DRAFT (2)

Alternate WAAS Network Time

IDA Task 1918.01

For Federal Aviation Administration (FAA) Satellite Navigation (SATNAV) Program Director

Final Report

30 November 2010

Chapter 1 Introduction

Introduction & Task: The Wide Area Augmentation System (WAAS) is a National Airspace System (NAS) augmentation of the Global Positioning System (GPS) to provide aviation quality integrity and enhanced accuracy, availability, and continuity of satellite navigation services throughout the NAS. The WAAS currently consists of 38 WAAS Reference Stations (WRS), three WAAS Master Stations (WMS), four Ground Uplink Stations (GUS), and transponders on two satellites in geostationary earth orbit (GEO).

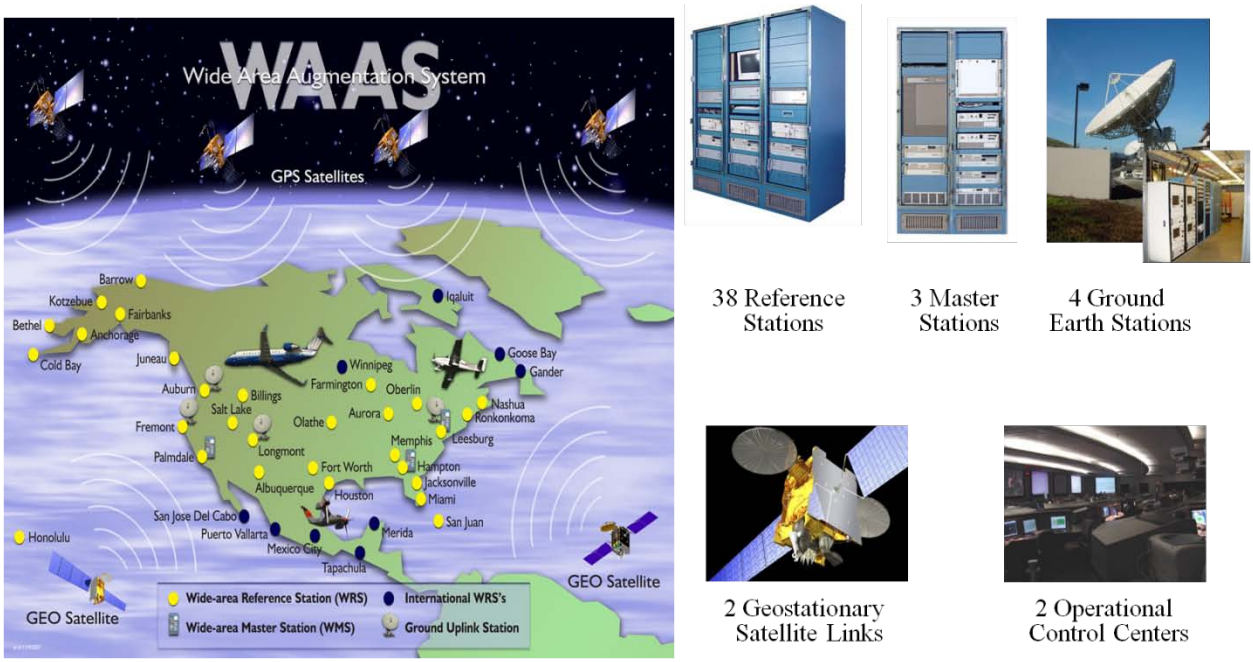


Figure 1. *Wide Area Augmentation System (WAAS) overview*

At each WRS, there are three independent GPS receiver systems, each consisting of precision surveyed and highly accurate GPS receiving antenna, high-end GPS receiver unit tracking GPS L1 and L2 signals (semi-codeless), cesium atomic frequency standard, and a data collection, communications, and power management system. There is a total of 114 cesium atomic frequency standards, geographically distributed throughout the NAS, three at each WRS. These standards are very stable, with frequency stability ($\Delta f/f$) of $1X10^{-13}$ averaged over a day; in terms of time uncertainty, these devices maintain accurate time within about 10 nanoseconds (ns) per day. Each cesium free runs independently, and only the 10 MHz output is used by the WAAS GPS receiver to which it is attached.

The task is to determine if by "coordinating" these 114 cesium frequency standards one could develop a robust, geographically distributed time system that might be used as a source of accurate time independent of GPS but synchronized with time as distributed by GPS itself. The technical requirement is to avoid disrupting WAAS operations in so coordinating these cesium frequency standards and also to avoid making changes to the WAAS itself. There is an unstated additional requirement—to assure that the professional time and frequency community finds the result of such coordination useful.

Summary Recommendations: The technical team assembled by the Institute for Defense Analyses (IDA) to perform the assessments found that the cesium frequency standards can and should be coordinated. In brief, the team recommends assembling each set of three cesium frequency standards at each WRS into an "ensemble," steering that ensemble to Coordinated Universal Time (UTC), and distributing accurate time and precise frequency from the ensemble locally for use by the FAA at each WRS location. Additionally, using data available at the WMS (and several other locations) from all 114 WAAS receivers, the team recommends creating a 114-cesium frequency standard ensemble, also steering it to UTC, and distributing accurate time and precise frequency from this robust geographically distributed ensemble throughout the NAS. NAS-wide distribution would be via the WAAS signals from the GEOs.

These recommendations are discussed in detail in the final section of this report.

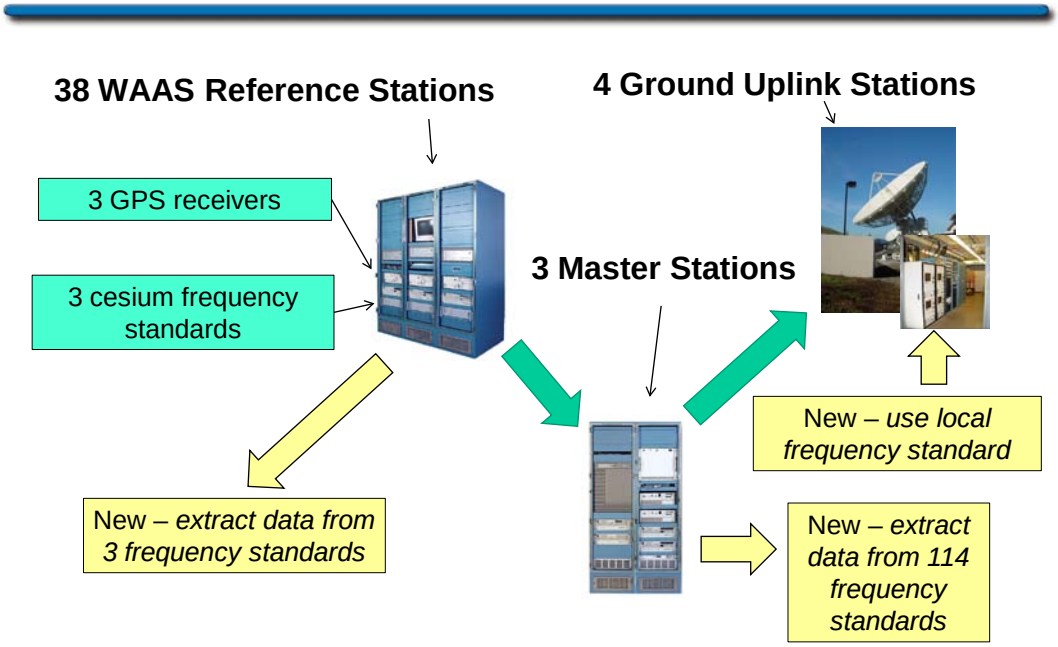


Figure 2. *Additions to WAAS (in yellow) to use as time & frequency system*

Report Organization: This report is organized into the following additional sections: Task Organization and Data Collection Process (Chapter 2), Technical Issues (Chapter 3), Alternatives (Chapter 4), Assessment (Chapter 5), Findings and Recommendations (Chapter 6), and Future Thoughts (Chapter 7). Appendices contain the team members and affiliations, data sources, interim reports, and some technical data supporting assessment and future work.

Chapter 2 Task Organization

Task Organization: There were two fundamental issues which guided the organization of the task, technical and operational.

Technical: The technical aspect is, of course, to assure adequate technical competence within the task team to understand time and frequency systems, positioning-navigation-timing (PNT) systems generally and aviation "safety-of-life" navigation systems specifically, and needs for PNT services by various types of users. The technical problem to be solved is determining if and how one could coordinate the 114 cesium atomic frequency standards in WAAS without adverse impact on WAAS's performance as an aviation safety-of-life navigation service. This is a not inconsequential requirement, not overly difficult but significant.

Operational: The operational aspect is to assure that, should the FAA Satellite Navigation (SATNAV) Director (task sponsor) implement the recommendations, the time and frequency technical community would be supportive of the results. In many regards, this is the more difficult requirement, in that it is the sponsor's prerogative to define an aviation navigation system's requirements, but should that sponsor decide to also make WAAS into a national "clock" service this moves into another operational area—maintaining and distributing accurate time and precise frequency. This is the operational requirement, within the U.S. Government, of the U.S. Naval Observatory (USNO) and the National Institute of Science and Technology (NIST). And there is a large professional stakeholder community of government, military, academia, and industry with significant operational interest in maintenance and distribution of accurate time and precise frequency. Should some or all within this "time and frequency" community not agree with the recommendations, they would be discredited.

Solution – Independent Assessment Team: To meet both requirements, technical and operational, the IDA team was organized as an *Independent Assessment Team (IAT)*. Each word in this phrase is important, starting with the last – team. A team works together to get results, in this case, to generate a set of recommendations which all members support. Counterpoints to some recommendations are allowed as needed and included with the recommendations. The team deliberates openly with each other, critiques and peer reviews ideas, and produces results that are the team's, not any individual member's.

Assessment means that alternatives are postulated and reviewed against a set of criteria agreed by the team to meet the sponsor's goals. As a practical matter, these criteria are also reviewed with the sponsor for concurrence. Findings and recommendations flow from the assessment. Because this is an assessment team, the findings and recommendations are not finally determined until being fully reviewed and vetted by the team as a whole.

Independent means just that. There is no predefined solution. The team has the problem statement from the sponsor, and it then sets out to collect data, develop alternatives, conduct assessments, and develop findings and recommendations. In other words, the sponsor asks the questions, the team

provides the answers—in the vernacular, there is "no school solution"—the team goes where the data take it.

IAT Membership Considerations: To meet the two requirements, technical and operational, the IDA task leadership solicited members for the team meeting the following criteria: scientific or engineering professional background; time and frequency, PNT, or safety-of-life navigation subject matter expertise; senior management experience in government, military, academia, or industry; and representative of key stakeholders in GPS, WAAS, other PNT, and time and frequency communities.

The IAT is thus composed of 18 members, a core team of seven IDA researchers, including the team chair and IDA task leader, plus ten stakeholder representatives, and an ex officio member from the sponsor's staff. Stakeholder representatives include US Air Force (GPS Wing and Air Force Space Command (AFSPC)), US Navy (US Naval Observatory (USNO) and Naval Research Laboratory (NRL)), National Aeronautics and Space Administration (NASA), National Geospatial-Intelligence Agency (NGA), National Institute of Science and Technology (NIST), and FAA (Navigation Systems and Technical Center). The team membership is listed in Appendix A.

Data Collection Process: To do an assessment, the team must have data. To do it well, the team must also have rules. We describe both here, beginning with the rules.

IAT Rules: In this sort of endeavor, much like in team sports, one can have all the best players in the world, but if they do not come together as a team, they do not succeed. Key to success is a set of simple rules, which all team members agree to live by. For the *WAAS Network Time (WNT) IAT* these rules include: non-attribution, no decision before there is a decision, critique ideas rather than criticize each other, and work hard to prepare before, to understand and share thoughts at, and to document thoughts after all data collection meetings.

Non-attribution is essential. The IAT collects its data from reports, in meetings with experts, often authors of reports, and during site visits. In the meetings in particular, the goal is to share information and data openly. To do this effectively, all need to be encouraged to speak freely—to share their organizational positions and, because they are knowledgeable professionals, their professional and personal opinions as well. This report lists in Appendix B, the sources of information and data assessed, and in the assessment section, it discusses how these data and information were used, but nowhere in this report or in discussions with IAT members does the IAT discuss "who specifically said what."

No decision before its time is key in the assessment. To elicit data, particularly during meetings, IAT members often ask provocative or leading questions. In reviewing answers, members may make strong statements, again to evoke a further response or assert a point. No matter how strongly a statement is made by an IAT member, it is only that member's personal opinion at the time, not a finding, nor preliminary position, nor even a hint of an opinion to be expressed by the IAT. In the final analysis, the IAT meets a final time to review and finalize the draft findings and recommendations into the final IAT position.

Critique ideas, do not criticize others, is also key. The WNT IAT membership was specifically selected to include individuals with very strong, often professionally, personally, or organizationally parochial, opinions. This is necessary to assure issues are critically examined from all perspectives, to avoid inadvertently reaching suboptimal solutions, and to help assure that consensus (perhaps with minor dissenting points) is achieved in the final recommendations. The IAT chair allows the meetings to be lively in challenging ideas but never being critical of individuals.

Finally, *work smart not hard* is quite necessary. The WNT IAT members are all very busy. They were selected in part because of this. Fundamentally, their agreement to join the IAT was based on the rule that they would be asked to spend a day or so preparing for each data collection or assessment meeting, come to the meeting to collect data and critique concepts, then spend about one more day reducing to writing their key thoughts for incorporation into the WNT IAT's final briefings and reports. Occasionally one or another could expect to be asked specific questions to augment the data. Each agreed the task was important enough to take this relatively small amount of time from their schedules, given that each meeting would be no more frequent than 1-2 month intervals.

WNT IAT Process: As discussed above, meetings and site visits are essential to the data collection and assessment process. Most of the work of the WNT IAT is done in the preparation for, conduct of, and review after the meetings. Meetings are generally two days in duration and conducted at a location where the needed data can be found.

Meetings are arranged by the WNT IAT chair about a month in advance, with the goals for the meeting outlined and some key questions to be addressed. This information is shared with WNT IAT members, who have the opportunity to suggest additional topics and changes. At the same time, the chair, assisted as needed by the core team or subject matter experts, arranges speakers with the appropriate expertise and sources of data to answer the questions and meet the goals of the meeting. In addition to briefers, the meeting agendas allow time for IAT discussion in plenary (with speakers present) or executive (without) session. At the end of the meeting, the chair closes with WNT IAT members sharing what they believe were the key points and what additional information is needed. The chair may then call for the members to write up selected comments or generally respond to the questions within a week. Each meeting ends with a tentative timeframe (several candidate weeks) and proposed venue for the next meeting, as well as the likely questions to be addressed at that meeting.

A list of meetings is included in Appendix C.

The Meetings: In the first phase of this effort, meetings were held at about 6 week intervals, first at IDA in Alexandria VA and USNO in Washington DC, then at NIST in Boulder CO and FAA's Air Route Traffic Control Center (ARTCC) in Longmont CO, and finally at Stanford University's Center for PNT in Palo Alto CA. An interim report briefing was then prepared for the sponsor (Appendix D) and vetted with the WNT IAT members electronically—this required several iterations to reach concurrence. After delivery to the sponsor, and receipt of sponsor feedback, another series of meetings was arranged. These were held at the FAA Technical Center in Atlantic City NJ and at IDA in Alexandria VA.

A second briefing, actually an update of the interim report, was delivered to the sponsor and the new FAA Director of Navigation Services. (This briefing is also in Appendix D.) Following feedback from this briefing and to collect data needed to refine and finalize the assessment and report, a number of mini-meetings were scheduled with select members of the WNT IAT for collection of remaining needed information. These were held at National Physical Laboratory outside London UK, NIST in Boulder and Longmont ARTCC, FAA Technical Center in Atlantic City, Stanford's Center for PNT in Palo Alto, and Sensis Corporation in Syracuse NY. Additionally, several members of the WNT IAT conducted individual research on specific technical issues and attended the FAA's Alternate PNT (APNT) Workshop at Stanford University.

Chapter 3 Technical Issues

Technical Issues: Before discussing alternatives, it is essential to address several technical issues which generally break down into two categories, technical elements and what to do with them. The first category includes discussion of time and frequency, national and international standards, and cesium atomic frequency standards used in WAAS. The second includes discussion of coordination of atomic frequency standards, steering ensembles of frequency standards, and distributing the results. Each is discussed below.

Time and Frequency: Though related, and very significantly so, these are two different outputs of an atomic frequency standard (or other timekeeping or oscillating device). To those who work dominantly in navigation systems they tend to be treated almost as synonyms, but to those in the time and frequency community they are unique and impose unique requirements on equipment and devices which produce or distribute them.

Time is generally measured against a reference standard. In the 19th century, most people would have measured time against the reference standard set by town's church bells, factory whistles, or railroad schedules, which standard was reconciled by its keepers with the diurnal rotation of the earth. Today the global standard is UTC, which is measured by counting transitions of cesium atoms from a set start date (epoch). The key is that time is meaningful only if referenced to a standard.

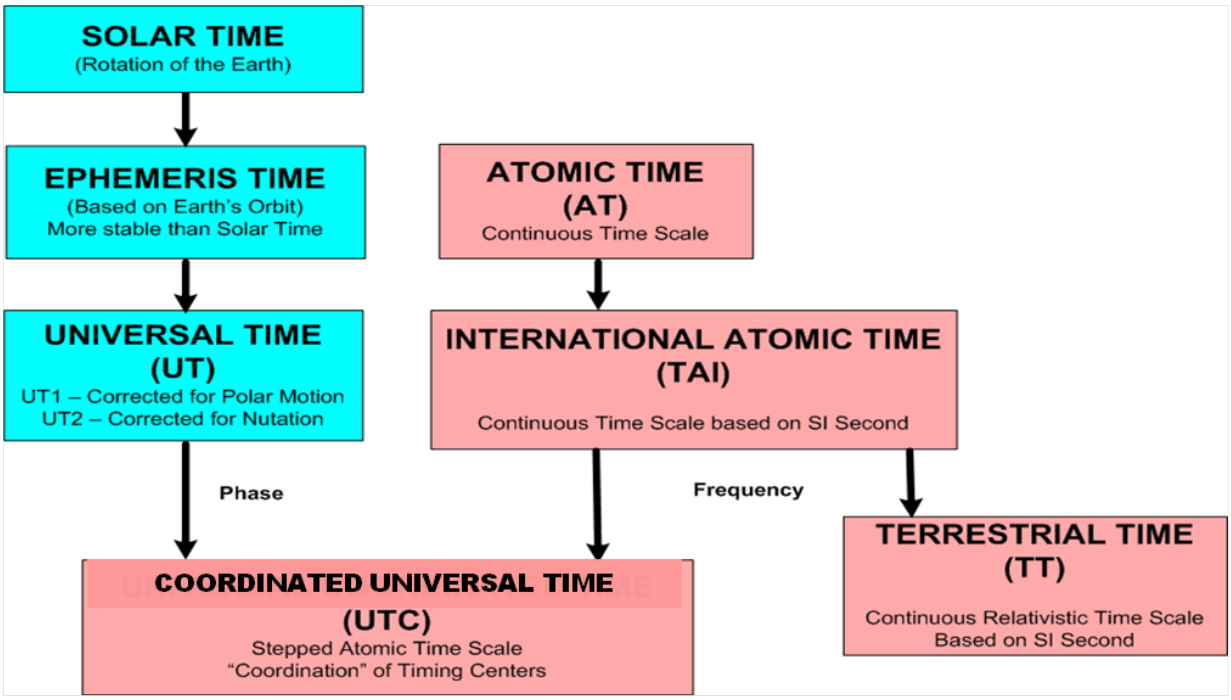
In today's world, knowing time accurately, within 50 ns of a global standard, is often important to maintain synchronization of events, start and stop times, at sites widely separated geographically. For example, consider the case of three ground sites each about 200-400 nautical miles from the others which are used for multi-lateration to track the horizontal location of an aircraft in flight. The plane emits a signal received by all three of them. If they all know time relative to each other within 50 ns, by comparing the time of arrival of the signal at each site, they can estimate the position of the airplane adequately to substitute for a radar surveillance system supporting en route navigation to regulated navigation performance of 0.3 nautical miles (RNP 0.3) standards.

Frequency on the other hand is important for its stability, that is $\Delta f/f$ measured over a given time interval (averaging time). The village clock in the town square on which the 19th church bells would have been based would have used a long pendulum as a frequency source, and counted the cycles of the pendulum to keep the clock relatively in time with the earth's movements. Today, most sources are crystal oscillators, ovenized crystals, or rubidium or cesium atomic frequency standards, with multiple orders of magnitude improved stabilities.

Stable frequency is used as a reference for radio frequency measurements and to maintain synchronous performance of a system, or in a set of systems working together. A key use of stable frequency is within communications networks. These generally require "Stratum 1" stability performance ($\Delta f/f < 1X10^{-11}$ averaged over a day) at all primary system nodes to guard against "cycle slips" and consequent loss of data. Stratum 1 performance has classically been provided in networks with installation of cesium atomic frequency standards at central offices and other key nodes. In recent years, lesser performing

(and lower cost) frequency standards stabilized by synchronization with specially designed GPS timing receivers have seen increasing use. In addition, as network capacities are increased, particularly using newer data encoding techniques and encryption, it is becoming important to extend Stratum 1 performance to subordinate nodes throughout networks, and this has only been economically feasible through use of low cost GPS-stabilized frequency sources.

One way to consider the difference between time and frequency is that knowing the time accurately at widely geographically separated sites is what enables synchronization, but having a source of stable, precise frequency enables maintaining synchronization between time transfer updates or synchronization intervals.



Source: Ron Beard, NRL, 26 Aug 2008

Figure 3. *Time references – Coordinated Universal Time (UTC) recommended*

National and international standards for time are discussed briefly here. The reader is encouraged to review any of several published articles for more detail. Two recommended articles are the following:

> Beard, Ronald L., "The Future of the UTC Time Scale", Navigation, Vol. 56, No. 1, Spring 2009, pp. 1-8. (Article is available on the Institute of Navigation's website, www.ion.org.)

Lombardi, Michael A., "Legal and Technical Measurement Requirements for Time and Frequency", Measure: The Journal of Measurement Science, Vol. 1, No. 3, September 2006, pp. 60-69. (This was also found on websites, e.g., http://tf.boulder.nist.gov/general/pdf/2125.pdf.)

Coordinated Universal Time (UTC) is the global standard for time; UTC is computed by the Bureau Internationale des Poids et Measures (BIPM) in Paris. It is calculated based on clock comparison measurements made at national time service laboratories throughout the world. The calculations by BIPM are made 30 days in arrears, as this is truly a "paper clock" timescale.

Real time estimates of the UTC timescale are maintained and distributed by national time service laboratories based on long term feedback from BIPM. These national laboratories use BIPM reports to maintain their timescales within ten nanoseconds ($10X10^{-9}$ seconds), or better, of UTC. In the United States, there are two national time service laboratories—USNO Master Clock (Washington DC, including contribution of Alternate Master Clock, AMC, Schriever AFB CO) and NIST (Boulder CO). Their real time implementations of UTC are denoted, respectively, as UTC(USNO) and UTC(NIST). UTC(USNO) is the standard timescale for the U.S. military and also the timescale from which GPS Time is calculated and to which GPS Time is steered. WAAS Time is calculated from GPS Time and then steered toward GPS Time.

Each national time service laboratory maintains a number of atomic frequency standards, most of which are installed in environmentally stable enclosures, carefully controlled for temperature, humidity, physical stability, and to prevent magnetic or electronic interference. For example, UTC(USNO) is computed based on the data from an ensemble of approximately 80 high performance cesium frequency standards, 25 hydrogen masers, and two new rubidium fountains.

UTC is a continuous time scale with time steps applied periodically. UTC is based on measuring atomic seconds from its epoch start date of 1 January 1958. However, to keep UTC in sync with astronomical time, or time as measured against Earth's motions within the universe, from time to time minor adjustments are needed in UTC. These are applied as 1-second time steps, called "leap seconds." Leap seconds have historically been applied at only widely spaced intervals of one or more years. Nothing is done to physically change the actual UTC clock, but all time service laboratories and timekeepers keep track of each leap second, and apply the sum of leap seconds as a correction whenever they display the time of day.

WAAS cesium atomic frequency standards are basically "entry level" cesium devices. They are extremely good atomic frequency standards, better than other less expensive technologies but not as good as the highest performing cesium standards used in national laboratories. The original WAAS cesium frequency standards were purchased from Datum, Inc., which was later acquired by Symmetricom, Inc. These devices are known in the industry as the Cesium III product line. Their performance provides frequency stability ($\Delta f/f$) of $1X10^{-13}$, which yields a time uncertainty of about 10 ns per day. The highest performing cesium frequency standards, the 5071A series (initially made by Hewlett-Packard, later by Agilent, and currently by Symmetricom) generally provide frequency stability about $1X10^{-14}$ and time uncertainty of about 1 ns per day. The frequency stability of both of these devices degrades somewhat at longer

averaging times, so that periodic comparisons with other devices are required. These periodic comparisons are also needed to detect both one-time non-recurring steps in the output and actual failure of the device.

Fundamentally, the block diagram of all cesium frequency standards, indeed of all atomic frequency standards, is generally the same and shown in the Figure 3. The three major subsystems are the physics package (top), the electronics package (lower right), and the local oscillator (lower right). The physics package is built around a cesium beam tube which contains a source of cesium atoms, whose transition from one energy state to another provide the fundamental long term stability of the device. The local oscillator is generally a very high end crystal, which provides both the short term stability of the device and also assures low phase noise in the device's outputs. The electronics package, generally divider circuitry and phase locked loop system, ties both together. The electronics package also includes control loops to maintain the stability of temperature, magnetic, and other environments that would affect the performance of the physics package or local oscillator.

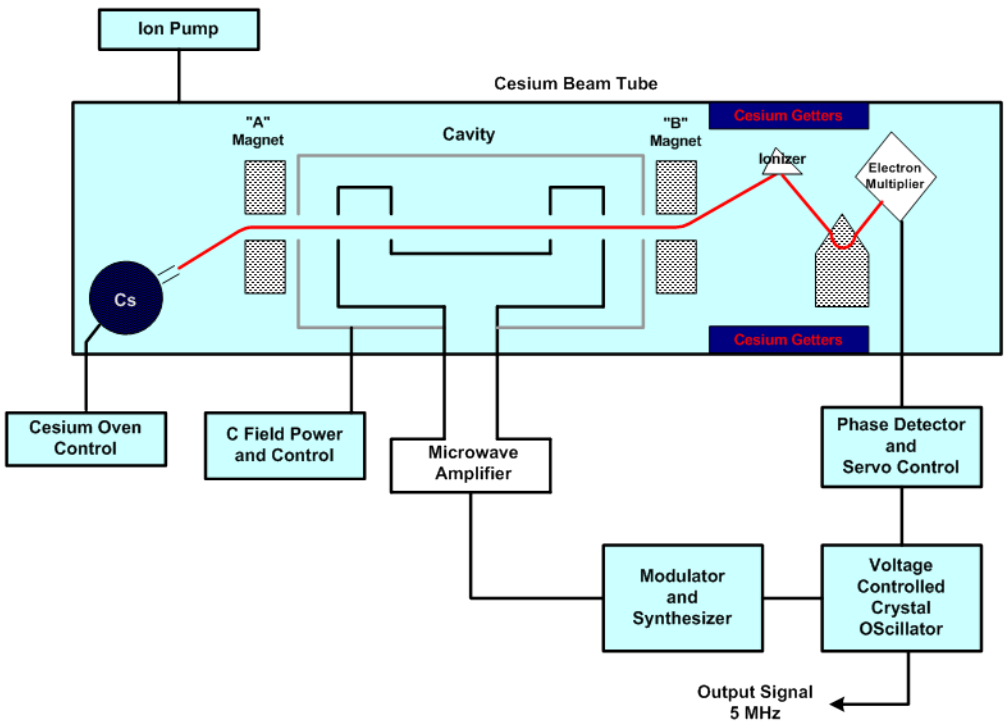


Figure 4. *Cesium atomic frequency standard – generic block diagram*

The outputs of a full atomic frequency standard generally include one or more analog frequency signals, the most common being 1 MHz, 5 MHz, and 10 MHz analog signals, often one or more digital signals of the same frequencies, and finally a digital 1 pulse per second (1PPS) signal. These signals are usually controlled within the electronics package such that leading edge transitions of digital and zero crossings of analog signals are synchronized. Most standards also include an internal capability to adjust the times

of the output signals in incremental steps on the order of nanoseconds (or several orders of magnitude less); adjustment of the output frequency of the device relative to the internal atomic frequency is also possible. The devices also accept a synchronizing input to adjust the leading edge and zero crossing outputs to some external signal. This external signal would typically be from another frequency standard, from an ensemble calculation of multiple frequency standards, or from a GPS timing receiver.

The differences in performance between a Cesium III and a 5071A device are due to several factors in the design. The cesium tubes used are different—the former uses a "standard performance" tube, while the latter uses a "high performance" tube, which operates at higher temperature. High performance tubes use more cesium in operation yielding a higher signal to noise ratio in measuring the state transition; standard performance tubes have an operating life of about 11 years, while the high performance tubes will deplete their cesium store in about 7 years. The local oscillator and electronics package in the 5071A are also higher performing and provide tighter regulation of all the various parameters that can affect the stability of internal measurements and generation of the outputs.

The 10-fold improvement in performance is not free; typical cost for a Cesium III is about $30K, while for a 5071A is about $65K. Replacement tubes, installed, cost about $35K, and they must be replaced 1.5 times as often in 5071As. And, in actual fact, the cost of installation of replacement tubes makes it more economical to "trade in" old Cesium IIIs for new when their tubes reach end of life, while it makes more economic sense to replace tubes in 5071As.

Coordinating, Steering, and Distributing Time and Frequency: Within WAAS, cesium atomic frequency standards were chosen based on the precision of the measurements needed in each WAAS reference station (WRS) receiver. It is not possible to make these measurements against even the best internal oscillator installed in the highest quality GPS receivers … and the WRS receivers are among the best ever made. Thus, the original design of WAAS required local oscillator stability that could only be provided by a cesium atomic frequency standard. The 10 MHz output of each Cesium III is connected directly to the external frequency reference input of its paired WAAS receiver. No other time or frequency outputs from the WAAS cesium frequency standards are used. Should either a cesium or WAAS receiver fail, then that receiver's set of GPS measurement data is down; because two independent sources of these data are required from each WRS, there are three independent receiver chains. Thus, each WRS is a triply redundant receiving system, with "hard fail" subsystems—should a receiver system (antenna, frequency standard, receiver itself, etc.) fail, shifting WAAS operational data to the third string is required at the cost of a small discontinuity in the data. Unfortunately, not all failures can be detected this way – a GPS receiver system or a cesium atomic frequency standard that fails but continues to produce an output signal can be detected only by comparing its output with the signals from the other devices, and there is no ability to do this locally at present.

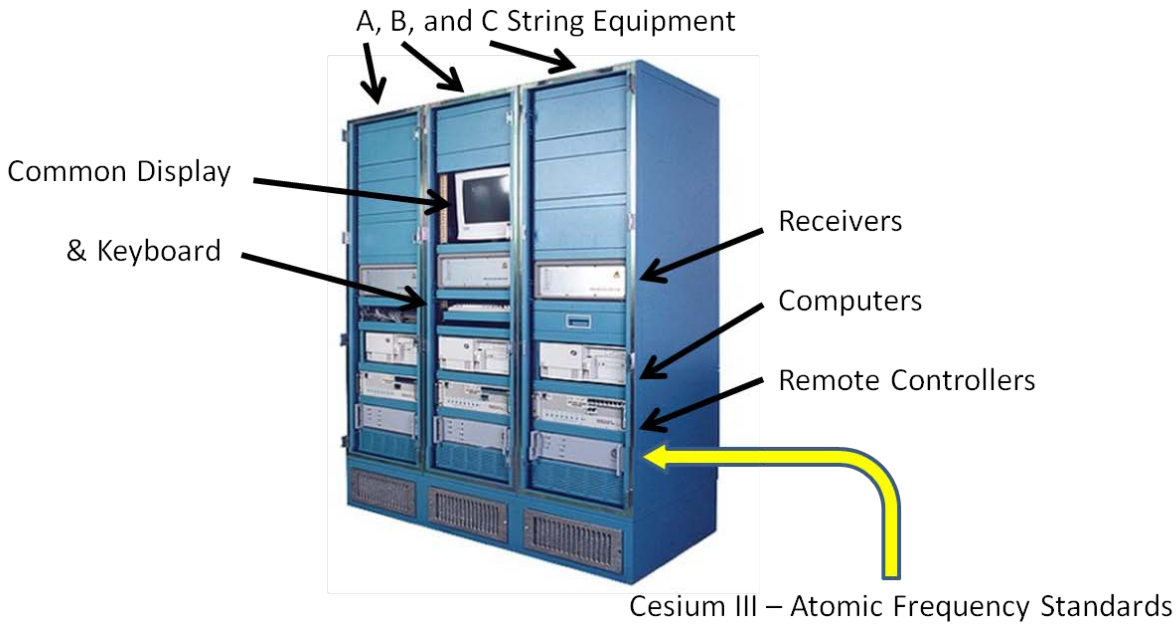


Figure 5. *WAAS Reference Station (WRS)*

Coordinating or "ensembling" frequency standards is a way to avoid such a discontinuity and to provide more rapid and more robust detection of failures or problems when the cesium frequency standards are used as a clock system. When there are several frequency standards in one place it is possible to assemble them into a timescale using a technique called ensembling. To explain, assume there are three cesium frequency standards, A, B, and C; comparisons are made between A and B, between B and C, and between C and A. Using one of several (publicly available or proprietary) ensemble algorithms, these measurements are compared against the results that were expected based on the past performance of each frequency standard. The differences between the expectations are the measurements used to detect failures and problems. In addition, the weighted average of the measurements is used to construct a "paper clock" based on the combined performance of the ensemble of A, B, and C. Fundamentally, these algorithms use a square root of sum of squares technique, with various filters and estimation algorithms applied to account for typical performance of the different cesium frequency standards' nominal performance expectations and observed performance variances. The time and frequency of the paper clock can be realized using external hardware such as a phase microstepper, which produces an output that can be controlled to generate an offset in time or in frequency from its reference input.

In addition to computing the average of local physical frequency standards and detecting failures and problems with them, many ensemble programs can automatically incorporate other external reference data, such as the output of a GPS receiver. The resulting ensemble has the additional benefit that its

paper clock output can be steered to GPS time or to UTC(USNO) as received from GPS satellites. The combined ensemble can also have different hold-over options: switching the paper clock to use the local clocks only if GPS fails or switching to GPS if there is a local problem.

Creating an ensemble provides several benefits. First, the stability of the ensemble is improved over the stability of an individual frequency standard. If the frequency standards are of equal stability, the stability of the ensemble is improved by the square root of the number of standards in the ensemble. Thus, given three Cesium IIIs at each WRS, the stability of each $1X10^{-13}$ and time uncertainty < 10ns/day, the stability of the ensemble of three is about $6X10^{-14}$ and time uncertainty < 6ns/day. This is not a significant improvement in stability or time-keeping performance. However, if one were to create an ensemble of all 114 Cesium IIIs in WAAS, stability would improve to better than $1X10^{-14}$ and time uncertainty to < 1ns/day – or about the same as a single 5071A. In short, it is apparent that one would not generally create an ensemble just to improve the performance (e.g., rather than purchase multiple $30K devices, one would simply get one $65K device—for better performance at lower total cost). There are therefore different reasons to ensemble.

One of the advantages of a local ensemble is more rapid and more robust detection of failures and problems with any single clock or receiver. In addition, many ensemble programs can utilize data from devices other than physical frequency standards – GPS receivers, for example. The resulting ensemble could automatically combine the advantages of a reference to the GPS system and the improved short-term stability of a set of local clocks. In addition, such a mixed ensemble could have various hold-over options: switching to using the local frequency standards only if the GPS signal were to be unavailable for any reason or switching to the GPS signal if there was a problem with the local devices.

There is another benefit of ensembling—redundancy and "soft fail" with no discontinuity in performance (for seamless use by downstream devices). With three co-located Cesium IIIs at each WRS, and with most WRS co-located with large FAA facilities such as ARTCCs, there are other systems co-located that could benefit from a source of time or frequency, or both, independent of GPS. If this source were chosen to be one of the Cesium IIIs, should that device reach end of life or fail, not only would that string of the WRS become unusable in WAAS but also all other systems which are using this particular cesium frequency standard's outputs. But, if the three Cesium IIIs were ensembled and the ensemble output used as the source for the other users, a failure of any one would only disrupt its WRS string and not all other systems. The difference between $1/\sqrt{3}$ and $1/\sqrt{2}$ in frequency stability or time uncertainty would be virtually unnoticeable, and there would be no discontinuity in the ensemble's output.

The benefit of creating an ensemble of all 114 WAAS Cesium IIIs is that the ensemble's performance is identical to a 5071A but immensely more robust. The failure of any one Cesium III, or even upwards of 10-20, would not be noticed. The bigger advantage is the 114 are geographically dispersed throughout the NAS, and thus, loss of an entire site, or even a number of sites, would not seriously impact the performance of the ensemble clock.

The output of an ensemble is called a timescale. Although the ensemble's timescale is calculated based on comparisons of the outputs of the frequency standards, the result is a calculation—usually represented as output from a computer program or a graph on a piece of paper. Most timescales are thus also referred to as "paper clocks," because they notionally exist only paper. However, to be used by other systems in real time, some form of physical realization is required. The normal method of creating this physical replica is to "steer" the output of some physical device to the timescale; the physical device so steered is either one of the frequency standards in the ensemble, a separate frequency standard (which might be of lesser stability than those in the ensemble) steered by adjusting the magnetic field within the standard, or a specialized time and frequency device, purpose built to be steered, called a "microstepper" which steers the frequency and time provided by a reference standard. Since this steering is done in an external device, the reference standard could be one of the standards in the ensemble. Steering and microsteppers are discussed in the subsection below (entitled "*Steering*…").

Steering is the method of relating the outputs of a particular frequency standard or ensemble of standards to some other standard or ensemble. The goal of steering is to relate the steered frequency standard's (or ensemble of frequency standards) outputs to a reference standard, such as UTC(USNO). Steering attempts to accomplish two functions: reduce toward zero (and maintain) the time offset between two frequency standards, and compensate for the frequency drift (or rate) difference between the two standards. In the case of the WAAS cesium frequency standards, steering would normally be applied to the ensembles of these standards to relate them to a higher order standard. Thus, for example, if the three cesium frequency standards at each WRS were ensembled into a timescale for that WRS, each such timescale could be steered to an external reference, for example, UTC(USNO). At the same time, if all 114 cesium frequency standards in WAAS were ensembled into a timescale for the entire system, this timescale could also be steered to the same external reference.

There are a number of steering algorithms available. If the concern is primarily the time offset, steering might be very simple—observe the growth of the offset and reset the time either when the offset is found to exceed a threshold value or periodically. In the days when most people used a mainspring type watch, this is essentially what they did—reset their watches once a day. For an ensemble of precision instruments, this technique is in fact fairly crude steering, a "time step" only, and it is generally not recommended for performance of the frequency standards in the steered ensemble, nor is it generally very useful for any downstream systems using the timescale as an input. The frequency standards in the ensemble and downstream systems both tend to need "gentler" steering. Applying Time steps to cesium (and other atomic) frequency standards tends to disrupt their smooth performance (e.g., cause non-linear changes in frequency drift), and time steps are also discontinuities that tend to negatively impact downstream systems.

Thus, it is desirable to use a more sophisticated steering algorithm that considers both frequency drift and time offset. These tend to work by first measuring the frequency drift between the steered and reference standards and applying small frequency corrections to bring it toward zero. Given knowledge of drift, and compensation for it, the algorithm would measure the time offset, then adjust the frequency corrections to also bring the time offset toward zero. The various algorithms tend to differ in

how they model drift (and hence compensate for it) and how they apply corrections depending on the magnitudes and polarities of both the frequency drift and time offset. Features of these algorithms, some of which are proprietary to the particular designer, depend on how they model typical frequency standard behavior and use the model to implement error boundary checking and other filtering of input data; setting sample periods and intervals between steering corrections; establishing limits on corrections; including ability to adapt algorithms based on comparison of actual to modeled behavior; alerting of failed (or failing) standard; and other features based on the designer's experience.

Fortunately, there are several commonly used steering algorithms for cesium frequency standards that would perform well in this application. Some higher end units are rack mounted systems, which can be purchased as "turnkey" solutions; others can be custom built with only those components specifically needed for this application. A complete timescale system would include the following:

- Comparator circuitry for ensemble measurements from the local frequency standards
- Algorithm to calculate the timescale of the local ensemble
- External reference standard input
- Algorithm to calculate drift and offset steering corrections between local timescale and reference
- Computer to run the algorithms
- Synthesized replica of the steered ensemble or outputs to steer an external device, such as a *microstepper* (see below)

Full systems, as well as components needed to custom build a system, are available as commercial off the shelf (COTS) products from several time and frequency companies.

A *microstepper* is a precision electronic device which enables inserting small variations into an output frequency without adversely impacting the stability ($\Delta f/f$) of the input frequency. State of the art COTS products can routinely apply femtosecond/second (fs/s) corrections to 1, 5, or 10 MHz signals without adversely impacting the stability of the input. In some cases, the output circuitry of a cesium frequency standard includes a microstepper section to allow "trimming" of the output or enable user selection of slightly different output frequencies. At any rate, a microstepper included with a steering system would be designed to apply the needed steering and either synthesize the physical replica of the steered timescale or apply the steering corrections to a local reference oscillator. (See "*Distribution*" below for discussion of replica signal.)

There are several options for the external reference to which the timescale and its physical replica can be steered. These include UTC, GPS Time, WAAS Time, some variant of one of these, some other reference, or no reference (free run). This study recommends UTC(USNO), or the same reference to which GPS is steered. As mentioned previously, UTC(USNO) is a robust physical implementation of UTC using a large ensemble of rubidium fountain, hydrogen maser, and high performance cesium atomic frequency standards. UTC(USNO) is the reference to which GPS Time is steered, and GPS Time is the reference to which WAAS Time is steered in the current operational implementation of WAAS.

Thus, GPS Time is a reasonable estimate of UTC(USNO), as also is WAAS Time. While UTC(USNO) is implemented on a robust ensemble of very stable state-of-the-art frequency standards, GPS Time is implemented on a much smaller set of standards, including those at remote global reference sites and those aboard satellites in the operational GPS constellation. The UTC(USNO) ensemble is maintained in tightly environmentally controlled chambers, while the standards contributing to the GPS Time estimate of UTC(USNO) are in much less well controlled environments. The result is that GPS Time, though very good and suitable for most users, is a somewhat "noisy" estimate of UTC(USNO). Further, since WAAS Time is derived from WAAS's estimate of GPS Time, based on observations of GPS satellites and estimation of clock errors, it is even noisier still. And WAAS Time is essentially maintained on a single high end cesium atomic frequency standard at the operating GUS for each WAAS GEO.

Assuming the desired external reference to be UTC(USNO), there are several ways to make the needed comparisons. For greatest accuracy, either two way satellite time transfer (TWSTT) or common view techniques should be used. Both make use of a satellite in simultaneous view of USNO and of timescale being steered, and require measurements made at both locations during a fixed period of time. TWSTT also requires leasing a transponder on the satellite being used for the duration of the measurements; both techniques require communication between the sites, so that observation data can be shared and calculations made based on them. Fundamentally, both rely on the assumption that most differences noted between the remote reference standard and local timescale are common path delays, which arithmetically cancel, and thus the remainder is the true difference between the reference and the timescale.

There are two other means of making similar measurements. One is to measure and smooth GPS Time observations over a day or so; the other is to use a one way time transfer observation. Both are a little less precise than TWSTT or common view, but would still be adequate for timescales at WRS. The first uses a GPS timing receiver tracking all GPS satellites in view, averaged over a day, and the daily average is taken as the UTC(USNO) estimate to be used for the reference. Before the recent decommissioning of the US Coast Guard Loran-C system, this was the method used for assuring synchronization of master transmitter signals, and was planned for initial use at all transmitters in the Enhanced Loran (eLoran) system. The other relies on the fact that there may already be a fairly robust TWSTT network in place spanning most WRS locations. Access to the data from these measurements, particularly the path link delay (common, cancelling errors TWSTT), could be used as a estimated path delay with a one way measurement. Of these, the team believes that use of an all-in-view GPS timing receiver is better of these two; this report does not consider further the use of one-way time transfer.

For more detailed information on time transfer methods, see the following recommended articles:

> Levine, Judah, "A Review of Time and Frequency Transfer Methods", Metrologia, Vol. 45, No. 6, Dec 2008, pp 162-174. (This article can also be found at http://tf.boulder.nist.gov/general/pdf/2311.pdf.)

Parker, Thomas, and Matsakis, Demetrios, "Time and Frequency Dissemination: Advances in GPS Transfer Techniques", GPS World, Nov 2004, pp 32-38. (This article can also be found at http://tf.boulder.nist.gov/general/pdf/1998.pdf.)

Distribution is the means of making the outputs of a particular frequency standard or ensemble useful to other systems. To discuss distribution, we must first discuss creating the physical replica of the steered local ensemble's timescale.

As discussed above, the ensemble timescale is in fact a paper clock, which exists in a computer as result of a set of calculations. To make use of this timescale, one must first build a physical replica. There are essentially two ways to build this replica: one is to steer an actual frequency standard to the ensemble timescale; the other is use a microstepper (device as discussed above). If using a frequency standard, it could be one of the cesium frequency standards in the ensemble or a separate standard. Many time and frequency experts recommend against steering any of the cesium frequency standards in the ensemble in general. And, in particular, because of the way the cesium frequency standards are used in WAAS, it would also be better not to steer one of them because the steering would have an impact on WAAS. Since the replica system will be steered on a regular basis to the ensemble, one could use a less expensive frequency standard, such as a rubidium atomic frequency standard, costing about $5K. Such standards generally have a stability of $1X10^{-11}$ averaged over an hour and about 1 µs/day time uncertainty. Such a standard may already exist at many WRS; for example, the team found during a visit to the WRS co-located at the Longmont CO (Denver) Air Route Traffic Control Center (ARTCC), there is a rubidium standard in the Voice Switching Control System (VSCS), located in the same room. In VSCS, only the 1 MHz output is used, as a frequency source for the system. Although further review would be needed to assure no adverse impact on VSCS, this might be a low-cost way to implement a physical replica at WRS co-located with ARTCCs.

If an ensemble of three timescale were created at each WRS, one can use its physical replica's outputs locally. For example, with most WRS co-located at ARTCCs, there are a number of local systems that need accurate time or precise frequency. Currently, most time service requirements are a few milliseconds (ms) accuracy for time-stamping of events and of signals sent and received. In future, such time-stamping requirements may increase in accuracy. The larger requirement, however, is for accurate time for more sophisticated applications, such as multi-lateration, which requires 50 ns or better accuracy. The more likely requirement locally, however, is for precise frequency. Most communications systems require a source of 1, 5, or 10 MHz as a local oscillator reference, and this reference needs to

meet “Stratum 1” requirements (or part in 10^{-11} frequency stability). For such time accuracy (50 ns or better) and frequency stability (Stratum 1 or better), most systems rely on a relatively inexpensive GPS-stabilized timing system. To be independent of GPS and operate through outages lasting upwards of a day or more, one would use the local timescale as the time and frequency source.

To do this, a distribution system is needed. Fundamentally, this distribution system consists of two types of elements: distribution amplifiers and distribution media. Amplifiers are needed to assure adequate power as well as signal isolation on 1PPS and various frequency signals. Care needs to be taken in the design to assure coherence of 1PPS with leading edges of digital frequency signals and zero crossings of analog frequency signals is maintained throughout the amplification process. For distribution media, use of high quality coaxial cable is recommended within the building and fiber optic cable when distributing throughout a campus. Both the length and temperature sensitivity of the cables used are critical to maintain signal coherence and time synchronization. Fortunately there are several manufacturers of such distribution systems, and quite often the distribution amplifiers are included within the same chassis that includes the timescale calculation and physical implementation of it. And manufacturers of such systems are available to design, implement, and maintain distribution networks on site.

The team examined means of distributing precise time, in particular, beyond the campus, e.g., to surrounding facilities upwards of 50-200 nautical miles distant, that might be used in a multi-lateration scheme (requiring 50 ns time synchronization with each other). Two methods were considered: using existing landline communications links, or using existing or new radio links.

Accurate time transfer, using two way techniques, has been demonstrated over fiber optic landlines of several hundred miles. The key to their working well is having “dark fiber” to maintain the optical path all the way to the remote site, including through optical switches. The problem is that most long-haul fiber networks use electronic switching nodes, converting the optical signal to electronics and back again at each switching node, breaking the optical connection, and also introducing new and unknown timing delays in the electronic switching systems. This is technically feasible bur very likely prohibitively expensive.

Time transfer over wired (copper) landline systems also does not appear technically feasible. Again, most landlines, including those called “dedicated circuits,” are in fact not point-to-point circuits but pass through several switching centers. Similar to long haul dark fiber and optical switches, it is extremely

rare that any landline leaving a campus will not encounter electronic switches and flexible routing. Thus, with today's modern communications technology, there is generally no way to use existing circuits for accurate time transfer. We did not investigate the concept of "boundary clocks," which has been proposed as a means of bridging the network elements on long-haul networks. This idea has been proposed as a means of extending the IEEE-1588 synchronization protocol to wide-area networks. It would, however, require the active collaboration of the telecommunications carriers to install this hardware at every network element, and is probably not practical for this reason. However, the telecommunications carriers may install boundary clocks for their own synchronization needs, and this idea might be more practical if and when that happens.

Radio communications circuits, particularly if direct line-of-sight and point-to-point, have potential to enable time transfer using two-way time transfer techniques. There are legacy microwave circuits installed between ARTCCs and outlying regional sites, and some are point-to-point. However, these are becoming increasingly rare, and as equipment requires upgrade or replacement, they tend to be replaced with vendor provided landlines (dominantly provided by the FAA Telecommunications Interconnect, or FTI, service contract). Additionally, if longer than "single hop," these circuits include electronic circuitry which may impede time transfer, or they may have interspersed landline circuits (and associated switching centers.

Other radio circuits that could be considered include ground wave signals operating in the low or medium frequency (LF or MF) bands. These include non-directional beacons (NDB) operating within a small MF band near 300 KHz, as well as the Maritime and Nationwide Differential GPS (generally referred to as NDGPS) operating in the same band (often reusing former maritime radiobeacon or aviation NDB frequencies). If a decision is made to reuse the Loran-C infrastructure as eLoran, these transmitters, operating in the 90-110 KHz LF band on a 100 KHz carrier could also be used. The joint FAA and USCG Loran Accuracy and Integrity Performance Panels (LORAPP and LORIPP) of the early 2000s found that eLoran could be used for time transfer, with accuracies of 50-100 ns, dependent on distance from transmitters or differential reference sites. The techniques applicable to eLoran are expected to work equally well, particularly at 50-200 nm distances, using MF NDB or NDGPS transmitters. Unfortunately, none of these transmitters is co-located with WRS, so there is still the issue of transferring the nearest WRS timescale to one of them.

eLoran: It is of interest to note that if eLoran were deployed throughout the US, it might make it unnecessary to distribute WRS timescales beyond their respective campus—eLoran time distribution would suffice. For more information on eLoran's potential, see the following articles:

> Lombardi, Michael, Celano, Tom, and Powers, Edward, "The Potential Role of Enhance LORAN-C in the National Time and Frequency Infrastructure", paper presented at the Annual Meeting and Technical Symposium of the International Loran Association (ILA), October 2005. (This paper can be found at http://tf.nist.gov/timefreq/general/pdf/2105.pdf.)
>
> Lombardi, Michael, Norman, Chuck, and Walsh, William, "The Role of LORAN Timing in Telecommunications", paper presented at the Annual Meeting of the Radio Technical Commission for Maritime Services (RTCM), May 2006. This paper can be found at http://tf.nist.gov/timefreq/general/pdf/2142.pdf.)

WAAS includes its own wide area distribution system—the WAAS signals from each of the WAAS GEOS. The WAAS GEOs are sited for NAS-wide coverage; thus, if WAAS can be used as a time distribution system, this distribution would also be NAS-wide. In fact, WAAS currently has the capability to distribute a time offset using WAAS Message Type 12 (MT12). If implemented as currently designed, WAAS MT12 would provide the offset between WAAS Time and GPS Time; MT12 is currently not implemented.

Chapter 4 Alternatives

Alternatives: In the interim report briefing, the WNT IAT included four alternatives; one was deferred based on feedback from that meeting with the sponsor. The others were further refined and are discussed in this section.

The first alternative is development of a timescale based on an ensemble of the three cesium frequency standards at each WRS. These small ensembles' timescales would be steered to UTC(USNO), and their physical implementations would be distributed for local use in and around their respective WRS.

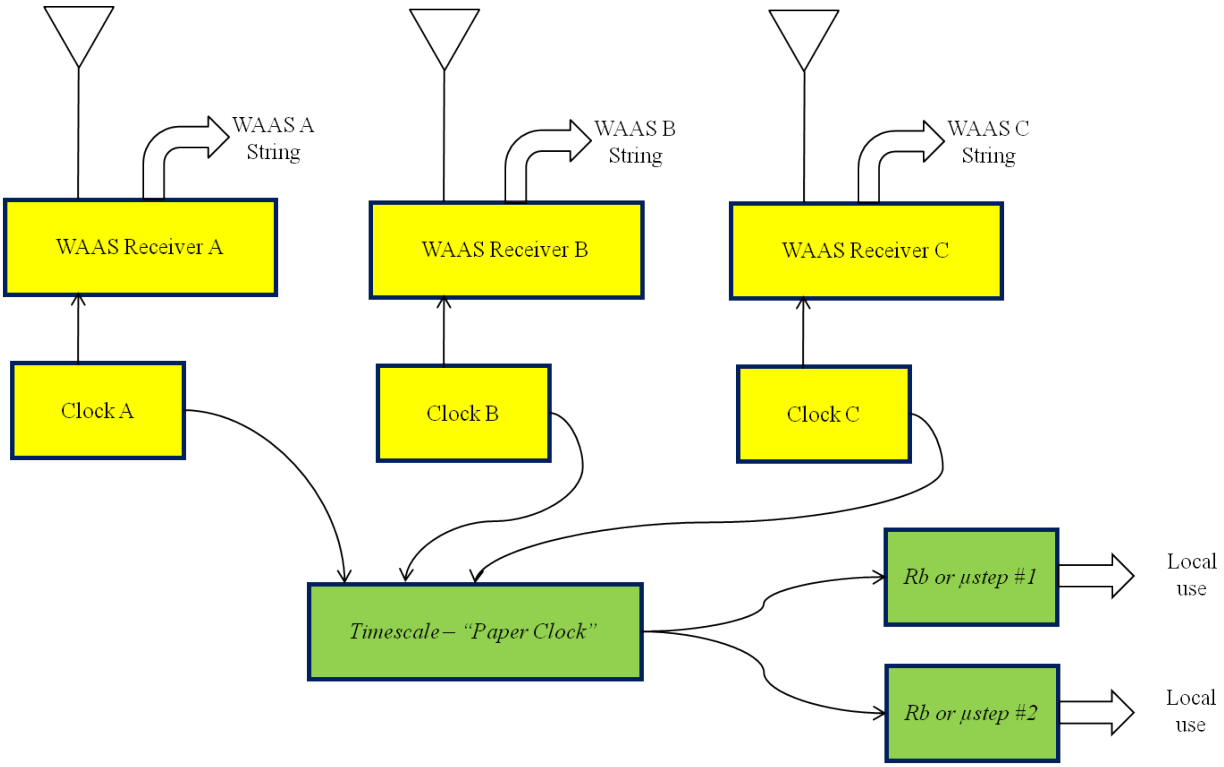


Figure 6. *Notional diagram of Alternative 1 – Ensemble of 3 at each WRS*

The second alternative is development of a timescale based on an ensemble of the entire 114 cesium frequency standards at one or more WMS, or other convenient locations within the WAAS network. These large ensembles' timescales would be steered to UTC(USNO), and their physical implementations would be distributed for NAS-wide use via the WAAS signal.

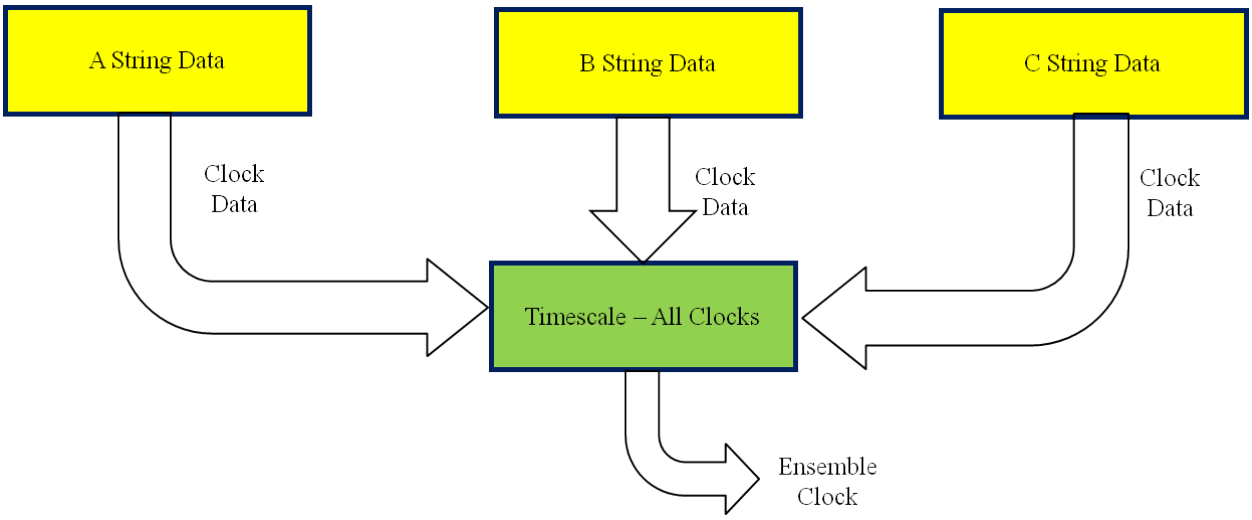


Figure 7. *Notional diagram of Alternative 2 – Ensemble of 114 at a central location*

The third alternative is expansion of the first to include regional distribution of the small WRS ensembles' timescales to other FAA sites within 50-200 nm of their respective WRS.

The fourth alternative, which was eliminated from further review, is integration of these FAA timescales with timescales developed at other agencies' sites, for example eLoran transmitters, for a distributed national time and frequency network. The rationale for eliminating this alternative is to determine how best to distribute the FAA timescales for internal FAA use first, then consider allowing opportunities as might develop to integrate with other agencies, based on the NAS-wide example.

Each of the first three is described further in this chapter, including several sub-alternatives.

Technical features of timescales: Before listing all the sub-alternatives, there are several options to consider for performing the comparison measurements, computing the timescale, steering the timescale, and developing the physical replica signals. These options are used in the sub-alternatives:

- *Comparison*: phase comparators or time interval counters:
    - Typically the more precise, more difficult, and more expensive means of making the A-B, B-C, and C-A comparisons is to use a set of phase comparators. These integrate over a number of cycles of one of the frequency outputs of the ensembled cesium standards. The integration also provides a degree of filtering. The comparators are generally very carefully designed precision-trimmed circuits.
    - An alternative, lower cost method is to compare the timing between the pairs of cesium standards in the ensemble. The instrumentation is simpler—a set of time interval counters—and they use the 1 PPS outputs from the cesium standards for comparison. Some filtering of the measurements is needed after they are taken, but the circuitry

needed is generally digital and of the sort included in reasonably precise (but relatively inexpensive) COTS time interval counter instruments.

- *Steering*: TWSTT, common view, or GPS all-in-view timing receiver:
    - TWSTT provides the highest accuracy and greatest independence from GPS and is generally the most costly approach for comparing a local timescale to a remote reference standard. TWSTT equipment must be installed at each WRS location, and time must be leased on a satellite transponder to perform the measurements each day. The technique requires sending time-tagged signals from the reference site (USNO) to each WRS, noting time of receipt, and from each WRS to USNO. Comparing the time delays, since the radio signal path are identical and the delays thus are common, the remainder is the time offset between the local timescale and remote reference.
    - Common view uses a similar calculation, but instead of including the exact same path in both measurements, it makes assumptions that two paths are "close enough" with major differences adequately modeled, that path delays cancel. The technique requires simultaneous measurements of a signal in view of both sites, generally a satellite signal, at the WRS and at the reference site (again presumed to be USNO). Since the viewed satellite signal starts at the same time, measuring the received time at each location and assuming path delays are common, the difference is time offset between local timescale and remote reference standard. This requires communications and coordination between the local timescale site and the reference standard site but has the advantage that any suitably observable and stable satellite signal might be used (for example, the WAAS signal) without leasing satellite time.
    - Using a GPS all-in-view timing receiver is one of the simplest methods to implement, and relatively inexpensive COTS GPS timing receivers are generally available. It has two negatives: it is not fully independent of GPS, and it compares the local timescale to the long term average GPS Time, which itself is an estimate of UTC(USNO), not UTC(USNO) directly. Given the stability of the ensemble timescales, loss of GPS reception for upwards of several days to a week would not be a major problem. Since GPS Time is maintained very close to UTC(USNO), with simple filtering (daily averaging of all observations of all GPS satellites), the result should be a very good estimate of UTC(USNO).
- *Replica*: Independent or switched replica of steered ensemble timescale:
    - An independent replica requires either an independent frequency standard, such as a rubidium or higher end quartz, or a precision microstepper device. This is the best way to create a physical replica of the timescale, as it allows all the cesium standards in the ensemble to remain completely independent, each to continue to free run normally with no steering applied, and enables seamless operation through failure of any cesium. It requires acquisition of an external device (frequency standard or microstepper) to create the physical replica.
    - A switched replica requires selection of one of the existing cesium frequency standards in the ensemble as the source of replica. Then the internal microstepper circuits in the

selected cesium can be used to create the steered replica. There are two operational negatives to this approach. The first is that the cesium that is steered is thus no longer free running; although the steering commands are expected to be small, the impact of the steering will need to be studied to determine if WAAS changes are needed to account for the steering commands to assure continued safe and proper WAAS operations. The second is that should the selected cesium fail, there will be a discontinuity in operations of the replica while another cesium is selected to become the replica. Generally such a system includes a relatively sophisticated switch subsystem, to somewhat smooth this discontinuity, in the event the standard used for the replica fails.

- *Ensemble*: AT1, KAS-2, or other ensemble algorithm:
    - There are several algorithms commonly used in government and commercial frequency standard ensemble, the most common of these are known as AT1 and KAS-2. Both of these algorithms have been around for quite a long time and have been used to develop many timescales based on multiple frequency standards. Purchase of a COTS system to create the ensemble will generally include a variant of one or the other.
    - A custom algorithm could be developed, but again, most time and frequency industry experts would be familiar with the commonly accepted algorithms, and it is likely that any custom algorithm would be a variant of one of them.
    - This reports assumes a common algorithm or variant will be selected at implementation by the FAA engineers or contractor; the team has not assessed the relative benefits of AT1, KAS-2, or other algorithms.

Alternatives:

1. *WRS Timescale of Three Cesium Standards*: This alternative develops a timescale from an ensemble of the three cesium atomic frequency standards at each WRS, steers each WRS timescale to UTC(USNO), develops a physical replica implementation of the timescale at each WRS, and distributes it locally.
    a. *Turnkey Ensemble and Steered Timescale System*: This is a generally a higher-end COTS solution, but all inclusive. Implemented in one or more rack-mounted chassis, it includes phase comparators, computer, steering reference standard subsystem, ensemble and steering algorithms, physical replica of the steered time and frequency outputs, and distribution amplifiers. Further subdivision of this sub-alternative is based on the method of steering to UTC(USNO):
        i. TWSTT
        ii. Common view
        iii. GPS Time
    b. *Turnkey Ensemble and Switched Timescale System*: This is another COTS solution, simplified by steering the outputs of one of the existing cesium atomic frequency

standards as the physical replica. It may or may not include distribution amplifiers. Similar to Alternative 1.a., there are further subdivisions based on steering:

i. TWSTT
ii. Common view
iii. GPS Time

c. *Custom Ensemble and Steered Timescale System*: This would be custom fabricated from COTS instrumentation components, including time interval counters, integrated by a system provider or internally by FAA system engineers. This is the custom equivalent of Alternative 1.a., and has the same subdivisions based on steering:

i. TWSTT
ii. Common view
iii. GPS Time

d. *Custom Ensemble and Switched Timescale System*: This is the custom-fabricated equivalent of Alternative 1.b., with same subdivisions based on steering:

i. TWSTT
ii. Common view
iii. GPS Time

2. *WMS Timescale of 114 Cesium Standards*: This alternative develops a timescale from an ensemble of all the cesium atomic frequency standards throughout the WAAS at each WMS (and possibly other locations), steers each WMS timescale to UTC(USNO), develops a physical replica implementation of the timescale at each WMS or GUS, and distributes it NAS-wide through the WAAS signals.

This alternative relies on the WAAS communications networks to transport data from all three of the WAAS receiver strings from all WRS. At the WMS, or at other convenient locations (such as the FAA Technical Center), these data are processed to determine performance of the underlying frequency standards, and further processed in the ensemble calculations to create the timescale. Sub-alternatives include options for distribution based on WAAS and their potential impacts on WAAS:

a. *Message Type 12 Implementation*: Message Type 12 (MT12) was established in WAAS to provide the WAAS Time offset from GPS Time; it has not yet been implemented. Although the message has been specified, there are adequate spare bits to allow it to be redefined to give the offset of WAAS Time from UTC(USNO). Currently in WAAS, there is no automated process to update MT12; the current state of development allows WAAS operators to manually insert data into this field, which data remain in place until manually changed. This alternative would use WAAS Network Time (WNT) based on the timescale of the ensemble of 114 cesium frequency standards in WAAS, compared to the UTC(USNO) as the input for the revised MT12, and would provide a daily update. The process of inserting the daily update of MT12 could be manual or automated. There

are three subdivisions of this alternative, based on the steering of the 114-ensemble WNT timescale:

i. TWSTT
ii. Common view
iii. GPS Time

b. *Steering GUS Cesium Frequency Standards*: In Alternative 2.a., time distribution is simply a data offset from UTC(USNO); there is minimal impact on WAAS other than implementing an unused but reserved message type; and it is not necessary to implement a true physical replica of the 114-ensemble WNT timescale (paper timescale suffices). This alternative includes Alternative 2.a. (implement MT12) and would construct physical replicas of the 114-ensemble WNT timescale on the 5071A cesium frequency standards at all GUS for the WAAS satellites. This would require steering these four cesium standards (one at each of two GUS for each WAAS satellite) to the 114-ensemble WNT timescale, which timescale itself would be steered to UTC(USNO). This entails a change in WAAS, as these cesium standards are currently replicas of WAAS Time, an internal WAAS estimate of GPS Time, with the offset of WAAS Time from GPS Time steered by WAAS toward zero. This would require a change in WAAS, but it would be limited to a simple change in reference standard for steering the 5071A cesium standards at the GUS. There are three subdivisions based on steering of the 114-ensemble WNT timescale:

i. TWSTT
ii. Common view
iii. GPS Time

c. *Replacing WAAS Time*: This alternative requires a more invasive change to WAAS, but it is technically the best method to implement a fully GPS-independent distributed time system within WAAS. This alternative goes beyond Alternative 2.b. (MT12 plus GUS cesium steering) to eliminate WAAS Time as currently calculated in WAAS and replace it with the 114-ensemble WNT timescale. As currently calculated, WAAS Time is an artifact of the initial WAAS design, which was required to correct for the deliberate perturbation of GPS Time known as Selective Availability (SA); SA was used in GPS until May 2000, when it was turned off. The initial reason was to keep WAAS Time close to the SA-varying GPS Time to minimize the size of WAAS differential corrections needed to meet data rate limitations of the WAAS downlink signal. Without SA, GPS Time is now constantly maintained within a few nanoseconds (ns) of UTC(USNO). Similarly maintaining WAAS Time also within a few ns of UTC(USNO), as proposed for the 114-ensemble WNT timescale, will now meet the need for minimal sized differential corrections and remain within data rate limitations. It also has the advantage of keeping the “new WAAS Time” or WNT independent of GPS. It requires a change in WAAS to (1) cease use of the current (or legacy) WAAS Time calculation in WAAS, (2) substitute WNT for WAAS Time, and (3) make a comparison between WNT and legacy WAAS Time calculations to assure against hazardously misleading information. This would also

simplify Alternative 2.b., in that existing WAAS steering algorithms for the GUS cesium standards would likely be reused. There are three subdivision based as steering of the 114-ensemble WNT timescale:

i. TWSTT
ii. Common view
iii. GPS Time

3. *Regional Distribution*: This alternative builds on Alternative 1 and distributes the 3-ensemble timescale replica beyond the campus on which each WRS is located. Most remote and austere sites of FAA, such as outlying DMEs or planned ground based transmitters (GBT) for ADS-B, are located within tens to hundreds of miles of larger FAA sites (ARTCCs, etc.) which have installed WRS. These remote sites are candidate sites to contribute to Alternate PNT (APNT) or NAS-wide multi-lateration surveillance systems, particularly if they can maintain time synchronization to within about 50 ns of each other. Given a 3-ensemble timescale, steered to UTC(USNO), at each WRS, it would suffice to support such synchronization if WRSs' accurate time could be transferred to outlying regional sites (approximately 50-200 nautical miles distant). Sub-alternatives include media for time transfer, including existing landline communications, new landline communications, and existing or new wireless (radio) communications:
    a. *Existing Landline Communication*s: This sub-alternative considers time transfer from WRS to outlying sites via existing landline communications circuits. Data collected during the study found that most of these outlying sites are connected to WRS locations (ARTCCs, et al) via existing landline services. Initially some services were dedicated line, FAA-owned, point-to-point circuits, although most have migrated to virtual point-to-point circuits or over common carrier switched telecommunications networks. These circuits use now use a mixture of copper and fiber cables, most with several central office or local electronic telecommunications switches (routers). Although not all services are provided by a single provider, the FAA appears to be moving to a services-based FAA Telecommunications Interconnect (FTI) contract, with prime contractor Harris Corporation, to manage and upgrade existing legacy circuits. Additionally, under the NAS-wide ADS-B contract with ITT Corporation, it appears that landline communications to planned GBTs will be implemented through a subcontract with ATT Corporation.
    b. *New Landline Communications*: Similar to Alternative 3.a., this sub-alternative considers time transfer over new, dedicated, point-to-point circuits. These would be implemented over dark fiber circuits; if switches are needed they would also be fiber.
    c. *Existing Radio Communications*: Similar to Alternatives 3.a. and 3.b., this sub-alternative recognizes that several radio links, generally microwave signals, connect ARTCCs with WRS to some outlying stations. If these are point-to-point, without intermediate switching circuits, they might be used for time transfer.
    d. *New Radio Communications*: Similar to Alternative 3.c., this sub-alternative would install new radio transmitter capabilities at or near WRS specifically for time transfer to outlying sites. These would generally use medium frequency (MF) transmitters in the

300 KHz range (often used for non-directional beacons (NDB) or for Nationwide DGPS (NDGPS) broadcast sites). This alternative would require point-to-point fiber optic links from WRS to the broadcast transmitter.

4. *WMS Ensemble of 114 Standards, Plus Other Agencies' Systems*: This alternative looked into coordinating the WAAS standards, plus approximately 90 each 5071A cesium atomic frequency standards in the US Coast Guard operated North American Loran service, and any atomic standards available in other agencies. This alternative was presented to the sponsor in the interim report with a recommendation to defer further consideration, with which the sponsor agreed.

   As an aside, as directed in the FY2010 budget, the Coast Guard terminated operations of the Loran service, with last signal transmission on 4 August 2010. Dismantling of infrastructure has begun, with removal of broadcast towers at two transmitters in Alaska and redistribution of a significant number of the cesium atomic standards to other government agencies. Since the Loran service, which would have been the largest potential partner with WAAS, has terminated, there is also less incentive to continue to pursue this alternative.

   The termination of Loran services, however, and potential for redistribution of its assets provides additional opportunities. These are discussed further in Chapter 7 Future Thoughts of this report.

Alternatives 1, 2, and 3, and their sub-alternatives, are assessed in detail in the next chapter, Chapter 5 Assessment. Except for opportunities for reuse of Loran assets discussed in Chapter 7 Future Thoughts, Alternative 4 is not discussed further in this report.

Chapter 5 Assessment

Assessment: First and foremost, selected alternatives must meet overarching considerations, and then be assessed against a set of criteria.

Overarching considerations: Selected alternatives cannot adversely affect WAAS's aviation safety-of-life navigation functions. That is, accuracy, integrity, continuity, and availability cannot be comprised. Additionally, alternatives should minimize (preferably avoid) changes to WAAS, and in any case, changes to WAAS must meet strict requirements to avoid creating hazardously misleading information (HMI). Second, the 114 cesium atomic frequency standards needed for proper WAAS operation also comprise a significant national asset. They should be coordinated to provide new or more robust operational capabilities, at least for the FAA, and possibly for the nation. Third, this should be done economically, with minimal need for new equipment or operational procedures, while partnerships with other agencies can be considered to assist.

Criteria for Assessment: The first consideration is *benefit to users*; why make a change unless there is a benefit? Classes of users that may benefit include aviation users in the NAS, FAA systems, and finally all others. Next is *ease of implementation*, both in terms of new equipment or changes to existing equipment needed and also new operations procedures. Closely related to ease of implementation is *reuse of existing assets*, both those within FAA systems or available from partner agencies. *Cost* is always a consideration, and like all other criteria is assessed qualitatively in this report. Finally, *political acceptance* needs to be a consideration in any alternative. This is particularly important in alternatives for WAAS Network Time (WNT)—this upgrades WAAS from an aviation navigation system only into a time and frequency distribution system also. FAA is responsible for aviation navigation, but other agencies are responsible for time and frequency distribution or make use of such services—WNT alternatives should not be unacceptable to those agencies.

Alternative 1, WRS Ensembles of Three Timescales: The sub-alternatives include 1.a. Turnkey Ensemble System, 1.b. Turnkey Switched System, 1.c Custom Ensemble System, and 1.d Custom Switched System; each is further subdivided into i. TWSTT, ii. Common view, or iii. GPS Time steering.

Overall, the *utility* of Alternative 1 (and all its sub-alternatives) is to provide accurate time or precise frequency *for use by other FAA systems* co-located at the same facility as the WRS. For example, at ARTCCs, there are approximately 15-20 systems that require an external source of time or frequency, and there are 2-4 legacy systems that serve as these sources (see Appendix E for list from one ARTCC). A relatively quick examination shows that the time and frequency references are increasingly based on GPS—even a cursory count of antennas on the roof of an ARTCC reveals upwards of 6-10 GPS antennas, and most of these are attached to timing receivers used as a time or frequency source for some system. The two types of systems using these reference signals are communications systems (requiring precise frequency to approximately Stratum 1 stability) and time tagging systems (requiring accurate time to millisecond (ms) accuracy).

Most legacy communications systems are in process of being upgraded to the FTI service. This service includes a carefully architected and controlled national network, which provides the needed Stratum 1 level frequency from multiple external sources, backed up with GPS timing receiver-based services at major nodes (such as ARTCCs). There appears to be an ability within the on-site FTI equipment to accept a local, independent source of Stratum 1 frequency, which could be provided by the WRS Timescale. Understanding that FTI uses the CXR Larus StarClock TeimPro 6400 GPS Timing Receiver system, the IAT reviewed the data sheet and other information on this system. This is discussed further in Appendix F.

Implementation of Alternative 1 (and its sub-alternatives) is *relatively easy*. Whether a turnkey (1.a. or 1.b.) or custom (1.c. or 1.d.) system is selected, a relatively small amount of additional equipment is needed. The impact on WRS equipment is minimal, just connection of cables between the timescale system and existing, currently unused outputs on each of the WRS's three cesium atomic frequency standards. There is unused space in the standard 3-rack WRS installation that would accommodate the needed timescale system. There is potential that the currently installed computer console (at least the display and keyboard) can be used as the local user interface to the new timescale system.

With exception of assuring minimal disruption of power to the cesium atomic frequency standards and documenting any major local events (such as loss of air conditioning in the facility or major maintenance of WRS components), virtually no other change appears needed in established facility maintenance procedures. The biggest change involves power—the first step in most maintenance procedures is to turn off power to the rack, and this will need to be changed to allow power to be turned off to all equipment but any cesium standard in the rack.

Since the local technicians are in place to perform maintenance and not conduct operations, WRS operations are in fact controlled centrally generally guided by WMS and overseen by operations and engineering staff in Oklahoma City and Atlantic City. The timescale system would also need to be "operated" and controlled centrally, at either of these locations or a partner agency location (such as USNO or NIST). Fortunately, the data communications capabilities in WAAS are adequate to support the additional data needed, and the existing WRS power and communications control system can provide these data.

Alternatives 1.a and 1.b are more costly. Turnkey systems exist, but most are focused on higher end installations, such as time service laboratories or large facilities requiring robust centrally distributed time and frequency. Such systems generally appear to have been designed to create timescales from ensembles of high performance cesium atomic standards and/or hydrogen masers. Most such systems require careful installation and management by experienced personnel, again based on the assumption of higher end users, and thus, most time service professionals recommend that either the turnkey system's manufacturer provide operational management assistance or comprehensive training to FAA employees. Based on the cost and complexity of these systems, *Alternatives 1.a and 1.b are assessed as not feasible for use in WRS Timescale implementation,* and are not discussed further in this report. See Appendix G for specification sheets on selected commercial systems downloaded from the vendor website.

Alternatives 1.b and 1.d provide less utility and more difficulty of implementation. In terminology used in this report, these are switched timescales; they steer one of the cesium atomic standards in the WRS as the physical replica of the timescale. This actually violates the first overarching concern, in that it does indeed change one of the frequency standards driving a WAAS receiver, and it therefore has an impact on that receiver's data string provided to WAAS. Additionally, these alternatives require implementation of a switch to be able to select another cesium for the replica, in the event the first should fail. This will introduce discontinuities in time and frequency from the timescale and require that downstream equipment be able to accommodate these discontinuities. *Alternatives 1.b and 1.d are thus assessed as not feasible for use in WRS Timescale implementation*, and are not discussed further in this report.

Alternative 1.c provides full utility and ease of implementation. There is potential to reuse an existing rubidium frequency standard within legacy communications systems at ARTCCs as physical replica of the 3-ensemble WRS timescale. However, if designing a low-cost custom suite of time interval counter instrumentation, computer, et al, it is assessed preferable to integrate either a new rubidium or microstepper with custom system to create the replica. (This is discussed further in Chapter 6 Recommendations.) Of Alternative 1.c's three subdivisions based on steering, TWSTT would be excessively costly for satellite transponder rental. Common view requires costs of communications between each WRS and USNO for the required comparison of data, and hence could involve some costs. GPS Time is essentially free after installation of timing receiver equipment at each WRS, and based on example of a decade of use at US Coast Guard Loran transmitters, it is easy to implement, fully automatic, and based also on analysis, provides an adequate degree of independence from GPS for an ensemble of three cesium atomic standards. For these reasons, *Alternative 1.c.iii is assessed as preferred; should more independence from GPS prove necessary in future, Alternative 1.c.ii would be recommended; Alternative 1.c.i is assessed not feasible due to cost.*

Alternative 2 WMS 114-Ensemble WNT Timescale: This set of alternatives provides significant utility to aviation users, to FAA systems, and to all other users of WAAS. Each sub-alternative implements an alternate distribution of accurate time and precise frequency via the WAAS signal. Users, in particular those in fixed locations (such as remote or austere FAA sites), can use a directional antenna system, with its beam steered toward the WAAS satellite, nulls steered toward interference sources, or both, to continue tracking the WAAS signal to derive time and frequency in the presence of interference or jamming. The sub-alternatives vary in the amount of utility provided, ease of implementation, and potential costs. Several require modification of WAAS.

To implement any of the sub-alternatives, the WNT timescale of the ensemble of 114 cesium standards must first be calculated. The needed data are available at all three WMS, at FAA operations and technical support centers (such as Oklahoma City and Atlantic City), and can be made available other nodes (existing or new) within the WAAS communications network (such as another FAA location, USNO, or NIST). At any, or all, of these sites with full data access, it is possible to implement a computer algorithm to calculate a WNT timescale from all the cesium standards (ideally all 114) at the 38 WRS. Wherever calculated, this WNT timescale would be a "paper clock," that is, existing only as a set of calculated results.

There are potentially several ways to compute this large timescale. The first way is essentially "brute force," or making all the comparisons of 114 vs. 114 standards. However, the computation load can be reduced and simplified through "federation." That is, given implementation of Alternative 1.c, a set of 38 ensembles of three will have been computed; data from these ensembles can be provided to the WMS or other central location(s), the ensemble of these ensembles can be compared via 38 vs. 38 comparisons. Also, given the design of WAAS as three strings of data from 38 WRS sites and the fact that WAAS actually processes these data to estimate GPS Time from 38 sites in each string, there may be potential to leverage the calculations already in WAAS. These string calculations are quite similar to ensemble calculations, and detailed examination may show WAAS has already (or nearly) created three ensembles of 38 in WMS calculations; if so, these three ensembles may be compared at the WMS to create the full 114-ensemble WNT timescale.

Once the full 114-ensemble WNT timescale is calculated, it will need to be steered to the external reference (UTC(USNO)). Each sub-alternative (2.a, 2.b, or 2.c) has subdivisions, i. TWSTT, ii. Common view, or iii. GPS Time. These subdivisions are listed in order of higher to lower accuracy, as well as higher to lower cost. However, *given the cost, complexity, and benefits of creating the 114-ensemble WNT timescale, the highest accuracy TWSTT alternatives are assessed as recommended. Common view and GPS Time alternatives are assessed as lesser accuracy and not recommended.* (Alternatives 2.a.ii, 2.a.iii, 2.b.ii, 2.b.iii, 2.c.ii, and 2.c.iii are not discussed further.) TWSTT comparisons to UTC(USNO) would be made daily.

Alternative 2.a.i MT12 Implementation: This alternative is the simplest to implement to distribute the steered 114-ensemble WNT timescale to users. It can be argued that it has no impact on WAAS, as MT12 was designed as part of WAAS, simply not yet implemented. The implementation would, however, require redefining MT12 to be the offset of the steered 114-ensemble WNT timescale from UTC(USNO). This would enable users tracking the WAAS signal to derive UTC(USNO) from WAAS. Implementation would require a means to insert the offset into MT12 data on a periodic basis. As currently implemented in WAAS, this would require a daily manual update of the MT12 data field. Alternatively, as part of the implementation of TWSTT steering, the same algorithm might include automatic update of the WAAS MT12 data field. *This alternative is assessed feasible and the minimum recommended.*

Alternative 2.b.i Steering GUS Cesium Frequency Standards: This alternative includes Alternative 2.a.i and also creates a physical replica of the 114-ensemble WNT timescale at each GUS, using its currently installed 5071A cesium atomic frequency standard. This alternative requires a change in WAAS, which is assessed as relatively minor. Currently GUS cesium standards are steered to WAAS Time, as calculated by WAAS; this alternative would instead steer these cesium standards to the WNT timescale, which itself has been steered to UTC(USNO). This alternative aligns the phase of the WAAS signal with the WNT timescale offset. In addition, it has the benefit that steering is based on the ensemble of 114 geographically distributed atomic standards, independent of GPS. Additional complexity is required because the 114-ensemble WNT timescale is calculated at WMS (or other locations) while the physical replicas are at GUS; this requires additional TWSTT equipment installed at each GUS. *This alternative is assessed feasible and recommended.*

Alternative 2.c.i Replacing WAAS Time: This alternative includes Alternative 2.b.i and also replaces WAAS Time as currently calculated in WAAS with WNT from the timescale based on the ensemble of 114 cesium atomic standards at the WRS. The 114-ensemble WNT timescale is steered to UTC(USNO) directly, while WAAS Time is steered to WAAS's estimate of GPS Time, which itself is an estimate of UTC(USNO). Given elimination of selective availability (SA) from GPS, the WAAS requirement to maintain WAAS Time close to GPS Time no longer requires steering WAAS Time to GPS Time. Since GPS Time is steered directly to UTC(USNO) and no longer varied with SA, replacing WAAS Time with WNT steered directly to UTC(USNO) will maintain the required closeness to GPS Time. This alternative requires a change to WAAS, which is assessed as relatively major. WAAS needs to be fully reviewed (1) to determine if there are other uses of WAAS Time within WAAS which would be affected and need modification and (2) to assure there is no potential of introducing hazardously misleading information to WAAS safety-of-life navigation users. An additional safety monitor may be needed in WAAS. *Because of the changes introduced to WAAS, this alternative is assessed as not feasible, is not recommended, and is not examined further.*

Alternative 3 Regional Distribution: This alternative and its sub-alternative variants provide utility for FAA sites near each WRS. All require installation of equipment to transfer accurate time from each WRS 3-ensemble timescale to the nearby sites over distances of some 50 to 200 nautical miles. All would use existing or new communications circuits as the medium for time transfer. The need is to maintain time accuracy better than 50 ns at each of these sites relative to each other. This alternative requires implementation of Alternative 1.c. The sub-alternatives are assessed below:

Alternative 3.a Existing Landline Communications: Accurate time transfer within a building or campus relies on dedicated communications lines between the WRS 3-ensemble timescale replica and the using equipment. There are basically two ways of accomplishing the time transfer over these lines: (1) if the length of the lines are well known (and their electronic time delays are well calibrated), time transfer can be accomplished simply by adding the calibrated line delay; or (2) a more accurate means would use a two-way time transfer measurement (similar to TWSTT, but not using a satellite), which would take account of changes in calibration of the lines due to temperature or other environmental variations. These same techniques, particularly two-way time transfer, can be applied over larger distances. However, if there is a switching center (such as a telephone company central office or local switch) at any point in the line between replica output and the using site, the electronic switches introduce timing uncertainties such that accurate time transfer cannot be accomplished. Since existing communications lines between WRS locations and regional sites are provided over commercial landline circuits, with embedded switching centers, time transfer over existing communications circuits is not feasible. Thus, *this alternative is assessed as not feasible and is not discussed further.* (However, this does not change the fact that the WRS timescale should be used as a source of precise frequency for FTI and other communications nodes co-located at WRS sites, as discussed in Alternative 1.c.)

Alternative 3.b New Landline Communications: As discussed under Alternative 1.c, a general rule for distribution of accurate time is use of calibrated copper coaxial cable within a building and calibrated fiber optic cable throughout a campus. The reason for fiber outside is to minimize impacts of

environmental variations (temperature et al) on calibration of line delays. If new landline communications circuits were to be provided to regional sites, they should be fiber and ideally would be point-to-point, with no intervening switching centers between the WRS 3-ensemble timescale replica and the using sites. That said, however, data collected during this study indicated that as long as dedicated dark fiber is provided over the entire length of the circuitry and as long as any intervening switch centers are optical only (with no conversion of the optical signals to electronic signals), accurate time transfer over paths hundreds of miles long has been demonstrated. The problem remains that dedicated dark fiber and optical switches must be guaranteed, and rigorously maintained, by the communications providers for such time transfer to work; this is assessed as either not achievable or if achieved prohibitively costly. For this reason, *this alternative is assessed as not reasonably feasible and is not discussed further.*

Alternative 3.c Existing Radio Communications: Similar to dedicated lines, a dedicated point-to-point radio circuit can be used for two-way time transfer. Some legacy communications circuits at ARTCCs include point-to-point microwave links to remote sites; these could be considered for time transfer to those sites. However, data collected indicates that these are being incorporated as part of the FTI service and may be converted to commercially provided landlines. Also, some of these circuits include dedicated microwave links to intermediate sites, which may then transfer the signals to landline. In these cases the electronics inserted into the circuits introduce timing uncertainties that make accurate time transfer impossible. Since there is not full coverage to all remote sites, and since the likelihood of intermediate switches is high, *this alternative is assessed as not feasible and is not discussed further*.

Alternative 3.d New Radio Communications: This alternative requires new broadcast transmitters installed at WRS. Transmitters and frequencies are selected to provide connectivity to remote sites in the region. These would either be line-of-site circuits, using for example VHF TV-type signals, or more likely ground wave propagation signals in MF or LF bands. Opportunities for ground wave propagation include: reuse of NDB transmitters, antennas, and frequencies near 300 KHz; shared use of NDGPS transmitters and antennas; and reuse of excess Loran-C transmitters and antennas. Given calibration of the radio links for time delay, adequately accurate time could likely be transferred over line-of-site links. Due to impact of ground conductivity changes, due to diurnal or seasonal effects, it is not likely that such a one-way time transfer would be accurate enough using MF or LF transmitters. However, assuring relative time accuracy among sites might be achieved through common view techniques at the sites. If additionally, at least one of the remote sites also had a similar MF/LF transmitter, or if one or more remote sites can access a line-of-site link, there is a possibility to combine two-way at these sites with common view to others to increase accuracy at all sites. *Due to expense of installing transmitters, this alternative is assessed not reasonably feasible but quite interesting and worthy of further study*.

Based on the foregoing assessment, the IAT's findings and recommendations are presented in Chapter 6 Recommendations, and additionally, follow-up studies and issues are presented in Chapter 7 Future Thoughts.

Chapter 6 Recommendations

Findings: First and foremost, the 114 Cesium III atomic frequency standards within WAAS are a significant national asset capable of providing a robust and survivable source of accurate time and precise frequency. These atomic frequency standards can be coordinated in ensembles to create timescales that are steered to UTC(USNO), with no adverse impact on WAAS. Distribution of these timescales provides benefit to aviation users, to other FAA systems, and to all users of WAAS.

Second, the design of WAAS facilitates creating timescales at WRS sites, at WMS sites, and at existing or new sites with access to all WAAS data. Creation of timescales requires only non-invasive changes to WAAS, such as connecting cables to unused output ports within WRS, minor changes in WRS maintenance procedures, and accessing available data outputs provided at WMS and other FAA locations for export of WAAS data.

Third, cost of creating the timescales is relatively small. Custom ensemble systems at WRS can be built from COTS time interval counters and timescale software. Similarly, at WMS and central locations, only the addition of timescale software is required. Steering the timescales to UTC(USNO) requires the addition of GPS timing receivers at WRS and TWSTT equipment at WMS.

Fourth, cost of distribution of resultant timescales is also relatively small, and at WMS requires only minor changes to WAAS. Distribution at WRS benefits installed FAA systems; it requires addition of a COTS microstepper or rubidium frequency standard, plus distribution amplifier and cabling. At WMS, it requires implementing MT12 and potentially changing the steering reference for the 5071A Cesium atomic frequency standard installed at each GUS.

Fifth, the major beneficiary of these timescales is the FAA itself, particularly the SATNAV program's Alternate PNT (APNT) initiative. The benefit is a robust, independent source of UTC(USNO), as well as precise frequency, for all candidate APNT sites (such as DMEs, GBTs, and others). Secondary beneficiaries are FAA systems installed at facilities co-located with WRS and all users of WAAS. The benefit for FAA is robust local source of UTC(USNO) and Stratum 1 frequency for all FAA systems at ARTCCs (and other WRS sites), including assured Stratum 1 for major FTI (and other communications) nodes. For all users of WAAS, particularly in fixed locations, the benefit is a robust, independent source of UTC(USNO) and precise frequency.

Finally, there are several alternatives worthy of further study, with potential additional benefit to FAA and all users. These are discussed further in Chapter 7 Future Thoughts.

Recommendations: Based on the discussion in the preceding Chapter 5 Assessment, the following alternatives and studies are recommended, in priority order; all require minor changes to maintenance procedures at WRS, particularly to avoid unnecessary power disruption to the cesium atomic frequency standards at WRS (discussed previously):

1. **Implementation** *of Alternative 2.a.i 114-Ensemble WNT Timescale at WMS and MT12 Implementation*: For all users of WAAS, but particularly potential FAA APNT sites, this is the minimum needed to provide a robust, independent source of UTC(USNO). This requires installation of timescale software and TWSTT equipment at WMS, cost of daily TWSTT measurements, update of MT12 specification to represent offset of steered WNT from UTC(USNO), and software or operational procedures to implement periodic update of MT12 data fields.
    a. **Interim Implementation** *via Alternative 2.a.iii*: Although eliminated from further discussion in the Chapter 5 Assessment, use of GPS Time for steering the 114-ensemble WNT timescale, can be considered as a lower cost, "initial step" implementation of the recommended Alternative 2.a.i. This has the advantage of nearly immediate installation (i.e., not waiting for acquisition and installation of TWSTT equipment at WMS); it is also a less costly alternative (avoiding costs of daily TWSTT measurements) to evaluate the utility of MT12 to APNT sites.
2. **Implementation** *of Alternative 1.c.iii Custom 3-Ensemble Timescale at WRS*: For FAA systems at WRS locations that require accurate time or precise frequency, particularly assured Stratum 1 frequency for FTI and other communications nodes at WRS locations, this is the alternative required. Additionally, implementation of these WRS timescales may assist with federalization of the 114-ensemble WNT timescale calculation at WMS. This requires design of the custom system using COTS products and installation at WRS. Installation includes cabling from the three existing atomic frequency standards' 1PPS outputs to a time interval counter system, timescale software, GPS timing receiver, steering software, and replica system. The time interval counter system can be either a set of three COTS time interval counters or a switching system plus a single time interval counter. The replica system can use either a microstepper or an additional controllable frequency standard, and in either case, should include a distribution amplifier to buffer the outputs of the replica.
    a. **Interim Implementation** *Eliminating the Replica System*: Recognizing that an initial benefit entirely within the SATNAV program is facilitating federalization of the 114-ensemble WNT timescale calculation (in Recommendation 1), the most important initial implementation is the set of WRS 3-ensemble timescale calculations. The other benefits of the WRS timescale are to other FAA systems, most of which are communications and air traffic control systems, and it is these that require the replica system. Thus, there is an opportunity to "cost share" with other programs for this system; additionally, at least the distribution amplifier portion of the replica and all cabling can be outside of the WRS.

3. **Implementation** *of Alternative 2.b.i 114-Ensemble WNT Timescale at WMS and Steering of GUS Cesium Frequency Standards*: This is an upgrade of Recommendation 1 to fully synchronize the WAAS signal with the steered WNT timescale. The primary beneficiary remains FAA APNT sites, with an increase in time transfer accuracy based on assuring the WAAS signal carrier is synchronized with same reference as MT12; all other users with carrier tracking receivers should also benefit. In addition to Recommendation 1, this requires a software change in WAAS at each GUS to use the steered WNT timescale, in lieu of the internal WAAS Time calculation, to generate the steering commands to the GUS 5071A cesium standards.
4. **Study** *of Alternative 3.d Regional Distribution via New Radio Communications*: Data needed include location of DME sites, planned GBT sites, and other candidate sites for APNT; locations of existing transmitters at or near WRS sites, or locations where new transmitters could be installed; and ground conductivities and topologies on various paths. The study would postulate candidate architectures and evaluate ability of each to distribute accurate time adequate to the APNT needs.
5. **Study** *of Upgrading Recommendation 3 to Alternative 2.c.i 114-Ensemble WNT Timescale at WMS and Replacement of WAAS Time*: Although this is ultimate logical implementation of Alternative 2, it has a major impact on WAAS. The study would need to review WAAS to catalog all the functions the current WAAS Time calculation supports and determine the impacts of substituting WNT. Perhaps more important, however, is determining if this change introduces potential HMI risk in WAAS, as well as whether additional safety monitors are required in WAAS.

Chapter 7 Future Thoughts

Follow-on Studies:

*Recommended Studies***:** Chapter 6 Recommendations listed two studies as Recommendations 4 and 5. The discussions in these recommendations include a description of the need and outline an approach for each. These studies address, respectively, *Regional Distribution of WRS Timescales to FAA Sites Via New Radio Communications*, and *Replacing WAAS Time with the 114-Ensemble WNT Timescale in WAAS*.

Additional Studies:

Study of Alternative 4 WMS Ensemble of 114 Standards, Plus Other Agencies' Systems: This alternative should be reviewed further. It was eliminated from further consideration after the interim report briefing to the sponsor, given sponsor feedback that the alternatives should focus only on use of frequency standards within FAA. The rationale was that if FAA set the example with its 114 cesium standards, other agencies would seek to partner with FAA in making this time and frequency system more robust, or would be amenable to suggestion that they should do so.

At the time of the interim report briefing, the USCG operated Loran-C system was still in operation and in process of being upgraded to Enhanced Loran (eLoran). This system included 29 operational transmitters, 18 in the conterminous US (CONUS), 6 in Alaska, and 5 in Canada, the latter operated by the Canadian Coast Guard (CCG) as part of the overall system under agreement with USCG. Additionally, an engineering transmitter was included at the USCG Loran Support Unit in Wildwood, NJ, with capability of being brought into the operational system. Each of these transmitters included a suite of three 5071A cesium atomic frequency standards, plus a dually redundant time and frequency equipment (TFE) system capable of creating an ensemble of each set of three cesiums and steering that timescale to UTC(USNO) via GPS Time. The eLoran upgrade plan included upgrading to TWSTT for steering at all transmitters. If the North American Loran-C (later upgraded to eLoran) system were included with WAAS, it would have added 90 higher performing cesium atomic frequency standards, in 30 geographically dispersed ensembles of 3, plus an LF broadcast transmitter at each ensemble location with capability to distribute its timescale directly. This would have been a powerful partnership; no longer available for partnership due to the FY2010 budget directed termination of Loran-C, there is potential for reuse of some of the excess Loran assets. This is discussed further under New Opportunities below.

Without the operational Loran system, study of Alternative 4 is still recommended as a future effort. In such study, data are needed on locations of other agencies' cesium atomic frequency standards, how many and what type are at each location, and how they are currently used. The purpose of the study would be to determine if there are other agencies that would partner with FAA in improving the 114-ensemble WNT timescale by adding their cesium standards to the ensemble or by assisting with managing the timescale. Potential sites include communications facilities, satellite operation and control centers, time service stations, and laboratories. The study should not limit the inventory of potential contributors to government agency sites but should also include commercial sites and

universities. This study should also look into the availability of co-located and nearby transmitters at each identified site that might assist in distribution of the larger timescale.

New Opportunities:

Reuse of Loran-C Cesium Standards: Agencies are lining up to request the excess 5071A cesium frequency standards no longer needed in the Loran system. These are valuable assets, not only in terms of their actual cost but in terms of the industrial base's ability to produce them; they should be reused. As discussed in Chapter 3 Technical Issues, a 5071A standard is nearly an order of magnitude more stable than a Cesium III standard. FAA should request some or all of the excess Loran cesium standards. There are several optional ways to employ these standards, which should be studied:

- Replace Cesium III standards with 5071A standards WRS, with sub-options:
    - Replace all Cesium III standards at selected WRS
    - Purchase additional 5071A standards and replace all Cesium III standards at all WRS
    - Replace C-string Cesium III standards at all WRS
    - Replace A- and B-string Cesium III standards at all or selected WRS
    - Reuse newly excess Cesium III standards at selected FAA sites (see below)
- Install two (or more) additional 5071A standards at each GUS
- Install 5071A (or newly excess Cesium III) standards at selected FAA sites (not necessarily in the WAAS network)
    - Install three (or more) at a smaller number of large sites
    - Install one at a larger number of smaller sites

The first option, *use at WRS*, would certainly improve the stability of the timescales at WRS, and the improved stability of the underlying frequency standards would likely improve WAAS performance. Since there are not enough excess standards to replace all 114 Cesium IIIs, the reasonable options are to replace all at selected WRS sites, replace only the "nominal spare" C-string Cesium III at all sites, or replace the A- and B-string (nominal operational strings) at all or most WRS sites. Replacing the C-string standards would have the effect of improving the stability of the timescales at all WRS, with limited impact on WAAS. This would mean that whenever the C-string was needed (due to failure of an A- or B-string Cesium III standard or loss of a string at the WMS), there would be a small impact on WAAS. Replacing A- and B-string Cesium III standards would have the same impact on WAAS. Overall, however, *use at WRS appears to have limited utility*.

The second option, *use at GUS*, would improve the stability of the WAAS signal and provide the opportunity for improved distribution of WNT via WAAS. This would provide an opportunity to create a timescale based on an ensemble of three 5071A cesium standards at each GUS, and with the addition of TWSTT at each GUS, enable this ensemble to be steered directly to UTC(USNO).This would actually provide better stability than implementation of Alternative 2.b.i (Recommendation 3). This would lead to options of either using the 114-ensemble WNT timescale as backup or perhaps not implementing it. *If*

at least eight excess 5071A cesium standards are obtained, however, this appears to be very good use of them.

The third option, *use at other FAA sites*, requires more study. Examples of the type of sites that might be candidate for three 5071A standards would be larger FAA sites with access to broadcast transmitters to serve as distribution centers for accurate time and precise frequency, for example, to candidate APNT sites. The type of sites that would be candidate for a single 5071A (or for reuse of a newly excess single Cesium III) standard would be APNT sites that need robust accurate time. *This option appears to have utility but requires more study.*

Reuse of Loran-C TFE: This is another interesting option. As discussed above the Loran-C TFE system includes all the equipment needed to create a timescale of three cesium standards, to steer those standards to an external standard, to implement a physical replica with a microstepper, and to distribute the results with a distribution amplifer. The current external standard used is GPS Time, which is accessed via a GPS timing receiver within each TFE system.

Each Loran-C transmitter includes a dually redundant TFE system, which means that some 60 TFE equipment sets should be available. This would be more than enough to equip all 38 WRS with a TFE system, effectively implementing Alternative 1.c.iii Custom Timescale System (perhaps Alternative 1.a.iii Turnkey Timescale System) without having to acquire much (perhaps any) new equipment. At the very least, even if excess Loran-C 5071A cesium standards cannot be obtained, the excess TFE systems should be obtained. The entire TFE installation at a Loran transmitter was installed in a standard 6-foot tall by 19-inch wide equipment rack. The 5071A standards were planned for immediate removal from Loran transmitters as soon as the signals were terminated. Thus, the TFE equipment racks currently remaining at the transmitters should include all remaining TFE equipments and possibly backup power supplies—*these full sets of TFE (less cesium standards) should be obtained by FAA.*

The TFE was originally built in the early 2000s by Timing Solutions Corporation, Boulder, CO, under contract to USCG and funded under interagency agreement by the FAA's Loran-C Modernization funds. Several years ago, Timing Solutions was acquired by Symmetricom, Inc. (current manufacturers of 5071A, Cesium III, and other time and frequency products). Symmetricom currently advertizes systems based on the Loran-C TFE as configurable timescale systems. This means that there is an opportunity to seek assistance from Symmetricom in configuring the excess Loran-C TFE equipment sets to be used at WRS.

Additionally, if excess Loran-C 5071A standards are obtained and reused at GUS or in multiple standard installations at other FAA facilities, these TFE equipment sets could also be used to create timescales at those locations.

The entire inventory of excess TFE equipment sets should be obtained by FAA.

Reuse of Loran-C Transmitters: Consistent with Alternative 3 Regional Distribution, and approaching Alternative 4 Partnering with Other Agencies, FAA could request some or all excess Loran-C transmitters

in situ. The most remote transmitters in Alaska, those at Attu (end of Aleutian Island chain) and at Port Clarence (north of Nome on the Bering Sea coast of Alaska), have been demolished. The vacuum tube transmitters at two other very remote transmitters in Alaska (Tok, about 4-6 hours east of Fairbanks on the ALCAN Highway, and Shoal Cove, on an uninhabited island about 2-3 hours by boat from Ketchikan) have not yet been replaced. Reuse of any of these four sites would be costly. However, the remaining 21 US sites (18 formerly operational plus one engineering transmitter in CONUS and two in Alaska) would be relatively easily reactivated.

The benefit of reusing Loran transmitters is that, with reinstallation of the 5071A frequency standards, they are ready to broadcast eLoran signals synchronized to UTC(USNO). Network connectivity exists, and there is a cadre of contractor and former USCG personnel that could be accessed to assist with reactivation and future operations. USCG operated the transmitters with crews of active duty personnel, crew size in CONUS generally four persons, and in Alaska larger. However, at the 21 sites mentioned, the infrastructure improvements needed for eLoran operations have been made, and a side benefit of those upgrades is that no on-site personnel are required for operations. Rather, a small traveling maintenance staff, and perhaps some local (part-time) caretakers are all that would be needed.

An additional benefit of reusing the Loran infrastructure is that a number of other countries appear to be using eLoran as their national backup system for GNSS. Several, particularly UK and France, are pursuing setting standards for eLoran as a backup to GNSS in a concept called Electronic Navigation (e-Navigation). Although focused initially on maritime operations, the operating agencies in these countries have obtained support from time and frequency users to expand eLoran as their national time and frequency (or full PNT) backup system. International partners would thus be available to assist FAA in reuse of the Loran infrastructure in the US.

Should reuse of the Loran infrastructure be limited to augmenting the WNT timescale and assisting in distribution to outlying FAA sites (via reuse of Loran-C's 100 KHz LF broadcast capability and frequency), not all of the 21 reusable sites would be required. FAA should study which transmitters would meet the following criteria: easily integrated into the WAAS network and collectively covering as much of the NAS as possible. *FAA should study reuse of the existing Loran infrastructure to implement Alternative 3.d. Regional Distribution and as a potential first step in Alternative 4 Partnering with Other Agencies.*

Appendix A:

Membership of WAAS Network Time Independent Assessment Team (WNT IAT)

Institute for Defense Analyses (IDA) – Research Staff – Science & Technology Division

James Doherty – WNT IAT Chair & Task Leader
Dr. William Klepczynski
Donald Jewell
Dr. Howard Last
Kirk Lewis
Dr. Benjamin Peterson
Phillip Ward

Agency Representatives and Subject Matter Experts

Ronald Beard – Naval Research Laboratory (NRL)
Keith Dale – Air Force Space Command (AFSPC)
Dr. Todd Kawakami – GPS Wing & National Geospatial-Intelligence Agency (NGA)
Dr. Judah Levine – National Institute of Science & Technology (NIST)
Dennis Manning – National Geospatial-Intelligence Agency (NGA)
Tom McHugh – Federal Aviation Administration Technical Center (FAA TC)
Mitchell Narins – FAA Headquarters (Navigation Services)
Dr. Robert Nelson – National Aeronautics and Space Administration (NASA)
Vannaroth Nuth – GPS Wing & Aerospace Corporation
Dr. Edward Powers – US Naval Observatory (USNO)
Pradipta Shome – FAA Headquarters – Sponsor's Representative

Appendix B:

Data Sources for WNT IAT Deliberations

Federal Aviation Administration (FAA)

- Satellite Navigation (SATNAV) Program – current and future
  - Emphasis on WAAS technical development & operations
- Next Generation National Airspace System (NAS) programs
  - Emphasis on Communications, Navigation, & Surveillance programs
- Alternate Positioning, Navigation, and Timing (APNT) program
- Automated Dependent Surveillance, Broadcast (ADS-B) program
- Multi-lateration programs
- Current & future communications programs
- Tour of FAA Technical Center (Atlantic City NJ)
  - Discussions with engineers
- Tour of FAA Air Route Traffic Control Center, Longmont CO (Denver & vicinity)
  - Discussions with engineers

Other Agencies

- US Air Force – GPS operations
  - Emphasis on development & management of GPS Time
  - Relationship with Coordinated Universal Time as maintained by USNO (UTC(USNO))
- US Naval Observatory (USNO) – time & frequency distribution & use
  - Management of USNO master clock & UTC(USNO), and future plans
  - New developments in clock technologies
  - Tour of master clock & laboratories, and discussions with engineers
- National Institute of Science & Technology (NIST) – time & frequency distribution & use
  - Management of NIST master clock & UTC(NIST), and future plans
  - New developments in clock technologies
  - Tour of master clock & laboratories, and discussions with engineers
- Naval Research Laboratory (NRL) – time & frequency technologies & developments
- National Aeronautics & Space Administration (NASA) – time & frequency use
  - Emphasis on needs of space systems
- NASA Jet Propulsion Laboratory (JPL) – time & frequency use
  - NASA's Global Differential GPS Service (GDGPS)
  - International GNSS Service (IGS)
- National Geospatial-Intelligence Agency (NGA) – time & frequency use
  - NGA monitor site support for GPS operations & data use within NGA systems
- Volpe National Transportation Systems Center (VNTSC) – backup timing studies

Industry, International, and Other Sources

- UK National Physical Laboratory (NPL) – UK master clock & UTC(NPL)
  - EGNOS Time
  - Plans for Galileo Time
- Stanford University – Center for PNT & new PNT technology developments
  - Potential developments in satellite navigation & APNT
  - WAAS design, current operations, emphasis on WAAS Time calculation & use
- Raytheon – technical details of WAAS development & operation
- Harris – FAA Telecommunications Interconnect (FTI) communications services contract
  - Network topologies & operations
- ITT – ADS-B developments & system architecture considerations
  - Also, multi-lateration considerations
  - GPS timing receiver operations
- Symmetricom – time & frequency management & distribution
  - Ensemble techniques, technologies, & systems
- Sensis – multi-lateration techniques
- Trimble – GPS timing receiver operations, modeling & stabilization of local clocks
- CXR Larus –GPS timing receiver operations, switching among various reference clocks
- Team Member Expert discussions
  - Enhanced Loran (eLoran) – development, management, & distribution of time
  - WAAS Time – as currently developed & used, plus considerations for future upgrade
  - Ensemble & time distribution methods & techniques
  - Data collection & maintenance standards for precise time & frequency systems

Appendix C:

Data Collection Meetings of WNT IAT

26-27 August 2008, IDA Alexandria VA & USNO Washington DC; initial meeting, focus on basics:

Meet & greet, set goals, etc.
"WAAS 101"
Time & frequency fundamentals
Primary time & frequency reference systems & distribution methods
Agencies' needs for time & frequency
Briefing & tour of USNO

15-17 October 2008, NIST Boulder CO & FAA ARTCC Longmont CO; focus on systems/ops:

GPS & WAAS design & operations
Development & management of GPS Time, WAAS Time, & other systems' time
Fundamentals of clock management – ensemble, steering, distribution, etc. techniques
Briefing & tour of ARTCC with installed WAAS Reference Station (WRS)

9-10 December 2008, Stanford University, Palo Alto CA; focus on potential use of WNT:

Potential benefits of WNT within WAAS, for other FAA systems, or for other users
Related emerging technologies
Future aviation safety & air traffic management systems & technologies
Commercial systems & industry perspectives
First detailed examination of FTI – vis-à-vis use or distribution of WNT, or both

24 April 2009, FAA HQ SATNAV Program Office, Washington DC; interim report briefing:

Discussions with SATNAV PM, WAAS technical staff, Communications PM, & DOT PNT director
Eliminated one recommendation from further consideration

6-7 October 2009, FAA Technical Center, Atlantic City NJ; focus on WNT development & potential use:

FTI & other communications systems needs & opportunities
ADS-B & multi-lateration backup surveillance needs
Next Generation technologies needs & opportunities
Tour of Technical Center laboratories & project spaces, and discussions with engineers

15-16 December 2009, IDA, Alexandria VA; focus on future systems, distribution of WNT:

FAA future navigation plans & backup systems
Time & frequency distribution via WAAS & other methods
Second round detailed discussion on ADS-B, multi-laterations, et al
Second round detailed discussion on FTI, emphasis time transfer opportunities & limitations
Potential near-term need for WNT distribution in Alaska

15 January 2010, FAA HQ Navigation Director's Office, Washington DC; briefing for new Director:

Review of alternatives still in active consideration, benefits & impacts
Discussion of remaining data collection needs

23-24 February 2010, National Physical Laboratory (NPL), Teddington UK; focus UK master clock:

IAT Chair invited to UK meeting on impacts of GPS interference on timing infrastructure
Discussions with time & frequency engineers about EGNOS & Galileo Time development
Toured NPL's master clock for UK & time service laboratories

16-17 March 2010, NIST Boulder Co and FAA ARTCC Longmont Co; focus on clock management:

Reviewed data from "trial ensemble" by NIST of WRS frequency standards at Longmont
Outlined additional data needed & maintenance changes required if WRS also used as a "clock"
Reviewed ensemble systems & how to implement in WRS
Collected data on current FAA systems located at ARTCC which use time or frequency

23 March 2010, FAA Technical Center, Atlantic City NJ; focus on WNT distribution via WAAS:

Reviewed in detail how WAAS Time currently calculated & used in WAAS
Reviewed impacts of implementing Message Type 12 & using WNT in lieu of WAAS Time

29 March 2010, Stanford University, Palo Alto CA; focus on WNT distribution via WAAS:

Updated discussions directional receiving antenna technology
Detailed discussions benefits & impacts of using WNT in lieu of WAAS Time

6 April 2010, Sensis Corporation, Syracuse NY; focus on timing needs:

For various multi-lateration methods—time synchronization requirements & means of providing

10-11 August 2010, Stanford University, Palo Alto CA:

IAT Chair participated in FAA's APNT workshop –reviewed timing needs & distribution options

Appendix D:

Interim Report Briefings:

FAA Headquarters, 24 April 2009

FAA Headquarters, 15 January 2010

FAA WAAS Network Time
Independent Assessment Team

Phase I Report to
FAA SATNAV Program Manager
FAA Headquarters
24 April 2009
v3

Charter

- **Task – Form panel of experts to independently develop & assess alternative means of coordinating cesium frequency standards in WAAS reference station network**
  - *38 Reference Stations throughout National Airspace System (NAS), extended into Canada & Mexico*
  - *3 GPS receivers at each reference station, each driven by its own cesium frequency standard – 114 total cesium*
  - *Alternatives cannot impact WAAS operations*

2

IAT Members

- James Doherty, IDA – Chair
- Dr. William Klepczynski, IDA – Co-Chair
- Donald Jewell, IDA – Executive Director
- Dr. Howard Last, IDA
- L. Kirk Lewis, IDA
- Dr. Benjamin Peterson, IDA
- Phillip Ward, IDA
- Ronald Beard, NRL
- Keith Dale, AFSPC (SI International)
- Todd Kawakami, GPS Wing (NGA)
- Dr. Judah Levine, NIST
- Dennis Manning, NGA
- Tom McHugh, FAA Tech Center
- Mitchell Narins, FAA
- Dr. Robert Nelson, NASA
- Van Nuth, GPS Wing (Aerospace)
- Dr. Edward Powers, USNO
- Pradipta Shome, FAA

3

Observations

- **Coordinating WAAS frequency standards**
  - *Is key enabler of seamless global aviation operations among regional SBAS (WAAS, EGNOS, MSAS, GAGAN)*
  - *Provides foundation for time & frequency distribution, independent of GPS, to current & future FAA systems; assures safe & efficient operations in National Airspace System*
  - *Benefits non-aviation users needing accurate time & precise frequency*
- **For very little cost**

4

Charter Tasking

- **What can be done to coordinate the clocks?**
  - *First IAT task: 3 candidate architectures*
  - *Second IAT task: recommended architecture*
- **Conditions for analyses**
  - *WAAS Network Time (WNT)*
    - **Generated for internal use**
    - **Steered close to GPS Time**
  - *If GPS reception interrupted*
    - **WNT would slowly drift from GPS Time**
    - **But has 114 clocks in 38 geographic locations**

5

Key Questions

- **Should the frequency standards in WAAS be coordinated & how?**
  - *Ensemble in chains, at each site, entirely, etc?*
- **To what external reference should the WAAS clock ensemble(s) be steered & how?**
  - *References: UTC, UTC(USNO), GPS Time, etc?*
  - *Method: TWSTT, timing rcvr, WAAS ref rcvr, etc?*
- **Should WNT be distributed & how?**
  - *To limited customers or all?*
  - *Used locally by FAA, e.g., as local time & frequency reference for ARTCC, comms, etc?*

6

IAT Process & Rules for Data Collection

- Consensus recommendations
  - *Goal, but divergent views to be included as needed*
- No IAT position before its time
  - *Ask questions, make statements – to collect data*
- Non-attribution – *most critical*
  - *List of entities providing data or hosting visits*
  - *But not who said what*
- Respect proprietary & classified information
  - *Advise in advance, recuse self if necessary*
- Member feedback each meeting
  - *Key questions, responses, rationale*

7

Overarching Considerations

- "Job 1" is aviation safety-of-life navigation
  - *WAAS operations for aviation accuracy, integrity, continuity, & availability cannot be compromised*
- 114 atomic frequency standards ("clocks") comprise a significant national asset
  - *If properly coordinated, they can provide new or more robust national capabilities*
- Coordination must be accomplished economically
  - *Minimal additional equipment or procedures*
  - *Support internal FAA needs and/or partner with other agencies*

8

Data Collection Meetings

- 26-27 August 2008, IDA, Alexandria VA
  - *Focus: "WAAS 101," time & frequency basics, primary time & frequency references & distribution methods*
  - *Included 27 August 2008 visit, briefing, & tour at USNO*
- 15-16 October 2008, NIST, Boulder CO
  - *Focus: GPS & WAAS ops, GPS Time, WAAS Time, clock management (ensemble, steering, & distribution)*
  - *Included 17 October 2008 visit & tour at Denver ARTCC*
- 9-10 December 2008, Stanford Univ, Palo Alto CA
  - *Focus: ops potential of WAAS Network Time, future air traffic mgmt, emerging technology, industry perspectives*
  - *Detailed examination of FAA's FTI network services contract & potential benefit from WAAS Network Time*

9

Definitions

- WAAS Network Time
  - *Sometimes abbreviated WAAS Time*
  - *Essentially WAAS's version of GPS Time*
  - *As currently calculated in WAAS*
  - *Internally required for proper WAAS function*
- WAAS Ensemble Time
  - *New term proposed herein for result of coordination of the cesium standards within WAAS*

10

Data Reviewed

- "WAAS 101" & WAAS operations
  - *WAAS Network Time (current & potential in future)*
  - *Current L1 & future L5 SBAS constraints & opportunities*
- National Airspace System (NAS) overview
  - *Current operations & future plans*
  - *WAAS contributions – current L1-only & future L1-L5*
- Coordinated Universal Time (UTC) … et al
  - *Definitions, sources, distribution methods, etc.*
  - *Reviewed perspectives from USNO, NIST, NGA, NASA, JPL, NRL, others vis-à-vis time & frequency*
  - *Reviewed time & frequency management in GPS, WAAS, IGS, GDGPS, eLoran, other systems*

11

Data Reviewed (cont.)

- Precise time & frequency management & distribution
  - *GPS Time & GPS Operations Center (GPSOC)*
  - *WAAS Time (as currently calculated) & what could be*
  - *Ensemble methods, opportunities & constraints*
  - *Distribution methods – local, campus, & wide-area*
- International issues
  - *Dominantly vis-à-vis GPS augmentations (WAAS, EGNOS, MSAS, GAGAN, et al)*
- Internet & telecommunications
  - *NTP, PTP (IEEE1588 protocol), internet timing*
  - *Telecommunications systems use of time & frequency*

12

Data Reviewed (cont.)

- **FAA needs for accurate time & precise frequency**
  - *Within ARTCC (campus-wide)*
  - *Distributed (regionally & wide-area)*
- **US needs for accurate time & precise frequency**
  - *Volpe timing & frequency needs (infrastructure) study for DHS*
  - *Modern (civil, commercial, consumer) systems' use of time & frequency*
- **Impacts of recent technology developments on user equipment**
  - *Cold atom technologies for inertial & clock systems*
  - *Chip scale atomic clocks*

13

WAAS Clocks

- **Symmetricom Cesium III**
  - *5 & 10 MHz sinewave &10 MHz digital outputs*
  - *1PPS output & synchronization input*
  - *RS-232 interface for remote control*
  - *Stability (per Symmetricom datasheet)*

Average Time (seconds)	Allan Deviation
1	<1.2 e-11
10	<8.6 e-12
100	<2.7 e-12
1000	<0.5 e-13
10000	<2.7 e-13
100000	<8.6 e-14
floor	<5.0 e-14

  - *In short, about 1 part in 10^{-13} per day, with estimated time uncertainty ~ 10 ns/day*

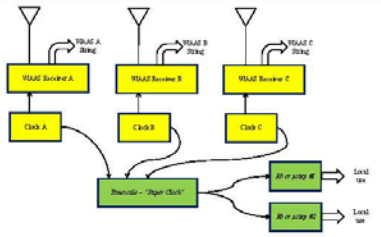
14

Ensemble of Clocks – Create Time Scale

- **Improves stability of time scale based on ensemble of N clocks by factor of √N**
  - *Time uncertainty of single clock ~ 10 ns/day*
  - *Improves to ~ 6 ns/day based on ensemble of 3 clocks*
- **Provides *redundancy* for clock failures**
  - *Cannot ensemble for WAAS (each WAAS reference receiver requires its own independent clock)*
  - *But is beneficial to ensemble for other local use – e.g., provide 5 or 10 MHz and/or 1PPS to communications equipment or for use in time-stamped applications*
  - *Requires physical implementation of timescale*
    - Additional equipment, such as microstepper (µstep)
    - Or existing, such as rubidium frequency standard (Rb)

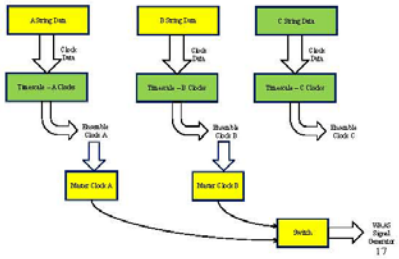
15

Candidate Ensemble for WAAS Reference Station



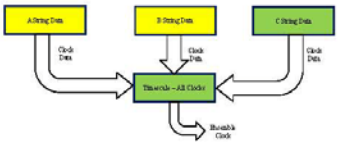
16

Candidate Ensemble at WAAS Master Station



17

Alternate Candidate Ensemble – Master



18

External Time Reference Candidates

- Astronomical time scales
  - *Solar Time – Earth rotation*
  - *Ephemeris Time – Earth orbit*
  - *Universal Time, current standard*
    - *UT1 – Corrected for Polar Motion*
    - UT2 – Corrected for Nutation
- Atomic time scales
  - *Atomic Time (AT) – continuous*
  - *International Atomic Time (TAI) – SI Second*
- *Coordinated Universal Time (UTC)*
  - *Stepped atomic time scale – compromise of atomic & solar time scales*
  - *Coordination among (atomic) timing centers*
    - *UTC(USNO)*, UTC(NIST), UTC(ABC) … UTC(XYZ)
- GPS Time, WAAS Time, et al … or other
  - *System implementations of time, generally based on UTC or UTC(XYZ)*

Source: Ron Beard, NRL, 16 Aug 2006

19

GPS Time

- De facto standard for time & frequency
  - *Globally distributed – ubiquitous coverage & availability*
  - *Conditions local oscillator to appear better than Stratum 1 level performance (i.e., virtually equivalent to having own cesium atomic frequency standard)*
- GPS Time is continuous, based on UTC(USNO)
  - *It is system time, not a recognized reference time scale*
  - *It is calculated from all system clocks, dominantly at monitor stations, but also on satellites*
  - *GPS Time is steered to UTC(USNO), and satellite clocks are steered to GPS Time*
  - *Leap seconds (time steps) are not inserted in GPS Time but must be accounted for in tracing back to UTC*

20

WAAS Network Time – current

- Also called WAAS Time, derived from GPS Time
  - *As measured in WAAS reference station receivers*
  - *Each of which uses independent, stable cesium atomic reference frequency standard*
  - *Long term (8-hour) offset from ensemble GPS estimates steered toward zero*
  - *Not steered to external reference, such as UTC(USNO)*
- An internally needed time calculation
  - *To keep WAAS corrections within message bandwidth*
  - *For seamless switchover between master stations*
- Also a convenient external system specification
  - *Less than 50 ns difference from GPS Time*
  - *Less than 100 ns difference to other SBAS*

21

Distribution

- WAAS Network Time is not distributed
  - *WAAS message type 12 allows distribution of an offset between WAAS Network Time & GPS Time – not currently used* **but should be**
  - *Must track GPS for GPS Time offset from UTC(USNO)*
- WAAS Ensemble Time could be distributed
  - *At WRS locations (mostly ARTCCs) – campus wide*
  - *Regionally around each WRS & wider through connection to regional broadcast site*
  - *Wide-area via some broadcast mechanism, such as via WAAS GEO, e.g., with new L5 SBAS message*
  - *NTP or PTP server*

22

Architecture Component Options

- Ensemble alternatives
  - *At each reference station (38 ensembles of 3)*
  - *Ensemble in strings – A, B, C (3 ensembles of 38)*
  - *Ensemble all individually (ensemble of 114)*
  - *Ensemble the ensembles*
  - *Not ensembled*
- Steering alternatives
  - *To (reference)*
    - GPS Time
    - WAAS Time
    - UTC(USNO)
    - UTC
    - Not steered
  - *By (method)*
    - GPS all-in-view timing rcvr
    - Common view WAAS GEO
    - Common view any GEO
    - TWSTT
    - Carrier phase GPS

23

Architecture Component Options (cont.)

- Distribution alternatives
  - *To*
    - WAAS refsta only
    - Local campus
    - Regionally
    - Wide area
    - Contribute to UTC
    - Not distributed
  - *By*
    - Hardwired within campus
    - Common view, TWSTT, etc.
    - Regional dedicated network
    - Network Time Protocol (NTP)
    - WAAS message type 12
    - New L5 message type

24

Technical Issues

- Need additional equipment to ensemble
  - *Clock comparison system – commercially available*
  - *Means of making the clock-to-clock comparisons*
    - Locally via cabling
    - Remotely via common view, two-way time transfer, etc.
    - WAAS External Interface (WEI) may be useful data port
  - *Physical replica of ensemble "paper" clock*
- Do not steer individual clocks in the ensemble
  - *Steer the paper clock & physical replica only*
  - *Preserves independence of WAAS receivers*
  - *Provides ability to report clocks into UTC*

25

Leap Seconds

- Leap seconds are time steps
  - *Included in UTC (& its contributors) to match continuous atomic time to solar time variations*
- Not included in GPS Time
  - *GPS Time is continuous, steered to UTC(USNO), but does not include leap seconds*
  - *To trace GPS Time back to UTC(USNO), user must keep track of leap seconds*
- Not included in WAAS Network Time
  - *Based on GPS Time*
- Not recommended for WAAS Ensemble Time

26

Alternative Architectures

1. Ensemble locally & distribute campus-wide
2. Ensemble all & distribute over wide area
3. Ensemble locally & distribute regionally
4. Ensemble all plus other agencies' systems & distribute over wide area

27

Criteria for Assessment

- Benefit to users
  - *Aviation users*
  - *FAA systems*
  - *Others*
- Ease of implementation
- Reuse of current capabilities
- Cost
- Political acceptance

28

Alternative 1

- Ensemble 3 cesium standards at each WRS, create physical replica & steer to UTC(USNO) daily (less leap seconds), distribute campus-wide
  - *Requires comparison system & local microstepper or rubidium for replica, plus distribution (copper & fiber)*
    - Single rubidium exists as part of legacy communications systems at ARTCC
  - *Requires common view or TWSTT equipment; (interim) alternative, all-in-view GPS timing receiver*
    - Alternative not fully independent of GPS, but good enough
    - Several GPS timing receivers exist at ARTCC
  - *Optionally connect as tertiary "Stratum 1" input in local FTI DNX-11 (requires conversion to T1 format)*
- Local only, low cost, no WAAS mods

29

Alternative 2

- Ensemble 114 cesium standards at central location, create physical replica & steer to UTC(USNO) daily (less leap seconds), distribute via WAAS
  - *Consider using WAAS External Interface (WEI) as means of exporting needed clock comparison data*
  - *Test at limited number WRS – e.g. Longmont ARTCC & NIST Boulder – consider partnership with NIST & USNO*
  - *Long term create ensemble in multiple locations (same data), such as GUS's, & implement replica in GUS cesium which generates WAAS signal*
  - *Implement WAAS message type 12 in L1 but for WAAS Ensemble Time offset from GPS Time; develop more robust message for L5 to provide offset to UTC(USNO)*
- Wide area, clock comparison costs, WAAS mods

30

Alternative 3

- Recommendation 1 plus regional distribution
  - *Examine regional FAA facilities near each WRS*
    - Determine criticality of need for Stratum 1 frequency and/or precise time, independent of GPS, at each
    - Consider extending campus-wide fiber network to such facilities and/or installing a single cesium at each
  - *Examine broadcast site opportunities near each WRS*
    - Include NDGPS, other government agency sites, TV transmitters, communications, etc.
    - Consider extending campus-wide fiber (in partnership with other agency or commercial provider) to sites
- Regional distribution, more costly w/cost-share opportunity, no WAAS mods

31

Alternative 4

- Partner with NIST and other agencies to develop robust (civil agency) distributed national clock
  - *Similar to Recommendation 2, partner with USNO & NIST, but extend network to other agencies, which may have sites with 3 or more cesium standards*
    - Includes NIST & USNO remote sites, NGA monitor stations, NOAA, NASA, national labs, and in particular USCG
  - *USCG operates eLoran network*
    - 18 CONUS, 6 Alaska, and 5 Canada (under bilateral agreement) Loran transmitters
    - Each transmitter site includes 3 cesium standards, ensemble comparison system, & daily steering to UTC(USNO) via TWSTT (initially via all-in-view GPS)
- Interagency partnership, ability to share costs of TWSTT, no WAAS mods needed

32

Assessment

- Alternative 1 is simple to implement
  - *Benefits FAA internally*
  - *No change to WAAS*
  - *Low cost*
- Alternative 2 provides global aviation benefits
  - *More difficult to implement*
  - *Minor change to WAAS*
  - *Higher cost*
- Alternative 3 prepares FAA for future needs
  - *Provides FAA-wide time & frequency independent of GPS*
  - *Technically more difficult*
  - *Higher costs (comms, frequency standards)*

33

Assessment (cont.)

- Alternative 4 provides greatest benefit nationally
  - *Most difficult to implement, technically & politically*
  - *Not all within FAA control*
  - *Option 3 sets example, others might join*
- Overall
  - *Alternative 1 ready for implementation*
  - *Test concepts Alternative 2 & develop further*
  - *Continue to study Alternative 3*
  - *Hold off, for now, further consideration of Alternative 4*

34

Way Ahead

- Implement Alternative 1
  - *Visit other WRS (at ARTCC & other FAA facilities)*
  - *Develop test with FTI to quantify benefit of providing tertiary input*
- Facilitate concept development of Alternative 2
  - *Test ensemble of cesium standards from multiple sites*
  - *Develop plan for full implementation*
  - *Coordinate minor WAAS modifications for distribution via GEO, upgrade of message type 12, etc.*
- Continue study of Option 3
  - *Examine technologies, performance potential, limitations, rough order of magnitude costs, etc.*
  - *Extend tests with FTI & also point-point fiber circuits*

35

BACKUP

36

Acronyms

AFSPC	Air Force Space Command
ARTCC	Air Route Traffic Control Center
AT	Atomic Time
DHS	Dept of Homeland Security
DNX-11	Specific comms device for FTI
EGNOS	European Geostationary Navigation Overlay Service
eLoran	Enhanced LORAN
FAA	Federal Aviation Administration
FTI	FAA Telecommunications Infrastructure
GAGAN	GNSS Aided GEO Augmented Navigation
GDGPS	Global Differential GPS
GEO	Geostationary Earth Orbit
GNSS	Global Navigation Satellite Service
GPS	Global Positioning System
GPSOC	GPS Operations Center
IAT	Independent Assessment Team
IDA	Institute for Defense Analyses
IEEE	Institute of Electrical and Electronics Engineers, Inc.
IGS	International GNSS Service
JPL	Jet Propulsion Laboratory
LORAN	Long Range Navigation
MSAS	Multi-functional Satellite Augmentation System
NAS	National Airspace System
NASA	National Aeronautics and Space Administration
NIST	National Institute of Standards and Technology
NGA	National Geospatial-Intelligence Agency
NRL	Naval Research Laboratory
NTP	Network Time Protocol
PTP	Precision Time Protocol
SBAS	Space Based Augmentation System

37

Acronyms (cont.)

SI Second	International time standard based on Cesium atom
TAI	International Atomic Time
TWSTT	Two-Way Satellite Time Transfer
USCG	United States Coast Guard
USNO	United States Naval Observatory
UT	Universal Time
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System
WET	WAAS Ensemble Time
WNT	WAAS Network Time
WRE	WAAS Receiver Equipment
WRS	WAAS Reference Station
1PPS	1 Pulse Per Second

38

FAA WAAS Network Time
Independent Assessment Team

Briefing for
FAA Navigation Director
FAA Headquarters
15 January 2010
v1

Charter

- **Task – Form panel of experts to independently develop & assess alternative means of coordinating cesium frequency standards in WAAS reference station network**
  - *38 Reference Stations throughout National Airspace System (NAS), extended into Canada & Mexico*
  - *3 GPS receivers at each reference station, each driven by its own cesium frequency standard – 114 total cesium*
  - *Alternatives cannot impact WAAS operations*

2

IAT Members

Institute for Defense Analyses (IDA)
- James Doherty, IDA – Chair
- Dr. William Klepczynski, IDA – Co-Chair
- Donald Jewell, IDA – Executive Director
- Dr. Howard Last, IDA
- L. Kirk Lewis, IDA
- Dr. Benjamin Peterson, IDA
- Phillip Ward, IDA

Position, Navigation, &Time (& Frequency) (PNT) Stakeholders
- Ronald Beard, Naval Research Laboratory (NRL)
- Keith Dale, Air Force Space Command (AFSPC)
- Todd Kawakami, GPS Wing & National Geospatial-Intelligence Agency (NGA)
- Dr. Judah Levine, National Institute of Science & Technology (NIST)
- Dennis Manning, NGA
- Tom McHugh, Federal Aviation Administration (FAA) Technical Center
- Mitchell Narins, FAA Headquarters
- Dr. Robert Nelson, National Air and Space Administration (NASA)
- Van Nuth, GPS Wing & Aerospace Corporation
- Dr. Edward Powers, U.S. Naval Observatory (USNO_
- Pradipta Shome, FAA

3

IAT Process & Rules for Data Collection

- **Consensus recommendations**
  - *Goal, but divergent views to be included as needed*
- **No IAT position before its time**
  - *Ask questions, make statements – to collect data*
- **Non-attribution – *most critical***
  - *List of entities providing data or hosting visits*
  - *But not who said what*
- **Respect proprietary & classified information**
  - *Advise in advance, recuse self if necessary*
- **Member feedback each meeting**
  - *Key questions, responses, rationale*

4

Observations

- **Coordinating WAAS frequency standards**
  - *Is key enabler of seamless global aviation operations among regional SBAS (WAAS, EGNOS, MSAS, GAGAN)*
  - *Provides foundation for time & frequency distribution, independent of GPS, to current & future FAA systems*
  - *Helps assure safe & efficient operations in National Airspace System*
  - *Benefits non-aviation users needing accurate time & precise frequency*
- **For relatively little cost**

5

Initial Key Questions

- **Should the frequency standards in WAAS be coordinated & how?**
  - *Ensemble in chains, at each site, entirely, etc?*
- **To what external reference should the WAAS clock ensemble(s) be steered & how?**
  - *References: UTC, UTC(USNO), GPS Time, etc?*
  - *Method: TWSTT, timing rcvr, WAAS ref rcvr, etc?*
- **Should WNT be distributed & how?**
  - *To limited customers or all?*
  - *Used locally by FAA, e.g., as local time & frequency reference for ARTCC, comms, etc?*

6

Overarching Considerations

- WAAS "Job 1" is aviation safety-of-life navigation
  - *WAAS operations for aviation accuracy, integrity, continuity, & availability cannot be compromised*
  - *Avoid (minimize) changes to WAAS*
- 114 cesium frequency standards ("clocks") comprise a significant FAA & national asset
  - *If properly coordinated, they can provide new or more robust capabilities for FAA & for other users*
- Coordination must be accomplished economically
  - *Minimal additional equipment or procedures*
  - *Support internal FAA needs and/or partner with other agencies*

7

Data Collection Meetings

- 26-27 August 2008, IDA, Alexandria VA
  - *Focus: "WAAS 101," time & frequency basics, primary time & frequency references & distribution methods*
  - *Included 27 August 2008 visit, briefing, & tour at USNO*
- 15-16 October 2008, NIST, Boulder CO
  - *Focus: GPS & WAAS ops, GPS Time, WAAS Time, clock management (ensemble, steering, & distribution)*
  - *Included 17 October 2008 visit & tour at Denver ARTCC*
- 9-10 December 2008, Stanford Univ, Palo Alto CA
  - *Focus: ops potential of WAAS Network Time, future air traffic mgmt, emerging technology, industry perspectives*
  - *Detailed examination of FAA's FTI network services contract & potential benefit from WAAS Network Time*

8

Data Collection Meetings (cont.)

- 24 April 2009, FAA HQ SATNAV Program Office
  - *Interim report to SATNAV PM*
  - *Discussions with SATNAV PM & WAAS technical staff, FAA COMMS PM, & DOT PNT lead official*
- 6-7 October 2009, FAA Technical Center
  - *FTI (& other comms) needs & opportunities*
  - *ADS-B & multi-lateration backup surveillance needs*
  - *Next Generation technologies needs & opportunities*
- 15-16 December 2009, IDA
  - *FAA future navigation & backup plans*
  - *Time & frequency distribution via WAAS*
  - *ADS-B & multi-lat, FTI & other comms in more detail*
  - *Near term needs – Alaska (Loran-C termination)*

9

Data Collected From …

- FAA – SATNAV, NAS (future nav & backup), Comms, & ADS-B (& multi-lateration) programs; Tech Center; Longmont ARTCC
- Raytheon (WAAS), Harris Corp (FTI), ITT (ADS-B & multi-lat)
- Symmetricom (time & frequency, distribution)
- Trimble & CXR Larus (timing receivers & uses)
- NASA HQ & JPL – IGS & NASA Global DGPS
- USAF – GPS Time, GPS operations
- NRL, USNO, NIST, NGA – time & time use
- Volpe Transportation Systems Center (backup time study)
- Stanford University – future PNT, GEAS, & time distribution
- EGNOS – time & time use
- eLoran – time & time use
- Planned – UK National Physics Laboratory

10

WAAS Clocks

- Symmetricom Cesium III
  - *5 & 10 MHz sinewave &10 MHz digital outputs*
  - *1PPS output & synchronization input*
  - *RS-232 interface for remote control*
  - *Stability (per Symmetricom datasheet)*

Average Time (seconds)	Allan Deviation
1	<1.2 e-11
10	<8.5 e-12
100	<2.7 e-12
1000	<8.5 e-13
10000	<2.7 e-13
100000	<8.5 e-14
floor	<5.0 e-14

  - *In short, about 1 part in 10^{-13} per day, with estimated time uncertainty ~ 10 ns/day*

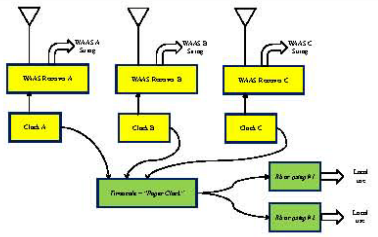
11

Ensemble of Clocks – Create Time Scale

- Improves stability of time scale based on ensemble of N clocks by factor of √N
  - *Time uncertainty of single clock ~ 10 ns/day*
  - *Improves to ~ 6 ns/day based on ensemble of 3 clocks*
- Provides *redundancy* for clock failures
  - *Cannot ensemble for WAAS (each WAAS reference receiver requires its own independent clock)*
  - *But is beneficial to ensemble for other local use – e.g., provide 5 or 10 MHz and/or 1PPS to communications equipment or for use in time-stamped applications*
  - *Requires physical implementation of timescale*
    - Additional equipment, such as microstepper (µstep)
    - Or existing, such as rubidium frequency standard (Rb)

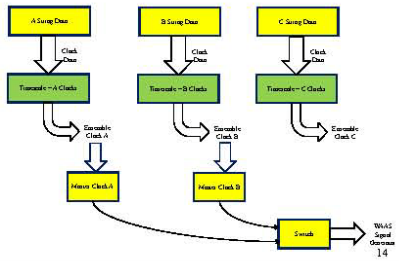
12

Candidate Ensemble for WAAS Reference Station



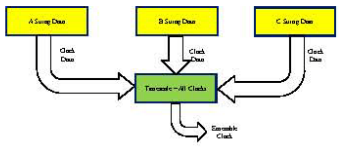
13

Candidate Ensemble at WAAS Master Station



14

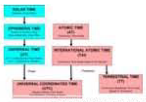
Alternate Candidate Ensemble – Master



15

External Time Reference Candidates

- **Astronomical time scales**
  - *Solar Time – Earth rotation*
  - *Ephemeris Time – Earth orbit*
  - *Universal Time, current standard*
    - *UT1 – Corrected for Polar Motion*
    - UT2 – Corrected for Nutation
- **Atomic time scales**
  - *Atomic Time (AT) – continuous*
  - *International Atomic Time (TAI) – SI Second*
- ***Coordinated Universal Time (UTC)***
  - *Stepped atomic time scale – compromise of atomic & solar time scales*
  - *Coordination among (atomic) timing centers*
    - *UTC(USNO)*, UTC(NIST), UTC(ABC)… UTC(XYZ)
- **GPS Time, WAAS Time, et al … or other**
  - *System implementations of time, generally based on UTC or UTC(XYZ)*



Source: Ron Beard, NRL, 16 Aug 2006

16

GPS Time

- **De facto standard for time & frequency**
  - **Globally distributed** – *ubiquitous coverage & availability*
  - *Conditions local oscillator to appear better than Stratum 1 level performance (i.e., virtually equivalent to having own cesium atomic frequency standard)*
- **GPS Time is continuous, based on UTC(USNO)**
  - *It is system time, not a recognized reference time scale*
  - *It is calculated from all system clocks, dominantly at monitor stations, but also on satellites*
  - *GPS Time is steered to UTC(USNO), and satellite clocks are steered to GPS Time*
  - *Leap seconds (time steps) are not inserted in GPS Time but must be accounted for in tracing back to UTC*

17

WAAS Network Time – current

- **Also called WAAS Time, derived from GPS Time**
  - *As measured in WAAS reference station receivers*
  - *Each of which uses independent, stable cesium atomic reference frequency standard*
  - *Long term (8-hour) offset from ensemble GPS estimates steered toward zero*
  - *Not steered to external reference, such as UTC(USNO)*
- **An internally needed time calculation**
  - *To keep WAAS corrections within message bandwidth*
  - *For seamless switchover between master stations*
- **Also a convenient external system specification**
  - *Less than 50 ns difference from GPS Time*
  - *Less than 100 ns difference to other SBAS*

18

Distribution

- WAAS Network Time is not distributed
  - *WAAS message type 12 allows distribution of an offset between WAAS Network Time & GPS Time – not currently used* but should be
  - *Must track GPS for GPS Time offset from UTC(USNO)*
- WAAS Ensemble Time could be distributed
  - *At WRS locations (mostly ARTCCs) – campus wide*
  - *Regionally around each WRS & wider through connection to regional broadcast site*
  - *Wide-area via some broadcast mechanism, such as via WAAS GEO, e.g., with new L5 SBAS message*
  - *NTP or PTP server*

19

Architecture Component Options

- Ensemble alternatives
  - *At each reference station (38 ensembles of 3)*
  - *Ensemble in strings – A, B, C (3 ensembles of 38)*
  - *Ensemble all individually (ensemble of 114)*
  - *Ensemble the ensembles*
  - *Not ensembled*
- Steering alternatives
  - *To (reference)*
    - GPS Time
    - WAAS Time
    - UTC(USNO)
    - UTC
    - Not steered
  - *By (method)*
    - GPS all-in-view timing rcvr
    - Common view WAAS GEO
    - Common view any GEO
    - TWSTT
    - Carrier phase GPS

20

Architecture Component Options (cont.)

- Distribution alternatives
  - *To*
    - WAAS refsta only
    - Local campus
    - Regionally
    - Wide area
    - Contribute to UTC
    - Not distributed
  - *By*
    - Hardwired within campus
    - Common view, TWSTT, etc.
    - Regional dedicated network
    - Network Time Protocol (NTP)
    - WAAS message type 12
    - New L5 message type

21

Technical Issues

- Need additional equipment to ensemble
  - *Clock comparison system – commercially available*
  - *Means of making the clock-to-clock comparisons*
    - Locally via cabling
    - Remotely via common view, two-way time transfer, etc.
    - WAAS External Interface (WEI) may be useful data port
  - *Physical replica of ensemble "paper" clock*
- Do not steer individual clocks in the ensemble
  - *Steer the paper clock & physical replica only*
  - *Preserves independence of WAAS receivers*
  - *Provides ability to report clocks into UTC*

22

Leap Seconds

- Leap seconds are time steps
  - *Included in UTC (& its contributors) to match continuous atomic time to solar time variations*
- Not included in GPS Time
  - *GPS Time is continuous, steered to UTC(USNO), but does not include leap seconds*
  - *To trace GPS Time back to UTC(USNO), user must keep track of leap seconds*
- Not included in WAAS Network Time
  - *Based on GPS Time*
- Not recommended for WAAS Ensemble Time

23

Alternative Architectures

1. Ensemble locally & distribute campus-wide
2. Ensemble all & distribute over wide area
3. Ensemble locally & distribute regionally
4. Ensemble all plus other agencies' systems & distribute over wide area

24

Criteria for Assessment

- Benefit to users
  - *Aviation users*
  - *FAA systems*
  - *Others*
- Ease of implementation
- Reuse of current capabilities
- Cost
- Political acceptance

25

Alternative 1

- Ensemble 3 cesium standards at each WRS, create physical replica & steer to UTC(USNO) daily (less leap seconds), distribute campus-wide
  - *Requires comparison system & local microstepper or rubidium for replica, plus distribution (copper & fiber)*
    - Single rubidium exists as part of legacy communications systems at ARTCC
  - *Requires common view or TWSTT equipment; (interim) alternative, all-in-view GPS timing receiver*
    - Alternative not fully independent of GPS, but good enough
    - Several GPS timing receivers exist at ARTCC
  - *Optionally connect as tertiary "Stratum 1" input in local FTI equipment*
- Local only, low cost, no WAAS mods

26

Alternative 2

- Ensemble 114 cesium standards at central location, create physical replica & steer to UTC(USNO) daily (less leap seconds), distribute via WAAS
  - *Consider using WAAS External Interface (WEI) as means of exporting needed clock comparison data*
  - *Test at limited number WRS – e.g, Longmont ARTCC & NIST Boulder – consider partnership with NIST & USNO*
  - *Long term create ensemble in multiple locations (same data), such as GUS's, & implement replica in GUS cesium which generates WAAS signal*
  - *Implement WAAS message type 12 in L1 but for WAAS Ensemble Time offset from GPS Time; develop more robust message for L5 to provide offset to UTC(USNO)*
- Wide area, clock comparison costs, WAAS mods

27

Alternative 3

- Recommendation 1 plus regional distribution
  - *Examine regional FAA facilities near each WRS*
    - Determine criticality of need for Stratum 1 frequency and/or precise time, independent of GPS, at each
    - Consider extending campus-wide fiber network to such facilities and/or installing a single cesium at each
  - *Examine broadcast site opportunities near each WRS*
    - Include NDGPS, other government agency sites, TV transmitters, communications, etc.
    - Consider extending campus-wide fiber (in partnership with other agency or commercial provider) to sites
- Regional distribution, more costly w/cost-share opportunity, no WAAS mods

28

Alternative 4

- Partner with NIST and other agencies to develop robust (civil agency) distributed national clock
  - *Similar to Recommendation 2, partner with USNO & NIST, but extend network to other agencies, which may have sites with 3 or more cesium standards*
    - Includes NIST & USNO remote sites, NGA monitor stations, NOAA, NASA, national labs, and in particular USCG
  - *USCG operates eLoran network*
    - 18 CONUS, 6 Alaska, and 5 Canada (under bilateral agreement) Loran transmitters
    - Each transmitter site includes 3 cesium standards, ensemble comparison system, & daily steering to UTC(USNO) via TWSTT (initially via all-in-view GPS)
- Interagency partnership, ability to share costs of TWSTT, no WAAS mods needed

29

Assessment

- Alternative 1 is simple to implement
  - *Benefits FAA internally*
  - *No change to WAAS*
  - *Low cost*
- Alternative 2 provides global aviation benefits
  - *More difficult to implement*
  - *Minor WAAS change – enables WAAS time distribution*
  - *Higher cost*
- Alternative 3 prepares FAA for future needs
  - *Provides FAA-wide time & frequency independent of GPS*
  - *Technically more difficult*
  - *Higher costs (comms, frequency standards)*

30

Assessment (cont.)

- Alternative 4 provides greatest benefit nationally
  - *Most difficult to implement, technically & politically*
  - *Not all within FAA control*
  - *Option 3 sets example, others might join*
- Overall
  - *Alternative 1 ready for implementation*
  - *Test concepts Alternative 2 & develop further*
  - *Continue to study Alternative 3*
  - *Hold off, for now, further consideration of Alternative 4*

31

Way Ahead (planned May 2009)

- Implement Alternative 1
  - *Visit other WRS (at ARTCC & other FAA facilities)*
  - *Develop test with FTI to quantify benefit of providing tertiary input*
- Facilitate concept development of Alternative 2
  - *Test ensemble of cesium standards from multiple sites*
  - *Develop plan for full implementation*
  - *Coordinate minor WAAS modifications for distribution via GEO, upgrade of message type 12, etc.*
- Continue study of Option 3
  - *Examine technologies, performance potential, limitations, rough order of magnitude costs, etc.*
  - *Extend tests with FTI & also point-point fiber circuits*

32

Currently Under Review (updated thru Dec 2009 meeting)

- Clock & ensemble performance
- Communications system stability improvement
- Synchronization of remote sites
  - *Candidate sites for wide-area multi-lateration*
- Distribution of precise time via WAAS
- Time transfer options
  - *Internal synchronization of WAAS Ensemble Clock*
- Near term opportunities

33

Draft *Observations*

- To use installed cesiums as "clocks"
  - *Can be done, performance as predicted can be attained*
  - *Need minimal set of clock management rules*
  - *Data discontinuities observed presumed based on maintenance actions*
- Support to communications
  - *Feasible at co-located sites – several technical options to implement & should be considered*
  - *Not likely to provide backup beyond co-located sites due network configuration*
  - *Contractual issues*

34

Draft *Observations (cont.)*

- Remote sites synchronization for multi-lateration
  - *Over wide area to support enroute RNP 0.3, need <50 ns time uncertainty at each site among all sites in a particular solution*
    - In a local area to support approach, need <20 ns; for surface navigation, need <10ns
    - Focus on wide area
  - *Nationwide some candidate 1000-2000 remote sites, most not co-located with WAAS Reference Stations*
    - Need means to distribute accurate time to each site
    - Need means to assure uninterrupted communications also

35

Draft *Observations (cont.)*

- Distribution of time via WAAS
  - *Message type 12*
  - *GPS Time vs. UTC(USNO) option*
- Internal WAAS time transfer options
  - *WAAS existing calculation*
  - *GPS timing receiver*
  - *Common view or two-way satellite time transfer*
- Near term
  - *Impact of Loran-C termination, e.g, on Alaska satellite communications network*
  - *Wide-area multi-lateration tests*

36

Questions?

BACKUP

38

Acronyms

AFSPC	Air Force Space Command	IDA	Institute for Defense Analyses
ARTCC	Air Route Traffic Control Center	IEEE	Institute of Electrical and Electronics Engineers, Inc.
AT	Atomic Time		
DHS	Dept of Homeland Security	IGS	International GNSS Service
DNX-11	Specific comms device for FTI	JPL	Jet Propulsion Laboratory
EGNOS	European Geostationary Navigation Overlay Service	LORAN	Long Range Navigation
		MSAS	Multi-functional Satellite Augmentation System
eLoran	Enhanced LORAN		
FAA	Federal Aviation Administration	NAS	National Airspace System
FTI	FAA Telecommunications Infrastructure	NASA	National Aeronautics and Space Administration
GAGAN	GNSS Aided GEO Augmented Navigation	NIST	National Institute of Standards and Technology
GDGPS	Global Differential GPS	NGA	National Geospatial-Intelligence Agency
GEO	Geostationary Earth Orbit		
GNSS	Global Navigation Satellite Service	NRL	Naval Research Laboratory
		NTP	Network Time Protocol
GPS	Global Positioning System	PTP	Precision Time Protocol
GPSOC	GPS Operations Center	SBAS	Space Based Augmentation System
IAT	Independent Assessment Team		

39

Acronyms (cont.)

SI Second	International time standard based on Cesium atom
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USCG	United States Coast Guard
USNO	United States Naval Observatory
UT	Universal Time
UTC	Coordinated Universal Time
WAAS	Wide Area Augmentation System
WET	WAAS Ensemble Time
WNT	WAAS Network Time
WRE	WAAS Receiver Equipment
WRS	WAAS Reference Station
1PPS	1 Pulse Per Second

40

Charter Tasking

- **What can be done to coordinate the clocks?**
  - ***First IAT task: 3 candidate architectures***
  - ***Second IAT task: recommended architecture***
- **Conditions for analyses**
  - ***WAAS Network Time (WNT)***
    - **Generated for internal use**
    - **Steered close to GPS Time**
  - ***If GPS reception interrupted***
    - **WNT would slowly drift from GPS Time**
    - **But WAAS has 114 clocks in 38 geographic locations**

41

Definitions

- **WAAS Network Time**
  - ***Sometimes abbreviated WAAS Time***
  - ***Essentially WAAS's version of GPS Time***
  - ***As currently calculated in WAAS***
  - ***Internally required for proper WAAS function***
- **WAAS Ensemble Time**
  - ***New term proposed herein for result of coordination of the cesium standards within WAAS***

42

Data Reviewed

- "WAAS 101" & WAAS operations
  - *WAAS Network Time (current & potential in future)*
  - *Current L1 & future L5 SBAS constraints & opportunities*
- National Airspace System (NAS) overview
  - *Current operations & future plans*
  - *WAAS contributions – current L1-only & future L1-L5*
- Coordinated Universal Time (UTC) … et al
  - *Definitions, sources, distribution methods, etc.*
  - *Reviewed perspectives from USNO, NIST, NGA, NASA, JPL, NRL, others vis-à-vis time & frequency*
  - *Reviewed time & frequency management in GPS, WAAS, IGS, GDGPS, eLoran, other systems*

43

Data Reviewed (cont.)

- Precise time & frequency management & distribution
  - *GPS Time & GPS Operations Center (GPSOC)*
  - *WAAS Time (as currently calculated) & what could be*
  - *Ensemble methods, opportunities & constraints*
  - *Distribution methods – local, campus, & wide-area*
- International issues
  - *Dominantly vis-à-vis GPS augmentations (WAAS, EGNOS, MSAS, GAGAN, et al)*
- Internet & telecommunications
  - *NTP, PTP (IEEE1588 protocol), internet timing*
  - *Telecommunications systems use of time & frequency*

44

Data Reviewed (cont.)

- FAA needs for accurate time & precise frequency
  - *Within ARTCC (campus-wide)*
  - *Distributed (regionally & wide-area)*
- US needs for accurate time & precise frequency
  - *Volpe timing & frequency needs (infrastructure) study for DHS*
  - *Modern (civil, commercial, consumer) systems' use of time & frequency*
- Impacts of recent technology developments on user equipment
  - *Cold atom technologies for inertial & clock systems*
  - *Chip scale atomic clocks*

45

Appendix E: FAA Systems Requiring External Source of Frequency or Time

Data provided during visit to Air Route Traffic Control Center (ARTCC) Longmont CO on 17 March 2010. Based on discussions in prior visit (October 2008) and when setting up this follow-up visit, chief engineer had completed survey of systems using external source of frequency or time at that facility. Systems are listed below, information as provided to IAT:

SBS/ADS-B: Surveillance Broadcast System for Automated Dependent Surveillance-Broadcast
- Uses IRIG-B timing
- From LAN

ADAS: Automated Data Acquisition System
- Uses IRIG-B timing
- From CTS

CTS: Coded Time Source
- Obtains time & frequency via GPS Timing Receiver

DSR: Display System Replacement
- From HOST

ECG/EBUS: En route Communications Gateway/Enhanced BackUp Surveillance
- Uses IRIG-B timing
- From CTS

ERAM: En Route Automation Modernization
- From NTS

ERIDS: En Route Information Display System
- From NTS

ERIT: En route Radar Intelligence Tool
- Does not require time or frequency input

FDIO-G: Flat Display Input Output Gateway
- From CTS via ECG

HIDNASLAN (HNL): Host Interface Device National Airspace System (NAS) Local Area Network (LAN)
- Also called LAN
- From HOST

HOST: Re-HOSTed from prior IBM-based system; En Route Automation System
- Uses IRIG-B timing
- From CTS

IDS4: Information Display System 4
- Unknown if requires time or frequency input

ITWS: Integrated Terminal Weather System
- Unknown if requires time or frequency input

NADIN: NAS Digital Information Network
- Unknown if requires time or frequency input

TFMS/ESIS: Traffic Flow Management System/En route Status Information System
- From its own Network Time Protocol (NTP) Server

TMA/CTAS: Traffic Management Advisor/Center-TRACON Automation System
- From HOST

URET: User Request Evaluation Tool
- From HOST

WAM: Wide Area Multi-lateration

- Does not require time or frequency input

WARP: Weather And Radar Processor

- From CTS

VSCS G/G Nodes: Voice Switching Control System

- Uses 1 MHz frequency reference
- From its own Rubidium atomic frequency standard

VCSU: VSCS Control System Upgrade

- Uses RS232 timing
- From CTS

DALR Voice Recorder: Digital Audio Legal Recorder

- Uses IRIG-B timing
- From (its own) GPS receiver

VTABS: Voice Training And Backup System

- Uses RS232 timing
- From CTS

Appendix F: Providing External Stratum 1 Frequency to FTI

Review of GPS receiver in the CXR Larus StarClock TiemPro 6400 Next Generation Timing Platform

It is available in a fully redundant GPS engine driven Stratum 1/PRC version. The GPS receiver is a 16-channel L1 C/A code receiver. It has a tracking sensitivity of -138 dBm = -168 dBW which is a 9.5 dB weaker signal than the specified minimum GPS L1 C/A code signal strength of -158.5 dBW (-128.5 dBm) into (effectively) a unity gain right-hand circularly polarized antenna. This translates into about 30 dB J/S performance, although no such claim is made for the product. It is specified with a timing accuracy with respect to UTC of 30 ns. (We believe they actually meant to say UTC(USNO).)

The receiver module (Model 6401-1) provides Stratum 1 level performance by extracting timing information from at least one orbiting GPS satellite. It provides the means to set the initial position of the antenna phase center into the receiver to achieve faster initial satellite signal acquisition, thereby entering into the Stratum 1 mode much quicker. Other design features include: (1) antenna short protection which is needed since there is power sent from the receiver to the antenna preamp (or preamp/down converter…see below) via the center conductor of the coaxial cable; (2) Leap Second prediction; (3) WAAS compatibility; and, (4) Time Receiver Autonomous Integrity Monitoring (TRAIM) support. Once the receiver is tracking more than four satellites so that the TRAIM can operate until Stratum 1 mode is entered, then the antenna phase center is very accurately located. Since, the phase center tends to be relatively stationary, then a “position hold, velocity equal zero” mode can be entered so that the number of GPS satellites being tracked can drop down to two and TRAIM is still effective for accurately computing “time bias and time bias rate” for each satellite while comparing these results to one another for anomalies. The number of satellites tracked can actually drop to one with good GPS time transfer accuracy, but without TRAIM assurance of signal integrity. It is highly unlikely that the level of satellite tracking degeneration will ever fall below two except under the condition of RFI, in which case all the satellites will be lost.

The system will switch to the external terrestrial reference inputs in the event of a GPS failure and the internal clocks will both automatically switch back to GPS tracking when the failure clears. There are options for other input reference signals when the unit is not in the GPS mode and there are cards that provide a jitter free tracking crystal oscillator signal or rubidium oscillator signal (depending on how equipped) to the output cards. The phase of the output signal is continuous during any switch from track to hold. There is no output phase discontinuity during the switch. An alarm is sent when one or more outputs have failed.

There is a proprietary DUC GPS Antenna Extender Kit available that permits the use of low cost generic RG58 type coaxial cable for run lengths up to 1500 ft (457 m) without loss of signal quality. The kit contains a GPS antenna with a built-in preamp and frequency down-converter for remote roof mounting and an up-converter on the receiver that converts the signal back to L1. The intermediate frequency is not disclosed, but its lower frequency supports lower coaxial cable losses and its signal conditioning (low noise amplification) in the down conversion unit compensates for any additional coaxial cable losses.

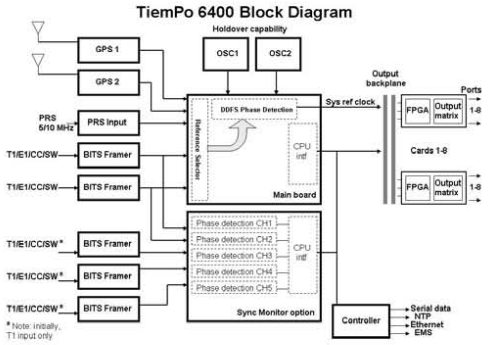
CXR Larus StarClock TiemPro 6400 GPS receiver (Description)

- Faruno Electric Model GT-8031 16-channel L1 C/A code receiver
  - Provides fully redundant GPS engine driven Stratum 1/PRC timing
  - Specified timing accuracy: 30 ns with respect to UTC
  - http://www.furuno.co.jp/en/product/gps/receiver/gt8031.html
- Tracking sensitivity: -138 dBm (-168 dBW)
  - Versus GPS guaranteed minimum: -128.5 dBm (-158.5 dBW)
  - Provides 9.5 dB tracking margin
    - Signal noise increase (jamming) capability not tested
    - Signal attenuation capability tested – meets 30 ns spec at minimum
- DUC GPS Antenna Extender Kit available
  - Permits low cost generic RG58 type coaxial cable for run lengths up to 1500 ft (457 m) without loss of signal quality.

CXR Larus StarClock TiemPro 6400 GPS receiver (Features)

- Time Receiver Autonomous Integrity Monitoring (TRAIM) support
  - Detects loss of integrity of GPS satellite and rejects bad SVs
    - Can provide accurate time transfer with as few as one SV tracked
  - System switches to external terrestrial reference inputs if GPS fails
  - Internal clocks will both automatically switch back to GPS tracking when failure clears
  - Untested for RFI or spoofing (typical for commercial GPS)
- WAAS compatibility
- Leap Second prediction
- Numerous GPS receiver parameter control features
- Antenna short protection
  - Protects power sent from the receiver to the antenna preamp via coax center conductor

External Reference Input



WAAS Clock -> PRS Input

- One or Two WAAS Cesium clocks could act as the external PRS input to the TiemPro 6400
- The system can be programmed to fall back to the external reference if GPS is lost.
- The system can even be programmed to bypass internal Rb Clock so the outputs are directly derived from the PRS inputs

Appendix G: Commercial Timescale System Examples

This appendix includes data sheets downloaded from www.symmetricom.com, the website for Symmetricom, Inc., a provider of time and frequency systems.

The first describes their full timescale system, with a photograph showing an equipment rack with three cesium atomic frequency standards and power conditioning equipment in the lower portion, and the actual timescale system in the upper portion. The second is an extract from the data sheet showing a modular system, which has been used as the basis for the USCG Loran-C Time and Frequency Equipment (TFE) suite.

TIMING, TEST & MEASUREMENT

Symmetricom

Commercial Time-Scale System

Fully Integrated, World-Class Turn-Key Timing System

STANDARD FEATURES

- Include Up To 7 High Performance Cs Clocks
- GPS Common View Time Comparison
- BIPM Reporting
- Frequency Accuracy +/- 1E-14 (Long Term)
- Time Accuracy to 5ns RMS to UTC (USNO)
- NTP
- Battery Back-Up
- Local GUI

OPTIONAL FEATURES

- Active H-Maser
- Multi-Channel Measurement System
- Hot Swap Distribution Chassis
- Multiple Outputs
- TWTT
- Data Storage

As the international standard time scale, Universal Coordinated Time (UTC) is the composite of clocks throughout the world. The time of each clock is reported to the International Bureau of Weights and Measures (BIPM) using either GPS common view (CV) or Two-Way Satellite Time and Frequency Transfer. National laboratories also compute a local time scale steered to agree with UTC designated as UTC(local). Local UTC time-scale systems have state-of-the-art frequency stability, phase noise performance, and system availability. To be incorporated in UTC, their internal clocks cannot themselves be steered by UTC and the CV data must be calculated and reported to the BIPM in accordance with its published method and format.

The Symmetricom Time-Scale System meets these requirements using Symmetricom manufactured commercial timing products. Compared to other solutions, Symmetricom offers faster deployment, lower ownership costs, higher product quality, spare parts that are easier and less expensive to get, and a single point of responsibility for all system support.

The Symmetricom solution unites these advantages with the world's most widely adopted frequency standards for UTC generation. (The Symmetricom 5071A, alone accounts for 76% of all UTC clocks and contributes 87% of UTC time.) The Symmetricom –Time-Scale System can combine up to seven high-performance frequency standards in a time scale that drives the local real-time clock (RTC) signal. A timing quality GPS receiver provides the information used to steer the system output to UTC and generates GPS common-view data. This allows the frequency standards to be reported to the BIPM for inclusion in the international time scale. As a fully integrated solution, the system provides industry-leading frequency stability, phase-noise performance, and time-scale availability in a unit as small as one instrument rack.
In short, it's now possible to purchase a fully integrated, world-class timing solution comparable to the best national laboratories with commercial hardware and software support included. A unique set of design features enables the state-of-the-art functionality, performance, and reliability needed to establish a national timing reference or a global or regional navigation satellite system.

FIG 1 Turn Key Timing System

CONFIGURATION OPTIONS

One advantage of a modular solution is the ability to cost-effectively plug and play components to tailor the solution to a specific need. Symmetricom offers a variety of frequency standards and other configuration options. A minimum system consists of:

- Equipment rack
- 5071A cesium standard
- Monitor
- Keyboard
- Battery backup unit (BBU)
- Modular chassis with controller, synthesizer, RF distribution amplifier, and GPS receiver,

This minimum system provides a time scale steered to UTC, real time frequency and time references, NTP, and GPS common view data that may be used to contribute clock data to the BIPM for the UTC calculation. Additional clocks, the clock measurement system, supplemental power backup, the database, additional signal generation, and additional signal distribution may be added later. Table 1 shows the equipment provided in the standard configuration and available equipment upgrades.

Some of the options available within the framework of the standard Timescale System are:

- Adding a two-way time transfer modem
- Adding or deleting output signal types and distribution
- Adding or deleting cesium standards
- Adding one or more active hydrogen masers

The choice of frequency standards depends on the applications for the system's frequency and time outputs. All Symmetricom atomic clocks interface to the Timescale System and provide status and fault monitoring information.

Standard Configuration (Single Cesium Clock Steered to UTC) Produces a real time clock steered to UTC via GPS. The RTC has 5 outputs at 5 MHz and a single 1 PPS output.
5071A High Performance Cesium Standard
Real Time Clock Subsystem
Switch & Distribution Subsystem
Battery Backup Subsystem
UTC Recovery, Clock Steering and Common View Monitor & Control Software
Rack, monitor, keyboard and cables
Upgrade to include 8-Clock Measurement System:
8 Channel Multi Clock Measurement System
Database
Multiple Clock Upgrade
5071A High Performance Cesium Standard (S)
MHM2010 Active Hydrogen Maser (S)
1MHz, 10 MHz, and IRIG-B Upgrade
Additional RF and timecode outputs

Table 1 Symmetricom Timescale System Configurations

COMMERCIAL TIME-SCALE SYSTEM

SYSTEM SPECIFICATIONS FOR STANDARD SYMMETRICOM TIME-SCALE SYSTEM

NUMBER OF CLOCKS: 3 or more high-performance 5071A cesium clocks

SYSTEM TIME AND FREQUENCY:
Time scale computed as the average of the clocks

Switching: automatic switching between clocks with no time or frequency discontinuities and long-term time or frequency errors

OUTPUTS

5 MHz (Steered system output)
Level: 13 ± 1 dBm, 50 W
Spurious: < -80 dBc
Harmonics: < -40 dBc
Phase noise:

Offset frequency (Hz)	dBc/Hz
1	-106
10	-136
100	-151
1 k	-156
10 k	-160
100 k	-160

SHORT-TERM STABILITY:

τ (s)	$\sigma y(t)$
1	$5x10^{-12}$
10	$3.5x10^{-12}$
100	$8.5x10^{-13}$
1 k	$2.7x10^{-13}$
10 k	$8.5x10^{-14}$
100 k	$2.7x10^{-14}$
500 k	$1x10^{-14}$

FREQUENCY ACCURACY: $\pm 1x10^{-14}$ for 10 day averages after 10 days of continuous operation

FREQUENCY HOLDOVER: ±1x10-13 for 30 days over the full temperature range

1 PPS

Time accuracy:	5 ns RMS relative to UTC(USNO) at time of shipment
Time stability (wander):	3 ns RMS relative to UTC(USNO) via passive GPS
Time holdover:	± 300 ns relative to UTC over the full temperature range after 10 days of operation
Time transfer accuracy:	2 ns RMS relative to UTC via GNSS common view
Jitter:	< 100 ps
Level:	Logic 0 < 0.8 V, Logic 1 > 4.5 V into a 50 W load
NTP	Transactions: > 200/s (without S250i)

DATA STORAGE: Sufficient to store all clock comparison measurements for 10 years

BATTERY BACKUP: 24 VDC Nominal
> 2 hrs

USER INTERFACE: All control through a local GUI using keyboard, mouse, and LCD display

STATUS MONITORING:
Outputs
System specifications
Clock parameters
Power supply voltages
Backup battery status
Faults stored in a database for analysis

TIME COMPARISON:
Passive GPS comparison with UTC via GPS (< 1 ns resolution)
-L2 codeless reception, GLONASS, and GALILEO upgrade optional

Two-way GPS comparison with UTC via BIPM Common-View and Clock Reports (< 2 ns RMS)

Time comparisons of 3 clocks and real-time steered clock < 1 ps

TIME SCALE
No discontinuity in time scale on clock additions or deletions

Clock models
- Cs clocks have white fm and random walk fm
- H masers have white pm, white fm, random walk fm, random walk frequency aging

Clock weighting to optimize short and long-term stability
- 3 weights per clock

Kalman filter time and frequency estimation
-Minimum squared error estimates
- Optimum transient response

Filter remains optimum even when measurement data are missing
- Bad data filtering
- Fast rejection based on matched filter response to known outlier types such as phase steps
- Robust outlier detection based on inconsistencies with the physical model

ENVIRONMENTAL

Power:	100, 120, 220, or 240 VAC nominal, 47-63 Hz, 1 kW maximum 24 VDC nominal
Ambient Temperature:	0 – 50 °C
GNSS Antenna Location:	Roof Mounted with clear view of sky above 10 degrees Surveyed antenna position with accuracy < 0.5 m required (survey service optional)

SYSTEM SPECIFICATIONS FOR STANDARD TIME-SCALE SYSTEM WITH AT LEAST 1 ACTIVE HYDROGEN MASER

Adding active hydrogen masers to the Turn-key Timing System provides additional output signals with the best frequency stability commercially available. As with the 5071A units, the masers can be reported to the BIPM for inclusion in the international time scale

NUMBER OF CLOCKS:

2 or more high-performance 5071A cesium clocks

1 or more MHM-2010 active hydrogen masers

SYSTEM TIME AND FREQUENCY:

Time scale computed as the weighted average of the clocks

Switching: automatic switching between clocks with no time or frequency discontinuities and long-term time or frequency errors

OUTPUTS

5 MHz (Steered system output)

Level:	13 ± 1 dBm, 50 W
Spurious:	< -80 dBc
Harmonics:	< -40 dBc

Phase noise:

Offset frequency (Hz)	dBc/Hz
1	-106
10	-136
100	-151
1 k	-156
10 k	-160
100 k	-160

SHORT-TERM STABILITY (1 HZ MEASUREMENT BANDWIDTH):

τ (s)	$\sigma y(t)$
1	2.5×10^{-13}
10	5×10^{-14}
100	1.3×10^{-14}
1 k	3.2×10^{-15}
10 k	3×10^{-15}
100 k	3×10^{-15}
500 k	4×10^{-15}

FREQUENCY ACCURACY:

±5x10-15 for 10 days after 10 days of continuous operation

FREQUENCY HOLDOVER:

±1x10-13 for 30 days over the full temperature range

1 PPS

Time accuracy:	5 ns RMS relative to UTC(USNO) at time of shipment
Time stability (wander):	3 ns RMS relative to UTC via passive GPS
Time holdover:	± 300 ns relative to UTC over the full temperature range after 10 days of operation
Time transfer accuracy:	2 ns RMS relative to UTC via GNSS common view
Jitter:	< 100 ps
Level:	Logic 0 < 0.8 V, Logic 1 > 4.5 V into a 50 W load

NTP

Transactions: > 200/s (without S250i Enterprise Time Servers)

DATA STORAGE: sufficient to store all clock comparison measurement for 10 years

BATTERY BACKUP: 24 VDC Nominal

> 1 hrs

Hotpack environmental chambers require facility backup power (e.g. generator)

USER INTERFACE: All control through a local GUI using keyboard, mouse, and LCD display

STATUS MONITORING:

Outputs
System specifications
Clock parameters
Power supply voltages
Backup battery status
Faults stored in a database for analysis

TIME COMPARISON:

Passive GPS comparison with UTC via GPS (< 1 ns resolution)
- L2 codeless reception, GLONASS, and GALILEO upgrade optional

Two-way GPS comparison with UTC via BIPM Common-View and Clock Reports (< 2 ns RMS)

Time comparisons of 3 clocks and real-time steered clock < 1 ps

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Clock models
- Cs clocks have white fm and random walk fm
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- Clock weighting to optimize short and long-term stability
- 3 weights per clock

Kalman filter time and frequency estimation
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- Filter remains optimum even when measurement data are missing

Bad data filtering
- Fast rejection based on matched filter response to known outlier types such as phase steps
- Robust outlier detection based on inconsistencies with the physical model

ENVIRONMENTAL

Power: 100, 120, 220, or 240 VAC nominal, 47-63 Hz, 1 kW maximum
24 VDC nominal
Hotpack Environmental Chambers require 208/230 V, 3 kW each

Ambient Temperature: 0 – 50 °C
Hotpack 0 - 30 °C
Without Hotpack, masers located in a room with 23 ± 0.15 °C temperature control
GNSS Antenna Location: Roof mounted with clear view of sky above 10 degrees
Surveyed antenna position with accuracy < 0.5 m required (survey service optional)

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System-2000 - Modular Distribution Solution, Frequency Distribution

System 2000

Loran-C Timing

Symmetricom designed this system for the US Coast Guard to provide timing for the US LORAN-C transmitter stations. This system contains a 2000 series chassis that performs UTC recovery, computes a local time scale from three cesium clocks, and steers the time scale to UTC (USNO). A separate chassis provides the transmitter specific signals needed to operate the station. Two redundant systems are included in the rack with automatic switching in the event of failure.

symmetricom.com/.../index.cfm?print&...