Iridium Satellite Time and Location® Performance Testing

Iridium STL® is a resilient, alternative positioning, navigation, and timing (PNT) service from low Earth orbit (LEO) satellites.

Telecom operators and other companies use STL today as a primary timing source, such as for 5G deployments where GPS/GNSS is unavailable indoors. Critical infrastructure owners and operators also rely on STL as an essential contingency capability to protect the operations of PNT-dependent systems and help ensure survivability and resilience.

Government authorities in the U.S. (NIST, DHS, DOT) and Europe have subjected STL to rigorous testing, and other entities have also studied the performance specifications of the service. This report provides in-depth background information and summarizes the key findings.

Many of the performance reports cited below were published when STL was provided by Satelles. Iridium acquired Satelles in April 2024, so many of the descriptions below refer to Iridium even though the published reports mention Satelles.

U.S. National Institute of Standards and Technology (NIST)

Iridium has supported NIST's multiple technical evaluations of STL. One of the tests conducted by NIST involved comparing a GPS-disciplined clock and an STL receiver to UTC(NIST) for 50 days. This was just one of the tests that led NIST to conclude that STL is a reliable source of timing that is highly consistent with Coordinated Universal Time (UTC).

Additionally, Iridium and NIST are working together under the terms of a Cooperative Agreement. One aspect of the agreement is for Iridium to provide STL to NIST so that it may explore options for using STL to distribute UTC(NIST) at sub-microsecond-level accuracy. The agreement also permitted Iridium to deploy an STL Ground Monitoring Station (GMS) within NIST's primary time lab, with a direct connection to the atomic clock ensemble that allows Iridium to propagate UTC(NIST) throughout the STL network.

Qualitative Assessments and Findings

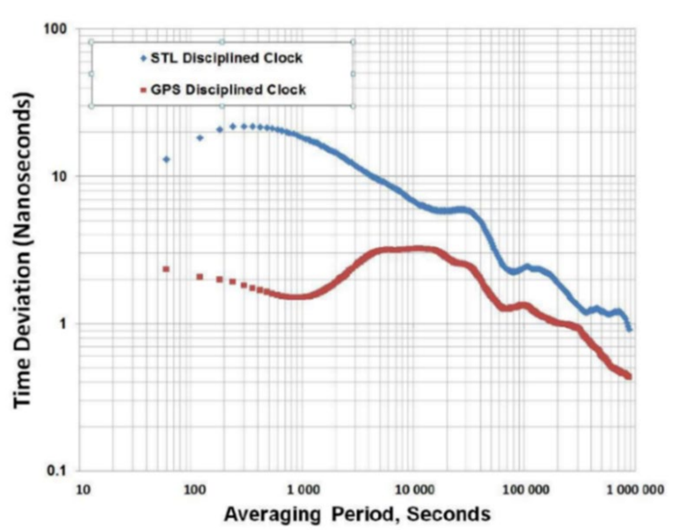
- NIST referred to STL as a commercial alternative that exists today to provide an essential capability that protects the operations of PNT-dependent critical infrastructure and helps ensure the survivability and resilience of our nation.
- NIST concluded that STL is a reliable source of timing that is highly consistent with Coordinated Universal Time (UTC) and is based on a signal that is independent from the Global Positioning System (GPS) and other Global Navigation Satellite Systems (GNSS). As a result, NIST determined that STL is capable of indirectly distributing UTC(NIST), thereby making STL a vital element of [NIST's resilient timing architecture](#).
- NIST determined that "[d]ue in part to the success of GPS, which has at least indirectly led to the demise of eLoran and other systems," only a limited number of public access time distribution systems remain that are under U.S. control. Referring to STL, NIST reported that "[a]ll but one of these systems [STL] have at least one caveat when considered for critical infrastructure usage, they are either not independent of GPS, not capable of microsecond-level accuracy, or both."

Table 4. A summary of non-GPS public access time distribution systems under U. S. control.

Public Access Time Distribution System	Capable of Microsecond Accuracy?	Independent of GPS?
CDMA	YES	NO
Public NTP Servers (non-NIST)	NO	NO
NIST Internet Time Service	NO	YES
WWV and WWVH	NO	YES
WWVB	NO	YES
STL	YES	YES

Quantitative Assessments and Findings

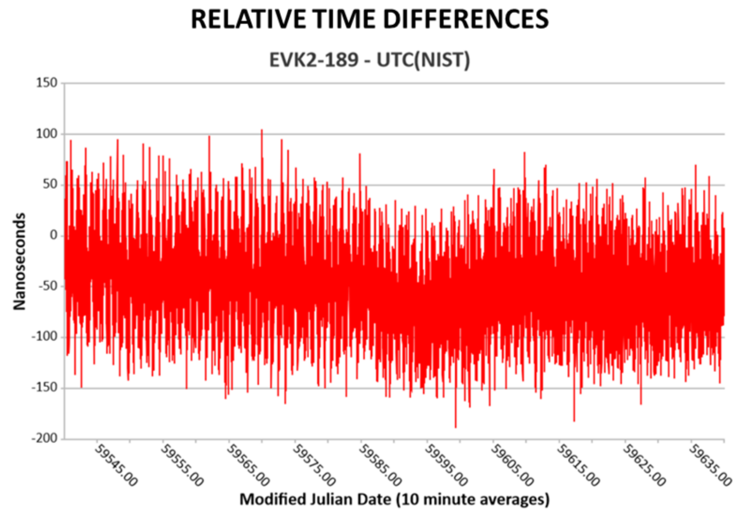
- [Testing conducted by NIST](#) compared a GPS-disciplined clock (getting its signal from an outdoor antenna) and an STL receiver (with an indoor antenna) to UTC(NIST) for 50 days. The study showed that based on one day of averaging, the GPS instability was less than two nanoseconds (< 2 ns), and the STL instability was only slightly higher at under three nanoseconds (< 3 ns).



(source: NIST)

- Testing by NIST also confirmed that "[t]he timing accuracy specification for STL is ±500 nanoseconds (0.5 microseconds) which meets critical infrastructure requirements." In fact, NIST acknowledged previously published measurements indicating that STL has timing accuracy better than 200 nanoseconds.

- After connecting an STL GMS to NIST's primary clock ensemble — an achievement that is very rare for a commercial entity — NIST compared timing provided by STL to UTC(NIST) and confirmed STL's long-term stability of better than 25 nanoseconds with short-term time deviation of 50 nanoseconds.



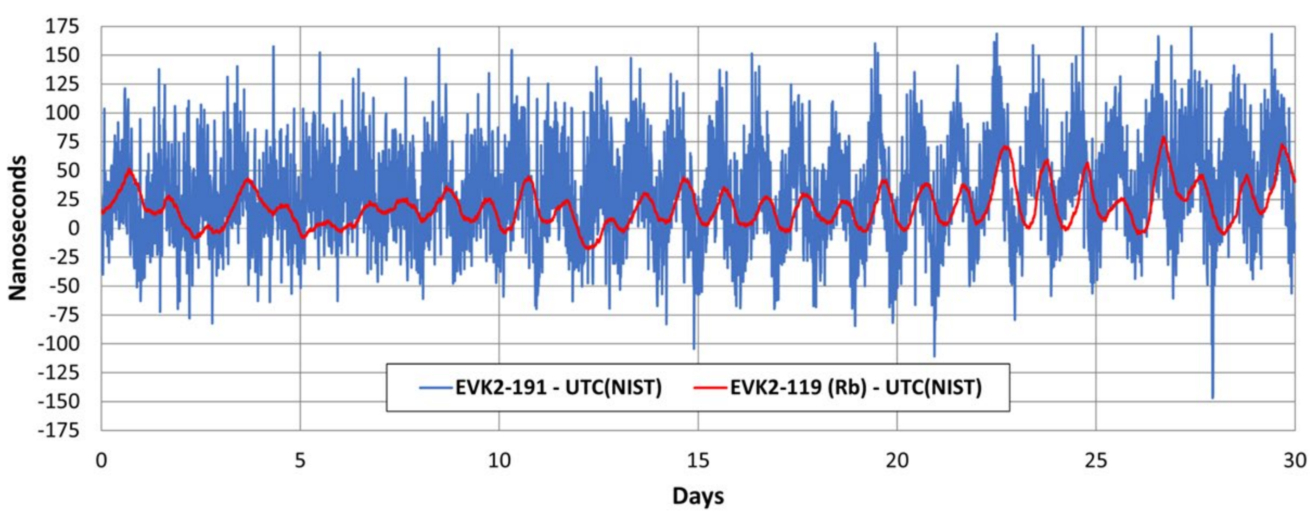
(*source: NIST*)

SPECIAL — Joint Research Papers by Iridium and NIST

Representatives from Iridium (formerly Satelles) and the U.S. National Institute of Standards and Technology (NIST) submitted a jointly written paper at the Institute of Navigation (ION) Precise Time and Time Interval Systems and Applications (PTTI) meeting in January 2023.

The paper, entitled "Measuring the Timing Accuracy of Satellite Time and Location (STL) Receivers," was co-developed by time experts at Iridium and NIST. The underlying research demonstrated that a calibrated STL receiver can achieve an average time offset better than 18 ns with respect to UTC(NIST) with a peak-to-peak variation of 325 ns for a typical OCXO receiver and better than 80 ns with a rubidium-based receiver.

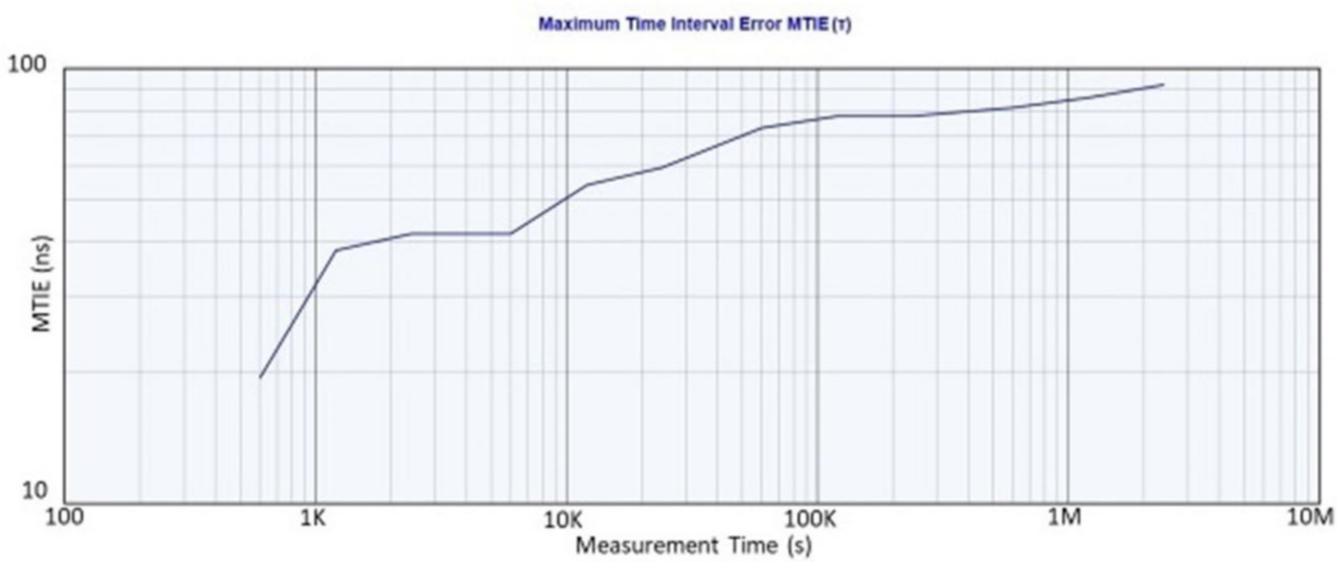
The following chart visualizes the comparison of STL to UTC(NIST) for a 30-day period. The blue line depicts the time offset between UTC(NIST) and an STL receiver with an OCXO oscillator, and the red line represents the same measurement for an STL receiver with a rubidium oscillator.



Another jointly written paper by Iridium and NIST was presented at ION PTTI in January 2024. This latest paper, "The Long-Term Timing Performance of Satellite Time and Location Receivers Utilizing Signals from Low Earth Orbit Satellites," was based on 66-day and 100-day testing conducted at Iridium (previously Satelles) and NIST facilities in 2023.

The study reached a number of conclusions relevant to civil government and commercial entities with timing synchronization requirements, including:

- STL timing receivers, utilizing only signals originating from a LEO satellite constellation, provide a globally available time reference that's a viable backup or alternative to GPS.
- Measurements verified that typical STL timing receivers can provide a very stable and accurate timing solution with an average offset within a few nanoseconds of UTC(NIST).
- STL timing receivers with a high-quality oscillator can maintain a Maximum Time Interval Error (MTIE) less than 100 ns for long durations, meeting the ITU-T G.8272 PRTC-A requirement for a primary reference clock.



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Satelles/NIST Technical Paper, "The Long-Term Timing Performance of Satellite Time and Location Receivers Utilizing Signals from Low Earth Orbit Satellites" (January 2024), https://www.nist.gov/publications/long-term-timing-performance-satellite-time-and-location-receivers-utilizing-signals

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U.S. National Institute of Standards and Technology, NIST Technical Note 2187 – A Resilient Architecture for the Realization and Distribution of Coordinated Universal Time to Critical Infrastructure Systems in the United States (November 2021), https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2187.pdf

U.S. National Institute of Standards and Technology, NIST Technical Note 2189 – *An Evaluation of Dependencies of Critical Infrastructure Timing Systems on the Global Positioning System (GPS)* (November 2021), https://nvlpubs.nist.gov/nistpubs/TechnicalNotes/NIST.TN.2189.pdf

Satelles press release, "NIST Confirms STL as an Accurate and Reliable Source for Wide-Area Delivery of Coordinated Universal Time" (April 21, 2021), https://satelles.com/nist-confirms-stl-as-an-accurate-and-reliable-source-for-wide-area-delivery-of-coordinated-universal-time/

Satelles press release, "NIST Confirms STL as Reliable Source of Resilient Time for Critical Infrastructure" (March 2, 2022), https://satelles.com/nist-confirms-stl-as-reliable-source-of-resilient-time-for-critical-infrastructure/

Satelles press release, "Satelles and NIST Team Up for Precision Timing" (March 30, 2022), https://satelles.com/satelles-and-nist-team-up-for-precision-timing/

Satelles web page, "Satelles and NIST Collaboration," https://satelles.com/nist/

U.S. Department of Homeland Security (DHS)

The FY 2017 National Defense Authorization Act (NDAA), required DHS "to address the needs for a GPS backup by identifying and assessing viable alternate technologies and systems."

Following an in-depth assessment of PNT systems currently used in the United States conducted by the Homeland Security Operational Analysis Center (HSOAC) on behalf of DHS and DOT, the Cybersecurity and Infrastructure Security Agency (CISA) summarized and analyzed HSOAC's assessment and provided "recommendations for the Federal Government's next steps in efforts to increase the resilience of US Critical Infrastructure to disruption of GPS services."

Assessments and Findings

The CISA report stated that "DHS could not identify generic specifications for a national backup" because "[t]he position and navigation functions in critical infrastructure are so diverse that no single PNT system, including GPS, can fulfill all user requirements and applications." However, as DHS explains, "a minimal acceptable precision of anywhere between 65-240 nanoseconds [...] supports all critical infrastructure requirements."

The report states that this range "is expected to meet future requirements, including 5G." Based on the precision of timing references used by receivers, STL currently delivers timing accuracies between 50 to 240 nanoseconds, proving that it is ready to meet timing requirements that strengthen the resilience of critical infrastructure.

Specifically, the report confirmed that STL is able to meet the precision timing synchronization requirements of financial services (50 milliseconds), phasor measurement units used in the electrical grid (1 microsecond), 4G-LTE wireless networks (1.5 microseconds), and 5G wireless networks (~240 nanoseconds). Furthermore, of the technologies evaluated by DHS, the report confirmed that STL is a nationwide service that is commercially available today.

Proposed Solutions	Precision Timing Requirements			
	5G	4G-LTE Network	Phasor Measurement Unit	Financial Services
μs = microseconds	~240 Nanosec.	1.5 μs	1 μs	50 ms
eLORAN	green	green	green	green
Locata	green	green	green	green
Network Time Protocol	red	red	red	red
NextNav	green	green	green	green
Precision Time Protocol	green	green	green	green
Satellite Time and Location (STL)	green	green	green	green
NIST WWVB Radio	red	red	red	yellow

■ Meets Precision ■ Precision within factor of 5 ■ Not close to req. precision

References

U.S. Department of Homeland Security – Homeland Security Operational Analysis Center (HSOAC; a RAND Corporation-operated FFRDC), *Analyzing a More Resilient National Positioning, Navigation, and Timing Capability* (finalized in October 2019; not published until May 2021), https://www.rand.org/pubs/research_reports/RR2970.html

U.S. Department of Homeland Security – Cybersecurity and Infrastructure Security Agency, Report on Positioning, Navigation, and Timing (PNT) Backup and Complementary Capabilities to the Global Positioning System (GPS) (submitted to U.S. congressional committee leaders on April 8, 2020; released to the public on May 6, 2020), https://www.cisa.gov/sites/default/files/publications/report-on-pnt-backup-complementary-capabilities-to-gps_508_0.pdf

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GPS World, "Homeland Security reports on PNT backup, Satelles responds" (June 8, 2020), https://www.gpsworld.com/homeland-security-reports-on-pnt-backup-satelles-responds/

U.S. Department of Transportation (DOT)

In March 2020, the U.S. Department of Transportation organized a demonstration of positioning, navigation, and timing (PNT) technologies from multiple providers. On January 14, 2021, DOT published an in-depth report for Congress entitled *Complementary PNT and GPS Backup Technologies Demonstration Report* as required by the FY 2018 National Defense Authorization Act (NDAA).

DOT echoed many of the sentiments expressed by DHS in the reports detailed in the previous section. In its statement from the Conclusions and Recommendations passage of the report (p. 194), DOT clearly expresses its alignment with DHS:

“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.”

The high-level summary of the 457-page report is as follows:

“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.”

The mention of “L-band satellite broadcasts” is a specific call-out of STL as an integral part of a multi-technology approach for PNT resilience. This is also highly consistent with the resilient timing architecture concept recommended by NIST (*see earlier section*).

Assessments and Findings

STL was one of the 11 technologies subjected to a range of testing scenarios during the demonstration for DOT, and it emerged as one of the top performers. The solutions were evaluated based on various measures of effectiveness (MoE), each with its own detailed rubric. For example, Iridium (Satelles at the time of the study) earned top-tier scores in categories such as Service Synchronization (MoE-7), PNT Signal Robustness (MoE-8), and Service Resilience (MoE-9).

The two most important top-level takeaways from the report are as follows:

- DOT applied weighting factors and technology considerations to produce scoring and ranking in six aggregate groupings. These high-level values were rolled up even further to generate combined scoring and overall ranking. In addition to being evaluated favorably in many individual underlying test scenarios and evaluation categories, STL was ranked #2 overall for timing and positioning in both the performance-sensitive weighting and cost-sensitive weighting classifications, and in some key categories Iridium performed better than the #1 overall provider.
- STL has some important distinctions compared to other solutions demonstrated, such as being the only solution that is nationally and globally scalable without incremental infrastructure expense. STL is available today across the entire United States — including urban centers, rural areas, and navigable waterways — as well as offshore locations. This ability to provide timing and 3-D positioning coverage in the U.S. and

worldwide is possible due to the multibillion-dollar investment that has already been made by Iridium to launch and operate its commercial satellite network.

STL also stood out in these specific areas:

- Technical Readiness (MoE-1, MoE-2) – In separate evaluations for both the system and user equipment, DOT rated STL at the highest technology readiness level (TRL 9) in all categories for which it was evaluated, including the challenging underground environment test. STL was one of only two time and location technologies that achieved TRL 9 *and* is fully operational today. As defined by DOT, TRL 9 means that a particular technology has been refined and adopted — the hallmark for commercially available solutions.

- Service Deployment Effort (MoE-5) – DOT acknowledged that the "demonstration effort was not comprehensive enough to formulate cost estimates for implementation" of the evaluated technologies. However, they stated that the demonstration "provide[d] a reasonable indication of service deployment effort." STL was rated 'Low' (best), meaning that "the time and materials needed to execute the demonstrated technology's PNT function" are less than those solutions rated at 'Medium' or 'High' on the scorecard.

- Time to Service Implementation (MoE-13) – According to DOT, this category "was formed as a mechanism to convey [subject matter expert] assessment of this key factor in the Government's strategy and expectations to implement one or more complementary PNT services." STL scored 'Short' (best), meaning that DOT estimated the implementation period to be "less than two years." In fact, STL can be *immediately* deployed for customers because it is fielded today as a commercially available service.

- Service Interoperability (MoE-11) – This category evaluated the extent to which "PNT technologies are suitable in combination with other PNT technologies." Iridium (previously Satelles) scored 'High' (best), meaning that STL "demonstrated some significant compatibility."

- PNT Information Security (MoE-12) – DOT evaluators "observe[d] security mechanisms, either explicitly in scenarios, or implicitly in the implementation of the PNT signal itself." STL scored 'High' (best), which, as DOT points out, is important because "[t]he information security and resilience of a given PNT signal have significant correlation when considering intentional disruption or manipulation of the PNT function."

References

U.S. Department of Transportation, *Complementary PNT and GPS Backup Technologies Demonstration Report* (January 2021), https://www.transportation.gov/sites/dot.gov/files/2021-01/FY%2718%20NDAA%20Section%201606%20DOT%20Report%20to%20Congress_Combinedv2_January%202021.pdf

Satelles postion statement (February 3, 2021), https://satelles.com/wp-content/uploads/pdf/DOT-PNT-Report-Satelles-Statement_3Feb2021.pdf

European Commission

Iridium (previously Satelles) was awarded a contract in October 2021 to participate in a demonstration and evaluation of alternative PNT technologies conducted by the European Commission (EC) Directorate-General for Defence Industry and Space (DEFIS). STL was subjected to a range of performance and operational tests in a technical evaluation conducted in late 2021 and early 2022 at the EC's Joint Research Centre (JRC) in Ispra, Italy.

As stated by the EC, the aim of this project was to "analyse the technologies which could deliver positioning and/or timing information independently from GNSS, to be effective backup in the event of GNSS disruption, and if possible, to be able to provide PNT in the environments where GNSS cannot be delivered."

Assessments and Findings

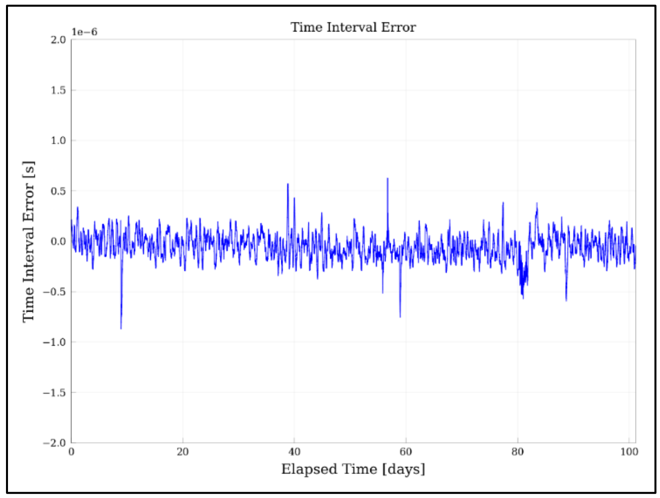
STL met or exceeded each of the top-level requirements of the EC evaluators:

European Commission AltPNT Performance Requirement	STL Performance
Act independent of GNSS and with no common points of failure; resilient to GNSS failure modes and vulnerabilities	STL is resilient to the loss of GNSS, without common modes of failure in the event of GNSS disruption or in environments where GNSS cannot be delivered. This was (1) verified by third-party testing conducted for the U.S. Department of Transportation (later published in the aforementioned report) and (2) confirmed in a study conducted by the U.S. National Institute of Standards and Technology.
Minimum performance for at least one day upon GNSS loss: • Positioning accuracy (horizontal and/or vertical 95%) < 100 meters • Availability > 99%	STL surpassed the EC's expectations in tests performed in the absence of GNSS: • Horizontal positioning accuracy (95%): range of 23.8 to 26.6 meters • Vertical positioning accuracy (95%): range of 7.2 to 16.8 meters • Availability: 100% for timing and positioning at 1, 14, and 100 days
Able to cover the EU European territory including inland waters	As a global service that can be broadcast to any point on the planet, the worldwide footprint of STL delivers service to the entire EU European territory and can also provide coverage to the EU's overseas countries and territories (OCT).
Technology Readiness Level (TRL) > 5 for positioning/navigation OR > 6 for timing services	Testing confirmed what customers that have been using the commercially available service for years already know — which is that the STL service and STL user equipment are both rated at TRL 9 (the highest technology readiness level). Substantiating the full maturity of the technology, STL receivers demonstrated true plug-and-play operation, with on-site calibration neither required nor applied in advance of any testing, taking less than 10 minutes to set up the equipment and under one minute to output an accurate position and time with an indoor antenna. Whereas other technologies in the EC study need to secure spectrum rights from government regulators, STL is a fully deployed global service that currently operates with all the necessary spectrum rights in Europe.

European Commission AltPNT Performance Requirement	STL Performance
Extend PNT provision to the environments where GNSS cannot be delivered (optional)	Iridium (formerly Satelles) demonstrated that STL operates within indoor environments during tests with an antenna positioned in the center of the ground floor of a large building at the Ispra facility. STL performed exceptionally whether placed on top of or inside a metal filing cabinet.

Key results are as follows:

- Outdoor Static Timing Test. The JRC studied STL while operating in the absence of a signal from Global Network Satellite Systems (GNSS), such as the U.S.-operated Global Positioning System (GPS) or the European Union-managed Galileo system, for progressively longer periods of 1, 14, and 100 days. Using a traditional, exterior roof-mounted antenna, STL achieved accuracy relative to Coordinated Universal Time (UTC) in the range of 100 to 150 nanoseconds across all test intervals with 100% availability and exceptional timing stability. For the 100-day test, STL produced timing accuracy of 135.4 nanoseconds with an incredible timing stability (Allan deviation) of 2.28E-13 — all while operating with 100% availability for the duration of the test.



- Indoor Static Timing Test. JRC testing also included two scenarios with a small indoor antenna located in the center of the ground floor of a large building at the JRC facility. With the antenna on top of a filing cabinet, STL achieved 100% availability with timing stability of 1.76E-12. With the antenna then placed inside the filing cabinet for a separate scenario, STL again achieved 100% availability with remarkable timing stability of 8.8E-12. During the demonstration day event, STL provided reliable service even when the indoor antenna and receiver were placed in a JRC bunker with concrete walls one meter thick and sealed by a heavy steel door.
- Static Positioning Tests. JRC engineers evaluated STL's positioning capabilities using the same outdoor and indoor fixed antenna configurations as the timing tests. Operating for 100 days — which far surpassed the EC's 7-day and 24-hour periods for outdoor and indoor testing, respectively — and with 100% availability, STL delivered horizontal positioning accuracy (95%) of 26.6 meters and vertical positioning accuracy (95%) of 16.8 meters. These values were significantly better than the EC's requirement, which called for PNT technologies to be accurate to within 100 meters at the 95th percentile.
- Thoroughly Simple Operation. STL receivers demonstrated true plug-and-play operation, with on-site calibration neither required nor applied in advance of any testing, including

the 100-day test. It took less than 10 minutes to set up the equipment and under one minute to output an accurate position and time with an indoor antenna, proving how easy it is for end users to get started with STL.

Detailed performance results from the test:

Key Performance Indicator	Length of GNSS Outage 1 day	14 days	100 days
Timing Stability (Allan Deviation)	2.57E-12	2.05E-13	2.28E-13
Positioning Accuracy (horizontal) (95%)	25.699 m	26.559 m	23.845 m
Positioning Accuracy (vertical) (95%)	7.200 m	9.670 m	16.800 m
Availability (%)	100%	100%	100%
Continuity (per hour)	100%	100%	100%
First time to provide continuous services upon cold start-up (including system and receiver contributions)	< 15 min	< 15 min	< 15 min

References

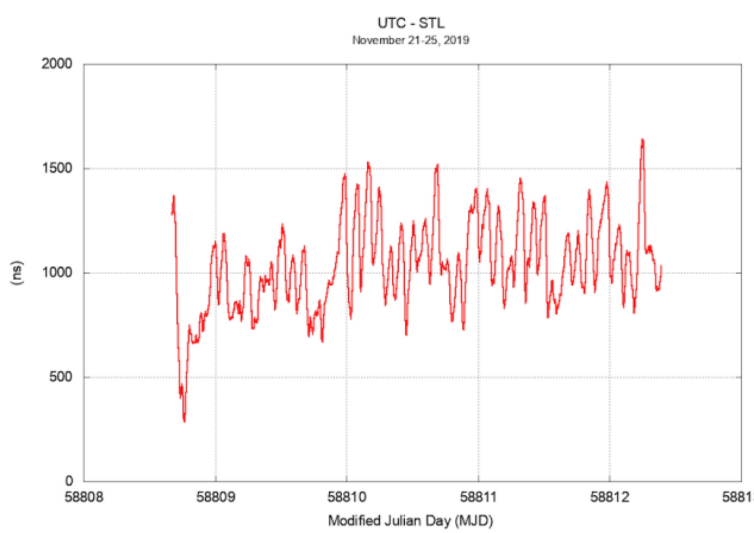
Satelles published a press release about the inclusion of STL in the alternative PNT study: https://satelles.com/press-release-pnt-study-by-european-commission-showcases-performance-of-stl/

The EC's Joint Research Centre maintains a web page for the project: https://joint-research-centre.ec.europa.eu/scientific-activities-z/critical-infrastructure-protection/alternative-pnt_en.

NOTE: *The EC conducted its test in late 2021 and early 2022, but they did not publish their results until March 2023. In the more than one year that elapsed between EC testing and report publication, Iridium has continued to optimize STL technology, achieving results as low as 26 nanoseconds at 1 sigma.*

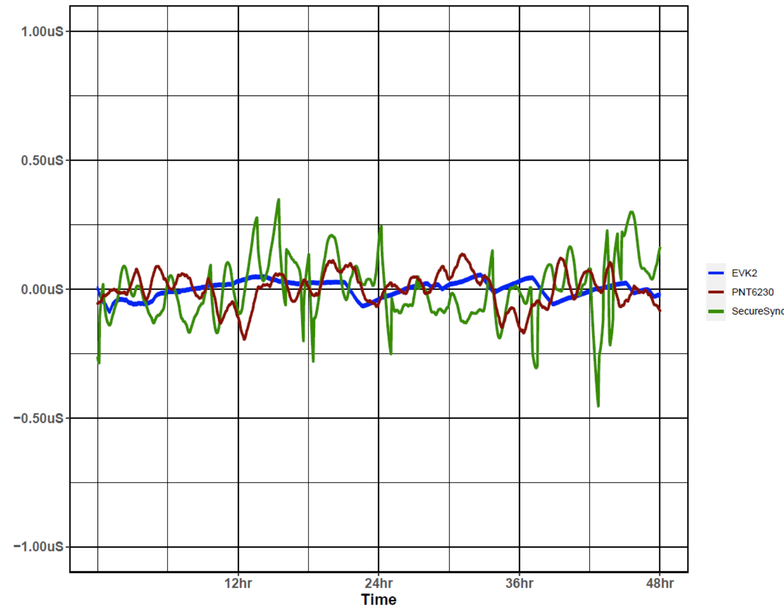
Other Testing

A February 2020 report in *Inside GNSS* described a PNT technology evaluation conducted by GMV, a Spanish multinational corporation. GMV tested an Orolia (now Safran Trusted 4D) SecureSync time and frequency reference system paired with Iridium STL. This indoor, underground test confirmed the resilience of STL, which is broadcast from low-Earth-orbit satellites.



Separately, a team of R&D engineers from Iridium authored a report in *Inside GNSS* that details some key performance characteristics of STL.

This piece underscores the exceptional quality of LEO PNT by proving that Iridium can deliver sub-microsecond timing performance without any reliance on GPS, thereby distinguishing it as a reliable backup to GPS/GNSS for critical infrastructure applications that require precise timing synchronization.



The study further demonstrates that STL is compatible with different types of equipment with wide-ranging operational features and superb performance characteristics, such as the receivers from Orolia (now Safran Trusted 4D) and Jackson Labs Technologies (subsequently acquired by VIAVI Solutions) featured in the *Inside GNSS* story.

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