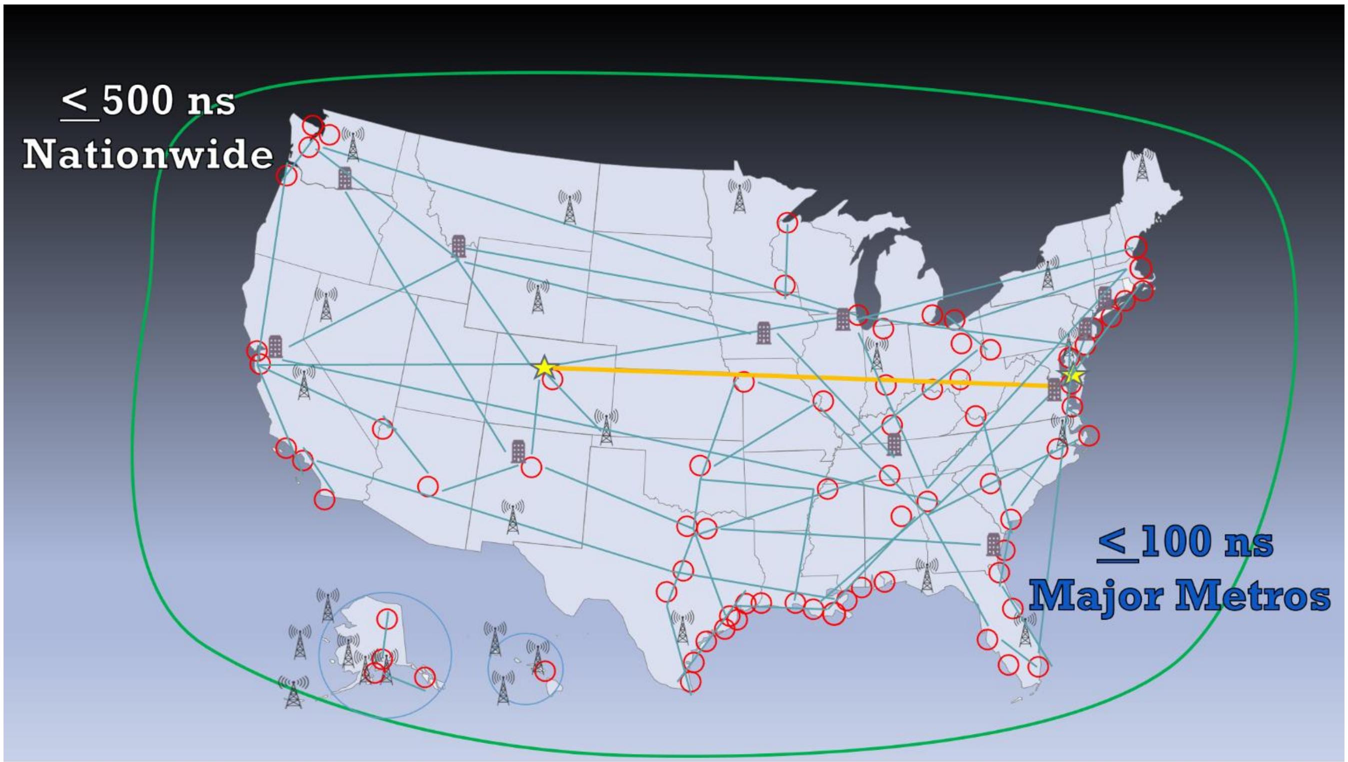
16 October 2020



A Resilient National Timing Architecture

SECURING TODAY'S SYSTEMS, ENABLING TOMORROW'S

DR MARC WEISS, DR PATRICK DIAMOND, MR DANA A. GOWARD

A Resilient National Timing Architecture

"Everyone in the developed world needs precise time for everything from IT networks to communications. Time is also the basis for positioning and navigation and so is our most silent and important utility." *The Hon. Martin Faga, former Asst Secretary of the Air Force and retired CEO, MITRE Corporation*

Executive Summary

Timing is essential to our economic and national security. It is needed to synchronize networks, for digital broadcast, to efficiently use spectrum, for properly ordering a wide variety of transactions, and to optimize power grids. It is also the underpinning of wireless positioning and navigation systems.

America's over-reliance for timing on vulnerable Global Positioning System (GPS) signals is a disaster waiting to happen. Solar flares, cyberattacks, military or terrorist action – all could permanently disable space systems such as GPS, or disrupt them for significant periods of time.

Fortunately, America already has the technology and components for a reliable and resilient national timing architecture that will include space-based assets. This system-of-systems architecture is essential to underpin today's technology and support development of tomorrow's systems.

This paper discusses the need and rationale for a federally sponsored National Timing Architecture. It proposes a phased implementation using Global Navigation Satellite Systems (GNSS) such as GPS, eLoran, and fiber-based technologies. These were selected because they:

- Provide maximum diversity of sources and least common failure modes,
- Are mature, have repeatedly been demonstrated to perform at the required levels, and are ready to deploy,
- Have the potential for further development to increase accuracy, resilience, and cyber security,
- Are already supported, to varying degrees, by existing infrastructure, and
- Require relatively modest investments.

Timing is essential to maintaining our economy and national security. Today's over-reliance on vulnerable GPS satellite signals is a disaster waiting to happen. America already has the technology and components for a reliable and resilient national timing architecture to underpin today's technology, and support development of tomorrow's systems. All that is needed is to bring all the parts together.

I. Imperatives

PNT Essential, GPS Users Threatened

The last ten years have seen ever more sophisticated ways of disrupting satellite-based positioning, navigation, and timing (PNT) services, as well as sharp yearly increases in the number of disruptions reported. Compounding this, the U.S. Federal Communications Commission has recently permitted an operation forecast to interfere with space based PNT for many users.

At the same time thousands of business models are built upon the assumption of continuously available, wide-area, wireless PNT. More and more lives depend upon uninterrupted PNT services. More and more new technologies - aerial drones, autonomous vehicles, intelligent transportation systems - are advancing, often just assuming PNT will be available.

The National PNT Architecture[1] is America's plan for sufficiently robust PNT to ensure national and economic security. Of P, N and T, the "T" is unquestionably foundational. GPS satellites, Loran transmitters, and other wide-area systems are just radios broadcasting time signals from known locations.

Thus, in building a National PNT Architecture, the first and most important step is Timing.

Important and Urgent

Establishing a National Timing Architecture that serves the entire nation has become an increasingly important and urgent task.

> **Current Dependence, Support to New Technology -** While GPS signals were never intended to be the nation's time standard, their low barrier to entry, precision, and wide availability have made them the de facto national reference. At the same time, such wide adoption means their vulnerabilities pose a near-existential threat.
>
> These vulnerabilities are problematic for existing systems and can limit development of PNT-dependent technologies. The following are examples of particularly dependent sectors:

[1] https://www.transportation.gov/pnt/national-positioning-navigation-and-timing-pnt-architecture

- **5G telecommunications** - While many systems appear to have alternate and diverse timing sources and pathways, such as use of the IEEE 1588-2019 Precision Time Protocol (PTP),[2] many, if not most, of these trace back to GPS as the primary reference. Thus, while 5G is moving forward, it is doing so with GPS time being a critical single point of failure.
- **Autonomy** – As remarked by a senior U.S. Department of Transportation official, "No one is going to accept autonomous vehicles without a rock-solid foundation of location and navigation." Drones losing GPS signals and crashing as they are captured by the wind, autonomous vessels being set on the rocks, demonstrations of cars in self-drive mode being forced off the highway by white-hat hackers – all reinforce the notion that reliable and robust PNT is on the critical path to further significant advances in autonomy.
- **Transportation –** Wireless PNT from GPS has been incorporated into every mode of transportation. Without it, every mode would slow, have less capacity, and be more accident prone.
- **Intelligent Transportation Systems (ITS)** – Traffic routing applications such as Waze,™ ride share services like Uber™ and Lyft,™ train/bus arrival notifications, optimized delivery service programs, traffic signal phase and timing coordination - all are early implementations of ITS. In the absence of GPS' wireless PNT none of these would be possible. Many businesses would either cease to exist or require massive retooling and capital investment. Implementation of future ITS features will likewise require robust, resilient, reliable PNT as part of their foundation.
- **Electric Power** - Smart grid technology using synchrophasers for real time control will bring greatly increased safety and efficiency to electrical power distribution. This is unable to move forward, though, without multiple, differently routed Coordinated Universal Time (UTC) time signals to ensure system reliability.
- **Financial Services –** Consumer financial services (ATMs, checking, banking) depend upon GPS' PNT for timestamping transactions and for network synchronization. Financial services regulated by the Security and Exchange Commission use GPS for some applications, but typically also maintain their own internal time "epochs" with suites of clocks to create timestamped event records, fiber, microwave links, etc. While they may be less vulnerable to disruption as a result, the large amounts of money involved make them a more tempting target for malicious PNT disruption.
- **Digital Broadcast & Land Mobile Radios –** GPS' precise timing is used to enable greatly increased use of fixed spectrum in digital radio and television broadcasts, as well as mobile radio networks, over what was available with earlier analog systems. As an example, in their analog form handheld and mobile radios used by security, first responder, military and others were able to support only one transmitter to be

[2] IEEE Standard 1588-2019, Standard for a Precision Clock Synchronization Protocol for Network Measurement and Control Systems https://standards.ieee.org/standard/1588-2019.html

on-air at a time, and one conversation on a frequency. Users had to be careful to push their radio key to talk and say "over" to indicate they were done before releasing the key and freeing up the frequency for a reply. With digital systems leveraging GPS' precise time signals to divide up the conversations into packets, multiple conversations can be had simultaneously on the same frequency.

Existential Contingency – Timing is an essential function for a wide variety of critical infrastructure. No developed nation can afford to risk losing timing.

This has led to many nations beginning to establish more robust and resilient terrestrial timing architectures to complement and backup GNSS. As examples:

- Europe has a well-developed 1588 PTP network infrastructure linking national timing clock suites.
- The United Kingdom is establishing a virtual National Timing Centre with distributed suites of atomic clocks at critical nodes throughout the nation. They are also transmitting precise time from a single eLoran source and appear to be contemplating additional transmitters.
- China has an exceptionally precise 1588 PTP network linking atomic clocks, and a robust Loran time network. Its stated goal of "comprehensive PNT" represents the world's most complete PNT architecture. China has mentioned in a recent publicly available paper that they will be constructing at least three new Loran transmission sites and advancing the capability of their system.[3]
- No information is immediately available about Russian 1588 PTP implementation, though it is clear from their Radionavigation Plan[4] that the Russian variant of Loran will continue to play an important role in national PNT.

Progress in the United States does not appear to be nearly as advanced. Several government departments and labs have distributed clock systems, though they do not appear to be linked in any way to provide national timing resilience. These might, however, have the potential to be incorporated into and benefit the National Timing Architecture. See "Technologies" section below.

Legislation – While progress on system coordination and implementation does not appear well advanced in the U.S. as in some nations, general awareness of the importance of timing resilience has increased. This has resulted in congressional interest and action. The National Timing Resilience and Security Act of 2018,[5] mandates the Department of Transportation establish at least one terrestrial timing system to backup GPS services by December of 2020.

---

[3] "High Accuracy Positioning Based on Psuedo-Ranges: Integrated Difference and Performance Analysis of the Loran System" *Sensors* 2020, *20*(16), 4436; https://doi.org/10.3390/s20164436
[4] https://rntfnd.org/wp-content/uploads/CIS-Russia-Radionav-Plan-2019-2024.pdf
[5] Sec 514, S140 "Frank LoBiondo Coast Guard Authorization Act of 2018 https://www.congress.gov/115/bills/s140/BILLS-115s140eas.pdf

This legislation both documents the existential imperative of ensuring non-space-based sources of timing and is a legal imperative in its own right.

II. Considerations

Architectural Considerations

Timing Architecture Goals

Establishment of a National Timing Architecture must:

- Increase time resilience and redundancy across 100% U.S. land area & maritime Exclusive Economic Zone (EEZ),
- Provide trusted time via multiple authenticated, cybersecure sources that can also validate each other,
- Support critical infrastructure and be a basis for commercial enhancement services,
- Provide a solid timing infrastructure upon which new technologies, research, and scientific applications can build,
- Ensure wireless access everywhere across 50 states and the EEZ to 500 nanoseconds or better accuracy relative to UTC,
- Ensure wireless access everywhere in major metro areas to 100 nanoseconds or better accuracy relative to UTC,
- Provide Network Access Points (NAPs) in metro areas with 100 nanoseconds or better accuracy relative to UTC for further network distribution/use,
- Ensure critical users have access to a minimum of three sources of timing (for redundancy & voting) relative to their required accuracies, and
- Ensure operational reliability is maintained to a “five 9’s” level of performance.

Characteristics

Redundancy - One of the more important principles of systems engineering and architecture is redundancy of critical systems. And the more critical the system, the more important redundancy. In the most important instances triplication is required.

From a concise on-line discussion:

> *In many safety-critical[6] systems, such as fly-by-wire and hydraulic systems in aircraft, some parts of the control system may be triplicated[7] which is formally termed triple modular redundancy (TMR). An error in one component may then be out-voted by the other two. In a triply redundant system, the system has three sub-components, all three of which must fail before the system fails. Since each one rarely fails, and the sub components are expected to fail independently, the probability of all three failing is calculated to be extraordinarily small; often outweighed by other risk factors, such as human error. Redundancy may also be known by the terms "majority voting systems"[8] or "voting logic".[9]*

The safety-critical nature of timing services means that the National Timing Architecture must be a hybrid network, or system of systems.

Diversity – Ensuring that the major timing sources in the architecture are as different from each other as possible will help avoid common vulnerabilities, threats, and failure modes. It will also help safety-critical users maximize triple modular redundancy.

Coordinated Universal Time (UTC) – Relative time is often sufficient for synchronization of networks and in many other applications. However, UTC with the government's imprimatur (by the National Institute of Standards and Technology (NIST) and the United States Naval Observatory (USNO)) must be the basis from which the National Timing Architecture provides absolute time across the nation.

Responsibility for Sources – The architecture must provide multiple diverse pathways for users to access and maintain time. Responsibility for providing these sources will vary. For example, the responsibility to establish and maintain UTC, as well as the GPS satellite constellation, is clearly that of the federal government. Holdover clocks, when needed or appropriate, are clearly the responsibility of users. Responsibility for other portions of the architecture will be the subject of policy decisions.

---

[6] A safety-critical system (SCS) or life-critical system is a system whose failure or malfunction may result in one of the following outcomes:

- death or serious injury to people
- loss or severe damage to equipment/property
- environmental harm

[7] Redundancy Management Technique for Space Shuttle Computers, IBM Research

[8] R. Jayapal (2003-12-04). "Analog Voting Circuit Is More Flexible Than Its Digital Version". elecdesign.com. Archived from the original

[9] *"The Aerospace Corporation | Assuring Space Mission Success". Aero.org. 2014-05-20*

Requirements

Current Dependence, Support to New Tech – Available literature[10] indicates that the following are representative of national requirements:

- **5G telecommunications** - Requires 1.1 microseconds accuracy relative to UTC for Radio Synchronization and overall network latency.[11]
- **Autonomy** – Still in development and expected to vary by platform. Requirements for lane keeping in vehicles are expected to range from 5 to 10 centimeters. This will likely exceed what can be reliably provided by infrastructure and require on-vehicle sensors/ augmentation. Establishment of the national timing architecture will still be key to provide a solid foundation upon which innovators can build.
- **Transportation –** Requirements vary by application. For consumer-level applications, 100 nanoseconds timing and ten meters location accuracy appear to be sufficient.
- **Intelligent Transportation Systems (ITS)** – Same as telecommunications requirements above.
- **Electric Power** - Synchrophasers for real time control require multiple differently routed UTC time signals at the 1 microsecond level or better.[12] [13]
- **Financial Services** – Individual firms frequently employ sufficient fiber and clock suites to maintain internal synchronization within their own epoch to very demanding limits, sometimes within a nanosecond. However, federal regulations only require firms to maintain 100 microseconds accuracy relative to UTC.

Technologies

UTC Access – Coordinated Universal Time (UTC) for the United States is maintained by the US Naval Observatory (USNO) in Washington, DC, and the National Institute of Standards and Technology (NIST) in Boulder, CO. To use and distribute UTC, a technology must synchronize with one of these two sources. Depending on the desired level of accuracy, this can be done in a variety of ways including Two Way Satellite Time Transfer (TWSTT), fiber connection, microwave link, GPS Common View, or from a GPS receiver.

---

[10] See for example 2019 Federal Radionavigation Plan - https://www.navcen.uscg.gov/pdf/FederalRadioNavigationPlan2019.pdf

[11] ATIS Standard 0900005 GPS Vulnerability https://access.atis.org/apps/group_public/download.php/36304/ATIS-0900005.pdf

[12] M.A. Weiss, A. Silverstein, F. Tuffner, Y. Li-Baboud, "The Use and Challenges of Precise Time in Electric Power Synchrophasor Systems," *Proc. 2017 PTTI and ITM of ION*, Jan 30, 2017, available from: https://www.nist.gov/publications/use-and-challenges-precise-time-electric-power-synchrophasor-systems

[13] *Consolidated Audit Trail (CAT) Reporting Technical Specifications for Plan Participants*, available from the Consolidated Audit Trail National Market System (CAT NMS) Plan website: https://www.catnmsplan.com/

It is even possible to "physically" transfer time. Before the digital and communications revolution, entities would bring suites of atomic clocks to USNO to synchronize, and then transport those clocks to sites like Loran and Omega transmitting stations as a way of distributing UTC.

Global Navigation Satellite Systems (GNSS)/GPS – The cornerstone of the National Timing Architecture will be GPS which has a U.S. government supported 78 ns accuracy. Approval by the Federal Communications Commission (FCC) of Europe's Galileo to be used within the United States allows this second GNSS to also be included. This gives added resilience to the space-based portion of the architecture. - Note that GPS actual performance is almost always better than nominal. Accuracies of < 10 ns for timing and < 10 ft for location are typical (1 ns ≈ 1 foot).

LEO PNT – Numerous government and commercial endeavors are examining the viability and benefits of providing PNT services from satellites in low earth orbit (LEO). This could be inferred from signals of non-PNT constellations. LEO PNT systems could also be created by sharing payloads with other missions, or with purpose-built and deployed constellations. We note that at least one vendor already offers time as a subscription service from LEO satellites.

Networks / Fiber – Various levels of timing accuracy are available by networks and fiber ranging from about tens of milliseconds for NTP, to about 1 ns for dedicated bi-directional wavelengths, each pair in a single fiber. Commercial providers have technology available to provide users with localized, point, and autonomous timing to meet requirements for better than 100 ns accuracy.[14] A newly released update to IEEE 1588-2019, also known as PTP, contains a "High-Accuracy Option."[15] This is a generalization for wide area usage of the White Rabbit standard developed at CERN for sub-nanosecond synchronization accuracy of more than 1,000 nodes via connections up to 10 km of length.

Wide Area Broadcast – Demonstrations in the United States and United Kingdom have shown that eLoran technology broadcasting at 100 kHz is capable of providing better than 1 microsecond accuracy over distances up to 1,600 km from the transmitter, and better than 100ns within 55 km of a differential reference station.[16]

[14] M. Weiss, L. Cosart, J. Yao, J. Hanssen, "Ethernet Time Transfer through a U.S. Commercial Optical Telecommunications Network, Part 2," in *Proc. Precise Time and Time Interval Meeting*, Monterrey, 2016, available from https://tf.nist.gov/general/pdf/2813.pdf

[15] IEEE Standard 1588-2019, Standard for a Precision Clock Synchronization Protocol for Network Measurement and Control Systems https://standards.ieee.org/standard/1588-2019.html

[16] G. Offermans, S. Bartlett, C. Schue, "Providing a Resilient Timing and UTC Service Using eLoran In the United States" in *ION Journal of Navigation Vol 64, Number 3 (Fall 2017)* available from https://www.ion.org/publications/abstract.cfm?articleID=102722

Note that WWVB broadcasting at 60 kHz could conceivably be developed for this purpose also. DARPA's STOIC program also envisions a wide area time service using Very Low Frequencies (VLF).

eLoran – eLoran is a form of wide area broadcast using 100 kHz. It is at TRL 9, requiring no development, and is compatible with other Loran systems in operation around the world. This provides significant technology synergies as well as the potential for positive and beneficial engagement with other national operators.

eLoran performance as a timing signal has been demonstrated to the U.S. Department of Homeland Security as part of a Cooperative Research and Development Agreement,[17] and by research in the United Kingdom.[18] A national eLoran timing system is also among the most recent recommendations of the US National Space-based PNT Advisory Board.[19] In 2015 the US President's National Space-based PNT Executive Committee committed to establishment of an eLoran-based timing system.[20]

Local Area Broadcast – Local broadcasts can provide timing, along with positioning and navigation information. The accuracy and geographic coverages of these local systems vary with the technology, density of transmitters, and other factors. Systems have been demonstrated to have pico-second level accuracy in some instantiations.

Distributed Clocks – The federal government maintains various federal clock suites for its own purposes that appear to be able to independently maintain a 1 microsecond level of accuracy relative to UTC indefinitely.

- The Department of Defense, in addition to maintaining UTC at the US Naval Observatory, Washington, DC, has a backup capability at Schriever AFB. Synchronization is maintained via two way satellite time transfer (TWSTT). DoD also maintains a Defense Regional Clock Program.
- The Department of Commerce also maintains UTC at NIST Boulder, CO, with a backup at Ft Collins, CO. Synchronization is maintained by GPS Common-View Time Transfer. NIST Gaithersburg, MD also maintains a clock suite using GPS Common View for synchronization. NIST is exploring synchronizing these sites with fiber networks, potentially at the 1 nanosecond level.
- The Department of Energy maintains suites of clocks at Oakridge, Sandia, and Lawrence Livermore.

[17] ibid
[18] See for example C. Curry "Delivering a National Time Scale Using eLoran" 7 June 2014 https://rntfnd.org/wp-content/uploads/Delivering-a-National-Timescale-Using-eLoran-Ver1-0.pdf
[19]https://www.gps.gov/governance/advisory/recommendations/2018-09-topic-papers.pdf
[20] Letter 8 Dec 2015 from PNT Executive Committee Co-chairs DoD Dep Sec Work and DoT Dep Sec Mendez to several members of Congress. See: https://rntfnd.org/wp-content/uploads/DSD-and-Dep-DOT-reply-to-Mr.-Garamendi.pdf

Network Access Points NAPs – NAPs are physical locations, usually in major cities, where Interexchange carriers, Independent Local Exchange Carriers, Competitive Local Exchange Carriers, National Carriers, Local Fiber Carriers, etc. "interconnect" with each other's services. All participating operators contribute to the cost. The national network is made up of hundreds of these NAPs.

The fiber component of the National Timing Architecture will have these interconnect "touch points" at its heart. All monitoring probes, testing, configurations, and connections for further, more localized distribution will occur at these locations.

Network Control & Performance Assurance – Coherent networks require management and control systems to ensure their operation and performance. These involve geographically distributed sensors, testing, performance and fault reporting. Such a control system requires its own redundancy and resilience. GPS, Loran-C and-similar systems have ensured that full network monitoring and control is available at two or more geographical locations remote from each other.

Cybersecurity – While not a technology in and of itself, authentication, access controls, system and user cybersecurity must be considered throughout. The ability of users to trust the timing they receive is paramount. If, as has been seen around the world with positioning, timing is not trustworthy, it may not be used. Worse, it could provide potentially hazardously misleading information.

Policy Considerations

Federal Leadership - *The first duty of government is to afford protection to its citizens.*[21]

Timing's criticality and essentiality to such a broad spectrum of the public and critical infrastructure means that government has a responsibility to ensure such an architecture is established, and quickly.[22]

The essentiality of time to a nation's economy and security has been recognized since at least 1714. The British "Longitude Act" of that year might have been better titled "The Time Keeping Act." It led to development of Harrison's chronometer and untold immediate benefits to the Royal Navy and merchant fleets. In the United States, USNO has been dropping a time ball since 1845 to mark mean solar noon. Since then, the U.S. government has been communicating time across increasingly large sections of the nation at increasing levels of accuracy.

---

[21] Cong. Globe, 39th Congress 2nd Sess. 101 (1867) (remarks of Rep. Farnsworth debating Reconstruction Act of 1867) See also Preamble to the Constitution: "…in Order to form a more perfect Union, establish Justice, insure domestic Tranquility, provide for the common defence, promote the general Welfare, and secure the Blessings of Liberty to ourselves and our Posterity…"

[22] As noted earlier, the responsibility to establish at least part of the timing architecture is required by the National Timing Resilience and Security Act of 2018.

The federal role is also essential as the government's imprimatur is required for a time signal to be credible, nationally interchangeable and as useful as possible. Any sufficiently stable time source is adequate for "relative time" to synchronize interconnected sources and other applications that require events to be coordinated only with each other, but not the world at large. Macro, national enterprise synchronization and interoperability, though, is only possible with a widely communicated time signal endorsed by the sovereign.

As discussed earlier, while the National Timing Architecture must provide multiple diverse pathways for delivery of authoritative time, responsibility for providing these sources will vary. Direct federal involvement (leadership, funding, etc.) must ensure all citizens have reasonable access to more than one path to UTC to prevent time being a single point of failure. Other aspects of the architecture such as augmentations that increase accuracy, hold-over time in the event no external sources are available, and supplemental space-based signals may be the responsibility of users.

The federal government's role in establishment and communication of national time is a critically important one. Yet it need not be onerous. Experience with similar efforts such as FirstNet and the FAA's ADS-B system has shown that often the least cost and quickest path to system implementation is a partnership between the government and the commercial sector.

Further reducing the burden on government is a recent technology demonstration done by the Department of Transportation. It showed that sufficient systems exist today to complete a robust National Timing Architecture.

Costs - *There are risks and costs to action. But they are far less than the long-range risks of comfortable inaction.* – *Attributed to President John F. Kennedy*

No discussion of a proposed federal investment would be complete without at least a general consideration of costs to both the federal government and users. These costs will be relatively modest, yet absolutely necessary.

Relatively Modest – By leveraging public-private-partnerships, service-agreements, and the like, government can encourage and establish the infrastructure described herein at a cost measured in tens of millions of dollars per year. This is relatively modest when compared to annual expenditures on GPS which exceed $1B.

The cost of end-user equipment will undoubtedly decline as more and more users access the fiber-based and wireless signals. As was the case with GPS and most other technologies, early user equipment will likely be larger and more expensive than in later receiver models. An early pallet-sized GPS receiver, complete with two operator chairs, was budgeted for hundreds of thousands of dollars. Miniaturization, technological advances, and mass production have enabled production of the cheapest GPS for several dollars each.

User costs will also be offset by the need to recapitalize equipment and improvements in utility.

After implementation of the National Timing Architecture there will be little incentive for production of GPS/GNSS-only timing receivers. Just as manufacturers have incorporated other GNSS systems alongside GPS in almost all new receiver models, so too will they almost certainly include over time the ability to use the architecture's terrestrial systems. Thus, the additional cost for new builds and recapitalized equipment will be only marginally greater than it would have been otherwise in these cases.

More resilient and reliable time will also provide many users increased functionality by virtually eliminating disruptions and providing a higher guaranteed accuracy. As one example of increased utility, this could allow reduced error margins in multiplexing wireless signals, enabling greater use of existing spectrum allocations.

Absolutely Necessary – Often lost in calculating the cost of doing something are the costs of doing nothing. When GPS fails, transportation-related systems immediately suffer. They become less efficient/ more costly, can carry less capacity, and are more accident prone. Land-mobile radio systems and digital broadcasts degrade or fail. In prolonged outages, two-thirds of U.S. wireless networks are projected to fail after about 24 hours. Then, as backup clocks de-synchronize, more network and other failures will ensue, including the loss of consumer financial services and impacts to utilities. One Air Force-sponsored academic paper projected civil unrest within 72 hours.

Quantitative analyses of the impact of GPS outages have always struggled. Most openly admit their inability to gauge the overall impact to the national economy and limit themselves to specific applications or sectors. Notable studies have estimated prolonged disruption of GPS signals costing the US economy across a wide range of $1B[23] to $82B[24]per day.

It is perhaps not possible to capture GPS' true economic value and the impact of its potential loss or prolonged outage. Dollar numbers may not have sufficient meaning in this context. As one writer replied when asked about the value of GPS – "What's the value of oxygen?"[25]

PNT services, especially timing services, are an existential necessity for life in the United States as we know it. Not ensuring they will always be available poses unthinkable risks and costs.

---

23 https://www.nist.gov/document/economic-benefits-global-positioning-system-gps-final-report
24 https://mkt-bcg-com-public-images.s3.amazonaws.com/public-pdfs/legacy-documents/file109372.pdf
25 "Pinpoint – How GPS is Changing our World and our Minds" – Greg Milner, Norton, 2016

Adoption

Wide adoption and use of the National Timing Architecture's terrestrial systems is key to its success. Merely making them available will not increase national and economic security a whit.

Fortunately, America's experience with implementation and adoption of GPS and other GNSS provides some lessons in this regard. And the government has a variety of tools available to encourage this process

The GPS Experience – While there were a number of technical and historical factors in the unparalleled wide adoption of GPS, the following were key:

- **No cost access** – GPS is free to access for anyone who can afford a receiver.[26] Access to the basic terrestrial services in the National Timing Architecture should be without charge also. This does not preclude the government, one of its partners, or another entity from providing fee-based services. But, in the interest of national and economic security, the service levels outlined herein must be without charge, to encourage wide use.
- **Broad availability** – GPS is available to anyone with a view of the sky. This means that it is not location dependent. Something developed for use with GPS in New York also works in California and Alaska. The architecture's terrestrial systems must be available to all users in the United States, regardless of location. The entire nation and its coastal waters will have an accuracy of $\leq$500 ns, with densely populated areas having $\leq$100 ns relative to UTC. However, after implementation of Phase III, any 70-mile wide area can be upgraded to $\leq$100 ns with the installation of a (<$75,000) differential reference station. This is relatively inexpensive when compared to the $400,000+ cost of a Differential GPS site.
- **Open source** – This has been a dual edged sword for GPS and other GNSS. While it allows for easy (and wide) adoption, use, and integration of signals into myriad applications, it has also made the system much easier to jam and spoof. America's terrestrial systems must walk a fine line between encouraging wide and wise use and doing as much as possible to prevent interference. There are many methods for doing this, including having parallel services (perhaps an open system for free public use and a closed, more secure one for government and fee-based use). Encryption, authentication and other security measures will be important aspects of development and operation.
- **Government agencies leading the way** – The initial goal of GPS was for the Air Force to "…put five bombs in the same hole."[27] Early in its implementation, though, many

[26] Early versions of the internet failed, in the opinion of many because administrators sought a small fee to cover overhead costs.
[27] Dr. Bradford Parkinson, Chief Architect of GPS, speaking at Smithsonian Air and Space seminar March 21, 2013

military leaders saw no need for the system and actively opposed it. In fact, at the end of the first Gulf War there was no plan to install GPS in military aircraft. Congress had to insist on it. Adoption and use of GPS by the government was key to its broader adoption across society. This led to a virtuous cycle of improved performance and usability with decreasing costs. The current administration's Executive Order on responsible use of PNT[28] already mandates federal leadership by mandating future federal contracts include a requirement for use of resilient PNT equipment and systems.

Every agency at every level of government has ample reasons to adopt terrestrial services from the National Timing Architecture. Dispatch, asset coordination, land mobile radios, networks – all are degraded or disabled in GPS-denied environments. Imagine the National Guard responding to a disaster without the ability to navigate easily or use their handheld radios. Government agencies and forces will need to use these terrestrial systems, if for no other reason than to ensure continuity of government.

The GNSS Experience

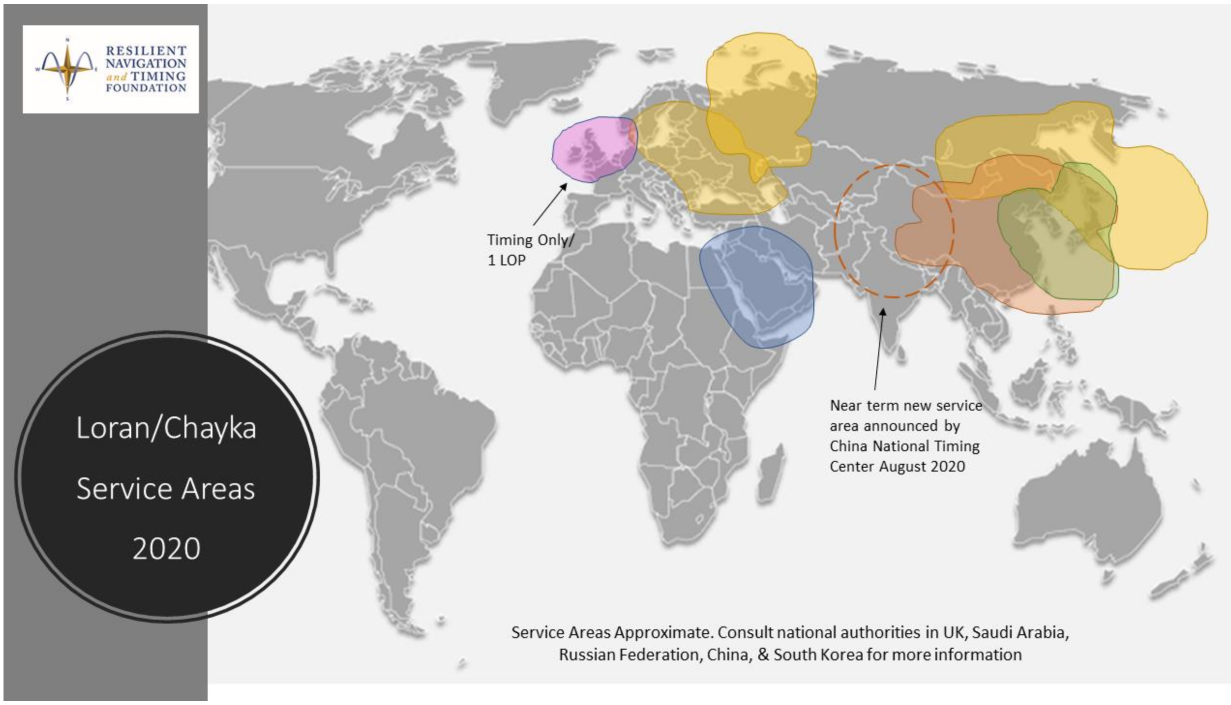
GPS was the world's first satellite navigation system available to consumers. As Russian and European systems became available, receiver manufacturers began incorporating the capability to use them on most of their products. This is happening again with inclusion of signals from the recently completed Chinese Bei Dou system. For years most receivers in the United States, for example, have included the ability to access Russia's GLONASS satnav system, despite federal prohibitions on its use. Many manufacturers ensure this feature is disabled while the equipment is within the U.S. but include it nonetheless. This is because:

- The additional cost is minimal due to decades of technological advancement,
- Building receivers to be as capable as possible is a competitive advantage, or at least prevents a competitive disadvantage,
- Making different receivers for different markets is not cost effective, and
- Users don't want their equipment restricted by geography and expect it to operate at maximum efficiency everywhere.

We can expect that as receiver technology develops and improves in the critical areas of size, weight, power and cost, more and more receivers will include the ability to use the terrestrial components of the National Timing Architecture as part of their timing and navigation solutions.

Incorporation of eLoran will be especially incentivized as compatible signals are already available across a significant portion of the globe (see graphic).

[28] Executive Order on Strengthening National Resilience through Responsible Use of Positioning, Navigation, and Timing Services – Issued February 12, 2020



Government Encouragement & Requirements

Officials truly concerned about the impact of timing resilience on the nation's security and economy have multiple tools at their disposal to encourage adoption of better systems and practices.

The February 2020 Presidential Executive Order on Responsible Use of PNT[29] outlined the administration's plan to use educational efforts and government contracting requirements to stimulate increased PNT resilience across critical infrastructure and industries.

Should these efforts not sufficiently protect the nation, greater incentives and requirements should be considered and implemented. In the past these have included things like tax credits for installing new equipment and performance-based regulations.

Putting Together the Pieces

Put simply, we find time transfer by eLoran and fiber are mature technologies easily capable of spanning the nation. When combined with GNSS, users will have three independent pathways for authoritative Coordinated Universal Time.

[29] Ibid

Maintaining and reinforcing America's network and IT infrastructure is more important now than ever.

Cyber security needs are increasing. Demands on telecommunications service providers are increasing. Space is more and more crowded. GNSS intentional or unintentional interference is increasing.

The COVID pandemic has greatly increased our reliance on networks and distributed work. The number of people who must work remotely, often in locations outside of major metropolitan network nodes has grown significantly. A failure or even temporary outage in any part of our far-flung networks will have much greater impact that it would have had even a year ago.

Adding to domestic concerns, we must also maintain the nation's competitiveness and standing in the world. Europe, China, and others have and are establishing foundational timing systems, sometimes as part of coherent architectures, to provide innovators and engineers needed infrastructure for current and yet-to-be-developed systems.

While the technologies we propose are mature, and the structure fairly uncomplicated, bringing a National Timing Architecture into reality will have its difficulties. Network design, implementation, contract and project management, ongoing operation – all will be challenges. The experiences of projects like FirstNet and ADS-B, though, will be good guides.

Most important and fundamental will be fostering and maintaining the political understanding and imperative for action outlined in the National Timing Resilience and Security Act of 2018.

The task is a relatively straight forward one.

We can ill afford to do less.

II. Proposed Architecture

Structure & Implementation

Recognizing the differences in readiness levels of various solutions, and the differences in cost and ease of implementation, this proposal takes a phased approach to implementing the National Timing Architecture.

Implementing by increments also provides opportunities for user feedback before the entire system is built out. If solutions are not adopted or prove difficult, the architecture and the systems it includes can be modified or changed completely without incurring major costs.

This proposal also:

- Recognizes the higher demand for timing services and concurrently higher return on investment in geographic centers of population and infrastructure,
- Conforms to the National PNT Architecture final report,
- Uses the layered principled outlined in the US Department of Defense PNT Strategy.[30]

Technologies

GNSS, eLoran, and fiber-based timing were selected as the primary sources for the National Timing Architecture because they:

- Provide maximum diversity of sources and least common failure modes,
- Are mature and ready to deploy,
- Have the potential for further development to increase accuracy, resilience, and cyber security, and
- Are already supported, to varying degrees, by existing infrastructure
  - GNSS is clearly fully deployed and in use
  - eLoran primary transmitter sites are already owned by the US government
  - Fiber networks and government distributed clock suites are extant and continue to grow.

And while a comparative cost analysis is not part of this paper, prima facia, the terrestrial systems listed above are of modest cost relative to GNSS and other terrestrial systems.

The selection of eLoran over other mature broadcast technologies is also based upon extensive research in the U.S. and U.K. showing its effectiveness (see previous references). Also, alternative analyses performed by the U.S. government show it as the only technology that combines wide area coverage with sufficient accuracy.[31]

---

[30] https://rntfnd.org/wp-content/uploads/DoD-PNT-Strategy.pdf

[31] See for example “GPS Dependencies in the Transportation Sector” August 2016, U.S. Department of Transportation, Volpe Center, pg 45

Network Control & Performance

Operational performance integrity will be key to acceptance and use of the National Timing Architecture. Critical users will demand "always on" performance, the ability to view the operational stability in real time, an automated failover capability, centralized reporting, and management in the event of a fault. Just as the Air Force commits to and publishes a performance standard for the broadcast of GPS signals, so too the government must commit to a performance standard for the terrestrial portions of the National Timing Architecture.

Notional Phases

The following notional implementation phases are suggested to progressively support critical infrastructure, technology development and maximize the practical use for citizens.

Phase I National Timing Architecture							
	Global Layer		***Continental Layer***		***Local Layer***		
	GNSS 78ns	LEO PNT	**eLoran ≤1 µs 6 sites**	**N. Clock Ntwk ≤100 ns**	**Df eLoran ≤100 ns**	**NAP ≤100 ns**	User Clocks
Fixed Users w/ntwk access							
Everywhere (50 states, EEZ)							
Major Metro					Selected	Selected	
Fixed Users w/ No ntwk access							
Everywhere (50 states, EEZ)							
Major metro					Selected		
Mobile Users							
Everywhere (50 states, EEZ)			*				
Major Metro			*		*Selected		
Govt sponsored/PPP, No/low barrier to entry				Available, commercial, fee based			

Phase I Notes:

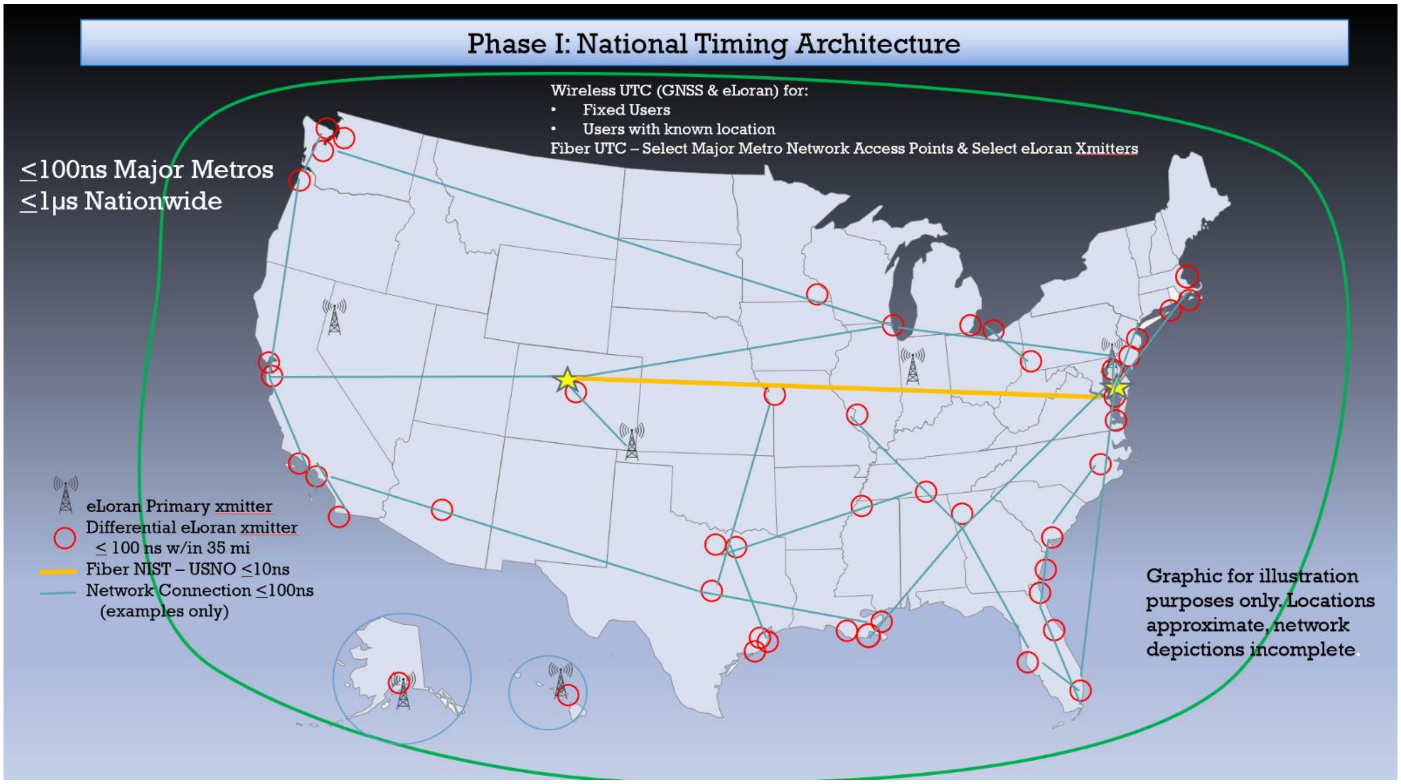
National Clock Network (N. Clock Ntwk) - Fiber: Connect

- NIST Boulder with USNO to establish ≤10 ns sync.
- Selected (TBD) major metros, eLoran differential transmitters, and eLoran primary transmitters ≤100 ns sync

eLoran: Establish 6 primary transmitter sites (4 in CONUS, 1 each in AK & HI)

Differential (Df) eLoran: Establish differential sites in selected (TBD) metro areas

*If GNSS location information is available to a mobile receiver, eLoran time info will be usable and, if properly integrated, can make receivers much less susceptible to GNSS disruption.



32

[32] Graphics adapted with permission from UrsaNav presentations

Phase II National Timing Architecture							
	Global Layer		*Continental Layer*		*Local Layer*		
	GNSS 78ns	LEO PNT	**eLoran ≤500 ns 12 sites**	**N. Clock Ntwk ≤100 ns**	**Df eLoran ≤100 ns 75 sites**	**NAP ≤100 ns**	User Clocks
Fixed Users w/ntwk access							
Everywhere (50 states, EEZ)							
Major Metro							
Fixed Users w/ No ntwk access							
Everywhere (50 states, EEZ)							
Major metro							
Mobile Users							
Everywhere (50 states, EEZ)			*				
Major Metro			*		*	*	
Govt sponsored/PPP, No/low barrier to entry				Available, commercial, fee based			

Phase II Notes:

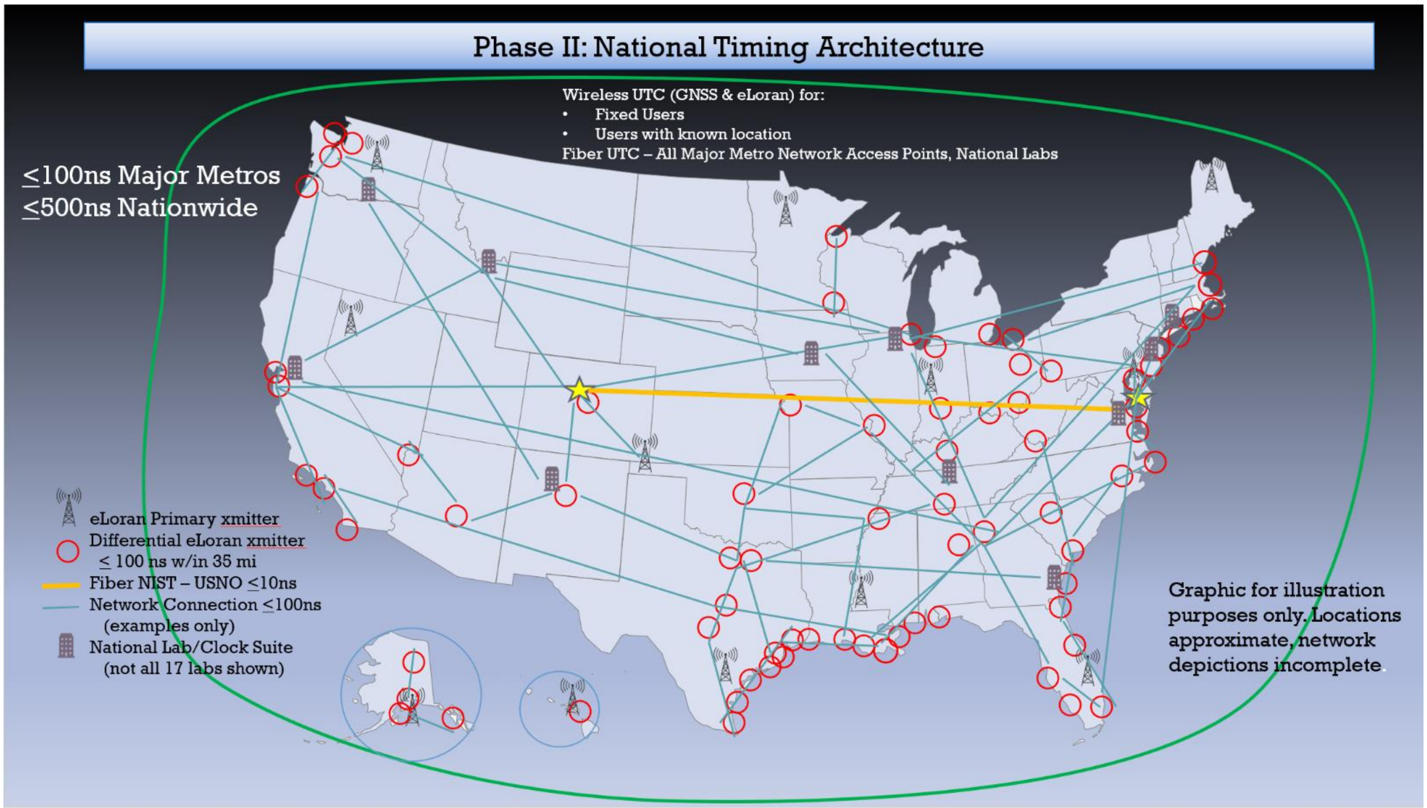
N. Clock Ntwk - National Clock Network (Fiber) Connect:

- National Laboratories & other federally endorsed clock suites. Maintain accuracy at the 100ns level or better (to be determined) relative to UTC.
- Connect to Network Access Points and differential eLoran sites in major metro areas at ≤100 ns level relative to UTC for possible further distribution by govt/ commercial services.

eLoran: Establish 6 additional primary transmitter sites in CONUS (system total of 10 in CONUS, 1 ea AK & HI) for ≤500 ns relative UTC (exception are remote areas of AK ≤1 µs)

Differential (Df) eLoran: Establish total of 75 differential sites to serve the 50 largest metro areas, 50 busiest airports, 50 busiest seaports in CONUS, 3 locations in AK and 1 in HI.

*If GNSS location information is available to a mobile receiver, eLoran time broadcast info will be usable. If properly integrated, eLoran signals can make receivers much less susceptible to GNSS disruption.



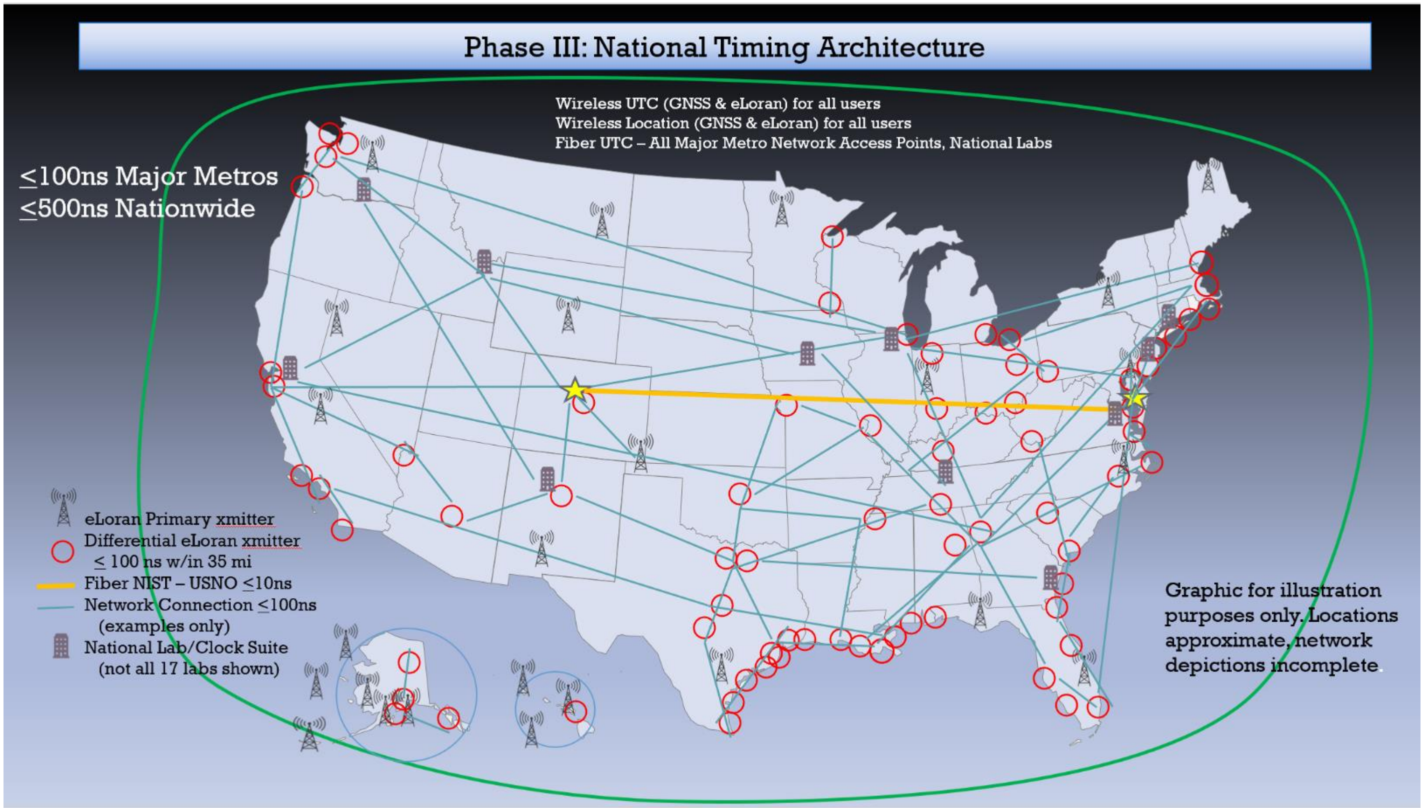
Phase III National Timing Architecture							
	Global Layer		*Continental Layer*		*Local Layer*		
	GNSS 78ns	LEO PNT	**eLoran ≤500 ns ≈25 sites**	**N. Clock Ntwk ≤100ns**	**Df eLoran ≤100 ns 75 sites**	**NAP ≤100 ns**	User Clocks
Fixed Users w/ntwk access							
Everywhere (50 states, EEZ)							
Major Metro							
Fixed Users w/ No ntwk access							
Everywhere (50 states, EEZ)							
Major metro							
Mobile Users							
Everywhere (50 states, EEZ)							
Major Metro							
Govt sponsored/PPP, No/low barrier to entry			Available, commercial, fee based				

Phase III Notes:

National Clock Network: Link in-development and future optical clocks for scientific and research. Frequency accuracies pushing the boundaries of science and human imagination.

eLoran: Establish ≈13 additional primary transmitter sites (total of ≈16 CONUS, 6 in AK, 3 in HI)

GPS/GNSS-Independent Positioning, Navigation, and Timing – Accessing terrestrial wireless time for mobile users requires their locations be known. Sufficient primary eLoran transmitters are deployed in Phase III to provide that information without regard to signals from space. This also enables positioning and navigation based solely on eLoran, in the event that signals from space become unavailable. Continuous synchronization with UTC by fiber or other means to one or more points in the primary eLoran transmitter network and the ability of the network to self-synchronize enables it to operate indefinitely providing PNT in the event of a prolonged GPS/GNSS outage.


Phase III: National Timing Architecture
Wireless UTC (GNSS & eLoran) for all users
Wireless Location (GNSS & eLoran) for all users
Fiber UTC – All Major Metro Network Access Points, National Labs
≤100ns Major Metros
≤500ns Nationwide
eLoran Primary xmitter
Differential eLoran xmitter
≤ 100 ns w/in 35 mi
Fiber NIST – USNO ≤10ns
Network Connection ≤100ns
(examples only)
National Lab/Clock Suite
(not all 17 labs shown)
Graphic for illustration purposes only. Locations approximate, network depictions incomplete.

About the Authors

Marc Weiss, PhD

Dr. Weiss worked at the NIST Time and Frequency Division from 1979 through 2013. He has since been a consultant on precision timing systems for NIST and for various companies. He received several awards during his tenure at NIST. He led the NIST program to support the GPS program office in developing their clocks and timing systems. In 1992, Dr. Weiss founded and has continued to lead the Workshop on Synchronization and Timing Systems (WSTS), now the premier conference on timing and synchronization in industry. In April, 2019, Dr. Weiss was awarded the Marcel Ecabert Lifetime Achievement Award "For his key contributions to remote clock comparisons, to time scale algorithm development and to accurate synchronization for science and industry."

Patrick Diamond, PhD

Dr. Diamond has 40+ years in development and design of network technologies. His tenure in the network technology, design and implementation marketplace has been, specifically in the commercial marketplace. He has and is a participant in Standards body development organizations, IEEE, IETF, ITU. He has helped develop numerous Wide Area Network technologies such as SONET/SDH, TCP/IP, IEEE 1588, IEEE 802.1AS, 3GPP and numerous others specifically dedicated to precision timing in networks and end user systems. He developed and managed organizations that created highly complex System on a Chip technologies in semiconductors for these end implementations. He now serves and a member of the US National Space-Based Positioning, Navigation and Timing Advisory Board.

Dana A. Goward, SES (ret), CAPT (ret)

Mr. Dana A. Goward is President of the Resilient Navigation and Timing Foundation, a scientific and educational charity dedicated to protecting GPS/GNSS signals and users.

He is a lifelong practical navigator orienteering ashore, serving as a ship's navigator at sea, and in the air as a career Coast Guard helicopter pilot.

He retired in 2013 from the Senior Executive Service as the maritime navigation authority for the United States and now serves as a member of the US National Space-Based Positioning, Navigation, and Timing Advisory Board. He is also a senior advisor to Space Command's Purposeful Interference Response Team, is an emeritus Chairman of the Board for the Association for Rescue at Sea, and is the proprietor at Maritime Governance, LLC.