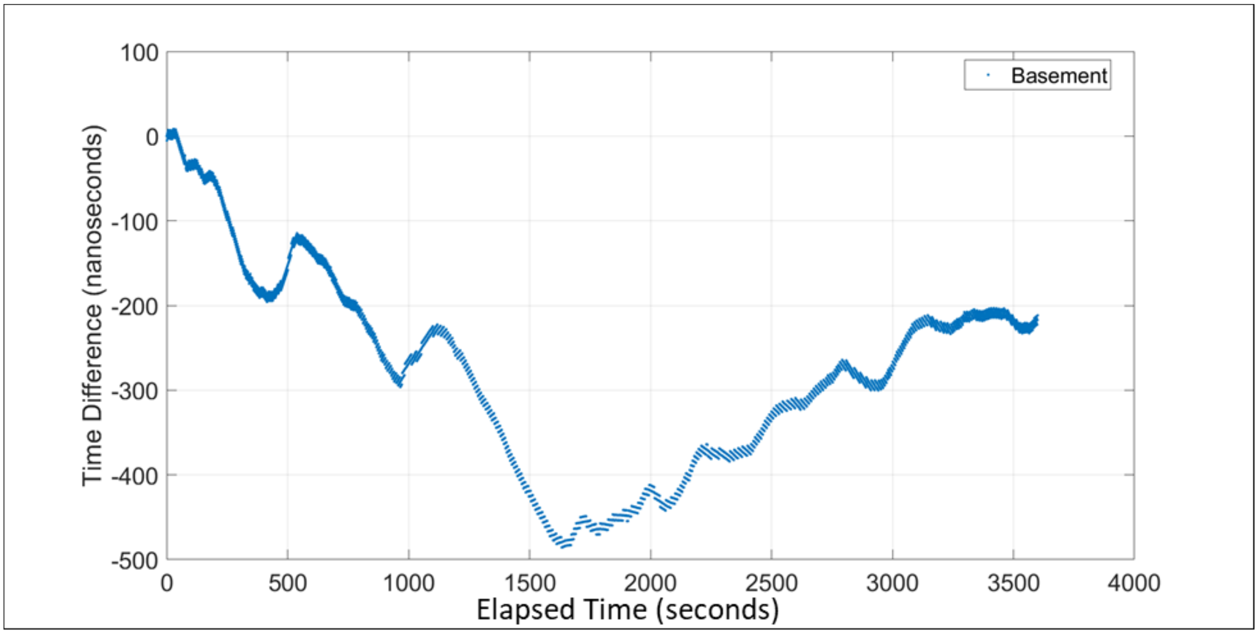


Figure 103. Static Basement Timing: Satelles – 1-pps Timing Difference (ns) Relative to UTC (detrended)

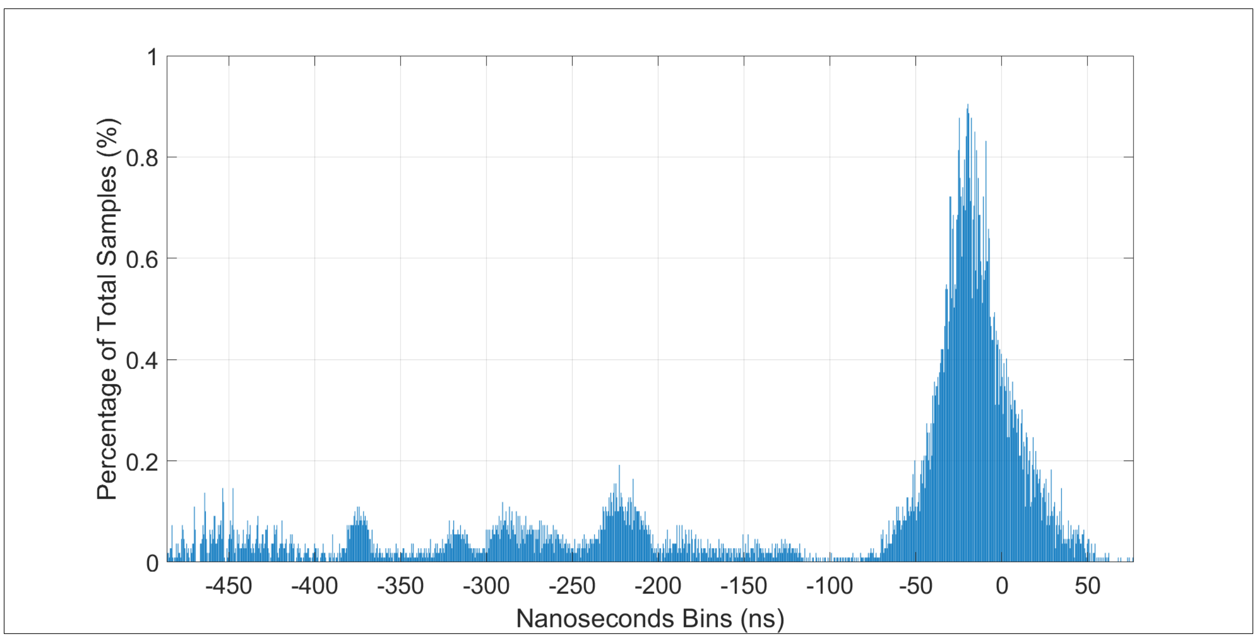


Figure 104. Static Basement Timing: Satelles – Distribution (% of Total Samples) of 1-pps Timing Difference (ns) Relative to UTC (detrended)

7.2.5 Scenario 9: eLORAN Reference Station Offset

The eLORAN Reference Station Offset scenario was developed to demonstrate the effects of eLORAN reference station corrections for progressively increasing baseline distances between the reference station and the UE. Each vendor installed their own reference station, at JBCC which transmitted correction information to UE.

As for the case of Scenario 4, the sensitivity of time error and short-term stability to the location of the outdoor UE antenna was performed to verify availability and to assess uniformity of coverage for eLORAN systems. However, since the demonstrated eLORAN system had a larger coverage region relative to the other RF-based, terrestrial-based systems participating in the demonstration, the offset locations were chosen to represent a larger coverage region. Additionally, the demonstrated eLORAN systems deployed had the potential to receive correction signals from their on-site reference station at JBCC, and therefore, it is informative (from a coverage perspective) to assess the time error characteristics and short term stability at locations with progressively large baselines to the reference station locations (one reference station location for each eLORAN system). This was done by performing a 60-minute data collection at each of three static locations, as described in section 5.8.2.5.

Table 62. Scenario 9 – eLORAN Reference Station Offset Timing Scenario Statistical Results

Vendor UE	Location/Baseline Distance to Reference Station* (nmi)	Slope (ns/hr)	Median (ns)	SD (ns)	|Max Deviation| (ns)	95th Percentile (|.|) (ns)
Hellen S§	SOF1/15	0.020	1.56	1.01	4.71	3.35
	SOF2/30	11.99	6.13	3.59	10.79	9.62
	SOF3/60	-8.50	-4.90	2.63	11.19	9.95
UrsaNav §	SOF1/15	6.35	21.35	10.41	44.26	37.51
	SOF2/30	1.63	26.43	5.85	36.20	32.90
	SOF3/60	6.93	0.42	4.92	12.75	9.74

" § " indicates that detrending was needed and performed.

*Distances are accurate up to a half-mile.

A time-series plot and corresponding histogram are shown for each of the vendors in Table 26 in Figure 105 and Figure 106 (Hellen), and Figure 107 and Figure 108 (UrsaNav).

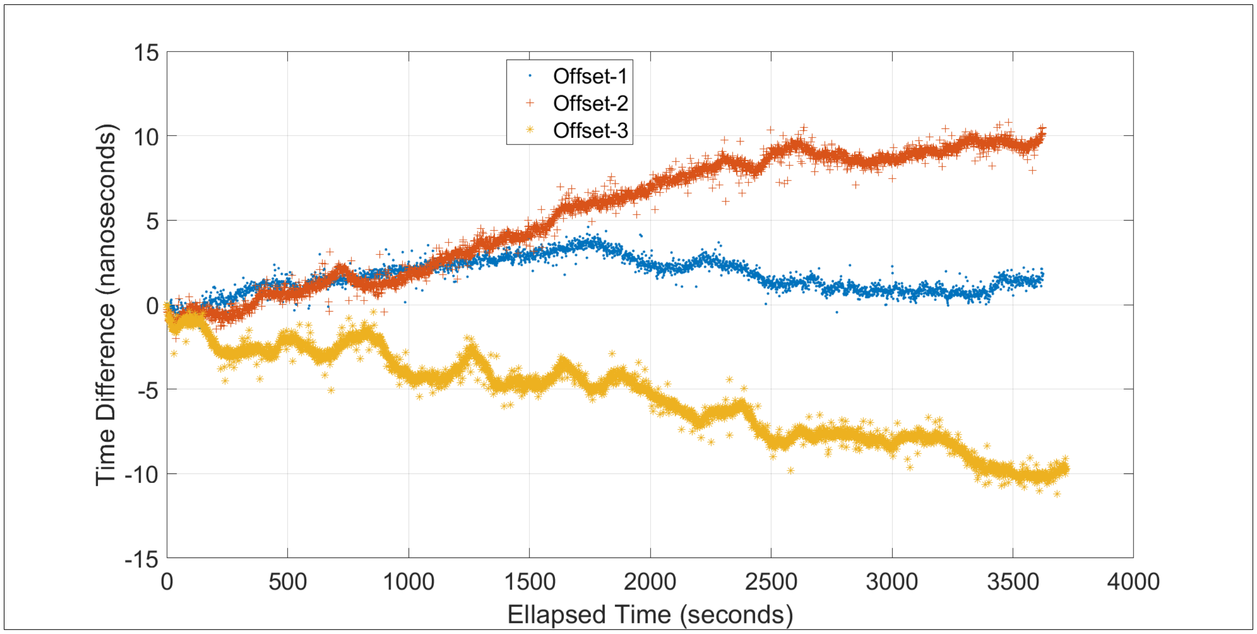


Figure 105. eLORAN Reference Station Offset Timing: Hellen – 1-pps Time Difference (ns) Relative to UTC (detrended)

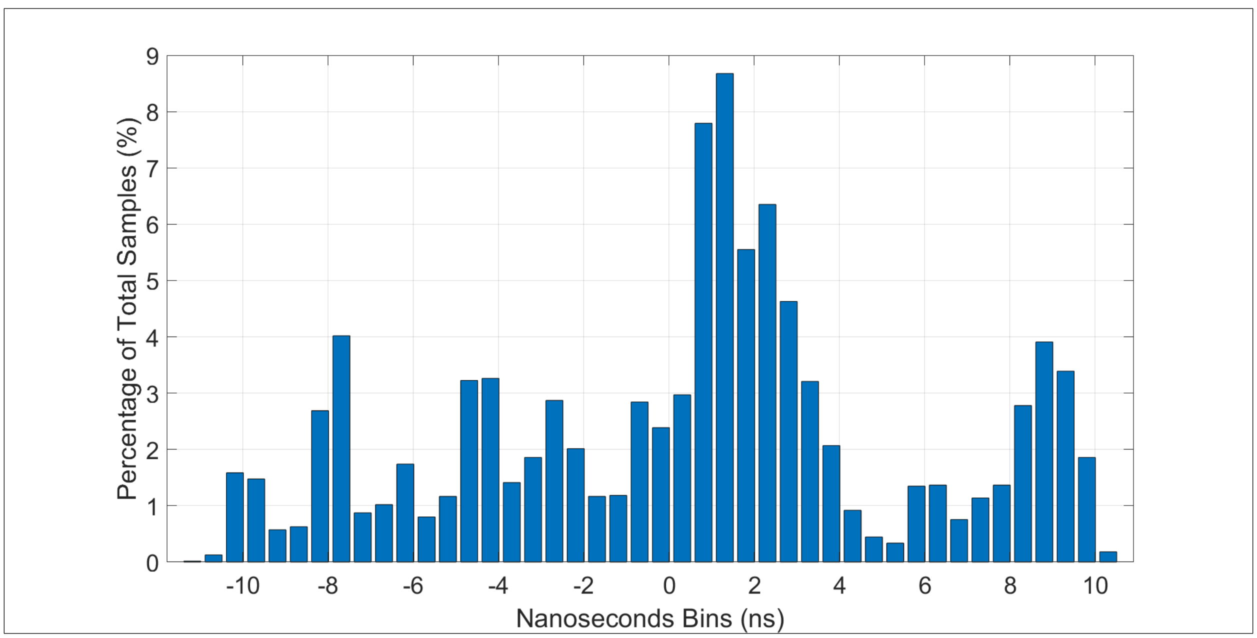


Figure 106. eLORAN Reference Station Offset Timing: Hellen – Distribution (% of Total Samples) of 1-pps Time Difference (ns) Relative to UTC (detrended)

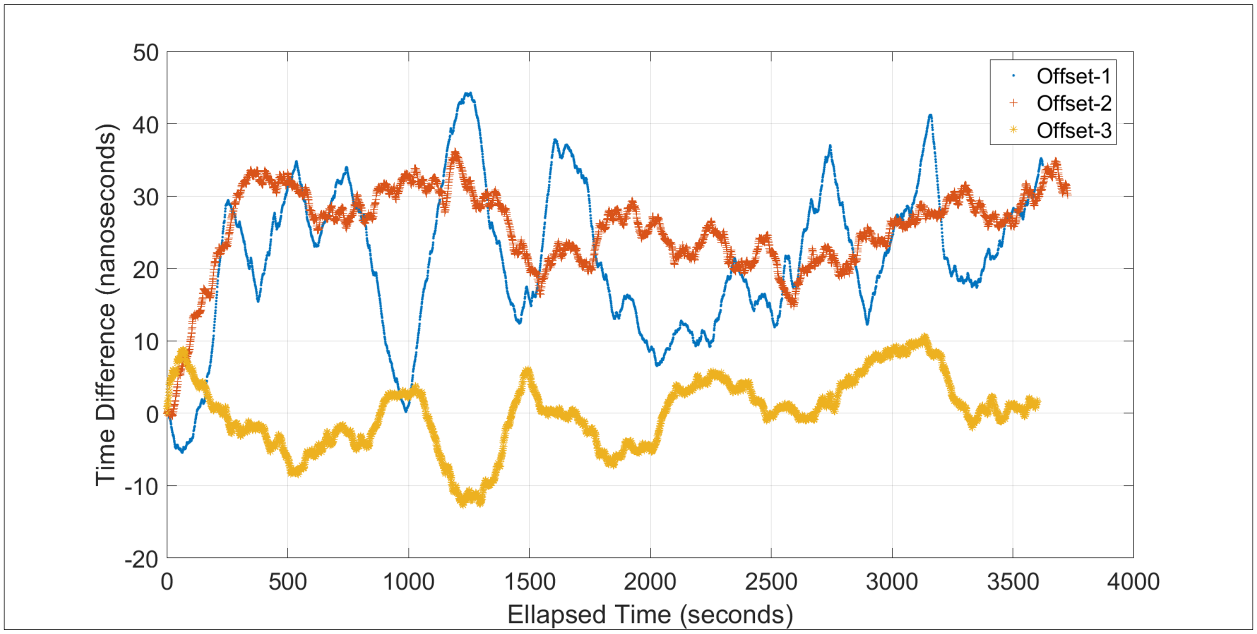


Figure 107. eLORAN Reference Station Offset Timing: UrsaNav – 1-pps Timing Difference (ns) Relative to UTC (detrended)

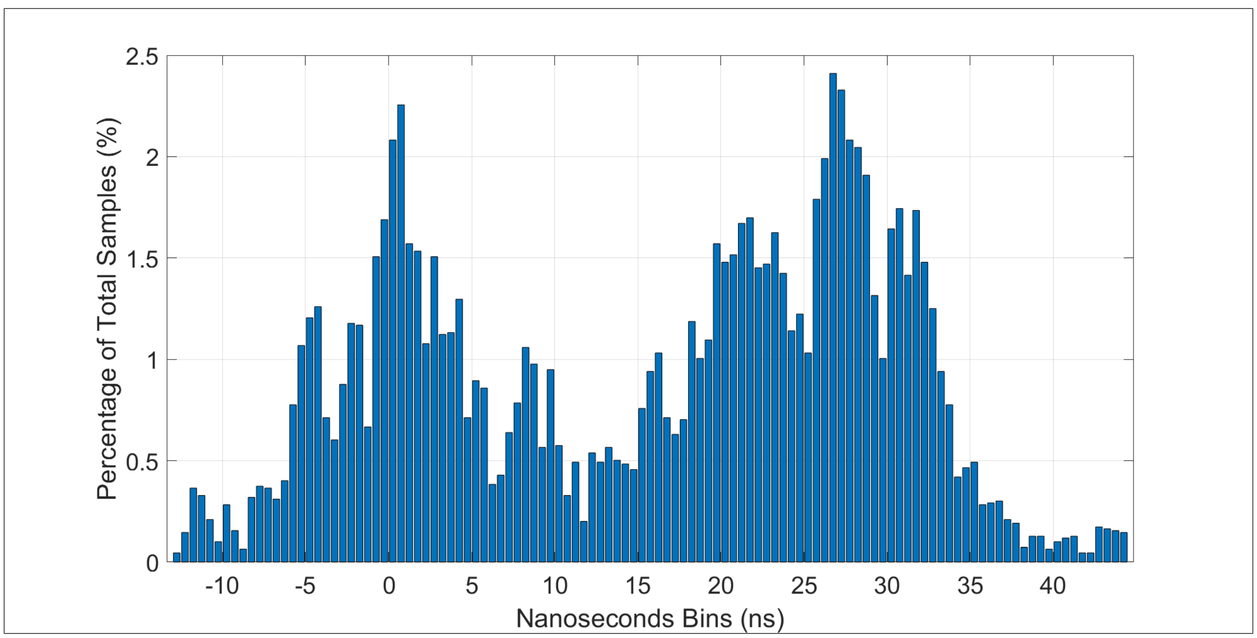


Figure 108. eLORAN Reference Station Offset Timing: UrsaNav – Distribution (% of Total Samples) of 1-pps Timing Difference (ns) Relative to UTC (detrended)

8 Measures of Effectiveness

This section describes three principal components of the information framework constructed around the PNT technology demonstration.

- **Definition** of 14 Measures of Effectiveness (MoEs) and the rationale for using scoring rubrics to apply them, followed by **evaluation** of all {technology, scenario} pairs against each MoE
- **Formulation of scoring function(s)** based on evaluated MoEs and stakeholder weightings
- **Hierarchical application of scoring functions** to support programmatic or strategic decisions

As previously noted in section 2.2, these MoEs fall into two logical subsets:

- Capability subset (MoE-1 through MoE-9). The MoEs can be evaluated using inherently more *quantitative* rubrics.
- Suitability subset (MoE-10 through MoE-14). The MoEs in this group which can be evaluated using inherently more *qualitative* rubrics.

MoE definition and first-round scoring results follow below in section 8.1. The results of the second-round adjudication are then presented in section 8.2.

8.1 Measures of Effectiveness: Definition and Results

The performance of the technologies demonstrated in each scenario underwent a two-round evaluation by the Government Team's subject matter experts (SMEs) based on information gathered during preparation and implementation of the demonstration (sections 3 and 5) and through analysis of the positioning and timing results demonstrated in the field campaign (Sections 6 and 7).

To create the framework for the evaluation, the Government Team defined 14 Measures of Effectiveness (MoEs), their respective rubrics, and the quantification (0% to 100%) of each rubric level for the purpose of writing a scoring function. All MoEs had a scorecard structured in a vendor technology-by -scenario matrix representing their participation (see section 5, Figure 13).

The first-round evaluation was performed independently by individual SMEs; followed by a second-round adjudication to reach consensus across the SMEs on each MoE evaluation.

The MoEs and their associated scorecards are presented below.

8.1.1 MoE-1: Technical Readiness–System

Prior to the demonstration, DOT's Request for Information (RF) activities (See section 2.5) established a minimum for the technical readiness of any given PNT technology to be demonstrated. Using the FHWA Technology Readiness Level Guidebook's[38] scale of TRL levels 1 to 9, the minimum was set at TRL 6. This minimum supported two core considerations: 1) that a system could be demonstrated in the field, and

[38] Federal Highway Administration, Technology Readiness Level Guidebook FHWA-HRT-17-047, September 2017. At https://www.fhwa.dot.gov/publications/research/ear/17047/17047.pdf

2) that a service could be rapidly implemented. Vendors submitted their self-survey of TRL from both a system perspective and a user equipment perspective. The SMEs used these self-surveys, along with observations made during demonstration fielding and execution, to assess the technical readiness of both the system and the user equipment. Generally, the system TRL was considered by the Government Team to be the more important, because this aligns with the GPS mode, in which investment and/or endorsement of public service is heavier on the provider side rather than the user equipment.

Rubric: Technical Readiness Level
Values: TRL 1–TRL 9, TRL 6 or above considered valid for demonstration
Quantification %: TRL 1–5 = 0%, TRL 6 = 20%, TRL 7 = 40%, TRL 8 = 70%, TRL 9 = 100%

Figure 109 presents the consensus scorecard for MoE-1.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					**N/A**		**8**		
Hellen Systems, LLC	JBCC	**8**			**8**	**8**				
NextNav LLC	LaRC	**9**	**9**	**9**	**9**	**N/A**	**9**	**9**	**9**	**9**
OPNT B.V.	LaRC	**9**				**N/A**				
PhasorLab Inc.	JBCC	**8**	**8**	**8**		**N/A**	**7**	**7**		**7**
Satelles, Inc.	JBCC	**9**	**9**	**9**	**9**	**N/A**		**9**		
Serco Inc.	JBCC					**N/A**	**5**	**5**		
Seven Solutions S.L.	LaRC	**9**				**N/A**				
Skyhook Wireless, Inc.	LaRC					**N/A**	**9**	**9**	**9**	**9**
TRX Systems, Inc.	LaRC					**N/A**	**7**	**7**	**7**	
UrsaNav Inc.	JBCC	**9**		**9**	**9**	**9**				
GPS (SPS PS)	All	**9**	**9**			**9**	**9**	**9**		**9**

Rubric:	level
	9
	8
	7
	6
	5

Figure 109. MoE-1. Technical Readiness–System Consensus Scorecard

8.1.2 MoE-2: Technical Readiness–User Equipment

The TRL of the user equipment was assessed to identify its potential influence on overall performance. Although not necessarily as important as the System TRL, the user equipment TRL provides a means for potential weighting in the MoE framework for decision making, should the Government wish to consider the impact on the end user of adopting different PNT technologies.

Rubric: Technical Readiness Level)
Values: TRL 1–9; TRL 6 or above considered valid for demonstration
Quantification %: TRL 1–5 = 0%, TRL 6 = 20%, TRL 7 = 40%, TRL 8 = 70%, TRL 9 = 100%
Quantification %: TRL 1–5 = 0%, TRL 6 = 20%, TRL 7 = 40%, TRL 8 = 70%, TRL 9 = 100%

Figure 110 presents the consensus scorecard for MoE-2.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		7		
Hellen Systems, LLC	JBCC	7			7	7				
NextNav LLC	LaRC	8	8	8	8	N/A	9	9	9	9
OPNT B.V.	LaRC	9				N/A				
PhasorLab Inc.	JBCC	8	8	8		N/A	7	7		7
Satelles, Inc.	JBCC	9	9	9	9	N/A		9		
Serco Inc.	JBCC					N/A	5	5		
Seven Solutions S.L.	LaRC	9				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	9	9	9	9
TRX Systems, Inc.	LaRC					N/A	8	8	8	
UrsaNav Inc.	JBCC	8		8	8	8				
GPS (SPS PS)	All	9	9			9	9	9		9

Rubric:	level
	9
	8
	7
	6
	5

Figure 110. MoE-2: Technical Readiness–User Equipment Consensus Scorecard

8.1.3 MoE-3: Timing and Positioning Accuracy

Accuracy is an essential performance consideration for a PNT service. Often, that importance can be overemphasized at early stages of consideration, when other important performance parameters, such as integrity, robustness, and availability, are more difficult to quantify. For this demonstration, the Government Team developed an Accuracy MoE to represent those quantitative performance parameters more broadly. Further, with the defined rubric, the Accuracy MoE is better able to capture the breadth of performance while setting the context for the PNT function being demonstrated.

Specifically, the Accuracy MoE is a scalar representation of the residual error of the timing or positioning function that a given technology demonstrated. It is assessed as residual error against the government reference system, and set as the observed 95% bound of that residual error in a given scenario for a given technology. The choice of a 95% bound acknowledges the broader context of performance parameters by extending assessment out into the wider distribution of residual error.

Quantification of the Accuracy (and later, Service Coverage) rubric values is, in contrast to the other MoEs, numerical, and is evaluated for each technology as the proportional inverse of 95% observed residual error against the range of all 95% residual error bounds— *i.e.*, of all technology-scenario pair entries.

Rubric: Residual error in positioning (m) or timing (ns) against Government reference system
Values: Scalar; largest 95% bound across all runs in a scenario
Quantification %: Proportional inverse error in range over all participating technologies

Because some vendors sought to demonstrate their PNT technologies in only certain scenarios, this MoE was subdivided into three independent elements, each using the same rubric, values, and quantification described above:

- MoE-3a: Timing Accuracy (ns)
- MoE-3b: Two-dimensional (2D) Positioning Accuracy (m)
- MoE-3c: Three-dimensional (3D) Positioning Accuracy (m)

Figure 111 presents the consensus scorecard for MoE-3.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					**N/A**		**333.2**		
Hellen Systems, LLC	JBCC	**114.9**			**failed to close**	**3.4**				
NextNav LLC	LaRC	**23.1**	**7.1**	**5.8**	**17.5**	**N/A**	**15.6**	**6.7**	**8.9**	**3.8**
OPNT B.V.^	LaRC	**0.2**				**N/A**				
PhasorLab Inc.	JBCC	**9.4**	**17.4**	**18.7**		**N/A**	**11.7**	**7.4**		**8.6**
Satelles, Inc.	JBCC	**75.5**	**75.0**	**9.0**	**117.0**	**N/A**		**9.0**		
Serco Inc.	JBCC					**N/A**	**DNQ**	**39.4**		
Seven Solutions S.L.^	LaRC	**0.1**				**N/A**				
Skyhook Wireless, Inc.	LaRC					**N/A**	**7.6**	**1.8**	**23.5**	**14.6**
TRX Systems, Inc.	LaRC					**N/A**	**9.7**	**6.2**	**9.8**	
UrsaNav Inc.	JBCC	**80.1**		**57.4**	**failed to close**	**9.7**				
GPS (SPS PS)	All	**30**	**30**			**30**	**5**	**5**		**7**

^ 1PPS from USG at measurement node

Rubric:

positioning: max 95%{runs} (m)
1.8 to 333

timing: max 95%{runs} (ns)
0.1 to 117

Figure 111. MoE-3: Timing and Positioning Accuracy Consensus Scorecard

8.1.4 MoE-4: Spectrum Protection

Regulatory protection of the distribution of PNT information is an important consideration in the viability and effectiveness of a PNT service, particularly for wireless radio-frequency (RF) technologies. The mode of distribution for each technology is further described in section 3.2. This MoE is also directly related to MoE-10 (PNT Distribution Mode). However, the allocation of spectrum can change over time—and can often be contentious, as illustrated by the current situation involving GPS/GNSS spectrum. The Government Team identified spectrum protection as a specific concern and an important MoE.

The values specified for spectrum protection describe what level of allocation (if applicable) is available to the given PNT technology being demonstrated. Those levels are then quantified by assignment to a point on the 0%-100% scale for possible later scoring purposes.

Rubric: FCC authorization level (for wireless RF-spectrum-based technologies)
Values: Protected (*e.g.*, Aeronautical Radionavigation Service [ARNS]), owned, leased, shared
Quantification %: protected = 100%, owned = 75%, leased = 50%, shared = 25%

Figure 112 presents the consensus scorecard for MoE-4.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		protected		
Hellen Systems, LLC	JBCC	protected			protected	protected				
NextNav LLC	LaRC	owned	owned	owned	owned	N/A	owned	owned	owned	owned
OPNT B.V.	LaRC	N/A				N/A				
PhasorLab Inc.	JBCC	shared	shared	shared		N/A	shared	shared		shared
Satelles, Inc.	JBCC	protected	protected	protected	protected	N/A		protected		
Serco Inc.	JBCC					N/A	protected	protected		
Seven Solutions S.L.	LaRC	N/A				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	shared	shared	shared	shared
TRX Systems, Inc.	LaRC					N/A	shared	shared	shared	
UrsaNav Inc.	JBCC	protected		protected	protected	protected				
GPS (SPS PS)	All	protected	protected			protected	protected	protected		protected

Rubric:

protected
owned
leased
shared

Figure 112. MoE-4: Spectrum Protection Consensus Scorecard

8.1.5 MOE-5: Service Deployment Effort

Cost is a central consideration in any PNT investment decision. This demonstration effort was not comprehensive enough to formulate cost estimates for implementation of a PNT service based on one or more of the included technologies. The demonstration did, however, provide a reasonable indication of service deployment effort in the form of the time and materials needed to execute the demonstrated technology's PNT function. Service Deployment Effort is a significant cost factor.

The Government Team gathered significant observations on the deployment effort through each phase of the demonstration process: the Federal acquisition process, demonstration site installation, the dry run, and the demonstration itself. The rubric condensed these observations into a low/medium/high metric and assigned quantification on the normalized scale at one-third increments.

Rubric: Observed effort/resource for demonstration
Values: Low, medium, high
Quantification %: low = 100%, medium = 66%, high = 33%

Figure 113 presents the consensus scorecard for MoE-5.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		low		
Hellen Systems, LLC	JBCC	medium			medium	medium				
NextNav LLC	LaRC	high	high	high	high	N/A	high	high	high	high
OPNT B.V.	LaRC	low				N/A				
PhasorLab Inc.	JBCC	high	high	high		N/A	high	high		high
Satelles, Inc.	JBCC	low	low	low	low	N/A		low		
Serco Inc.	JBCC					N/A	medium	medium		
Seven Solutions S.L.	LaRC	low				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	low	low	low	low
TRX Systems, Inc.	LaRC					N/A	medium	medium	medium	
UrsaNav Inc.	JBCC	medium		medium	medium	medium				
GPS (SPS PS)	All	low	low			low	low	low		low

Rubric:

low
medium
high

Figure 113. MOE-5: Service Deployment Effort Consensus Scorecard

8.1.6 MoE-6: Service Coverage per Unit of Infrastructure

Service Coverage is the second performance consideration (after Accuracy) that is quantified numerically. It is also a second important cost factor to which the demonstration can contribute information. The infrastructure (transmitters, linkages, antennas, etc.) needed to execute a given technology's PNT function under the use case scenarios provided the Government SMEs an observable quantity to use when assessing the ratio of infrastructure used to the instrumented coverage region. In addition, the demonstration provided a mechanism to both count and [coarsely] project the scale of infrastructure needed for broader coverage.

Service Coverage MoE was modeled as a linear function of the "baseline" infrastructure as the incept, and the" marginal" infrastructure as the slope, to separate the "baseline" infrastructure a given technology needs to operate, and the "marginal" infrastructure that the technology would need to extend coverage geographically. The resulting model provides scalable cost factor for assessing infrastructure per coverage area. The model for the Coverage MoE did not account for second-order factors such as demographics or fielding suitability—*e.g.*, ocean versus land, that are addressed by other MoEs. Thus, the Service Coverage MoE is similar to the Deployment Effort MoE in that it serves only as a factor for cost estimation in subsequent efforts and/or strategies.

The rubric for Service Coverage is similar to that for Accuracy in that it is a scalar representation of the infrastructure per coverage area. Here, the intercept is the baseline number of transmitters needed regardless of how much area is covered, and the slope is the number of additional transmitters needed to extend coverage to a target area.

A visual form of the Service Coverage rubric is given in Figure 114 for Positioning and Figure 115 for Timing. The curves in each graphic are a given technology's transmitter density, which is used to demonstrate positioning/timing capability for the coverage area. Note that the curves for satellite-based technologies (GPS, Echo Ridge, and Satelles) are constants at their respective constellation counts.

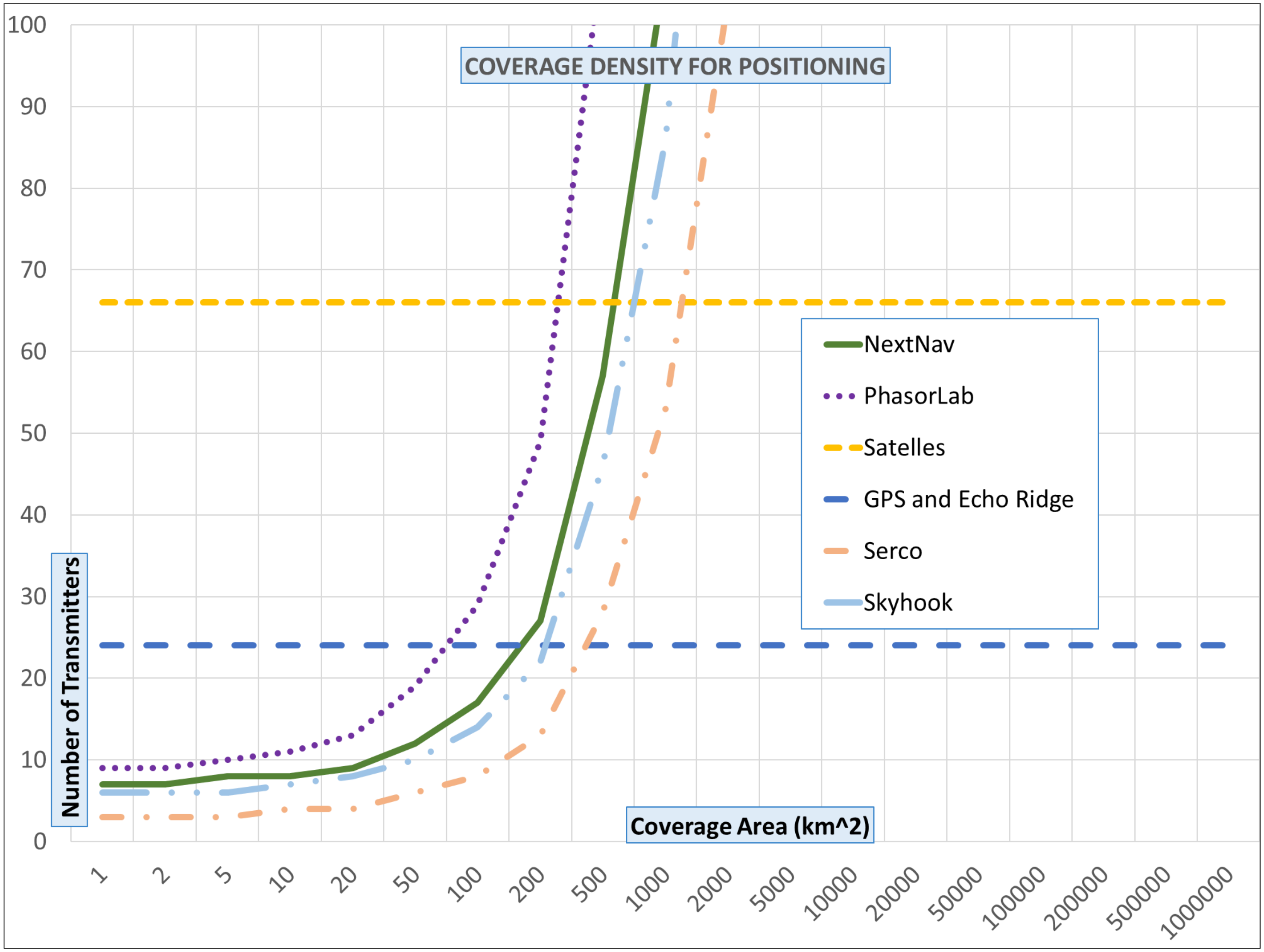


Figure 114. Transmitter density curves for those technologies demonstrating positioning service over the demonstration coverage area.

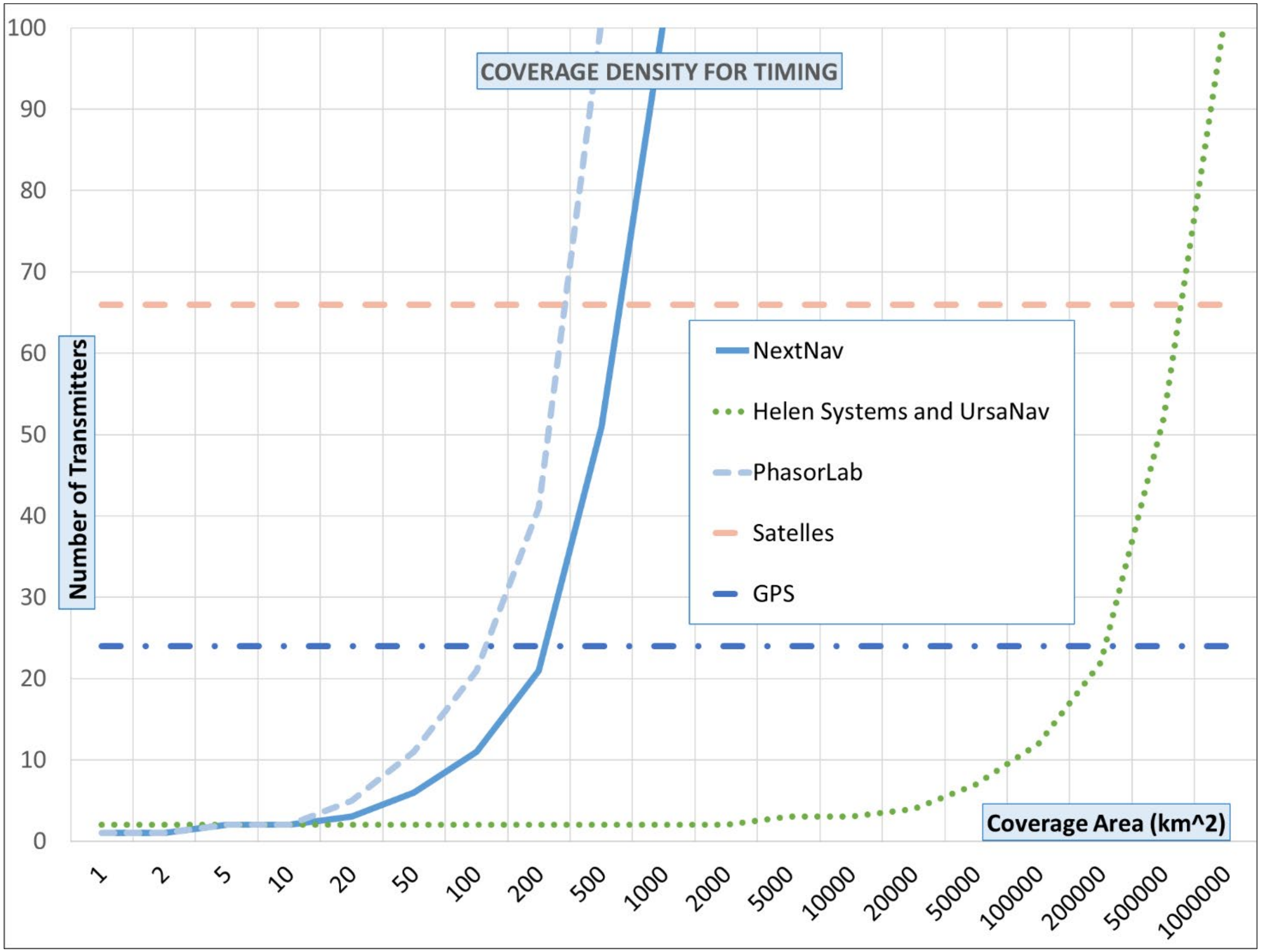


Figure 115. Transmitter density curves for those technologies demonstrating timing service over the demonstration coverage area.

The scoring quantification of Service Coverage is then evaluated (rather than explicitly assigned) at a given target coverage area as the proportional inverse of that unit coverage value in the range of all unit coverage values, *i.e.*, all (technology, scenario) pair entries.

Rubric: Infrastructure per covered area, affine model of baseline + marginal
Values: Number of transmitters in target coverage area (units per square kilometer)
Quantification %: Proportional inverse unit coverage in range over all participating technologies

Since some PNT technologies only sought to participate in certain aspects of the demonstration, this MoE was subdivided into three independent elements, each using the same rubric, values, and quantification described above:

- MoE-6a: Service Coverage per Unit of Infrastructure for Timing
- MoE-6b: Service Coverage per Unit of Infrastructure for Two-dimensional (2D) Positioning
- MoE-6c: Service Coverage per Unit of Infrastructure for Three-dimensional (3D) Positioning

"In Situ" indicates when the user solution must be collocated with the service, i.e. there is no broadcast of PNT signals. Figure 116 presents the consensus scorecard for MoE-6.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning	scale
Echo Ridge LLC	LaRC					**N/A**		**24**			0
Hellen Systems, LLC	JBCC	**2**			**2**	**2**					0.0001
NextNav LLC	LaRC	**11**	**11**	**11**	**11**	**N/A**	**17**	**17**	**17**	**17**	0.1
OPNT B.V.	LaRC	**in situ**				**N/A**					N/A
PhasorLab Inc.	JBCC	**21**	**21**	**21**		**N/A**	**29**	**29**		**32**	0.2
Satelles, Inc.	JBCC	**66**	**66**	**66**	**66**	**N/A**		**66**			0
Serco Inc.	JBCC					**N/A**	**8**	**8**			0.05
Seven Solutions S.L.	LaRC	**in situ**				**N/A**					N/A
Skyhook Wireless, Inc.	LaRC					**N/A**	**14**	**14**	**14**	**14**	0.08
TRX Systems, Inc.	LaRC					**N/A**	**in situ**	**in situ**	**in situ**		N/A
UrsaNav Inc.	JBCC	**2**		**2**	**2**	**2**					0.0001
GPS (SPS PS)	All	**24**	**24**			**24**	**24**	**24**		**24**	0

Rubric:

units/km^2

2

to

66

in situ

100 target coverage area (km^2)

Figure 116. MoE-6: Service Coverage per Unit of Infrastructure Consensus Scorecard

8.1.7 MoE-7: Service Synchronization

A fundamental principle in time distribution and in many of the derived positioning techniques is the synchronization of the PNT service to a single time base. The modern standard for timing services is traceability to Universal Coordinated Time (UTC); GPS is a canonical example of this traceability. In operational PNT services, however, there is typically a trade-off in designing or enforcing this traceability against other cost/performance criteria for the service.

With regard to this demonstration and the motivating policy and legislation, traceability to UTC was identified as a central measure of effectiveness. The Service Synchronization MoE was formed as a rubric on the immediacy in the PNT function to a UTC-traceable source. Of the technologies demonstrated, the range of possibilities extended from a direct link 1-pps feed from the Government reference system UTC representation to a self-synchronizing system (effectively unsynchronized with UTC).

The Government Team assigned a quantization leaning toward the two traceable technologies (UTC or cascade) and gave no credit in this MoE to self-synchronizing systems.

Rubric: Transmitter time traceability to UTC
Values: UTC, cascade, self-synchronizing
Quantification %: UTC = 100%, cascade = 75%, self-synchronizing = 0%

Figure 117 presents the consensus scorecard for MoE-7.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		self-sync		
Hellen Systems, LLC	JBCC	UTC			UTC	UTC				
NextNav LLC	LaRC	cascade	cascade	cascade	cascade	N/A	cascade	cascade	cascade	cascade
OPNT B.V.	LaRC	UTC				N/A				
PhasorLab Inc.	JBCC	cascade	cascade	cascade		N/A	cascade	cascade		cascade
Satelles, Inc.	JBCC	UTC	UTC	UTC	UTC	N/A		UTC		
Serco Inc.	JBCC					N/A	cascade	cascade		
Seven Solutions S.L.	LaRC	UTC				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	self-sync	self-sync	self-sync	self-sync
TRX Systems, Inc.	LaRC					N/A	N/A	N/A	N/A	
UrsaNav Inc.	JBCC	UTC		UTC	UTC	UTC				
GPS (SPS PS)	All	UTC	UTC			UTC	UTC	UTC		UTC

Rubric:

UTC
cascade
self-sync

Figure 117. MoE-7: Service Synchronization Consensus Scorecard

8.1.8 MoE-8: PNT Signal Robustness

The PNT Signal Robustness MoE was formulated to convey the information gathered from the demonstration. As detailed in section 3, the use case scenarios were explicitly designed to allow technology vendors to exemplify the strengths of their PNT functions. These scenario rationales, in keeping with the “shown in best light” theme, included dynamics (stationary or in-motion), extended coverage areas, challenging but persistent environments (e.g., indoor or subterranean locations), and vertical and horizontal (2D/3D) dimensions.

There is extreme variation in the received signal power for RF-spectrum-based systems under these scenarios. Emitted power at the transmitter, propagation losses, antenna gains, and environmental effects would all need to be controlled or at least accounted for.

Rather than attempting to measure received signal power, the PNT Signal Robustness MoE distilled the assessment to observation of the PNT function being demonstrated in any given scenario. As such, the rubric was a binary (weak or strong), and the vendor’s choice of scenarios would serve as the free parameter. The coarse distinction of strong expresses whether the PNT solution at the UE point of use was stable and successful throughout the demonstration scenario.

Rubric: Signal reception under nominal operating condition
Values: strong, weak
Quantification %: strong = 100%, weak = 0%

Figure 118 presents the consensus scorecard for MoE-8.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					**N/A**		**weak**		
Hellen Systems, LLC	JBCC	**strong**			**weak**	**strong**				
NextNav LLC	LaRC	**strong**	**strong**	**strong**	**strong**	**N/A**	**strong**	**strong**	**strong**	**strong**
OPNT B.V.	LaRC	**strong**				**N/A**				
PhasorLab Inc.	JBCC	**weak**	**weak**	**weak**		**N/A**	**weak**	**weak**		**weak**
Satelles, Inc.	JBCC	**strong**	**strong**	**strong**	**strong**	**N/A**		**strong**		
Serco Inc.	JBCC					**N/A**	**strong**	**strong**		
Seven Solutions S.L.	LaRC	**strong**				**N/A**				
Skyhook Wireless, Inc.	LaRC					**N/A**	**weak**	**weak**	**weak**	**weak**
TRX Systems, Inc.	LaRC					**N/A**	**strong**	**strong**	**strong**	
UrsaNav Inc.	JBCC	**strong**		**strong**	**weak**	**strong**				
GPS (SPS PS)	All	**weak**	**weak**			**weak**	**weak**	**weak**		**weak**

Rubric:

strong
weak

Figure 118. MoE-8: PNT Signal Robustness Consensus Scorecard

8.1.9 MoE-9: Service Resilience

Resilience is a growing consideration in many service sectors, including Government-provided or Government-endorsed services. Use of best practices and lessons learned are common approaches used in system and service design and implementation. Much of the posture for improving resilience of critical infrastructure dependent on PNT services, particularly GPS, has begun to take shape in policies such as EO 13905 and guidance in the form of standards, testing, and monitoring. There is also extensive work beyond the scope of this demonstration on resilience against specific threats from natural or intentional actors.

The Government Team shaped the Service Resilience MoE to convey the information that the demonstration effort was able to gather and observe. Observations focused on the respective system's response to off-nominal or changing conditions and what information was conveyed by the PNT function about its operating state. The rubric for assessment was chosen as a four-level characterization: fail-safe, fail-over, fail-soft, and fail-hard; all but the fail-hard level were given some level of credit for resilience. With regard to each level, the discriminations in response to an off-nominal condition were as follows:

- Fail-safe: The system monitor (if available and in use) or the user equipment transitions to a secondary source for the PNT function and continues service without interruption.
- Fail-over: The system or user equipment, if interrupted, indicates loss of service and a prompt indicates that the PNT function should transition to another service.
- Fail-soft: The system or user equipment stopped providing the PNT function.
- Fail-hard: The system or user equipment provided an undefined or uninterpretable output PNT function

Rubric: Service response to off-nominal/changing conditions
Values: fail-safe, fail-over, fail-soft, fail-hard
Quantification %: fail-safe = 100%, fail-over = 60%, fail-soft = 40%, fail-hard = 0%

Figure 119 presents the consensus scorecard for MoE-9.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		fail-soft		
Hellen Systems, LLC	JBCC	fail-hard			fail-hard	fail-hard				
NextNav LLC	LaRC	fail-over	fail-over	fail-over	fail-over	N/A	fail-over	fail-over	fail-over	fail-over
OPNT B.V.	LaRC	fail-safe				N/A				
PhasorLab Inc.	JBCC	fail-over	fail-over	fail-over		N/A	fail-over	fail-over		fail-hard
Satelles, Inc.	JBCC	fail-over	fail-over	fail-over	fail-over	N/A		fail-soft		
Serco Inc.	JBCC					N/A	fail-hard	fail-hard		
Seven Solutions S.L.	LaRC	fail-over				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	fail-soft	fail-soft	fail-soft	fail-soft
TRX Systems, Inc.	LaRC					N/A	fail-hard	fail-hard	fail-hard	
UrsaNav Inc.	JBCC	fail-hard		fail-hard	fail-hard	fail-hard				
GPS (SPS PS)	All	fail-hard	fail-hard			fail-hard	fail-hard	fail-hard		fail-hard

Rubric: failure mode
fail-safe
fail-over
fail-soft
fail-hard

Figure 119. MoE-9: Service Resilience Consensus Scorecard

8.1.10 MoE-10: PNT Distribution Mode

One requirement placed on participation in the demonstration by the Volpe Center RFQ (see section 2.6) was that the PNT technology being demonstrated must provide a signal or service, as opposed to simply augmenting some other service or improving the PNT techniques within existing user equipment, *e.g.*, directional GPS antennas. As noted in section 2.1, the scope of the demonstration was to assess technologies that were suitable as services in which the Government could acquire or invest as a PNT provider. The implication of this requirement was that the PNT function must be actively provided by the service provider, and the inherent effect is that the PNT signal must be distributed.

MoE-10, PNT Distribution Mode, is the first of the MoEs in the Suitability subset, and its application can be adapted to the specific perspective of the decision maker. That is, evaluation using this rubric is responsive to a large extent to the evaluators' context. The Government Team formed this MoE using the same mechanics of the other MoEs so that it can, if desired, be used as either a contributor in the decision framework or as a filtering requirement when evaluating a technology under consideration.

There were four distribution modes for the PNT signal among the 11 demonstrated technologies—terrestrial RF, orbital RF, fiber optics, and electronic databases—defined for this MoE's rubric. While the quantification for these modes was assigned, the rubric is used as a proscription (*i.e.*, the filtering mechanism described above) in the preparation of the decision framework.

Rubric: Information mode; may also be treated as a qualifier/filter
Values: terrestrial RF, orbital RF, fiber, database
Quantification %: terrestrial RF = 100%, orbital RF = 80%, fiber = 60%, database = 40%

In the decision framework this MoE can be utilized either as a constraint which obviates the quantification or a performance metric which retains it. Examples of both are provided later in the report. The general preference is to use the MoE as a constraint.
Figure 120 presents the consensus scorecard for MoE-10.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					**N/A**		**orbital RF**		
Hellen Systems, LLC	JBCC	**terra RF**			**terra RF**	**terra RF**				
NextNav LLC	LaRC	**terra RF**	**terra RF**	**terra RF**	**terra RF**	**N/A**	**terra RF**	**terra RF**	**terra RF**	**terra RF**
OPNT B.V.	LaRC	**fiber**				**N/A**				
PhasorLab Inc.	JBCC	**terra RF**	**terra RF**	**terra RF**		**N/A**	**terra RF**	**terra RF**		**terra RF**
Satelles, Inc.	JBCC	**orbital RF**	**orbital RF**	**orbital RF**	**orbital RF**	**N/A**		**orbital RF**		
Serco Inc.	JBCC					**N/A**	**terra RF**	**terra RF**		
Seven Solutions S.L.	LaRC	**fiber**				**N/A**				
Skyhook Wireless, Inc.	LaRC					**N/A**	**terra RF**	**terra RF**	**terra RF**	**terra RF**
TRX Systems, Inc.	LaRC					**N/A**	**database**	**database**	**database**	
UrsaNav Inc.	JBCC	**terra RF**		**terra RF**	**terra RF**	**terra RF**				
GPS (SPS PS)	All	**orbital RF**	**orbital RF**				**orbital RF**	**orbital RF**		**orbital RF**

Rubric:

terra RF
orbital RF
fiber
database

Figure 120. MoE-10: PNT Distribution Mode Consensus Scorecard

8.1.11 MoE-11: Service Interoperability

A beneficial attribute of PNT systems is their interoperability with other PNT services. The Government Team formed the Service Interoperability MoE as a binary rubric. The demonstration effort did provide some information at this coarse level of granularity by revealing where given PNT technologies are suitable in combination with other PNT technologies, such as at the transmitter (*e.g.*, layering fiber time service to remote wireless transmitters, integrated receiver, cross-monitoring or simultaneous operation) or at the user equipment (*e.g.*, on-chip fabrication for integrated/fused receivers). A high Interoperability means that the vendor technology demonstrated some significant compatibility.

Rubric: Compatibility with GPS and other PNT systems, layering of services
Values: high, low
Quantification %: high = 100%, low = 0%

Figure 119 presents the consensus scorecard for MoE-11.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		high		
Hellen Systems, LLC	JBCC	low			low	low				
NextNav LLC	LaRC	high	high	high	high	N/A	high	high	high	high
OPNT B.V.	LaRC	high				N/A				
PhasorLab Inc.	JBCC	low	low	low		N/A	low	low		low
Satelles, Inc.	JBCC	high	high	high	high	N/A		high		
Serco Inc.	JBCC					N/A	low	low		
Seven Solutions S.L.	LaRC	high				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	high	high	high	high
TRX Systems, Inc.	LaRC					N/A	low	low	low	
UrsaNav Inc.	JBCC	low		low	low	low				
GPS (SPS PS)	All	high	high			high	high	high		high

Rubric:

high
low

Figure 121. MoE-11: Service Interoperability Consensus Scorecard

8.1.12 MoE-12: PNT Information Security

The information security and resilience of a given PNT signal have significant correlation when considering intentional disruption or manipulation of the PNT function. While this demonstration did not focus on those specific threat categories, the effort did yield relevant supporting information. During preparation and execution of the demonstration, the Government Team had the opportunity to observe security mechanisms, either explicitly in scenarios, or implicitly in the implementation of the PNT signal itself. We formed the Information Security MoE as a broad, three-level rubric (low, medium, or high) to assess a given technology's inclusion of security measures and exposure. Considerations included whether the signal was point-to-point, broadcast, or otherwise controlled (electronic transfer); whether signals were encrypted/authenticated/open; whether the system monitored or authorized user equipment; and, whether that information was auditable.

With regard to quantization of the rubric, since security is a highly technical and variable enterprise, credit was given to any system that demonstrated a link between transmitter and receiver. More credit was given to the medium and high levels, which had to show one (medium) or more (high) security measures.

Rubric: Level of information exposure
Values: high, medium, low
Quantification %: high = 100%, medium = 75%, low = 25%

Figure 122 presents the consensus scorecard for MoE-12.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		high		
Hellen Systems, LLC	JBCC	medium			medium	medium				
NextNav LLC	LaRC	high	high	high	high	N/A	high	high	high	high
OPNT B.V.	LaRC	medium				N/A				
PhasorLab Inc.	JBCC	low	low	low		N/A	low	low		low
Satelles, Inc.	JBCC	high	high	high	high	N/A		high		
Serco Inc.	JBCC					N/A	low	low		
Seven Solutions S.L.	LaRC	medium				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	low	low	low	low
TRX Systems, Inc.	LaRC					N/A	medium	medium	medium	
UrsaNav Inc.	JBCC	medium		medium	medium	medium				
GPS (SPS PS)	All	low	low			low	low	low		low

Rubric:

Rubric
high
medium
low

Figure 122. MoE-12: PNT Information Security Consensus Scorecard

8.1.13 MoE-13: Time to Service Implementation

Developing accurate estimates of the time needed to implement PNT functions of any of the demonstrated technologies was not possible, given the limited observations gathered from the demonstration. Likewise, those observations were highly correlated with the information used to determine the MoEs associated with TRL and Deployment Effort. However, the practical experience gained between the Government Team and the PNT technology vendors does offer insight on a time-to-implement each service, even if uncertain or somewhat subjective in nature. Government Team SME considerations included maturity of documentation (which was related to standards and specifications work); maturity of operational configurations, consoles, and monitoring; availability and fielding of equipment; siting prerequisites, etc.

The Time to Service Implementation MoE was formed as a mechanism to convey coarse SME assessment of this key factor in the Government's strategy and expectations to implement one or more complementary PNT services. The rubric was set at three levels: less than two years, two to five years, and more than five years to implementation, with an even scoring quantization of those levels across the 0–100% scoring.

Rubric: Range of time needed to implement service
Values: short (< 2 yrs.), medium (2 to 5 yrs.), long (> 5 yrs.)
Quantification %: short = 100%, medium = 66%, long = 33%

Figure 123 presents the consensus scorecard for MoE-13.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		medium		
Hellen Systems, LLC	JBCC	long			long	long				
NextNav LLC	LaRC	short	short	short	short	N/A	medium	medium	medium	medium
OPNT B.V.	LaRC	short				N/A				
PhasorLab Inc.	JBCC	medium	medium	medium		N/A	long	long		long
Satelles, Inc.	JBCC	short	short	short	short	N/A		short		
Serco Inc.	JBCC					N/A	long	long		
Seven Solutions S.L.	LaRC	short				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	short	short	short	short
TRX Systems, Inc.	LaRC					N/A	medium	medium	medium	
UrsaNav Inc.	JBCC	long		long	long	long				
GPS (SPS PS)	All	short	short			short	short	short		short

Rubric:

< 2yrs	short
2 to 5 yrs	medium
> 5yrs	long

Figure 123. MoE-13: Time to Service Implementation Scorecard

8.1.14 MoE-14: PNT System/Service Longevity

Similar to the Time-to-Implement MoE, the demonstration effort offered some observations on the potential longevity of a PNT service, even if more uncertain than other information from the demonstration. Likewise, that service longevity information is correlated with other MoEs—in particular, Spectrum Protection, Service Interoperability, and Information Security—so that the collection of MoEs should not be considered in isolation when developing any Government strategy. SME considerations on service longevity included infrastructure equipage, user equipment and out-of-band interoperability, layering of PNT capabilities, operational costs, signal bandwidth availability, and suitability for security measures such as authentication.

The System/Service Longevity MoE conveys a coarse SME assessment of the complementary PNT technology's service outlook as an analog to the GPS model. The rubric was set at three levels: less than 15 years, 15 to 30 years, and more than 30 years of service, with an even scoring quantization of those levels across the 0–100% scoring.

Rubric: Projected operating life
Values: long (>30 yr), medium (15 to 30 yr), short (< 15 yr)
Quantification %: long = 100%, medium = 66%, short = 33%

Figure 124 presents the consensus scorecard for MoE-14.

PNT Technology Vendor	Demo Site	72-Hr Bench Static Timing	Static Outdoor Timing	Static Indoor Timing	Static Basement Timing	Reference Station Offset (eLoran Timing)	Dynamic Outdoor Positioning with Holds	Static Outdoor Positioning	Static Indoor Positioning	Airborne Positioning
Echo Ridge LLC	LaRC					N/A		medium		
Hellen Systems, LLC	JBCC	medium			medium	medium				
NextNav LLC	LaRC	long	long	long	long	N/A	long	long	long	long
OPNT B.V.	LaRC	long				N/A				
PhasorLab Inc.	JBCC	long	long	long		N/A	long	long		long
Satelles, Inc.	JBCC	medium	medium	medium	medium	N/A		medium		
Serco Inc.	JBCC					N/A	long	long		
Seven Solutions S.L.	LaRC	long				N/A				
Skyhook Wireless, Inc.	LaRC					N/A	long	long	long	long
TRX Systems, Inc.	LaRC					N/A	short	short	short	
UrsaNav Inc.	JBCC	medium		medium	medium	medium				
GPS (SPS PS)	All	long	long			long	long	long		long

Rubric:

> 30 yrs	long
15 to 30 yrs	medium
< 15 yrs	short

Figure 124. MoE-14: PNT System/Service Longevity Consensus Scorecard

8.2 Scoring Functions to Support Stakeholder Strategy

The MoE scorecards provided useful consolidation of the information gathered for each technology throughout the demonstration. However, the Government Team determined that MoE raw scores alone might not provide the detailed context needed to guide further analysis or decision-making. Consequently, two additional components were established to distill the MoE information content.

For the first component, each MoE rubric was quantified on a 0%–100% scale—that is, each rubric level was assigned (or computed, in the case of Accuracy and Coverage MoEs) a value on the 0%–100% scale. The specific values assigned are described in detail in section 8.1 above, and shown below in Figure 125.

Measure of Effectiveness (MoE)	Rubric	Rubric Level Definitions	Rubric Levels and Corresponding Quantification Value (0%-100%)									
			Level	Value	Level	Value	Level	Value	Level	Value	Level	Value
MoE01: System TRL	Technical Readiness Level (TRL)	TRL 1–TRL 9 as defined by FHWA Technology Readiness Level Guidebook: TRL 6 or above considered valid for demonstration.	TRL-9	100%	TRL-8	70%	TRL-7	40%	TRL-6	20%	TRL-5	0%
MoE02: User Equipment TRL	Technical Readiness Level (TRL)											
MoE03a: Timing Accuracy (ns)	Residual error timing (ns) against Government reference system	Scalar, largest 95% bound across all runs in a scenario; from best observed accuracy (100%) to worst observed accuracy (0%)	Best (0.1 ns)	100%	Worst (Failed)	0%						
MoE03b: 2D Positioning Accuracy (m)	Residual error in positioning (m) against Government reference system	Scalar, largest 95% bound across all runs in a scenario; from best observed accuracy (100%) to worst observed accuracy (0%)	Best (1.8 m)	100%	Worst (1157 m)	0%						
MoE03c: 3D Positioning Accuracy (m)												
MoE04: Spectrum Protection	FCC authorization level (for wireless RF spectrum-based technologies)	Four Alternatives: Protected, Owned, Leased, Shared	protected	100%	owned	75%	leased	50%	shared	25%		
MoE05: Deployment Effort	Observed effort/resource for demonstration	Three levels: Low, Medium, High	low	100%	medium	66%	high	33%				
MoE06a: Unit Coverage (timing)	Infrastructure per covered area necessary for timing, 2D positioning, or 3D positioning; affine model of baseline + marginal	Transmitters (units per square kilometer) for target coverage area; fewest units=100%, most units=0%	Fewest (2.1/km^2)	100%	Most (212/km^2)	0%						
MoE06b: Unit Coverage (2D posiitoning)	Infrastructure per covered area necessary for timing, 2D positioning, or 3D positioning; affine model of baseline + marginal	Transmitters (units per square kilometer) for target coverage area; fewest units=100%, most units=0%	Fewest (2.1/km^2)	100%	Most (212/km^2)	0%						
MoE06c: Unit Coverage (3D posiitoning)												
MoE07: System Synchronization	Transmitter time traceability to UTC	Three levels (UTC, Cascade, Self-synchronizing)	UTC	100%	cascade	75%	self-sync	0%				
MoE08: Signal Robustness	Signal reception under nominal operating condition	Binary: Strong, Weak	strong	100%	weak	0%						
MoE09: Service Resilience	Service response to off-nominal or changing conditions	Four alternatives: Fail-safe, Fail-over, Fail-soft, Fail-hard	fail-safe	100%	fail-over	60%	fail-soft	40%	fail-hard	0%		
MoE10: PNT Mode	Information mode (may also be treated as a qualifier/filter)	Four alternatives: Terrestrial RF, Orbital RF, Fiber, Database	terra RF	100%	orbital RF	80%	fiber	60%	database	40%		
MoE11: System Interoperability	Compatibility with GPS and other PNT systems; layering of services	Binary: High, Low	high	100%	low	0%						
MoE12: PNT Information Security	Security level of information	Low - no authentication, encryption, or monitoring, Medium - one of thos functions, High - two or more of those functions	high	100%	medium	75%	low	25%				
MoE13: Time to Capability	Timeframe needed to implement service	Short (< 2 yrs.), Medium (2 to 5 yrs.), Long (> 5 yrs.)	short	100%	medium	66%	long	33%				
MoE14: Service Longevity	Projected operating life	Long (>30 yrs), Medium (15 to 30 yrs), Short (< 15 yrs)	long	100%	medium	66%	short	33%				

Figure 125. Definition of Measure of Effectiveness Rubrics

Second, stakeholder needs are captured in a vector of weights. These weights are used as MoE coefficients, with one weight assigned for each MoE. The weighting vector captured the relative stakeholder importance of each MoE for any given strategy. These weights could be set based on either a) a hypothetical need, b) through a stakeholder interview process, or c) as an interpretation of requirements, policy, or regulation. Using this approach, weightings can scale the relative importance of each MoE based on the prioritized needs of specific stakeholders, i.e. for each modal administration or user category. The weights are set as a percentage (from 0%–100%) with the sum of all weights totaling 100%. These weights can be quickly adjusted, making the information framework useful as a tool to explore alternatives.

Note that certain entries in the weight vector can include a scenario-defined domain of applicability—*i.e.*, timing, 2D positioning, and 3D positioning. This allows each domain to be addressed individually if desired. This approach is reflected in the sample weighting schema shown in Figure 126, where there are multiple entries for Accuracy (identified as MoE-3a, -3b, and -3c) and Coverage (identified as MoE-6a, -6b, and -6c). Figure 126 also shows three sample schemas that assign hypothetical weights based on three different needs, *i.e.*, "timing," "positioning," "broadcast."

Figure 126 presents the general form and conceptual application of the MoE scores, the stakeholder weightings, and the resulting score/rank output of the scoring function. The scoring function is the summation of the weighted MoE scores—*i.e.*, the inner product of the MoE vector and the weighting vector. The lower block of weight vectors in Figure 124 gives a series of six different scoring constructs. The development of a variety of scoring functions is instructive, even in the absence of ranking or filtering, as a central capability of this information framework. These scoring functions can be used to show trends, compare outcomes based on different needs, display relative performance, and identify strong performers. This reinforces that within the scope of this report, the information used to assess each MoE was drawn only from the demonstration, and not from vendor literature, prior analysis, or other sources. The information framework is widely applicable, but for the scope of this report the supporting information is limited to the demonstration results.

Figure 126. Conceptual Diagram for Applying the MoE Framework.

The Government Team applied a wide range of stakeholder weighting vectors and technology constraints. Examples of those results, with weights, constraints, and yielded scores/ranks, represent six hypothetical constructs:

1. **Timing Performance.** This construct constrains the weighted scoring function for technologies to their demonstrated TIMING PERFORMANCE only.
2. **Positioning Performance.** This construct constrains the scoring function for technologies to their demonstrated POSITIONING PERFORMANCE only.
3. **Timing-terrestrial broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND the technology be a terrestrial RF broadcast.
4. **PNT-terrestrial broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND a positioning function AND the technology be a terrestrial RF broadcast.
5. **Timing-broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND the technology be a RF broadcast.
6. **PNT broadcast.** This scoring applies the constraints that a technology must demonstrate a timing function AND a positioning function AND the technology be a terrestrial RF broadcast.

These six constructs as implemented in the information framework are shown in Figure 127. Each construct maps by name to one of the six rows of weights in the bottom block of the worksheet. The corresponding score and rank results for each construct appear in the six pairs of columns on the right end of the vendor/MoE matrix.

PNT Technology Vendor	MoE01: System TRL	MoE02: User Equipment TRL	MoE03a: Accuracy (timing)	MoE03b: Accuracy (2D positioning)	MoE0c: Accuracy (3D positioning)	MoE04: Spectrum Protection	MoE05: Deployment Effort	MoE06a: Unit Coverage (timing)	MoE06b: Unit Coverage (2D positioning)	MoE06c: Unit Coverage (3D positioning)	MoE07: System Synchronization	MoE08: Signal Robustness	MoE09: Service Resilience	MoE10: PNT Mode	MoE11: System Interoperability	MoE12: PNT Info. Security	MoE13: Time to Capability	MoE14: Service Longevity	Score: timing performance	Rank: timing performance	Score: positioning performance	Rank: positioning performance	Score: timing - ground broadcast	Rank: timing - ground broadcast	Score: PNT - ground broadcast	Rank: PNT- ground broadcast	Score: timing - broadcast	Rank: timing - broadcast	Score: PNT - broadcast	Rank: PNT - broadcast
Echo Ridge	70	40	0	4.8	0	100	100	0	65.6	0	0	0	40	80	100	100	66	66	0	-	38	5	0	-	0	-	0	-	0	-
Hellen Systems	70	40	33.8	0	0	100	66	100	0	0	100	100	0	100	0	75	33	66	62	6	0	-	66	3	0	-	66	4	0	-
NextNav	100	100	88.9	97.8	99.2	75	33	86	76.6	76.6	75	100	60	100	100	100	100	100	91	1	91	1	82	1	82	1	82	1	82	1
OPNT	100	100	100	0	0	0	100	0	0	0	100	100	100	60	100	75	100	100	87	2	0	-	0	-	0	-	0	-	0	-
PhasorLab	70	70	87.4	97.6	97.8	25	33	70.3	56.3	53.1	75	0	60	100	0	25	66	100	62	6	62	3	52	4	51	2	52	5	51	3
Satelles	100	100	53.1	97.7	0	100	100	0	0	0	100	100	60	80	100	100	100	66	78	4	78	2	0	-	0	-	80	2	82	1
Serco	0	0	0	44.5	0	100	66	0	90.6	0	75	100	0	100	0	25	33	100	0	-	0	-	0	-	0	-	0	-	0	-
Seven Solutions	100	100	100	0	0	0	100	0	0	0	100	100	60	60	100	75	100	100	84	3	0	-	0	-	0	-	0	-	0	-
Skyhook	100	100	0	96.9	96.1	25	100	0	81.3	81.3	0	0	40	100	100	25	100	100	0	-	47	4	0	-	0	-	0	-	0	-
TRX Systems	40	70	0	97.8	0	25	66	0	0	0	0	100	0	40	0	75	66	33	0	-	38	5	0	-	0	-	0	-	0	-
UrsaNav	100	70	44.4	0	0	100	66	100	0	0	100	100	0	100	0	75	33	66	69	5	0	-	70	2	0	-	70	3	0	-
GPS (SPS PS)	100	100	75.1	98.7	98.3	100	100	65.6	65.6	65.6	100	0	0	80	100	25	100	100	67		67		0		0		70		71	
Stakeholder Weights																														
timing performance	10%	10%	10%	0%	0%	0%	0%	10%	0%	0%	10%	10%	10%	0%	0%	10%	10%	10%												
positioning performance	10%	5%	0%	10%	5%	15%	5%	0%	10%	5%	0%	10%	10%	0%	5%	5%	0%	5%												
timing ground broadcast	10%	-	10%	-	-	10%	10%	10%	-	-	10%	10%	10%	-	5%	5%	5%	5%												
PNT ground broadcast	10%	-	5%	5%	-	10%	10%	5%	5%	-	10%	10%	10%	-	5%	5%	5%	5%												
timing broadcast	10%	-	10%	-	-	10%	10%	10%	-	-	10%	10%	10%	-	5%	5%	5%	5%												
PNT broadcast	10%	-	5%	5%	-	10%	10%	5%	5%	-	10%	10%	10%	-	5%	5%	5%	5%												

Figure 127. Application of Scoring Functions with Weighting and Explicit Requirement Filters

These six examples illustrate how the scoring function can be used to weight or prioritize specific factors (represented by MoEs)—such as timing performance (MoE-3a), positioning performance (MoE-3b and MoE-3c), or PNT distribution mode (MoE-10)—as filters against different technologies (shown in each row). For example, if the notional requirement is for a PNT technology to use terrestrial RF distribution is a primary requirement, scoring for MoE-10 can be filtered to enforce that constraint. Similarly, if providing both timing (MoE-3a) and positioning (MoE-3b and MoE-3c) is an important capability, those factors can be weighted and filtered accordingly.

The Government Team evaluated a series of progressive scoring functions to support decision maker requests in addressing the motivating needs. As shown in Figure 127, applying some constraints can severely limit technology options, for example positioning functions from ground broadcast narrow to only two technologies (NextNav and PhasorLab). The information framework provides a convenient, controlled capability to address expanded interpretations that yield helpful information on which technologies are strong performers as different constraints are tightened or relaxed.

8.3 Hierarchical Scoring for Strategy and Management Usage

At this point, the information extracted from the demonstration is already twice distilled by the weighted scoring functions described in section 8.2—first, by the quantified MoE rubric, and second, by the summation of those weighted MoEs to a single score for a technology. This establishes a scoring hierarchy, in that the weights are applied as ascending groups that accumulate lower levels of MoE. For example, the performance/schedule/cost weighting is one level above the MoEs, and condenses the 14 to 3.

At the decision-making level, those scores are useful in exploring the relative strengths and weaknesses of the various demonstrated PNT technologies, as well as in exploring the alignment of a technology's suitability across the needs of various stakeholders. Having such an analytical tool is one of the intended uses of this decision framework.

However, this decision framework offers additional capability beyond comparability and suitability. If the MoE data are consolidated into higher-level programmatic or decision-making dimensions such as performance, schedule, and cost drivers, the information available from the demonstration can be readily expressed in terms familiar to Department leadership and acquisition strategy decision makers.

Figure 128 shows the conceptual form of this hierarchical scoring framework.

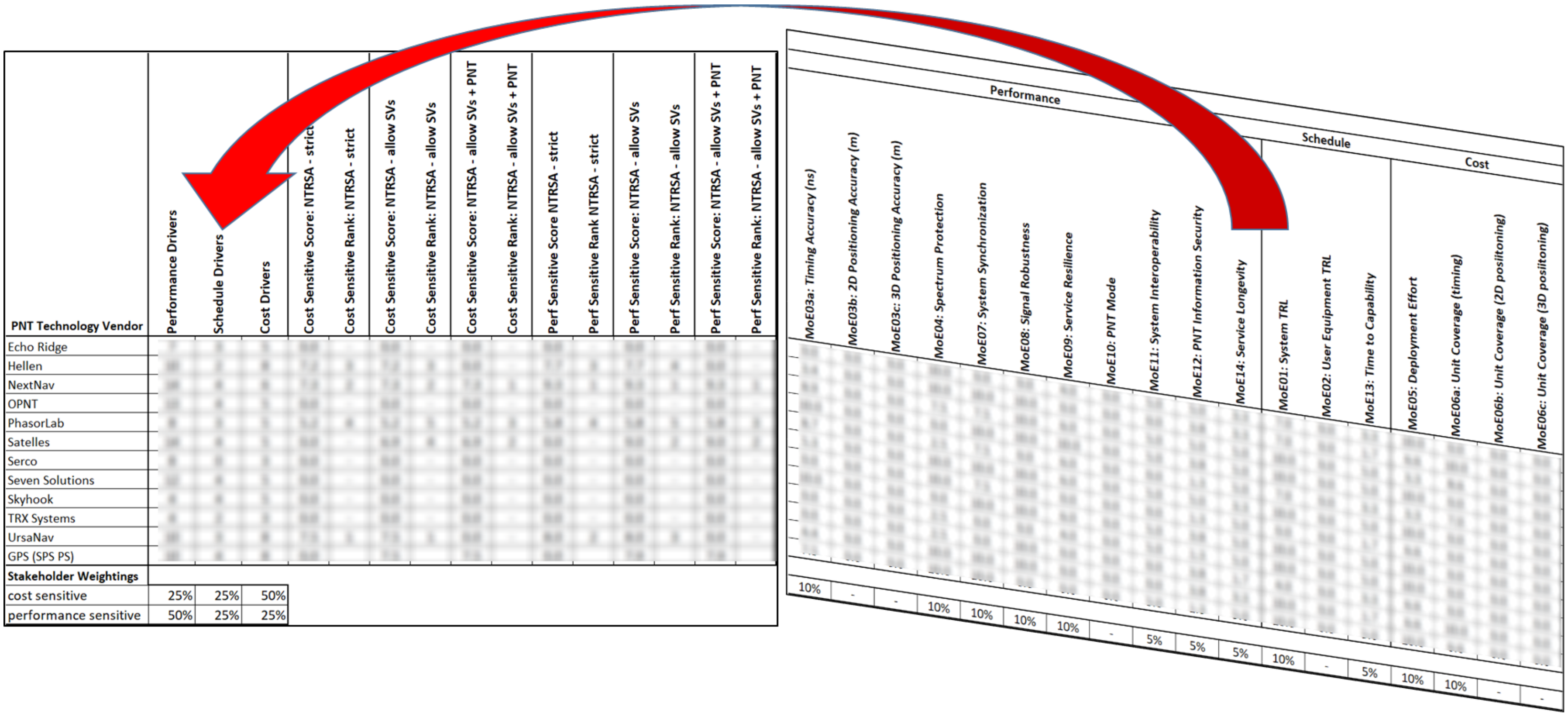


Figure 128. Hierarchical Grouping of MoEs into Higher-Level Categories for Programmatic and Strategic Support

The Government Team's hierarchical scoring function is potentially helpful in supporting strategic and programmatic decision making. First, Figure 129 shows the specific performance/schedule/cost grouping of MoEs, retaining their basic weighting (lower block using the "timing" framework described earlier), but then applying a group weighting to the hierarchical (performance/schedule/cost) scoring function.

	Performance											Schedule			Cost			
PNT Technology Vendor	**MoE03a: Timing Accuracy (ns)**	**MoE03b: 2D Positioning Accuracy (m)**	**MoE03c: 3D Positioning Accuracy (m)**	**MoE04: Spectrum Protection**	**MoE07: System Synchronization**	**MoE08: Signal Robustness**	**MoE09: Service Resilience**	**MoE10: PNT Mode**	**MoE11: System Interoperability**	**MoE12: PNT Information Security**	**MoE14: Service Longevity**	**MoE01: System TRL**	**MoE02: User Equipment TRL**	**MoE13: Time to Capability**	**MoE05: Deployment Effort**	**MoE06a: Unit Coverage (timing)**	**MoE06b: Unit Coverage (2D positoning)**	**MoE06c: Unit Coverage (3D positoning)**
Echo Ridge	0.0	0.0	0.0	10.0	0.0	0.0	4.0	0.0	5.0	5.0	3.3	7.0	0.0	3.3	10.0	0.0	0.0	0.0
Hellen Systems	3.4	0.0	0.0	10.0	10.0	10.0	0.0	0.0	0.0	3.8	3.3	7.0	0.0	1.7	6.6	10.0	0.0	0.0
NextNav	8.9	0.0	0.0	7.5	7.5	10.0	6.0	0.0	5.0	5.0	5.0	10.0	0.0	5.0	3.3	8.6	0.0	0.0
OPNT	10.0	0.0	0.0	0.0	10.0	10.0	10.0	0.0	5.0	3.8	5.0	10.0	0.0	5.0	10.0	0.0	0.0	0.0
PhasorLab	8.7	0.0	0.0	2.5	7.5	0.0	6.0	0.0	0.0	1.3	5.0	7.0	0.0	3.3	3.3	7.0	0.0	0.0
Satelles	5.3	0.0	0.0	10.0	10.0	10.0	6.0	`	5.0	5.0	3.3	10.0	0.0	5.0	10.0	0.0	0.0	0.0
Serco	0.0	0.0	0.0	10.0	7.5	10.0	0.0	0.0	0.0	1.3	5.0	0.0	0.0	1.7	6.6	0.0	0.0	0.0
Seven Soln	10.0	0.0	0.0	0.0	10.0	10.0	6.0	0.0	5.0	3.8	5.0	10.0	0.0	5.0	10.0	0.0	0.0	0.0
Skyhook	0.0	0.0	0.0	2.5	0.0	0.0	4.0	0.0	5.0	1.3	5.0	10.0	0.0	5.0	10.0	0.0	0.0	0.0
TRX Systems	0.0	0.0	0.0	2.5	0.0	10.0	0.0	0.0	0.0	3.8	1.7	4.0	0.0	3.3	6.6	0.0	0.0	0.0
UrsaNav	4.4	0.0	0.0	10.0	10.0	10.0	0.0	0.0	0.0	3.8	3.3	10.0	0.0	1.7	6.6	10.0	0.0	0.0
GPS (SPS PS)	7.5	0.0	0.0	10.0	10.0	0.0	0.0	0.0	5.0	1.3	5.0	10.0	0.0	5.0	10.0	6.6	0.0	0.0

timing	10%	-	-	10%	10%	10%	10%	-	5%	5%	5%	10%	-	5%	10%	10%	-	-

Figure 129. MoEs Grouped by Performance, Schedule, and Cost Factor

The hierarchical scoring function was then achieved by assigning a weight (performance, schedule, cost) to each MoE group. Figure 130 shows the impact of applying “performance-sensitive” weighting to the MoEs in the performance group more heavily than those in the schedule and cost driver groups.

PNT Technology Vendor	Performance Drivers	Schedule Drivers	Cost Drivers	Perf Sensitive Score: timing - ground broadcast	Perf Sensitive Rank: timing - ground broadcast	Perf Sensitive Score: timing - broadcast	Perf Sensitive Rank: timing - broadcast	Perf Sensitive Score: PNT - broadcast	Perf Sensitive Rank: PNT - broadcast
Echo Ridge	7	3	5	0.0	-	0.0	-	0.0	-
Hellen Systems	10	2	8	7.7	3	7.7	4	0.0	-
NextNav	14	4	6	9.3	1	9.3	1	9.3	1
OPNT	13	4	5	0.0	-	0.0	-	0.0	-
PhasorLab	8	3	5	5.8	4	5.8	5	5.8	3
Satelles	14	4	5	0.0	-	9.0	2	9.0	2
Serco	8	0	3	0.0	-	0.0	-	0.0	-
Seven Solutions	12	4	5	0.0	-	0.0	-	0.0	-
Skyhook	4	4	5	0.0	-	0.0	-	0.0	-
TRX Systems	4	2	3	0.0	-	0.0	-	0.0	-
UrsaNav	10	3	8	8.0	2	8.0	3	0.0	-
GPS (SPS PS)	10	4	8	0.0		7.9		7.9	
Top Hierarchy Weightings									
performance sensitive	50%	25%	25%						

Figure 130. "Performance Sensitive" Hierarchical Scoring Function

Similarly, Figure 131 applied “cost-sensitive” weighting. Note that the rankings change under Constructs 3 and 5 (Timing-terrestrial broadcast v. Timing-broadcast) when compared to the “Performance Sensitive” scoring function, but the full-PNT objective ranking remains unchanged.

PNT Technology Vendor	Performance Drivers	Schedule Drivers	Cost Drivers	Cost Sensitive Score: timing - ground broadcast	Cost Sensitive Rank: timing - ground broadcast	Cost Sensitive Score: timing - broadcast	Cost Sensitive Rank: timing - broadcast	Cost Sensitive Score: PNT - broadcast	Cost Sensitive Rank: PNT - broadcast
Echo Ridge	7	3	5	0.0	-	0.0	-	0.0	-
Hellen Systems	10	2	8	7.2	3	7.2	3	0.0	-
NextNav	14	4	6	7.3	2	7.3	2	7.3	1
OPNT	13	4	5	0.0	-	0.0	-	0.0	-
PhasorLab	8	3	5	5.2	4	5.2	5	5.2	3
Satelles	14	4	5	0.0	-	6.9	4	6.9	2
Serco	8	0	3	0.0	-	0.0	-	0.0	-
Seven Solutions	12	4	5	0.0	-	0.0	-	0.0	-
Skyhook	4	4	5	0.0	-	0.0	-	0.0	-
TRX Systems	4	2	3	0.0	-	0.0	-	0.0	-
UrsaNav	10	3	8	7.5	1	7.5	1	0.0	-
GPS (SPS PS)	10	4	8	0.0		7.5		7.5	
Top Hierarchy Weightings									
cost sensitive	25%	25%	50%						

Figure 131. "Cost Sensitive" Hierarchical Measures of Effectiveness

9 Conclusions and Recommendations

The decision framework expresses three levels of information gathered by this demonstration:

- As a condensed representation of the effectiveness of the 11 PNT technologies demonstrated across 14 different measures.
- As an efficient presentation of the alignment between stakeholders' needs and suitable PNT technologies.
- Expression of performance-schedule-cost factors derived from the demonstration results.

Each of these levels can be used by stakeholders to make comparisons, to help develop acquisition strategies, and to inform policy and management expectations in relation to providing PNT functions that serve the public's transportation and critical infrastructure needs.

There are four key findings from the DOT technology demonstration:

1. All TRL-qualified vendors demonstrated some PNT performance of value, but only one vendor, NextNav, demonstrated in all applicable use case scenarios.
2. Neither eLORAN technology succeeded in the challenged environment "basement" timing scenario.
3. One technology, R-Mode ranging in the MF band, did not meet the minimum technology readiness level (TRL) of 6.
4. Deployment effort and coverage (infrastructure per unit area) are both significant cost factors.

The demonstration indicates that there are suitable, mature and commercially available technologies to backup or complement the timing services provided by GPS. However, the demonstration also indicates that none of the systems can universally backup the positioning and navigations capabilities provided by GPS and its augmentations. The critical infrastructure positioning and navigation requirements are so varied that function, application, and end-user specific positioning and navigation solutions are needed. This necessitates a diverse universe of positioning and navigation technologies.

Further, cost is a central consideration in any PNT investment decision. This demonstration effort was not comprehensive enough to formulate cost estimates for implementation of a PNT service using one or more of the included technologies. The demonstration was, however, informative on two cost factors, MOE-5: Service Deployment Effort and MOE-6: Service Coverage per Unit Infrastructure. The Government Team had a strong, quantitative indication of service deployment effort in the form of the time and materials needed to execute the demonstrated technology's PNT function.

The demonstration also yielded enough information to estimate a linear model of the infrastructure-to-coverage-area relationship for each technology. The MOE-6 model is an intercept (the minimum number of transmitters in a technology, *i.e.*, a baseline) and a slope (the number of transmitters needed to increase the coverage area by one square kilometer, *i.e.*, a marginal addition). Service Deployment Effort and Coverage per Unit Infrastructure are significant cost factors.

Combining this decision framework with the policy and legislative guidance identified in section 1, two initiatives based on the information from the demonstration emerge.

Again, suitable and mature technologies are available to owners and operators of critical infrastructure to access complementary PNT services as a backup to GPS. To achieve the parallel objective of resilience, as described in Executive Order (EO) 13905, that path should involve a plurality of diverse PNT technologies. Promoting critical infrastructure owner/operator use of those technologies that show strong performance, operational diversity, operational readiness, and cost-effectiveness is worthwhile. Based on this demonstration, those technologies are LF and UHF terrestrial and L-band satellite broadcasts for PNT functions with supporting fiber optic time services to transmitters/control segments.

As communicated during the August 21, 2020 briefing to the EXCOM, DOT makes two recommendations from this demonstration:

1. DOT should develop system requirements for PNT functions that support safety-critical services.

2. DOT should develop standards, test procedures, and monitoring capabilities to ensure that PNT services, and the equipage that utilizes them, meet the necessary levels of safety and resilience identified in Recommendation 1.

Recognizing that the transportation sector has some of the most stringent performance requirements in terms of accuracy, integrity, availability, and reliability, developing system requirements that focus on safety and resiliency will allow determination of which requirements are being met by current capabilities and which requirements may require further commercial innovation. DOT supports open safety standards to promote private-sector innovation and commercial product development.

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