GLOBAL POSITIONING SYSTEM TIMING CRITICALITY ASSESSMENT − PRELIMINARY PERFORMANCE RESULTS

Dr. James Carroll
John A. Volpe National Transportation Systems Center
55 Broadway, Cambridge, MA 02142, USA
(617) 494-2908, *James.Carroll@dot.gov*

Mr. Kirk Montgomery
Symmetricom, Inc.
kmontgomery@symmetricom.com

Abstract

Precision timing and time interval (PTTI) capabilities are becoming more commonplace throughout the world. The increasing demand for and use of precise time comes with a potentially increasing risk of over-reliance on a single timing source. In addition, many precise time applications are considered "critical," in that service disruption could result in severe consequences. The Global Positioning System (GPS) provides PTTI services that meet or exceed most user requirements, at increasingly lower cost. It is important to ensure that critical PTTI services are maintained during periods of disruption or loss of the GPS signal.

This paper presents key findings, conclusions, and recommendations from a Timing Criticality analysis of the impact of loss of GPS time and frequency on important sectors of U.S. society. The focus in this paper is on civil and commercial sectors, including telecommunications and electric power. The goal of the analysis was to assess the consequences of disruption of GPS time on applications critical to the safety, security or economic well-being of the United States. The corollary goal was to determine the benefits and costs of backup systems − including modernized Loran − that mitigate the impact of the GPS disruption.

The timing criticality analysis extends and updates prior work, in particular the DOT/Volpe Center and Homeland Security Institute (HSI) GPS vulnerability studies, and the HSI timing criticality study. The prior work facilitated identification of Subject Matter Experts (SME) in timing and in the critical applications (for example, electric power distribution) that depend on precise time and frequency. For each sector, assessments of timing requirements and of the performance impact under representative GPS outage scenarios were conducted. An early finding is that use of GPS backup systems needs to be clarified to some GPS timing users. Another finding is that GPS disruption has resulted in lost utility billing information. While this particular economic disruption is marginally tolerable for the time being, many electric power distribution SMEs predict a growing dependence on GPS time (hence, on the backup to GPS) for real time maintenance and grid stability.

The paper also discusses a closely related project involving the preliminary evaluation and testing of the Enhanced Loran Research Receiver (ELRR). Symmetricom, NIST, and the Volpe Center have three of the eight ELRR evaluation units currently being tested. Current testing involves time recovery using both indoor and outdoor antennas and comparing the 1PPS output of the ELRR to the 1PPS output to a known reference.

INTRODUCTION

This paper presents the main results from the study performed by the DOT/Volpe National Transportation Systems Center for the U.S. Federal Aviation Administration and the U.S. Department of Homeland Security. Where appropriate it also provides clarification on points made in the original study, as well as additional data and information that have recently been made available. The views and opinions stated in this paper, however, are solely those of the authors. The goal of the study was to "assess the consequences of GPS timing services outages or disruptions, and to determine the benefits and relative costs of alternate systems that mitigate the impact of a GPS outage on the national Time and Frequency (T/F) infrastructure critical to the safety, security, or economic well-being of the United States."

The study focused on the T/F needs of the nation's civilian critical infrastructure, including energy (electric power) and telecommunications. Particular emphasis is given in this paper to the electric power and telecommunications sectors because of their direct impact to all of the other critical infrastructure sectors. Secondary objectives included identifying T/F subject matter experts, gathering information from them about the level of dependence on GPS, and the degree that potential T/F backup systems can cost-effectively mitigate the loss of GPS.

Many applications that depend on obtaining the Time of Day (TOD) do not currently require highly accurate timing or PTTI services. However, evolving trends show some evidence of a growing need for not only the ability to recover time more precisely, but to also have the system(s) using a common time reference to operate more efficiently and to maintain safety and security. Current accuracy requirements range from:

- One second for some financial transaction;
- Tens of milliseconds for wide area data logging, astronomy, Internet authentication, and the Network Time Protocol (NTP);
- Tens of microseconds for VHF special communications, Code Division Multiple Access (CDMA) base stations. CDMA networks have the most stringent timing requirement (±10 µs) of the mobile telephone networks. GPS provides a cost-effective method of meeting this requirement and nearly all CDMA base stations are equipped with GPS-disciplined oscillators;
- Microsecond to 50 nanoseconds for power line fault location and phasor measurements, data sharing among power grids, and for other advanced communications.

Many of the issues addressed in this paper are exemplified in an incident that occurred almost 2 years ago in San Diego Harbor.

GPS INTERFERENCE INCIDENT, SAN DIEGO

The impact of even relatively minor, local interference of the GPS signal can be large, as the unintentional jamming of GPS in San Diego Harbor in January 2007 showed. The disruption affected light aircraft and, more critically, cell phones and pagers. It also took a long time to locate the jamming source. The following is extracted from a report presented by U.S. Coast Guard Captain Matthew Blizard, the Commanding Officer of the U.S. Coast Guard (USCG) Navigation Center (NAVCEN), as reported by Don Jewell in *GPS Insights*, April 2007.

The U.S. Navy was conducting a scheduled communications jamming training exercise in the Port of San Diego. Two Navy ships participated in the exercise for approximately 2 hours. Although it involved communications jamming, GPS agencies, including NAVCEN, were not notified because the intended jamming was not planned to be in the GPS spectrum. GPS was jammed and the jamming continued for approximately 2 hours. The jamming was terminated only after the technicians involved in the exercise could not get their GPS on the second ship (the one being jammed) to initialize. They correctly suspected the first ship was inadvertently jamming GPS, immediately returned to the first ship, and shut down the jammer. In less than 30 minutes from the time the inadvertent, yet highly effective jamming began, the GPS agencies started receiving calls concerning GPS outages in the San Diego harbor area. These outages affected both telephone switches and cellular phone operations and even shut down the Naval Hospital's mobile paging system. General aviation GPS navigation equipment outages were reported, but no commercial airlines were affected, or at least none officially reported any outages. Reports continued to flow in for more than 4 hours. The Navy technicians shut down the unintentional jamming signal, but did not report the incident outside of normal channels. Consequently, it took NAVCEN and supporting agencies a longer time to pinpoint the jamming source.

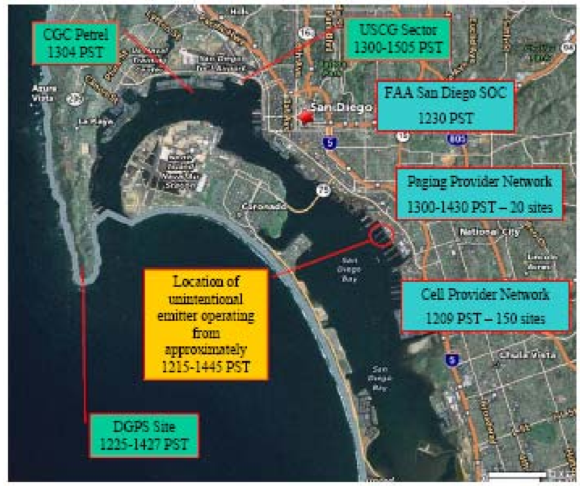

Figure 1. San Diego Harbor during RFI incident.

This incident highlights the vulnerability of the low-power GPS signal to jamming and interference. It also clearly demonstrates that procedures are not yet in place – despite determined efforts of coordinated agencies – to pinpoint jamming in a timely manner and take actions to mitigate it. Despite the clarity of this message, some experts claim that GPS or timing backups are not needed.

THE ROLE OF TIME AND FREQUENCY

Time and Frequency play an important and often critical role in just about every human activity worldwide. Time and frequency standards are carefully coordinated and disseminated worldwide and are maintained in the U.S. at the Commerce Department's National Institute of Standards and Technology (NIST) and the United States Naval Observatory (USNO).

Electric power companies use synchronized clocks throughout their power grids to quickly transfer power to parts of the grid where it is needed most. They also use synchronized clocks to determine the location of faults along a transmission line and to investigate and analyze abnormalities and incidents that cause loss of system efficiency and effectiveness.

Telecommunication networks make use of the *stratum* hierarchy for synchronization of the network clocks (including atomic clocks). This hierarchy classifies clocks based on their frequency accuracy, which translates into time accuracy relative to other clocks in the network. The best clocks, known as

Stratum 1, are defined as autonomous timing sources. This means that they require no input from other clocks, other than perhaps a periodic calibration, typically from GPS. Stratum clocks less accurate than level 1 (Higher Stratum levels) require input and adjustment from another network clock of a lower or equal stratum level. See Figure 2.

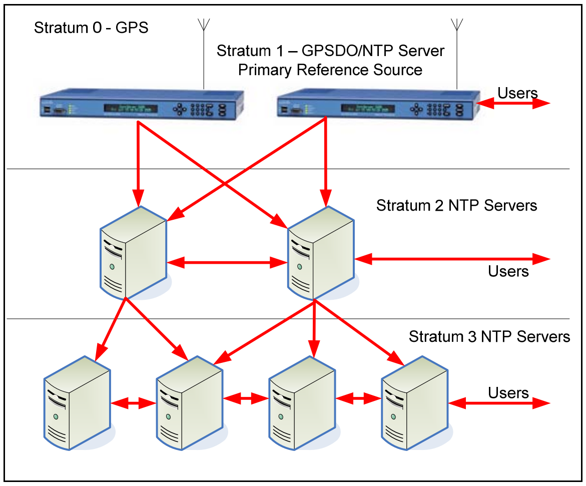

Figure 2. NTP hierarchy.

GPS: TIMING CRITICALITY AND VULNERABILITY

The U.S. Government has formally recognized that GPS is vital to the safety and security of several critical infrastructure sectors **[1]**. GPS now plays an important role in providing accurate timing worldwide, and its role is expected to expand. GPS has features that make it very useful in many applications. Its highly accurate signal is available globally at no direct cost to users. But GPS has vulnerabilities: the signal arrives at or near the earth's surface at power levels well below ambient noise, and reliable performance requires a direct line of sight from the satellite transmitter to the receiver antenna. The vulnerabilities of GPS, plus a growing dependence on it, demand the use of an adequate backup with capabilities that will maintain essential timing and frequency services. It is expected that as positioning, navigation, and timing (PNT) dependence on GPS grows, threats to GPS will become more serious. Thus, a proactive policy to enhance the robustness of GPS becomes increasingly important.

The following information was taken from the *"GPS 'Spoofing' Could Threaten National Security"* article in *Discovery News*. "The average person doesn't realize how much infrastructure is based on GPS and how vulnerable it is," said Brent Ledvina of Virginia Tech, who helped build a spoofer to show weaknesses in the system. "But the truth is that a lot can be done about these vulnerabilities." The easiest way to disrupt a GPS device is simply to jam it, or create a false GPS signal that overpowers the real GPS signal. In this case, the victim would know about the sabotage right away; often the GPS receiver simply doesn't work. The second, more sinister, method is called spoofing. In spoofing, the intended target doesn't know that the signal received from a GPS unit is wrong: A spoofer creates a false GPS signal that passes as a real GPS signal, and an incorrect time or location appears on the intended receiver. "It looks exactly like a real GPS signal," said Ledvina. "Everything looks completely normal, but the spoofer is controlling your position in time and space." Being a couple microseconds off of the real time might not sound like a big deal to the average consumer with a GPS car navigation system, but GPS has spread far beyond what its creators envisioned in the 1970s **[2]**.

In September 2008, the Air Force 746th Test Squadron from Holloman Air Force Base gave a presentation on *"Civilian GPS Systems and Potential Vulnerabilities"* at the Government Synchronization Workshop in Reston, Virginia. The 746th Test Squadron is the group that runs the GPS JAMFEST Testing (see the article in the July/August 2008 edition of *Inside GNSS*). In this presentation, they warned about the increasing reliance on GPS throughout the civilian infrastructure and pointed out that GPS jamming techniques are well known and jammers are easy to build or even purchase. They warned GPS users that the infrastructure is vulnerable to disruptions and to look for weaknesses within their applications and implement the appropriate mitigation strategies. Two issues they discussed were spoofing (counterfeit signals) and meaconing (delay and rebroadcast), both with the ability inject misleading GPS information.

The susceptibility of GPS to jamming was demonstrated during JAMFEST testing on the White Sands Missile Range in November 2007. GPS-disciplined quartz and rubidium oscillators were tested under a variety of test scenarios, each lasting about 30 minutes. The GPS-disciplined clocks would have drifted outside the Stratum 1 level in less than an hour in every test. An Enhanced Loran Reference Receiver (ELRR) was also operating during these same tests and maintained Stratum 1 time and frequency performance at all times **[3]**. See the **Telecommuncations** sub-section under the **Mitigation** section.

ALTERNATE T/F PROVIDERS

External time and frequency reference sources such as GPS provide a traceable means of aligning a local clock to a national time standard, in this case UTC (USNO). Other T/F systems provide varying levels synchronization and/or position and navigation backup capability to GPS. These include other global navigation satellite systems (GNSS), Loran-C, enhanced Loran (*eLoran*), radio-controlled clocks, Internet Time Services, and atomic and quartz clocks. Information on four emerging timing service providers – GPS III, Galileo, chip-scale atomic clocks, and miniature atomic clocks is also provided later in this paper.

LORAN-C

Loran-C (LOng-RAnge Navigation) provides coverage for maritime navigation in U.S. coastal areas. It provides navigation, location, and timing services for both civil and military air, land, and marine users. Loran-C is approved as an en route supplemental air navigation system for limited visibility operations. The Loran-C system serves the 48 conterminous states, their coastal areas, and parts of Alaska **[4]**. Loran-C was developed to provide military users with a radionavigation capability with much greater coverage and accuracy than its predecessor (Loran-A). Loran-C can also be used for precise time interval and highly accurate frequency applications. The U.S. Government recently (February 2008) announced its intention to retain Loran as a positioning and timing backup to GPS and migrate to eLoran.

ENHANCED LORAN (ELORAN)

Enhanced Loran is a PNT service proposed for use in many positioning and timing modes of transport and in other applications. eLoran has been shown to meet the accuracy, availability, integrity, and continuity performance requirements for aviation non-precision approaches, maritime harbor entrance and approach maneuvers, land-mobile vehicle navigation, and location-based services. With Stratum 1 capability, eLoran would be also a precise source of time and frequency for applications such as telecommunications **[5]**. eLoran would be an independent complement to satellite navigation systems such as GPS. eLoran would allow GNSS users to retain key safety, security, and economic benefits of GNSS even when their satellite services are disrupted.

eLoran is being designed for use in many parts of the world. At the present time, non-operational eLoran signals are available in the U.S. (the conterminous 48 states [CONUS] and parts of Alaska), and southern Canada. eLoran transmissions would be synchronized to UTC by a method wholly independent of GNSS. Synchronizing to a common time source will also allow receivers to employ a mixture of eLoran and GNSS signals. The eLoran data channel conveys application-specific corrections, warnings, and signal integrity information to the user's receiver **[6]**.

RADIO SOURCES (WWVB, WWV, WWVH) [7]

Millions of clocks, clock radios, and wristwatches throughout the world set themselves to NIST time. These radio-controlled clocks contain tiny radio receivers tuned to NIST radio station WWVB, located near Fort Collins, Colorado. WWVB continuously broadcasts time and frequency signals at 60 kHz, in the LF (low frequency) radio band. The WWVB signal includes a time code containing information to synchronize radio-controlled clocks in the U.S. and surrounding areas. In addition, calibrating and testing laboratories use the 60 kHz WWVB carrier frequency as a reference for calibration of electronic equipment and frequency standards. WWV and WWVH operate in the HF (high frequency) part of the radio spectrum. Both stations broadcast continuous time and frequency signals on 2.5, 5, 10, and 15 MHz, and WWV also broadcasts on 20 MHz. Both stations provide information in their broadcasts in addition to time.

WWV and WWVH broadcast the same program on all frequencies, 24 hours a day. At least one of the frequencies should be usable at any given time of day. While the most commonly used frequency is 10 MHz, which can be used 24 hours a day, the frequencies above 10 MHz generally work best in daytime, and the frequencies below 10 MHz work best at night. The 2.5 MHz stations work best in the area near the stations, since propagation is similar to the commercial AM broadcast band.

INTERNET TIME SERVICES

Internet time services use several standard timing protocols, the three major ones being the Time Protocol, the Daytime Time Protocol, and the Network Time Protocol (NTP). NTP is the most commonly used Internet time protocol, and the one that provides the best performance. Software manufacturers often include the NTP software bundled with their operating systems. The client software runs continuously as a background task that periodically gets updates from one or more servers. NTP synchronizes computer system clocks across IP networks to accurate time sources such as GPS. NTP is also useful for any application involving multiple computers/hosts. The current NTP architecture, Version 4, provides for operation in point-to-point and point-to-multipoint modes, and includes provisions for secure authentication using both symmetric key and public key cryptography.

NTP provides accuracies in the range of a millisecond or two in LANs and up to a few tens of milliseconds in global WANs. NTP can also be directly supported in the computer kernel and, if implemented properly, can bring the time accuracies down by an order of magnitude to single-digit microseconds when the client and server are operating on the same LAN segment **[8]**. Accuracy can be improved ultimately on the order of 20-100 nanoseconds when using the Precise Time Protocol (IEEE-1588).

ATOMIC AND QUARTZ CLOCKS

Atomic clocks lock an electronic oscillator to the inherently stable atomic resonances between an atom's electrons and its nucleus. The resonance acts like a pendulum or a balance wheel in a conventional clock. Although atomic clocks can be built using a number of different elements, rubidium, cesium, and hydrogen are common choices.

LIMITATIONS FOR CLOCK USERS

Typical limitations for any clock includes size, weight, device life expectancy, and power consumption weighed against the initial cost and ongoing operational costs for the device. Another important issue to consider is synchronizing the clock itself to a source of UTC accurate enough to meet the user's requirements. This is typically done by using GPS as the Primary Reference Source (PRS). According to NIST, using a well-designed receiver it is possible to obtain time from GPS to within an accuracy of 100 ns in a few minutes, and to about ±10 nanoseconds (ns) with a 24-hour average **[9]**. The advantages of using GPS to discipline a clock are:

- GPS provides UTC (USNO) referenced time and frequency;
- GPS removes the oscillator's frequency offset;
- The proper steering algorithm can smooth out the moment-to-moment GPS signal deviations;
- The local clock provides some level of holdover when GPS is lost.

There can be issues with GPS-disciplined oscillators (GPSDOs) when GPS is denied or spoofed. Based on recent testing, the performance of the clocks through these events appears to be guided by two factors: 1) The initial condition of the GPS-disciplined device prior to the outage and 2) The nature of the outage (jamming vs. spoofing). When GPS is denied, the GPSDO typically goes into holdover (free runs). The performance of the clock is typically based on the filter and steering algorithm of the system; the better the knowledge of the clock frequency at the time of the outage, the better the holdover performance. This holdover performance from that point forward is then limited to the stability of the clock itself. If GPS is being spoofed, it is possible that the GPSDO may not recognize this and the "false" data could potentially be pulled in and the clock steering is then based on what could be referred to as Hazardously Misleading Information (HMI). This condition will persist as long as the system is being provided the false data unless the system has another source of UTC knowledge (e.g., eLoran).

There are several other factors that will impact the clock performance especially while in holdover. Every clock suffers from frequency drift or aging, and changes in the clocks operating environment such as temperature, humidity, and pressure will impact the clocks performance over time. Random events such as shock, vibration, or radiation can also adversely impact the clocks performance.

FUTURE SYSTEMS AND TECHNOLOGIES

GALILEO

Galileo is a new European GNSS similar in many ways to GPS and the Russian GLONASS system. The European Union (EU), in close cooperation with the European Space Agency (ESA), is developing Galileo. Currently published plans are for Galileo to be operational in approximately 2014, although recent information indicates that this will likely slip.

GPS-III

GPS Block III will be the next block of GPS satellites. GPS IIIA will transmit a new civilian signal (L1C), which is designed to be highly interoperable with the European Galileo satellite navigation system signal and intended to be fully compatible and interoperable with those signals planned for broadcast on Japan's Quazi-Zenith Satellite System (QZSS). For military users, GPS IIIA satellites will provide further increases in the anti-jam capability of the M-Code signals. The GPS III satellites will be developed in three increments, with each increment including more capabilities based upon technical maturity. GPS IIIA is projected to be available for launch in 2013 **[10]**.

CHIP-SCALE AND MINIATURE ATOMIC CLOCKS

The traditional use of atomic clocks has been accurate time measurement (often in a laboratory environment) or in PNT applications involving GPS and Loran. Recent trends for PNT applications have focused on reducing the size and cost of rubidium clocks. As these clocks continue towards meeting their performance goals, they are anticipated to see widespread use.

CRITICAL TIME & FREQUENCY SECTORS

This section presents several "key" sectors of the U.S. national infrastructure that do or could use GPS for timing or frequency. The benefits of using GPS, as well as impacts resulting from the loss or disruption of GPS-based time or frequency, are outlined. Interestingly, the investigation into the use of time in this sector found that not all users are or were aware of the fact that their reference systems rely on GPS.

The two particularly critical national infrastructure sectors in the U.S. are the *Electric Power (Energy)* and *Telecommunications* Networks. Loss of electric power or telecommunications or disruptions and inefficiencies in these networks can cause great economic damage, as well as put lives at risk. Very often these disruptions are caused by a loss of accurate timing. Accuracy must be maintained by utilizing adequate backups to the primary timing source. *The report showed that the technology is at hand and it is available at acceptable cost to ensure reliable timing services for all of the civilian timing-critical applications.*

ELECTRIC POWER (ENERGY)

Identified as an especially critical sector, it is composed of a wide variety of production and distribution facilities, ranging from power generating plants to local power grids. These systems are directly linked to consumer applications, so that a sudden loss of electrical power has an immediate effect on the public and potentially on all levels of the national infrastructure. The industry makes most of its money generating power. Until recently, there has been less concern about the distribution network, but this is starting to change due to the increasing incidents of brownouts and outages, which directly affect revenue. The efficiency of power transmission across grids depends on precise phase matching, and improving the efficiency of the grid saves power companies significant revenue and increases the amount of power they can provide to their customers.

ELECTRIC UTILITIES

The U.S. power generation hierarchy consists of three major interconnected networks of power grids: the Western Interconnection, Eastern Interconnection, and Texas Interconnection (Figure 3), operated by six

Independent System Operators (ISO). Hydro Quebec, a non-U.S. major Interconnection, extends also into the Northeast U.S (Figure 4). The interconnected network consists of a connected alternating current (AC) power grid that operates at the same frequency. These networks consist of additional high-voltage connections among individual utilities designed to permit the transfer of electrical energy from one part of the network to another.

GRID STABILITY

Management of the power grid requires a responsive command and control capability based on reliable communications to all points of the network. Distribution of electric power is, therefore, not independent of telecommunications.

The 2005 Defense Science Board (DSB) Task Force Report on *The Future of the Global Positioning System* **[11]** stated that, nationwide, many electric power companies have begun to use GPS timing and frequency services to improve the economy and efficiency of their operations. The DSB report noted that GPS signals were used primarily for monitoring the stability of line frequencies, synchronization (time), and syntonization (frequency) services with adjacent power company networks, and for isolating faults in transmission networks. It maintained that the fidelity of service provided by GPS exceeds the routine needs of power companies, but that its ready and free availability makes it very appealing to the industry. The DSB report also emphasized that GPS is the technology of choice for maintaining phase differences to very tight standards when loads are transferred among substations, as would happen as a consequence of a major power perturbation. It pointed out that the use of GPS has enabled load transfers to be accomplished in a few hours, rather than days, as required by previous techniques. With increasing deregulation of electrical service and growing threats of intentional power grid disruptions, the report stressed, there are growing interoperability dependencies between individual service providers, noting that these have further heightened the importance of GPS. The report concluded that *the importance of GPS for timing and synchronization will increase as power producers have to respond to widespread load variations and to system surges created by environmental effects such as solar storms or intentional disturbances.*

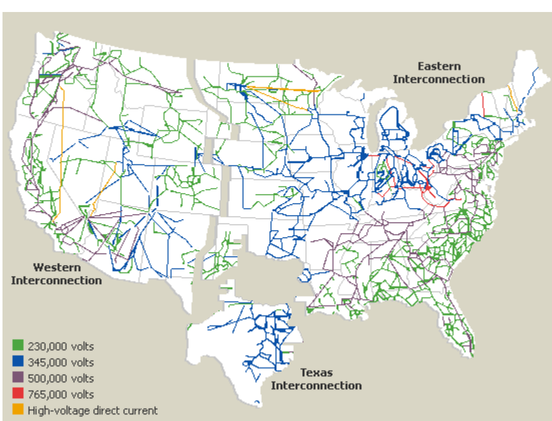

Figure 3. U.S. electrical power grid transmission (MSN Encarta).

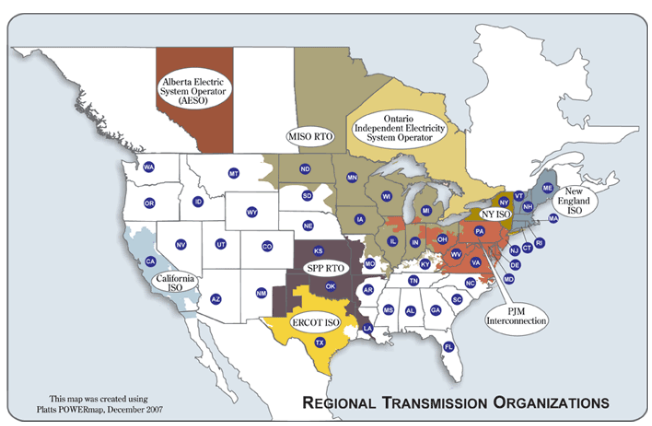

Figure 4. Map of regional organizations (NERC).

ELECTRIC POWER INDUSTRY REQUIREMENTS

"The timing requirements of the power industry vary (Table 1), because different parts of the system were designed at different times, and the entire system has evolved over many years. The older parts of the system have less stringent requirements because they were designed using technologies that predated GPS. The newer parts of the system rely on the ability of GPS to provide precise time synchronization over a large geographic area **[12]**."

Table 1. Time synchronization for the electric power industry.

System Function	Measurement	Time Requirements
Generation Control	Generator phase	10 ms
Event Recorders	Time tagging of records	1 ms
Stability Controls	Phase angle, ±1°	46 µs
Networked Controls	Phase angle, ±0.1°	4.6 µs
Traveling wave fault locators	300 meter tower spacing	1 µs
Synchrophasor measurements	Phase angle, ±0.022°	1 µs

GPS applications for electric power facilities involve providing UTC-synchronized time for event timing, scheduling power flows, monitoring line frequencies, and power line fault detection and location. The growing market penetration of GPS is partly in response to the need to collect more accurate timing data for power flow generation, transmission, and fault location, involving the following data collection systems:

- Supervisory Control and Data Acquisition (SCADA) data systems and alarm logs for power generation and transmission are used for collecting, storing, and reporting on automatic generator controls, voltage frequency, and energy trading;
- GPS is a key component of the Wide Area Monitoring System (WAMS), mandated in 2005 to help establish a real-time transmission monitoring system capable of mitigating and preventing major disturbances on the transmission system;
- GPS is also a key component of phase monitoring units (PMU), a WAMS component consisting of sensors for measuring power flow variability and use. When combined with time stamps from GPS and connected to a WAMS, the PMUs can help deliver real-time pictures of the grid to monitor voltage and frequency, and locate faults;
- GPS is also used as a component of Disturbance Monitoring Equipment (DME) to help record data from each disturbance and synchronize the internal clocks in DME devices to within 2 milliseconds or less of UTC. The purpose of the standard, adopted in response to the August 2003 blackouts, is to ensure standard regional reliability standards and disturbance recording and reporting.

In general, GPS outages can be tolerated for several hours or days before problems develop. Power companies and system operators are responding to these timekeeping requirements by installing time and frequency measurement and synchronization systems throughout their infrastructure **[13]**. According to industry sources, GPS and backup timing and synchronization signals need to meet six criteria:

1. Timing accuracy to within 1 millisecond, the resolution of the modern sequence-of-events recorders (SERs);
2. The time standard is referenced to a UTC source such as those maintained at NIST and USNO;
3. The system can be operated without the need for regular maintenance;

4. The system is reliable;
5. The system uses standard hardware for easier and less costly implementation and management; and
6. The cost per installation is reasonable.

A major synchronization and timing server equipment supplier (Symmetricom, Inc., Santa Rosa, California) indicated that power generator manufacturers (e.g., General Electric), power plants, and local power distributors are also buying timing and synchronization equipment for synchrophasors. Phasor measurement units use GPS time for better than 1 μs accuracy, but may also use atomic clocks for backup. The electric power grids, thus, may be becoming more and more dependent on GPS, and this trend may continue in the effort to enhance reliability and power quality **[14]**.

REGULATORY REQUIREMENTS

There are regulatory timing requirements related to billing, frequency control, and power flow. The level of these requirements is well within GPS capabilities, and these needs can easily be served by lower accuracy time dissemination methods other than GPS. Time is generally to the nearest 0.5 s and frequency to 0.001 Hz. Applications that are run within the company for company purposes often have much tighter requirements, but regulatory authority does not govern these. Reliability councils mandate some tighter regulations, such as local time recording to the millisecond accuracy level, but compliance at this time is still voluntary **[15]**.

A considerable number of systems within the company are synchronized from external NTP servers over the Internet. These can keep a number of subsystems synchronized, though currently there is no way to "steer" the main timing system with this source. Most customers have a few days before the UTC time disparity gets too large. Users were not always aware of the fact that most Stratum 1 Time Servers obtain their time from GPS and the higher level stratum servers in turn get their time from these Stratum 1 Servers (Figure 2).

ELECTRIC POWER OUTAGES

The findings of this section are based in part on the use of Meta analysis, a method that combines data or results from a number of different studies and uses them to arrive a reasonable range of values for a parameter to be estimated. More detail on the Meta Analysis was provided in the Final Report, which is not currently available to the public. The industry consists of over 3,170 traditional utilities and about 2,000 non-utilities engaged in generation, transmission, and distribution of electric power, with annual operating revenues of over $326 billion. There are about 136 million electric power users in the U.S., 87% of which are residential, 11% commercial, and 1% industrial, reflected in the available data from 2006. Industrial and commercial users of electricity are more vulnerable to economic losses resulting from routine power outages.

The average annual losses to the economy from unreliable electric power and routine power outages are approximately $100 billion, roughly 1% of the GDP. The magnitude of this loss is driven by the outage frequency rather than duration, and is borne by the commercial and industrial sectors. They account for 12% of the users, but 97% of the losses. Losses from a 1-hour outage amount to $18.7 billion, with $13.2 billion attributed to commercial losses, $5.1 billion to industrial losses, and $309 million to residential.

GPS makes a significant contribution to the power industry's robustness and fault tolerance. Given the growing dependence of the electric power industry on the GPS timing and synchronization services, and given the accelerated deployment of wide-area monitoring and disturbance detection and data collection systems such as WAMS, PMU, and SCADA, a plausible case can be made for cost-effectiveness in using a redundant timing system such as eLoran. GPS, or another accurate UTC reference source, can play a significant role in augmenting the robustness of electric power transmission and distribution. It can serve as a buffer against disruption and make it this tightly coupled interdependent system more fault-tolerant. Figure 6 compares the relative costs of GPS mitigation and eLoran backup and the recurrent losses from power outages. With its continued market penetration, the value of GPS to the power industry is likely to grow, along with the impacts of unanticipated disruptions. A cost-beneficial backup system is, therefore, justified for the near future. The benefits of backing up GPS with a system like eLoran include avoiding the recurrent and low-impact, as well as high-impact, low-probability power outages. In view of the relatively low costs needed for eLoran, the study recommends considering its use as a backup for GPS where such use is cost-beneficial.

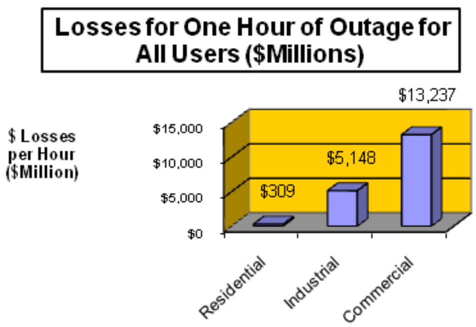

Figure 5. Estimated losses for 1-hour of outage .

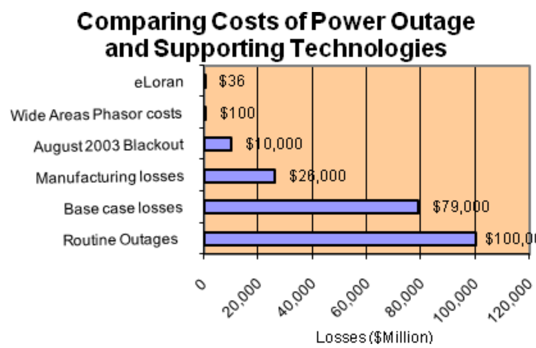

Figure 6 . Relative costs of GPS and eLoran mitigation compared to recurrent losses due to power outages.

Telecommunications

Code Division Multiple Access (CDMA) and UMTS wireless networks both use GPS timing for network synchronization. Time-synchronization of messages – voice, data, or video – to UTC using GPS precision is essential for accurate time stamping and queuing message exchanges between base station towers and mobile cell phones.

Statistics provided by the Cellular Telecommunications and Internet Association indicate that 41% of all Internet users in the U.S. (56 million Americans) can now access the Internet wirelessly. Half of all U.S. cell phone owners can browse the Web, and a third use data applications, at a monthly volume exceeding 7.3 billion messages (June 2005). The “3G” broadband wireless access networks are currently evolving from Wi-Fi hotspots with a range of 300 ft to 1 mile to WiMAX networks with ranges of 4 to 6 miles, extendable to 30 miles **[16]**. Sprint Nextel, Intel, Motorola, Samsung, and Clearwire are rapidly deploying WiMAX networks that reach far beyond the Wi-Fi hotspots. The current plans for the 4G mobile broadband communications and information network are enabled by new GPS chipsets embedded in personal phones, which will deliver dual-mode CDMA/WiMAX services. The ongoing technology convergence and interoperability trend allows for multiple IT data, video, and voice messaging to stream to a single handset (now equipped with embedded GPS chips for LBS); it also may also lead to greater complexity, vulnerability, and interdependencies, should GPS-dependent time synchronicity be lost.

Generally, mobile network coverage, quality, and capacity must be traded off for a desired level of system performance. Wider coverage requires higher power for mobile phones, which means more radio interference. Increasing capacity means that more calls must share available spectrum, so more calls may be blocked and voice quality will decrease due to compression to fit the bandwidth. Synchronization is essential to quality of service. It is not uncommon today to have periods of limited mobile phone or GPS reception, despite the present network of base stations. There is a high level of user tolerance for intermittently poor service quality or unavailability, and mobile wireless providers have sufficient network resiliency and redundancy to hand over a call to the available tower if the nearest one has exceeded its capacity.

Digital telecommunications networks generally depend on inter-tower GPS synchronization and timing to maintain service capacity and quality. The services include Information Processing (IP), wireline and wireless telephony, TV and video data (HDTV), and data transmission. Within each sector of digital radio-communications, there is wide tolerance for the impact of the cumulative loss of synchronicity, whether due to GPS outage or to another source of timing. Secure communications and optical data transmissions require greater timing synchronization (milliseconds to microseconds) than voice and data, though the service level will eventually degrade to an unusable level.

Requirements for Telephones (Landlines) [12]

When a telephone connection is established between two voice channels originating from different clocks, the time error needs to be less than one half of the sample, or 62.5 μs. Half of the period is used to indicate the worst case, which exists when two clocks of the same stratum are moving in opposite directions. If the time error exceeds 62.5 μs, a cycle slip occurs resulting in the loss of data, noise on the line, or, in some cases, a dropped call.

Requirements for Mobile Telephones [12]

Mobile telephone networks depend upon precise time and frequency. Code division multiple access (CDMA) networks have the most stringent requirements. CDMA networks normally comply with the TIA/EIA IS-95 standard **[12]** that defines base station time as GPS time. Thus, nearly all of the more than 100,000 CDMA base stations in North America contain GPSDOs (Figure 7). The time requirement is ± 10 μs even if GPS is unavailable for up to 8 hours. During normal operation, base stations are synchronized to within 1 μs. The frequency requirement is 5×10^{-8} for the transmitter carrier frequency, but the carrier is normally derived from the same GPSDO as the time, and is usually much better than the specification.

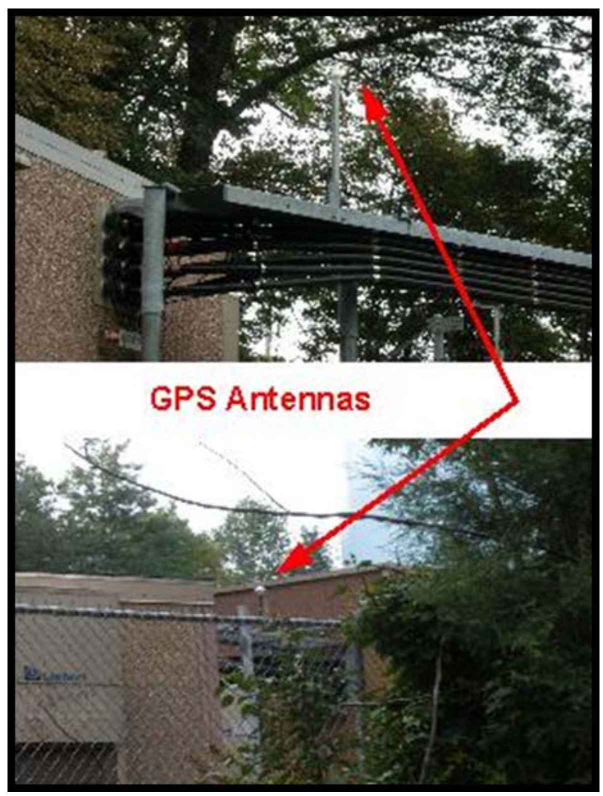

Figure 7. Typical cellular site installation.

Although not yet as popular as CDMA in the United States, GSM is the most popular standard for mobile phones in the world, currently used by over one billion people in more than 200 countries. GSM is a time division multiple access (TDMA) technology that works by dividing a radio frequency into time slots and then allocating slots to multiple calls. Unlike CDMA, GSM has no time synchronization requirement that requires GPS performance, but the uncertainty requirement for the frequency source is 5 $\times 10^{-8}$, generally requiring a rubidium or a high- quality quartz oscillator to be installed at each base station **[12]**.

Requirements for Wireless Networks

"Although they operate at much higher frequencies than those of the radio and television stations discussed earlier, wireless networks based on the IEEE 802.11b and 802.11g have a similar acceptable tolerance for carrier frequency departure of $\pm 2.5 \times 10^{-5}$. The specifications call for the transmit frequency and the data clock to be derived from the same reference oscillator" **[12]**.

GPS Outages and Telecommunications

This assessment reflects input from several telecommunications SMEs. Referenced SME responses ranged broadly from 1 hour to 1 day and up to 1 year, but were not generally specific. The SMEs all agreed, however, on the need for GPS timing backups with independent technology and reliability for long duration, with negligible drift (loss of synchronization).

The duration of network operation after GPS signal loss depends on the type, accuracy, and stability of its Primary Reference Source (PRS) or Primary Reference Clock (PRC) used for timing, which differs by Stratum level for nodes and switches in the network hierarchy. CDMA base stations are synchronized to within 1 microsecond when GPS is available, but when GPS synchronization is lost, the time alignment will drift and mobile phone service will degrade. The degree to which the system can remain synchronized depends on the type of PRC backup used in the base stations.

The NIST researchers also tabulated the performance of stand-alone oscillators, typically used in conjunction with GPS for precise GPS-disciplined network synchronization. Quartz clocks are the most inexpensive ranging from ($1K-$3K), but they suffer more from aging and drift. Rubidium clocks range from ($1.5K- $15K) and have an annual aging rate of 1 to 5×10^{-10}. Cesium-beam clocks, which cost more than $30K, are three orders of magnitude more accurate than the rubidium clock and may keep time as a PRC for 5 to 15 years with great stability and accuracy. The inference is that if such stable oscillators were installed in key network nodes and initially synchronized (as may be the case for military and secure communication nodes), they can keep operating for years without GPS. This, unfortunately, is not always the most practical option.

The key question of how long these networks can continue to operate when GPS time is lost depends on the quality of backup clocks used in the Stratum 1 communication nodes, each of which tags its time signal on a message. When GPS outages disable positioning services, several of the base stations, which are geo-referenced, can be used for geo-location (some vendors claim "comparable accuracy").

An OMNI economist who recently analyzed the precise timing market for Symmetricom summarized the difficulty of estimating the operational and economic impacts for any GPS outage scenario: *"The total economic impact (of a GPS outage) is difficult to assess, given the broad reaching consequences associated with not only a loss of subscriber mapping but the data services that are dependent on position-based data. Cell phones using GPS for E911 reveal the vulnerability of some emerging 3G technologies, but the back-up is use of a relative position index generated by the distance between base stations (by triangulation and geo-mapping)."*

Questions were asked of industry SMEs to clarify the operational and economic consequences of GPS satellites outages (whether natural or intentional) on mobile data and voice communication networks, in particular those dependent on GPS (GPS) synchronization. The focus was on CDMA services, which use GPS-based synchronization for proper operation and may also depend on GPS-enabled handsets and on the type, extent, and duration of service disruption expected. Few of those interviewed, who discounted the threat of mobile communications or IP network loss of GPS timing because of the availability of NIST for backup timing, were unaware that NIST itself often depends on a GPS satellite for synchronization of ground-based atomic clocks. NIST uses the “common-view” technique to compare its time and frequency standards to the International Bureau of Weights and Measures (BIPM) located near Paris, France. NIST also uses the common-view technique to maintain agreement between NIST standards at radio stations in Fort Collins, Colorado, and Kawai, Hawaii, and the NIST Boulder, Colorado, Laboratory. The common-view reference is usually a GPS satellite, although other satellites and land based signals are sometimes used.

NSTAC Report [17]

The National Security Telecommunications Advisory Committee recently released a report on the impacts of a GPS loss or outage on the telecommunications industry. Their key findings were:

- Generally, short-term loss or disruption of the GPS signals for timing will have minimal impact on the commercial communications infrastructure and its operations.
- Short-term loss or disruption of GPS signals will affect the ability to determine accurate location information for wireless E911 purposes.
- The impact of medium to long-term loss or disruption of GPS will vary based on a number of factors, including the specific function or application being supported by GPS, the duration of the loss/disruption, the geographic size of the affected region, and the availability and implementation of effective backup capabilities and contingency plans.

It should be noted that these findings, insofar as they minimize the impact of a short-term loss or disruption of GPS on telecommunications, are not fully accepted by other SMEs and the Volpe Center.

MITIGATING SYSTEM VULNERABILITIES

Once the vulnerabilities of a critical infrastructure are understood, it is possible to begin looking at ways to create a resilient critical infrastructure. A decision has been made by the Federal Government to complete implementation of an enhanced Loran navigation system to serve, in part, as a backup to GPS **[18]**. The fiscal year 2009 (FY09) budget proposal contains language “migrating” the Loran-C system − including its $34.5 million budget and 294 positions − from the USCG to the Department of Homeland Security’s National Protection and Programs Directorate (NPPD). A USCG “Posture Statement” on the FY09 budget indicates that the action was taken “in preparation for conversion of Loran-C operations to Enhanced Loran (eLoran).”

Since eLoran has the potential to provide time transfer with an accuracy of 50-ns timing relative to UTC and a Stratum 1 frequency reference at low cost, its capabilities should merit consideration. At least three integrated GPS-eLoran receiver products could be available within a few months in up to 10K quantities for $700-1000 each **[19]**. The most appropriate technology for mitigation of the loss of GPS will undoubtedly depend on specific applications.

ELECTRIC POWER (ENERGY)

A critical infrastructure is characterized as resilient if it has adequate layers of redundancy (without violating cost efficiency criteria) and robustness so that it can withstand threats and adapt to changing conditions. The survey of literature and preliminary interviews indicated that, at the present time, the primary use of the GPS signals is limited to obtaining national time standards and synchronizing the clocks at the control centers to UTC. Telephone interviews with the experts at NERC and Generating Availability Data System (GADS) Services have indicated that for the industry, GPS is not currently a mission-critical technology and GPS is not the only source of time. Users can rely on the NIST radio broadcasts and internal clocks to get the accurate time, although there is disagreement on the accuracies to which users will be able to recover time. The impact, on the whole, the NERC experts maintain, would be minor, as indicated in a telephone interview with Mr. Don Benjamin, NERC, GADS Services, Princeton, New Jersey, on 28 September 2006. It is unclear how or if the August 2003 outage influenced this opinion. A consensus of opinion presented in this report argues convincingly that GPS is rapidly becoming a "mission-critical technology." Loran-C also has been designated as a backup in limited cases, and eLoran could provide even better backup capability over the entire CONUS. There is, however, an increasingly critical need for the T/F services in grid monitoring and outage mitigation that GPS provides, as power demand in the U.S. – and the accompanying outages – keep growing rapidly.

The North American Electric Reliability Council report **[20]** on the August 2003 blackout makes recommendations which are summarized below:

- Recommendation 12: Install Additional Time-Synchronized Recording Devices as needed. The NERC Planning Standard I.F – Disturbance Monitoring requires location of recording devices for disturbance analysis. All digital fault recorders, digital event recorders, and power system disturbance recorders should be time stamped at the point of observation with a precise GPS synchronization signal. Recording and time-synchronization equipment should be monitored and calibrated to assure accuracy and reliability.

- Recommendation 12a: The reliability regions are requested to facilitate the installation of an appropriate number, type, and location of recording devices within the region as soon as practical to allow accurate recording of future system disturbances and to facilitate benchmarking of simulation studies by comparison to actual disturbances.

- Recommendation 12b: Facilities owners shall, in accordance with regional criteria, upgrade existing dynamic recorders to include GPS time synchronization and, as necessary, install additional dynamic receivers

Given the growing dependence of the electric power industry on the GPS timing and synchronization services, and given the accelerated deployment of wide-area monitoring and disturbance detection and data collection systems such as WAMS, PMU, and SCADA, a plausible case can be made for the cost-effectiveness of funding a redundant timing system such as the NIST broadcast time, clock oscillators, or Loran-C (eLoran). In addition to using GPS and NTP servers, a number of systems within each power company can be synchronized with WWV, WWVB, and the IEEE 1588 network time dissemination **[15]**.

To clarify two points in the original report, the IEEE-1588 protocol is currently capable of providing accurate time to within 20-100 ns over Ethernet. The protocol is, however, limited to the Local Area Network (LAN) and is not sent over any part of the telecommunications network. The use of atomic/quartz clocks is also possible; however, users still need to have a method of providing (transferring) a UTC source to synchronize the local clocks to a common reference. This is typically done by recovering absolute time from an accurate source, such as GPS.

The performance of the ELRR during the JAMFEST testing on White Sands Missile Range in November 2007 **[3]** showed that adding the Time of Day message to Loran-C through the Loran Data Channel would be accurate enough to satisfy/exceed most of the current requirements for the electrical power industry. During the JAMFEST test period, the time-of-day messages were transmitted from Coast Guard Loran Transmitting Station Las Cruces, New Mexico, and were demodulated by the ELRR. The time-of-day messages allowed the eLoran receiver to recover absolute time and steer its internal clock synchronizing the receiver to UTC (USNO). One significant difference to point out between Loran-C and eLoran is the addition of correction messages. The plans for the eLoran system are to provide signal corrections, thereby allowing users to recover time to within 50 ns RMS of UTC (USNO). There were no corrections either broadcast or applied during the testing. Had the correction messages been broadcast, the receiver would have further compensated for small variations in the received signal due to propagation changes caused by temperature and weather, and the overall performance of the ELRR would also have improved. The timing performance of the Loran-disciplined receiver was acceptable as a GPS alternative, with a standard deviation of 33ns over the 5-day test.

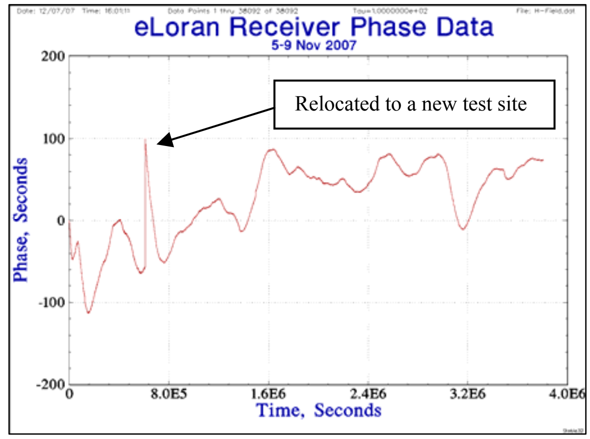

Figure 8. ELRR phase data from JAMFEST.

Telecommunications

The telecommunications industry has moved from analog to asynchronous digital to synchronous digital architectures. Moreover, the divestiture of the Bell System changed the industry from one major provider to a variety of providers all requiring accurate synchronized timing that can be successfully distributed over many networks **[21]**. This need for accurate and reliable timing across many geographically distributed networks has been met to a large degree by GPS.

Should GPS be lost, wire line networks would slowly degrade within a week to a month. As synchronization degrades, the different systems and technologies will be affected in varying degrees. While voice communications is very tolerant of the loss of or degradation of synchronization, the associated signaling network is not, as it is highly encrypted. While the payload transmission network could still carry voice communications, no calls could be established because the encrypted signaling network could not instruct the switches to set up the calls **[21]**.

To protect critical functions such as network timing and synchronization, companies currently employ multiple layers of backup capabilities, mitigation strategies, and contingency plans to provide protection against GPS outages and disruptions. Technological, economic, and regulatory considerations necessarily factor into individual company decisions; therefore, specific mitigation strategies and backup capabilities will vary.

Given the anticipated availability of eLoran, the degree to which individual sectors could use eLoran, or another system, as a backup to GPS will depend on the economics of specific applications. For example, the economics of integrating GPS/eLoran chips with suitable antennas into CDMA handsets may be quite different from those of installing integrated GPS/eLoran timing receivers at CDMA base stations. Nevertheless, it appears likely that eLoran could provide much needed backup to GPS in many applications requiring accurate, reliable timing traceable to UTC.

The most persuasive arguments documented in the Sandia, NIST, Volpe Center, and HSI studies were that any timing backup system for GPS timing services should not use adjacent frequency bands, as do the other GNSS. Therefore, NIST and USNO SMEs have recommended the proposed eLoran system as the best and most cost-effective backup. An adequate planning horizon must be provided for industry to adapt and manufacture transceivers at low cost and high volume, capable to operate at such disparate frequencies, in order to capture fully potential technical, operational, and economic benefits.

Selection of eLoran as the backup to GPS was supported by the unanimous recommendations of the Independent Assessment Team (IAT) to "retain eLoran as primary backup for critical GPS PNT applications, develop funding plan for completion of eLoran, convert to unmanned model (as in Europe), stimulate receiver development and equipage, and from a long term strategic perspective, GPS should be a critical component of a national research, development, and technology strategy to reduce critical infrastructure vulnerabilities" **[19]**.

eLoran was evaluated as a potential GPS backup during JAMFEST 2007 using 2 Symmetricom SSU-2000s. The SSU-2000, a Synchronization Supply Unit, is a Synchronization Status Messaging (SSM) compliant Timing Signal Generator (TSG) or Synchronization Supply Unit that provides network synchronization signals for the telephone and telecommunications industry. The system conforms to specifications for International, European, and North American applications as a Primary Reference Source (PRS). The SSU-2000 allows for the integration of a variety of synchronization reference schemes, including GPS or other external references **[3]**. See Figure 9.

Each SSU-2000 had a rubidium (2E) and quartz (3E) clock installed. One system used GPS as the primary reference source and a 10-MHz signal from the eLoran receiver as an alternate reference input. The other SSU-2000 relied solely on the eLoran input as the reference in order to monitor and evaluate the ability of the eLoran system as a stand-alone primary reference. The idea behind this configuration was to evaluate the ability of the two reference systems to work together and have one system back up (eLoran) the other (GPS) while monitoring the phase relationship between the two references simultaneously.

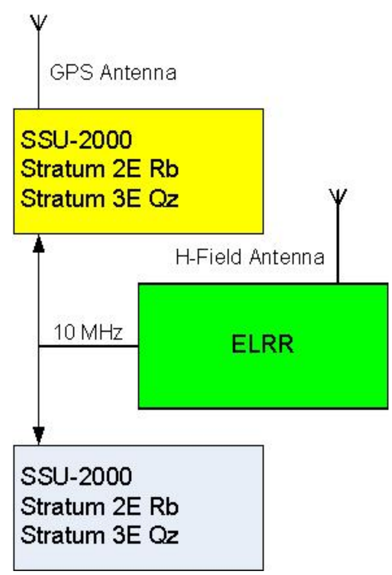

Figure 9. JAMFEST telecommunications test setup.

The SSU-2000 with the GPS receiver installed was impacted to varying degrees on each day, based on the scenarios run during each test period. During those periods when GPS was denied, the system automatically switched over to the eLoran reference input and continued operating. The ELRR allowed the SSU-2000s to meet/exceed system specifications during GPS outages, and during most of the period the eLoran-disciplined SSU-2000 actually outperformed the GPS-disciplined unit. The eLoran receiver met/exceeded the Stratum I specification for the SSU-2000 units (see Figure 10). It took approximately 24 hours for the 3E Quartz clock to become stable. This issue was noted with this clock module during initial testing in the lab; however, there was not enough time to obtain a replacement prior to starting the test. Fortunately, the clock did settle as it had in the lab testing and the performance for the rest of the period was comparable to that of the 2E rubidium clock. This again emphasizes the ability of the primary reference source to discipline the local clocks when that reference is available and providing valid information.

CLOSING

There is a close interdependence between the sources of accurate timing and frequency. Both redundancy and resiliency in any PNT architecture is necessary to avoid “common cause failures.” This can be accomplished through the use of multiple PNT sources as well as timely outage and error detection and user notification for each PNT source within the architecture. No matter which enabling technologies are developed and implemented, future PNT architectures that use GPS-enabled PNT services must continue to ensure Continuity of Operations during partial or total GPS outages that last for any period of time. In addition, there is a need to mitigate GPS vulnerability to radio frequency interference (RFI), whether unintentional or malicious.

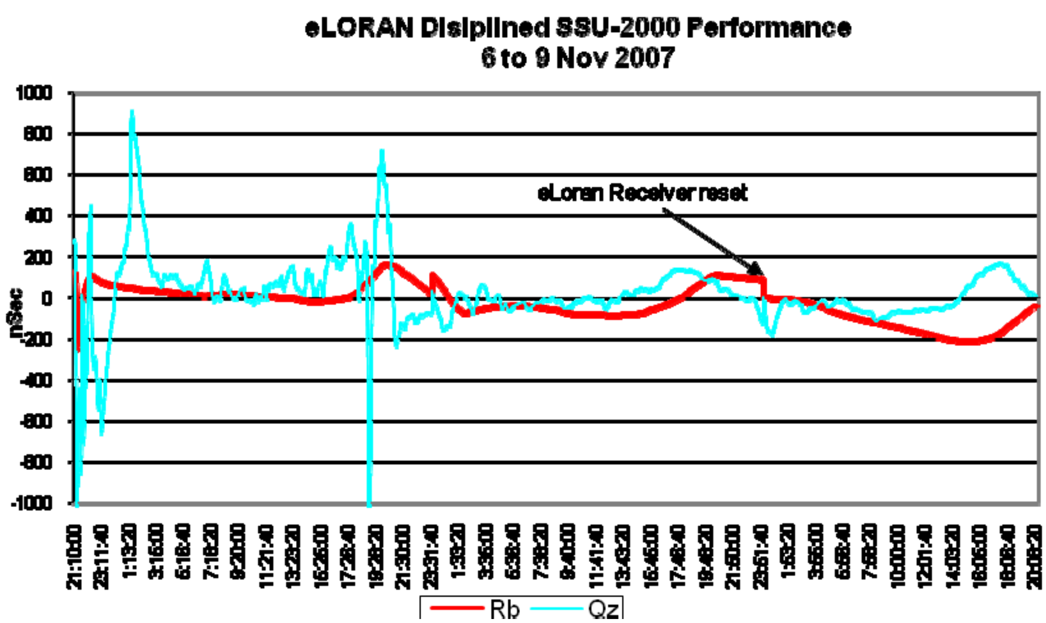

Figure 10. SSU-2000 phase data with ELRR as the primary reference.

A cost-beneficial backup system is therefore justified for the near future. The benefits of backing up GPS with alternate timing sources, such as precision clocks and eLoran, cannot be underestimated. In view of the relatively low costs needed for operating eLoran, the study recommended considering its use as a backup for GPS where such use is cost-beneficial. The report also cited several other cost-effective backup options that are ready for use now. By implementing the appropriate backup options, T/F users will realize the full benefit of precise timing and be fully capable of avoiding any potential pitfalls.

AUTHORS' COMMENTS

This paper outlines the results of the study in order to provide the members of the PTTI community and opportunity to review and comment on those results. The information was obtained through research and by interviewing subject matter experts in this field. The authors invite those members of the community that have updated facts and figures, research, or counter arguments to the results to please provide them in order to allow those decision makers within government and industry the ability to make sound decisions based on the latest facts.

The eLoran information contained in this paper was provided to give the user community an opportunity to see the current capabilities of the modernized LORAN-C system that is capable of providing an alternate source of UTC. Please keep in mind that the current performance is limited by the fact that the system is not broadcasting any differential corrections and the data from the ELRR is not being post-processed to remove any errors introduced by changes in propagation or weather.

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